3,3'-Bis(acylamino)-2,2'-bipyridine discotics: desymmetrization and functionalization

Citation for published version (APA):

DOI:
10.6100/IR657799

Document status and date:
Published: 01/01/2010

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
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3,3'-Bis(acylamino)-2,2'-bipyridine discotics: desymmetrization and functionalization

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op woensdag 24 februari 2010 om 16.00 uur

door

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geboren te Heerlen
Dit proefschrift is goedgekeurd door de promotor:

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Copromotor:
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Cover design: ICMS animatiestudio (dr. ir. Koen Pieterse)
Printing: Gildeprint Drukkerijen, Enschede

A catalogue record is available from the Eindhoven University of Technology Library


This work has been financially supported by the Dutch National Research School Combination Catalysis (NRSC-Catalysis)
3,3'-Bis(acylamino)-2,2'-bipyridine discotics

Desymmetrization and functionalization

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Desymmetrization and functionalization of discotics

Abstract. This introductory Chapter deals first with the appealing properties of desymmetrized discotics, a selection of their molecular structures created up to now and the synthetic routes to approach them. Desymmetrized discotics may give rise to multifunctional self-assemblies by incorporation of one function in an individual disc. Thereafter, the study of desymmetrized and functionalized 3,3'-bis(acylamino)-2,2'-bipyridine based discotics is presented as the main theme of the thesis.
1.1 Introduction

Discotics, disc-like molecules with potential mesogenic properties, are important building blocks in the field of supramolecular chemistry. Together with the important class of calamitic, i.e. rod-like mesogens, disc-like mesogens are liquid crystals (Figure 1). Liquid crystals are very important in daily life; they are the main components in LCD screens for example. Liquid crystal are considered as a fifth state of matter, besides solids, liquids, gases and plasmas, the latter state of matter being by far the most abundant state of matter: it is the building material of stars. A liquid crystal can be defined as a self-assembled material that possesses orientational order without or with only short range positional order; the order is less than three-dimensional, since the latter is characteristic of a crystal. At the molecular level, liquid crystal behavior is directly related to structure and can be induced by a combination of structural factors that may be divided into three classes: anisotropic shape of the molecules, micro-phase-separation between incompatible rigid and non-rigid segments (usually between a rigid aromatic part and a flexible aliphatic part) and specific interactions between individual molecules. Considering dicotics, the interplay between these structural factors is dominated by the presence of a rigid disc-like core.

Figure 1: Schematic representation of calamitic and discotic mesogens.

Mesophases of discotics can be divided into two nematic mesophases, discotic nematic (N\textsubscript{D}), columnar nematic (N\textsubscript{C}) and into columnar mesophases. In the N\textsubscript{D} mesophase, the discotics possess only orientational order without any long range positional order. In the N\textsubscript{C} mesophase, the discotics are assembled into short, disordered stacks that display only some positional order along their columnar axis and the discotics possess orientational order. Both nematic mesophases are rather fluid compared to the columnar mesophases and are usually assigned on the basis of Schlieren textures observed under the optical microscope using crossed polarizing filters. The columnar mesophases are usually characterized by the presence of focal-conic textures. A more detailed discussion of the columnar mesophases is given in the introduction to Chapter 3. In the following paragraphs, supramolecular mesogens, composed of more than one type of molecule, that form columnar self-assemblies, and single-core desymmetrized discotics (composed of one type of molecule) are described. Symmetrical discotics are outside the scope of this thesis and these mesophases are not discussed here but details can be found in some excellent reviews.
1.2 Supramolecular columnar mesogens

As well as single-core discotics also other molecular structures can give rise to columnar self-assemblies. Such molecules are often already desymmetrized and possess some functionality as is shown in the examples below. These molecular structures can be divided into three main categories: Firstly, supramolecular polymers and dendrimers, secondly self-assembled disc-shaped structures and finally single-core molecules with non-discoid shapes. Well-known examples of the latter are the bowl-shaped mesogens, some of which display ferro-electric or anti-ferroelectric columnar mesophases. The category of columnar liquid crystalline dendrimers and polymers has been thoroughly investigated in the groups of Percec and Serrano, and an appealing example of the genre is shown in Figure 2a. Attractive aromatic interactions between a polymer equipped with electron donating functionalities and wedge-shaped acceptors together with phase separation induce self-assembly into a columnar mesophase, giving materials that display high charge carrier mobilities. Helical liquid crystalline hydrogen bonded polymers were first investigated in the early 1990s. Hydrogen bonding and also ionic interactions may induce the formation of supramolecular mesogenic polymers. Hydrogen bonding or ionic/complexation interactions are responsible for the formation of self-assembled disc-shaped structures as well.

Figure 2: Two appealing examples of helical columnar assemblies of non-single core mesogenic molecules. a) Self-assembly of a polymer equipped with electron donating functionalities possessing fluorinated wedges into multi-layered conductive columns. b) Cation templated self-assembly of four folic acid based units into a disc-shaped supramolecule that forms columnar liquid crystals.
An example of a hydrogen bonded supramolecular discotic is depicted in Figure 2b. Here, a combination of two-fold hydrogen bonding between the pterin rings of a folic acid unit together with alkali metal ion-carbonyl complexation ensures the formation of the rosette structure. Disc-shaped rosettes form hexagonal columnar mesophases when equipped with the appropriate alkoxy tails. Derivatives based on hydrogen bonded rosettes incorporating folic acid and glutamic acid moieties display helical columnar self-assemblies of biased handedness, as was confirmed using CD spectroscopy. Finally, these cation templated columnar mesogens may be good candidates for one-dimensional conductive materials.

Another type of hydrogen bonded supramolecular discotics that self-assembles into helical structures is derived from a mono-alkylated melamine unit and three V-shaped 3,5-disubstituted benzoic acid derivatives (Figure 3). The supramolecular discotic gives rise to columnar mesophases by a combination of π-π stacking and lateral interactions of the peripheral V-shaped units. The existence of a columnar mesophase is not dependant on the presence of alkoxy tails on the R₁ or R₃ position of discs 1 (compounds 1a-1f). Because the hydrogen bonded discotics adopt a propeller-shaped conformation, the stacks are helical, and display a preference for the P-helix when S-chiral tails are present or for the M-helix with R-chiral tails (compounds 1d, Figure 3). Upon incorporation of azo-benzene functionalities in the V-shaped wedges of the propellers, the helical sense of the columns of the latter can be tuned by means of circularly polarized light in which cis-trans isomerization of the azo unit takes place. Helicity in columnar liquid crystals has been observed more often and a good overview has been published recently.

Figure 3: Self-assembly of three identical alkylated V-shaped benzoic acids with an alkylated melamine moiety into novel propeller-shaped discs 1a-1f. These propellers self-assemble into helical columns in the mesophase with a preference for a single-handed helix when chiral alkoxy tails are present.
1.3 Desymmetrized single-core discotics

Self-assembly of symmetrical discotics in dilute solution is primarily unidirectional i.e. the growth of the supramolecular structure takes place into one direction as well as the interactions between the units.\(^5\) No other interactions will occur in addition to this one-dimensional growth. This is in contrast with self-assembling systems in nature which develop multiple interactions with their neighbors.\(^27\) To extend the potential value and use of artificial self-assembling systems and to resemble more closely the behavior of natural systems, the presence of functionality in the former is required.\(^28\) In the previous paragraph some supramolecular columnar systems were described, of which the majority possess some functionality. For the sake of synthetic simplicity, most single-core discotics possess axial symmetry and are equipped with only one kind of peripheral group.\(^29\) However, the properties of discotics may be enhanced to a large extent by desymmetrization of the molecular structure, which allows the introduction of functional groups and alters self-assembly behavior.\(^1,11,20,30-32\) Sometimes desymmetrization involves adaptation of a disc-shaped core,\(^33\) but usually the core remains symmetric to guarantee comparable stacking properties and, hence, the periphery has to be altered instead.\(^34\) Generally speaking two types of synthetic strategies may be recognized; in the first approach, two or more reactants, the same as those that would be used to synthesize symmetrical discotics, are reacted simultaneously to yield a statistically determined mixture of desymmetrized discotics. Then, the desired product has to be separated from this mixture, which can be very tedious if not impossible. In the second approach, the core of the discotic is built in a step-wise fashion from different precursors avoiding the formation of statistical mixtures. These precursors are usually derivatives of those that are used to synthesize the symmetrical discotics. Although the second, step-wise, method often involves more synthetic steps than the first method, purification steps are usually easier and the intermediates involved may serve as a starting point for the rapid synthesis of a family of desymmetrized discotics in relatively good yield.

1.3.1 Triphenylenes

The most studied discotics are the family of triphenylenes. A wide variety of desymmetrized structures has been reported with the goal of altering mesophases, inducing mesophases or introducing functionality.\(^1,31,35\) Here, the most important synthetic methodologies directed to the synthesis of desymmetrized triphenylenes will be described. A division can be made between synthetic variations in the structure of the core or variations made in the aliphatic periphery of the triphenylene disc. Several approaches to the synthesis of the triphenylene structure have been described (Scheme 1).\(^31\) The most common approaches are the cyclo-trimerization of a benzene derivative (route a), the coupling of a biphenyl unit with a benzene unit (route b) and the cyclization of a terphenyl (route c). Symmetric triphenylenes are usually synthesized via route a. Regarding synthesis of desymmetrized triphenylenes, route a may involve the reaction of up to three different benzene derivatives with each other, while in route b and c two species and a single species are involved, respectively.
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Scheme 1: Schematic representation of the three most common approaches adopted to obtain desymmetrized triphenylenes.\textsuperscript{31} \textbf{a}) Trimerization of benzene derivatives, \textbf{b}) Coupling of a biphenyl with a benzene derivative and \textbf{c}) Cyclization of a terphenyl. The aromatic species shown here are decorated with a wide variety of functional groups in real-life examples of course. The atom numbering together with the indication of the \(\alpha\)- and \(\beta\)-positions on the triphenylene structure are shown.

1.3.1.1 Desymmetrized triphenylenes via route a

The first triphenylene discotics possessing columnar mesophases were described in 1978\textsuperscript{36} and the first desymmetrized derivative already in 1981\textsuperscript{37} The synthesis of the latter was statistically determined; two kinds of dialkoxybenzenes underwent cyclization to give the triphenylenes. In this reaction the formation of four different discotics is possible and they were all formed in a statistical ratio. The separation of this mixture was very tedious. In a slightly different approach, triphenylene functionalized polysiloxanes were synthesized in which monoester 2 is the key intermediate (Scheme 2).\textsuperscript{38} This work was the first example of a liquid crystalline disc-functionalized polymer and was done in the group of Ringsdorf. The synthesis of triphenylene 2 started with an oxidative trimerization of 1,2-dimethoxybenzene (3) by chloranil in acidic conditions to afford hexaether disc 4. Oxidative trimerization of 1,2-dialkoxybenzenes is the most convenient method to afford symmetrical alkoxylated triphenylenes. Then, hexaester 5 was synthesized by ether cleavage with boron tribromide and subsequent acylation of the corresponding phenols in acetic anhydride. Finally, in situ ester hydrolysis and ether formation with bromopentane afforded disc 2 after acylation and separation of the statistical mixture. Thus, the statistically determined disc desymmetrization was performed in the last step.

Scheme 2: The synthesis of non-symmetric disc 2 starting from 1,2-dimethoxybenzene (3).\textsuperscript{39} Note that the first reaction step took 10 days.

The cyclo-trimerization conditions to afford disc 4 are quite harsh, limiting the variety of functional groups that could be selected (Scheme 2). Milder oxidation reagents have been studied like molybdenum(V)chloride,\textsuperscript{39} iron(III)chloride\textsuperscript{40} and vanadiumoxytrichloride.\textsuperscript{41} The
milder conditions afforded higher yields and allowed to introduce a wider variety of functional groups. Hydroxy functionalized triphenylenes are versatile precursors for a wide variety of functionalized compounds possessing for example chiral tails,\textsuperscript{42} acetylene moieties,\textsuperscript{43} cationic groups,\textsuperscript{44} fluorinated tails\textsuperscript{45} or anthraquinone moieties.\textsuperscript{46} Triphenylenes equipped with cationic imidazoliums may form complexes with the phosphate groups of DNA and RNA resulting in mixed columnar phase-separated phases.\textsuperscript{47} Hydroxytriphenylenes are the precursors for a wide variety of disc-functionalized oligomers and polymers\textsuperscript{48} which is illustrated by block-copolymer 6 that was obtained from acrylate disc 7 (Scheme 3).\textsuperscript{49} First, polyacrylate 8 carrying triphenylene side chains was synthesized by atomic transfer radical polymerization (ATRP)\textsuperscript{50} and then, an aliphatic block was added by a second ATRP with the triphenylene block 8 as a macrorinitiator. In these block-copolymers, microphase separation took place in which the disc-functionalized part was hexagonally columnar liquid crystalline.

\begin{align*}
\textbf{Scheme 3:} & & \text{Synthesis of block-copolymer 6 consisting of a discotic-functionalized block and a tertiary-butylated block by sequential ATRP.} & \text{PMDETA} = N,N',N'',N'''\text{-pentamethyl diethylenetriamine}. \\
\end{align*}

1.3.1.2 Desymmetrized triphenylenes via route b

In the second approach towards desymmetrized triphenylenes, 3,3′,4,4′-tetraalkoxybiphenyl 9 was reacted with dialkoxy benzene 10 to afford triphenylene 11 (Scheme 4).\textsuperscript{51} The biphenyl moiety as well as the benzene derivative may contain one or two different alkoxy functionalities resulting in a triphenylene containing between two and four different groups.\textsuperscript{52} The biphenyl group requires four electron donating ether functionalities to achieve reaction with the benzene moiety, thus hexa-alkoxy triphenylenes are usually obtained.

\begin{align*}
\textbf{Scheme 4:} & & \text{Biphenyl synthesis by Suzuki coupling of bromide 12 and boronic acid 13 and subsequent oxidative coupling giving disc 11 carrying three different substituents.} & \text{PPPh}_3 = \text{triphenylphosphine}, \quad \text{DME} = \text{dimethoxyethane}. \\
\end{align*}

To introduce another heteroatom than oxygen, hydroxyalkoxytriphenylenes are derivatized with tetrazole units followed by catalytic hydrogenation forming triphenylenes possessing free, reactive sites for aromatic substitution.\textsuperscript{53} By applying VOCl\textsubscript{3} as oxidant a wide variety of
Desymmetrization and functionalization of discotics

interesting desymmetrized discotics has been synthesized. A family of discotics equipped with an amide, urea or thiourea in one of the six alkoxy tails has been synthesized using the biphenyl method and FeCl₃ mediated cyclization. Peripheral hydrogen bonding units stabilize the columnar mesophase to a certain extent by additional intracolumnar hydrogen bonding. However, disruption of the columnar mesophases may occur when the hydrogen bonding interactions do not match with the aromatic stacking of the triphenylenes. This shows the necessity of creating an appropriate balance between several reversible interactions in functionalized discotics to afford the desired supramolecular structure.

1.3.1.3 Desymmetrized triphenylenes via route c

The third approach towards desymmetrized triphenylenes involves terphenyl cyclization (Scheme 5), usually accomplished by oxidative cyclization as used for methods a and b (Schemes 1, 2 and 4). Sequential palladium catalyzed cross-coupling between 1,2-dihalobenzene and two arylzinc halides produces terphenyl which is then cyclized to give triphenylene in the same conditions as used for methods a and b.

Scheme 5: The synthesis of highly desymmetrized triphenylene starting from 2-bromo-1-iodo-4,5-dimethoxybenzene via terphenyl intermediate.

In a similar approach, a triphenylene possessing two hexyloxy tails and four thioether linked hexyl tails was obtained. Similar to symmetrical hexa(thioether) triphenylenes, this desymmetrized triphenylene exist in a helical mesophase, depending on the position of the two hexyloxy tails. Recently, disc and its 2,3,6,11-tetra(hexyloxy) isomer were converted into a family of functionalized triphenylenes possessing two aromatic units. The study of the mesophase behavior of this family showed that the perturbation of the molecular structure through variation of substituent is important for the bulk phase properties and that it is impossible to change electronic properties of the triphenylenes without concomitant steric and conformational changes.

1.3.1.4 Desymmetrized triphenylenes by core derivatization

In addition to the relatively easy substitution at one of the peripheral β positions of triphenylene, the less reactive bay α positions may be derivatized by employing electrophilic substitution. This substitution is controlled by steric and electronic effects. Although the α-positions undergo severe steric hindrance, nitrato substitution can be performed in rather mild conditions, due to the electron donating ethers present at the β-positions of the triphenylene core and the small size of the nitronium cation. Even the introduction of multiple nitrogroups has been reported yielding C₃-symmetrical discotics equipped with three nitrogroups. The nitrogroup allows further derivatization as depicted in Scheme 6.
Nitro-disc 19 was converted into amino-disc 20 that allowed to synthesize amide-disc 21 or azide-disc 22 for example (Scheme 6). All α-substitutions result in the deformation of the originally planar conformation of the triphenylene core giving rise to helicity. Halogenation instead of nitration of hexaalkoxytriphenylene 23 on the α-position with the concomitant induction of a propeller shaped conformation, which may induce helical stacking, has been reported as well.62,66 The core-substitution with electron-withdrawing functionalities resulted in stabilized mesophases despite the deplanarization of the triphenylene disc. This is rationalized by the minimization of repulsive interactions between the aromatic cores and by the generation of a dipole moment in the core that might facilitate anti-parallel stacking.43,65,67 Interestingly, α-monofluorinated hexa(hexyloxy)triphenylene could be deuterated on its remaining five α-positions by refluxing in CF₃COOD for 24 hours; the product was useful for detailed ²D-NMR studies.62,66 The small fluorine atom does not induce deplanarization of the triphenylene disc to a large extend, and the in-plane electric dipole caused by the polarized C-F bond stabilizes the mesophase. ²D-NMR is a convenient method to gain detailed information on the orientational ordering and dynamics of discotics in their columnar mesophase provided that a deuterated analog of the discotic is accessible.

1.3.1.5 Extended core triphenylene derivatives
Other desymmetrized derivatives from the triphenylene discs are the core-extended derivatives, usually containing a pyrazine ring. They combine the appealing properties of heterocycles, like charge generation and photophysical effects, with those of columnar liquid crystals and this can be beneficial for molecular electronic devices.69,70 One of the first examples involves the synthesis of phenamine derivative 24 (Scheme 7), starting from dihydroxytriphenylene 25 that was oxidized to quinone 26. The latter was easily reacted with 1,2-diaminobenzene to afford phenamine 24. However, phenamine 24 had a very narrow liquid crystalline window only, in contrast to dipolar dicyano analog 28 that shows liquid crystallinity in a window of more than 200 K (Scheme 8).71 Apparently, the presence of polar functionalities is necessary to achieve mesophase behavior over a broad temperature range.72
Desymmetrization and functionalization of discotics

Scheme 7: Three-step synthesis of phenanine 24 carrying four alkoxy tails starting from mono-hydroxy disc 27.\textsuperscript{70} CAN = \( \text{Ce(NH}_3\text{)}_6(\text{NO}_3\text{)}_6 \).

Dicyno-quinoxaline 28 has been synthesized via a slightly different approach in which the pyrazine moiety was formed prior to cyclization, thus via 2,3-bisphenylpyrazine intermediate 29 (Scheme 8a).\textsuperscript{71} Initially, the latter was synthesized from diketone 30. However, in further synthetic approaches towards quinoxaline derivatives, the cyclization was performed prior to pyrazine formation (Scheme 8b).\textsuperscript{72} This has the advantage of easier cyclization and the possibility to synthesize a wide variety of functionalized discotics in just one step by reacting any functionalized 1,2-diaminobenzene with phenanthrene-9,10-dione 31 (Scheme 8b). The superiority of the approach via phenanthrene-9,10-dione intermediates 31 was further proven in a study of hexaalkoxy phenazine derivatives where the overall yield of this approach was twice as high as that via alkoxyated derivatives of 2,3-bisphenylpyrazine 29.\textsuperscript{73}

Scheme 8: Synthesis of dicyano quinoxaline 28 via two methods, both starting with \( \alpha \)-diketone 30. a) Involving 2,3-bisphenylpyrazine 29 as the key intermediate.\textsuperscript{71} b) Involving phenanthrene-9,10-dione 31 as the key intermediate.\textsuperscript{72}

Inspired by quinoxaline 28 and its large mesogenic window, a family of desymmetrized dicyano-dibenzoquinoxalines 32 has been reported, with the aim to improve mesophase behavior (Scheme 9).\textsuperscript{73} They all rely on the synthesis of diketone intermediate 33, which was easily synthesized from diphenylacetylene derivatives 34 in high yield. The latter were formed in a Sonogashira coupling.\textsuperscript{33}

In a later study, phenazines equipped with an ester or an acid functionality as well as a whole family of functionalized derivatives were successfully synthesized\textsuperscript{74} by the method depicted in Scheme 9. These phenazines allow correlation of the molecular structure with the mesophase behavior.\textsuperscript{67} Recently, a family of mixed tail discotics based on the dibenzophenazine unit has been synthesized to control transition temperatures allowing access to room temperature liquid crystalline materials. Their synthesis was straightforward when applying the route via
the phenanthrene-9,10-dione intermediate (Scheme 9) and reacting the latter with alkylated diaminobenzene derivatives. A dipole moment present in the phenazines facilitates anti-parallel alignment of the columnar aggregates in the mesophase, which was observed in solution, and stabilizes the columnar mesophase. Derivatives equipped with carboxylic acid groups display further stabilized mesophases due to acid dimerization along the columns or by the formation of elliptical dimers.

Scheme 9: Synthesis of phenazines 32 with four alkoxy tails. Only two of the six published products are depicted. The phenanthrene-9,10-dione species 33 are the key intermediates.

1.3.2 Hexa-peri-hexabenzocoronenes
First introduced as a columnar liquid crystalline material in 1996, and thoroughly investigated in the group of Müller, hexa-peri-hexabenzocoronenes (HBCs) possess appealing material properties like stable columnar mesophases, thermal stability and high charge carrier conductivities and they have potential applications in solar cells. Compared to discotics containing smaller cores, HBCs undergo more efficient π-π stacking but the drawback is that the molecules are insoluble in the absence of solubilizing peripheral tails. In addition, these tails are responsible for the liquid crystalline behavior.

1.3.2.1 Apolar functionalized HBCs
The synthesis of desymmetrized HBCs involves the reaction of diphenylacetylene 35 with tetraphenylcyclopentadiene 36 in a [4+2] cycloaddition to afford non-symmetrical hexaphenylbenzene 37. Hexaphenylbenzene 37 was then further aromatized to afford desired HBC disc 38 substituted with one or two bromides (Scheme 10).

Scheme 10: Synthesis of non-symmetrical HBCs 38 carrying one or two bromides and five or four decyl tails.
Tetraphenylcyclopentadienone 36 was obtained via a double Knoevenagel condensation of ketone 39 with 1,2-diketone 40. The latter was synthesized by oxidation of diphenylacetylene 41. Diphenylacetylene 35 and 41 might be synthesized in a Sonogashira coupling starting from aryl halides, or in a Kumada-type Grignard reaction starting from 4,4'-dibromodiphenylacetylene. Mono-ketone 39 can be synthesized effectively from 1,3-bis(4-bromophenyl)-2-propanone. The bromo functionalized HBCs allow the synthesis of HBC discotics containing one or two electron releasing or withdrawing functionalities via nucleophilic aromatic substitution. The presence of these electron-withdrawing functionalities stabilizes the columnar mesophase. Also, HBCs containing polymerizable groups, COOH terminated alkyl tails or imidazolium terminated alkyl tails have been synthesized which allow further supramolecular interactions or polymerization of the columnar mesophase. A nice example of this is the interaction of a carboxylic acid functionalized HBC with poly(ethyleneimine) resulting in mixed columnar LC phases that possesses a higher degree of intracolumnar order compared to the pure discotic. In a more recent example, the same discotic was complexed with an $\alpha$-helix containing block-copolymer. In this case it was shown that two mixed columnar hexagonal mesophases form in which the helical polymer chains are arranged in a relatively well-ordered hexagonal superlattice within the Col$_h$ phase of the HBC. The intracolumnar order in the higher temperature Col$_h$ phase is enhanced with respect to the low temperature phase, while the intercolumnar correlation length in the two-dimensional columnar lattice is decreased compared to pure HBCs.

Introduction of additional peripheral phenyl groups to symmetrical HBCs induced helical self-assembly as was proved by detailed X-ray diffraction measurements and CD spectroscopy in the mesophase. Helical assemblies in the mesophase were also observed when alternating apolar and polar peripheral tails were introduced on the HBC core or in combination with the introduction of a triangular aromatic shape. The latter discotics display very high one-dimensional charge carrier mobilities that largely enhance possible applications of these materials. Besides these symmetrical adaptations on HBCs, peripheral hydrogen bonding amide and urea units have been used to increase the order in HBC based self-assemblies (Scheme 11). These functionalized HBCs were derived from mono-halogenated HBCs. The reinforcement was maximal for the structures containing the strongest hydrogen bonding group or the least bulky substituent (Scheme 11). The reinforced stacking enabled the formation of fluorescent gels in organic solvents for which a Cotton effect was observed in the case of amide disc but not in the case of urea disc. For urea, however, the presence of chiral fibers was demonstrated with SEM. Presumably for both HBCs and helical structures are present in solution due to a rotation between superimposed discs in which both the intermolecular hydrogen bonding and the $\pi-\pi$ stacking are maximized.
Scheme 11: HBCs 42 equipped with one amide or one urea hydrogen bonding unit.\textsuperscript{91}

1.3.2.2 Amphiphilic functionalized HBCs

Another family of desymmetrized hexabenzocoronenes that deserves attention is the class of amphiphilic HBCs 43 that is synthesized with the goal to obtain novel helical conductive nanotubes and nanocoils (Scheme 12).\textsuperscript{92} These discotics contain only four alkyl tails but still display solubility in either polar solvents like THF or relatively apolar solvents like dichloromethane. The amphiphilic discotics have been synthesized starting from hexaphenyl benzene 44 as is depicted in Scheme 12. Tetraphenylcyclopentadienone 45 was synthesized in a manner analogous to that of ketone 36. Disubstituted acetylene compound 46 carrying polar tails was synthesized in two steps from biphenyl derivative 47 (Scheme 12).

\textbf{Scheme 12: Synthesis of amphiphilic HBCs 43 with two apolar and two polar tails starting from bromoalcohol 47 and ketone 45. DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene (non-nucleophilic base).}

Phase separation between the apolar tails and the polar medium induced the formation of a bilayer of HBCs consisting of bilaterally coupled one-dimensional HBC columns. This bilayer is stabilized by the interdigitation of the apolar tails while the interaction of the polar tails with the polar solvent prevents the formation of multi-layer structures. Rolling-up of the two-dimensional bilayer gives the hollow helical nanotube or, if water is present, a looser nanocoil (Figure 4). The latter proved to be metastable but could be preserved by covalent fixation of the coil by ROMP.\textsuperscript{93,94} In a detailed study the presence of the two additional phenyls and sufficiently long apolar tails proved to be essential to generate these novel nanotubes. The presence of the polar EO tails on the HBCs is not essential, but they greatly contribute to the stability of the nanotubes.\textsuperscript{95} These nanotubes, which can grow till lengths of several tens of microns, can be processed into aligned fibers by simple fishing them out of solution.\textsuperscript{96} The
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diameter and the thickness of the tubes have been controlled by making use of complexation between pyridine functionalized amphiphilic HBCs 48a and Pt^{2+} metal ions.\(^9^7\) Equipping the amphiphilic HBCs with stereocenters in the polar tails allowed biasing the helical sense of the nanotube (Figure 4).\(^9^8\) A small amount of chiral S (48b) or R (48c) in a co-assembly with achiral (43) or a small enantiomeric excess of either S (48b) or R (48c) in their co-assembly proved to be sufficient to bias the helical sense to P or M, respectively. Both phenomena have been described for chiral polyisocyanates and self-assembled C\(_5\)-symmetrical discotics too.\(^9^9,1\)0\)

Figure 4: Left: Supramolecular helical nanotubes by the self-assembly of amphiphilic HBCs in polar media like methylTHF. First a meta-stable coil (below) is formed that turns into the thermodynamically more stable tubular structure.\(^9^9\) S-disc (48b) will form the right handed tube and R-disc (48c) the left-handed one. Right: Achiral, chiral and functionalized amphiphilic HBCs 43 and 48.

The high stability of the helical nanotubes in suspension was shown with a post-functionalization experiment in which the exterior part of the nanotube was functionalized selectively.\(^1\)0\) Amphiphilic HBCs decorated with electron accepting trinitrofluorenones (48d) (Figure 4) have been synthesized to create coaxial supramolecular nanotubes consisting of two electron releasing HBC layers in the center of the wall of the nanotube and electron deficient trinitrofluorenone-containing HBC layers on the periphery of the nanotube wall. These functionalized nanotubes display very good photoconductive properties.\(^1\)0\) Mixing unfunctionalized amphiphilic HBCs (43) with trinitrofluorenone functionalized HBCs (48d) further increases the photoconductivity.\(^1\)0\) Besides the covalent fixation by metathesis,\(^9^3\) supramolecular fixation has been brought about for these helical nanotubes.\(^1\)0\) To do so, amphiphilic HBCs were decorated with cationic isothiouronium moieties (48e, Figure 4) that allow complexation with anionic poly(4-styrenesulfonate). The formed complexes, in which the original tubular structure was preserved, were stable in conditions that normally would
dissolve the anionic polymer or the amphiphilic HBCs. Overall, the appealing properties of these supramolecular nanotubes and the ability to tailor their properties using supramolecular synthesis make them—as well as are their non-amphiphilic analogs—promising building blocks for nano-electronics.

### 1.3.3 Phthalocyanines

Phthalocyanines are very versatile discotics that, in contrast to many other discotics, display absorption in the visible and even near-infrared range. Other appealing properties are columnar mesophase behavior, high charge carrier mobilities, and sensing. Phthalocyanines are employed in efficient organic solar cells and n-type field effect transistors as well. Well-known are the derivatives equipped with crown ether functionalities that may self-assemble into aggregates of tunable helicity. Their self-assembly and optical properties can be adjusted by variation of the peripheral tails, incorporation of peripheral electron withdrawing groups or by variation of the central metal ion. In the majority of phthalocyanines the tails are located at the most peripheral β-position, but some α-substituted derivatives with mesophase behavior are also known. A convenient method to synthesize symmetrical, soluble, alkylated phthalocyanines was published in 1980 in which 4,5-dialkoxy-1,2-dicyanobenzene derivatives are the key precursors. The phthalocyanine itself was synthesized from a 1,2-dicyanobenzene derivative that was either directly cyclotetramerized or first converted into a diiminoisoindole followed by cyclotetramerization of the latter.

#### 1.3.3.1 Desymmetrized phthalocyanines

Employing the one-step cyclization methods as described above for the synthesis of desymmetrized phthalocyanines involves the statistically determined reaction between two dicyanobenzene derivatives called A and B. The separation of the reaction mixture to gain the desired desymmetrized phthalocyanine can be very tedious if not impossible. Two synthetic routes can be distinguished that differ in the ratio between A and B: First, the synthesis of AABB or ABAB derivatives and, second, the synthesis of A₃B derivatives. The former are built from two types of isoindole derivatives in a 1:1 ratio and the latter are built from two types of isoindole derivatives in a 3:1 ratio. In the statistically determined synthesis six different phthalocyanines (AAAA, BBBB, AABB, ABAB, ABBB, AAAB) will be formed. A successful separation can usually be performed only if the precursors differ enough in polarity to allow separation by chromatography. This has been performed successfully for phthalocyanines equipped with a combination of apolar alkyl and polar oligo(ethylene oxide) tails. A similar type of synthesis was employed to afford polar phthalocyanine 49 (Scheme 13), which was the first discotic reported containing a large dipole moment. The synthesis of 49 was performed via the isoindole method in which isoindoles 50 and 51 were reacted in a three-to-one ratio. Cyano functionalized isoindole 51 was obtained in one step from 1,2,4,5-tetracyanobenzene 52, but alkylated isoindole 50 required five synthetic steps, starting from ortho-xylene.
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Scheme 13: Synthesis of polar, desymmetrized phthalocyanine 49 starting from ortho-xylene and 1,2,4,5-tetracyanobenzene 52.\textsuperscript{117}

To allow the synthesis of desymmetrized phthalocyanines without the necessity of a statistical approach, selective syntheses have been investigated. This started in the 1980s with the ring expansion of sub-phthalocyanines 53, which can be prepared in a yield of \(-50\%\) by reaction with diiminoisoindole 54 or 55 (Scheme 14).\textsuperscript{118,119} The method proved to be selective, but also proved to be rather unpredictable and highly sensitive to the specific reaction conditions and the reactants.

Scheme 14: Synthesis of desymmetrized phthalocyanines 56 and 57 via ring expansion. These phthalocyanines could not be obtained via a statistically determined synthesis.\textsuperscript{114} Cl-Nap = 1-chloronaphthalene.

More selective synthetic approaches have been used to arrive at functionalized phthalocyanines\textsuperscript{115} and a wider variety of functionalized phthalocyanines can be obtained by performing substitution on the phthalocyanine structure itself. A convenient method to achieve the latter is to synthesize iodo-functionalized phthalocyanines and perform a metal catalyzed cross-coupling to introduce further functionality.\textsuperscript{120} By doing so, valuable materials have been made that are applied, for example, in efficient organic solar cells.\textsuperscript{121}

1.3.3.2 Functionalized phthalocyanines

Because of their attractive absorption characteristics, high stability and good conducting properties, phthalocyanines are popular as electron donating materials in organic photovoltaics.\textsuperscript{105} By deploying phthalocyanines in organic solar cells, a maximum efficiency of 5.7\% has been achieved.\textsuperscript{109} In these photovoltaics, fullerene is used as the electron accepting material. A major point in the efficiency of organic solar cells is control over morphology which can be improved by a better control over the supramolecular organization of the molecules in the active layer of the device. This might be achieved by deploying columnar organization as is found in liquid crystalline phases of mesogenic phthalocyanines.\textsuperscript{122} However, the bulky fullerene unit is not easily accommodated into a columnar mesophase.
Therefore, blends of symmetrical, mesogenic phthalocyanine 58 and fullerene functionalized phthalocyanines 59 were prepared (Figure 5), the latter being equipped with several central metals and peripheral groups to evaluate their influence on the mesomorphic properties of its blends.\textsuperscript{123}

![Figure 5: Mesogenic phthalocyanine 58 and non-mesogenic phthalocyanine 59 that upon mixing give rise to columnar liquid crystalline blends in which charge transfer from a phthalocyanine chromophore to the fullerene may occur.\textsuperscript{123}]

Mixtures of discs 58 and 59 were prepared in a 1:1 molar ratio and all mixtures proved to be Col\textsubscript{h} over a wide temperature range. X-ray diffraction data suggested that phthalocyanines 58 and 59 were mixed throughout the columns in the mesophase but with a partial preference for alternating stacking. Thus, this method might be useful to improve the morphology in bulk heterojunction photovoltaics to increase the dissociation efficiency of the bound electron-hole pairs at the donor (phthalocyanine 58) -acceptor (fullerene) interface.\textsuperscript{123} Although columnar mesophases of phthalocyanines are well known, long one-dimensional self-assemblies in solution are not common.\textsuperscript{124} Usually, a peripheral adaptation of the phthalocyanine structure is necessary. It is well known that crown ether functionalized phthalocyanines may give long, helical self-assemblies in solution.\textsuperscript{111} Threading of these peripheral crown ethers with a cationic templates can give rise to new self-assemblies. Monofunctionalized, amphiphilic phthalocyanine 60 equipped with one crown ether and six octyloxy tails was synthesized in a statistically determined reaction as described in Scheme 13 (Figure 6).\textsuperscript{125} Upon mixing of phthalocyanine 60 with a benzylated diammonium salt in chloroform dimeric dialkylpseudorotaxane complex 61 was formed. Dimer 61 may give access to phthalocyanine based supramolecular electron- and energy-transfer complexes.
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Figure 6: Threaded, dimeric phthalocyanine complex 61 that is formed by complexation of the crown ethers of two phthalocyanines 60 with a bisammonium species.\textsuperscript{125}

In the field of supramolecular chemistry, control over self-assembly is one of the major targets.\textsuperscript{126} Achieving a higher level of order in mixed self-assemblies is desirable for potential applications and the introduction of alternation in columnar aggregates might be a useful example of this, as was discussed in the previous paragraph.\textsuperscript{127} Alternating self-assembly was observed for dimeric phthalocyanine 62 in solution (Figure 7). This phthalocyanine dimer consists of an electron-deficient Ni(II)-phthalocyanine decorated with alkylsulfonyl peripheral groups and an electron-releasing Zn(II) phthalocyanine possessing alkoxy peripheral groups (Figure 7).\textsuperscript{128} The periphery of the phthalocyanines was designed to suppress columnar aggregation. Long, one-dimensional self-assemblies of 62 were formed due to the attractive hetero-interaction between the two subunits as was confirmed using spectroscopic and electron microscopic studies. Monomeric phthalocyanines 63 and 64, however, did not yield large self-assemblies upon mixing, thus supporting the stacking of dimer 62 as represented in Figure 7. Donor-acceptor interactions between similar phthalocyanines were used to stabilize charge-separated states of a zinc-phthalocyanine-fullerene diad.\textsuperscript{129}

Figure 7: Electron-withdrawing and -releasing phthalocyanines 63 and 64 and their covalently fused analog 62 together with a schematic representation of their alternating self-assembly.\textsuperscript{128}
1.3.4 Porphyrins

Functionalized porphyrins possessing mesogenic properties are not as common as their phthalocyanine analogs, but many examples are known of porphyrins possessing appealing supramolecular properties. The core structure of the porphyrin can be functionalized on the pyrrole ring on the meso-position or on both. The synthesis involves the reaction between four aldehydes and four pyrroles to give the porphyrin structure in a one-pot reaction. In a slightly different strategy, coupling of two dipyrrylmethanes with two aldehydes yielded the desired porphyrin. A catalytic amount of a strong Brønsted acid or a Lewis acid like BF₃•Et₂O is usually required. Selective approaches towards desymmetrized porphyrins are known as well and this is exemplified by the efficient synthesis of porphyrins carrying four different meso-substituents. Recently, the versatility of the porphyrin moiety in columnar liquid crystals and as functional material has been established in a beautiful example (Scheme 15).

Scheme 15: Synthesis of amphiphilic, fused porphyrin dimer 68. Only the synthesis of the desymmetrized, amphiphilic compound 68 is shown, but also the symmetrical derivatives were synthesized. DDQ = 2,3-dichloro-4,5-dicyano-benzoquinone, Sc(OTf)₃ = scandium(III) triflate.

The adaptation of the central metal, the nature of the periphery and the size of the aromatic core have been used to tailor the material properties, finally resulting in room temperature columnar liquid crystals with very high one-dimensional electron mobilities. First, two porphyrins 65 and 66, each equipped with nine apolar or nine polar alkoxy tails on the meso-positions, were synthesized by deploying Suzuki-type chemistry. Then, porphyrins 65 and 66 were coupled under Suzuki conditions to give 67, which was cyclized to triply fused bisporphyrin 68, carrying nine apolar and nine polar tails (Scheme 15). Porphyrin 68 displays a novel rectangular columnar mesophase induced by phase separation between the apolar and polar wedges. Interestingly, the apolar and polar symmetrical derivatives of porphyrin 68 do not display a mesophase. The highly ordered mesophase of 68 gives very high one-dimensional electron mobilities making porphyrin 68 a good candidate as an n-type material.
1.3.5 Oligobenzoate stars

An additional family of desymmetrized discotics is based on the 1,3,5-trihydroxybenzene (phloroglucinol) central core diversified by means of oligobenzoate arms.\textsuperscript{32} Compared to the stilbenoid C\textsubscript{5}-symmetrical stars,\textsuperscript{136} these discotics are much more flexible. The C\textsubscript{5}-symmetrical oligobenzoate stars were synthesized from 1,3,5-tri hydroxybenzene and display columnar mesophases.\textsuperscript{137} To arrive at desymmetrized derivatives in an efficient manner, a synthesis was developed for phenol 69: A benzene-1,3,5-tri hydroxy derivative carrying two different protected and one free hydroxy group (Scheme 16).\textsuperscript{138} The synthesis of 69 is based on two selective debenzylation s and the product was easily obtained on a multigram scale.

Scheme 16: Synthesis of key precursor 69 for desymmetrized benzene-1,3,5-tri hydroxy based star-discotics with three different arms. The overall yield was 39 %.\textsuperscript{138}

By using precursor 69, star-discotic 70 carrying three arms that differ in the length of chromophore was synthesized successfully in good yield (Scheme 17).\textsuperscript{138-140} The desired discotic was obtained in three sequential esterification and deprotection steps. Eventually, discotics equipped with three incompatible arms; lipophilic, hydrophilic and fluorophilic might be synthesized that would probably result in interesting mesophase behavior by phase separation.\textsuperscript{32}

Scheme 17: Step-wise synthesis of star shaped disc 70 with three different arms and containing a naphthalene unit. Subsequent esterification and deprotection chemistry was deployed.\textsuperscript{139} DCC = dicyclohexylcarbodiimide, DPTS = dimethylpyridinium toluyl sul fonate, TBAF = tetrabutylammonium fluoride.
1.3.6 Benzene-1,3,5-tricarboxamide systems

Another family of phenyl centered star-shaped discotics is based on the benzene-1,3,5-tricarboxamide (BTA) unit. Secondary amide based hydrogen bonding is essential for their self-assembly properties and mesogenic behavior. The first synthesis of these three-armed discs was already described in 1915.\(^{141}\) When equipped with alkyl tails of sufficient length, stable columnar hexagonal mesophases are formed\(^{142}\) as well as organo-gels.\(^{143}\) Crystal structural analysis showed that a combination of triple intermolecular hydrogen bonding and aromatic stacking results in a helical, columnar assembly.\(^{144}\) The appearance of this structure was confirmed in the mesophase\(^{145}\) as well as in solution\(^{146}\) and in organogels.\(^{147}\) Various functionalized \(C_3\)-symmetrical BTAs are known such as BTAs in which additional ethers are attached to the benzene core\(^{148}\) to force the secondary amides out of the plane of the central ring or BTAs equipped with diphenyloxadiazole groups to afford fluorescent organogels.\(^{149}\) Symmetrical BTA units have been used to preorganize other disc-shaped entities like porphyrins\(^{150}\) or triphenylenes.\(^{151}\) The synthesis of the \(C_3\)-symmetrical BTA derivatives is very straightforward; in a single step reaction any primary amine might react with trimesyl chloride to afford the \(C_3\)-symmetrical discotic.

1.3.6.1 Desymmetrized BTAs

The next, obvious step is desymmetrization of BTAs to introduce additional functionalities. This can be achieved by a statistically determined synthesis where two kinds of amines were reacted in an appropriate ratio with trimesyl chloride (71) followed by chromatographic separation of the discotics (Scheme 18).\(^{152,153}\) This allowed access to four pure discotics, \(72, 73, 74\) and \(75\) in a one-pot reaction; the latter three molecules could be used to evaluate the effect of polar tails on the helical self-assembly. BTA \(76\) was obtained in a separate reaction. Only apolar BTA display helical, self-assembly in the columnar mesophase and in apolar solution. Due to partial backfolding of the ethylene oxide tail accompanied by interference with the intermolecular hydrogen bonding units, the self-assembly of disc \(74\) was diminished. Its association constant in apolar solvent was reduced by a factor of \(10^7\) compared to that of \(C_3\)-symmetrical apolar discotic \(72.\)\(^{154}\) When two polar tails were incorporated, the disc (75) becomes water soluble, but no helical self-assemblies were detected, either in bulk or in apolar solution or in water. In the latter solvent, the absence of hydrophobic shielding allows water to interfere with the secondary amide hydrogen bonds. \(C_3\)-symmetrical polar discotic \(73\) is completely water soluble and does not self-assemble. The length of the ethylene oxide tail proved to be essential; the association constant of disc \(76,\) lacking the possibility of backfolding, only dropped by a factor 10 compared to disc \(72\) in apolar solvent.\(^{153}\) These observations are in contrast with discotics displaying self-assembly based on aromatic interactions that stack in aqueous media.\(^{155-157}\)
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Scheme 18: A family of BTA discotics that was used to investigate the effect of the presence of polar oligo(ethylene oxide tails) on the disc’s self-assembly behavior.\textsuperscript{153} TEA = triethylamine.

In contrast, the step-wise synthesis towards desymmetrized BTAs involves consecutive deprotection and amidation steps (Scheme 19) in which a wider variation of products is possible.\textsuperscript{158} Key-precursor 77 was synthesized by the selective saponification of trimethyl 1,3,5-benzenetricarboxylate (78). The synthesis of 77 has been reported under a variety of conditions.\textsuperscript{158,159} Double amidation and subsequent deprotection of the last ester functionality gave acids 79. In addition, reaction of 79 with diamine 80 resulted in the formation of dumbbell-shaped products 81 (Scheme 19a) which are, together with the copolymeric analogs, useful supramolecular polymeric materials.\textsuperscript{158} By deploying achiral acid 79b, BTAs equipped with one chiral and two achiral tails (82) were synthesized in which the position of the stereocenter on the chiral tail was varied (Scheme 19b).\textsuperscript{155}

Scheme 19: a) Step-wise synthesis to afford dumbbell shaped compounds 81 containing a polymer linker, starting from triester 78.\textsuperscript{158} b) Precursors 79 may also give a family of BTAs (82) equipped with one chiral tail and two achiral tails, of which also the enantiomers were synthesized.\textsuperscript{155} EDCI = 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride, DMAP = 4-(dimethylamino)-pyridine.

Discotics 82 self-assemble into helical stacks both in apolar solution and in the columnar mesophase as was evidenced by optical spectroscopy and X-ray diffraction. Surprisingly, the sign of the CD effect inverts when the stereocenter was shifted one carbon on the tail; for BTAs 82a and 82c a negative Cotton effect was observed while for BTA 82b a positive Cotton effect was observed. A similar effect was observed for oligothiophenes equipped with chiral oligo(ethylene oxide) tails.\textsuperscript{160} Shifting the methyl group in the alkyl tail closer to the core
stabilized the helical aggregate as was shown by temperature dependent optical spectroscopy. In the mesophase, the presence of a single chiral side chain in discotic 82a already increases the transition temperature from the helical Col\textsubscript{h} phase to the isotropic liquid by up to 50 °C, while preventing crystallization. With the goal of making novel polymeric nanomembranes, carboxylic acid functionalized BTAs were mixed with poly(propylene-imine) dendrimers; the mixture self-assembled into a new type of Col\textsubscript{h} LC phase that displays a highly ordered superlattice. The orthogonal combination of amide hydrogen bonding in the columnar direction and ionic dendrimer-disc interactions in the plane perpendicular to the columns gives rise to a structure in which the dendrimer is confined to separate columnar domains.\textsuperscript{152}

1.3.6.2 Bipyridine based discotics possessing a BTA core

Besides equipping the small BTA core with rather floppy peripheral units, preorganized aromatic amide units may be incorporated to afford preorganized discotics \textsuperscript{83} (Figure 8a). These 2,2'-bipyridine discotics were introduced by Anja Palmans \textit{et al.} in the late 1990s\textsuperscript{161} and are characterized by the presence of strong intramolecular hydrogen bonding between the secondary amides and the bipyridine nitrogens. The presence of nine sufficiently long alkoxy tails ensures stable helical columnar liquid crystallinity over more than 350 K and the formation of helical assemblies in solution. The helicity is induced by the propeller-shaped conformation that the discotics adopt in the self-assembled state (Figure 8b).\textsuperscript{162} Further intriguing properties of these discotics include helical self-assembly in polar media and water,\textsuperscript{155,156} control of the helical sense by amplification of chirality,\textsuperscript{99,156,163} an intrinsic fluorescence upon aggregation\textsuperscript{164} and lyotropic mesophase behavior.\textsuperscript{165} Straightforward synthesis of symmetrical, peripherally functionalized derivatives possessing potential biological applications\textsuperscript{166} or for obtaining conductive supramolecular fibers\textsuperscript{167} has been reported, but –in contrast– desymmetrized bipyridine-based discotics have been obtained with great difficulty only.\textsuperscript{168} The study of desymmetrized and functionalized analogs will be the topic of this thesis as is explained in the next paragraph.

\textbf{Figure 8:} a) C\textsubscript{3}-symmetrical discotics \textsuperscript{83} based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit decorated with apolar (83a,b) or polar (83c,d) tails. Their preorganized conformation is shown, together with the intramolecular hydrogen bonding represented as dashed lines. b) Schematic representation of their helical J-type self-assembly in which the discotics adopt a propeller-shaped conformation.\textsuperscript{169}
1.4 Aim and outline of the thesis

Control over self-assembly is one of the main targets in the field of supramolecular chemistry.\textsuperscript{126} This control is absolutely necessary to obtain complicated structures that may eventually mimic part of biological systems or achieve good performance in organic electronic devices like organic photovoltaics.\textsuperscript{7,28,170} Control over self-assembly of organic molecules can be accomplished by adaptation of their environment as is shown by changing the phase of liquid crystalline systems upon changing temperature or by changing the molecular assembly in solution upon variation of the concentration of their components. However, a higher level of control of self-assembly is accomplished by allowing interaction of the assembling components with other molecules or substrates. To do this, the assembling component has to be equipped with a functional site, which requires derivatization. Also, derivatization in itself may result in enhanced, beneficial supramolecular behavior. In this thesis, work is described directed towards derivatization of disc-shaped molecules at their periphery with the goal of introducing functionality into the discotics and of allowing the discotics to perform desirable, programmed interactions with other molecules. The one-dimensional self-assembly of discotics is highly dependent on the presence of a rather rigid aromatic core and of a flexible aliphatic periphery as is the case for almost all discotics that self-assemble into one-dimensional structures. Therefore, functionalization of the discotics at their periphery should be performed without undoing their ability to self-assemble. The latter is likely to happen when the complete periphery of the discotic is functionalized, and hence partial peripheral derivatization of the discotics will be the main strategy adopted in this thesis.

As mentioned in section 1.3.6.2, the discotics considered in this thesis are composed of a central trimesic core, radially equipped with three 2,2'-bipyridinyl-3,3'-diamine moieties that in turn are linked to three gallic moieties decorated with peripheral tails (Figure 8a). In Chapter 2, synthetic strategies to replace one of the 3,4,5-trialkoxyphenyl units with a phenyl or 4-pyridyl unit will be discussed. This affords the target molecules 84 and 85 as depicted in Figure 9. The first synthetic strategy is based on a statistic approach and the second one on a step-wise approach involving protective group chemistry. The results will show that both strategies afford the desired desymmetrized discotics, but that the second strategy has got many advantages over the first. Importantly, the desymmetrization process does not affect the internal, preorganized structure of the discotics significantly. The self-assembly properties of desymmetrized discotics 84 and 85 are reported in Chapter 3. The detection of helical, columnar self-assembly for both desymmetrized discotics is shown, both in the mesophase and in apolar solution. Importantly, the observed helical assembly is similar to that of their $C_3$-symmetrical analog showing that desymmetrization and functionalization of the discotics is possible without undoing their self-assembly capabilities. In Chapter 4 the interaction of pyridyl containing discotic 85 with chiral acids is described. First a screening of suitable acids is discussed to reveal which acids may be used to bind selectively with the discotic without disrupting its supramolecular properties. Appropriate chiral acids are then used to achieve supramolecular chiral induction into the helical assemblies of the discotic in solution. It will be shown that the efficiency of the transfer of chirality is not only determined by the strength of
the chiral acid used, but also by steric effects. Also, the stability of the chiral complex proved to be highly sensitive and dependent on the helix stability, the strength of the acid-base complex and the solubility of the components. The topic of Chapter 5 will be the employment of a functionalized discotic in polymers. To do so, desymmetrized discotic 86 (Figure 9) with a dangling hydroxy group is synthesized as a starting point for a wide variety of functionalized discotics. To illustrate this, the discotic is equipped with a polymerizable methacrylate group and subsequently copolymerized under ATRP conditions to afford a disc-functionalized poly(butyl methacrylate) copolymer. The latter is expected to serve as a novel material for supramolecular, fluorescent polymeric nanoparticles in which the fluorescence originates from the luminescent helical J-aggregates of the discotic. Finally, a novel C₃-symmetrical, adapted discotic is introduced in Chapter 6. By replacing the originally hydrophobic hydrocarbon periphery by a fluorophilic fluorocarbon periphery (disc 87, Figure 9), helical self-assembly in fluorinated media becomes accessible, besides the reported self-assembly in apolar hydrocarbon and polar aqueous media. Very stable columnar mesophases of fluorinated discotic 87 will be described. Surprisingly, a proper choice of solvent combination will allow the formation of mixed assemblies in which both discotics possessing a hydrocarbon periphery and fluor discotics 87 are present, together with transfer and amplification of chirality.

![Figure 9: Target discotics of this thesis. Desymmetrized discotics 84 and 85 which are the main topics of Chapters 2, 3 and 4. Hydroxy-functionalized discotic 86 is introduced in Chapter 5. Teflon disc 87 is the key molecule from Chapter 6. The intramolecular hydrogen bonding is represented as dashed lines.](image-url)
1.5 References


[2] We would like to adopt the definition of 'discotic' as given in the Review of Laschat et al. (ref. [1], page 4835) and in the Handbook of liquid crystals volume 2B (ref. [3], page 749): "Strictly speaking, it is the molecules that are discotic and not the mesophases, which may be columnar, nematic or lamellar." Thus we can make a difference between 'single discotics' and 'supramolecular' discotics, the former meaning one disc-shaped molecule that displays mesogenic behavior and the latter meaning an assembly of smaller molecules which possess not necessarily mesogenic properties and that form together a supramolecule that does reveal mesogenic properties. A good example of a single discotic is an alkylated hexabenzocoronene (K. Müllen et al., see ref. [78]) and a good example of a 'supramolecular discotic' is an alkoxylated hydrogen-bonded folate rosette (T. Kato et al., see ref. [23]).


[9] The mesophases of calamatic LC’s will not described here but their most common mesophases are the nematic (N) mesophase in which orientational long-range order is present and the smectic (Sm) mesophase in which orientational as well as positional long-range order is present. Also chiral derivatives of the nematic and smectic mesophases are known, the chiral nematic (N*) (cholesteric) and the chiral smectic (Sm*) mesophases, in which a twist or tilt is present between the layers of chiral calamitic mesogens. See: D. Demus, J.W. Goodby, G.W. Gray, H.W. Spiess, V. Vill, W.G. John, W.G. George, *Handbook of Liquid Crystals*: Vol. 1, *Guide to the Nomenclature and Classification of Liquid Crystals*, Wiley-VCH, Weihem, 1998, 17-23.


Chapter 1


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Desymmetrization and functionalization of discotics


Desymmetrization and functionalization of discotics


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Desymmetrization and functionalization of discotics


Synthesis of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit

Abstract. Desymmetrization of discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit is described with the goal of introducing peripheral functionality into these discotics. Two synthetic approaches have been applied, both relying on the solubility of the reacting components as the key for success. First, a divergent approach based on a one-pot synthesis is described in which two kinds of aromatic amines are allowed to react sequentially with trimesyl chloride (Schemes 4 and 6). In this approach, the formation of desymmetrized discotics is statistically determined requiring elaborate chromatographic purification. The second synthesis is based on a convergent approach involving protecting group chemistry (Schemes 8 and 9). An alkylated aromatic amine was reacted with a previously desymmetrized trimesic derived core followed by a deprotection step and subsequent acid chloride formation under mild conditions. In the final step, the second aromatic amine was reacted with the acid chloride to afford the desired desymmetrized disc without the need for elaborate chromatographic purification. Two desymmetrized discs were synthesized lacking both a trialkoxy phenyl wedge; a chiral discotic that possesses a phenyl moiety and an achiral discotic that possesses a pyridyl unit. NMR spectroscopy reveals the preorganization for both discotics in the molecularly dissolved state due to strong intramolecular hydrogen bonding. Because of this, the molecules adopt on average a flat conformation enabling their self-assembly in poor solvents and access to the liquid crystalline state.

Synthesis of desymmetrized discotics based on the 3,3′-bis(acylamino)-2,2′-bipyridine unit

2.1 Introduction

Since their discovery in 1977 by Chandrasekhar et al., discotics have been prominently featured in the field of supramolecular chemistry. They have the ability to self-assemble in the solid state and in solution. In the solid state columnar liquid crystals are often formed in which the rigid core of the discotics is organized into one-dimensional columns, while the more flexible peripheral tails remain liquid-like. The self-assembly capabilities and properties of discotics are determined both by the nature of the rigid core and the flexible periphery. For the sake of synthetic simplicity most discotics possess axial symmetry and are equipped with only one kind of peripheral group. However, the properties of many discotics can be enhanced to a large extent by desymmetrization of the molecular structure. By doing so, one functional group per molecule can be incorporated in the discotic. The synthesis of a wide variety of symmetric, desymmetrized and functionalized discotics has been frequently reviewed. Sometimes desymmetrization involves adaptation of the core of a discotic but usually the core remains symmetric to guarantee comparable stacking and the periphery is altered instead. An attractive family of discotics is based on the benzene-1,3,5-tricarboxamide (BTA) unit. These rather small discotics self-assemble into helical stacks by a combination of triple hydrogen bonding and π-π stacking as is observed in the crystal structure, the solid state and in solution. Desymmetrization of these compounds results in useful structures with possible applications in areas such as polymer science. Desymmetrization of the benzene-1,3,5-tricarboxamides is achieved by either a convenient statistical synthesis or a step-wise approach based on protecting group chemistry.

In this chapter the periphery of a special kind of discotic, a molecule based on a benzene-1,3,5-tricarbonyl core linked to three 2,2′-bipyridine-3,3′-diamine units (discotics 1, Figure 1) is adjusted with the aim of widening the applicability of these star-shaped molecules.

Figure 1: a) Apolar (1a,b) and polar (1c,d) C-symmetrical discotics 1 based on the 3,3′-bis(acylamino)-2,2′-bipyridine unit. The intramolecular hydrogen bonding is shown with dashed lines. b) Schematic representation of their helical self-assembly.

Discotics 1 have been studied in our group for more than a decade and possible applications are emerging. The self-assembly properties are based on the strong sixfold intramolecular hydrogen bonding between amide N-H groups and bipyridine N-atoms preorganizing the
molecule into an on average $C_2$-symmetrical planar conformation.\textsuperscript{20,24} Aromatic stacking of the core and phase separation with the nine alkoxy tails induce the formation of propeller shaped helical stacks (Figure 1b) in the columnar mesophase,\textsuperscript{24,25} gel state\textsuperscript{30} and in solution.\textsuperscript{27-29} A more detailed discussion of the self-assembly behavior of discotics 1 and their desymmetrized analogs is given in Chapter 3, while this Chapter will focus on the synthetic approaches towards the desymmetrized discotics. The desymmetrization of discotic 1 should not interfere with its helical self-assembling properties. Adaptation of the core of discotics 1 has been investigated previously but did not result in improved self-assembling properties.\textsuperscript{20,30} More precisely, addition of six methoxy groups to the bipyridine units or increasing the core-size by replacing the bipyridine units with dianilino-pyrazine units has been performed. Although these adaptations gave rise to even stronger aggregation, the formation of highly ordered helical stacks is hampered in the mesophase as well as in solution.\textsuperscript{20} Also, replacement of the three central secondary amide functionalities by urea groups resulted in the formation of stable, intermolecular hydrogen-bonded helical self-assemblies in solution, the gel state and the mesophase, together with the observation of micrometer long fibers by AFM.\textsuperscript{31} However, these discotics containing three urea units lack amplification of chirality in solution. Hence, to satisfy our requirements, the core of discotics 1 should not be changed. Instead, discotics 2 and 3 were designed (Figure 2). They both lack one peripheral 3,4,5-trialkoxybenzene wedge which is replaced by a phenyl or a pyridyl group, respectively. Discotic 2 is decorated with chiral tails to enable the study of its self-assembly behavior using chiral-optical techniques. The self-assembly behavior of discotics 2 and 3 is discussed in detail in Chapter 3.

**Figure 2:** Target desymmetrized discotics discussed in this Chapter; chiral disc 2 possessing a peripheral phenyl group and achiral disc 3 possessing a 4-pyridyl peripheral group.

### 2.1.1 Previously reported attempts to desymmetrize $C_2$-symmetrical discotics 1

Desymmetrization of discotics 1 to obtain an amphiphilic discotic has been pursued via two strategies by Koen Pieterse and Judith van Gorp.\textsuperscript{32,33} In the first approach, one molar equivalent of apolar monoamidated diaminobipyridine and two equivalents of 2,2'-bipyridine-3,3'-diamine were added to trimesyl chloride in a one-pot reaction (Scheme 1). After isolation of the desired aromatic diamine, the final product 4 was obtained by acylation with two
equivalents of a polar acid chloride. Although this method gave desired amphiphilic disc 4 in only two reaction steps, two severe limitations have to be mentioned. First of all, the product formation in the one-pot reaction is statistically determined. Secondly, due to the bisnucleophilic character of 2,2'-bipyridine-3,3'-diamine, 'dumbbell' shaped side-products containing two trimesyl moieties were formed in the one-pot reaction. Both drawbacks hamper purification of the aromatic diamine, which was isolated in 10 % yield only.

Scheme 1: Synthesis of amphiphilic disc 4 starting from trimesyl chloride. After a one-pot reaction a key intermediate diamine was isolated which was eventually acylated with a polar wedge. Reaction yields were low.

The second approach deployed by Koen Pieterse is based on a more step-wise synthesis combined with protecting group chemistry (Scheme 2).

Scheme 2: Step-wise synthesis to afford amphiphilic disc 4. The key steps involve the usage of an already non-symmetric acid chloride and the deprotonation of 2,2'-bipyridine-3,3'-diamine to increase its nucleophilicity. Fair yields were obtained in all steps.
First, one of the ester functionalities of trimethyl 1,3,5-benzenetricarboxylate was converted into an acid chloride. Then, in three steps, one apolar wedge was introduced and the two remaining methyl esters were converted into activated esters. The limited nucleophilicity of 2,2'-bipyridine-3,3'-diamine requires deprotonation to obtain the diamino key intermediate. Finally, the desired amphiphilic disc 4 was obtained after acylation with a polar wedge. All reaction steps proceed in fair yields. However, many reaction steps were involved and the use of a strong base limits the diversity of the first wedge to be incorporated.

### 2.2 Syntheses based on statistical approaches

#### 2.2.1 Synthesis of disc 2 via diamine intermediate

In view of the drawbacks mentioned above regarding the syntheses depicted in Schemes 1 and 2 in the Introduction, non-symmetric disc 2 (Figure 2) was synthesized according to a modified version of the approach in Scheme 1. It was expected that the presence of the phenyl and BOC groups would enable the separation of the statistical mixture. Especially the bulky BOC group, which is situated close to the core of precursor 8, might suppress undesired stacking. The synthesis towards disc 2 is summarized in Schemes 3 and 4. The use of monoBOC protected 6 instead of 2,2'-bipyridine-3,3'-diamine (7) will prevent the formation of larger 'dumbbell' side products and enhance the solubility of the key intermediate 8. Its BOC groups will allow incorporation of any alkylated wedge after deprotection with TFA. Thus, monobenzyoylated 5 and mono-BOC protected 6 are synthesized by reacting 2,2'-bipyridine-3,3'-diamine (7) with one molar equivalent of an acid chloride or anhydride (Scheme 3). The synthesis of BOC-protected 6 was slightly adjusted due to the low reactivity of poorly nucleophilic 7 towards di-tertiary-butyl dicarbonate. Deactivation of the second amino functionality of 2,2'-bipyridine-3,3'-diamine (7) due to intramolecular hydrogen bonding and concomitant planarization ensures highly selective mono-acylation.

![Scheme 3: Synthesis of monoamines 5 and 6.](image)

Non-symmetric discotic compound 2 was synthesized as depicted in Scheme 4. This statistical synthesis started with the slow addition of monoamine 5 to trimesyl chloride in order to achieve on average monoacylation. Then, a slight excess of BOC protected amine 6 was added to the same reaction mixture to ensure complete amidation of the remaining acid chloride functionalities furnishing diBOC compound 8. However, complete purification of the latter proved to be difficult. During the statistical two-step reaction, analogs of diBoc compound 8 were formed which possess comparable polarities and hydrodynamic volumes. Analytical GPC, for example, did not show a significant difference in retention time between the
different components. Also, stacking of the different components during column chromatography hampers their efficient separation. Eventually, the purification of 8 was performed in two steps. Precipitation of the reaction mixture in a polar solvent allows the removal of unreacted mono-protected amine 6 and DIPEA-salts by simple filtration. Then, the crude product was further chromatographically purified with a chloroform-pyridine mixture as the eluting solvent to minimize stacking. However, according to 1H-NMR spectroscopy and MALDI-TOF mass spectrometry some impurities remained.37 In the second step, the BOC groups of intermediate product 8 were removed by TFA. Surprisingly, the TFA salt is soluble in both dichloromethane and acetone, while the neutralized product 9 is not (Scheme 4). The limited solubility of this diamine (9) required polar N-methyl-2-pyrrolidone as solvent in the final reaction step in which diamine 9 was reacted with chiral acid chloride 10. The latter acid chloride was obtained from the corresponding carboxylic acid 11 according to a slightly modified literature procedure.24,38 Precipitation and repeated column chromatography gave pure, non-symmetric discotic 2 and an unknown side-product, the latter severely hampering the purification of 2 due to their very similar polarities and hydrodynamic volumes. Based on amino-precursor 5 the overall yield of target disc 2 amounted to 14 % while the side-product (12) (Scheme 5) was present in about 1.4 % according to 1H-NMR analysis of the crude mixture.

Scheme 4: One-pot reaction and subsequent deprotection towards diamine 9. Acylation of the latter afforded desired desymmetrized disc 2. DIPEA = N,N-diisopropylethylamine.

Analysis of side product 12 with 1H-NMR and MALDI-TOF MS identified it as an analog of disc 2 in which one of the 3,4,5-trialkoxybenzamide aromatic hydrogens is substituted by a chlorine. The NMR spectrum is discussed in Section 2.4. This side-product can only be explained by partial chlorination of the aromatic core during the synthesis of acid chloride 10 with thionyl chloride (Scheme 5). Presumably substitution with thionyl chloride occurs on the phenyl ring of acid 11 forming a sulfanyl chloride intermediate due to the presence of electron donating ethers.39 Then, aryl chloride (13) is formed by elimination of unstable SO.40 The latter
decomposes into SO$_3$ and elemental sulfur. Fortunately, use of oxalyl chloride instead of thionyl chloride prevents this side-reaction.$^{29}$

**Scheme 5:** The unexpected formation of monochlorinated disc 12 via the double chlorination of carboxylic acid 11 with thionyl chloride.

By applying the statistical method via diamine 9, the desired desymmetrized product can be isolated, but two reaction steps are involved, each requiring elaborate purification of the desired product. Also, key-intermediate 9 is only sparingly soluble in any common organic solvent, thus hampering the final amidation step and preventing a satisfactory yield. Because of these drawbacks, the statistical approach towards desymmetrized discotics was investigated using a single-step synthesis.

**2.2.2 Direct, single step one-pot synthesis of disc 3**

Non-symmetric functionalized discotic 3 was synthesized via an adjusted statistical method (Scheme 6). Importantly, the subsequent reaction of a functionalized amine (14) and a much bulkier alkylated amine (16) with trimesyl chloride allows the purification of the statistical mixture based on differences in hydrodynamic volume (Scheme 6b). Recycling GPC proved to be an effective method to purify discotics equipped with bulky alkylated wedges; the side-products either lack or have an excess of three, long alkoxy tails or even a complete 3’-(3,4,5-trisalkoxy-benzoylamino)-2,2’-bipyridyl-3-amine wedge. Furthermore, the desired product (3) was obtained in just one step and no intermediates of limited solubility are involved. The synthesis of 4-pyridyl functionalized amine precursor 14 is shown in Scheme 6a. Pyridine-4-carbonyl chloride HCl salt (15) was synthesized by reacting isonicotinic acid in hot thionyl chloride.$^{41}$ Then, amine 14 was afforded by slow addition of acid chloride 15 to diamine 7 to prevent diacylation and maximize product formation.$^{14}$ The synthesis of hydrophobic aromatic amine precursor 16 has been reported previously.$^{24}$ In a one-pot reaction, amines 11 and 12 were added successively to a solution of trimesyl chloride to afford disc 2 together with its statistically determined analogs. Chromatographic purification, as described above, yielded pure disc 2 in a yield of 12 % based on amino precursor 11.
2.3 Syntheses based on a convenient step-wise approach

The results shown in section 2.2 indicate that the synthesis of desymmetrized discotics like 2 and 3 is possible using a statistical approach. However, the separation of the statistical mixtures proved to be troublesome. Preparative recycling GPC gave pure product, but has got severe limitations with respect to the scale of the separation. Regarding Scheme 2, the major problem is the conversion of a carboxylic acid into an acid halide in the presence of secondary amide functionalities. The use of another activation method is only applicable if the corresponding aromatic amines are also activated (i.e. deprotonated) due to their limited nucleophilicity. The most common methods to convert a carboxylic acid into an acid chloride are to use thionyl chloride or oxalyl chloride as chlorination agents. However, these reagents will convert a secondary amide into an imidoyl chloride.\textsuperscript{42,43} Theoretically, this should not be a problem, since these imidoyl chlorides can be converted back into secondary amides by hydrolysis with water.\textsuperscript{43,44} An attempt to convert a derivative of the diacid shown in Scheme 2 into a bisacid chloride with concomitant imidoyl chloride formation using thionyl chloride failed; only insoluble products were obtained. Thus, a new approach towards desymmetrized discs was selected (Scheme 8). This method involves three main requirements. First of all solubilizing (alkoxy) tails have to be present throughout the whole synthesis, this has been a lesson for other people too.\textsuperscript{23} Secondly, a carboxylic acid has to be converted into an acid chloride without affecting the secondary amides. Finally, intermediate and final products have to be accessible on a multigram scale, thus only common purification techniques should be involved. The synthesis started with the conversion of already non-symmetric ester-diacid 17 into ester-di(acid chloride) 18.\textsuperscript{15} Amidation with apolar, readily soluble amine 16 yielded readily soluble ester 19. Precipitation and digestion or simple column chromatography proved to be sufficient to remove the excess of amine 16 and impurities originating from acid chloride degradation. However, due to some ester hydrolysis by HCl in the first reaction step, some C\textsubscript{3}-symmetrical impurity (discotic 1b) was formed in the amidation step. This C\textsubscript{3}-impurity
displays similar polarity to ester 19, but could easily be removed from acid 20 after the subsequent saponification step. The latter was performed by employing LiOH in THF-water to prevent hydrolysis of the aromatic amides. Then, chemoselective acid chloride formation was guaranteed using 1-chloro-\(N,N,2\)-trimethylpropenylamine. This mild chlorination agent is also known as Ghosez reagent\(^{45}\) and the conversion of a carboxylic acid into an acid chloride is driven by the formation of stable \(N,N\)-dimethylisobutyramide.\(^{46}\) The mechanism is shown in Scheme 7. First, the carboxylic acid (20) protonates the chloroanamine on the double bond, facilitated by the electron donating nitrogen. Then, substitution by the carboxylate on the electron-poor carbon takes place in which an ammonium ester intermediate is formed. The latter species could be detected with NMR spectroscopy.\(^{46}\) Finally, the chloride anion attacks the ester carbonyl giving rise to the formation of the tertiary amide and the acid chloride (21).

\[
\text{Scheme 7: The mechanism of carboxylic acid chloride 21 formation from carboxylic acid 20 with 1-chloro-}N,N,2\text{-trimethylpropenyl-1-amine.}^{46}
\]

The conversion of carboxylic acids in the presence of aromatic amides by employing 1-chloro-\(N,N,2\)-trimethylpropenylamine has been described previously.\(^{47}\) According to infrared spectroscopy, the formation of acid chloride 21 proceeded quantitatively within a few hours and indeed, the secondary amide bonds of compound 21 were not affected. Finally, reaction of acid chloride 21 with amine 14 afforded desired non-symmetric disc 3.

\[
\text{Scheme 8: Synthesis of achiral 4-pyridyl desymmetrized disc 3 by a step-wise approach starting from desymmetrized ester-diacid 17.}
\]
Synthesis of desymmetrized discotics based on the 3,3' -bis(acylamino)-2,2'-bipyridine unit

Starting from acid chloride 21, a wide variety of functionalized discs are, in principle, accessible by reaction with an appropriate aromatic amine. This synthetic sequence was also employed to afford chiral disc 2 (Scheme 9). In this case, reaction of diacid chloride 18 with chiral amine 22 gave chiral ester 23. The subsequent saponification of ester 23 was performed under reflux to decrease reaction time and increase solubility of the reacting components. After the formation of acid chloride 25, disc 2 was synthesized in good yield.

![Diagram showing synthesis of chiral discotic 2](image)

**Scheme 9:** Step-wise synthesis of chiral phenyl disc 2 via acid chloride 25. The first three reaction steps till acid 24 were performed by Jolanda Spiering.

Both discotics 2 and 3 were completely characterized and identified by $^1$H-NMR, $^{13}$C-NMR, FT-IR spectroscopy, elemental analysis and mass spectrometry. According to TLC and analytical GPC both compounds proved to be pure. Especially, analytical GPC proved to be a very convenient tool to determine the purity of the desymmetrized discotics because of the large difference between the hydrodynamic volume of the desired product and possible impurities. NMR spectroscopy provides a lot structural information on discs 2 and 3 and will be discussed in more detail.

**2.4 NMR Spectroscopy of discotics 2, 3, and 12**

Previous studies on $C_3$-symmetrical discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine units have shown that they are preorganized by strong intramolecular hydrogen bonding between amide N-H and neighboring pyridine N's. This hydrogen bonding is observable with $^1$H-NMR in CDCl$_3$ in which the amide protons are shifted downfield to approximately 15 ppm together with a downfield shift of several aromatic core protons indicative of an on average flat conformation of the compound. This $C_3$-symmetrical preorganization allows the molecules to form long stacks primarily by $\pi-\pi$ stacking in which they adopt a more propeller
shaped conformation. The helical stacking behavior of discotics 2 and 3 in alkane solution and the mesophase is discussed in Chapter 3.
When a $^1$H-NMR spectrum of discotic 3 was taken in CDCl$_3$, protons characteristic for a preorganized structure were observed (Figure 3). In chloroform, discotic 2 and 3 are mainly molecularly dissolved resulting in sharp peaks allowing a structural investigation of the compounds. Peak assignment of discotics 2 and 3 in CDCl$_3$ was confirmed with gCOSY $^1$H-$^1$H 2D NMR spectroscopy. Almost all aromatic and amide protons are observed in a 2:1 integration ratio corresponding to the alkylated/non-alkylated wedge ratio of 2:1 (Figure 3). Between 16 and 14 ppm the secondary amide protons 7 are located, indicative of very strong intramolecular hydrogen bonding with the nitrogen atoms of the bipyridine system. Between 9.6 ppm and 9.3 ppm the aromatic protons 4 are located due to strong anisotropical deshielding by the adjacent amide carbonyl. Around 9 ppm, the peaks belonging to central benzene core protons 10 and 11 are located and are almost coincident. It is remarkable that protons 6$'$ and 10$'$ of the outer pyridine rings are shifted 0.75 ppm downfield compared to protons 6 and 10 of the inner pyridine rings. This may reflect deshielding of protons 6$'$ and 10$'$ by the neighboring amide carbonyls which is a strong indication for an on average rather planar conformation of discotic 3.$^{24}$ This means that the aromatic amide core of disc 3 is $C_5$-symmetrical as is drawn in Figure 3. Finally, between 7.8 and 7.2 ppm less deshielded aromatic protons are observed of which the complete assignment is given in the experimental section.

![Figure 3: $^1$H-NMR spectra of disc 3 in CDCl$_3$ at 3 mM. The hydrogen bonded and aromatic protons are shown.](image)

Besides $^1$H-NMR spectroscopy, $^{13}$C-NMR spectroscopy can be used to study the preorganized conformation of discotic 3 in chloroform. A change in the three-dimensional orientation of compound 3 can influence the chemical shifts of the carbon signals to large extent. The $^{13}$C-NMR spectrum of disc 3 is shown in Figure 4. Peak assignment was confirmed with gHMQC and gHMBC 2D NMR spectroscopy. The addition of a limited amount of HFIP to achieve better solubility does not influence the $^{13}$C-NMR spectrum to a considerable extent.$^{48}$
Figure 4: $^{13}\text{C}-\text{NMR}$ spectrum of discotic 3 in CDCl$_3$ with 8 vol% HFIP-D$_2$ concentration = 28 mM. Only the aromatic and carbonyl region are depicted. Complete assignment is given in the Experimental section.

The carbonyl carbons 8, 8’, [8] and [8]’ are positioned furthest downfield. The remarkable difference between the carbonyl next to the gallic moiety and the other ones is probably caused by an interaction of HFIP with carbonyl 8’ making the latter more electron poor. Normally, ortho-carbons of a pyridine moiety are positioned downfield around 150 ppm, which is the case for carbon [11]’ of the peripheral pyridyl group of disc 3. But the carbons 6, 6’, [6], [6]’, 2, 2’, [2], and [2]’ are shifted far more upfield indicating less electron density on the neighboring nitrogen atom. This is evidence for the presence of the strong intramolecular hydrogen bond between the bipyridine nitrogen and the amide N-H moiety. Carbons 4, 4’, [4], and [4]’ are positioned around 130 ppm while the signals for these carbons in 3,3’-diamino-2,2’-bipyridine (7) (Scheme 3) occur at 123 ppm. This deshielding is caused by the nearby amide carboxyls that are in plane with the bipyridyl group. The overall planarity of the bis(acylamino)bipyridine moiety has been confirmed by X-ray crystallography too. Overall, the $^{13}\text{C}-\text{NMR}$ spectrum of disc 3, like the $^1\text{H}-\text{NMR}$ spectrum, shows that 3 adopts an on average rather flat conformation confirming its disc-like shape in solution. Chiral disc 2 displays analogous chemical shifts in its NMR spectra. Thus, discotics 2 and 3 adopt a similar preorganized conformation as their $C_2$-symmetrical analogs 1 and the removal of one alkylated, disordered part does not affect their overall conformation.

Figure 5: $^1\text{H}-\text{NMR}$ spectrum of desymmetrized chlorinated disc 12 in CDCl$_3$. 

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1H-NMR spectroscopy also revealed the additional asymmetry resulting from the chlorination in discotic 12. The 1H-NMR spectrum of chloro-compound 12 is given in Figure 5. Especially, the presence of 6 different N-H signals (protons a-d) and 2 signals for the trialkoxy aryl-H protons (k and m) are proof of the presence of two different trialkoxyphenyl units in disc 12.

2.5 Conclusions
Two desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit, chiral disc 2 possessing a phenyl moiety and achiral disc 3 possessing a 4-pyridyl moiety have been synthesized. Two synthetic methods were applied successfully. In the first method, a statistical reaction was employed in which two different aromatic monoamines react with trimesyl chloride in a one pot reaction. Elaborate purification of the statistical mixture afforded discotics 2 or 3 in rather disappointing yields. In the second method, one type of aromatic amine, equipped with solubilizing tails, is allowed to react with an already non-symmetric benzene-1,3,5-tricarboxylic acid derived core. Then, after deprotection, the final carboxylic acid functionality is activated towards the acid chloride under mild conditions. Finally, the latter is reacted with a functionalized aromatic amine to complete the desymmetrized disc synthesis resulting in the isolation of discs 2 and 3 in satisfactory yields. Two important requirements have to be satisfied to succeed in the desymmetrized disc syntheses. First of all, solubilizing groups have to be present during the synthesis to ensure solubility of the reacting components. Secondly, acid chlorides are necessary to achieve amide bond formation regarding the limited nucleophilicity of the aromatic amines used. Although the statistical syntheses only require one or two reaction steps, the presence of insoluble intermediates and elaborate purifications hamper the high-yield syntheses of the target discotics. The second, step-wise syntheses, require more reaction steps but involve easier purifications compared to the first method, and allow the syntheses of the desired desymmetrized discs in multi-gram quantities. Another important advantage of the step-wise syntheses is the isolation of a readily soluble, stable carboxylic acid intermediate that may act as a precursor for a wide variety of functionalized, desymmetrized discotics.
Compared to their C3-symmetrical analogs 1 both discotics 2 and 3 lack a trialkoxy phenyl wedge which may influence their appealing helical self-assembly behavior. The latter is caused by strong intramolecular hydrogen bonding between amide N-H's and bipyridine nitrogens with concomitant preorganization into a disc-like, C3-symmetrical shape. NMR spectroscopy performed on non-symmetric discotic 3 in the molecularly dissolved state reveals the presence of these strong intramolecular hydrogen bonds and the preorganized structure. Thus, desymmetrized discotic 3 (and 2) may be able to form helical self-assemblies like discotic 1 and this will be the main topic in the next Chapter. Finally, pyridyl functionalized discotic 3 may interact with chiral acids with the goal of achieving supramolecular transfer of chirality and this will be the topic of Chapter 4.
2.6 Experimental section

The syntheses of 2,2'-bipyridine-3,3'-diamine (7), 3,4,5-tris((S)-3,7-dimethyl-octyloxy)-benzoic acid (11), and 3'(3,4,5-trisdecyloxy-benzoylamino)-2,2'-bipyridine-3-amine (16) was described previously. Jolanda Spiering is acknowledged for the synthesis of chiral acid. All solvents were of AR quality if not stated otherwise and were purchased from Biosolve (www.biosolve.nl). Trimesyl chloride, trifluoroacetic acid, 1-chloro-2,N,N-trimethylpropenylamine, benzoyl chloride, diisopropylethylamine, isonicotinic acid, oxalyl chloride, and magnesium sulfate were purchased from Acros (www.acros.be). Triethylamine, di-tertiary-butyl dicarbonate LiOH•H₂O and thionyl chloride were purchased from Fluka (www.aldrich.com). Sodium carbonate was purchased from Merck (www.merck.nl). Deuterated solvents were purchased from Cambridge Isotope Laboratories (www.isotope.com) and were dried over mol sieves. Dichloromethane was distilled over Merck P₂O₅, THF and diethyl ether were distilled over Merck 4 Å mol sieves before use. Water was demineralized before use. Triethylamine was stored over KOH and DIPEA and DMF were stored over Merck 4 Å mol sieves. All spectroscopic measurements and chromatography were performed at room temperature unless stated otherwise. Melting points were determined using a Büchi Melting Point B-540 device and measurements were performed in duplo. ¹H-NMR and ¹³C NMR spectra were recorded on a Varian Mercury Vx 400 MHz (100 for ¹³C), a Varian 400MR 400 MHz (100 for ¹³C), a Varian Gemini 300 MHz (75 MHz for ¹³C) or a Varian Mercury Plus 200 MHz (50 MHz for ¹³C) NMR spectrometer. ¹H Chemical shifts were determined with tetramethylsilane as internal standard (0 ppm), and are given in ppm. ¹³C chemical shifts were determined from the deuterated solvent CDCl₃ (77.16 ppm) or tetramethylsilane (0 ppm) as internal standard. gCOSY 2D experiments were performed in CDCl₃ on a Varian Mercury 400 MHz spectrometer using standard Varian parameters for CDCl₃. gHMQC and gHMBC spectra were measured on a Varian 400MR 400 MHz spectrometer using standard Varian parameters for CDCl₃. 90 Degree pulse determination was performed prior to the heteronuclear measurements. Infrared spectra were recorded in the solid state or as a liquid film on a Perkin Elmer Spectrum One 1600 FT-IR spectrometer, equipped with a Perkin Elmer Universal ATR Sampler Accessory. Wavenumbers are given in cm⁻¹. UV/Vis spectra were recorded on a Perkin Elmer Lambda 40 UV/Vis spectrometer, a one cm quartz cuvette was used for the measurements, wavelengths are given in nm and absorptions in l/mol/cm. Optical rotations were measured on a Jasco DIP-370 polarimeter at a wavelength of 589 nm (Na D line) at room temperature in a 5 cm or 10 cm cuvette. Matrix assisted laser desorption/ionization mass spectra were measured on a Perseptive Biosystems Voyager-DE PRO spectrometer with a Biospectrometry workstation, α-Cyano-4-hydroxycinnamic acid (CHCA) or 2-[(2E)-3-(4-tert-butylphenyl)-2-methylprop-2-enylidene] malononitrile (DCTB) were used as matrix material. M/z values are given in gram/mol. Elemental analysis was performed on a Perkin Elmer 2400 and the elemental content is given in weight percentages. GC-MS measurements were performed using a Shimadzu GC-17A gas chromatograph equipped with a Zebron ZB-35 column. M/z values are given in gram/mole. Analytical GPC was performed using a Shimadzu system equipped with a Shimadzu LC-10ADvp pump, 2 × PL gel 3 μm 100 Å columns in series and a Shimadzu SPD-M10Avp PDA detection system with detection at 290 nm and 350 nm, chloroform was used as the eluent with a flow of 1 mL/min. Manual injection has been performed and the injection volume amounted to 20 μL. Preparative recycling GPC was performed using a Shimadzu system equipped with a Shimadzu LC-10ADvp pump, a Jai-Gel 2.5 H and a Jai-Gel 2 H column in series and a Shimadzu SPD-10AV vp UV/Vis detection system performing detection at 254 nm and 350 nm. Chloroform was used as the eluent with a flow of 3.5 mL/min and manual injection was performed with a volume of 2 mL. One cycle through the system took 1 hour. Manual column chromatography was carried out using Merck 60 Å pore size silica gel (particle size: 63-200 μm) or flash silica gel (particle size: 40-63 μm). Flash column chromatography was performed on a Biotage SP1.
column-machine with a Biotage SNAP KP Sil 25 g cartridge. TLC analysis was performed using Merck Kieselgel F-254 precoated silica gel 60 Å plates, detection was performed by UV light at 254 or 365 nm.

3′-Benzoylamino-2,2′-bipyridine-3-amine (5)<sup>34</sup>
Under argon, a solution of benzoyl chloride (0.88 mL, 10.2 mmol) in distilled diethyl ether (110 mL) was added dropwise to an ice-cold well-stirred dark-yellow suspension of 2,2′-bipyridine-3,3′-diamine (7) (1.744 g, 9.37 mmol) and triethylamine (1.65 mL, 11.9 mmol) in distilled diethyl ether (95 mL). After 15 min a white-yellow precipitate formed and the solution turned brownish. The reaction mixture was allowed to reach room temperature and stirred for 28 h under argon. Subsequently, the brown-yellow suspension was washed with ice-cold water (2 × 100 mL), the aqueous layers were combined and extracted with dichloromethane (2 × 50 mL). The organic layers were combined, washed with brine (2 × 100 mL), dried with MgSO<sub>4</sub> and filtered.<sup>50</sup> Concentration of the filtrate in vacuo gave a brownish residue that was purified by column chromatography (silica gel, 3 vol% CH<sub>3</sub>CN in CHCl<sub>3</sub> to elute the bisamide side product and 10 vol% CH<sub>3</sub>CN in CHCl<sub>3</sub> to elute the target product) which gave 5 as a yellow powder. Finally, recrystallization from boiling CH<sub>3</sub>CN (30 mL) gave pure product 5 (2.35 g, 85 %) as a crystalline, yellow solid.

R<sub>f</sub> = 0.29 (silica gel, 3 vol% CH<sub>3</sub>CN in CHCl<sub>3</sub>); GC-MS: R<sub>f</sub> = 8.26 min, m/z: calcd for: 290.12; found: 290 (radical cation); m.p. 168.0-168.5 °C (Lit. 167.5-168.5 °C)<sup>34</sup>; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): δ = 14.70 (s, 1H, [7]), 9.29 (d, 1H, <sup>3</sup>)(H,H) = 8.46 Hz, [4]), 8.31 (d, 1H, <sup>3</sup>)(H,H) = 4.43 Hz, [6]), 8.07 (d, 2H, <sup>3</sup>)(H,H) = 6.25 Hz, [10]), 7.10 (m, 1H, [6]), 7.56-7.49 (3H, [11]+[12]), 7.40 (dd, 1H, <sup>3</sup>)(H,H) = 8.46 and <sup>3</sup>)(H,H) = 4.43 Hz, [5]), 7.13-7.08 (2H, [4]+[5]), 6.60 ppm (s, 2H, [7]); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>, APT): δ = 166.6, 145.3, 143.7, 140.9, 138.6, 136.4, 135.8, 134.9, 131.8, 128.7, 128.6, 127.6, 125.4, 130.2, 122.8; FT-IR (ATR): ν (cm<sup>-1</sup>) = 3427 and 3285, (NH<sub>2</sub>), 3028, 2754 (C-H aryl), 1649 (amide C=O), 1601, 1569 (amide N-H), 1558, 1520, 1492, 1471, 1453, 1439, 1329, 1309, (amide C-N), 1272, 1250, 1208, 1198, 1162, 1066, 1028, 1001, 979, 967, 930, 906, 865, 795, 733, 720, 701, 672; Elemental analysis calcd (%) for C<sub>16</sub>H<sub>11</sub>N<sub>3</sub>O: C 70.33, H 4.86, N 19.30; found: C 70.04, H 4.76, N 19.17.

3′-Tertiary-butoxycarbonylamino-2,2′-bipyridine-3-amine (6)<sup>3</sup>
Under argon, 2,2′-bipyridine-3,3′-diamine (7) (3.310 g, 17.78 mmol) and di-tertiary-butyl dicarbonate (4.646 g, 21.29 mmol) were dissolved in ethanol (32 mL) at room temperature under stirring. The stirred solution was heated at 35 °C for 5.5 h, and subsequently allowed to reach room temperature. Diethyl ether (100 mL) was added to give an orange solution that was washed with dilute brine (3 × 50 mL), dried with MgSO<sub>4</sub> and filtered. Concentration of the filtrate in vacuo gave an orange, sticky residue that was purified by column chromatography (silica gel, 20 vol% ethyl acetate in heptane to elute the diBoc-protected side product and 40 vol% ethyl acetate in heptane to elute the desired compound) to give amine 6 as a yellow, thick syrup that solidified after thorough drying (3.378 g, 73 %).

R<sub>f</sub> = 0.39 (silica gel, 40 vol% ethyl acetate in CHCl<sub>3</sub>); GC-MS: R<sub>f</sub> = 6.51 min, m/z: calcd for: 286.34; found: 286 (radical cation); m.p. 83.0-84.5 °C; <sup>1</sup>H-NMR (400 MHz, CDCl<sub>3</sub>, 25 °C): δ = 12.46 (s, 1H, 7), 8.75 (d, 1H, <sup>3</sup>)(H,H) = 8.43 Hz, 4), 8.21 (d, 1H, <sup>3</sup>)(H,H) = 4.40 Hz, 6), 7.99 (d, 1H, <sup>3</sup>)(H,H) = 3.66 Hz, 6), 7.21 (dd, 1H, <sup>3</sup>)(H,H) = 8.43 and <sup>3</sup>)(H,H) = 4.40 Hz, 5), 7.06-7.04 (2H, 4+5), 6.36 (s, 2H, 7), 1.53 ppm (s, 9H, 11); <sup>13</sup>C-NMR (75 MHz, CDCl<sub>3</sub>, 25 °C, APT): δ = 153.5, 144.6, 143.1, 139.6, 138.8, 136.3, 135.3, 127.2, 124.8, 123.8, 122.6, 80.0, 28.4; FT-IR (ATR): ν (cm<sup>-1</sup>) = 3429 and 3291 (NH<sub>2</sub>), 3055, 2980, 2928 (C-H aryl and alkyl), 1700 (urethane C=O), 1604, 1578 (urethane N-H), 1504, 1475, 1454, 1438, 1402, 1391, 1366, 1330, 1308,
Synthesis of desymmetrized discotics based on the 3,3’-bis(acrylamino)-2,2’-bipyridine unit

N-[3-[3’-(Benzoylamino)-2,2’-bipyridyl]-N’,N’’-bis[3’-[tertiary-butoxycarbonylamino]-2,2’-bipyridyl]benzene-1,3,5-tricarboxamide (8)

Under argon, diisopropylethylamine (0.70 mL, 4.0 mmol) and aromatic amine 5 (0.984 g, 3.39 mmol) dissolved in distilled dichloromethane (60 mL) were added dropwise to a well-stirred chilled (10 °C) solution of trimesyl chloride (0.90 g, 3.39 mmol) in distilled dichloromethane (60 mL). After stirring for 3 h during which the reaction temperature was allowed to reach room temperature, diisopropylethylamine (1.4 mL, 2.092 g) and aromatic amine 6 (2.092 g, 7.306 mmol) dissolved in distilled dichloromethane (55 mL) were added dropwise to the well-stirred, chilled (10 °C) white suspension. During stirring overnight, the yellow solution turned turbid and orange and was subsequently concentrated in vacuo. The residue was dissolved in a minimal amount of hot chloroform (12 mL) and precipitated in chilled methanol (160 mL). Filtration over a Büchner funnel yielded a beige residue which was washed with methanol (2 × 20 mL), redissolved in chloroform (150 mL) and filtered over celite. Concentration of the filtrate in vacuo yielded a beige residue which was purified by column chromatography (silica, 3 vol% pyridine in chloroform) to give discotic 8 as a beige, sticky solid (2.140 g, 62%) which was used as such.

Rf = 0.32 (silica gel, 4 vol% pyridine in CHCl3); m.p. decomposes; 1H-NMR (400 MHz, CDCl3): δ = 14.41 (s, 1H, [7]), 14.38 (s, 2H, 7), 14.27 (s, 1H, [7’]), 12.65 (s, 2H, 7’), 8.81 (d, 1H, 3J_H,H = 7.42 Hz, [4]), δ = 8.53 (d, 1H, 3J_H,H = 7.43 Hz, [4’]), 8.44-8.42 (m, 4H, 4+4’), 8.36 (d, 1H, 3J_H,H = 2.74 Hz, [6’]), 8.33 (d, 1H, 3J_H,H = 2.74 Hz, [6’]), 7.84 (s, 1H, 10), 7.73 (s, 2H, 11), 7.63 (d, 2H, 3J_H,H = 6.64, [10’]), 7.50 (d, 2H, 3J_H,H = 2.74, 6), 7.37 (t, 1H, 3J_H,H = 6.64, [12’]), 7.32-7.26 (m, 3H, [6] and [11’]), 6.88 (dd, 2H 3J_H,H = 7.82 and 3J_H,H = 3.52 Hz, 5), 6.81 (dd, 1H, 3J_H,H = 7.82 and 3J_H,H = 3.52 Hz, [5]), 6.46 (dd, 2H, 3J_H,H = 7.42 and 3J_H,H = 3.52 Hz, [5’]), 6.41 (dd, 1H, 3J_H,H = 7.42 and 3J_H,H = 3.52 Hz, [5’]), 1.49 (s, 18H, 11’); FT-IR (ATR): ν (cm⁻¹) = 2953, 2925 and 2869 (C-H alkyl), 1670 (amide C=O), 1567 (amide N-H), 1509 and 1492 (aromatic), 1468, 1445, 1427, 1369, 1328, 1296 (amide C-N), 1239, 1201, 1115, 1074, 1029, 997, 945, 913, 865, 798, 746, 730, 716, 700; MALDI-TOF MS: m/z: calcd for: 1018.39; found: 1019.27 (M+H⁺), 1041.27 (M+Na⁺), 1057.27 (M+K⁺).

3,4,5-Tris-((S)-3,7-dimethyloctyloxy)benzoyl chloride (10)

Under argon, thionyl chloride (3.5 mL, 29.4 mmol) and DMF (2 drops) were added to a stirred solution of benzoic acid 11 (0.534 g, 9.03 mmol) in distilled dichloromethane (20 mL) at room temperature. The reaction mixture was stirred overnight at room temperature and concentrated in vacuo. Traces of volatiles were removed under high vacuum to yield acid chloride 10 as a beige, thick oil which was used as such. FT-IR (ATR): ν (cm⁻¹) = 3433, 2954, 2926, 2870, 1752 (C=O), 1581, 1496, 1466, 1428, 1383, 1366, 1324, 1235, 1185, 1140, 1115, 1028, 984, 918, 852, 762, 736, 693, 665.
N,N'-Bis[3'-{(3,4,5-tris(S,3,7-dimethylene)loxybenzoylamo)-2,2'-bipyridyl}]-N''-{3'[2-(benzoylamino)-2,2'-bipyridyl]}benzene-1,3,5-tricarboxamide (2)

Under argon, a mixture of TFA (5 mL) and dichloromethane (5 mL) was added dropwise to an ice-cold, stirred solution of diBoc compound 8 (0.806 g, 0.791 mmol) in distilled dichloromethane (20 mL). The yellow reaction mixture was stirred at room temperature for 5 h, concentrated in vacuo without heating and dried under vacuum to yield a dark-yellow shining residue which was dissolved in acetone (30 mL). Triethylamine (5 mL) dissolved in acetone (25 mL) was added dropwise to this stirred solution of the TFA salt followed by stirring for another 10 min. Then, the formed beige suspension was filtered over a Büchner funnel. The obtained residue was washed with acetone (2 × 10 mL) and ethanol (2 × 50 mL) to yield yellowish product 9 (0.5274 g, 81%) which was used as such.

Under argon, diamine 9 (0.333 g, 0.406 mmol), gallic acid chloride 10 (0.550 g, 0.903 mmol) and diisopropylethylamine (0.5274 g, 81%) which was used as such.
Synthesis of desymmetrized discotics based on the 3,3’-bis(acylamino)-2,2’-bipyridine unit

(54H, 21’+22’); FT-IR (ATR): ν (cm⁻¹) = 2953, 2925, 2869, 1720, 1673, 1567, 1493, 1445, 1371, 1331, 1297, 1261, 1240, 1201, 1169, 1106, 1074, 1043, 1029, 946, 913, 865, 798, 749, 730, 716, 701, 676; MALDI-TOF MS³: m/z: calcd for: 1998.21; found: 1999.03 (M+H+), 2020.98 (M+Na+), 2036.93 (M+K+), 2061.93 (M+Cu+).

Pyridine-4-carbonyl chloride • HCl (15)
Under argon, isonicotinic acid (2.059 g, 16.7 mmol) was added slowly to refluxing, stirred thionyl chloride (80 mL). The reaction mixture was refluxed for 5 h and subsequently concentrated in vacuo yielding a beige solid. High vacuum was used to remove traces of volatile compounds. The residue was used without further purification. ¹H-NMR (200 MHz, acetone-D₆, 25 °C): δ = 9.43 (d, 2H, [10’]) and 8.84 ppm (d, 2H, [11’]); FT-IR (ATR): ν (cm⁻¹) = 3070, 2965, 2714, 2563, 2097, 2071, 1892, 1814, 1750, 1732, 1637, 1607, 1506, 1497, 1394, 1336, 1275, 1236, 1195, 1129, 1064, 1044, 1003, 898, 823, 757, 729, 684.

3’-(4-Pyridylcarbonylamino)-2,2’-bipyridine-3-amine (14)
Under argon, pyridine-4-carbonyl chloride HCl salt (14) (2.97 g, 16.7 mmol) dissolved in distilled dichloromethane (110 mL) and DIPEA (4 mL) was added dropwise to a well-stirred, ice-cold solution of 2,2’-bipyridine-3,3’-diamine (7) (2.590 g, 13.9 mmol) and DIPEA (3 mL) in distilled dichloromethane (110 mL). The stirred, brownish clear reaction mixture was allowed to reach room temperature, stirred for an additional 5 h ad subsequently washed with aqueous Na₂CO₃ solution (saturated, 2 × 50 mL). The aqueous layers were combined and extracted with dichloromethane (1 × 50 mL). The combined organic layers were washed with brine (2 × 25 mL) and dried with MgSO₄. Filtration gave a clear, brown filtrate was concentrated in vacuo. Column chromatography of the residue (silica, 5 vol% pyridine in chloroform) yielded a yellow compound that was crystallized from a mixture of boiling ethanol (200 mL) and ethyl acetate (5 mL) to yield product 13 as yellow needles (2.02 g, 50%).

R₁ = 0.33 (silica gel, 5 vol% pyridine in CHCl₃); GC-MS: R₁ = 9.15 min, m/z: calcd for: 291.11; found: 291 (radical cation); m.p. 199.5-200.0 °C; ¹H-NMR (400 MHz, CDCl₃): δ = 15.10 (s, 1H, [7’]), 9.25 (d, 1H, J(H,H) = 8.30 Hz, [4’]), 8.84 (d, 2H, J(H,H) = 4.57 Hz, [11’]), 8.36 (d, 2H, J(H,H) = 4.57 Hz, [6’]), 8.00 (d, 1H, J(H,H) = 3.95 Hz, [6]), 7.89 (d, 2H, J(H,H) = 4.57 Hz, [10]), 7.32 (dd, 1H, J(H,H) = 8.30 and J(H,H) = 4.57 Hz [5’]), 7.18-7.12 (2H, [4’]+[5’], 6.70 ppm (s, 2H, [7’]); ¹³C-NMR (50 MHz, CDCl₃, APT): δ = 164.1, 150.7, 145.4, 143.6, 142.8, 141.3, 138.0, 135.7, 134.6, 128.5, 125.5, 124.4, 122.6, 121.2; FT-IR (ATR): ν (cm⁻¹) = 3357 and 3241, (NH₃), 3026, 2821 (C-H aryl), 1946, 1664 (amide C=O), 1605, 1572 (amide N-H), 1554, 1512, 1493, 1473, 1454, 1439, 1408, 1400, 1346.
1327, 1312, (amide C-N), 1276, 1259, 1216, 1200, 1152, 1132, 1099, 1060, 999, 972, 959, 910, 875, 847, 819, 797, 750, 732, 721, 696, 674; Elemental analysis calcd (%) for C_{16}H_{23}N_{3}O: C 65.97, H 4.50, N 24.04; found: C 65.57, H 4.22, N 23.70.

N-{3'[4-(Pyridyl-carbonylamino)-2,2'-bipyridyl]-N,N'-'bis[3'-(3,4,5-tris(dodecyloxy)benzoyl amino)-2,2'-bipyridyl]benzene-1,3,5-tricarboxamide (3)

Under argon, a mixture of aromatic monoamine 14 (0.759 g, 2.60 mmol) and DIPEA (0.9 mL) mixed in distilled dichloromethane (65 mL) was added dropwise to a chilled, well stirred solution of trimesyl chloride (0.693 g, 2.61 mmol) in distilled dichloromethane (65 mL). After 10 min, a solution of apolar monoamine 16 (4.600 g, 5.45 mmol) and DIPEA (1.2 mL) in distilled dichloromethane (5 mL) was added dropwise to the brownish, turbid, well stirred reaction mixture. The reaction mixture was stirred for another 3 h and subsequently concentrated in vacuo. The obtained dark-grey residue was dissolved in hot chloroform (20 mL) and precipitated into acetone (250 mL). Then, the suspension was filtered using a Büchner funnel. The grey residue was dissolved in hot chloroform (50 mL) and subsequently acetone (100 mL) was added to give a grey suspension that was refluxed for 0.5 h. Filtration over a Büchner funnel yielded a grey residue that was washed with a mixture of acetone and chloroform (10 vol% chloroform in acetone, 2 x 20 mL). Repetitive column chromatography (silica gel, 2 vol% ethyl acetate in chloroform), (silica gel, 2.5 vol% methanol in chloroform) and (flash silica gel, 5-10 vol% triethyl amine in chloroform) gave a crude, brown-beige product (0.886 g, 16%). Finally, 0.290 g crude product was purified using preparative recycling GPC (chloroform, 2 x Jai-Gel column) to yield desired compound 3 (0.224 g, 77 %) as a beige-white sticky solid.

R_f = 0.34 (silica gel, 5 vol% triethyl amine in CHCl_3), R_f = 12.1 min (GPC, CHCl_3, 2 x PL gel 3 µm 100 Å column, one peak), 1H-NMR (400 MHz, CDCl_3, 3.3 mL): δ = 13.59 (s, 2H, 7), 15.36 (s, 1H, [7]), 14.96 (s, 1H, [7]), 14.29 (s, 2H, 7), 9.50-9.46 (3H, 4+4[4]), 9.33-9.30 (3H, 4+4[4]), 9.03 (d, 1H, 3/H,H) = 6.28 Hz, [6]), 8.97-8.96 (5H, 10+11+6), 8.78 (d, 2H, 3/H,H) = 6.04 Hz, [11]), 8.27-8.24 (3H, 4+4[6]), 7.75 (d, 2H, 3/H,H) = 5.64 Hz, [10]), 7.46-7.39 (3H, 5+5[5]), 7.38-7.33 (3H, 5+5[5]), 7.18 (s, 4H, 10'), 4.05-4.00 (12H, 13+14'), 1.89-1.75 (12H, 15'), 1.53-1.48 (12H, 16'), 1.39-1.29 (96H, 17+18+19'), 0.92-0.87 ppm (18H, 20'); 13C-NMR (100 MHz, CDCl_3 with 8 vol% HFIP, 28 mM, APT): δ = 168.5 (8'), 165.3+165.2 (8 +8[8]), 165.1 (8'), 153.5 (11'), 149.4 ([11'], 144.2 ([9]), 143.0 ([6]), 142.8+142.3+142.3 (2+2+[2]+[2]), 141.6 (6'), 141.4 (6), 141.1 (12'), 137.3+137.0+136.8+136.5+136.5+136.4 (3+3+[3]+3+9+12), 131.0+131.0+130.8+130.7 (4+4+[4]+[4]), 130.5 (9'), 130.1 (10+11), 125.2+125.1 +125.0+124.8 (5+5+[5]+5), 122.4 ([10]), 106.4 (10'), 75.0 (13'), 70.0 (14'), 32.2-32.2 (18'), 30.2+30.0+29.9 +29.9+29.9+29.9+29.8+29.7+29.6+29.5 (15+17'), 26.3+26.1 (16'), 22.9+22.9 (19'), 14.2+14.2 ppm (20'); FT-IR (ATR): ν (cm⁻¹) = 2921 and 2852 (C-H alkyl), 1671 (amide C=O), 1567 (amide N-H), 1510 and 1493 (aromatic), 1467, 1445, 1428, 1370, 1330, 1296 (amide C-N), 1239, 1201, 1118, 1074, 1029, 1005, 945, 913, 863, 799, 745, 729, 717, 696; UV/Vis (dodecane, 17 µM): λ_max (ε) = 209 (94.9 x 10^4), 294 (62.3 x 10^4), 353 (shoulder, 31.5 x 10^4), 364 (36.1 x 10^4), 383 nm (25.2 x 10^3 M⁻¹cm⁻¹), UV/Vis (chloroform, 19 µM): λ_max (ε) = 293 (83.2 x 10^3), 341
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(shoulder, 48.6 x 10^3), 352 (51.9 x 10^3), 366 nm (shoulder, 34.2 x 10^3 M^-1 cm^-1), MALDI-TOF MS: m/z: calcd for: 2133.43; found: 2134.26 (M+H^+), 2156.48 (M+Na^+), 2172.47 (M+K^+), 2197.29 (M+Cu^+); Elemental analysis calcd (%) for C_{131}H_{182}N_{10}O_{12}: C 73.73, H 8.74, N 8.53; found: C 73.65, H 8.63, N 8.51.

Methyl 3,5-bis(carbonylchloride)benzoate (18)^15

Under argon, oxalyl chloride (0.24 mL, 2.795 mmol) and DMF (1 droplet) were added dropwise to a well-stirred solution of 5-methoxy carbonyl-isophthalic acid (17) (0.300 g, 1.326 mmol) in distilled THF (10 mL). The escape of gases indicated proceeding of the reaction. After 2.5 h conversion was complete according to FT-IR spectroscopy and the beige solution was concentrated in vacuo. Remaining volatiles were removed by high vacuum yielding a beige syrup (0.346 g, 1.33 mmol) that was used as such. FT-IR (ATR): ν (cm^-1) = 3086, 3010, 2957, 2850, 2007, 1758 (C=O acid chloride), 1730 (C=O ester), 1601, 1446, 1432, 1308, 1211, 1145, 1061, 1019, 1000, 988, 920, 814, 771, 741, 697, 685.

Methyl 3,5-bis[3’-(3,4,5-tris(dodecylxyloxy)benzoylamo)-2,2’-bipyridyl]aminocarbonyl]benzoate (19)

Under argon, ester bis(acid chloride) 18 (0.346 g, 1.33 mmol) dissolved in distilled dichloromethane (10 mL) was added dropwise to a well-stirred solution of aromatic amine 16 (2.358 g, 2.80 mmol) and triethyl amine (0.45 mL, 3.23 mmol) in distilled dichloromethane (10 mL) at room temperature. After complete addition, the reaction mixture was stirred for another 2 h after which FT-IR spectroscopy indicate complete conversion of the acid chlorides. The brownish reaction mixture was concentrated in vacuo. The residue was dissolved in hot chloroform (8 mL) and precipitated into well-stirred acetone (200 mL) to give a beige suspension. Filtration over a Büchner filter and subsequent washing with acetone (2 x 20 mL) gave a beige residue that was redissolved into a mixture of hot chloroform (5 mL), ethyl acetate (90 mL) and acetone (50 mL). The solution was allowed to reach room temperature during which a beige precipitate formed. The precipitate was filtered over a Büchner funnel and washed with acetone (2 x 20 mL) to give a beige residue. The latter was suspended in a mixture of hot chloroform (15 mL), ethyl acetate (30 mL) and acetone (30 mL), cooled down and subjected to Büchner filtration. The new beige residue was washed with acetone (2 x 20 mL) and dried under vacuum to give a white-beige solid (2.02 g, 80 %) which was used as such. According to ^1H-NMR, the product contained 5 mol-% of C5-symmetrical discotic (1b).

Rf = 0.43 (silica gel, 5 vol% ethyl acetate in CHCl3), ^1H-NMR (400 MHz, CDCl3): δ = 15.31 (s, 2H, 7), 14.34 (s, 2H, 7), 9.51 (dd, 2H, ^3J(H,H) = 8.5 Hz and ^1J(H,H) = 1.2 Hz, 4), 9.40 (dd, 2H, ^3J(H,H) = 8.5 and ^1J(H,H) = 1.6 Hz, 4'), 9.17 (s, 1H, 10), 9.01 (s, 2H, 11), 8.86 (dd, 2H, ^3J(H,H) = 4.4 Hz and ^1J(H,H) = 1.6 Hz, 6), 8.41 (dd, 2H, ^3J(H,H) = 4.4 Hz and ^1J(H,H) = 1.6 Hz, 6), 7.52 (dd, 2H, ^3J(H,H) = 8.5 Hz and ^1J(H,H) = 4.6 Hz, 5'), 7.46 (dd, 2H, ^3J(H,H) = 8.5 Hz and ^1J(H,H) = 4.5 Hz, 5), 7.27 (s, 4H, 10'), 4.10-4.04 (15H, 13+14+OCH3), 1.90-1.75 (12H, 15'), 1.55-1.47 (12H, 16'), 1.36-1.27 (96H, 17'+18'+19'), 0.90-0.86 ppm (18H, 20');

^13C-NMR (100 MHz, CDCl3): δ = 166.2, 165.7, 163.8, 153.2, 142.2, 142.0, 141.5, 140.9, 140.4, 137.7, 137.4, 135.9, 131.4, 131.3, 131.0, 130.2, 129.9, 129.7, 124.5, 124.1, 106.7, 73.6, 69.6, 52.7, 31.9, 31.9, 30.4, 29.8-29.4, 26.1, 26.1, 22.7, 14.1 ppm; FT-IR (ATR): ν (cm^-1) = 2922, 2853, 1728 (C=O ester), 1668 (C=O amide), 1568, 1516, 1493, 1467, 1441, 1427, 1370, 1330, 1297, 1239, 1201, 1117, 1074, 1030, 993, 945, 915, 861, 799, 753, 729, 721, 665; MALDI-TOF MS: m/z: calcd for:
3,5-Bis[3′-(3,4,5-tris(dodecyl oxy)benzoylamino)-2,2′-bipyridyl]aminocarbonyl]benzoic acid (20)

LiOH·H₂O (0.075 g, 1.78 mmol) dissolved in water (8 mL) was added to ester 19 (1.82 g, 0.97 mmol) dissolved in distilled THF (150 mL) under stirring. The formed suspension was heated to 45 °C to achieve dissolution. After 2.5 h, FT-IR indicated complete saponification after which the reaction mixture was cooled in an ice-bath. TFA (0.5 mL) was added to the suspension followed by stirring for 0.5 h and centrifugation (4300 rpm). After removal of the supernatant, the residue was resuspended into acetone (80 mL) and water (20 mL). Centrifugation gave a beige residue which was purified by column chromatography (silica gel, 5 vol% methanol-chloroform) to give acid 20 (1.34 g, 74 %) as a beige, sticky compound.

\[ R_1 = 0.28 \] (silica gel, 5 vol% methanol in CHCl₃), \[ R_2 = 12.9 \text{ min} \] (GPC, CHCl₃, 2 × PL gel 3 μm 100 Å column, one tailing peak), \[ ^1H-NMR \] (400 MHz, CDCl₃ + 10 vol% HFIP-D₂): \[ δ = 15.39 \text{ (s, 0.2H, 7), 15.37 \text{ (s, 0.4H, 7), 14.49 \text{ (s, 0.4H, 7)}, 9.35 \text{ (d, 2H, } ^{3}J(\text{H,H}) = 8.5 \text{ Hz, 4), 9.17 and 9.16 \text{ (3H, 4}^\prime, 4^\prime+10), 9.07 \text{ (s, 2H, 11), 8.81 \text{ (d, 2H, } ^{3}J(\text{H,H}) = 4.1 \text{ Hz, 6), 8.42 \text{ (d, 2H, } ^{3}J(\text{H,H}) = 4.3 \text{ Hz, 6), 7.54-7.50 \text{ (4H, 5}^\prime+5), 7.20 \text{ (s, 4H, 10)}, 4.11-4.06 \text{ (12H, 13}^\prime+14), 1.90-1.75 \text{ (12H, 15), 1.54-1.44 \text{ (12H, 16), 1.38-1.27 \text{ (96H, 17}^\prime+18)+19)}, \text{ 0.91-0.86 ppm (18H, 20)}, \text{ } ^{13}C-NMR \] (100 MHz, CDCl₃ + 10 vol% HFIP-D₂): \[ δ = 169.3, 167.2, 163.8, 153.2, 141.6, 140.6, 137.1, 136.9, 135.7, 131.8, 130.3, 129.9, 124.7, 124.2, 106.4, 74.1, 69.7, 32.0, 30.3, 29.7, 29.5, 29.4, 26.1, 22.7, 14.1 ppm; FT-IR (ATR): \[ ν \text{ (cm}^{-1}) = 3091, 2956, 2920, 2852, 1725 \text{ (C=O acid), 1679 \text{ (C=O amide), 1586, 1568, 1517, 1495, 1467, 1440, 1372, 1333, 1300, 1222, 1119, 1072, 1030, 1001, 914, 852, 800, 729, 722, 672; MALDI-TOF MS: } m/z \text{: calcld for: 1860.33; found: 1861.33 (M+H), 1883.45 (M+Na), 1899.36 (M+K), 1923.33 (M+Cu)}; \text{ Elemental analysis calcld (%) for } C_{135}H_{174}N_{16}O_{12}: C 74.23, H 9.43, N 6.02; \text{ found: C 74.41, H 9.43, N 6.05.}

3,5-Bis[3′-(3,4,5-tris(dodecyl oxy)benzoylamino)-2,2′-bipyridyl]aminocarbonyl]benzoyl chloride (21)

Under argon, carboxylic acid 19 (1.00 g, 0.536 mmol) was suspended in dichloromethane (6 mL) and 1-chloro-N,N,2-trimethylpropenyleneamine (0.2 mL, 1.5 mmol) was added at room temperature. The reaction mixture was stirred overnight after which FT-IR indicated complete conversion accompanied by complete dissolution of the reaction mixture. Evaporation of the solvent in vacuo and subsequent removal of remaining volatiles by high vacuum gave acid chloride 21 as a sticky yellow compound that was used as such.

FT-IR (ATR): \[ ν \text{ (cm}^{-1}) = 2921, 2853, 1756 \text{ (C=O acid chloride), 1668 \text{ (C=O amide), 1568, 1515, 1494, 1467, 1442, 1427, 1371, 1330, 1297, 1238, 1201, 1181, 1118, 1074, 1030, 986, 912, 862, 843, 801, 739, 730, 688.}

N-[3′-(4-Pyridyl-carbonylamino)-2,2′-bipyridyl]-N′,N″-bis[3′-(3,4,5-tris(dodecyl oxy)benzoyl amino)-2,2′-bipyridyl]benzene-1,3,5-tricarboxamide (3)

Synthesis via step-voice method. Under argon, acid chloride 21 (0.536 mmol), amine 14 (0.170 g, 0.584 mmol) and triethylamine (0.1 mL, 0.718 mmol) were dissolved under stirring in dichloromethane (10 mL). After overnight reaction, FT-IR indicated complete conversion of the acid chloride and acetone (15...
mL) was added upon which a beige suspension formed. Filtration over a Büchner funnel and washing of the residue with acetone (2 × 5 mL) gave a beige solid that was redissolved in hot chloroform (15 mL). Acetone was added (15 mL) during which a beige suspension formed. The suspension was heated till reflux for 5 min, allowed to reach room temperature and filtered over a Büchner funnel. This procedure was repeated twice to give another beige residue. Column chromatography (silica gel, gradient 1:3 vol% methanol in chloroform) gave title compound 3 as a beige sticky solid (0.37 g, 32%). Analysis: see previous synthesis.

Methyl 3,5-bis(3′-(6S)-3,7-dimethyloctyloxy)benzoylamino)-2,2'-bipyridylaminocarbonyl)benzoate (23)

Under argon, ester bis(acid chloride) 18 (0.98 g, 3.76 mmol) dissolved in distilled dichloromethane (50 mL) was added dropwise to a well-stirred solution of amine 19 (6.00 g, 7.90 mmol) and triethyl amine (1.6 mL, 11.3 mmol) in distilled dichloromethane. After reaction overnight, FT-IR indicated complete conversion of the acid chlorides. Concentration of the reaction mixture gave a residue that was dissolved in chloroform (65 mL) and precipitated in acetone to give a beige residue after Büchner filtration. Column chromatography (silica gel, 5 vol% ethyl acetate in chloroform) gave pure ester 22 (4.00 g, 63 %) as a beige, sticky compound. 

3,5-Bis(3′-(6S)-3,7-dimethyloctyloxy)benzoylamino)-2,2'-bipyridylaminocarbonyl)benzoic acid (24)

LiOH · H₂O (0.24 g, 5.63 mmol) dissolved in water (10 mL) was added to methyl ester 23 (3.20 g, 1.88 mmol) dissolved in THF (250 mL). The stirred reaction mixture was refluxed overnight, after which TLC showed the absence of starting material. The reaction mixture was allowed to reach room temperature and subsequently TFA (0.65 mL) was added under stirring. After stirring for 1 h, the reaction mixture was concentrated and redissolved in chloroform. The chloroform solution was washed with water and dried with MgSO₄. The organic layer was filtered over a glass filter and concentration in vacuo to give a residue. The residue was purified by column chromatography (silica gel, 3 vol% isopropanol in chloroform) to yield chiral acid 24 as a beige sticky solid (2.27 g, 71 %). Rₚ = 0.28 (silica gel, 5 vol% methanol in CHCl₃); ¹H-NMR (400 MHz, CDCl₃): δ = 15.33 (s, 2H, 7), 14.37 (s, 2H, 7′), 9.94 (dd, 2H, ḟ(H,H) = 8.5 and ḟ(H,H) = 1.5 Hz, 4′), 9.39 (d, 2H, ḟ(H,H) = 8.5 and ḟ(H,H) = 1.5 Hz, 4), 9.17 (s, 1H, 10), 9.05 (s, 2H, 11), 8.87 (dd, 2H, ḟ(H,H) = 4.6 and ḟ(H,H) = 1.7 Hz, 6), 8.39 (dd, 2H, ḟ(H,H) = 4.6 and
\( ^3J(H, H) = 1.2 \text{ Hz, 6}, 7.50 \text{ (dd, 2H,} \ ^3J(H, H) = 8.3 \text{ and} \ ^3J(H, H) = 4.6 \text{ Hz, 5')}, 7.42 \text{ (dd, 2H,} \ ^3J(H, H) = 8.3 \text{ and} \ ^3J(H, H) = 4.6 \text{ Hz, 5'), 7.27} \text{ (s, 4H, 10'), 4.17-4.03} \text{ (1 2H, 13'+14'), 1.96-1.83} \text{ (6H, 15'), 1.74-1.70} \text{ (6H, 16'), 1.69-1.59} \text{ (6H, 15'), 1.58-1.48} \text{ (6H, 20'), 1.40-1.12} \text{ (36H, 17'+18'+19'), 1.03-0.94} \text{ (m, 18H, 22'), 0.93-0.86} \text{ ppm (m, 36H, 21');} \ ^{13}C-\text{NMR (100 MHz, CDCl}_3):} \delta = 168.8, 166.3, 163.6, 153.3, 142.0, 141.4, 141.0, 140.3, 137.7, 137.4, 135.9, 131.7, 130.7, 130.1, 130.0, 129.7, 124.6, 124.1, 106.7, 71.8, 68.0, 39.4, 39.3, 37.6, 37.4, 36.5, 29.9, 29.7, 28.0, 24.6, 22.7, 22.6, 19.6 \text{ ppm; FT-IR (ATR):} \nu (\text{cm}^{-1}) = 2953, 2925, 2869, 1723 (\text{C=O acid}), 1669 (\text{C=O amide}), 1567, 1513, 1493, 1467, 1440, 1427, 1370, 1328, 1297, 1226, 1200, 1114, 1073, 1046, 957, 916, 863, 800, 747, 729, 696, 670; \text{MALDI-TOF MS:} m/z: \text{calcd for:} \ 1692.14; \text{found:} \ 1692.15 \text{ (M⁺), 1715.17 (M+Na⁺), 1731.17 (M+K⁺), 1755.14 (M+Cu⁺).} \text{Elemental analysis calcd} (%) \text{for C}_{103}H_{150}N_8O_{12}: \text{C 73.10, H 8.93, N 6.62; found: C 73.35, H 8.89, N 6.49.}

3,5-Bis(3\[3'-(S)-3,7-dimethyloctyloxy)benzoylamino)-2,2'-bipyridylaminocarbonyl)benzoyl chloride (25)

Under argon, carboxylic acid 24 (0.435 g, 0.257 mmol) was suspended in dichloromethane (3 mL) and 1-chloro-\text{N,N',2-trimethylpropenylamine} (0.06 mL, 0.45 mmol) was added. The yellow reaction mixture was stirred for 2.5 h after which FT-IR indicated complete conversion accompanied by complete dissolution of the reaction mixture. Evaporation of the solvent \textit{in vacuo} and subsequent removal of remaining volatiles by high vacuum gave acid chloride 25 as a sticky yellow compound that was used as such. FT-IR (ATR): \nu (\text{cm}^{-1}) = 2954, 2926, 2870, 1759 (\text{C=O acid chloride}), 1666 (\text{C=O amide}), 1650, 1568, 1515, 1492, 1468, 1443, 1427, 1370, 1328, 1295, 1238, 1199, 1178, 1115, 1074, 1045, 984, 912, 862, 840, 799, 729, 698, 688, 662.

\[ \text{N,N'-Bis[3'-(3,4,5-tris((S)-3,7-dimethyloctyloxy)benzoylamino)-2,2'-bipyridyl]}-\text{N''-[3'[benzoyl amino)-2,2'-bipyridyl]benzene-1,3,5-tricarboxamide (2)} \]

\text{Synthesis via step-wise method.} \text{Under argon, acid chloride 25 (0.44 g, 0.257 mmol) and amine 5 (0.09 g, 0.30 mmol) were mixed in distilled dichloromethane (3 mL) under stirring. Triethylamine (0.06 mL, 0.4 mmol) was added and the dark reaction mixture was stirred overnight under argon after which FT-IR showed the complete conversion of the acid chloride. acetone (10 mL) was added inducing the formation of a beige precipitate. Büchner filtration yielded a beige residue that was washed with acetone (2 × 5 mL). The residue was purified with flash column chromatography (silica gel, gradient pure chloroform to 5 vol% ethyl acetate in chloroform) to yield pure disc 2 as a white sticky solid (0.408 g, 81%). Analysis: see previous synthesis.}
2.7 References


[36] Eluent: chloroform, column: 2 x PL gel 3 μm 10 Å columns

[37] The usage of an even more bulky protective group compared to the BOC group (e.g. 1-(3,5-di-t-butylphenyl)-1-methylethyl carbamate) or a more polar amino-protective group might enhance the separation of the statistical mixture.


Synthesis of desymmetrized discotics based on the 3,3′-bis(acylamino)-2,2′-bipyridine unit


[48] The same was observed in 1H-NMR: addition of HFIP does not induce large shifts in the aromatic region and the preorganized structure remains intact.


[50] 1H-NMR analysis of the crude product indicated the presence of only 5 mol-% bisamide sideproduct showing the preference for selective mono-amidation.

[51] The sample was rather concentrated causing an upfield shift of the aromatic signals and peak broadening.

[52] Heating of a TFA salt of an amine can cause the formation of a TFA amide

[53] The observed isotope pattern is clearly indicative for the presence of chlorine.

[54] Assignment was done with gHMQC and gHMBC NMR, some 13C peaks split due to partial N-H exchange with deuterium from HFIP-D2).

[55] Some peaks are not observed due to peak broadening and concomitant peak merging.

[56] The yield is rather disappointing due to losses during the filtration steps.

[57] Some peaks lack typical couplings due to the rather high concentration and concomitant peak broadening.
Self-assembly behavior of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit

Abstract. In the previous chapter, the synthesis of two desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit is described with the aim of introducing peripheral functionality into this appealing class of compounds. Disc 2 is equipped with six chiral tails while one of the trialkoxyphenyl units in the original $C_3$-symmetrical disc is replaced by a simple phenyl unit. This compound is ideal for the study of its self-assembly behavior using CD spectroscopy. Achiral disc 3 possesses a pyridyl group instead of a trialkoxyphenyl wedge allowing complexation with other compounds to be performed in future studies. The influence of the absence of one-third of the alkylated, disordered part of the disc on the self-assembly behavior is studied in the liquid crystalline state and in solution. According to microscopy, DSC and X-ray diffraction both discotics 2 and 3 are helical columnar liquid crystalline over a window of more than 300 K like their symmetrical counterparts. However, they possess two rectangular mesophases due to their structural asymmetry; in the lower temperature mesophase a rare unit cell containing four discs has been found. The presence of either a phenyl or a pyridyl group has no other significant influence on the characteristics of the columnar mesophase. Helices are present in the mesophase in which the helical pitch amounts 33-35 discotics per turn. To give strong evidence for the supramolecular helical structure, adamantane discotic 6 was synthesized with a less disordered periphery (the trialkoxyphenyl wedges replaced by adamantyls) enabling the formation of needle-like crystals. UV/Vis and fluorescence spectroscopy of discotic 3 in dilute solution revealed the presence of helical $J$-aggregates in alkane solvents. According to CD spectroscopy, both chiral disc 2 and $C_3$-symmetrical achiral derivative 1b coexist in helical self-assemblies. Remarkably, these desymmetrized discotics, lacking one trialkoxybenzene wedge, behave similarly to the symmetric parent compound.

3.1 Introduction

Discotics were discovered in the late seventies and display appealing properties due to their one-dimensional self-assembly. In the solid state, discotics may form columnar liquid crystals that are characterized by one-dimensional organization of a rigid core and more flexible liquid-like organization of the periphery. Some rare examples are known of inverted disc-shaped mesogens which have a stiff, aromatic periphery and an aliphatic, flexible inner part. The different types of columnar mesophases are depicted in Figure 1 and were first introduced by Levelut in 1983. The most common mesophases are the columnar hexagonal lattice and the columnar rectangular lattices with p2gg and c2mm plane groups. The highly symmetrical columnar hexagonal and tetragonal lattices are observed when circular shaped discotics organize perpendicular relative to the columnar axis and have rotational freedom. A less symmetric rectangular mesophase is usually observed if the discotic does not have a circular shape, has no rotational freedom around the vertical axis or displays a tilt with respect to the vertical columnar axis.

![Figure 1: The different columnar mesophases with the plane group parameters and the amount of discotics per unit cell.](image)

The most simple rectangular mesophase (Figure 1, g) and the tetragonal mesophase (Figure 1, b) are not common because of inefficient space filling compared to the face centered rectangular lattices and the hexagonal lattice. The mesogens in the rectangular and oblique lattices in Figure 1 are depicted as ellipsoids to show the orientational difference between the mesogens, but are not necessarily ellipsoid shaped. The type of mesophase as depicted in Figure 1 can be assigned by studying textures with polarizing optical microscopy and by using X-ray diffraction. In the direction of the columnar axis, structural order or disorder may be present. An ordered mesophase will give a sharp reflection in the wide angle region corresponding to the interdisc distance in the columns. Also, a broad halo should be observed which is a proof for the liquid-like behavior of the aliphatic periphery of the discs. The
indexation of a columnar rectangular mesophase can be complex and, if not enough reflections are observed, not completely unambiguous. For these rectangular mesophases, 'extinction rules' are applicable which determine the absence of reflections in a certain rectangular lattice due to extinction of scattered X-rays (Table 1).

<table>
<thead>
<tr>
<th>Plane group</th>
<th>Extinction rule (these reflections are NOT observed)</th>
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<tbody>
<tr>
<td>c2mm</td>
<td>hk: ( h + k = 2n + 1 )</td>
</tr>
<tr>
<td>p2gg</td>
<td>h0: ( h = 2n + 1 ), 0k: ( k = 2n + 1 ), hk: all observed</td>
</tr>
<tr>
<td>p2mg</td>
<td>0k: ( k = 2n + 1 ), hk: all observed</td>
</tr>
</tbody>
</table>

The properties and self-assembly characteristics of discotics in the mesophase and in solution are mainly determined by the nature of the core and the flexible periphery. This results in appealing properties important for light-emitting diodes, one-dimensional semiconductors or photovoltaic cells for example. The particular properties of columnar mesophases enables easily aligned self-healing fluid materials with high charge carrier mobilities. In solution, discotics may self-assemble into fiber-like structures. For example large aromatic cores or the presence of electron donor-acceptor groups are beneficial for one-dimensional charge transport. Peripheral groups are responsible for the phase separation behavior in both the mesophase and solution and determine the disc's solubility. Numerous non-symmetric discotics have been described with the aim to alter mesophase properties and transitions, to allow interactions and functionality in the mesophase, or to produce disc-shaped mesogens with special optical properties. In solution, desymmetrized, amphiphilic hexabenzocoronenes, which are designed to self-assemble into chiral, helical tapes and nanotubes are well known as are nanofiber-forming amphiphilic, ionic hexabenzocoronenes. Some desymmetrized discotics are prone to covalent or even supramolecular fixation.

![Figure 2](image)

**Figure 2:** a) Apolar (1a,b) and polar (1c,d) C$_5$-symmetrical discotics 1 based on the 3,3’-bis(acylamino)-2,2’-bipyridine unit. The intramolecular hydrogen bonding is shown with dashed lines. b) Schematic representation of their helical self-assembly behavior, which is a simplification of the stack depicted in Figure 3.
In the previous Chapters, the 3,3’-bis(acylamino)-2,2′-bipyridine discotic 1 has been introduced (Figure 2a). The self-assembly properties of these compounds are based on the strong intramolecular hydrogen bonding between amide N-H groups and bipyridine N-atoms preorganizing the molecule into an average planar C₂-symmetrical conformation enabling aromatic stacking (Figure 2a). Stacking due to mainly aromatic interactions occurs in the solid state and in dilute solution. In these stacks the discotics adopt a propeller like conformation to afford helicity (Figure 2b). The nine peripheral alkoxy tails induce phase separation and solubility and they determine the polarity of the compounds. In the solid state, columnar liquid crystallinity is present over a very broad temperature window (> 300K) provided sufficiently long peripheral tails are present. According to detailed X-ray diffraction and modeling studies together with solid state NMR, a helical pitch of approximately 28 discotics was determined for disc 1b. The results of this modeling study are shown in Figure 3. The tight and helical packing of the molecules is clearly visible in Figure 3a. The rotation between superimposed discotics in the stack is made clear in Figure 3b. The central phenyl ring remains perpendicular with respect to the columnar axis while the bipyridine units undergo translational rotation. Importantly, and in contrast to the behavior of N,N’,N”-trialkyl benzene-1,3,5-tricarboxamides, there is no intermolecular hydrogen bonding present between superimposed discotics and self-assembly occurs mainly by π-π stacking. However, the carbonyl moieties of the secondary amides may be involved in attractive intermolecular n→π* interactions resulting from the overlap of a lone pair (n) of the oxygen of one carbonyl with the antibonding orbital (π*) of another carbonyl. This electronic delocalization plays an important role in many interactions in proteins and peptides.

Novel lyotropic mesophases are formed when the discotics are mixed with alkanes in which the columns can be oriented in an electrical field. The same helical columns are formed in the gel phase which is obtained by preparing a concentrated solution of discotics 1a in dodecane. In solution, the presence of these tails not only ensures solubility but also allows introduction of chirality into the system. Bipyridine discotics equipped with polar oligo (ethylene oxide) tails (discotics 1c and 1d, Figure 2) also have been described and they display solubility and express chirality in polar and aqueous media. Both apolar and polar bipyridine discotics obey the “Sergeant and Soldiers” principle in dilute solution, while for the apolar discotics the “Majority Rules” has been reported as well.
In Chapter 2, the synthesis by statistical and step-wise methods of desymmetrized discotics 2 and 3, analogs of bipyridine discotics 1, has been described. The main purpose of desymmetrization is introducing additional functionality at the periphery into these structures. Then, the main question that arises is whether the helical, columnar self-assembly behavior will be affected by removal of one-third of the alkylated, disordered part as is done for discs 2 and 3. In this respect, there can be a difference in self-assembly behavior between the mesophase and in solution, because of intercolumnar interactions in the former situation.

In this Chapter, the self-assembling properties of non-symmetric discotics 2 and 3 (Figure 4) will be discussed in detail.

**Figure 4:** Desymmetrized discotics discussed in this chapter; chiral disc 2 and achiral disc 3 incorporating a phenyl and 4-pyridyl peripheral group, respectively.
3.2 Columnar liquid crystalline behavior of discotics 2 and 3

Both non-symmetric compounds 2 and 3 are sticky solids at room temperature, as are the majority of their C₃-symmetrical analogs. The latter display a very broad liquid crystalline window of more than 300 K. The mesogenic properties of both discotics 2 and 3 were determined using differential scanning calorimetry (DSC), polarizing optical microscopy (POM) and X-Ray diffraction (XRD). The influence of the adaptation, in which a disordered, trialkoxy bulky group is replaced by a rigid, small moiety on the liquid crystalline properties of discotics 2 and 3, is of especial interest. Thermal gravimetric analysis (TGA) was used to determine the thermal stability of non-symmetric discotics 2 and 3. No degradation was observed below 350 °C under a nitrogen atmosphere. However, severe decomposition starting from 300 °C was observed when TGA was performed under an oxygen-rich atmosphere. Therefore, DSC and POM were conducted under a nitrogen atmosphere to ensure reliable results.

3.2.1 DSC and polarizing optical microscopy analysis

For compounds 2 and 3 a transition to the isotropic melt at about 325 °C was observed in both DSC and POM allowing the growth of typical liquid crystalline textures by slow cooling. These textures provide an important proof of the mesogenic properties of the discotics. In Figures 5a and 6a, the pseudo-focal-conic textures of discs 2 and 3 are depicted, which are typical of columnar mesophases, and are exhibited around 300 °C. The straight lines present on the textures are indicative for an ordered columnar mesophase. The enthalpy values associated with the clearing point are of the same order of magnitude as those of similar C₃-symmetrical discotics (Table 2).

### Table 2: DSC data for the phase transitions of discotics 2 and 3.

<table>
<thead>
<tr>
<th>Compound</th>
<th>First cooling run (10 °C/min)</th>
<th>Second heating run (10 °C/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T&lt;sub&gt;onset&lt;/sub&gt; (°C)</td>
<td>ΔH (kJ/mol)</td>
</tr>
<tr>
<td>2</td>
<td>329</td>
<td>5.7</td>
</tr>
<tr>
<td>2</td>
<td>201</td>
<td>8.7</td>
</tr>
<tr>
<td>3</td>
<td>336</td>
<td>6.2</td>
</tr>
<tr>
<td>3</td>
<td>206</td>
<td>10.3</td>
</tr>
<tr>
<td>-3</td>
<td>37.9</td>
<td>LC-Cr</td>
</tr>
</tbody>
</table>

*Measurements were conducted between -50 °C and 350 °C. The onset was taken as transition temperature. | Type of phase transition according to POM. Exact mesophase was determined with XRD. Interestingly, a transition to a lower temperature mesophase was detected by DSC for both 2 and 3 at approximately 200 °C (Table 2). This transition is not present in their symmetrical analogs. Apparently, it does not matter whether a phenyl or pyridyl group replaces the trialkoxyphenyl wedge in 2 and 3 for the appearance and thermal position of the transition between the two mesophases. Also the transition temperature between the two mesophases is not influenced by branching in the aliphatic tails. The enthalpy values associated with this transition are relatively small meaning that there is no large structural difference between the
two mesophases of discs 2 and 3. The transition between the two mesophases can actually consist of a two-step transition as is supported by the presence of two almost coincident peaks in the DSC run of disc 2.\textsuperscript{48} By POM, this transition was observed for discs 2 and 3 by a rapid change of the texture around 210 °C,\textsuperscript{49} while the compound remains fluid under pressure (Figure 5b and 6b).

![Figure 5: POM pictures of disc 2, cooling from the isotrope. a) 295 °C, b) 175 °C (same area, rotated).](image)

![Figure 6: POM pictures of disc 3, cooling from the isotropic melt. a) 315 °C, b) 160 °C (same area).](image)

The compounds display a very broad liquid crystalline window (> 300 K) and are liquid crystalline at room temperature which is important for future applications.\textsuperscript{8,14} Apparently, the removal of one trialkoxylated unit, compared to their \(C_3\)-symmetrical analogs, does not decrease the ability of discotics 2 and 3 to form mesophases. Below room temperature discotic 3 exhibits a Cr-LC transition. Although the observed texture undergoes only very subtle changes, we assign the transition as crystallization as it is accompanied with a large enthalpic change compared to the transitions at approximately 200 °C and 325 °C (Table 2). For compound 2 no melting transition was observed. The absence of melting point is probably caused by the presence of branched tails in compound 2 which will lower the melting point.\textsuperscript{50} The isotropic transitions of both discs 2 and 3 are lower than that of discotics 1a,b which is in agreement with other reported desymmetrized systems.\textsuperscript{24,51} All discussed phases in discotics 2 and 3 are enantiotropic and little hysteresis was observed for the LC-LC transitions at approximately 200 °C for both 2 and 3 and for the Cr-LC transition of discotic 3.
Self-assembly behavior of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit

3.2.2 Small and wide angle X-ray diffraction

Discotics 2 and 3 were investigated by small (SAXD) and wide (WAXD) angle X-ray diffraction with the aim of verifying the type of mesophase and to determine the structural parameters. As foreseen from the DSC traces, the structures of the mesophases at room temperature (RT) and above are equivalent for both compounds. Below RT an additional phase was detected for discotic 3 and for that reason, the results for discotic 3 will be discussed in particular. All SAXD and WAXD data for both discotics 2 and 3 are gathered in Table 3.

Table 3: X-ray results for the mesophases of desymmetrized discotics 2 and 3.

<table>
<thead>
<tr>
<th>Compd.</th>
<th>T [°C]</th>
<th>Phase</th>
<th>h k l</th>
<th>d_{obs} [Å]</th>
<th>d_{calcd} [Å]</th>
<th>Lattice constants [Å]</th>
<th>( \rho_{calcd} ) [g cm(^{-3})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>discotic 2</td>
<td>RT</td>
<td>Col(_2)</td>
<td>2 0 0</td>
<td>50.3</td>
<td>50.3</td>
<td>( a = 100.5 )</td>
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<tr>
<td></td>
<td></td>
<td>P2gg</td>
<td>1 1 0</td>
<td>34.5</td>
<td>34.5</td>
<td>( b = 36.8 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 0 0</td>
<td>25.4</td>
<td>25.1</td>
<td>( c = 38.0^\circ )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0 2 1</td>
<td>16.6</td>
<td>16.6</td>
<td>( h = 3.3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 2 1</td>
<td>15.8</td>
<td>15.7</td>
<td>( Z = 4^f )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 2 1</td>
<td>14.4</td>
<td>14.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 1 0</td>
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<td>13.4</td>
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<td>Alkyl</td>
<td>( \pi-\pi )</td>
<td>4.5 (br.(^a))</td>
<td>3.3</td>
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<tr>
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<td>230(^b)</td>
<td>Col(_3)</td>
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<td>( a = 69.4 )</td>
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</tr>
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<td>Z = 2(^f)</td>
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</tr>
<tr>
<td>discotic 3</td>
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<td>Col(_1)</td>
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<td>( a = 106.6 )</td>
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<td>( b = 40.6 )</td>
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</tr>
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<td>3 1 0, 4 0 0</td>
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</tr>
<tr>
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<td></td>
<td>Alkyl</td>
<td>( \pi-\pi )</td>
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</tr>
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<td>3 3 3</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>53.8</td>
<td>( a = 107.6 )</td>
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<td>37.0</td>
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<td>( h = 3.3 )</td>
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<td>16.5</td>
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<td>Alkyl</td>
<td>( \pi-\pi )</td>
<td>4.5 (br.(^a))</td>
<td>3.3</td>
<td></td>
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</tr>
<tr>
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<td></td>
<td></td>
<td>240(^b)</td>
<td>Col(_3)</td>
<td>2 0 0</td>
<td>33.4</td>
<td>33.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c2mm</td>
<td>1 1 0</td>
<td>31.7</td>
<td>31.7</td>
<td>( b = 34.8^c )</td>
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</tr>
<tr>
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<td></td>
<td>4 0 0</td>
<td>18.1</td>
<td>18.0</td>
<td>Z = 2(^f)</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) br. = broad maximum. \(^b\) No WAXD measurement is available above 200 °C. \(^c\) Crystalline phase. \(^d\) Calculated density for two columns per unit cell in the case of Col\(_3\) and four columns per unit cell in the cases of Col\(_1\) and Col\(_2\). \( \rho_{calcd} = (10 \times Z \times Mw)/(a \times b \times h \times 6.02) \), where Mw is the molecular weight and h is assumed to equal 3.3 Å for Col\(_3\). \(^e\) c corresponds to the periodicity of the helix. \(^f\) Z is the number of discotics per slice of the unit cell.
The WAXD profile of discotic 3 at RT (Figure 7a) exhibits two features in the wide-angle region. One peak corresponds to a distance of 3.3 Å, which is in the range of the stacking distance between aromatic rings in the liquid crystalline state. This confirms the ordered columnar structure of the phase. The other feature is a diffuse halo corresponding to a distance of about 4.5 Å, the typical distance between molten alkyl chains in a mesophase. These features remained present up to the maximum temperature limit of 200 °C of the WAXD setup. Upon cooling from RT to -21 °C the alkyl chains freeze into a more ordered or crystalline phase and the diffuse halo turned into a peak corresponding to 4.2 Å.

Figure 7: a) WAXD profiles for discotic 2 at RT (black) and 201 °C (gray). b) SAXD profiles for discotic 2 at r.t. (black), 210 °C (gray) and 230 °C (dashed). c) WAXD profiles for disc 3 at -21 °C (dotted line), RT (dashed line) and 200 °C (solid line). d) SAXD profiles for discotic 3 at -21 °C (solid line), RT (gray line), 200 °C (dashed line) and 240 °C (dotted line), inset: vertical expansion of the graph at 240 °C to visualize the small 4 0 0 reflection. e) Structures of Col\(_2\) (P2gg) and Col\(_3\) (C2mm) phases for disc 3. The unit cell is filled with diagonal lines.
SAXD patterns of discotic 3 at -21 °C and RT are analogous and display a set of maxima with an additional peak at the lower temperature (Figure 7d). The ratio between the spacings corresponding to the peaks is not in a reciprocal ratio indicative of square or hexagonal two-dimensional lattices. However, they can be indexed according to a rectangular symmetry p2gg (Figure 1d) based on the extinction rules (Table 1). The lattice parameters of the rectangular arrangement are given in Table 3. The phase at -21 °C has the same structure as the liquid crystalline phase at RT, except for the peripheral alkyl chains, which are crystallized in the Col_{13} phase. Upon increasing the temperature, a third phase Col_{13} appears. The SAXD profile at 240 °C is simpler than at lower temperatures. Only three peaks are present in the small-angle region (the 400 reflection is visualized in the inset of Figure 7d), which can be indexed according to a rectangular lattice too. Nevertheless, the unit cell for this Col_{13} phase is much smaller than for the lower temperature phases (Table 3) and c2mm rectangular symmetry was assigned. As commented above, WAXD data were not available for this phase because of experimental limits. In a columnar rectangular phase, there are typically two columns per unit cell, one of which is in the center and the other is in the corner of the unit cell. This is the case for the Col_{13} phase, which exhibits similar lattice parameters to those of the Col_{1} phase of the symmetrical compound taking into account the differences in the structure of the discs and in the temperature of the measurements. However, in Col_{11} and Col_{12} phases an unusual value of Z = 4 was calculated based on density considerations (Table 3). When comparing the lattice parameters, b is similar for all phases for both disc 2 and disc 3, but parameter a in Col_{11} and Col_{12} is nearly twice parameter a in the Col_{13}. It is assumed that at lower temperatures the symmetry decreases and, as a result, two unit cells of Col_{13} combine to give rise to the new unit cell of the Col_{12} and Col_{11} phases (Figure 7e).

The loss of symmetry in the supramolecular organization when lowering the temperature might arise from different orientation in the plane of the non-symmetric molecules or from a vertical shift of neighboring columns. As will be discussed in section 3.4, the columns formed by discotics 2 and 3 are inherently helical in solution. X-ray diffraction studies on aligned samples can be used to elucidate the structure of the helix in the liquid crystalline phase. SAXD and WAXD patterns of an aligned sample of discotic 3 at RT (Col_{12}) are shown in Figure 8. The meridional position of the peak due to the π–π stacking in addition to the three most intense peaks in the small-angle region being on the equator, confirms that the phase is columnarly ordered with the central benzene ring of disc 3 being perpendicular to the axis of the columns (Figure 8a). In the helical organization the molecules adopt a propeller shape in which the bipyridine units are tilted with respect to the central benzene unit. This deviation of coplanarity together with the helical 'entanglement' between superimposed discs might be a reason for the extraordinary mesophase stability of bipyridine discotics as was rationalized for perylene bisimides and for ester substituted triphenylenes. Therefore, an additional meridional maximum at a slightly lower diffraction angle than the π–π stacking maximum corresponding to 3.7 Å is ascribed to the perpendicular distance between the bipyridine units of consecutive discs. The less intense maxima in the small-angle region are split into a four-spot pattern (Figure 8b). This feature is ascribed to helical intracolumnar order and to the existence of three-dimensional order in the mesophase. From the split maxima a periodicity
of 36.5-38.0 Å can be measured along the axis of the columns. This value is only slightly larger than the helical periodicity of the symmetrical discotic 1a,b\(^{35}\) although a three-time larger value would be expected in this case, due to the absence of C\(_{3}\)-symmetry. We have two hypotheses to explain this observation. Firstly, there is no correlation between the position of the pyridine moieties in consecutive discotics disordered along the column, so that the overall symmetry is the same as with C\(_{3}\)-symmetrical derivatives 1a,b. Secondly, electron density is similar for alkylated and non-alkylated wedges so that they are not distinguished by X-ray diffraction. In the structure we propose, the relative rotation between consecutive discotics in a column of discotic 3 is about 11° and around 33 discotics are needed for a complete rotation of 360° (35 discotics in the case of disc 2). Upon increasing the temperature, the helicity in the columns of disc 2 might get lost due to an increase of thermal motions of the discotics. Thus, in the Col\(_{3}\) mesophase no helical columns might be present which can be an additional explanation for the larger symmetry of the Col\(_{3}\) rectangular lattice compared to the rectangular Col\(_{2}\) and Col\(_{1}\) lattices.

![Figure 8](image_url)

**Figure 8**: (a) WAXD and (b) SAXD patterns of an aligned sample of disc 3 at RT. The capillary axis is vertical.

### 3.3 Attempt to solve the helical structure with crystallography

In the previous section, the presence of a helical organization in columnar stacks of discs 2 and 3 was discussed. The same helical structure was detected for C\(_{3}\)-symmetrical derivatives.\(^{33,35}\) Also in a poor solvent in which discs 1 are stacked, a helical self-assembly is present according to optical spectroscopy, especially CD spectroscopy.\(^{41,42}\) The helical self-assembly of discs 2 and 3 is discussed in the next section. However, the best evidence of a helical structure is gained by solving a crystal structure by X-ray diffraction. The most famous example of this is determination of the α-helical structure of polypeptides by Pauling *et al.*\(^{58}\) Crystallography has been successfully used to prove the triple helical type of intermolecular hydrogen bonding involved in assemblies of \(N,N',N''\)-trialkyl-benzene-1,3,5-tricarboxamide discotics, for example disc 4 possessing peripheral ester functionalities (Figure 9).\(^{36,59}\) Also, well aligned fibers can give precise structural information, as has been achieved for the DNA double helix\(^{60}\) and hexabenzocoronene discs.\(^{54}\)
Self-assembly behavior of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit

3.1.1 Synthesis of crystalline discotics

Discotic 1, 2 and 3 are liquid crystalline at room temperature thus preventing the growth of crystals. Also, long aliphatic tails will introduce disorder in a crystal. It is known that polar groups on the periphery of a molecule will enhance strong packing in the solid state ensuring the formation of stable crystals. However, strong, lateral interactions between these peripheral group will frustrate columnar stacking resulting in herringbone organization in the crystal. This is observed for benzene-1,3,5-tricarboxamides with polar peripheral groups that do not crystallize into columnar structures. Therefore, two apolar \( C_3 \)-symmetrical discotics lacking long tails have been synthesized. Discotic 5 (Scheme 1) incorporates nine short propoxy tails to resemble the original structure as much as possible. Disc 6 (Scheme 2) contains three adamantyl groups instead of the gallic moieties. The adamantyl group will provide enough solubility, but may also help to ensure crystallinity. The synthesis of disc 5 is depicted in Scheme 1 and is analogous to the synthesis of discs 1a.

Scheme 1: Five-step synthesis towards \( C_3 \)-symmetrical short-tail discotic 5.
The synthesis of the periphery of disc 5 started with the alkylation of methyl gallate with bromopropane according to a literature procedure. Subsequent saponification of ester 8 to give acid 9 and subsequent chlorination to acid chloride 10 were performed in good yields. The desired small mono-wedge 12 was obtained after selective acylation of diamine 11 with acid chloride 10. Finally, reaction of amine 12 with trimesyl chloride yielded disc 5 (Scheme 1). However, to obtain disc 5 pure, preparative recycling GPC was necessary. The synthesis of the triadamantyl disc 6 was executed via similar, established procedures (Scheme 2).

![Scheme 2: Three-step synthesis of C₅-symmetrical adamantane disc 6.](image)

Commercially available 1-adamantanecarboxylic acid (13) was converted with oxalyl chloride into acid chloride 14. The latter was reacted with 3,3'-diamino-2,2'-bipyridine (11) from which amine 15 was obtained in good yield thanks to selective mono-acylation of diamine 11. Mono-amine 15 could be easily recrystallized affording beige crystals. The bisamide side-product proved to be highly crystalline too. Both compounds could be separated by selective crystallization. Eventually, mono-amine 15 was reacted with trimesyl chloride to afford adamantane disc 6, which was purified by crystallization.

### 3.3.2 Crystal growth and analysis

According to ¹H-NMR spectroscopy, both C₅-symmetrical discotics 5 and 6 are preorganized in a similar fashion to their previously reported analogs 1 (Figure 2). Their NMR spectra and peak assignments are shown in Figure 10. A more detailed explanation of the typical chemical shift accompanying the preorganized structure is given in Chapter 2, section 2.4. Amide N-H protons 7 and 7' are positioned strongly downfield for both 5 and 6 and bipyridine protons also experience downfield shifts. These observations make clear that both discotics 5 and 6 have a preorganized conformation, caused by strong intramolecular hydrogen bonding between the amide N-H moieties and bipyridine nitrogens. Apparently, these compounds have the capability to self-assemble in a similar fashion to discotics 1. Thus, solving their crystal structure might help in the visualization of the stacking of discotics 1. Only N-H protons 7’ of discs 5 and 6 differ from each other and this is rationalized by the presence of an aromatic peripheral group in disc 5 and an aliphatic one in disc 6. The solid material displays intrinsic yellow-green fluorescence, suggesting columnar aggregation.
Self-assembly behavior of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit

Figure 10: $^1$H-NMR spectra of discs 5 (a) and 6 (b) in CDCl$_3$ together with the peak assignment. Concentration = 1 mM.

Short-tail disc 5 proved to be only sparingly soluble in chloroform and insoluble in polar solvents like acetone, methanol, DMSO, and DMF. Crystallization could be performed from solvents like toluene, MIBK and chloroform but only fine suspensions were obtained. Disc 5 exists as a slightly sticky solid at room temperature suggesting that it might be liquid crystalline. DSC and POM confirmed this assumption; around 325 °C disc 5 turns into an isotropic liquid. Under slow cooling textures can be grown that are indicative for a columnar mesophase. No crystallization transition was observed, thus this compound is not suitable to grow single crystals.

Disc 6 and its amino precursor 15, however, could be crystallized rather easily. Discotic 6 does not display any thermal transitions; no isotropization was observed and it remains a hard solid upon heating above 350 °C. The best solvent for growing crystals proved to be a 1:1 mixture of toluene (or benzene) and chlorobenzene. An unsaturated solution of disc 6 was prepared at approximately 100 °C and cooled slowly in a Dewar with hot water. During the cooling thin, needle-like, fluorescent crystals grow, their shape being an indication for the preferred one-dimensional growth. Examples of the grown needle-like crystals are shown in Figure 11. Their maximum diameter is approximately 20 μm which is too small to be analyzed in a conventional X-ray diffraction apparatus.$^{68}$ X-ray diffraction was performed by Dr. Martin Lutz and Dr. Ehmke Pohl from the universities of Utrecht and Durham respectively. Especially Dr. Ehmke Pohl, Dr. Olga Chetina, Prof. Judith Howard and Prof. Jim Feast of the University of Durham are greatly acknowledged for helping with and attempting of crystal structure analysis. Unfortunately, the crystals do not diffract in an ordered fashion when irradiated with intense synchrotron X-rays either.$^{69}$ Probably, the crystals are not really single crystal, although they look fine under the polarizing optical microscope (Figure 11b). Apparently, not enough lateral interactions are present in the crystal preventing convenient crystal growth perpendicular to the stacking direction. A discotic equipped with a slightly more polar periphery than adamantyl or alkyl group might afford better quality crystals.
Figure 11: a) Typical needle-like crystals of disc 6 grown by slow cooling of a solution in chlorobenzene-toluene 1:1 (v:v). The maximal diameter is approximately 20 μm. b) Crystals of disc 6 viewed with cross polarizers.

3.4 Self-assembly behavior of discotics 2 and 3 in solution

Besides the formation of columnar assemblies in the liquid crystalline state, discotics 2 and 3 also self-assemble in apolar solution.41 The helical self-assembly is made possible by strong intramolecular hydrogen bonding as is discussed in Chapter 2, section 2.4 for discotic 3. In a good solvent however, disordered aggregates may be present at rather high concentrations for disc 2 and this has been studied with 1H-NMR in CDCl$_3$. For chiral disc 1a, helical stacks can be detected with CD spectroscopy in alkane solution where a Cotton effect corresponding to an electronic transition in UV/Vis will be visible.41 In this section, CD, UV/Vis and PL spectroscopy is discussed to reveal whether discs 2 and 3 adopt helical self-assemblies in alkane solvents.

3.4.1 NMR spectroscopy

When a 1H-NMR spectrum of discotic 2 was taken in CDCl$_3$, protons characteristic for a preorganized structure were observed (Figure 12a). Sharp signals in the aromatic region show the absence of or very little interdisc interactions at a rather low (0.5 mM) concentration. Peak assignment was discussed in Chapter 2 section 2.4, for disc 3 and coincides with the assignment of disc 2. With increasing concentration of discotic 2 in CDCl$_3$, peak broadening and upfield shifts can be observed indicative of aggregation (Figure 12b,c). The largest upfield shift (9.25 to 8.8 ppm) is observed for central benzene protons 10 and 11. The upfield shift is indicative of anisotropic deshielding of the aromatic protons by aromatic units of a neighboring disc and that these units are within 7 Å of each other.71 Peak broadening suggests restricted freedom of the aromatic protons involved, which is expected to result from disc aggregation. However, no ordered, helical aggregates are formed in chloroform at mM concentrations according to CD and UV/Vis spectroscopy. The hydrogen bonded amide protons 7, 7’, [7] and [7]’ only display a limited upfield shift resulting from the disc aggregation upon increasing the concentration. Thus, the strength of the hydrogen bond between the amide N-H and the bipyridine nitrogen is independent of the concentration which is typical for an intramolecular hydrogen bond.
Self-assembly behavior of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit

Figure 12: $^1$H-NMR spectra of discotic 2 in CDCl$_3$ at 0.5 mM (a), 6 mM (b) and 14 mM (c) at 25 °C. Only the aromatic and hydrogen bonded proton region are depicted; the peaks belonging to the aliphatic region do not change with changing concentration.

3.4.2 Optical spectroscopy

The self-assembly of discotic 2 was further investigated using CD spectroscopy with the aim of establishing how the removal of one alkylated, bulky group influences the self-assembly behavior of these discotics in apolar, dilute solution. To compare the aggregation behavior of discotic 2 with the parent C$_7$-symmetrical compounds a mixing experiment in which chiral discotic 2 is added to achiral, symmetric discotic 1b (Figure 2) has been performed (Figure 13). C$_7$-symmetrical discotic 1b is known to self-assemble into well defined supramolecular, helical columns in alkanes like heptane due to phase separation, π-π stacking and preorganization by intramolecular hydrogen bonding. The chiral analog of discotic 1b equipped with dihydro-citronellyl side chains (discotic 1a, Figure 2) is able to shift the equilibrium between right handed (P) and left handed (M) helices to one of them, creating an overall chiral supramolecular structure. From mixing experiments in alkanes it is known that a small amount of chiral discotic 1a is able to bias the helicity of columns of achiral discotic 1b. This is known as the "Sergeant and Soldiers" experiment in which chiral 1a acts as a sergeant who directs a platoon of achiral soldier-discotics 1b. These experiments have been performed for desymmetrized N,N',N'''-trialkyl-1,3,5-benzene tricarboxamide discotics, but none of them was lacking a complete aliphatic part. If desymmetrized, chiral discotic 2 is able to bias the helicity of achiral discotic 1b in a similar fashion we may assume discotic 2 and achiral analog 3 display the same aggregation behavior as C$_7$-symmetrical discotic 1b and its analogs. The latter is a requisite to transfer the knowledge gained from symmetrical systems to the design of a desymmetrized discotic equipped with the desired functional group for supramolecular interactions. Thus, dilute solutions of discotic 2 in heptane were added to dilute solutions of discotic 1a of the same concentration in heptane (Figure 13). For every
measuring point in Figure 13, a fresh mixture was prepared from the two stock solutions of discotics 2 and 1b, respectively.

**Figure 13:** a) CD and UV/Vis spectra of the Sergeant and Soldiers experiment with discotics 2 and 1b. b) g-Values plotted as a function of the chiral disc content. g-Values were measured at 387 nm for mixtures of discs 2 and 1b in heptane at room temperature. Concentration = 27 µM. The magnitude of the Cotton effect is stable after mixing.

In Figure 13b the Cotton effect, given as the anisotropic g-factor, is plotted against the amount of chiral disc added; a strong non-linear dependence is clearly visible. Already after addition of 5 mol-% chiral disc 2 the same amplitude of the Cotton effect as with 100 mol-% chiral 2 is observed. This indicates a strong bias of the helical sense of assemblies of achiral 1b by chiral 2, thus strongly suggesting the presence of mixed assemblies of discotic 2 with 1b. The Cotton effect emerges immediately after mixing and is stable with time indicating that the dynamic system immediately adopts its thermodynamically most favorable state. The positive Cotton effect of pure disc 2 between 300 nm and 350 nm cannot be explained and will need further investigation. A difference in the shape of the Cotton effect between mixtures of achiral and chiral discs and pure chiral disc was observed previously. The maximum in CD intensity was observed around 25 mol-% disc 2, which might be rationalized by more efficient packing of achiral disc 1b, lacking methyl branches, compared to chiral disc 2. A dependence of the aggregation on the branched character of the aliphatic periphery has been observed for hexabenzocoronene discotics.

For achiral discotic 3, temperature dependent self-assembly in apolar solution has been examined with UV/Vis and fluorescence spectroscopy to study its aggregation behavior in dilute apolar solution (Figure 14). Upon cooling, the UV/Vis absorption spectrum of discotic 3 in dodecane displays a bathochromic shift between 100 °C and 70 °C accompanied by a decrease in extinction coefficient (ε). A bathochromic shift together with a small increase of ε is observed between 70 °C and 10 °C. The bathochromic shift of the absorption maximum belonging to the gallic moieties amounts to 2 nm (292-294 nm) and the bathochromic shift of the absorption maximum belonging to the bipyridine moiety amounts to 4 nm (360-364 nm). In the region of the π-π* transition of the bipyridine system around 362 nm the fine-structure becomes more pronounced. This fine structure, displaying absorption maxima at 364, 383 nm, and a shoulder at 351 nm is indicative of the formation of well-ordered, helical stacks in
The shape of the spectrum at 100 °C is similar to a spectrum of discotic 3 in chloroform (Figure 14a), in which the discotics are molecularly dissolved. The latter spectrum shows a hypsochromic shift of about 12 nm compared to the spectrum of discotic 3 in dodecane.

![Figure 14](image_url)  
**Figure 14:** a) Temperature dependent UV/Vis absorption spectra of discotic 3 in dodecane, \(c = 17 \, \mu M\), cooling rate = 1 K/min. Spectrum in chloroform is taken at room temperature, \(c = 19 \, \mu M\). b) Temperature dependent fluorescence spectra of discotic 3 in dodecane, \(c = 1 \, \mu M\), cooling rate = 1 K/min. Excitation performed at 365 nm.

In the fluorescence spectrum (Figure 14b) a large, gradual increase of the fluorescence intensity can be observed upon cooling. This increase is, together with the red shift in UV/Vis, indicative for the formation of J-aggregates in dilute solutions in dodecane, a phenomenon also observed for discotics containing oxadiazole moieties. This formation of J-aggregates coincides with our molecular picture of a helical stack of discotic 3 in which the 3,3'-bis(acylamino)-2,2'-bipyridine chromophores are placed on top of each other in a slipped and tilted ship’s propeller-like manner. When a dilute solution of discotic 3 in dodecane is heated to 100 °C, the fluorescence is largely quenched as in a chloroform solution at room temperature in which the molecularly dissolved state of 3 is present. The fluorescence maximum is located at 513 nm reflecting a large Stokes shift of about 148 nm presumably due to intramolecular double proton transfer within the diamino bipyridine moieties in the excited state.

### 3.5 Conclusions

Like their \(C_3\)-symmetrical counterparts 1, non-symmetric discotics 2 and 3 display helical columnar liquid crystallinity over a very broad temperature window and are mesogenic at room temperature. According to X-ray diffraction and DSC analysis two mesophases are present for both discotics 2 and 3, while for discotics 1 only one mesophase has been reported. Below 200 °C, a novel rectangular mesophase is identified with four discotics in the unit cell. The symmetry of the lattice increases when the temperature is raised resulting in a more symmetric rectangular mesophase. X-ray diffraction revealed a helical structure with a pitch of 33 discotics in the rectangular mesophase, similar to that observed in the rectangular mesophase of \(C_3\)-symmetrical disc 1. Single crystal X-ray diffraction would be a convenient method to prove the presence and exact conformation of the helical structure of self-assembled
Chapter 3

disc 1. To allow isolation of single crystals, two C₃-symmetrical discotics possessing a less disordered periphery were synthesized. Whereas nonapropoxy-disc 5 proved to be liquid crystalline, discotic 6, equipped with adamantyl peripheral groups, could be crystallized to give needle-like crystals. The latter were analyzed with X-ray diffraction, but a crystal structure could not be resolved. Further analysis in solution revealed that discotics 5 and 6 display similar self-assembly behavior as to discotics 1-3, thus the presence of only a small aliphatic periphery does not prevent helical stacking. The latter is enabled by the preorganized structure of the discotics as was described in Chapter 2. Optical spectroscopy shows well-ordered helical stacking of discotic 3 in non-solvents like alkanes together with expression and amplification of chirality as is observed for disc 2 with the sergeant and soldiers mixing experiment. Excitingly, the replacement of one of the trialkoxyphenyl disordered wedges by a rigid moiety does not prevent the formation of helical columnar mesophases and highly ordered helical stacking in solution. They even mix at the molecular level with their C₃-symmetrical parent compounds showing that their self-assembly in solution is identical. The latter property will be exploited in the next Chapter, where the control of the supramolecular helicity of disc 2 by chiral templates is described.

3.6 Experimental section

For other experimental conditions concerning synthesis, see Chapter 2. Bromopropane and methyl 3,4,5-trihydroxybenzoate were purchased from Fluka (www.aldrich.com), 1-adamantane carboxylic acid from Acros (www.acros.com) and potassium iodide and sodium hydroxide from Merck (www.merck-chemicals.com). Chlorobenzene was purchased from Acros and was of HPLC grade quality. Dodecane, chloroform and heptane used for optical spectroscopy were of spectrograde quality and purchased from Aldrich, dodecane from Acros. All spectroscopic measurements were performed at room temperature unless stated otherwise. CD spectra were recorded on a Jasco J-600 spectropolarimeter equipped with a Jasco PTC-348WI Peltier type temperature control system, UV/Vis spectra were recorded on a Perkin Elmer Lambda 40 UV/Vis spectrometer equipped with a Perkin Elmer PTP-1 Peltier temperature control system and fluorescence spectra were measured on a Perkin Elmer LS50B luminescence spectrometer equipped with a Perkin Elmer PTP-1 Peltier temperature control system. A one cm quartz cuvette was used for the measurements, wavelengths are given in nm and absorptions in 1/mol/cm. Thermal gravimetric analysis (TGA) was carried out on a Perkin Elmer Pyris 6 Thermogravimetric Analyser. Heating was performed from 30 °C till 600 °C with a gradient of 10 °C per minute under a nitrogen atmosphere. Polarized optical microscope images were made on a Carl-Zeiss Jenaval polarization microscope equipped with a Linkam THMS 600 heating device and a Polaroid digital camera model PDMC-2. Measurements were performed under a nitrogen atmosphere to prevent thermal degradation. DSC analysis was performed on a Perkin Elmer Pyris 1 or Thermal Analysis Q2000 instrument under a nitrogen atmosphere. For all SAXD and WAXD measurements the crude product was filled in a Lindemann glass capillary (0.9 mm diameter). Aligned samples were obtained by shearing inside the capillary at the temperature of the mesophase, typically at 160 °C. The studies on the aligned sample were carried out at the University of Zaragoza with a pinhole camera (Anton-Paar) operating with a point-focused Ni-filtered CuKα beam. The capillary axis was perpendicular to the X-ray beam and the pattern was collected on a flat photographic film perpendicular to the beam. Spacings were obtained via Bragg’s law. In this setup the whole beam path was under vacuum for RT measurements. SAXD measurements were made using a homemade setup at ALMOLF, with a rotating anode X-ray generator.
Self-assembly behavior of desymmetrized discotics based on the 3,3’-bis(acylamino)-2,2’-bipyridine unit

(Rigaku RU-H300, 18 kW) equipped with two parabolic multilayer mirrors (Bruker, Karlsruhe, Germany), giving a highly parallel beam (divergence about 0.025°) of monochromatic Cu Kα radiation (λ = 1.54 Å). The SAXD reflections were collected with a two-dimensional gas-filled wire detector (Bruker Hi-Star). To change the temperature an adapted Linkam THMS 600 hot-stage was used. Powder XRD measurements were performed on a home-built system at Philips (Eindhoven) consisting of a sealed X-ray tube (Cu-Kα radiation), a primary graphite monochromator, a pinhole collimator, a sample stage, and a Siemens Hi-Star area detector. Samples were prepared in a 0.9 mm diameter Lindemann capillary tube and mounted in a home-built furnace, based on a TMS94 Linkam hot stage. WAXD patterns were recorded with a sample-to-detector distance of 8.1 cm.

Methyl 3,4,5-tripropoxybenzoate (8)
Under argon, methyl gallate (7) (5.129 g, 27.84 mmol), bromopropane (10.2 mL, 0.112 mol), potassium iodide (0.145 g, 0.873 mmol) and finely powdered, dry K$_2$CO$_3$ (23.0 g, 0.166 mol) were mixed in acetone (60 mL) at room temperature under vigorous stirring. Under argon, the white suspension was heated under reflux and vigorous stirring for 23 h after which TLC and 1H-NMR showed the presence of product only. Subsequently, the reaction mixture was concentrated in vacuo and the residue was partitioned between dichloromethane (50 mL) and salty water (100 mL). The aqueous layer was extracted with dichloromethane (50 mL), the organic layers were combined, dried with MgSO$_4$, and filtered over a glass filter. Subsequent concentration in vacuo yielded an thick oily residue (2.50 g) that almost exclusively consists of desired product. NMR analysis of the aqueous layer showed the presence of little starting material (methyl gallate), but no intermediate products. Purification by column chromatography (silica gel, 9-10 vol% ethyl acetate in heptane) yielded ester 8 (2.324 g, 27 %) as a colorless oil that solidifies upon thorough drying.

R$_f$ = 0.32 (silica gel, 10 vol% ethyl acetate in heptane); GC-MS: R$_f$ = 6.21 min (one peak), m/z: calcd for: 310.18; found: 310 (radical cation); 1H NMR (400 MHz, acetone-D$_6$): δ = 7.26 (s, 2H, 2), 4.00 (t, 4H, 1J(H,H) = 6.4 Hz, 7), 3.99 (t, 2H, 1J(H,H) = 6.4 Hz, 6), 3.85 (s, 3H, OCH$_3$), 1.83 (sextet, 4H, 1J(H,H) = 7.0 Hz, 9), 1.78 (sextet, 2H, 1J(H,H) = 7.0 Hz, 8), 1.06 (t, 6H, 1J(H,H) = 7.6 Hz, 11), 1.05 ppm (t, 3H, 1J(H,H) = 7.6 Hz, 10);

13C NMR (100 MHz, acetone-D$_6$): δ = 166.8 (5), 153.7 (3), 143.3 (4), 125.7 (1), 108.6 (2), 75.3 (6), 71.2 (7), 52.2 (OCH$_3$), 24.3 (8), 23.4 (9), 11.0 (10), 10.9 ppm (11); FT-IR (ATR): ν (cm$^{-1}$) = 2964, 2938, 2878, 1718 (C=O), 1587 (Ar C=C), 1499, 1446, 1430, 1387, 1331, 1301, 1242, 1211, 1118, 1097, 1060, 1041, 1016, 999, 959, 936, 906, 862, 822, 760, 670; Elemental analysis calcd (%) for C$_{17}$H$_{25}$O$_3$: C 65.78, H 8.44; found: C 66.13, H 8.45.

3,4,5-Tripropoxybenzoic acid (9)
Sodium hydroxide (0.358 g, 8.95 mmol) dissolved in water (2 mL) was added to a well-stirred solution of ester 8 (1.010 g, 3.25 mmol) in ethanol (16 mL). The reaction mixture was refluxed for 5 h after which TLC indicated complete conversion. Subsequently, ethanol was removed from the reaction mixture under reduced pressure. The aqueous residue was partitioned between brine (10 mL), aqueous HCl solution (6 M, 5 mL) and dichloromethane (10 mL). The water layer was extracted with dichloromethane (3 × 10 mL), the organic layers were combined, dried with MgSO$_4$, and filtered over a glass filter. After concentration in vacuo and thorough drying, acid 9 was obtained as a white residue (0.930 g, 97 %).

R$_f$ = 0.27 (silica gel, 3 vol% methanol in chloroform); m.p. 93.3-93.7 °C (Lit. 93 °C);1H NMR (400 MHz, acetone-D$_6$): δ = 7.30 (s, 2H, 2), 4.01 (t, 4H, 1J(H,H) = 6.4 Hz, 7), 3.99 (t, 2H, 1J(H,H) = 6.4 Hz, 6), 1.83 (sextet, 4H, 1J(H,H) = 7.0 Hz, 9),
1.74 (sextet, 2H, 3J(H,H) = 7.0 Hz, 8), 1.07 (t, 6H, 3J(H,H) = 7.3 Hz, 11), 1.05 ppm (t, 3H, 3J(H,H) = 7.2 Hz, 10); 13C NMR (50 MHz, acetone-D6, APT): δ = 167.3 (5), 153.6 (3), 143.0 (4), 125.9 (1), 108.7 (2), 75.2 (6), 71.0 (7), 52.2 (OCH3), 24.2 (8), 23.3 (9), 18.8 (10), 10.8 ppm (10); FT-IR (ATR): ν (cm⁻¹) = 2963, 2937, 2876, 2647 (acid), 2589 (acid), 2524 (acid), 1686 (C=O), 1588 (C=C Ar), 1503, 1462, 1454, 1428, 1396, 1387, 1348, 1326, 1282, 1224, 1111, 1097, 1062, 1042, 1004, 962, 952, 936, 863, 821, 760, 724, 678; Elemental analysis calcd (%) for C16H12O3: C 64.84, H 8.16; found: C 65.10, H 8.14.

### 3,4,5-Tripropoxybenzoyl chloride (10)
Under argon, oxalyl chloride (0.7 mL, 8.2 mmol) and DMF (two drops) were added to a well-stirred, ice-cold solution of 3,3'-diamino-2,2'-bipyridine (11) (0.925 g, 3.12 mmol) in distilled dichloromethane (25 mL). Escape of gases took place and the reaction mixture was stirred overnight under argon after which FT-IR indicated complete conversion. Concentration in vacuo and subsequent removal of volatiles under high-vacuum yielded acid chloride 10 as a beige oil that was used as such.

1H NMR (300 MHz, acetone-D6): δ = 7.39 (s, 2H, 2), 4.09 (t, 2H, 3J(H,H) = 6.3 Hz, 6), 4.07 (t, 4H, 3J(H,H) = 6.5 Hz, 7), 1.85 (sextet, 4H, 3J(H,H) = 7.0 Hz, 9), 1.75 (sextet, 2H, 3J(H,H) = 6.9 Hz, 8), 1.07 (t, 6H, 3J(H,H) = 7.3 Hz, 11), 1.05 ppm (t, 3H, 3J(H,H) = 7.4 Hz, 10); FT-IR (ATR): ν (cm⁻¹) = 2966, 2938, 2879, 1748 (C=O), 1583 (C=C Ar), 1496, 1465, 1428, 1387, 1349, 1326, 1234, 1140, 1121, 1101, 1060, 1029, 994, 957, 936, 914, 851, 788, 752, 692, 664.

### 3'-(3,4,5-Tripropoxybenzoylamino)-2,2'-bipyridine-3-amine (12)
Under argon, a solution of acid chloride 10 (3.12 mmol) in distilled dichloromethane (25 mL) was added dropwise to a well-stirred, ice-cold solution of 3,3'-diamino-2,2'-bipyridine (11) (0.580 g, 3.12 mmol) and triethylamine (0.65 mL, 4.7 mmol) in distilled dichloromethane (30 mL). After complete addition, the yellowish reaction mixture was allowed to reach room temperature and subsequently stirred under argon overnight. Then, the reaction mixture was washed with aqueous sodium hydroxide solution (1 M, 25 mL) and the obtained aqueous layer was extracted with dichloromethane (2 x 20 mL). The organic layers were combined, washed with brine (20 mL), dried with MgSO4 filtered over a glass filter and concentrated in vacuo. The brownish residue was purified with column chromatography (silica gel, 4.5 vol-% acetonitrile in chloroform) to yield amine 12 as a yellow solid (1.00 g, 69 %).

Rf = 0.38 (silica gel, 5 vol-% CH3CN in chloroform); GC-MS: Rf = 11.62 min (one peak), m/z: calced for: 464.24; found: 465 (radical cation), m.p. 101.4-101.9 °C; 1H NMR (400 MHz, CDCl3): δ = 14.31 (s, 1H, 7 N-H), 9.25 (dd, 1H, 3J(H,H) = 8.5 Hz and 4J(H,H) = 1.6 Hz, 4), 8.29 (dd, 1H, 3J(H,H) = 4.6 Hz and 4J(H,H) = 1.6 Hz, 6), 7.67 (dd, 1H, 3J(H,H) = 4.1 Hz and 4J(H,H) = 1.8 Hz, 6), 7.29 (s, 2H, 10), 7.28-7.27 (m, 1H, 5), 7.11-7.04 (2H, 4+5), 6.63 (s, 2H, 7 NH2), 4.05 (t, 4H, 3J(H,H) = 6.6 Hz, 14), 4.04 (t, 2H, 3J(H,H) = 6.6 Hz, 13), 1.87 (sextet, 4H, 3J(H,H) = 7.1 Hz, 16), 1.81 (sextet, 2H, 3J(H,H) = 7.1 Hz, 15), 1.08 (t, 3H, 3J(H,H) = 7.4 Hz, 17), 1.07 ppm (t, 6H, 3J(H,H) = 7.1 Hz, 18); 13C NMR79 (100 MHz, CDCl3, APT): δ = 166.3 (8'), 153.2 (11), 145.2 (3), 143.7 (2'), 141.8 (12), 140.9 (6'), 138.9 (2), 136.3 (3'), 135.0 (6), 130.7 (9'), 128.8 (4'), 125.3 (4), 124.2 (5), 122.9 (5'), 106.8 (10'), 75.3 (13'), 71.2 (14'), 23.7 (15'), 22.9 (16'), 10.7 ppm (17'+18'); FT-IR (ATR): ν (cm⁻¹) = 3420 (NH2), 3266 (NH2), 3039, 2964, 2936, 2876, 1660 (C=O), 1572, 1519, 1493, 1468, 1426, 1394, 1328, 1307, 1294, 1262, 1205, 1151, 1118, 1099, 1065, 996, 957, 910, 880, 859, 793, 745, 730, 702; Elemental analysis calcd (%) for C26H22N4O2: C 67.22, H 6.94, N 12.06; found: C 67.13, H 6.82, N 12.09.
N,N’,N’’-Tris[3’-(3,4,5-tripropoxybenzoylamino)-2,2’-bipyridyl]benzene-1,3,5-tricarboxamide (5)

Under argon, a solution of trimesyl chloride (0.163 g, 0.614 mmol) in distilled dichloromethane (2.5 mL) was added dropwise to a well-stirred solution of amine 12 (0.860 g, 1.85 mmol) and triethylamine (0.45 mL, 3.23 mmol) in distilled dichloromethane (7.5 mL). After complete addition a white precipitate formed and the reaction mixture was stirred overnight under argon. Then, the reaction mixture was concentrated in vacuo, redissolved in hot chloroform (7 mL) and precipitated in well-stirred, chilled methanol (100 mL). Filtration of the obtained suspension over a Büchner funnel yielded a sticky, beige residue (0.80 g, 67%). The latter was pure according to 1H-NMR and TLC analysis, but analytical GPC (CHCl₃, 2 × PL gel 3 μm 100 Å column) showed the presence of a minor impurity. Eventually, 0.133 g crude product was further purified with recycling GPC (chloroform, 2 × Jai-Gel column) to yield pure disc 5 (0.120 g, 90%) as a white, sticky solid.

Rᵣ = 0.30 (silica gel, 3 vol-% pyridine in chloroform); Rᵣ = 12.52 min (GPC, CHCl₃ 2 × PL gel 3 μm 100 Å column, one peak). 1H NMR (400 MHz, CDCl₃, conc. = 1 mM): δ = 15.49 (s, 3H, 7-N-H), 14.36 (s, 3H, 7’-N-H), 9.58 (dd, 3H, 3J(H,H) = 8.5 Hz and 3J(H,H) = 1.5 Hz, 4), 9.40 (dd, 3H, 3J(H,H) = 8.6 Hz, and 3J(H,H) = 1.5 Hz, 4), 9.24 (s, 3H, 10), 9.04 (dd, 3H, 3J(H,H) = 4.6 Hz and 3J(H,H) = 1.5 Hz, 6), 8.45 (dd, 3H, 3J(H,H) = 4.6 Hz and 3J(H,H) = 1.5 Hz, 6), 7.54 (dd, 3H, 3J(H,H) = 8.5 Hz and 3J(H,H) = 4.5 Hz, 5), 7.51 (dd, 3H, 3J(H,H) = 8.6 Hz and 3J(H,H) = 4.6 Hz, 5), 7.29 (s, 6H, 10), 4.07 (t, 12H, 3J(H,H) = 6.7 Hz, 14), 4.05 (t, 6H, 3J(H,H) = 6.6 Hz, 13), 1.90 (sextet, 12H, 3J(H,H) = 7.2 Hz, 16), 1.82 (sextet, 6H, 3J(H,H) = 7.1 Hz, 15), 1.10 (t, 18H, 3J(H,H) = 7.4 Hz, 18), 1.08 ppm (t, 9H, 3J(H,H) = 7.1 Hz, 17); 13C NMR ¹³C (100 MHz, CDCl₃, with 6 vol% HFIP:HFIP-D₂): 1:1 (v:v), conc. = 19 mM, APT: δ = 168.1 (8’), 164.8 (8), 153.4 (11’), 142.6 (2+2’), 142.3 (6’), 142.2 (2+2’), 141.3 (6+ 12’), 137.1+136.9+136.7+136.2 (3+3’), 136.3 (9), 130.7+130.6 (4+4’), 130.4+130.3 (9’), 129.9 (10), 124.9+124.6 (5+5’), 106.4 (10’), 76.2 (13), 71.4 (14), 23.4 (15’), 22.7 (16), 10.5+10.4 ppm (17’+18’); FT-IR (ATR): ν (cm⁻¹) = 2962, 2936, 2877, 1669 (C=O), 1567, 1511, 1489, 1443, 1427, 1368, 1328, 1293, 1226, 1199, 1118, 1094, 1073, 1030, 998, 957, 913, 860, 798, 743, 729, 717; MALDI-TOF MS: m/z: calcd for: 1549.71; found: 1550.76 (M+H⁺), 1572.80 (M+Na⁺);

Elemental analysis calcd (%) for C₃₀H₂₆N₂O₁₃: C 67.43, H 6.24, N 10.85; found: C 67.09, H 6.12, N 10.75.

1-Adamantane-carbonyl chloride (14)

Under argon, oxalyl chloride (3.4 mL, 39.6 mmol) and DMF (two drops) were added to a well-stirred solution of 1-adamantane-carboxylic acid (13) (5.99 g, 33.2 mmol) in dichloromethane (120 mL). Escape of gases took place and the reaction mixture was stirred for 3.5 h under argon after which FT-IR indicated complete conversion. Concentration in vacuo and subsequent removal of volatiles under high-vacuum yielded acid chloride 14 as a beige solid (6.60 g, 33.2 mmol) that was used as such.

FT-IR (ATR): ν (cm⁻¹) = 2908, 2855, 1824, 1781 (C=O), 1664, 1474, 1453, 1345, 1315, 1265, 1189, 1166, 1130, 1103, 1047, 983, 943, 912, 881, 819, 783, 751, 738, 705, 662.

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3’-(1-Adamantanecarboxamido)-2,2’-bipyridine-3-amine (15)
Under argon, a solution of acid chloride 14 (5.05 g, 25.4 mmol) in distilled dichloromethane (250 mL) was added dropwise to a well-stirred, ice-cold solution of 3,3’-diamino-2,2’-bipyridine (11) (4.97 g, 26.7 mmol) and triethylamine (4.5 mL, 32.3 mmol) in distilled dichloromethane (250 mL). After complete addition, the yellowish reaction mixture was allowed to reach room temperature and subsequently stirred under argon overnight. Then, the reaction mixture was concentrated in vacuo, and digerated into hot methanol (30 mL) and water (40 mL). The obtained suspension was filtered over a Büchner funnel to afford a brownish residue that was crystallized from hot acetonitrile (335 mL) to give colorless crystals and an orange filtrate after Bückner filtration. According to TLC analysis, the colorless crystals consist of bisamide side product and the orange filtrate of predominately desired product. The orange filtrate was concentrated in vacuo to give an orange-brown residue which was purified by crystallization from hot ethanol and ethyl acetate-heptane (1:3 v:v) to afford desired 15 as orange-yellow crystals (5.75 g, 65 %).

Rt = 0.31 (silica gel, 2 vol-% methanol in chloroform); GC-MS: Rt = 9.84 min (one peak), m/z: calcld for: 444.18 (TFA-amide, C32H33F3N8O2); found: 444 (radical cation), m.p. 155.5-155.8 °C; 1H NMR (400 MHz, CDCl3): δ = 13.29 (s, 1H, 7 N-H), 9.01 (dd, 1H, 3J(H,H) = 8.4 Hz and 4J(H,H) = 1.6 Hz, 4'), 8.30 (dd, 1H, 3J(H,H) = 4.6 Hz and 4J(H,H) = 1.6 Hz, 6'), 7.99 (dd, 1H, 3J(H,H) = 6.0 Hz and 4J(H,H) = 3.1 Hz, 6), 7.27 (dd, 1H, 3J(H,H) = 8.4 Hz and 4J(H,H) = 4.6 Hz, 5), 7.17 and 7.16 (2H, 4+5), 6.13 (s, 2H, 7 NH2), 2.17 (s, 3H, 11'), 2.00 (d, 6H, 3J(H,H) = 2.9 Hz, 10'), 1.77 ppm (dd, 6H, 3J(H,H) = 14.0 Hz and 4J(H,H) = 5.2 Hz, 12'); 13C NMR (100 MHz, CDCl3, APT): δ = 178.0 (8'), 144.8 (3), 143.6 (2'), 140.4 (6'), 138.7 (2), 136.3 (3'), 134.9 (6), 128.7 (4'), 125.0 (4), 124.0 (5), 122.7 (5'), 42.3 (9'), 39.4 (10'), 36.7 (12'), 28.3 ppm (11'); FT-IR (ATR): ν (cm⁻¹) = 3386 (NH), 3328 (NH), 3163, 2909, 2850, 1647 (C=O), 1606, 1572, 1560, 1509, 1471, 1455, 1435, 1404, 1370, 1362, 1320, 1305, 1292, 1273, 1264, 1238, 1214, 1197, 1186, 1154, 1126, 1105, 1065, 1027, 976, 939, 930, 919, 875, 853, 836, 978, 768, 733, 728, 674 ppm; Elemental analysis calcld (%) for C32H33F3N8O2: C 72.39, H 6.94, N 16.08; found: C 72.38, H 6.59, N 15.98.

N,N’,N”-Tris[3’-(1-adamantanecarboxamido)-2,2’-bipyridyl]benzene-1,3,5-tricarboxamide (6)
Under argon, a solution of trimesyl chloride (0.611 g, 2.303 mmol) in distilled dichloromethane (25 mL) was added dropwise to a well-stirred solution of amine 15 (2.490 g, 7.146 mmol) and triethylamine (1.2 mL, 8.6 mmol) in distilled dichloromethane (25 mL). After addition of 1/3 of the acid chloride solution, more distilled dichloromethane (25 mL) was added to the reaction mixture and refluxing was applied due to the formation of a thick suspension. After complete addition, the reaction mixture was stirred and refluxed under argon for an additional 1.5 hours after which FT-IR indicated complete conversion of the acid chloride. The suspension was allowed to reach room temperature and filtered over a Büchner funnel to give a white residue after washing with dichloromethane (2 × 25 mL). The white residue was dissolved into hot chlorobenzene (200 mL) to give a beige solution. Subsequently, this hot solution was passed through a paper filter and then allowed to reach room temperature during which a white precipitate formed. Then, the obtained white suspension was filtered over a Büchner funnel to give a white residue after washing with chlorobenzene (2 × 30 mL) and dichloromethane (2 × 25 mL). The residue was suspended in dichloromethane (100 mL) and refluxed for 1 h. Subsequently, this suspension was allowed to reach room temperature and filtered over a Büchner funnel to give a white residue after washing with dichloromethane (25 mL). Thorough drying of this white residue yielded discotic 6 as a white crystalline solid (2.013 g, 73 %).
Self-assembly behavior of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit

\[ R_t = 0.26 \] (silica gel, 2 vol-% methanol in chloroform); \[ R_t = 13.08 \text{ min (GPC, CHCl}_3, 2 \times \text{PL gel 3 } \mu\text{m 100 } \AA \text{ column, } >99 \% \text{ pure}) \]

\[ ^1H \text{ NMR (400 MHz, CDCl}_3, \text{ conc. = 1 mM)}: \delta = 15.45 \text{ (s, 3H, 7' N-H), 13.73 (s, 3H, 7 N-H), 9.53 (dd, 3H, } \text{ } J_{(H,H)} = 8.5 \text{ Hz, and } J_{(H,H)} = 1.5 \text{ Hz, 4'), 9.32 (dd, 3H, } \text{ } J_{(H,H)} = 8.5 \text{ Hz and } J_{(H,H)} = 1.4 \text{ Hz, 4'), 9.20 (s, 3H, 10), 8.97 (dd, 3H, } \text{ } J_{(H,H)} = 4.6 \text{ Hz and } J_{(H,H)} = 1.5 \text{ Hz, 6'), 8.43 (dd, 3H, } \text{ } J_{(H,H)} = 4.5 \text{ Hz, and } J_{(H,H)} = 1.6 \text{ Hz, 6'), 7.50 (dd, 3H, } \text{ } J_{(H,H)} = 4.4 \text{ Hz and } J_{(H,H)} = 4.3 \text{ Hz, 5'), 7.47 (dd, 3H, } \text{ } J_{(H,H)} = 8.5 \text{ Hz and } J_{(H,H)} = 4.6 \text{ Hz, 5'), 2.16 (s, 3H, 11), 2.07 (d, 6H, } \text{ } J_{(H,H)} = 2.3 \text{ Hz, 10'), 1.82 ppm (m, 6H, 12')); ^{13}C \text{ NMR (100 MHz, CDCl}_3 \text{ with 6 vol% HFIP:HFIP-D}_2 \text{ 1:1 (v:v), conc. = 33 mM, APT): } \delta = 180.0+179.9 \text{ (8'), 164.3+164.2 (8), 142.1+142.1 (2+2'), 141.9+141.0 (6+6'), 136.9+136.7+136.7+136.7+136.5 (3+3'), 135.8+135.7 (9), 130.5+130.0+129.6 (4+4'+10), 124.5+124.3 (5+5'), 42.6 (9'), 39.4 (10'), 36.5 (12'), 28.3 ppm (11'); MALDI-TOF MS: m/z: calcd for: 1200.57; found: 1201.64 (M+H'), 1223.63 (M+Na'), 1239.61 (M+K'); Elemental analysis calcd (%) for C_{32}H_{27}N_{12}O_{6}: C 71.98, H 6.04, N 13.99; found: C 70.21, H 5.91, N 13.62.

### 3.7 References


Self-assembly behavior of desymmetrized discotics based on the 3,3'-bis(acylamino)-2,2'-bipyridine unit


Due to a poor thermal isolation in the Linkam heat stage compared to that of the DSC machine the transition temperature will differ.


Self-assembly behavior of desymmetrized discotics based on the 3,3’-bis(acylamino)-2,2’-bipyridine unit


[68] Dr. Olga Chetina of the University of Durham is acknowledged for helping with the crystal growth.

[69] A synchrotron measurement was performed by Dr. Ehmke Pohl of the University of Durham on the protein crystallography beamline X10SA of the Swiss Light Source.

[70] NMR measurements in apolar solvents in which the discs are aggregated will display very broad signals.


[75] Instead of heptane dodecane was selected for these spectroscopic measurements due to its higher boiling point.


[78] The yield is rather disappointing due to losses during the extraction.

[79] Assignment was done with gHMQC and gHMBC 2D NMR.

[80] Assignment was done with gHMQC and gHMBC 2D NMR, some $^{13}$C peaks split due to partial N-H exchange with deuterium from HFIP-D$_2$.

[81] The presence of four signals originating from two carbons can be deduced to the partial deuteration of the secondary amides in HFIP-D$_2$/HFIP.
Supramolecular chiral induction into helically assembled desymmetrized discotics

Abstract. In this Chapter the supramolecular transfer of chirality from chiral acids to helical self-assemblies of pyridine-functionalized, 3,3'-bis(acylamino)-2,2'-bipyridines discotic 3, is described. The synthesis and self-assembly properties of non-symmetric 3 were described in the previous chapters. Firstly, a screening of several types of acids has been performed to select an acid for selective complexation with the pyridyl nitrogen of discotic 3. Although discotic 3 possesses three bipyridine units which can also act as hydrogen bond acceptors, these were considered less prone to acid-base interaction due to the strong intramolecular hydrogen bonding with the adjacent amide N-H functionalities. Acids of intermediate strength like derivatized phosphonic and tartaric acids selectively interact with the peripheral pyridyl group of discotic 3 of which the preorganized conformation remained intact. In chloroform solution in which discotic 3 is molecularly dissolved, 1H-NMR spectroscopy was used to verify interaction between the acids and discotic 3. Optical spectroscopy was used to examine the complexes between helically aggregated discotic 3 and the chiral acids in apolar alkane solution. UV/Vis spectroscopy revealed whether the same type of helical aggregates were present after addition of the acids. In CD spectroscopy, the presence of a Cotton effect in the absorption region of the bipyridine chromophore of discotic 3 showed the transfer of chirality from the chiral acid to the supramolecular assembly of 3. In the case of chiral phosphonic acid 7, derived from 6,7-dihydrocitronellol, this transfer of chirality is very limited. However, when chiral tartaric acid derivatives 12 or 13 were employed, a strong Cotton effect was observed comparable in magnitude to that of chiral discotics. This proves an efficient transfer of chirality from the chiral acid to the stack, presumably caused by the sterically confined chiral environment of the tartaric acids. Also, a less polar analog of diacid 12 was synthesized to minimize its precipitation from methylecyclohexane that served as apolar solvent during spectroscopic measurements. Fortunately, this diacid 15 equally induced efficient transfer of chirality. Finally, temperature dependent optical spectroscopy revealed an unprecedented, delicate balance between the strength of the acid-base complex, the stability of the helical stacks of discotic 3 and the solubility of the chiral acid used.
4.1 Introduction

Chirality is essential in biological systems. On the macroscopic level in nature chirality is widespread, for example it can be found in shells of mollusks and in growing plants (Figure 1). On the molecular level chirality is essential in molecular recognition. For example all natural amino acids are of L-chirality and tasting and smelling of substances is often enantiomerically selective. Another well-known example of chiral molecular recognition in nature is the tobacco mosaic virus in which a helical RNA strand acts as a template for the helical self-assembly of 2130 identical proteins. This self-assembly into a chiral nano-structure is the only building mechanism for this virus and has inspired synthetic chemists to mimic this process with artificial building blocks.

![Figure 1: a) Macroscopic chirality in nature: an escargot snail (helix pomatia, Dutch: wijngaardslak), which can be found in South Limburg. b) Spiral blooming orchid (Spiranthes lacera, Dutch: Schroeforchis), which can be found in eastern North-America.](image)

In supramolecular chiral systems, the components involved in the supramolecular structure self-assemble in an asymmetric manner. In natural systems as described above, supramolecular assembly and chirality is often involved and we are just at the beginning of understanding these processes. Some appealing examples of control over chirality in supramolecular self-assembled systems and chiral recognition are known. For example, melamine and chiral barbituric acid based building blocks self-assemble into enantiopure hydrogen bonded double rosettes. Substitution of the chiral barbituric acid with achiral cyanurate, that forms stronger hydrogen bonds with melamines, preserves the chiral double rosette structure showing memory of the supramolecular chirality. In these novel hydrogen bonded rosettes, amplification of chirality via the ‘Sergeant and Soldiers’ effect was also described. One important process in supramolecular chiral recognition is control over the sense of helicity. This can be achieved by selecting building blocks that self-assemble into right handed (P) or left handed (M) helices owing to their chiral information. This has been shown for discotics, foldamers, helical polymers, hydrogen bonded helical systems, helical rosette nanotubes, hydrogen bonded folic acid containing self-assemblies, and helically assembled chromophores. A nice example is the helical organization of porphyrins.
between two poly(trimethylene iminium) strands via ionic interactions between ammonium and 2,6-bis(2-oxazolyl)pyridine groups (Figure 2).25

Figure 2: Self-assembly of two poly(trimethylene iminium) strands with 2,6-bis(2-oxazolyl)pyridine functionalized porphyrins into artificial double helices by hydrogen bonding between the 2,6-bis(2-oxazolyl)pyridine functionalities and the ammonium units of the polymer and by porphyrin stacking.25 The helical sense is biased due to the presence of two stereocenters in the porphyrin.

In another beautiful example, amphiphilic hexabenzocoronenes self-assemble into helical nanotubes26 and if equipped with chiral polar tails and achiral apolar tails, nanotubes of one handedness were observed as well as amplification of chirality (Chapter 1, section 1.3.2).15 In these examples, the chiral information is covalently embedded in the self-assembling moieties. However, controlling chirality by supramolecular interactions may have several advantages over structures in which the chiral information is enclosed in a covalent fashion. First, no tedious asymmetric synthesis is required to introduce chirality but readily available chiral templates may be used instead. Second, better control of the chirality is possible simply by varying the amount of chiral template, using another enantiomer or by using a chiral template that possesses another affinity for the achiral host. Supramolecular control of chirality was shown for urea substituted calix[4]arenes that form dimeric enantiomeric self-assemblies; addition of a chiral guest induces the preference for the formation of one enantiomer only.27 Tetrarosette derivatives of the hydrogen bonded complexes described on the previous page may enantioselectively recognize sugars resulting in the resolution of the racemic tetrarosette hosts.28 Supramolecular induction of chirality was also shown in a very nice example involving complexation of chiral acids with a porphyrin double decker complex equipped with peripheral pyridyl groups (Figure 3).29 Binding of the first chiral diacid is unfavorable due to suppression of the free rotation of the two porphyrins, but this results in a preorganized structure favoring the binding of three other diacids. This is known as a positive allosteric effect.30
Supramolecular chiral induction into helically assembled desymmetrized discotics

Figure 3: CD active porphyrin self-assembly where the binding of four chiral diacids onto a Ce⁴⁺-porphyrin double decker equipped with 8 pyridyl units results in the formation of the chiral complex.²⁹

The principle of supramolecular control of chirality has been applied for helical systems based on polymeric,⁳¹,³² oligomeric⁳³ and porphyrin⁳⁴ based systems too. Chromophores equipped with diamino-triazine units can be organized in a helical fashion by using DNA monodisperse oligomers as a template in which the chromophore is hydrogen bonded with thymine units of the DNA oligomer.³⁵,³⁶ By doing so, control over the size of the helical self-assemblies of the chromophores is possible. In another example anthracene chromophores have been arranged in a helical fashion between two DNA strands.³⁷ A beautiful example of control over helicity in a supramolecular fashion is the work done on helical polyacetylenes in the group of Yashima.³⁸-⁴⁰ Poly(phenyl acetylenes) equipped with chiral cyclodextrines (poly-2β, Figure 4) form left-handed helices in alkaline water and right-handed helices in DMSO that are interchangeable into each other. This helix inversion is accompanied by an inversion of the Cotton effect and a color change due to a conformational change of poly-2β.⁴⁰ Both helices can be cross-linked in either water (CL(water)poly-2β) or DMSO (CL(DMSO)poly-2β).⁴⁰

Figure 4: Control over helicity of helical poly(phenyl acetylene) (poly-2β) that forms a left-handed single helix in water and a right-handed double helix in DMSO. Both helices could be cross-linked using epichlorohydin or 2,4-diisocyanatotoluene, respectively.⁴⁰
The helical sense of intramolecular hydrogen bonding preorganized propeller shaped \( C_3 \)-molecules was controlled by the hydrogen bond accepting properties of the solvent.\(^{41}\) Similar control over helicity by supramolecular interaction with external stimuli like solvents has been reported for discotics as well.\(^{42}\) In the group of Serrano, chiral acids were used successfully to induce and bias columnar helicity into melamine based columnar mesophases. In a first study they demonstrate that an optimal combination of steric effects of the chiral acid and the alkylated melamine proved to be crucial to obtain stable, well-defined columnar mesophases with helical structures.\(^{43}\) Secondly, it was found that chiral diacids were able to link two dimeric melamine discotics by clipping which gave rise to regular interdisc distances and forced the hydrogen bonded discotics to stack in a biased, helical fashion (Figure 5a).\(^{44}\) The amount of acid proved to be crucial; if the acid ratio is too high, steric hindrance prevents the formation of the most favorable helical structure and hence, the latter was formed with the smallest substoichiometric amount of diacid ratio (4:1) according to CD spectroscopy (Figure 5a, last cartoon). However, the most stable mesophase was formed when the melamine-diacid ratio amounted to 2:1 (Figure 5a, middle cartoon). Thus, the chiral induction depends on a subtle balance between aromatic stacking, steric hindrance and hydrogen bonding. In our group, chiral solvent has been applied to bias the helicity of supramolecular stacks of bipyridine discotic 2 (Figure 6b).\(^{14}\) Also, a nice example has been reported for helically assembled oligo(\( p \)-phenylenevinylene) (OPV) hydrogen bonded dimeric systems where effective bias of helicity was achieved with citronellol derived carboxylic acids in diluted apolar solution.\(^{45}\) The presence of chiral acids in these solutions gave strong bisignated CD effects in the absorption region of the OPV unit (Figure 5b) as well as amplification of chirality.

**Figure 5:** a) Clipping of a chiral diacid to hydrogen-bonded melamine-based columnar liquid crystals affording supramolecular induction of helicity and chirality into the columns. The supramolecular structure depends on the ratio between diacid and disc, molar ratios are given between melamine units and diacid.\(^{44}\) b) Schematic representation of the chiral induction from \( S \)-citronellic acid (\( S \)-CA) or \( R \)-citronellic acid (\( R \)-CA) by hydrogen bonding with the ureidotriazine group of the achiral OPV system resulting in right- or left-handed supramolecular helices, respectively. The latter was observed via opposite bisignated Cotton effects in CD spectroscopy.\(^{45}\)
Inspired by the examples described above, we aimed at controlling the helicity of our supramolecular columnar stacks in dilute solution by a reversible chiral induction from chiral acids. In Chapter 2 desymmetrized discotic 3 containing a peripheral pyridyl group (Figure 6b) was introduced. Its self-assembly behavior in solution appeared to be similar to that of C₅-symmetrical discotics 1 and 2 (Figure 6a) as was shown with the aid of spectroscopic techniques in Chapter 3. So, in this Chapter chiral acids have been applied to bias the helicity of disc 3 by hydrogen bonding in dilute solution. First of all, a selection was made of suitable acids to bind with disc 3. Then, mixtures of these acids and disc 3 were studied with optical spectroscopy to establish the formation of the acid-base complexes and transfer of chirality to helical self-assemblies of disc 3.

**Figure 6:**

(a) C₅-symmetrical discotics 1 (chiral) and 2 (achiral). Chiral disc 1 will preferably self-assemble into helices of one handedness in apolar solvents like alkanes, while disc 2 is present in equal amounts of left and right handed helices. The right-handed helix is depicted as a cartoon. A more realistic representation is shown in Figure 3, Chapter 3. (b) Non-symmetric, achiral disc 3 possessing a pyridyl group as hydrogen bond acceptor.

### 4.2 Selection of acids to bind pyridyl-functionalized disc 3

Discotic 3 was mixed with acids of several acidic strengths to examine which acid selectively interacts with the free pyridyl unit. It is important that the inner bipyridine nitrogens remain unaffected by the acid. If not, the strong intramolecular hydrogen bond between the bipyridine nitrogens and the amide N-H groups will be disrupted and the preorganized, disc-shaped structure of 3 will be lost.

**Figure 7:** Four different acids with increasing pKa: Sulphonic acid 4 (pKa ≈ -1), fluorinated acid 5 (pKa = 0), phosphonic acid 6 (pKa₁ = 2.5 and pKa₂ = 8) and carboxylic acid 7 (pKa = 4). (pKa values in water). The pKb of the pyridyl group of disc 3 is approximately 12 according to the reported value forisonicotinic amide.
Four acids with increasing pKa were selected: (1R)-camphor-10-sulphonic acid (4), perfluorinated dodecanoic acid (5), tetradecyl phosphonic acid (6) and (S)-3,7-dimethyl octanoic acid (7) (Figure 7). Pyridine-acid 7 interactions will cause changes in the vibration of the carbonyl group of acid 7 that can be studied with FT-IR spectroscopy. Hydrogen bonding or protonation of the pyridyl group of disc 3 will diminish the electron density on the nitrogen atom causing the neighboring aromatic protons to shift downfield in \( ^1H \)-NMR. Eventual protonation of bipyridine nitrogens may also be detected. Considering acid 6 and its derivatives, \( ^{31}P \)-NMR can be employed to study its binding behavior. \( ^{13}C \)-NMR was not used because of inherent broadening of the NMR signals when measuring concentrated solutions of disc 3. Mixtures of acids 4, 5, or 6 with disc 3 were made in CDCl\(_3\) and their \( ^1H \)-NMR recorded.

The most important results are shown in Figure 8. Unfortunately, acid 7 did not display any interaction with disc 3 as was deduced from FT-IR spectroscopy by the lack of changes in the acid carbonyl vibrations. In Figure 8d, the hydrogen bonding region and aromatic region of discotic 3 are shown. The chemical shifts of pure discotic 3 in CDCl\(_3\) were discussed in section 3.4.1 and previously those of \( C_2 \)-symmetrical derivatives were described.\(^{49}\) The acids shown in Figure 7 are aliphatic, thus lacking peaks in this region which could interfere with the signals belonging to disc 3. One molar equivalent of sulphonic acid 4 causes the aromatic and amide signals of disc 3 to shift slightly downfield (Figure 8a). Protons h and j, belonging to the pyridyl group undergo the largest downfield shift. Apparently, sulphonic acid 4 forms a strong complex with disc 3 and causes a slight change in the conformation of disc 3 or the latter's interaction with other discs in solution. In the mixture of disc 3 and fluorinated acid 5 (Figure 8b) the most remarkable observation is peak broadening and an overall upfield shift, except for proton j. An explanation of this upfield shift is that the protons in question may be less than 7 Å separated from the aromatic plane of a neighboring discotic, in other words these protons experience an anisotropic shielding due to the proximity of another aromatic unit.\(^{50}\)

![Figure 8: \( ^1H \)-NMR spectra of mixtures of disc 3 with one molar equivalent of acids 4, 5 and 6, respectively, in CDCl\(_3\), disc conc. = 3 mM. a) disc and acid 4, b) disc and acid 5, c) disc and acid 6, d) only disc 3. Mixtures were prepared by mixing the components in chloroform, evaporating the solvent and redissolving in CDCl\(_3\).]()}
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The presence of the long fluorinated tail of acid 5 make discotics 3 likely to approach each other in solution, presumably due to a fluorophobic effect. Because of this, the employment of fluorinated acids was abandoned. One molar equivalent of phosphonic acid 6 does not induce significant differences in the $^1$H-NMR spectrum (Figure 8c). An acid-base interaction would increase the electron density on the phosphorus atom causing an upfield shift. In phosphorus NMR, an upfield shift of only 2 ppm was observed, thus the interaction between acid 6 and disc 3 is rather weak. Next, the experiment was repeated using more equivalents of strong acid 4 and weaker acid 6, which were added to disc 3 to evaluate whether protonation of core nitrogens occurs. The results are shown in Figure 9. The mixtures of disc 3 and excesses of phosphonic acid 6 (Figure 9a1-a3) do not differ that much from pure disc 3 in CDCl$_3$ (Figure 8d) while the sulphonic acid mixtures differ strongly (Figure 9b1-b3). The largest difference can be observed in the amide proton region, which broadens and shifts upfield by > 3 ppm (Figure 9b3). Thus, sulphonic acid 1, if used in excess, will protonate the bipyridine nitrogens of disc 3 and will disrupt the preorganized structure of the disc. An addition of an excess of phosphonic acid 6, however, does not destroy the intramolecular hydrogen bonding within disc 3, as can be deduced from Figure 9a1-a3. The largest shift is observed for proton j in Figure 9a3 and might be explained by the selective protonation of the peripheral pyridyl group of disc 3 only, even when 10 molar equivalents of phosphonic acid 6 were added.

![H-NMR spectra of mixtures of disc 3 with different amounts of strong acid 4 or weaker acid 6 in CDCl$_3$, disc conc. = 3 mM. a1) 1 mol eq. acid 6, a2) 2 mol eq. acid 6, a3) 10 mol eq. acid 6, b1) 1 mol eq. acid 4, b2) 2 mol eq. acid 4, b3) 10 mol eq. acid 4. Mixtures were prepared by mixing the components in chloroform, evaporating the solvent and redissolving in CDCl$_3$.](image)

To conclude, phosphonic acids or acids of similar strength are the best candidates for achieving reversible interactions with disc 3 without disrupting the latter's preorganized
structure. Stronger acids will affect the basic moieties of the core of disc 3 if used in an excess and weaker acids are not able to give a significant interaction with the pyridyl group of disc 3. This shows the delicate balance between desired and undesired similar supramolecular interactions within this particular supramolecular complex.

4.3 Chiral induction using phosphonic acids

4.3.1 Synthesis

Inspired by supramolecular chiral induction by (S)-citronelic acid in self-assemblies of hydrogen bonded chromophores in dilute solution\textsuperscript{45} and by (R)-3-methyladipic acid in columnar mesophases of hydrogen bonded dimers,\textsuperscript{44} we decided to synthesise and investigate chiral citronellol-derived phosphonic acids 8 and 9 which should be capable of transferring their chirality to discotic 3 via H-bonding. The synthesis is depicted in Scheme 1.

Chiral alcohol 10 (e.e. = 98.4) was brominated\textsuperscript{52,53} using NBS and PPh\textsubscript{3} to afford bromide 11 which was subsequently converted into diethyl phosphonate 12 using triethyl phosphite in the Michaelis-Arbusov rearrangement.\textsuperscript{54} This reaction has to proceed at elevated temperature, not only to enable the \textit{S}$_{N}$2 substitutions to take place, but also to remove bromoethane (bp. = 38 °C). Otherwise, the latter may react with triethyl phosphite resulting in the formation of diethyl ethylphosphonate and (again!) bromoethane. The formation of this ethylphosphonate was confirmed with GC-MS. GC-MS and \textsuperscript{31}P-NMR also showed the formation of triethyl phosphate due to the oxidation of triethyl phosphite, which may be prevented by degassing the reaction mixture prior to heating. Eventually, product 12 could be obtained pure by distillation. Using phosphonate ester group hydrolysis in either acidic or basic conditions (S)-3,7-dimethyloctyl phosphonic acid (8) or ethyl (S)-3,7-dimethyloctyl phosphonic acid (9) respectively, were synthesized (Scheme 1).\textsuperscript{55,56}

![Scheme 1: Synthesis of chiral phosphonic acids 8 (two acidic Hs) and 9 (one acidic H) starting from (S)-6,7-dihydrocitronellol (10).](image)

Phosphonic acid derivatives 8, 9 and 12 were characterized by \textsuperscript{1}H-NMR, \textsuperscript{13}C-NMR, \textsuperscript{31}P-NMR, FT-IR and MS techniques. Using a combination of the typical \textsuperscript{13}C-\textsuperscript{31}P coupling constants and gCOSY, gHMQC 2D and APT \textsuperscript{13}C NMR, the proton and carbon spectra of the phosphonic acid derivatives were assigned unambiguously (see Experimental section). The enantiomeric excess (e.e.) of phosphonic acids 8 and 9 is assumed to be the same as the starting alcohol (10).
4.3.2 NMR study
Because acid 9 possesses only one acidic proton, this acid was used in NMR studies to probe the selective binding with disc 3. Mixtures of acid 9 and disc 3 have been made in CDCl₃ and the ¹H-NMR and ³¹P-NMR spectra are shown in Figure 10. A downfield shift of the pyridyl protons as observed in Figure 10a1-3 point to an increased complex formation. Increasing the acid 9 content from 2 to 4.5 molar equivalents does not induce a further shift (Figure 10a4). Probably, all peripheral pyridyl groups are occupied at this point. Then, an excess of pyridine is added to the mixture of disc 3 and 4.5 molar equivalents of acid 9 to break up the disc-acid complex, this is accompanied by an upfield shift of the pyridyl protons and illustrating reversibility (Figure 10a5). Analogous behavior is observed in the ³¹P-NMR spectrum (Figure 10b). Further, ¹H-NMR spectra showed no significant shifts of the N-H amide signals proving that the preorganized structure of disc 3 remains intact. The behavior of chiral phosphonic acid 8 when mixed with disc 3 in CDCl₃ resembles that of phosphonic acid 6 and, therefore, is not discussed further.

Figure 10: NMR spectra of mixtures of disc 3 with phosphonic acid 9 in CDCl₃; a1) ¹H-NMR spectrum of pure disc 3 (3 mM), a2) with 0.5 mol-eq. acid, a3) with 2 mol-eq acid, a4) with 4.5 mol-eq. acid, a5) with 4.5 mol-eq. acid and an excess of pyridine (33 mol-eq.). The circles indicate the protons of the peripheral pyridyl group of disc 3. The large peak at 8.6 ppm in spectrum a5 belongs to protons of the pyridinium salt. b1) ³¹P-NMR spectrum of pure acid 9. b2)-b5): ³¹P-NMR spectra of the same mixtures. Disc concentration was 2 mM in all mixtures.
4.3.3 CD and UV/Vis spectroscopy

CD and UV/Vis spectroscopy were used to investigate whether the chirality of the acids is transferred to the helical self-assemblies of disc 3 and whether the conformation of the helices changes at the same time. Optical spectra are shown for mixtures of disc 3 and acid 8 in methylcyclohexane (MCH) in Figure 11a. Measurements were performed at several concentrations (0.20 mM and 0.020 mM), acid equivalents (1, 2, 10 and 90 molar equivalents) and temperatures (between 90 and 0 °C). No transfer of chirality was observed since all samples were CD silent (data not shown). On the contrary, significant linear dichroic effects were observed when more than one molar equivalent of acid 8 was used (black line, Figure 11a). These LD effects are similar in shape to the absorption spectra and may indicate the presence of larger aggregates caused by the bivalent character of acid 8.57 The presence of an excess of acid 8 may enable the formation of larger, hydrogen bonded aggregates.

![Figure 11:](image)

Typical optical spectra of mixtures of disc 3 with phosphonic acid 9 are shown in Figure 11b. In this case a small CD effect was observed in the absorption region of the 3,3'-bis(acylamino) bipyridine chromophore between 350 and 400 nm indicating chirality transfer from acid 9 to the helical self-assemblies of disc 3 (black line, Figure 11b). Heating of the sample caused the CD effect to disappear while subsequent cooling to 0 °C induced a small increase of the CD effect (dashed line, Figure 11b). Remarkably, after 9 days the CD effect has an inverted sign (gray line, Figure 11b). LD measurements confirmed the absence of linear dichroism, thus the observed CD effect can be attributed to transfer of chirality on the molecular scale. However, the conformation of the helical aggregate changes over time under the influence of the phosphonic acid as is derived from a small blue shift and an increase in absorption around 350 nm in UV/Vis (gray line, Figure 11b). Increasing the amount of phosphonic acid 9 in the mixture did not result in a larger Cotton effect. The magnitude of the CD effect in Figure 11b is approximately 7 times smaller than the values observed for chiral C₃-symmetrical14 and desymmetrized discotics.58 This is in contrast with chiral induction from citronellic acid into hydrogen bonded OPV helices in solution, where the absolute Cotton effect is similar in size to
that of the homochiral OPV systems.\textsuperscript{45} Apparently, the transfer of chirality from phosphonic acid 9 to helically aggregated disc 3 is not efficient to achieve complete bias of the helical sense. Because of this, bulkier more sterically confined chiral acids derived from tartaric acid and having a similar pK\textsubscript{a} as phosphonic acids 8 and 9 were investigated in mixtures with disc 3,\textsuperscript{39} which will be the topic of the next section.

4.4 Chiral induction using tartaric acids derivatives

L-(-)-Tartaric acid (13, Figure 12b) ((2R,3R)-dihydroxysuccinic acid) is a common natural substance found in plants, for example in grapes and bananas, and is one of the main acids in wine.\textsuperscript{60} Tartaric acid and its derivatives have been important in understanding organic stereochemistry.\textsuperscript{61} In chemistry, chiral tartaric acids are used frequently in the resolution of racemates.\textsuperscript{62} Their derivatives are well-known sources of non-covalent chirality in supramolecular complexes in the crystal state,\textsuperscript{63,64} liquid crystals,\textsuperscript{65,66} gels,\textsuperscript{67} and in solution.\textsuperscript{29,68,69} Also the transfer of chirality to a catalytically active copper surface has been reported.\textsuperscript{70} The pK\textsubscript{a} values of tartaric acid are about 3 and 4.5 for the first and second carboxylic acid group, respectively; which is in the range of the phosphonic acids used in the work described in the previous section. Complexes of nicotinamide and tartaric acid have been reported in the crystal state.\textsuperscript{64} So, it was concluded that these acids may be able to form a complex with disc 3. In this section several dibenzoylated tartaric acids (Figure 12b) will be discussed. In these dibenzoylated tartaric acids, the hydroxy groups were esterified, increasing the acidity, the solubility in apolar organic solvents and the bulkiness and chiral confinement of space. The latter may be important to achieve efficient transfer of chirality to disc 3.\textsuperscript{39,71}

4.4.1 Infrared spectroscopy

First of all, complexes of disc 3 with readily available tartaric acid 14 were made in the solid state and measured with FT-IR spectroscopy to evaluate changes of the carbonyl vibrations. In case of acid-base interaction, the carbonyl vibration of the tartaric acid will move to lower wavenumbers.\textsuperscript{44,66,72} The result is shown in Figure 12a.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure12}
\caption{a) FT-IR spectra of disc 3 (black line), chiral diacid 14 (dashed line) and mixture of 3 and 14 (0.46 mol-eq. diacid 14, gray line). b) The two enantiomeric diacids R,R-14 and S,S-15 and meso-diacid 16.}
\end{figure}
Chapter 4

The amide I carbonyl vibration of disc 3 is situated at 1671 cm\(^{-1}\) which is a typical position for the intramolecular hydrogen bonded amides of the bipyridine disc.\(^{23}\) This position is unaffected by the addition of diacid 14 meaning that intramolecular hydrogen bonding of disc 3 remains intact. Pure diacid 14 displays various vibrations in the carbonyl region, belonging to the ester and acid carbonyls. The strongest vibration at 1725 cm\(^{-1}\) and the broader one at 1738 cm\(^{-1}\) belong to the ester carbonyl, while the vibrations at 1706 cm\(^{-1}\) and 1768 cm\(^{-1}\) belong to acid carbonyl. The observation of two sets of carbonyl vibrations indicates that the acid is present in its monomeric and dimeric hydrogen bonded form. Upon mixing with discotic 3 (Figure 12a, gray line) all carbonyl vibrations merged into one broad hump showing that the acid was involved in an interaction with, probably, the pyridyl moiety of disc 3. The acid carbonyls of 14 will shift to higher wavenumber if they are not involved in hydrogen bonding due to acid-base interaction with the pyridyl group acting as a hydrogen bond accepter.\(^{74}\) No bands indicative for pyridine complexes around 2500 cm\(^{-1}\) and 1950 cm\(^{-1}\) were observed showing that the complex between disc 3 and diacid 14 is weak in the solid state.

4.4.2 CD and UV/Vis spectroscopy

CD and UV/Vis spectroscopy were performed to probe the chirality transfer of diacids 14 and 15 to disc 3 and to evaluate the presence of helical aggregates in dilute apolar solution. Disc 3 is known to form helical aggregates in alkane solution and chiral diacid 14 binds to the pyridyl moiety of disc 3. By doing so, the chirality of diacid 14 may be transferred to disc 3 resulting in a bias of its helical sense. The resulting different concentration of left and right handed helices can be detected, using CD spectroscopy by the presence of a Cotton effect in the absorption region of the bipyridine chromophore.\(^{14}\) All solutions for spectroscopy were made by mixing the diacid and disc 3 in the appropriate ratio in a good solvent (chloroform), evaporation and thorough drying and subsequent redissolution into methylcyclohexane (MCH) by sonication and gentle heating. Solutions were made with several diacid ratios at concentrations of 1.5 \(\times\) 10\(^{-4}\) and 1.5 \(\times\) 10\(^{-5}\) M. Diacid 14 itself is completely insoluble in methyl cyclohexane and using more than 0.5 molar equivalent to disc 3 resulted in turbid mixtures. These turbid mixtures display strong linear dichroic artifacts in CD spectroscopy suggesting the formation of larger aggregates by acid dimerization. Therefore, less than 0.5 molar equivalent of diacid 14 was used to ensure that all acid is able to form a complex with disc 3 hence preventing precipitation from the MCH solution. After preparation, the solution was heated and cooled in a controlled manner to enable the formation of a stable acid-base complex and helical aggregates. Temperature dependent measurements of a 10\(^{-4}\) M solution of disc 3 and diacid 14 are shown in Figure 13. In the UV/Vis spectrum, the presence of partially resolved, red shifted absorption bands (\(\lambda_{\text{max}} = 349, 365\) and 384 nm) proved disc 3 to be present as helical self-assemblies (Figure 13a).\(^{14}\) When heating to 90 °C, these absorption bands merge into a broader band (\(\lambda_{\text{max}} = 362\) nm) with two shoulders indicating that the helical assembly is, to a large extent, melted at 90 °C. Surprisingly, in the CD spectra (Figure 13a) no significant Cotton effect is observed at 0 °C and 90 °C, while at 30 °C and at 60 °C a Cotton effect is present. The absence of chiral structures in solution at 90 °C is as expected, however this is not the case for the measurement at 0 °C, since the UV/Vis spectra indicate that well-ordered helices are
Supramolecular chiral induction into helically assembled desymmetrized discotics

present at the latter temperature; also, the acid-base interaction between disc 3 and diacid 14 should be strongest at 0 °C. Apparently, for some reason chiral acid 14 is not able to transfer its chirality at this low temperature. This is further confirmed by the temperature scan at 387 nm (Figure 13b) in which a maximum in the Cotton effect is observed around 45 °C.

Figure 13: Temperature dependent CD and UV/Vis spectra of disc 3 and 0.46 molar equivalent of diacid 14. a) Full spectra at four temperatures. b) Temperature scan at 387 nm, at this wavelength the Cotton effect belonging to the bipyridine chromophore is maximal. Concentration = 0.20 mM in MCH, cooling rate = 10 °C/h.

Mixtures of disc 3 and diacid 14 were investigated at 10^{-5} M concentrations too (Figure 14). In the UV/Vis spectra (Figure 14a), the blue shift of the broad absorption band at 90 °C is slightly more pronounced than for the 10^{-4} M solution (\lambda_{\text{max}} = 360 nm versus 362 nm). The molecularly dissolved state is more easily obtained in the more dilute conditions as is observed for N,N',N''-trialkyl-benzene-1,3,5-tricarboxamide^{16,75} and hexabenzocoronene^{76} discotics in apolar solution. In contrast to the 10^{-4} M solution, the most intense Cotton effect is observed at 0 °C. In the temperature scan (Figure 14b) an increase in the magnitude of the Cotton effect is observed when cooling the solution. Surprisingly, a plateau is present around 60 °C probably showing the occurrence of a two-state process during cooling. The heating and cooling treatment of the solution causes a decreased maximal induction of chirality compared to the situation before the thermal treatment (Figure 14a, dotted gray line). The magnitude of the CD effect before heating is comparable in size with that of pure, chiral discotics in diluted apolar solution.^{14} In the cooling run, the extinction coefficient at 387 nm gradually increases with 6 \times 10^3 M^{-1} cm^{-1}, coinciding with the sharpening of the UV band at this wavelength upon helix formation. The density change of the solvent between 90 °C and 0 °C is less than 10 %.^{77}
Figure 14: Temperature dependent CD and UV/Vis spectra of a mixture of disc 3 with 0.46 molar equivalent of diacid 14, concentration of 3 = 0.020 mM in MCH. a) Full spectra at three temperatures and directly after preparation of the sample. b) Temperature scan at 387 nm, cooling rate = 15 °C/h.

The other enantiomer of diacid 14, diacid 15 (Figure 12b) gave an opposite Cotton effect as is shown in Figure 15a. This strongly confirms that the observed Cotton effect is indeed resulting from the supramolecular chirality transfer from the diacid to the helical stack. However, after storing the dilute solution for two weeks, the Cotton effect had reversed sign for both enantiomers accompanied by an increase of the absorption around 365 nm in the UV/Vis spectrum. These observations show that the helical aggregate is not stable in time; the diacid may interfere with the bipyridine moieties of disc 3 over a prolonged period of time. Temperature scans of solutions of disc 3 and either enantiomer 14 or 15 show similar behavior as is depicted in Figure 15b. A maximum in the Cotton effect was observed at either 30 °C or 40 °C, apparently depending on the small difference in cooling speed. Upon cooling, the extinction coefficient at 387 nm gradually increases.

Figure 15: CD and UV/Vis spectra of 0.17 mol-eq. diacid 14 (R,R-enantiomer) or diacid 15 (S,S-enantiomer) with disc 3 in MCH, concentration = 0.020 mM, room temperature. a) Spectra recorded of the mixtures immediately after preparing the solution and after two weeks. b) Temperature scans at 387 nm, cooling rate = 120 °C/h (diacid 14) and 150 °C/h (diacid 15). Only a small amount of diacid is used to prevent any precipitation.

The results shown in Figures 13, 14 and 15 prove that the benzyolated tartaric acid derivatives 14 and 15 are capable of efficient induction of chirality into helical stacks of discs 3 by an acid-base interaction. According to UV/Vis spectroscopy, the structure of the helical aggregate is
almost unaffected by the presence of the acid and only the helix direction is biased. CD spectroscopy shows that the bias in helicity is similar in magnitude as compared to homochiral discotics. Temperature dependent measurements show as expected an increase of induced chirality upon cooling from 90 °C to 40 °C, however below 30 °C, the Cotton effect diminishes in most cases. Apparently, the acid-base complex between diacid 14 or 15 and the pyridyl group of disc 3 is not strong enough to prevent precipitation of the diacid from solution below room temperature or after prolonged time.

4.5 Chiral induction with a less polar tartaric acid derivative

To inhibit precipitation of the chiral diacid from apolar solution, the solubility was increased by incorporating six alkoxy tails onto the benzoyl moieties. It was decided to use short tails to limit undesired steric upon binding with disc 3, which might reduce the binding strength. Starting from (2R,3R)-tartaric acid (13), diacid 17 was synthesized in two steps (Scheme 2).80

First, diacid 13 was acylated with acid chloride 19 and converted into chiral, cyclic anhydride 18 in one step. The third equivalent of acid chloride 19 is required as dehydration reagent to afford ring closure.80 Secondly, hydrolysis of anhydride 18 afforded diacid 17 in good yield without racemization. Solutions of disc 3 and diacid 17 were prepared by consecutive mixing of the appropriate ratio of diacid and disc in the good solvent chloroform, followed by evaporation and thorough drying and subsequent redissolution into MCH by sonication and gentle heating. Several solutions were prepared with different equivalents of diacid 17. As can be observed in Figure 16a, more than 0.5 molar equivalent of diacid 17 present in solution results in significant LD artifacts in CD spectroscopy. These LD effects were observed in the absorption region belonging to the diacid only (Figure 16a). Apparently, disc 3 can bind no more than 0.5 molar equivalent of diacid 17 and the remaining excess of 17 will form aggregates by acid dimerization. Probably, both carboxylic acid functionalities of 17 were involved in binding with disc 3. Addition of less than 0.5 molar equivalent of diacid 17 to disc 3 results in efficient transfer of chirality as is depicted in Figure 16b. The magnitude of the Cotton effect is proportional to the amount of chiral diacid added. Apparently, the chiral information of diacid 17 is not transferred to all helical stacks of disc 3 as is observed for mixtures of chiral and achiral discs.14 Thus, no amplification of chirality occurs. When 0.45
molar equivalents of diacid 17 were used, the intensity of the Cotton effect coincides with the intensity observed for pure chiral discs in apolar solution (Figure 16b, gray dashed line).

![Figure 16](image_url)

**Figure 16:** LD, CD and UV/Vis spectra of disc 3 in the presence of different amounts of diacid 17, concentration = 0.018 mM in MCH, T = 40 °C. a) LD and UV/Vis spectra showing the linear dichroism if more than 0.5 mol-eq. of 17 is used. b) CD and UV/Vis spectra showing the gradual increase of the CD effect with increasing amount of 17.

The shapes of the UV/Vis spectra are independent of the amounts of diacid present showing that the helical structure is not disturbed by the acid-base interaction. Some minor deviations in the extinction coefficient were observed which can be attributed to sample preparation. Temperature dependent measurements were performed on solutions with 0.38 molar equivalent of diacid 17. As can be observed in Figure 17a, a Cotton effect is absent at 90 °C and is maximal between 30 °C and 60 °C. At 0 °C, the Cotton effect is almost absent. UV/Vis spectroscopy showed melting of the helical aggregates at 90 °C. Temperature dependent optical spectroscopy of the diacid-disc mixture was performed with several cooling rates to evaluate whether the maximal amplitude of the Cotton effect is dependent on the cooling rate (Figure 17b).

![Figure 17](image_url)

**Figure 17:** Temperature dependent CD and UV/Vis spectra of disc 3 and 0.38 mol-eq. diacid 17 in MCH, concentration = 0.018 mM. a) Full spectra at four temperatures. b) Temperature scans at 387 nm with four cooling rates. The kink in the solid line at 20 °C is probably due to an instrument error.
All cooling speeds reveal a maximum of the Cotton effect between 35 °C and 45 °C. A high cooling speed of 90 °C resulted in hysteresis regarding the course of the CD effect below 30 °C which does not reach a plateau value (Figure 17b, gray line). This behavior is uncommon for discotic 3 and its derivatives, because the most stable self-assembly in solution is reached within seconds. However, hysteresis is observed for bipyridine discotics with urea instead of amide linkages. The remarkable maximum of the temperature dependent Cotton effect depicted in Figure 17b was largest if a moderate cooling rate of 30 °C per hour was applied. UV/Vis spectroscopy shows only a gradual increase of the extinction coefficient as was shown in Figures 14 and 15. The long term stability of the solutions containing disc 3 and chiral diacid 17 was determined to gain an idea about the strength of the acid-base complex. A fresh solution of disc 3 and 0.38 molar equivalents of diacid 17 does display a Cotton effect in CD spectroscopy as discussed before. LD measurements show the absence of linear dichroism (Figure 18a, solid line), but if the solution was stored for a prolonged period of time, an LD effect appears (dotted line). This was accompanied by the absence of a Cotton effect. The CD effect cannot be restored by heating to 90 °C and subsequent slow cooling. The LD effect is only visible in the absorption region of the diacid, thus disc 3 is not involved in the formation of another aggregate over time.

Figure 18: Time dependent LD, CD and UV/Vis spectra of disc 3 and 0.38 mol-equ. diacid 17, concentration = 0.019 mM. a) LD and UV/Vis spectra at room temperature of the mixture directly after preparing the solution and after three weeks storage in the same cuvette. b) CD and UV/Vis spectra of the mixture at 40 °C, directly after sample preparation and after four weeks storage at 40 °C in the same cuvette.

Temperature dependent absorption spectra of diacid 17 are depicted in Figure 19a. It is believed that diacid 17 is not stable in solution over time and crystallizes irreversibly. To confirm this, the aged solution (Figure 18b, dotted line) was removed from its cuvette without disturbing the solution. Then the cuvette was filled again with the solvent t-butyl methyl ether (tBME), which is a good solvent for diacid 17, but is also able to dissolve disc 3. The absorption spectrum is shown in Figure 19b (dashed line). Clearly, diacid 17 dominates in the spectrum, regarding the maximum at 265 nm and the shoulder at 287 nm. Disc 3 is only present in a very little amount. Thus, diacid 17 is not stable in combination with disc 3 in MCH solution if stored for a prolonged period of time. Apparently, the strength of the acid-base complex between diacid 17 and disc 3 is not large enough to prevent diacid precipitation. Also
at 40 °C, where the induction of chirality is maximal, storing of a solution resulted in vanishing of the CD effect (Figure 18b). The absorption spectrum does not display significant changes showing that the helical structure of disc 3 is not affected by breaking of its complex with diacid 17 or that disc 3 precipitates from solution.

**Figure 19:** Solubility of diacid 17 in MCH and its precipitation over time. a) 0.029 mM solution of chiral diacid 17 in MCH at four temperatures and in tBME at room temperature. b) Black line: 0.008 mM solution of diacid 17 in tBME at room temperature. Gray line: 0.019 mM solution of disc 3 and 0.38 mol-equivalents of diacid 17 in MCH at 40 °C (Figure 18b, dashed line). Dashed line: Residue of the previous saved solution, dissolved in tBME (concentration unknown, normalized to solid graph at 290 nm).

To conclude, within a reasonable period of time, diacid 17 is an efficient source of chirality for stacks of pyridyl functionalized discs 3. The measured Cotton effect in solutions of disc 3 and diacid 17 is very sensitive towards temperature changes showing a delicate balance between the acid-base equilibrium, the tendency of diacid 17 to crystallize from solution and the equilibrium between disc 3 present in helical aggregates and as molecularly dissolved species. The optimum for this system is apparently located around 40 °C, at which the largest induction of chirality was detected. Regarding other supramolecular complexes which rely on a delicate equilibrium between the assembling species involved, the stability of the formed complex usually increases with decreasing temperature with concomitant increase of the observed CD effect. This behavior is observed for DNA templated discrete self-assemblies, perylene bisimide aggregates, OPV helical stacks, helical polymers and foldamers.

Compared to these systems the behavior of the chiral, supramolecular complex between diacid 17 and disc 3 is unprecedented and resembles more temperature induced switching of helicity as is observed in certain helical polyacetylenes.
4.6 Outlook

Efficient transfer of chirality of divalent tartaric acids 14, 15 and 17 to helical assemblies of disc 3 was observed. However, the instability of the chiral acid-disc 3 complex and the tendency of the chiral acids to precipitate from solution hampered a full, detailed investigation of the chiral complexes. This limited solubility makes it hard to increase the concentration of the solutions in methycyclohexane, and this prevents concentration dependent studies. The latter may give information on the binding strength between disc 3 and the chiral acid used. This has been performed successfully for chiral acid induced bias of helicity in OPV self-assemblies and hydrogen bonded rosette assemblies or for chiral base induced bias of helical sense of phosphonic acid functionalized helical polymers. Also, FT-IR and NMR studies in solution require a rather high concentration of the disc-diacid complex. FT-IR is a convenient method to prove the existence of the acid-pyridine complex as is reported for liquid crystalline supramolecular side-chain polymers and chiral stilbazole-tartaric acid complexes. Clipping of a bivalent chiral acid, together with supramolecular chiral induction into hydrogen bonded helical columnar systems was studied with infrared spectroscopy too. 'H-NMR spectroscopy in combination with (vibrational) CD spectroscopy may give information about the absolute conformation of the tartaric acid involved in the binding process with disc 3. CD spectroscopy cannot be used for this particular system because the Cotton effect originating from the chiral acid is buried under the one originating from the disc. Vibrational CD however, might be applied. The conformations of tartaric acid derivatives are shown in Figure 20 for diacid 14. Particularly interesting is the G− conformation, in which the carboxylic acid groups are oriented into the same conformation while the bulky side groups are pointing away from the binding side. Observation of this G− conformation would support the possible presence of a clipping interaction of the tartaric acid with two discotics.

[Figure 20: Newman projections of the three staggered conformations of (2R,3R)-tartaric acid dibenzoate (14), the conformational preference can be confirmed using 'H-NMR and (vibrational) CD spectroscopy.]

To increase the solubility of the chiral complex between disc 3 and the tartaric acid derivative two strategies may be pursued. First, the propoxy tails of diacid 17 might be replaced with longer alkoxy tails. By doing so, the para-position of the benzoyl moiety can be left unsubstituted, thus preventing the electron releasing effect of the para-ether group. The latter decreases the acidity of the acid functionalities of diacid 17 and thus decreases the strength of the acid-base complex. Second, one of the acid functionalities of diacid 14 can be masked as a tertiary amide. The advantage of this strategy is that only one-to-one binding between discotic 3 and the chiral acid will occur. The synthesis of these monoacids is straightforward (Scheme...
Chiral cyclic anhydride 20 can be easily synthesized from diacid 14 (or its enantiomer). Then, using any secondary amine, chiral acids 21 possessing two alkyl tails can be synthesized, although the risk of base induced racemization would have to be kept in mind.

Scheme 3: Convenient synthesis of chiral tertiary amides 21 via anhydride 20. Diacid 14 and its enantiomer are commercially available.

Finally, the strength of the acid-base complex might be enhanced by increasing the hydrogen bond accepting nature of the non-symmetric discotic used. Thus, instead of the isonicotinic acid derived pyridyl group of disc 3, a nicotinic acid derived pyridyl group should be incorporated. In the latter case, the amide carbonyl is placed meta instead of para with respect to the pyridine nitrogen, thus enhancing its basicity. Replacing the pyridyl group by a melamine or dianaminotriazine derived unit would enable multiple hydrogen bonding between the acid and discotic 3.

4.7 Conclusions
In this chapter successful supramolecular chiral induction from chiral acids to desymmetrized bipyridine discotic 3 and its helical self-assemblies was investigated. A selection of acids was made to evaluate which derivatives selectively bind to discotic 3, the latter being equipped with a peripheral pyridyl unit. Importantly, the acids should on the one hand not interfere with the bipyridine units in the core of disc 3, but on the other hand they may not be too weak. The carbonyl group para to the nitrogen atom of the peripheral pyridyl group of disc 3 lowers the basicity of this pyridyl moiety and weakens the binding. Spectroscopic studies prove that phosphonic acids and tartaric acids, which are of comparable acidic strength, can bind selectively with disc 3 in apolar media like chloroform and alkane solvents. Two chiral phosphonic acids derived from citronellol were synthesized, but only ethyl phosphonic acid 9 containing a more bulky acid group was able to transfer its chirality in alkane solution as was determined with CD spectroscopy.

Dibenzoyl tartaric acids 14 and 15 mixed with discotic 3 in methylocyclohexane induce Cotton effects in CD spectroscopy comparable in magnitude with homochiral discotics. The transfer of chirality proved to be dependent on concentration and temperature. The concentration effect may be explained by a difference in equilibrium between diacid 14 and basic disc 3 causing a difference in the concentration of free acid. The free acid has the tendency to precipitate in MCH solution. Because of this, diacid 17 was synthesized as a less polar analog of diacid 14. Also this acid displayed efficient transfer of chirality as was shown by CD spectroscopy in dilute MCH solutions. When more than 0.5 molar equivalents of either diacid 14 or 17 was
used the formation of larger aggregates was postulated. This is probably due to hydrogen bonding between the free acids and implied that only one acid functionality of the diacid is involved in binding with disc 3. Amplification of chirality was not observed in the mixtures of chiral acids 14 or 17 with disc 3; apparently helices that are biased by the chiral acid are not able to transfer their helix direction to non-biased helices of disc 3. This may imply phase separation between stacks to which chiral acids are bound and between acid-free, non-biased stacks.

In the temperature dependent induction of chirality from acids 14 and 17 in solution a maximal Cotton effect around 40 °C was observed. This suggests a delicate balance between the stability of the helical aggregates of disc 3, the acid-base equilibrium between disc 3 and the diacid and the tendency of diacid 17 to precipitate from solution. In the long term, the complex between disc 3 and diacid 17 appeared to be unstable as irreversible precipitation of diacid 17 from solution was observed. The latter disadvantage might be prevented by using more soluble derivatives of diacid 17, either with longer tails or with one of the acid functionalities converted into a tertiary amide (mono acids 21, Scheme 3). Both improvements should yield a more stable system between the chiral acid and disc 3 allowing a more detailed and complete study of the chiral induction process.

4.8 Experimental section
For other experimental conditions concerning synthesis, see Chapters 2 and 3. (S)-3,7-dimethyloctanol (8) was kindly provided by Robert Abbel and obtained from (S)-citronellol by catalytic hydrogenation. This (S)-citronellol (e.e. = 98.4, [α]D20 = -5.36) was a generous gift from Takasago. The synthesis of 3,4,5-tripropoxybenzoyl chloride (19) was described in Chapter 3. Triphenyl phosphine and triethyl phosphite were purchased from Aldrich (www.aldrich.com), N-bromo-succinimide (NBS) was purchased from Acros (www.acros.com) and recrystallized from water before use. (2R,3R)-dihydroxysuccinic acid (L(+)-tartaric acid) (13) ([α]D20 = +12.94 ° (water, c = 10.05 mg/mL)) was purchased from Merck (www.merck-chemicals.com) and dried under vacuum with P2O5 before use. (2R,3R)-Dibenzoyloxysuccinic acid (14) ([α]D20 = -116.4 ° (ethanol, c = 11.22 mg/mL, measured value), -116 ° (value from Aldrich)) and (2S,3S)-dibenzoyloxysuccinic acid (15) ([α]D20 = +107.8 ° (ethanol, c = 12.06 mg/mL, measured value), +117 ° ± 2 ° (value from Aldrich)) were purchased from Aldrich and used as received. All solvents were of AR quality if not stated otherwise and were purchased from Biosolve (www.biosolve.nl). Dichloromethane was distilled over Merck P2O5 and dioxane and THF were distilled on 4 Å molsieves before use. Methylcyclohexane and t-butyl methyl ether were of spectrograde quality and purchased from Aldrich.

All spectroscopic measurements were performed at room temperature unless stated otherwise. 31P-NMR was recorded on a Varian Mercury Vx 400 MHz (162 for 31P) or a Varian Mercury Plus 200 MHz (81 MHz for 31P) NMR spectrometer. 31P chemical shifts were determined with 85 % phosphoric acid as external standard. CD spectra were recorded on a Jasco J-815 spectropolarimeter equipped with a Jasco PTC-413S/15 Peltier type temperature control system and UV/Vis spectra were recorded on a Perkin Elmer Lambda 40 UV/Vis spectrometer equipped with a Perkin Elmer PTP-1 Peltier temperature control system. A one cm quartz cuvette was used for the measurements in the 0.01 mM range and a 1 mm quartz cuvette was used for measurements in the 0.1 mM range, wavelengths are given in nm and absorptions in l/mol/cm. For temperature dependent measurements, a screw-cap sealed quartz cuvette was used. Mixtures of disc 3 and acids were all prepared in the same manner: the appropriate amounts of disc 3 and the acid were homogeneously mixed in chloroform (a good solvent), concentrated in vacuo.
and the residue dried in the presence of P₂O₅ under vacuum. Finally, the residue was redissolved into the alkane or NMR deuterated solvent by gentle heating and sonication.

1-Bromo-(S)-3,7-dimethyloctane (11)\textsuperscript{53,90}
Under argon, NBS (11.97 g, 67.3 mmol) was added portion-wise to a well stirred ice-cold solution of alcohol 10 (9.93 g, 63.1 mmol) and triphenyl phosphate (18.30 g, 70.0 mmol) in distilled dichloromethane while shielding the solution from light. The temperature of the reaction mixture was kept below 20 °C. After complete addition of the NBS, the reaction mixture was allowed to reach room temperature and stirred under argon overnight. When monitoring with \(^1\)H-NMR indicated complete conversion, the solvent was removed \textit{in vacuo} without heating. The beige residue was dissolved in chloroform (100 mL) and acetone (50 mL) and subsequently heptane (250 mL) was added at once to precipitate the formed succinimide. The suspension was cooled in an ice-bath under stirring for 0.5 h and subsequently filtered over a glass filter. The filtrate was concentrated \textit{in vacuo} to give a sticky residue that was suspended into heptane (200 mL) and stirred for 0.5 h. Filtration over a paper filter to remove the triphenyl phosphineoxide and subsequent washing with heptane (2 × 20 mL) yielded another filtrate. Concentration \textit{in vacuo} of the latter gave a beige oil that was purified by fractional vacuum distillation (70 °C, 1 mbar) to give bromide 11 as a colorless oil (8.503 g, 61%).

\[ R_1 = 0.74 \text{ (silica gel, 5 vol-% ethyl acetate in chloroform); GC-MS: } R_1 = 4.05 \text{ min (one peak), } m/z: \text{ calcd for: 220.08 (C}_{10}H_{23}Br); found: 220 \text{ (radical cation); } \text{^1H NMR (400 MHz, CDCl}_3): } \delta = 3.49-3.37 \text{ (2H, 2), 1.88 (m, 1H, 3), 1.71-1.60 (2H, 3+4), 1.53 (nonet, 1H, 5), 3.49-3.37 (2H, 2), 1.88 (m, 1H, 3), 1.71-1.60 (2H, 3+4), 1.53 (nonet, 1H, 5), 1.34-1.22 and 1.16-1.09 (6H, 3+6+7), 0.90-0.86 ppm (9H, 9+10); } \text{^31P NMR (162 MHz, CDCl}_3): } \delta = 40.1 \text{ (2), 39.2 (7), 36.7 (5), 32.1 (3), 31.7 (4), 28.0 (8), 24.6 (6), 22.7 and 22.6 (10), 19.0 (9) ppm; FT-IR (ATR): \nu (cm}^{-1}) = 2955, 2928, 2870, 1647, 1465, 1385, 1367, 1261, 1245, 1217, 1170, 1012, 920, 874, 754, 735; } [\alpha]_D^{20} = +4.7 \degree \text{ (CHCl}_3, c = 8.87 \text{ mg/mL).}\text{\textsuperscript{91}}

Diethyl (S)-3,7-dimethyloctylphosphonate (12)
Under argon and stirring, bromide 11 (7.58 g, 34.3 mmol) and triethyl phosphite (30 mL, 29 g, 175 mmol) were refluxed overnight after which TLC and GC-MS showed complete conversion of the bromide. GC-MS and \(^31\)P-NMR showed the formation of desired product and diethyl ethylphosphonate as expected side-product.\textsuperscript{92} Repetitive fractional vacuum distillation to distill the major impurities and subsequently the desired product (85 °C, 0.02 mbar) yielded phosphonate 12 (8.416 g, 88 %) as a colorless oil.

\[ R_1 = 0.23 \text{ (silica gel, 5 vol-% ethyl acetate in chloroform); GC-MS: } R_1 = 4.05 \text{ min (one tailing peak), } m/z: \text{ calcd for: 278.20 (C}_{13}H_{30}O,P); found: 278 \text{ (radical cation); } \text{^1H NMR (400 MHz, CDCl}_3): } \delta = 4.15-4.04 \text{ (m, 4H, 11), 1.78-1.60 (4H, 2+3), 1.52 (nonet, 1H, 3), 3.49-3.37 (2H, 2), 1.88 (m, 1H, 3), 1.71-1.60 (2H, 3+4), 1.53 (nonet, 1H, 5), 3.49-3.37 (2H, 2), 1.88 (m, 1H, 3), 1.71-1.60 (2H, 3+4), 1.53 (nonet, 1H, 5), 1.34-1.22 and 1.16-1.09 (6H, 3+6+7), 0.88-0.86 ppm (9H, 9+10); } \text{^31P NMR (50 MHz, CDCl}_3): } \delta = 61.4 \text{ (d, 3J(C,P) = 5.8 Hz, 11), 39.2 (7), 36.6 (5), 33.5 (d, 3J(C,P) = 17.3 Hz, 4), 29.1 (d, 2J(C,P) = 5.0 Hz, 3), 27.9 (8), 24.6 (6), 22.7+22.6 (10), 23.3 (d, 2J(C,P) = 140.3 Hz, 2), 19.1 (9), 16.5 ppm (d, 2J(C,P) = 5.8 Hz, 12); } \text{^31P NMR (162 MHz, CDCl}_3): } \delta = 33.3 \text{ ppm; FT-IR (ATR): } \nu (cm}^{-1}) = 3487, 2955, 2928, 2870, 1647, 1465, 1385, 1367, 1249 (P=O), 1164, 1098, 1056 (P-O-C), 1026 (C-O), 955 (P-O), 785, 743, 709; } [\alpha]_D^{20} = +0.77 \degree \text{ (neat).} \]
(S)-3,7-Dimethyloctyl phosphonic acid (8)
Phosphonate 12 (1.01 g, 3.63 mmol) was dissolved into a mixture of distilled dioxane (3 mL) and aqueous hydrochloric acid (12 M, 1 mL) under stirring. The mixture was refluxed for 48 hours under argon after which $^{31}$P and $^1$H-NMR indicated complete conversion of the reactant and the formation of one major product. Water (25 mL) was added to the turbid reaction mixture followed by extraction with diethyl ether (3 × 25 mL). The combined organic layers were washed with brine (10 mL), dried with MgSO$_4$ and filtered over a glass filter. Concentration in vacuo yielded a beige residue that was crystallized from hot heptane several times to obtain phosphonic acid 8 (0.501 g, 62 %) as a colorless crystalline solid.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta = 10.46$ (s, 2H, 11), 1.76-1.57 (3H, 2+3), 1.52 (nonet, 1H, $^3$(H,H) = 6.6 Hz, 1H, 8), 1.49-1.39 (2H, 3+4), 1.35-1.19 and 1.17-1.06 (6H, 5+6+7), 0.87-0.86 ppm (9H, 9+10); $^{31}$P NMR (50 MHz, CDCl$_3$, APT): $\delta = 39.2$ (7), 36.5 (5), 33.3 (d, $^3$(C,P) = 17.0 Hz, 4), 28.8 (3), 27.9 (8), 24.6 (6), 23.0 (d, $^3$(C,P) = 145 Hz, 2), 22.7+22.6 (10), 19.0 ppm (9); $^{13}$C NMR (162 MHz, CDCl$_3$): $\delta = 37.9$ ppm (1); FT-IR (ATR): $\nu$ (cm$^{-1}$) = 2955, 2924, 2868, 2319, 1467, 1410, 1383, 1366, 1319, 1260, 1237 (P=O), 1169, 1146, 1108, 1079, 996, 949 (P-O), 932, 780, 728; Elemental analysis calcd (%) for C$_{10}$H$_{25}$O$_3$P: C 54.04, H 10.43; found: C 54.13, H 10.38; $[\alpha]_D^{20} = +0.67$ ° (neat).

O-Ethyl (S)-3,7-Dimethyloctyl phosphonic acid (9)
Phosphonate 12 (1.605 g, 5.76 mmol) was dissolved into ethanol (11 mL) and water (1.5 mL) under stirring followed by addition of ground NaOH (1.06 g, 26.5 mmol). Under argon, the turbid mixture was heated till reflux causing complete dissolution. After maintaining reflux for 3 h, $^{31}$P and $^1$H-NMR indicated complete conversion of the reactant. Subsequently, aqueous hydrochloric acid (12 M) was added to reach pH ≈ 0. Then, the solvents were removed in vacuo under gentle heating and chloroform (25 mL) was added to obtain a suspension of the salts. The suspension was filtered over a paper filter and the residue washed with chloroform (2 × 10 mL). The combined filtrates were concentrated in vacuo to yield a residue (1.42 g) that consisted of predominantly the desired product. The residue was dissolved into aqueous NaOH (2 M, 20 mL) and water (10 mL) and the mixture was extracted with diethyl ether (3 × 20 mL) to remove neutral organic impurities. Then, the aqueous layer was acidified with ice-cold aqueous HCl (12 M) to reach pH = 0 and extracted with ethyl acetate (3 × 25 mL). The combined ethyl acetate layers were concentrated in vacuo to yield an oil that was dissolved into CHCl$_3$. This solution was filtered over a paper filter to remove brownish residues. The filtrate was concentrated in vacuo to yield phosphonic acid 7 (1.299 g, 90 %) as a colorless oil.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta = 10.49$ (s, 1H, 13), 4.13-4.05 (m, 2H, 11), 1.82-1.58 (3H, 2+3), 1.52 (nonet, 1H, $^3$(H,H) = 6.6 Hz, 1H, 8), 1.51-1.39 (3H, 3+4), 1.33 (t, 3H, $^3$(H,H) = 7.1 Hz, 12), 1.35-1.19 and 1.17-1.06 (6H, 5+6+7), 0.87-0.86 ppm (9H, 9+10); $^{13}$C NMR (50 MHz, CDCl$_3$, APT): $\delta = 60.9$ (d, $^3$(C,P) = 6.3 Hz, 11), 39.2 (7), 36.6 (5), 33.4 (d, $^3$(C,P) = 17.4 Hz, 4), 28.9 (d, $^3$(C,P) = 4.4 Hz, 3), 27.9 (8), 24.7 (6), 23.5 (d, $^3$(C,P) = 143.2 Hz, 2), 22.7+22.6 (10), 19.1 (9), 16.3 ppm (d, $^3$(C,P) = 16.3 Hz, 12); $^{31}$P NMR (162 MHz, CDCl$_3$): $\delta = 36.3$ ppm (1); FT-IR (ATR): $\nu$ (cm$^{-1}$) = 2955, 2927, 2870, 2612, 2288, 1678, 1464, 1408, 1384, 1367, 1243 (P=O), 1191, 1166, 1098, 1042 (P-O-C), 982, 961 (P-O), 803, 852, 735; $[\alpha]_D^{20} = 0.67$ ° (neat).
(3R,4R)-Di(3,4,5-tripropoxybenzoyloxy) succinic anhydride (18)

Under argon, a mixture of 3,4,5-tripropoxy-benzoyl chloride (19) (0.532 g, 1.69 mmol) and (2R,3R)-dihydroxy succinic acid (13) (74 mg, 0.49 mmol) was first heated at 80 °C for 1 h and then at 150 °C for 4 h after which FT-IR indicated no further change of the reaction mixture. Heating was continued for another hour. Then, the mixture was allowed to reach room temperature and toluene (20 mL) was added to give a beige suspension. The suspension was filtered over a paper filter and subsequently the filtrate was diluted with heptane (20 mL). This solution was placed in a refrigerator overnight during which a white precipitate formed. The suspension was filtered over a Büchner funnel and the residue was washed with an ice-cold mixture of heptane and toluene (1:1 v:v, 10 mL). Drying of the residue in a vacuum oven gave chiral anhydride 18 (0.172 g, 50 %) as a white powder.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta = 7.28$ (s, 4H, 5), 5.88 (s, 2H, 2), 4.04 (t, 4H, $^3$J(H,H) = 6.5 Hz, 8), 3.98 (t, 8H, $^3$J(H,H) = 6.4 Hz, 9), 1.85 (sextet, 8H, $^3$J(H,H) = 7.1 Hz, 11), 0.77 (sextet, 4H, $^3$J(H,H) = 7.1 Hz, 10), 1.06 (t, 12H, $^3$J(H,H) = 6.5 Hz, 13), 1.04 ppm (t, 6H, $^3$J(H,H) = 7.0 Hz, 12); $^{13}$C NMR (50 MHz, CDCl$_3$, APT): $\delta = 165.4$ (3), 163.7 (1), 153.0 (6), 144.1 (7), 121.2 (4), 108.8 (5), 75.3 (8), 73.0 (2), 70.9 (9), 23.5 (10), 22.6 (11), 10.6 (13), 10.5 (12) ppm; FT-IR (ATR): $\nu$ (cm$^{-1}$) = 2964, 2941, 2878, 1894 (ester), 1704 (acid, dimeric form), 1587, 1499, 1464, 1432, 1387, 1352, 1338, 1302, 1232, 1194, 1115, 1097, 1059, 994, 956, 913, 887, 862, 758, 663; MALDI-TOF MS: m/z: calcd for: 706.42 (M$^+$), 729.41 (M+Na$^+$); $[\alpha]_D^{20}$ = -100.6 $^\circ$ (ethanol, c = 8.87 mg/mL).

(3R,4R)-Di(3,4,5-tripropoxybenzoyloxy) succinic acid (17)

Anhydride 18 (39 mg, 0.057 mmol) was dissolved into a mixture of water (10 mL) and distilled THF (5 mL) and refluxed for 3.5 h after which FT-IR indicated complete hydrolysis of the anhydride. Then, the solvents were removed in vacuo to give a residue. The latter was purified with column chromatography (silica gel, gradient from CHCl$_3$:HCOOH 98:2 v:v to 95:5 v:v to elute a side-product and finally CHCl$_3$:HCOOH 95:5 v:v to CHCl$_3$:HCOOH:Ethyl acetate 55:540 v:v:v to elute the desired product) to yield chiral diacid 17 (48 mg, ~99 %) as a colorless solid.

$^1$H NMR (400 MHz, CDCl$_3$): $\delta = 7.26$ (s, 4H, 5), 5.87 (s, 2H, 2), 3.99 (t, 4H, $^3$J(H,H) = 6.5 Hz, 8), 3.90 (t, 8H, $^3$J(H,H) = 6.4 Hz, 9), 1.80-1.71 (12H, 10+11), 1.00 (t, 6H, $^3$J(H,H) = 7.5 Hz, 12), 0.97 ppm (t, 12H, $^3$J(H,H) = 7.2 Hz, 13); $^{13}$C NMR (50 MHz, CDCl$_3$, APT): $\delta = 167.4$ (1), 165.1 (3), 152.9 (6), 143.0 (7), 123.6 (4), 108.6 (5), 75.1 (8), 71.7 (2), 70.7 (9), 23.6 (10), 22.6 (11), 10.6 (12), 10.5 ppm (13); FT-IR (ATR): $\nu$ (cm$^{-1}$) = 3179, 2965, 2938, 2879, 2604, 1768 (acid, monomeric form), 1730 (ester), 1704 (acid, dimeric form), 1587, 1499, 1464, 1432, 1387, 1352, 1338, 1302, 1232, 1194, 1115, 1097, 1059, 994, 956, 913, 887, 862, 758, 663; MALDI-TOF MS: m/z: calcd for: 706.42 (M$^+$), 729.41 (M+Na$^+$); $[\alpha]_D^{20}$ = -100.6 $^\circ$ (ethanol, c = 8.87 mg/mL).
4.9 References


116
Supramolecular chiral induction into helically assembled desymmetrized discotics


[80] Disc 3 is helically self-assembled in bBME according to UV/Vis spectroscopy.


119
The optical rotation changes sign upon bromination.

During the desired reaction between bromide 9 and triethyl phosphite bromoethane (bp. 38 °C) is formed. If not continuously removed by evaporation, the bromoethane will react with triethyl phosphite to give diethyl ethylphosphonate and bromoethane (!).

Unfortunately, the $^2J(C,P)$ coupling was not observed due to slightly broadened peaks.
Abstract. In this Chapter, the step-wise synthesis of a desymmetrized hydroxy functionalized disc is described, together with its conversion into a polymerizable disc and the successful incorporation of the latter into polymethacrylate copolymers. First a 3,3’-diamino-2,2’-bipyridine trialkoxy phenyl wedge containing one dangling protected hydroxy group was synthesized. The latter was converted to the desired hydroxy functionalized disc by using a ‘2/3rd-disc’ acid chloride as described in Chapter 2. The peripheral position of the hydroxy group allows easy synthesis of the corresponding methacrylate substituted disc in one step. In combination with butyl methacrylate, this discotic was polymerized under ATRP conditions to give a methacrylate copolymer with dangling disc-shaped side-groups. Prior to this, ATRP had to be optimized in order to cope with the possible complexation properties of the bipyridines present in the disc structure. The amount of ligand that forms a complex with the copper catalyst during ATRP proved to be especially crucial. The copolymer carrying discotics as side-chains was of high molecular weight, low polydispersity and displayed enhanced aggregation behavior, probably due to the high local concentration of discotics. Nevertheless, the polymer proved to be well-soluble. Deaggregation of the copolymer was demonstrated in a temperature dependent $^1$H-NMR measurement. This copolymer functionalized with discotics might be a useful candidate for the preparation of fluorescent supramolecular single-polymer nanoparticles.
5.1 Introduction

The combination of discotics and polymers may be advantageous in material science by combining the desired optical, electronic and organizing properties of columnar mesophases with mechanical and thermal stability provided by polymers. Often, polymeric materials are required for industrial applications. The disc-shaped moiety can be combined with the polymer in three ways (Figure 1). In polymers carrying discotics as side-chains, the discotics are connected/grafted to the polymer chain by a (flexible) spacer. In main-chain polymers, the discotics are an integral part of the polymer backbone. Finally, discotic network polymers are constructed from discotics possessing multiple polymerizable groups. In this Chapter, disc-functionalized side-chain polymers are targeted.

Figure 1: Three molecular structures for discotic polymers: a) side-chain polymer; b) main-chain polymer; c) discotic-containing network polymer.

A second distinction can be made between polymers that are functionalized with discotics (post-functionalization) and polymers that are obtained by (co-)polymerizing discotics equipped with polymerizable groups. A disadvantage of the first strategy is the difficulty to functionalize all reactive groups on the polymer chain, while in the second case the discotic may be incompatible with the polymerization conditions. Also, alignment of columnar mesophases can be difficult in the first case because of a high viscosity of the polymer carrying discotics, while in the second case an aligned columnar mesophase can be formed prior to polymerization. This is especially important in the construction of functional nanomaterials where a preorganized structure has to be fixated. In discotic-functionalized polymers several cores have been applied, including phthalocyanines, phenylethynyl cores, triphenylenes and hexabenzocoronenes. Triphenylene-containing polymers –as well as the concept of mesogenic discotic-functionalized polymers– was pioneered by Ringsdorf et al. who reported polysiloxanes possessing triphenylene side-chains. An appealing application of discotic-functionalized polymers is the fabrication of optical compensation layers for LC displays consisting of triphenylenes polymerized in a nematic mesophase. Columnar organization of disc-containing polymers in Langmuir-Blodgett films was demonstrated for phthalocyanines and triphenylenes. In the bulk, many discotic-functionalized polymers form columnar mesophases with similar transition temperatures compared to their corresponding monomers. However, crystallization is usually suppressed by polymerization and upon cooling of the columnar mesophase an ordered glass is formed instead. The presence of a flexible polymer backbone and sufficiently long spacers between the polymer backbone and the disc-shaped side-chains is important to ensure stable columnar mesophases. Another way to introduce a
columnar mesophase or to control mesophase behavior is to mix discotic-functionalized polymers with electron accepting units, which was extensively studied in the groups of Picken,3 Wendorff15 and Ringsdorf.16 Besides the creation of novel mesogenic materials the polymerization of discotics may result in fixated self-assembled structures that enable a more detailed study of the supramolecular structure. This has been shown for meta-stable nano-coils of amphiphilic hexabenzocoronenes,17 hydrogen bonded helices of benzene-1,3,5-tris-carboxamide discotics18 and triazine discotics.19 The latter is a clear example of an irreversible nanostructure obtained by complete fixation of an, in first instance, reversible helical stack. However, to maintain the reversibility of the supramolecular structure, only mono-functionalized discotics should be applied, together with the incorporation of an aliphatic co-monomer to ensure solubility. If the polymerization is then performed in conditions were no interactions between the discotics are present a highly reversible material might be obtained. In this Chapter this approach to arrive at flexible polymers equipped with discotics based on the 3,3’-bis(acylamino)-2,2’-bipyridine unit is described. The polymerization technique of choice is atom transfer radical polymerization (ATRP) because of high tolerance of functional groups and the possibility to synthesize polymers of controlled molecular weight and low molecular weight distribution. In the following section this technique is discussed in more detail.

5.2 Atom transfer radical polymerization (ATRP)

Free radical polymerization is the main technique to afford commodity polymers in industry. Termination, however, prevented the application of radical polymerization for the synthesis of more complex polymers with a narrow molecular weight distribution and for this goal usually anionic, cationic and ring-opening polymerizations were applied. The polydispersity problem in free radical polymerizations is caused by reactions between growing chains which results in termination. These reactions can be divided into bimolecular radical coupling, leading to formation of a covalent bond between two growing chains, disproportionation, which involves transfer of a hydrogen radical from one to another radical chain, or finally termination originating from chain transfer agents, like solvent impurities (Scheme 1).

Scheme 1: Termination via a) bimolecular radical coupling or b) disproportionation.

To overcome these termination problems, living radical polymerization (LRP) and controlled radical polymerization (CRP) were developed.20 Living radical polymerization is based on a fast equilibrium between a small amount of growing radical chains and a majority of dormant species. Several kinds of living radical polymerizations have been introduced, including atom transfer radical polymerization (ATRP), metal-catalyzed LRP, single electron transfer LRP (SET LRP), degenerative transfer (DT), reversible addition fragmentation chain transfer (RAFT), nitroxide mediated polymerization (NMP), and stable free radical polymerization (SFRP).21 In this chapter only ATRP is discussed.
For ATRP the equilibrium between active and dormant species mentioned above is depicted in Scheme 2. Initiation occurs when the active, polymerizing chain is created by transfer of a (pseudo)halogen to a transition metal catalyst, which is oxidized during this process. During propagation, the radical chain continues to bind monomers, until the (pseudo)halogen is transferred back and the catalyst returns to its lower oxidation state. If the majority of all species is dormant, termination is prevented and polymers with a narrow molecular weight distribution will be obtained. Besides these advantages, which are typical for controlled radical polymerization (CRP) in general, ATRP is favorable compared to other CRP techniques in many respects. Advantages of ATRP in particular are its compatibility with a wide range of monomers, (macro)initiators and solvents, a simple reaction setup, and the ability to perform ATRP over a large range of temperatures and dispersed media (emulsions and suspensions).

\[
R-X + M_i^m - Y / \text{Ligand} \xrightarrow{k_{\text{ext}}} R^+ + X - M_i^{m+1} - Y / \text{Ligand}
\]

Scheme 2: The ATRP equilibrium between dormant and active species. \(X = \text{halogen}, M_i^m = \text{transition metal with oxidation state } n, Y = \text{anion.}\)

A simple homopolymerization with ATRP in bulk requires at least four components: initiator, monomer, catalyst and ligand. An extensive overview of commonly used components can be found in a recent review. ATRP is applicable to monomers with side-chains that stabilize the growing radical. Often used monomers with this property are (meth)acrylates, (meth)acrylamides, acrylonitrile, styrene and derivatives of these compounds (Figure 2).

Figure 2: Monomers that are often polymerized under ATRP conditions.

The initiator plays two roles in ATRP. First, the initiator is the starting point for the growing chain. The amount of initiator determines the number of chains that will be initiated and thus the average molecular weight. Second, the ratio of monomer and initiator determines the maximal degree of polymerization that can be expected theoretically. In general initiators are alkyl halides carrying an activating substituent attached to the \(\alpha\)-carbon, e.g. aryl, allyl and carbonyl substituents (Figure 3).

Figure 3: Some initiators used for ATRP (\(X = \text{Cl or Br}\)).\(^{21,23}\) \(R = \text{alkyl group.}\)

Initiation involves a combination of elevated temperature (or UV light) and a transition metal catalyst. Upon initiation, the carbon-halogen bond is cleaved homolytically and the halogen is
transferred to the catalyst, causing oxidation of the latter. The most common initiators contain a chlorine or bromine, because these halogens can be transferred easily to the transition metal catalyst. Also some successful polymerizations with alkyl-iodide initiators have been reported. Fluoride is never used, because of the high strength of the C-F bond which cannot be cleaved homolytically. Since polymers obtained using ATRP possess a living halide end-group, these polymers can be used in post-polymerizations. These initiators are known as macro-initiators. The catalyst is important in ATRP, because it is essential for the dynamical equilibrium between the dormant and active species. Five conditions determine whether a catalyst is suitable for ATRP. First, the transition metal should possess two easily accessible oxidation states, separated by one electron. Second, the transition metal should have a good affinity for the (pseudo)halogen of the initiator. Third, the coordination sphere of the metal should be expandable in such a way, that it selectively binds the (pseudo)halogen. Fourth, the ligand and metal should form a relatively strong complex. Fifth, position and dynamics of the ATRP equilibrium should be suitable for the catalyst. Several transition metals have been screened in ATRP, including molybdenum, titanium, chromium, osmium, cobalt, rhenium, ruthenium, iron, rhodium, nickel, palladium, and copper. The latter is most frequently used, due to its low costs and versatility, although environmental considerations stimulate a shift towards iron-catalyzed ATRP.

The choice of ligand is determined by the transition metal selected. Besides enhancing solubility, the ligand also determines the activity of the catalyst. Most ligands are either nitrogen-based, or phosphorus-based. For copper-catalyzed ATRP only nitrogen-based ligands are suitable (Figure 4). Studies comparing several copper-ligand complexes reported trends for catalytic activity and ligand structure. Catalytic activity increases with the number of coordinating nitrogens (N4 > N3 > N2 >> N1) and decreases with the spacer length between the nitrogens (C2 > C3 > C4). Also the substituents attached to the nitrogens influence the catalytic activity. Phosphorus ligands having the general formula Pr3 (especially PPh3 but also P(n-Bu)3) and are used in combination with most of the metals mentioned above, except copper.

![Figure 4: Common nitrogen ligands used in ATRP. PMDETA = N,N',N,N'-pentamethyldiethylenetriamine, TPMA = tris(2-pyridylmethyl)amine, Me5-TREN = tris[2-(dimethylamino)ethyl]amine.](image)

ATRP is performed in several solvents, or preferably in bulk, provided the polymer is soluble enough in the monomer from which it originates. Heterogeneous systems, like emulsion or suspension polymerizations are compatible with ATRP too. However, the solvent may influence the ATRP in three other ways: First, the possibility of chain transfer to the solvent. Second, undesired interactions between the solvent and catalyst (catalyst poisoning, structure...
change of the catalyst/ligand complex induced by the solvent). Third, side reactions on the polymer that are promoted by the solvent may occur. A wide range of solvents is compatible with ATRP: common solvents like toluene, anisole, ethyl acetate, acetone, DMF, ethanol and water, but also less common solvents like supercritical carbon dioxide and ethylene carbonate have been reported.\textsuperscript{21,26}

ATRP has been used before to obtain discotic-functionalized block-copolymers based on triphenylenes as is described in Chapter 1.\textsuperscript{24} Hydroxy-functionalized phthalocyanines have been synthesized that were easily converted towards their polymerizable acrylate and methacrylate analogs.\textsuperscript{27} In this Chapter, hydroxy functionalized desymmetrized discotic 1 will be introduced that may act as a precursor for a wide variety of functionalized discotics (Figure 5). This will be illustrated by the introduction of a methacrylate functionality (disc 2) and subsequent copolymerization with butyl methacrylate under ATRP conditions (polymer 20). Methacrylates are preferred over acrylates because of enhanced stability. Copolymerization will ensure solubility and processability of the polymer. By doing so, a polymer with several dangling discotics will be obtained, which may collapse under conditions where stacking of the discotics will take place. Also, the incorporation of non-discoid monomers will prevent frustrated self-assemblies when the distances between repeating units in the polymer do not match with distances within the helical stack. Prior to polymerization of disc 2, the polymerization conditions for butyl methacrylate in the presence of bipyridine discotics were optimized.

![Figure 5: Target desymmetrized discotics 1 and 2 possessing a peripheral alcohol and a methacrylate moiety, respectively. C\textsubscript{s}-symmetrical disc 3 was used in test polymerizations.](image)
5.3 Synthesis of hydroxy disc 1

To arrive at desired discotic 1 with one dangling hydroxy functionality, two components are necessary. The synthesis of '2/3rd disc' (acid chloride) 15 was described in Chapter 2, Scheme 8. It was decided to take advantage of mono-amine 4 containing two octyl tails and one protected hydroxy functionality connected via a -C\(_{11}\)H\(_{22}\) spacer (Scheme 3). The shorter octyl tails will ensure the accessibility of the dangling hydroxy group. In Chapter 3 was shown that discotics lacking a complete trialkoxy peripheral unit still display helical self-assembly analogous to that of their nona-alkoxy analogs. Thus, the presence of two additional octyloxy tails in wedge 4 might not be logical. However, their presence will enhance solubility, especially in case of subsequent polymerization, which will result in a high local concentration of discotics increasing their tendency to aggregate with concomitant decreasing solubility. The synthesis of hydroxy-protected wedge 4 was performed according to a slightly adjusted procedure as used by L. Brunsveld et al.\(^{28}\) Retrosynthetically, wedge 4 can be constructed from diamine 5, ester 6 and bromide 7. Conversion of ester 6 into the corresponding acid chloride, reaction of the latter with diamine 5 followed by deallylation of the resulting monoamine and finally etherification with bromide 7 should give amine 4 (Scheme 4). The most important difference embraces the use of the allyl ether protecting group in 6 instead of a benzyl ether, because the removal of the latter under catalytic hydrogenation condition in combination with the presence of diaminobipyridine moieties was expected to give problems.\(^{29}\)

![Scheme 3](chart.png)

**Scheme 3: Retrosynthesis to afford desired functionalized amine 4.**

The key step towards amine 4 involves the synthesis of ester 6 containing two different alkyl ethers. This was accomplished by selective alkylation of tetra-ester 8 with allylbromide (Scheme 4) according to a previously reported synthesis.\(^{30}\) Tetraester 8 was in turn synthesized by reacting methyl gallate with acetic anhydride in the presence of triethylamine.\(^{30}\) Monoalkylation on the para-position is feasible due to the electron withdrawing effect of the carbonyl functionality on the 1-position of tetraester 8 which enhances the reactivity of the acetoxy group on the para-position. By doing so, the desired mono-allyl ether 9 was obtained in good yield, however contaminated with ~4 mol-% diallylated side-product.\(^{31}\) After removal of the two remaining acetoxy groups in the next step, diol 10 was obtained pure by recrystallization owing to sufficient difference in polarity between desired dihydroxy ester 10 and the diallylated side-product. Then, diol 10 was alkylated to afford ester 6 which was converted via carboxylic acid 11 into acid chloride 12.\(^{32,33,34}\) Selective acylation of 2,2'-bipyridine-3,3'-diamine (5) with acid chloride 12 gave monoamine 13 in good yield (Scheme 4).\(^{32,33}\) The allyl ether protective group was removed in good yield according to established procedures\(^{36}\) giving phenol 14. Surprisingly, the latter was selectively O-alkylated to amine 4.
with bromide 7 under typical Williamson ether synthesis conditions by employing K$_2$CO$_3$ as base without alkylating the aromatic amino group, although the latter has been reported frequently. THP (tetrahydropyranyl) protected bromide 7 was synthesized according to the literature. Then, amine 4 was reacted with acid chloride 15 to give THP protected disc 16 which was easily converted into disc 1 (Scheme 4). Although the synthesis of disc 1 involves eleven steps, all reactions and purifications are straightforward and high-yielding. The synthesis of key-intermediate phenol 14 is feasible on a multigram scale. Phenol 14 can be easily converted into a wide variety of functionalized wedges that may afford the corresponding functionalized discotics after coupling with acid chloride 15. According to $^1$H-NMR analysis, discotic 16 is pseudo-C$_3$-symmetrical because of the rather long spacer between its hydroxy group and its core.

Scheme 4: Multi-step synthesis of hydroxy-functionalized disc 1 in which the key steps involve the selective saponification and ether synthesis towards allyl ether 9 and the amidation to afford protected disc 16.
5.4 ATRP homopolymerizations of butyl methacrylate

The main target of this research involves the synthesis of discotic-functionalized methacrylate polymers possessing appealing supramolecular properties. Prior to this, the influence of the bipyridine discotic on ATRP was investigated. These discotics may influence ATRP by complexation with the copper catalyst and by increasing the viscosity of the reaction mixture by stacking. Also, according to Scheme 4, the synthesis of functionalized discotic 1 and its derivatives involves a big effort, thus consuming these discs in optimization-studies is not attractive. Butyl methacrylate was used in the model polymerizations since it was also used to obtain the desired copolymer. Furthermore, copper(I)bromide was employed as catalyst and PMDETA (Figure 4) as ligand. The latter was chosen due to its good availability and for its more active and stable complexes with copper(I) compared to 2,2'-bipyridine.\textsuperscript{25} 2-Bromo-2-methyl propanoate derived initiators were used.

In the model polymerizations high molecular weights, low polydispersity and compatibility of bipyridine discotics with ATRP were aimed for. As discussed in section 5.2, ATRP is suitable to achieve the first two aims and its tolerance to a wide variety of functional groups is beneficial to achieve the third aim.

5.4.1 Initiators 17 and 18

Besides the commonly used ethyl initiator 17, also another initiator was used that allows \textsuperscript{1}H-NMR end-group analysis to determine the average molecular weight. This requires the presence of a resolved peak originating from the initiator. Therefore, benzylated initiator 18 was synthesized that is very similar to initiator 17 (Scheme 5) with respect to reactivity.\textsuperscript{3940}

Reaction of acid bromide 19 with benzyl alcohol afforded benzyl ester 18 after chromatographic purification. In \textsuperscript{1}H-NMR, the benzyl -CH\textsubscript{2} proton signals of 18 are present at 5.20 ppm, hence they will not overlap with peaks associated with other components in the reaction mixture.

\[\text{Scheme 5: The two bromide initiators used in the polymerizations: a) ethyl 2-bromo-2-methylpropanoate (17) and b) the preparation of benzylated initiator 18.}\]

5.4.2 Test polymerizations of butyl methacrylate

The most important conditions and results of the polymerizations, derived from \textsuperscript{1}H-NMR and GPC analyses, are summarized in Table 1. During reaction, samples were taken to determine conversion and molecular weight during the polymerization. More details about the reaction conditions are given in the experimental part. Regarding the results in Table 1, it is clear that both initiators give good conversions. Comparison of the average molecular weight calculated from NMR end-group analysis\textsuperscript{41} (29450 g/mol) and the one determined with GPC (41421 g/mol) shows a 40% higher value for GPC (Table 1, reaction 1.1). The NMR end-group analysis nicely corresponds with the expected average molecular weight after a certain conversion. The
overestimation of the molecular weight from GPC calibration might be explained by a different hydrodynamic volume of the target poly(butyl methacrylate) polymers compared to that of the poly(methyl methacrylate) standards, the latter polymer being more polar than the former.

**Table 1: Model polymerizations performed in which five variables were investigated.**

<table>
<thead>
<tr>
<th>Pol.</th>
<th>DP</th>
<th>BMA</th>
<th>Disc</th>
<th>Ligand</th>
<th>In.</th>
<th>Tol.</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>(ml)</td>
<td>(eq)</td>
<td>(ml)</td>
<td></td>
<td></td>
<td>NMR</td>
<td>GPC</td>
</tr>
<tr>
<td>1. Degree of polymerization (DP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(t/conv.)</td>
<td>(Mn/PDI)</td>
</tr>
<tr>
<td>1.1</td>
<td>200</td>
<td>2</td>
<td>1.1</td>
<td>18</td>
<td>2</td>
<td>4h/91% 38954/1.15 193/27603</td>
<td>on/97% 41421/1.22 206/29450</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>300</td>
<td>2</td>
<td>1.1</td>
<td>18</td>
<td>2</td>
<td>4h/70% 55778/1.11 213/30445</td>
<td>on/90% 70023/1.27 288/41102</td>
<td></td>
</tr>
<tr>
<td>2. Bipyridine discotic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>200</td>
<td>2</td>
<td>3.03</td>
<td>11</td>
<td>17</td>
<td>6h/87% 5862/1.05</td>
<td>on/98% 10119/1.07</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>300</td>
<td>2</td>
<td>3.03</td>
<td>11</td>
<td>18</td>
<td>6h/79% 6227/1.33 316/45081</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>300</td>
<td>2</td>
<td>3.03</td>
<td>11</td>
<td>18</td>
<td>4h/78% 14850/1.11</td>
<td>on/91% 15932/1.12</td>
<td></td>
</tr>
<tr>
<td>3. Scale of the reaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>300</td>
<td>1</td>
<td>1.1</td>
<td>17</td>
<td>1</td>
<td>4h/60% 43949/1.12</td>
<td>on/63% 42830/1.20</td>
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</tr>
<tr>
<td>3.2</td>
<td>300</td>
<td>0.5</td>
<td>1.1</td>
<td>17</td>
<td>0.5</td>
<td>6h/45% 25967/1.16</td>
<td>on/62% 39115/1.52</td>
<td></td>
</tr>
<tr>
<td>3.3</td>
<td>300</td>
<td>2</td>
<td>1.1</td>
<td>18</td>
<td>2</td>
<td>4h/70% 55778/1.11 213/30445</td>
<td>on/90% 70023/1.27 288/41102</td>
<td></td>
</tr>
<tr>
<td>4. Dilution</td>
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<td></td>
</tr>
<tr>
<td>4.1</td>
<td>200</td>
<td>2</td>
<td>1.1</td>
<td>17</td>
<td>18</td>
<td>6h/56% 24977/1.17 122/17513</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>300</td>
<td>2</td>
<td>1.1</td>
<td>18</td>
<td>15</td>
<td>6h/58% 42621/1.11 186/26608</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>200</td>
<td>2</td>
<td>1.1</td>
<td>17</td>
<td>18</td>
<td>4h/91% 38954/1.15 193/27603</td>
<td>on/97% 41421/1.22 206/29450</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>300</td>
<td>2</td>
<td>1.1</td>
<td>18</td>
<td>18</td>
<td>4h/70% 55778/1.11 213/30445</td>
<td>on/90% 70023/1.27 288/41102</td>
<td></td>
</tr>
<tr>
<td>5. Ligand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>300</td>
<td>0.5</td>
<td>1.1</td>
<td>17</td>
<td>0.5</td>
<td>6h/45% 25967/1.16</td>
<td>on/62% 39115/1.52</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>300</td>
<td>0.5</td>
<td>3.03</td>
<td>9.09</td>
<td>17</td>
<td>7h/35% 5352/1.14</td>
<td>on/38% 5456/1.13</td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>300</td>
<td>1</td>
<td>3.03</td>
<td>54.55</td>
<td>18</td>
<td>6h/75% 69558/1.13 303/43234</td>
<td>8h/79% 62281/1.24 327/46644</td>
<td></td>
</tr>
</tbody>
</table>

1 BMA = butyl methacrylate, | DP | degree of polymerization as expected from the monomer to initiator ratio, | In. = initiator used, | Conversion (conv.) based on integrals in 1H-NMR, t = reaction time, | Mn = number average molecular weight and PDI = polydispersity index as determined with GPC with THF as eluent, | E-G A = End-group analysis and r.u. = repeating units as was determined with 1H-NMR and from which an average molecular weight (Mw) was calculated. Reliable end-group analysis could be done when benzyl initiator 18 was used. | on = overnight reaction. 1H-NMR based calculations are explained in the Experimental section (Figure 9). Note that some reactions overlap. Samples were taken during reaction of which the important results are summarized.**

**Degree of polymerization. (Table 1, entry 1)** It was expected that increasing the monomer-initiator ratio would result in longer polymer chains, but also in a smaller conversion because less growing chains are present. To verify this, polymerizations were performed containing a monomer/initiator ratio of 200:1 and 300:1. Furthermore, it was observed that the viscosity of
the reaction mixture increases with reaction time. The poor mixing that accompanies the higher viscosity probably prevents further growth of the polymers. (Table 1, entry 1)\textsuperscript{42}

**Influence of discotics. (Table 1, entry 2)** C\textsubscript{3}-symmetrical bipyridine discotic 3 (Figure 5) was added to the reaction mixture to determine its influence. Apparently, discotic 3 displayed a significant effect on the molecular weight of the polymers, although conversion of the monomer was almost complete after overnight reaction. Obviously, the discotics disturb full growth of the chains. Since breakage of the polymer chains is highly unlikely, termination of growing chains and initiation of new chains by radical transfer to monomers enhanced by the discotics is a reasonable explanation of this observation. Thus the discotic might act as a chain transfer agent. Complexation of copper by the bipyridine moieties could be expected, but this is in disagreement with high conversions observed, that are similar to polymerization in the absence of discotic 3.

**Reaction volume. (Table 1, entry 3)** The scale of the reaction was examined, because sampling might influence the reaction mixture, especially in the small-scale reactions. Obviously, the conversion was lower in the case of the small-scale reactions. Although sampling might influence the progress of the reaction, mixing by stirring of the reaction mixture was not optimal for the smaller-scale reactions.

**Concentration. (Table 1, entry 4)** Related to the previous two cases, the dilution of the reaction mixture with toluene was studied. Increasing the reaction volume with solvent might enhance mixing, decrease the viscosity of the reaction mixture and prevent undesired stacking of the bipyridine discotics. According to temperature dependent \textsuperscript{1}H-NMR measurements performed on a chiral analog of discotic 3 in toluene, some degree of stacking might be present at 90 °C,\textsuperscript{43} although the influence of monomer and polymer should be taken into account. A higher viscosity is known to enhance termination reactions while the propagation rate will decrease because of lower diffusion rates of the monomer. However, dilution of the reaction mixture will decrease the propagation rate and thus the conversion too (Table 1, reactions 4.1 and 4.2).

**Ligand excess. (Table 1, entry 5)** Finally, the amount of ligand was varied.\textsuperscript{44} It was observed that the polymerization of vinyl pyridine under ATRP conditions needed an excess of ligand PMDETA to ensure a convenient reaction rate because of competitive coordination of vinyl pyridine and the PVP product with the copper catalyst.\textsuperscript{45} An excess of aliphatic amine ligand may act as a reducing agent to convert copper (II) back into copper (I) and thus influencing the reaction rate.\textsuperscript{46} Regarding the results from reactions 2.1-2.3, the presence of discotic 3 influenced the polymerization dramatically, thus in this case the amount of ligand was increased to counterbalance this undesired effect. However, in this case the reaction rate was almost not affected as was the case for PVP. Fortunately, the use of a large excess of ligand (Table 1, reaction 5.3) resulted in good conversions together with good molecular weights and PDIs. Using a moderate excess of ligand did not result in desired molecular weights (Table 1, reaction 5.2). It has to be mentioned that in the case of reaction 5.3 (Table 1), copper(I)bromide and the ligand PMDETA were premixed before adding discotic 3.
5.4.3 Overall conclusions of the homopolymerizations

To conclude, bipyridine discotics do have an effect on ATRP, but this can be counterbalanced by increasing the amount of ligand. The exact influence of the discotic remains unknown, but might be related to enhanced radical transfer from growing chains to monomers. Also, the scale of the reaction appeared to be important; a reaction volume of 1-2 ml seems to be minimal, this is probably related to mixing efficiency. Finally, the molecular weight of the polymer could be controlled by variation of the amount of initiator.

5.5 Targeting copolymer 20 carrying dangling discotics

5.5.1 Synthesis

Using the results form the previous section, random copolymer 20, grafted with discotics, was synthesized. First of all, discotic 1 was equipped with a methacrylate unit (Scheme 6). Column chromatography afforded pure disc 2 (purity was confirmed by using TLC), which was facilitated by a large difference in $R_f$ values and the disc’s intrinsic bright fluorescence when irradiated with 366 nm UV light. Analytic GPC is of less use because of the very little difference in hydrodynamic volume between discs 1 and 2. The most convenient ratio between monomer 2 and butyl methacrylate was determined, this in view of the high molecular weight of disc 2 which hampers incorporation of more than 10 mol-% discotic monomers (Table 2).

Table 2: Overview of mol and weight percentages of the monomers in the resulting copolymer provided 1, 5 or 10 mol-% methacrylate disc 2 is incorporated.

<table>
<thead>
<tr>
<th>Butyl methacrylate</th>
<th>Methacrylate disc 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>mol-%</td>
<td>weight-%</td>
</tr>
<tr>
<td>99</td>
<td>84.2</td>
</tr>
<tr>
<td>95</td>
<td>50.5</td>
</tr>
<tr>
<td>90</td>
<td>32.6</td>
</tr>
</tbody>
</table>

The resulting copolymer will contain around 200-300 repeating units, thus if 5 mol-% disc monomer 2 will be incorporated, a polymer chain will contain approximately 10-15 discotics. In this case the expected molecular weight will be between 53447 Da and 65950 Da. According to table 2, the mass of the polymer will be determined by the discotic for 50% if 5 mol-% of disc 2 will be incorporated. This monomer-ratio was chosen to ensure enough discotics in the copolymer to be present to allow stacking within single polymer chains. An excess of PMDETA and rather dilute conditions to guarantee solubility were applied, according to the results from section 5.4. To prevent a small-scale reaction, additional solvent was added to the reaction mixture. The latter, undesired conditions might be prevented by the synthesis of discotic 2 on a larger scale and thus performing its polymerization on a larger scale.
Scheme 6: Synthesis of methacrylate functionalized disc 2 and its transformation into copolymer 20. PMDETA = N,N,N',N''-pentamethyl diethylenetriamine. The disc-unit is depicted schematically. The distribution of the discotics over the polymer was believed to be random.

After running the reaction overnight, precipitation to remove excess butyl methacrylate and simple column chromatography to remove excess disc-monomer 2 yielded desired polymer 20 pure. The copolymer proved to be highly fluorescent when irradiated with UV light of 360 nm, indicating that the discotics are present as helical J-aggregates. The conversion was almost 50% after overnight reaction, and was probably hampered by the dilute conditions. Because of this, the yield of copolymer based on mass amounted to 20% only. However, the chromatographic purification allowed a large amount of unreacted disc 2 to be recovered.

5.5.2 GPC analysis of copolymer 20

During the synthesis of copolymer 20, two peaks were detected on GPC with a UV/Vis detector at 350 nm, at which wavelength only the discotic absorbs (Figure 6a). One, sharp, peak corresponds to monomer 2 and the other, broader, peak to the copolymer product. This proves that discotic 2 was incorporated in the polymer. After longer reaction time, the polymer peak was clearly shifted towards larger hydrodynamic volumes (Figure 6a, dashed line). This was also clarified by the calculated number average molecular weights (Table 3). After purification, the polymer displayed only one, broad peak (Figure 6a, gray line). Interestingly, chloroform had to be used as eluent for GPC because of severe stacking of the polymer on the column when THF was applied as eluent. This is shown in Figure 6b. After 5h of polymerization, the polymer peak as detected by GPC displayed an absorption spectrum corresponding to assembled discotics, while the absorption spectrum of the monomer peak indicates its molecularly dissolved state. This is in contrast with the higher concentration of the monomer on the GPC column (Figure 6b). Apparently, the local high concentration of the disc in copolymer 20 induces self-assembly in conditions were monomeric, unlinked discotics are normally molecularly dissolved.
A desymmetrized discotic as precursor for functionalized polymers

Figure 6: GPC and UV/Vis analysis of copolymer 22. a) GPC chromatograms of the polymerization after 5h, overnight reaction and the pure polymer. Eluent = chloroform. b) GPC chromatogram after 5h reaction, eluent = THF. Inset: Normalized UV/Vis spectra of the peaks belonging to the polymer and monomer. UV/Vis detection performed at 350 nm with a PDA detector.

Molecular weights of copolymer 20 were measured using GPC with chloroform as the eluting solvent, since the stacking of the discotics of copolymer 20 in THF prevented reliable analysis. The results are summarized in Table 3.

Table 3: Summation of the analyses of copolymer 20 during reaction and after purification.

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Pure polymer 20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NMR E-G A&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NMR GPC</td>
</tr>
<tr>
<td>5h/26%</td>
<td>17628/1.10</td>
<td>75/-</td>
</tr>
<tr>
<td>on/35%</td>
<td>50431/1.14</td>
<td></td>
</tr>
</tbody>
</table>

<sup>1</sup> Conversion based on the integral ratio between polymer and the monomers in <sup>1</sup>H-NMR.
<sup>2</sup> GPC performed with chloroform as eluent, calibration performed with PS standards.
<sup>3</sup> E-G A = End-group analysis and r.u. = repeating units as was determined with <sup>1</sup>H-NMR and from which an average molecular weight (Mw) was calculated. This Mw could only be determined for the pure polymer.
<sup>4</sup> Ratio between disc-units and butyl units as determined from integral ratios in <sup>1</sup>H-NMR, this ratio could only be determined for the pure polymer.
<sup>5</sup> on = overnight.

Although the conversion increased only by 9% during overnight reaction, the molecular weight as determined by GPC calibration increased by a factor of 2.6 while the molecular weight distribution remained similar. The values of the average amount of repeating units in polymer 20 as determined by end-group analysis in <sup>1</sup>H-NMR nicely coincides with the conversion (Table 3, samples 1 and 2). The ratio between discotics and butyl units in 20 was only determined for the pure polymer by comparing integration values in <sup>1</sup>H-NMR and according to <sup>1</sup>H-NMR analysis the ratio between discotics and butyl units in 20 is approximately 1:9, thus the discotics will amount for two-third of the total mass of the polymer (Table 2). Regarding a Mn of approximately 45 kDa for the pure polymer and Mw(disc 2) = 2643 Da, on average 11 discotics are present per polymer chain of copolymer 20.<sup>48</sup>

This number might be confirmed by using a UV/Vis absorption spectrum of 20 in combination with a concentration dependent calibration line of discotic 3 in a solvent in which both 20 and 3 are molecularly dissolved.
5.5.3 $^1$H-NMR analysis of copolymer 20

The stacking of the discotics in copolymer 20 was further studied with temperature dependent $^1$H-NMR spectroscopy. A spectrum of copolymer 20 in CDCl$_3$ gave broad peaks only, which is in contrast to non-polymerized discotics as is described in Chapter 2, section 2.4. Hence, deuterated tetrachloroethane was used as solvent which allows heating (Figure 7). Broad peaks for the aromatic and amide protons of the discotics of copolymer 20 were observed at room temperature indicating stacking. Sharpening of the peaks was indeed observed when increasing the temperature above 50 °C but at 125 °C still some line broadening was present. Interestingly, the aromatic proton signals belonging to the discotic barely undergo a downfield shift when going to the more disassembled state at higher temperature which is in contrast to the C$_3$-symmetrical discs in toluene.$^{43}$

![Figure 7: a) Temperature dependent $^1$H-NMR of copolymer 20 in C$_2$Cl$_4$D$_2$, concentration = 15 mg/ml. a = aromatic amide protons, b = bipyridine and trialkoxyphenyl aromatic protons, c = ether and ester protons, x = -CH$_2$- signals from benzyl endgroup (could only be observed in the 125 °C which was run for 45 min.), * = solvent signal (C$_2$Cl$_4$HD and C$_2$Cl$_4$H$_2$). The assignment of all peaks is given for the spectrum at 125 °C in the experimental section.](image-url)
5.6 Outlook

Although the successful incorporation of bipyridine discotics into methacrylate polymers was shown one problem still needs to be solved. This is the contrast between undesired aggregation of these discotics in concentrated conditions and the bad performance of many polymerizations in dilute conditions. Two solutions to this problem can be used: using a polymerization technique that allows dilute conditions or perform a post-functionalization on a polymer. A candidate for the first method might be metathesis polymerization from which especially ROMP (Ring Opening Metathesis Polymerization) is known for the efficient synthesis of functionalized polymers\textsuperscript{49,50} by which also well-defined polymers might be obtained.\textsuperscript{51} For example, the polymerization of Upy functionalized norbornenes was performed in dichloromethane at a concentration of 0.01 M.\textsuperscript{50} Post-functionalization of polymers will allow the synthesis of well-defined polymers equipped with small, dangling functional groups that do not interfere with the polymerization and that can be reacted with the functionalized discotic afterwards. This approach was shown for poly(acrylicacid)-b-polystyrene block-copolymers of which the carboxylic acids were decorated with oligo(ethylene oxide) tails and chelating DOTA units.\textsuperscript{52} Also poly(methacrylates) containing isocyanate functionalities were synthesized using RAFT controlled radical polymerization.\textsuperscript{53} The isocyanates were reacted with amines. An attractive approach might be the copolymerization of a methacrylate monomer possessing an acetylene with another alkyl methacrylate followed by copper catalyzed 1,3-dipolar cycloaddition\textsuperscript{54} of the acetylene groups with an azide functionalized discotic. Hydroxy discotic 1 might be converted to its azide analog in two steps via the tosylate. This type of post-functionalization was successfully shown by the functionalization of acetylene-containing poly(methacrylates) with azide-containing sugar units.\textsuperscript{55}

Finally, disc-functionalized copolymer 20 may be a good candidate for supramolecular, polymeric, fluorescent nanoparticles because of its enhanced and tunable self-assembly behavior and intrinsic fluorescence in the collapsed state. Especially, the possibility to dissolve copolymer 20 in a solvent like THF where the polymer backbone is present as a random coil and the side-group containing the discotics are stacked might be beneficial to obtain single-chain polymeric nanoparticles. Fluorescent polymeric nanoparticles have been reported for BODIPY dye functionalized polymethacrylates of narrow molecular weight distribution that were synthesized by RAFT\textsuperscript{56} radical polymerization (Figure 8).\textsuperscript{57} The dye functionalized homopolymer self-assembles into large, micrometer-sized particles due to strong π-π interactions between polymer chains. However, the living homopolymer could be extended with a polystyrene block that allows the collapse into real fluorescent nanoparticles. Probably, the PS block is present on the exterior of the particle preventing inter-polymer interactions. The aromatic stacking of the dyes is the supramolecular driving force for the collapse of the polymer into the nano-particle structure.
Figure 8: RAFT synthesis of a methacrylate homopolymer equipped with dyes that collapsed into metastable particles that will form undefined aggregates. When the homopolymer was used as a macroinitiator to connect a polystyrene block stable, fluorescent particles were obtained.\textsuperscript{57}

5.7 Conclusions

The successful synthesis of versatile hydroxy functionalized discotic 1, its polymerizable derivative 2 and the corresponding methacrylate copolymer 20 were described. Hydroxy disc 1 could be obtained –according to the procedure developed in Chapter 2– by a convenient step-wise synthesis involving a '2/3\textsuperscript{rds} disc' acid chloride. The other '1/3\textsuperscript{rd} disc' needs to incorporate the peripheral hydroxy functionality. The latter was introduced via selective ester hydrolysis and in situ 4-O-allylation on methyl 3,4,5-triacetoxybenzoate, which was subsequently converted into phenol containing bipyridine wedge 14 via straightforward syntheses in good yield and on multi-gram scale. Phenol 14 is not only relevant for the synthesis of disc 1 but may act as a precursor for almost any functionalized diamino-bipyridine wedge. After incorporation of the protected, dangling hydroxy group into wedge 14, subsequent disc synthesis and deprotection, hydroxy disc 1 could be realized. Again, this molecule may be a versatile starting point for a wide variety of functionalized discotics and this was shown by converting it into polymerizable methacrylate disc 2. Because ATRP can give access to well-defined methacrylate polymers and tolerates a wide variety of functional groups, disc 2 was polymerized using this technique. Solubility of the copolymer was guaranteed by the incorporation of butyl methacrylate as copolymer which also should prevent the formation of frustrated helices when the discotics of the copolymer would self-assemble. Optimal ATRP conditions were pursued with a series of test-polymerizations of butyl methacrylate with the main goal to test the influence of bipyridine discotics on copper catalyzed ATRP. The desired catalytic activity of the catalyst could be maintained with a large excess of ligand, while undesired stacking of discotics could be counterbalanced by working in dilute conditions. Homopolymers possessing a narrow molecular weight distribution were obtained. Although the dilute conditions decreased conversion and thus limited the yield of the discotic-functionalized copolymer, its molecular weight was still high with a polydispersity lower than 1.2 and an efficient incorporation of discotics. The copolymer
A desymmetrized discotic as precursor for functionalized polymers displays good solubility and enhanced aggregation as was deduced from UV/Vis spectra and temperature dependent $^1$H-NMR. Unfolding was achieved by heating of a solution of the copolymer in tetrachloroethane above 100 °C. Finally, this copolymer might be a useful candidate for supramolecular single-polymer nanoparticles in which the self-assembly of the discotics, triggered by external stimuli, induce the collapse of the polymer. The intrinsic fluorescence of the self-assembled discs may result in fluorescent nanoparticles and help with their detection.

5.8 Experimental Section

The reader is also referred to the experimental conditions in Chapters 2, 3 and 4. The synthesis of 2,2'-bipyridine-3,3'-diamine (13) and 2-(11-bromoundecyloxy)tetrahydropryan (7) have been described previously. Discotic 3 was kindly provided by Anja Palmans and Rafael Martín-Rapún. The synthesis of acid chloride 17 was described in Chapter 2. Allyl bromide, bromoocctane, palladium tetrakistriphenylphosphine and 2-bromo-2-methylpropionyl bromide (19) were purchased from Acros (www.acros.com), and methacryloyl chloride and sodium borohydride from Fluka (www.aldrich.com). Para-toluenesulfonic acid was obtained from Merck (www.merck.nl) while acetic anhydride was obtained from Biosolve (www.biosolve-chemicals.com). CuBr, PMDETA, ethyl 2-bromo-2-methylpropanoate and butyl methacrylate were purchased from Aldrich (www.aldrich.com). Toluene was distilled over sodium before use. Analytical GPC was performed using a Shimadzu system equipped with a Shimadzu LC-10ADvp pump, 2 × PL gel 3 μm 100 Å columns in series and a Shimadzu SPD-M10Avp PDA detection system with detection at 290 nm and 350 nm, chloroform was used as the eluent with a flow of 1 mL/min. Manual injection has been performed and the injection volume amounted to 20 μL. GPC chromatograms of the polymers were measured on a chloroform system or a THF system. Chloroform GPC system: Mixed D PL gel 5 μm column (300 × 7.5 mm) with a mass range between 200 and 400000 Da or mixed E PL gel 3 μm column (300 × 7.5 mm) with a mass range between 100 and 30000 Da. Pump: Shimadzu LC-10 AD vp, detection: UV/Vis at 254 or 310 nm using a Shimadzu SPD-10 AV vp detector. Flow: 1 mL/min, injection: 20 μL, sample concentration: 0.5 mg/mL in chloroform; measuring time: 15 minutes. THF GPC system: Mixed C PL gel 5 μm column (300 × 7.5 mm) with a mass range between 200 and 200000 Da and a mixed D PL gel 5 μm column (300 × 7.5 mm) with a mass range between 200 and 400000 Da in series. Pump: Shimadzu LC-10 AD vp. Detection: UV/Vis at 254 or 310 nm using a Shimadzu SPD-M10A vp photo diode array detector. Flow: 1 mL/min, injection: 20 μL, sample concentration: 1 mg/mL in THF; measuring time: 30 minutes. Determination of the number average molecular weight (Mn) and polydispersity index (PDI = Mw/Mn) was performed with polystyrene standards for the chloroform column or PMMA standards for the THF column. End-group analysis was performed with $^1$H-NMR when benzyl initiator 18 was used. The integrals of the peaks originated from the benzyl -CH$_2$-, the -CH$_2$- directly next to the ester functionality of the polymer and the monomer and the ether -CH$_2$- of the discotic were used. The conversion of a polymerization was also determined by $^1$H-NMR where the peaks originated form the double bond of the monomers and the peaks from the -CH$_2$- directly next to the ester functionality of the polymer and the monomer were used.
5.8.1 Syntheses of discotic 1, 2 and their precursors

**Methyl 3,4,5-triacetoxybenzoate (8)**

Triethylamine (154 ml, 1.11 mol) was added dropwise under an argon atmosphere to an ice-cooled solution of methyl gallate (49.65 g, 270 mmol) in acetic anhydride (104 ml, 1.11 mol). After stirring for 1 h at 0°C, the excess acetic anhydride was neutralized by dropwise addition of ethanol (17.5 ml, 300 mmol). Then, the mixture was poured into 0.1 M HCl (50 ml) and subsequently ice-water (500 ml) was added. The aqueous mixture was extracted with ethyl acetate (300 ml), brine was added to the aqueous layer and it was again extracted with ethyl acetate (1 × 300 ml, 2 × 200 ml). The organic layers were combined and washed with brine (500 ml), dried with MgSO$_4$, filtered over a glass filter and concentrated in vacuo. Recrystallization of the residue from hot ethanol gave compound 8 (79.9, 96%) as white crystals.

R$_t$ = 0.31 (silica gel, 50 vol% ethyl acetate in heptane); GC-MS: R$_s$ = 7.24 min (one peak), m/z: calcd for: 310.26; found: 310 (radical cation); $^1$H-NMR (400 MHz, acetone-D$_6$): $\delta$ = 7.78 (s, 2H, 2), 3.90 (s, 3H, OCH$_3$), 2.33 (s, 3H, 7), 2.31 ppm (s, 6H, 9). $^{13}$C-NMR (100 MHz, acetone-D$_6$, APT): 167.6 (5/6), 166.5 (8), 164.5 (5/6), 144.8 (3), 139.1 (4), 128.9 (1), 122.7 (2), 52.9 (OCH$_3$), 20.5 (9), 20.0 (7) ppm; FT-IR (ATR): ν (cm$^{-1}$) = 3372, 3079, 3012, 2956, 2853, 1774 (C=O), 1721 (C=O), 1613, 1600, 1514, 1497, 1436, 1371, 1312, 1277, 1201, 1094, 1052, 1041, 1016, 928, 902, 857, 768, 749, 740; Elemental analysis: calculated: C 54.20, H 4.55; found: C 54.20, H 4.47.

**Methyl 4-allyloxy-3,5-diacetoxybenzoate (9)**

Under argon, tetraester 8 (18.64 g, 60 mmol) and anhydrous, powdered K$_2$CO$_3$ (24.39 g, 180 mmol) were mixed in dry DMF (50 ml) by stirring. After addition of allyl bromide (10.5 ml, 120 mmol) the reaction mixture was stirred for 23h at 35°C. More allyl bromide (3.5 ml, 40 mmol) was added and the reaction mixture was stirred for another 23h at 35°C. Diethyl ether (500 ml) was added affording a white suspension that was filtered over a paper filter and the resulting residue (inorganic salts) was washed with diethyl ether (2 × 125 ml). Then, the mixture was poured into 0.1 M HCl (50 ml) and subsequently ice-water (500 ml) was added. The aqueous mixture was extracted with ethyl acetate (300 ml), brine was added to the aqueous layer and it was again extracted with ethyl acetate (1 × 300 ml, 2 × 200 ml). The organic layers were combined and washed with brine (500 ml), dried with MgSO$_4$, filtered over a glass filter and concentrated in vacuo. Recrystallization of the residue from hot ethanol gave compound 9 (11.13 g, 36 mmol) as white crystals (13.64 g, 0.054 mol, 74%). $^1$H-NMR indicated the presence of app. 4 mol-% diallylated side-product. The crude product was used as such. R$_t$ = 0.45 (silica gel, 20 vol% ethyl acetate in heptane); GC-MS: R$_s$ = 7.27 min (one peak), m/z: calcd for: 310.26; found: 310 (radical cation); $^1$H-NMR (400 MHz, acetone-D$_6$): $\delta$ = 7.68 (s, 2H, 2), 5.97 (ddd, 1H, J(H,H) = 10.2 Hz, 8c), 3.89 (s, 3H, OCH$_3$), 2.32 ppm (s, 6H, 10); $^{13}$C-NMR (100 MHz, acetone-D$_6$, APT): $\delta$ = 168.4 (9), 165.2 (5), 147.2 (4), 144.1 (3), 133.0 (7), 125.5 (1), 122.6 (2), 118.0 (8), 74.5 (6), 52.4 (OCH$_3$), 20.7 ppm (10); FT-IR (ATR): ν (cm$^{-1}$) = 3442, 3080, 2955, 1772 (C=O), 1722 (C=O), 1648, 1615, 1581, 1497, 1436, 1426, 1370, 1323, 1211, 1184, 1093, 1046, 1016, 979, 927, 904, 863, 816, 768, 700, 674.

**Methyl 4-allyloxy-3,5-dihydroxybenzoate (10)**

Under argon, anhydrous, powdered K$_2$CO$_3$ (29.85 g, 216 mmol) was added to a well-stirred solution of allyl ether 9 (11.13 g, 36 mmol) in methanol (150 ml) and water (42 ml) at room temperature. During reaction the solution changed from colorless to red. After stirring for 1 h the solution was acidified to pH 3 by dropwise addition of 3 M HCl (± 125 ml). The resulting yellow solution was extracted with ethyl acetate (2 × 110 ml). The combined organic layers were washed with brine (2 × 100 ml), dried with...
MgSO₄ filtered over a glass filter and concentrated in vacuo. Crystallization of the residue from hot 20 vol% ethyl acetate in heptane yielded pure dihydroxy 10 (6.53 g, 29 mmol, 81%) as orange crystals. 

Rf = 0.33 (silica gel, 50 vol% ethyl acetate in heptane); ¹H-NMR (400 MHz, acetone-D₆): δ = 8.31 (s, 2H, 9), 7.09 (s, 2H, 2), 6.11 (dd, 1H, ³J(H,H) = 6.1, 10.5 and 17.0 Hz, 7), 5.30 (d, 1H, ³J(H,H) = 17.2 Hz, 8t), 5.16 (d, 1H, ³J(H,H) = 10.4 Hz, 8c), 4.66 (d, 2H, ³J(H,H) = 6.1 Hz, 6), 3.81 ppm (s, 3H, OCH₃). ¹⁳C-NMR (100 MHz, acetone-D₆, APT): δ = 166.9 (5), 151.4 (3), 138.7 (4), 135.3 (7), 126.4 (1), 118.4 (8), 109.8 (2), 73.9 (6), 52.1 (OCH₃) ppm; FT-IR (ATR): ν (cm⁻¹) = 3385, 3083, 2954, 2698, 1697 (C=O), 1648, 1596, 1522, 1438, 1348, 1242, 1176, 1096, 1053, 1002, 978, 938, 872, 814, 771, 761, 739, 720; Elemental analysis: calculated: C₁₁H₁₈O₃ (224.21): C 58.93, H 5.39; found: C 59.09, H 5.40.

Methyl 4-allyloxy-3,5-dioctyloxybenzoate (6)

Under argon, dihydroxy compound 10 (4.50 g, 20 mmol) and anhydrous, powdered KHCO₃ (10.55 g, 76 mmol) were suspended in DMF (100 ml) and heated to 70 °C until complete dissolution. Subsequently, 1-bromooctane (8.0 ml, 46 mmol) was added and the solution was stirred for 1.5 h at 70 °C. After cooling to room temperature, ice-water (225 ml) and subsequently 3 M HCl (± 25 ml to reach pH 3) were added to the reaction mixture. Then, the aqueous mixture was extracted with diethyl ether (3 × 200 ml) and the combined organic layers were washed with a saturated KCl solution (250 ml), dried with Na₂SO₄ and filtered over a glass filter. Purification of the resulting oil by column chromatography (silica gel, 25 vol% heptane in CHCl₃ yielded ether 6 as a colorless oil (8.24 g; 92%).

Rf = 0.35 (silica gel, 25 vol% heptane in CHCl₃); GC-MS: Rf = 9.14 min (one peak), m/z: calcld for: 448.32; found: 448 (radical cation); ¹H-NMR (400 MHz, acetone-D₆): δ = 7.27 (s, 2H, 2), 6.08 (dd, ³J(H,H) = 5.4, 10.8 and 16.9 Hz, 1H, 7), 5.37 (d, 1H, ³J(H,H) = 17.0 Hz, 8t), 5.16 (d, 1H, ³J(H,H) = 10.3 Hz, 8c), 4.57 (d, ³J(H,H) = 5.3 Hz, 2H, 6), 4.05 (t, 4H, ³J(H,H) = 6.2 Hz, 9), 3.85 ppm (s, 3H, OCH₃). FT-IR (ATR): ν (cm⁻¹) = 3385, 3083, 2954, 2698, 1697 (C=O), 1648, 1596, 1522, 1438, 1348, 1242, 1176, 1096, 1053, 1002, 978, 938, 872, 814, 771, 761, 739, 720; Elemental analysis: calculated: C₁₁H₁₈O₃ (224.21): C 72.28, H 9.89; found: C 72.51, H 9.87.

4-Allyloxy-3,5-dioctyloxybenzoic acid (11)

Methyl ester 6 (8.05 g, 17.9 mmol) was dissolved in ethanol (163 ml) and then a solution of LiOH (1.6 g, 38 mmol) in water (16 ml) was added. Under argon, the mixture was stirred under reflux for 1.5 h. After cooling to room temperature, the solution was acidified with 3 M HCl to pH 1. Then, ethanol was evaporated in vacuo and water was added (60 ml) after which the mixture was extracted with dichloromethane (2 × 200 ml). The organic layers were combined and washed with brine (100 ml), dried with MgSO₄ and filtered over a glass filter and concentrated in vacuo. Crystallization of the residue from a hot mixture of 40 vol% water in acetone yielded benzoic acid 11 (7.28 g; 93%) as a fluffy white solid.

Rf = 0.36 (silica gel, 50 vol% ethyl acetate in heptane); ¹H-NMR (400 MHz, acetone-D₆): δ = 7.30 (s, 2H, 2), 6.09 (dd, 1H, ³J(H,H) = 5.1 Hz, 9.8 Hz and 17.2 Hz, 7), 5.37 (d, 1H, ³J(H,H) = 17.2 Hz, 8t), 5.16 (d, 1H, ³J(H,H) = 9.8 Hz, 8c), 4.57 (d, 2H, ³J(H,H) = 5.1 Hz, 6), 4.07 (t, 4H, ³J(H,H) = 6.3 Hz, 9), 1.82 ppm (t, 6H, ³J(H,H) = 6.8 Hz, 10), 1.54 ppm (qu, 4H, ³J(H,H) = 7.2 Hz, 11), 1.34 (16H, 12+13+14), 0.88 ppm (t, 6H, ³J(H,H) = 6.0 Hz, 15); ¹⁳C-NMR (100 MHz, CDCl₃, APT): δ = 170.5 (5), 152.8 (3), 142.4 (4), 134.3 (7), 123.7 (1), 117.6 (8), 108.4 (2), 74.0
4-Allyloxy-3,5-diocyloxybenzoyl chloride (12)
Under argon, oxalyl chloride (1.3 ml, 15.1 mmol) and two drops of DMF were added to a solution of benzoic acid 13 (5.03 g, 11.6 mmol) in distilled dichloromethane (115 ml) at room temperature. The reaction mixture was protected from light and stirred for 2 h under argon. After removal of the solvent in vacuo and volatiles with high vacuum, acid chloride 12 (5.21 g) was obtained as a clear oil and was used as such. FT-IR (ATR): v (cm⁻¹) = 3750, 3081, 2920, 2853, 2642, 2584, 1686 (C=O), 1587, 1504, 1467, 1428, 1386, 1327, 1273, 1227, 1114, 983, 921, 863, 817, 767, 726, 680, 664; MALDI-TOF MS: m/z: calcd for: 434.30; found: 434.33 (M+H⁺), 457.33 (M+Na⁺), 485.41 (M+K⁺); Elemental analysis: calculated: C₂₆H₂₆ClO₅ (434.61): C 71.85, H 9.74; found: C 72.42, H 9.81.

3′-(4-Allyloxy-3,5-dicycloxybenzoylamino)-2,2′-bipyridine-3-amine (13)
Under argon, a solution of acid chloride 12 (5.21 g, 11.6 mmol) in distilled dichloromethane (115 ml) was added dropwise to an ice-cold well-stirred solution of 3,3′-diamino-2,2′-bipyridine (5) (2.41 g, 12.9 mmol) and triethylamine (2 ml, 14.3 mmol) in distilled dichloromethane (115 ml). The yellow reaction mixture was allowed to reach room temperature and stirred overnight under argon. Then, the solvent was removed in vacuo giving a brown residue that was dissolved in hot methanol (50 ml). Cooling of the resulting solution to 0 °C afforded a yellow suspension. After 1.5 h, more methanol (35 ml) was added and the suspension was filtered over a Büchner funnel and the resulting residue was washed with methanol (20 ml). Then, the crude product was purified by flash column chromatography (silica, gradient 5-50 vol% ethyl acetate in heptane) affording monoamine 15 (5.62 g; 80%) as a yellow solid. Rf = 0.26 (silica gel, 25 vol% ethyl acetate in heptane); ¹H-NMR (400 MHz, CDCl₃): δ = 14.25 (s, 1H, 7′), 9.23 (dd, 1H, ³J(H,H) = 8.3 Hz and ³J(H,H) = 1.6 Hz, 4′), 8.34 (dd, 1H, ³J(H,H) = 4.7 Hz and ³J(H,H) = 1.5 Hz, 6′), 8.00 (dd, 1H, ³J(H,H) = 3.8 Hz and ³J(H,H) = 1.9 Hz, 6), 7.32 (dd, 1H, ³J(H,H) = 4.7 Hz and 8.3 Hz, 5′), 7.27 (s, 2H, 10′), 7.13 (2H, 4 + 5), 6.55 (s, 2H, 7), 6.11 (ddd, 1H, ³J(H,H) = 5.5 Hz, 10.2 Hz and 17.1 Hz, 15′), 5.36 (d, 1H, ³J(H,H) = 17.5 Hz, 18′), 5.20 (d, 1H, ³J(H,H) = 11.0 Hz, 18′), 4.60 (d, 2H, ³J(H,H) = 5.9 Hz, 13′), 4.08 (t, 4H, ³J(H,H) = 6.7 Hz, 14′), 1.85 (qu, 4H, ³J(H,H) = 6.7 Hz, 16′), 1.50 (qu, 4H, ³J(H,H) = 7.2 Hz, 17′), 1.26-1.35 (16H, 19′+ 20′+21′), 0.88 ppm (t, 6H, ³J(H,H) = 6.9 Hz, 22′); ¹³C-NMR (100 MHz, CDCl₃, APT): δ = 166.2 (7′), 153.1 (11′), 145.1 (3′), 143.6 (2′), 140.9 (12), 140.8 (6′), 138.8 (2), 136.2 (3′), 134.9 (6), 134.5 (15′), 130.9 (9′), 128.7 (4′), 125.2 (4), 124.1 (5), 122.8 (5′), 117.5 (18′), 106.4 (10′), 74.1 (13′), 69.5 (14′), 31.8 (20′), 29.4+29.3+29.3 (16′+19′), 26.1 (17′), 22.7 (21′), 14.1 ppm (22′); FT-IR (ATR): v (cm⁻¹) = 3422, 3273, 2952, 2855, 1739 (C=O), 1663 (C=O, amide I), 1573 (N-H, amide II), 1520, 1493, 1469, 1453, 1426, 1396, 1330, 1309, 1295, 1262, 1206, 1151, 1114, 1067, 1029, 987, 925, 879, 861, 795, 748, 732, 703, 674; MALDI-TOF MS: m/z: calcd for: 602.38; found: 603.45 (M+H⁺), 625.43 (M+Na⁺); Elemental analysis: calculated (%) for C₂₆H₂₆N₃O₅ (602.81): C 71.93, H 8.36, N 9.29; found: C 71.97, H 8.45, N 9.24.
3′-(4-Hydroxy-3,5-dioctyloxybenzoylamin o)-2,2′-bipyridine-3-amine (14)

A solution of allyl ether 13 (4.50 g, 7.46 mmol) in distilled THF (25 ml) was purged with argon for 30 minutes under continuous stirring after which Pd(PPh₃)₄ (86 mg, 74.6 µmol) and NaBH₄ (634 mg, 16.8 mmol) were added. During reaction, the suspension changed color from orange-red to dark brown. After stirring overnight under argon, methanol (27 ml) was added, and subsequently 1 M HCl (27 ml) was added dropwise to neutralize residual NaBH₄. Finally, water was added to afford a grey precipitate. Filtration over a Büchner funnel gave a grey residue that was suspended in a hot mixture of methanol (50 ml), triethylamine (3 ml) and acetone (7 ml). Subsequently, insoluble impurities were removed by hot filtration over a paper filter. Upon cooling of the filtrate, a grey precipitate formed. Filtration over a Büchner funnel gave phenol 14 (3.47 g; 83 %) as a grey solid.

$R_t = 0.20$ (silica gel, 25 vol% ethyl acetate in heptane); $^1$H-NMR (400 MHz, CDCl₃): $\delta = 14.20$ (s, 1H, 7'), 9.23 (dd, 1H, $^3$(H,H) = 8.5 Hz, $^4$(H,H) = 1.4 Hz, 4'), 8.33 (dd, 1H, $^3$(H,H) = 4.6 Hz and $^4$(H,H) = 1.5 Hz, 6'), 8.01 (dd, 1H, $^3$(H,H) = 3.9 Hz and $^4$(H,H) = 2.0 Hz, 6), 7.32 (dd, 1H, $^3$(H,H) = 4.0 Hz and $^4$(H,H) = 8.0 Hz, 5'), 7.26 (s, 2H, 10'), 7.13 (m, 2H, 4+5), 6.55 (s, 2H, 7), 5.83 (s, 1H, 13'), 4.15 (t, 2H, $^3$(H,H) = 6.8 Hz, 14'), 1.87 (qu, 4H, $^3$(H,H) = 6.9 Hz, 15'), 1.48 (qu, $^3$(H,H) = 7.2 Hz, 4H, 16'), 1.29-1.39 (16H, 17'+18'+19'), 0.88 ppm (t, 6H, $^3$(H,H) = 6.8 Hz, 20'); $^{13}$C-NMR (100 MHz, CDCl₃, APT): $\delta = 166.2$ (8'), 146.4 (11'), 145.1 (3), 143.6 (2'), 140.7 (6'), 138.9+138.8 (2+12'), 136.3 (3'), 134.8 (6), 128.7 (4'), 126.7 (9'), 125.2 (4), 124.0 (5), 122.8 (5'), 106.1 (10'), 69.8 (14'), 31.8 (18'), 29.3+29.3+29.2 (15'+17'), 26.0 (16), 22.7 (19'), 14.1 ppm (20'); FT-IR (ATR): v (cm⁻¹) = 3526, 3429, 3276, 2924, 2854, 2716, 1739, 1642, 1601, 1573, 1527, 1499, 1469, 1454, 1432, 1394, 1328, 1309, 1205, 1153, 1102, 1067, 1030, 946, 879, 799, 748, 732, 702, 671, 664; MALDI-TOF MS: m/z: calcd for: 562.35; found: 562.35 (M+H⁺);

Elemental analysis: calculated: C₃₂H₂₆N₂O₂ (562.74): C 70.43, H 8.24, N 9.96; found: C 70.66, H 8.32, N 9.84.

3′-[3,5-Dioc tlyoxy-4-[11-(2-pyran ylox y)undecyloxybenzoylamin o]-2,2′-bipyridine-3-amine (14)

A solution of phenol 14 (1.00 g, 1.78 mmol) in DMF (25 ml) was purged with argon for 30 min under continuous stirring, followed by addition of anhydrous, powdered K₂CO₃ (0.50 g, 3.55 mmol). The temperature was raised to 85 °C, during which the suspension’s color changed from brown to red. Then, bromide 7 (0.718 g, 2.14 mmol) was added with a syringe. After 5.5 h, the reaction mixture was poured into ice-water (100 ml) and the resulting aqueous mixture was extracted with dichloromethane (3 x 30 ml). The organic layers were combined and washed with saturated KCl solution (40 ml) and brine (30 ml), dried with MgSO₄, filtered over a glass filter and concentrated in vacuo. The remaining brown oil was dissolved into hot mixture of methanol (20 ml) and water (2 ml). Upon cooling, the solution separated into a brownish oil and a white emulsion. Centrifugation (3500 rpm, 12 min) gave a brown oil and a colorless supernatant. The latter was removed and the brown oil was mixed with methanol (20 ml) and water (2 ml) and the centrifugation process was repeated another three times. The brownish oils were combined and concentrated in vacuo, giving amine 4 (1.22 g; 84%) as a brownish waxy substance.

$R_t = 0.21$ (silica gel, 25 vol% ethyl acetate in heptane); $^1$H-NMR (400 MHz, CDCl₃): $\delta = 14.25$ (s, 1H, 7'), 9.24 (dd, 1H, $^3$(H,H) = 8.5 Hz and $^4$(H,H) = 1.7 Hz, 4'), 8.38 (dd, 1H, $^3$(H,H) = 4.5 Hz and $^4$(H,H) = 1.5 Hz, 6'),
8.01 (dd, 1H, 3\(^{(1)}\)(H,H) = 3.7 Hz and 3\(^{(1)}\)(H,H) = 2.1 Hz, 6), 7.20 (dd, 1H, 3\(^{(1)}\)(H,H) = 4.5 Hz and 8.5 Hz, 5'), 7.27 (s, 2H, 10'), 7.13 (2H, 4+5), 6.55 (s, 2H, 7), 4.58 (s, 1H, 23'), 4.06 (6H, 13'+14'), 3.87 (m, 1H, 24'a), 3.73 (m, 1H, 22'), 3.50 (m, 1H, 24'a), 3.38 (m, 1H, 22'), 1.88-1.29 (48H, 15'+16'+17'+18'+19'+21'+25'), 0.88 ppm (t, 3\(^{(1)}\)(H,H) = 6.8 Hz, 6H, 20'); \(^{13}\)C-NMR (100 MHz, CDCl\(_3\), APT): δ = 166.2 (8'), 153.1 (11'), 145.1 (3), 143.6 (2'), 141.6 (12'), 140.8 (6'), 138.8 (2), 136.2 (3'), 134.9 (6), 130.6 (9'), 128.7 (4'), 125.2 (4), 124.1 (5), 122.8 (5), 110.6 (10'), 98.8 (23'), 73.6 (13'), 69.5 (14'), 67.7+62.3 (22'+24'), 31.8+30.8+30.4+29.8+29.3+26.3+26.1+25.5+22.7+19.7 (15'+16'+17'+18'+19'+21'+25'), 14.1 ppm (20'); FT-IR (ATR): ν (cm\(^{-1}\)) = 3417, 3264, 2925, 2854, 1667 (C=O), 1574, 1521, 1495, 1468, 1454, 1427, 1398, 1331, 1309, 1295, 1261, 1207, 1115, 1078, 1067, 1073, 990, 905, 869, 797, 749, 733, 703, 664; MALDI-TOF MS: m/z: calc'd for: 816.58; found: 816.65 (M\(^{+}\)); Elemental analysis: calc'd (%) for C\(_{64}H_{128}N\(_2\)O\(_5\): 817.15; C: 72.02, H 9.37, N 6.86; found: C: 72.07, H 9.42, N 6.68.

N-[3\(^{(1)}\)-(3,5-Dioctyloxy-4-[11-(2-pyrranyloxyundecylbenzoylamino)-2,2’-bipyridyl)-N’N’’-bis[3\(^{(1)}\)-(3,4,5-tridecylbenzoylamino)-2,2’-bipyridyl]benzene-1,3,5-tricarboxamide (16)

Under argon, a solution of amine 4 (0.354 g, 0.435 mmol) and TEA (0.08 ml, 0.71 mmol) in distilled CH\(_2\)Cl\(_2\) (1.8 ml) was added dropwise to a well-stirred and ice-cooled solution of acid chloride 15 (0.714 g, 0.38 mmol) in distilled dichloromethane (2 ml). The reaction mixture was allowed to reach room temperature and after 1.5 h acetone (11 ml) was added resulting in a grey suspension. The suspension was stirred for 5 min, filtered over a Büchner funnel, after which the residue was washed with acetone (25 ml) and dried overnight. Purification of the residue by flash column chromatography (silica, gradient 0-3.5 vol% ethyl acetate in chloroform) afforded protected dicotocic 16 (735 mg, 73%) as a beige sticky solid.

R \(_g\) = 0.44 (silica gel, 5 vol% ethyl acetate in chloroform); \(^{1}H\)-NMR (400 MHz, CDCl\(_3\)): δ = 15.48 (s, 3H, 7), 14.36 (s, 3H, 7'), 9.56 (d, 3H, 3\(^{(1)}\)(H,H) = 8.5 Hz, 4), 9.38 (d, 3H, 3\(^{(1)}\)(H,H) = 8.5 Hz, 4'), 9.17 (s, 3H, 10), 9.03 (d, 3H, 3\(^{(1)}\)(H,H) = 4.4 Hz, 6'), 8.39 (d, 3H, 3\(^{(1)}\)(H,H) = 4.2 Hz, 6), 7.51 (dd, 3H, 3\(^{(1)}\)(H,H) = 4.5 Hz and 8.5 Hz, 5'), 7.46 (dd, 3H, 3\(^{(1)}\)(H,H) = 4.5 Hz and 8.5 Hz, 5), 7.26 (s, 6H + CHCl\(_3\), 10'), 4.58 (s, 1H, 23'), 4.14-4.03 (18H, 13'+14'), 3.88 (m, 1H, 24'e), 3.74 (m, 1H, 22'), 3.50 (m, 1H, 24'a), 3.39 (m, 1H, 22'), 1.90-1.24 (17H, 15'+16'+17'+18'+19'+21'+25'), 0.88 ppm (24H, 20'); \(^{13}\)C-NMR (100 MHz, CDCl\(_3\), APT): δ = 166.0, 163.6, 153.2, 142.0, 142.0, 141.3, 141.1, 140.0, 137.6, 137.6, 135.5, 130.1, 129.6, 129.5, 129.3, 124.5, 123.9, 106.7, 98.9, 73.6, 69.7, 67.7, 62.3, 32.0, 32.0, 31.9, 30.8, 30.5, 29.8, 29.8, 29.7, 29.7, 29.6, 29.6, 29.5, 29.5, 29.4, 29.4, 26.3, 26.2, 26.2, 25.5, 22.7, 22.7, 19.7, 14.1 ppm; FT-IR (ATR): ν (cm\(^{-1}\)) = 3422, 2253, 1669 (C=O), 1568, 1515, 1494, 1467, 1445, 1427, 1369, 1330, 1296, 1240, 1202, 1118, 1074, 1031, 998, 946, 914, 864, 799, 754, 744, 729, 716; MALDI-TOF MS: m/z: calc'd for: 2658.89; found: 2576.80 (M-THP+2), 2681.83 (M+Na\(^{+}\)), 2697.80 (M+K\(^{+}\)), 2722.73 (M+Cu\(^{+}\)+1); Elemental analysis: calc'd (%) for C\(_{64}H_{128}N\(_2\)O\(_5\): 2659.79; C: 74.06, H 9.40, N 6.32; found: C: 74.33, H 9.26, N 6.25.
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N-(3′-[3,5-Diacyloxy-4-(11-hydroxyundecyloxy)benzoylamino]-2,2′-bipyridyl)-N′,N″-bis[3′- (3,4,5-tridodecyloxybenzoylamino)-2,2′-bipyridyl]benzene-1,3,5-tricarboxamide (1)

Para-toluensulfonic acid monohydrate (33.4 mg, 0.175 mmol) was added to a well-stirred solution of THP protected discotic 16 (500 mg, 0.188 mmol) in dichloromethane (7 ml). Then, methanol (1.4 ml, 34.5 mmol) was added dropwise to prevent precipitation of the discotics. During the reaction methanol (0.85 ml, 20.9 mmol) and dichloromethane (0.5 ml) were added portionwise over 7 h in order to keep the mixture dissolved. After stirring overnight, acetone (50 ml) and TEA (1 ml) were added giving rise to a suspension. The latter was filtered over a Büchner funnel, and the residue washed with acetone (2 × 25 ml) and dried in vacuo at 60 °C. Purification by flash column chromatography (silica, gradient 0-5 vol% ethyl acetate in chloroform), gave deprotected discotic 1 (467 mg, 96%) as a white sticky solid.

Rf = 0.16 (silica gel, 5 vol% ethyl acetate in chloroform); 1H-NMR (400 MHz, CDCl3): δ = 15.50 (s, 3H, 7), 14.36 (s, 3H, 7′), 9.57 (d, 3H, 3J(H,H) = 8.3 Hz, 4), 9.39 (d, 3H, 3J(H,H) = 8.5 Hz, 4′), 9.21 (s, 3H, 10), 9.04 (dd, 3H, 3J(H,H) = 4.5 Hz and 3J(H,H) = 1.3 Hz, 6′), 8.41 (dd, 3H, 3J(H,H) = 4.5 Hz and 3J(H,H) = 1.3 Hz, 6), 7.53 (dd, 3H, 3J(H,H) = 4.7 Hz and 8.6 Hz, 5′), 7.49 (dd, 3H, 3J(H,H) = 4.7 Hz and 8.4 Hz, 5), 7.27 (s, 6H + CHCl3, 10′), 4.10-4.04 (18H, 13′+14′), 3.65 (t, 2H, 3J(H,H) = 6.5 Hz, 23′), 1.90-1.75 (18H, 15′), 1.60-1.48 (20H, 16′+22′), 1.37-1.27 (126H, 17′+18′+19′+21′), 0.90-0.86 ppm (24H, 20′); 13C-NMR (100 MHz, CDCl3, APT): δ = 166.0 (8′), 163.6 (8′), 153.2 (14′), 142.0+141.9 (2+2′), 141.3 (6′), 141.0 (12′), 140.0 (6), 137.6+137.5 (3+3′), 135.5 (9), 130.1 (9′), 129.5+129.4+129.2 (4+4′+10), 124.5 (5), 123.8 (5), 106.7 (10′), 73.5 (13′), 69.7 (14′), 63.1 (23′), 32.9 (22′), 32.0+31.9 (18′), 30.5+29.8+29.8+29.7+29.7+29.7+29.6+29.5+29.5+29.5+29.4+29.4 (15′+17′), 26.2+26.2 +26.2 (16′), 25.8 (21′), 22.7 (19′), 14.1 ppm (20′); FT-IR (ATR): ν (cm⁻¹) = 3503 (OH), 2921, 2853, 1670 (C=O amide), 1567, 1515, 1493, 1467, 1445, 1428, 1369, 1330, 1296, 1240, 1202, 1118, 1074, 1030, 1001, 946, 914, 863, 799, 744, 729, 716; MALDI-TOF MS: m/z: calc for: 2574.84; found: 2598.68 (M+Na⁺+1), 2613.69 (M+K⁺), 2638.60 (M+Cu⁺+1); Elemental analysis: calc (%) for C₁₄₉H₂₄₈N₁₂O₁₆ (2575.74): C 74.14, H 9.39, N 6.53; found: C 74.41, H 9.45, N 6.44.

N-[3′-[3,5-Diacyloxy-4-[11-(methacryloyloxy)undecyloxy]benzoylamino]-2,2′-bipyridyl]-N′,N″-bis[3′- (3,4,5-tridodecyloxybenzoylamino)-2,2′-bipyridyl]benzene-1,3,5-tricarboxamide (2)

Under argon, methacryloyl chloride (0.02 ml, 0.12 mmol) dissolved in distilled dichloromethane (0.5 ml) was added dropwise to an ice-cold well-stirred solution of hydroxy disc 1 (0.191 g, 0.074 mmol) and triethylene (0.013 ml, 0.094 mmol) in distilled dichloromethane (2.5 ml). The temperature of the reaction mixture was kept below 5 °C. After 1.5 h, an additional amount of methacryloyl chloride (0.01 ml, 0.06 mmol) and triethylene (0.01 ml, 0.072 mmol) dissolved in distilled dichloromethane (0.5 ml) were added to the well-stirred reaction mixture. Then, the reaction mixture was stirred under argon for 0.5 h after which TLC indicated complete conversion of the alcohol disc. The reaction mixture was
precipitated into acetone (65 ml) to give a suspension that was filtered over a Büchner funnel. The residue was washed with acetone (2 × 20 ml) and purified by flash column chromatography (silica gel, 0-5 vol% ethyl acetate in chloroform) to afford methacrylate disc 2 (0.117 g, 60%) as a white sticky solid. \( R_f = 0.60 \) (silica gel, 5 vol% ethyl acetate in chloroform);

\[ ^1H-NMR \ (400 \text{ MHz, CDCl}_3) : \delta = 15.52 \ (s, 3H, 7'), 14.37 \ (s, 3H, 7'), 9.60 \ (d, 3H, 3'); 1.95 \ (s, 3H, 27'), 1.87 \ (qu, 12H, 145) \]

Benzyl 2-bromo-2-methylpropanoate 18

Under argon, first a solution of acid bromide 19 (6.8 ml, 55.0 mmol) in distilled dichloromethane (50 ml) and then an additional amount of dichloromethane (5 ml) were added dropwise to a well-stirred, ice-cold mixture of benzyl alcohol (4.8 ml, 46.3 mmol) and triethylamine (7.7 ml, 55.0 mmol). The temperature of the reaction mixture was kept below 5 °C. After complete addition, the reaction mixture was allowed to reach room temperature and stirred overnight under argon. Then, diethyl ether (100 ml) was added to the reaction mixture giving rise to a white suspension that was filtered over a glass filter after which the residue was washed with diethyl ether (20 ml). The filtrate was washed with 1 M HCl solution (2 × 50 ml), 0.1 M HCl solution (3 × 50 ml), brine (50 ml), a mixture of brine and water (10 ml brine, 40 ml water) and water (50 ml). The organic layer was then dried with MgSO₄ filtered over a glass filter and concentrated in vacuo. The residue was purified by flash column chromatography (silica gel, gradient 10-33 vol% ethyl acetate in heptane) to afford ester 18 as a colorless oil (10.94 g, 92 %). Ester 18 needed to be stored in a dark and cool place. \( R_f = 0.44 \) (silica gel, 33 vol% ethyl acetate in heptane); GC-MS: \( R_f = 5.38 \) min (99.5% pure), \( m/z \) calc'd for: 258.01; found: 258 (radical cation); \[ ^1H-NMR \ (400 \text{ MHz, CDCl}_3) : \delta = 7.37-7.30 \ (5H, 2+3+4), 5.20 \ (s, 2H, 5), 1.94 \text{ ppm (s, 6H, 8)}; ^{13}C-NMR \ (100 \text{ MHz, CDCl}_3, \text{ APT}) : \delta = 171.5 \ (6),

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135.5 (1), 128.6+128.4+127.9 (2+3+4), 67.6 (5), 55.8 (7), 30.8 ppm (8); FT-IR (ATR): ν (cm⁻¹) = 3067, 3035, 3006, 2977, 2933, 1732 (C=O), 1609, 1587, 1498, 1456, 1389, 1372, 1270, 1212, 1151 (C-O), 1106, 1082, 1030, 1011, 966, 905, 882, 820, 734, 695.

5.8.2 Synthesis of the polymers

General procedure for the synthesis of poly(butyl methacrylate) homopolymers with ATRP.

Under argon, the initiator (ethyl 2-bromo-2-methylpropanoate (17) or benzyl 2-bromo-2-methylpropanoate (18)) and the ligand (PMDETA) were mixed with butyl methacrylate and distilled toluene in a dry Schlenk flask followed by air removal using three or four freeze-pump-thaw cycles or until no more gas bubbles escape from the solution when thawing. The initiator and PMDETA were added as stock solutions in distilled toluene. Another argon-rinsed dry Schlenk flask containing the catalyst (CuBr) and, when applicable, discotic 3 was prepared. Chloroform was added to the Schlenk flask to dissolve disc 3 followed by thorough drying by a nitrogen flow. This guaranteed the removal of any air that was enclosed in the sticky disc 3. Then, the degassed solution was transferred via an argon-rinsed needle to the Schlenk flask containing the catalyst. Subsequently, this flask was closed with a septum allowing sampling through a needle without disrupting the reaction mixture too much. Then, the reaction mixture was heated till 90 °C and at time intervals samples for ¹H-NMR and GPC analysis were taken. An argon over-pressure was guaranteed throughout the entire process and when benzyl 2-bromo-2-methylpropanoate (18) was used as initiator the reaction mixture was shielded from light with aluminum foil. The GPC (molecular weight and molecular weight distribution) and ¹H-NMR (conversion and end-group analysis when initiator 18 was used) results are summarized in table 1.

The reaction schemes are depicted in Scheme 7. The ¹H-NMR based end-group analysis and conversion is clarified in Figure 9 for polymerization 5.3.

Scheme 7: Polymerization of butyl methacrylate initiated by benzyl initiator 18 (a) or ethyl initiator 17 (b). The numbers are used in the NMR assignment.

Figure 9: ¹H-NMR spectrum of polymerization 5.3 after 8 h reaction. Italic numbers are the protons of butyl methacrylate monomer and the polymer as shown in Scheme 7.

Conversion = [int.(3+5+ethers(3))-int.(C₆(3)*6)-(int.(2)*2)]/[int.(3+5+ethers(3))-int.(C₆(3)*6)].

End-group analysis = [int.(3+5+ethers(3))-int.(C₆(3)*6)-(int.(2)*2)]/[int.(4)].

int. = integration value of the mentioned signals.
Polymer 1.1
Used: 16.2 mg (0.0629 mmol) benzyl 2-bromo-2-methylpropanoate, 9.0 mg (0.063 mmol) CuBr, 12.0 mg (0.0692 mmol) PMDETA, 2.0 ml (12.6 mmol) butyl methacrylate and 1.7 ml toluene. After 6h a dark precipitate formed in the mixture and on the glass-wall. The viscosity of the reaction mixture clearly increased after 4h reaction and a dark-green suspension formed. Samples were taken after 4h and overnight reaction. The reaction was stopped after 19h. $^1$H-NMR of reaction mixture (400 MHz, CDCl$_3$): $\delta = 6.10+5.53$ (2), 5.11-4.99 (4), 4.14 (t, $^3$(H,H) = 6.5 Hz, 3), 3.95+3.94 (5), 2.01-1.23 (6), 1.15-0.88 ppm (7).

Polymer 1.2
Used: 10.8 mg (0.0419 mmol) benzyl 2-bromo-2-methylpropanoate, 6.0 mg (0.042 mmol) CuBr, 8.0 mg (0.046 mmol) PMDETA, 2.0 ml (12.6 mmol) butyl methacrylate and 1.8 ml toluene. After 6h a dark precipitate formed in the mixture and on the glass-wall. The viscosity of the reaction mixture clearly increased after 4h reaction and a dark-green suspension formed. Samples were taken after 4h and overnight reaction. The reaction was stopped after 19h. $^1$H-NMR of reaction mixture (400 MHz, CDCl$_3$): $\delta = 6.09+5.52$ (2), 5.12-5.00 (4), 4.14 (t, $^3$(H,H) = 6.6 Hz, 3), 3.95+3.94 (5), 2.01-1.23 (6), 1.15-0.89 ppm (7).

Polymer 2.1
Used: 12 mg (0.063 mmol) ethyl 2-bromo-2-methylpropanoate, 10 mg (0.063 mmol) CuBr, 12 mg (0.069 mmol) PMDETA, 340 mg (0.13 mmol) discotic 3, 2.0 ml butyl methacrylate (12.6 mmol) and toluene (2.0 ml). After heating till 90 °C a light-green precipitate formed which increased afterwards. The viscosity of the reaction mixture clearly increased after overnight reaction. Samples were taken after 1h, 3h, 6h and overnight reaction. The reaction was stopped after 19h. Chloroform (4 ml) was added to the reaction mixture after which 1 ml of the resulting solution was taken and precipitated into methanol (150 ml) giving rise to a blue solution containing a white precipitate. Büchner filtration and washing of the resulting residue yielded the desired polymer combined with discotic 3 as a white, sticky solid (0.134 g). $^1$H-NMR (400 MHz, CDCl$_3$): $\delta = 15.50$, 14.30, 9.59+9.57, 9.41+9.39, 9.22, 9.04+9.03, 8.43+8.42, 7.55-7.27, 4.11-3.94 (discotic 3), 6.09+5.52 (2), 5.12-5.00 (4), 4.14 (t, $^3$(H,H) = 6.6 Hz, 3), 3.95+3.94 (5), 2.00-1.28 (6+discotic 3), 1.12-0.88 ppm (7+discotic protons).

Polymer 2.2
Used: 10.8 mg (0.0419 mmol) benzyl 2-bromo-2-methylpropanoate, 6.0 mg (0.042 mmol) CuBr, 8.0 mg (0.046 mmol) PMDETA, 0.341 g (0.127 mmol) discotic 3, 2.0 ml (12.6 mmol) butyl methacrylate and 1.7 ml toluene. After 6h a dark precipitate formed in the mixture and on the glass-wall. A sample was taken after 6h and then the reaction was stopped. $^1$H-NMR of reaction mixture (400 MHz, CDCl$_3$): $\delta = 15.13$, 14.12, 9.22+9.20, 8.86, 7.95, 7.44-7.40, (discotic 3), 6.08 and 5.54 (2), 5.11-4.99 (4), 4.12 (t, $^3$(H,H) = 6.6 Hz, 3+discotic 3), 3.95+3.93 (5), 2.03-1.26 (6+discotic 3), 1.14-0.88 ppm (7+discotic 3).

Polymer 2.3
Used: 8.2 mg (0.042 mmol) ethyl 2-bromo-2-methylpropanoate, 6.0 mg (0.042 mmol) CuBr, 8.0 mg (0.046 mmol) PMDETA, 341 mg (0.13 mmol) discotic 3, 2.0 ml (12.6 mmol) butyl methacrylate and 2 ml toluene. After 6h a dark precipitate formed in the mixture and on the glass-wall. Samples were taken after 4h and overnight reaction and then the reaction was stopped. $^1$H-NMR of reaction mixture (400 MHz, CDCl$_3$): $\delta = 15.45$, 14.34, 9.54+9.52, 9.38+9.36, 9.08, 9.04+9.03, 8.32+8.31, 7.46-7.34, (discotic 3), 6.09+5.52 (2), 4.14 (t, $^3$(H,H) = 6.7 Hz, 3), 4.07-4.02 (discotic 3), 3.95+3.94 (5), 2.01-1.23 (6+discotic 3), 1.11-0.89 ppm (7+discotic 3).
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Polymer 3.1
Used: 4.1 mg (0.021 mmol) ethyl 2-bromo-2-methylpropanoate, 3.0 mg (0.021 mmol) CuBr, 4.0 mg (0.023 mmol) PMDETA, 1.0 ml (6.3 mmol) butyl methacrylate and toluene (1.0 ml). After heating till 90 °C a dark-green precipitate formed. The viscosity of the reaction mixture clearly increased after overnight reaction. Samples were taken after 4h and after overnight reaction. The reaction was stopped after 19h. ¹H-NMR of reaction mixture (400 MHz, CDCl₃): δ = 6.09+5.52 (2), 4.15 (t, ³J(H,H) = 6.4 Hz, 3), 3.95+3.94 (5), 2.01-1.23 (6), 1.12-0.90 ppm (7).

Polymer 3.2
Used: 3.9 mg (0.020 mmol) ethyl 2-bromo-2-methylpropanoate, 1.5 mg (0.011 mmol) CuBr, 2.0 mg (0.012 mmol) PMDETA, 0.50 ml (3.1 mmol) butyl methacrylate and toluene (3.1 ml). The reaction mixture started colorless but a white precipitate formed after 4h. The viscosity of the reaction mixture did not change significantly. A sample was taken after 4h reaction. The reaction was stopped after 19h. ¹H-NMR of reaction mixture (400 MHz, CDCl₃): δ = 6.08+5.48 (2), 4.11 (t, ³J(H,H) = 6.6 Hz, 3), 3.95+3.94 (5), 2.07-1.21 (6), 1.07-0.88 ppm (7).

Polymer 3.3
Used: 10.8 mg (0.0419 mmol) benzyl 2-bromo-2-methylpropanoate, 6.0 mg (0.042 mmol) CuBr, 8.0 mg (0.046 mmol) PMDETA, 2.0 ml (12.6 mmol) butyl methacrylate and 1.8 ml toluene. After 6h a dark precipitate formed in the mixture and on the glass-wall. The viscosity of the reaction mixture clearly increased after 4h reaction and a dark-green suspension formed. Samples were taken after 4h and overnight reaction. The reaction was stopped after 19h. ¹H-NMR of reaction mixture (400 MHz, CDCl₃): δ = 6.09+5.52 (2), 5.12-5.00 (4), 4.14 (t, ³J(H,H) = 6.6 Hz, 3), 3.95+3.94 (5), 2.01-1.23 (6), 1.12-0.90 ppm (7).

Polymer 4.1
Used: 16.2 mg (0.0629 mmol) benzyl 2-bromo-2-methylpropanoate, 9.0 mg (0.063 mmol) CuBr, 12.0 mg (0.0629 mmol) PMDETA, 2.0 ml (12.6 mmol) butyl methacrylate and 4.7 ml toluene. After 6h a dark precipitate formed in the mixture and on the glass-wall. A sample was taken after 6h reaction and then the reaction was stopped. ¹H-NMR of reaction mixture (400 MHz, CDCl₃): δ = 6.09+5.50 (2), 5.11-4.99 (4), 4.12 (t, ³J(H,H) = 6.4 Hz, 3), 3.95+3.94 (5), 2.03-1.25 (6), 1.14-0.91 ppm (7).

Polymer 4.2
Used: 4.1 mg (0.021 mmol) ethyl 2-bromo-2-methylpropanoate, 3.0 mg (0.021 mmol) CuBr, 4.0 mg (0.023 mmol) PMDETA, 0.50 ml (3.1 mmol) butyl methacrylate and toluene (2.9 ml). The reaction mixture started colorless but a white precipitate formed after 4h. Samples were taken after 1h, 3h and 7h and after overnight reaction. The reaction was stopped after 24h. ¹H-NMR (400 MHz, CDCl₃): δ = 15.50, 14.38, 9.59+9.57, 9.42+9.40, 9.18, 9.06, 8.36, 7.49-7.31, (discotic 3), 6.08+5.50 (2), 4.13 (t, ³J(H,H) = 6.7 Hz, 3), 3.95+3.94 (5), 2.02-1.22 (6), 1.14-0.91 ppm (7).
Polymer 5.3

The polymerization was performed in a slightly different manner compared to the previous ones. Toluene (1.0 ml), butyl methacrylate (1.0 ml) and benzyl 2-bromo-2-methylpropanoate 18 (0.021 mmol, 50 µL of a 0.42 M stock solution in distilled toluene) were mixed in a dry Schlenk flask and degassed. CuBr (3.0 mg, 0.021 mmol), PMDETA (198 mg, 1.14 mmol) and toluene (1.0 ml) were mixed in another dry Schlenk flask and degassed. Symmetrical discotic 3 (171 mg, 0.0635 mmol) was dissolved in chloroform in a third Schlenk flask and dried by a nitrogen flow. The contents of the first and the second flask were added to the third one by an argon rinsed syringe and the resulting reaction mixture was heated till 90 °C. The initial blue color quickly changed to green. After 3h the viscosity did not change significantly. After 8.5 h, the viscosity of the reaction mixture increased and the color remained green. Samples were taken after 3h, 6h and 8.5h reaction time. The reaction was stopped after 8.5h.

Copolymer 20

Under argon, benzyl 2-bromo-2-methylpropanoate (0.65 mg, 0.0025 mmol), was mixed with butyl methacrylate (0.114 ml, 0.72 mmol) and distilled toluene (0.9 ml) in a dry Schlenk flask followed by air removal using freeze-thaw cycles until no more gas bubbles escaped from the solution when thawing. Another argon-rinsed dry Schlenk flask containing CuBr (0.36 mg, 0.0025 mmol) and PMDETA (11.8 mg (0.068 mmol)) together with toluene (0.1 ml) was prepared. The initiator and PMDETA were added as degassed stock solutions in distilled toluene. Discotic 2 (0.100 g, 0.0378 mmol) was weighed in a third Schlenk flask, dissolved in chloroform (1 ml) and then the chloroform was evaporated by a nitrogen flow. Then, the two degassed solutions were transferred via an argon-rinsed needle into the Schlenk flask containing disc 2. Subsequently, this flask was closed with a septum and shielded from light with aluminum foil while an argon overpressure was guaranteed during reaction. The reaction mixture was heated till 90 °C during which a green precipitate formed. Samples were taken after 5h and 7h. Since the conversion did not increase between 5h and 7h, 0.30 mg CuBr was added. The reaction was heated overnight after which more green precipitate was observed. Another sample was taken and the heating was stopped after 24h reaction time. Subsequently the mixture was transferred into a round bottom flask and concentrated in vacuo. The residue was dissolved in chloroform (1 ml) and precipitated into a mixture of acetone and methanol (45 ml acetone, 5 ml methanol). The residue was collected by Büchner filtration and dried in a vacuum oven (yield: 83 mg). Purification by flash column chromatography (silica gel, ethyl acetate in chloroform to remove unreacted methacrylate disc 2) afforded copolymer 20 (20 mg, 20% as a white, sticky solid. $R_f = 0.21$ (silica gel, 25 vol% ethyl acetate in chloroform): $^1$H-NMR polymer (400 MHz, CDCl$_3$, 125 °C, 15 mg/ml): $\delta = 15.12$ (15), 14.03 (9), 9.50 (12), 9.32 (13), 9.13 (14), 8.89 (16), 8.40 (10), 7.42 (11), 7.26 (17), 4.06 (8), 3.94 (5), 1.97-1.27 (6+8), 1.13-0.85 ppm (7+8).
5.9 References


Careful monitoring of the reaction with $^1$H-NMR and control of temperature minimizes the formation of the diallylated side-product which, unfortunately, is very similar in polarity to the desired product hampering its removal.


See also Scheme 1, Chapter 3. LiOH, which is slightly milder compared to NaOH, has been used to saponify ester 6.

See also Scheme 1, Chapter 3.


Gaby van Gemert is acknowledged for giving valuable tips concerning this synthesis.

Splitting of the benzyl -CH$_2$- protons was observed, probably due to the proximity of different stereocentra near the initiating unit. However, this is at the same time a proof that benzyl compound 18 indeed acted as an initiator for growing chains.

To achieve polymers with a higher molecular weight, ARGET ATRP conditions were applied too. Higher molecular weights were demonstrated with both GPC and $^1$H-NMR, but the molecular weight distribution also increased significantly. Since a low polydispersity was targeted, ATRP in the presence of a reducing agent was not continued.


See experimental section.

For this calculation the hydrodynamic volume of copolymer 20 is assumed to approach the hydrodynamic volume of the used polystyrene standard.


A desymmetrized discotic as precursor for functionalized polymers

[59] The neutralization of the base (triethylamine) in the absence of acetic anhydride and in the presence of water is very important because the product is very sensitive to basic hydrolysis.
[61] $^1$H-NMR of the crude reaction mixture after overnight indicated the formation of 84 mol-% product, 5 mol-% bisamide and 11 mol-% 2,2'-bipyridine-3,3'-diamine (based on the initial amount of 2,2'-bipyridine-3,3'-diamine).
[62] Due to anisotropy effects of the ether oxygen the chemical shift of the axial (endo) and equatorial (exo) protons differs thus complicating peak assignment.
[63] Sometimes the meta-coupling is not visible due to peak broadening.
[64] Peak assignment was confirmed with gHMQC and gHMBC 2D NMR.
[65] For a complete assignment of the protons of discotic 3 see: ref. [32].
[66] Unfortunately no MALDI-TOF MS spectrum could be obtained of copolymer 20.
Helical self-assembly of fluorinated, preorganized discotics and their unprecedented co-assembly with chiral discotics

Abstract. The synthesis and self-assembly properties in the mesophase and in solution of a novel, heavily fluorinated C$_3$-symmetrical 3,3'-bis(acylamino)-2,2'-bipyridine discotic are described. The fluorinated periphery allows to study self-assembly of discotics and novel mixed self-assembly with hydrocarbon discotics in fluorinated media. A fluorinated 3,4,5-trialkoxybenzoyl chloride was coupled to 2,2'-bipyridine-3,3'-diamine to afford a fluorinated aromatic amine on a multi-gram scale. Three-fold reaction of this amine with trimesyl chloride yielded the desired fluorinated disc. This discotic proved to be columnar liquid crystalline over a temperature window of more than 350 K in which a helical rectangular and a hexagonal mesophase were detected by means of X-ray diffraction. $^1$H-NMR spectroscopy showed the presence of a preorganized structure by strong intramolecular hydrogen bonding between amide N-H's and bipyridine nitrogens, even in the presence of a large excess of HFIP. This preorganized structure allows the formation of helical self-assemblies in fluorinated solvents as was detected with UV/Vis spectroscopy. Mixtures of fluorinated disc and two analogs equipped with chiral hydrocarbon tails could be solubilized into a 1:10 v:v mixture of MNFB and Freon 113. The C$_3$-symmetrical chiral disc was, however, only soluble in the presence of the fluorinated disc. The latter suggests an attractive interaction between hydrocarbon and fluorocarbon discs which was further investigated with CD spectroscopy. A non-linear relationship between the Cotton effect and the amount of chiral disc was observed showing amplification of chirality and hence the presence of both discotics in one type of helical stack. The observations point to the unprecedented preference for alternating self-assemblies of chiral, hydrocarbon discotics and fluorocarbon discotics.
6.1 Introduction

Self-assembly of discotics into well-ordered systems in solution and in the solid state is an appealing subject in supramolecular chemistry.\(^1\) There are potential applications in e.g. solar cells,\(^2\) field-effect transistors,\(^3\) nanomembranes,\(^4\) supramolecular polymers\(^5\) and supramolecular scaffolds for biological systems like bacteria.\(^6\) Since the discovery of columnar liquid crystalline behavior shown by discotics in 1977,\(^7\) numerous disc-shaped molecules have been synthesized and investigated. Their design is based on the presence of a rigid core and a flexible aliphatic periphery which cause their liquid crystalline properties.\(^8\) This design is responsible for the one-dimensional self-assemblies in solution too. The control of mesophase behavior and assembly in solution is important to achieve efficient devices and to mimic natural systems to a larger extent.\(^9\) Control of self-assembly of columnar mesogenic systems may rely on the introduction of perfluorinated tails in the periphery,\(^10\) which is believed to stabilize mesophases,\(^11,12\) to improve alignment behavior\(^13\) and to improve phase separation.\(^14-16\) Such improved properties by the incorporation of perfluorinated tails has been shown for columnar self-assembling dendrons\(^17,18\) and for dendrimers.\(^19\) The self-assembly of fluorinated dendrons may drive the formation of supramolecular columnar helical liquid crystals with promising opto-electronic properties like high charge-carrier mobilities.\(^20\) The latter was also achieved in columnar mesophases of partially fluorinated perylene bisimides.\(^21\) Mesophase behavior of hydrogen-bonded assemblies of alkylated melamine derivatives and benzoic acids has been tuned by variation of the ratio between fluorinated tails and hydrogenated tails on the benzoic acids to give smectic, cubic or columnar mesophases (Figure 1).\(^22\) The advantage of these hydrogen bonded supramolecular systems is that with a limited number of precursors a wide variety of appealing liquid crystalline materials was obtained.

Fluorination with the aim of improving properties of single-core discs in solution were reported for heavily fluorinated porphyrin\(^23\) and phthalocyanine\(^24\) derivatives that possess potential gas or drug carrier applications. Fluorinated phthalocyanines possessing catalytic activity allow recovery of the catalysts by fluoruous solvent extraction.\(^25\) The improvement of properties by incorporating a fluorinated periphery is due to the reduced miscibility of these fluorinated moieties with other parts in the molecule, the so-called fluorophobic effect.\(^26,27\) The latter is caused by the increased rigidity, linearity and low surface energy of the perfluorinated alkyl tail compared to a hydrocarbon alkyl tail. Also, perfluorinated alkyl chains are much bulkier than hydrocarbon chains, with cross sections in the 27-30 Å\(^2\) range for the former and 18-21 Å\(^2\) range for the latter, with the exact value depending on the packing situation.\(^27\) However, fluorination of aromatic units will enhance their interaction with non-fluorinated aromatics because of attractive interactions between electron-rich and electron-poor nuclei. By doing so mixed assemblies may be obtained.\(^28\) This has been observed in the columnar mesophase for blends of triphenylene functionalized polymers with perfluorotriphenylene derivatives\(^29\) and for helically twisted columnar aggregates.\(^30\) In organo-gels, alternation by perfluoroarene-arene interactions is also known.\(^31\) Like in the mesophase, co-assembly of different species in solution is usually based on donor-acceptor systems. Examples of such systems include OPV structures,\(^32\) phthalocyanines,\(^33\) porphyrin-pyrene complexes\(^34\) and
This type of co-assemblies was observed in columnar mesophases too for hexabenzocoronene-perylenebisimide mixtures, symmetrical triphenylene derivatives and mixtures of pyrene-based hydrogen bonded discotics with trinitrofluorenone. Interestingly, alternation of the different species is often involved in these mixed assemblies, resulting in a higher level of order.

Figure 1: Changing the type of mesophase and the lattice parameters of partially fluorinated hydrogen bonded liquid crystals. a) 1:1 Ratio between alkylated melamine and bisfluorinated wedge results in a rectangular mesophase. b) 1:1 Ratio between alkylated melamine and trisfluorinated wedge results in a hexagonal mesophase. c) 1:3 Ratio between alkylated melamine and bisfluorinated wedge results in another hexagonal mesophase.

Our aim has been to use the fluorophobic effect to alter the self-assembly process of discotics based on the 3,3′-bis(acylamino)-2,2′-bipyridine unit. The liquid crystalline and self-assembly behavior of these discs is described in previous chapters and in the literature. Phase separation between the rigid core and the disordered periphery of these discs is based on the presence of these sufficiently long apolar hydrocarbon or polar oligo(ethylene oxide) tails and may be further exploited by the incorporation of fluorinated tails. The latter is expected to stabilize the columnar mesophase. Besides this, unprecedented helical self-assembly in fluorinated solvents will become possible. Like in previous work, we would like to confirm the presence of these highly ordered, but also reversible helical structures in solution by the ‘Sergeant and Soldiers’ effect in which a small amount of chiral disc is able to bias the helical sense of a platoon of achiral discs, the latter being the fluorinated discs in this case. This would prove the presence of both fluorinated-alkyl tail discotics and hydrocarbon-tail discotics in the same helical assembly in fluorinated media, which was never observed before. Pursuing this, we would like to introduce a novel C₃-symmetrical discotic based on the 3,3′-bis(acylamino)-2,2′-bipyridine unit possessing a perfluorinated periphery (disc 1, Figure 2). This heavily fluorinated disc and its appealing self-assembly behavior is the topic of this Chapter. Discotic 1
was synthesized by a slightly adapted, convenient convergent synthetic approach comparable to those of hydrocarbon-tail analogs.\textsuperscript{40} Its mesophase properties have been investigated with differential scanning calorimetry (DSC), polarizing optical microscopy (POM) and X-ray diffraction (XRD). Self-assembly studies were performed in solution with optical spectroscopy. Finally, mixing of fluorinated disc 1 with chiral discs 2 and 3 (Figure 2) will be shown in fluorinated media together with amplification of chirality which might be probed with CD spectroscopy. Desymmetrized, chiral disc 3 was employed because it displays better solubility in fluorinated solvents compared to C\textsubscript{5}-symmetrical chiral disc 2, albeit that their helical self-assembly behavior is similar.\textsuperscript{51}

![Figure 2: Discotics presented in this Chapter: a) C\textsubscript{5}-symmetrical disc 1 equipped with nine perfluorinated tails. b) C\textsubscript{5}-symmetrical disc 1 possessing nine chiral, apolar, dihydrocitronellyloxy tails and desymmetrized disc 3, equipped with six dihydrocitronellyloxy tails. Intramolecular hydrogen bonding is represented with dashed bonds. A schematic representation of their supramolecular helical organization is depicted in Chapter 2, Figure 1.](image)

### 6.2 Synthesis of fluorinated discotic 1.

The synthesis of chiral discotics 2 and 3 was discussed in Chapter 2 and in the literature\textsuperscript{41} and is based on a convergent approach from periphery to center. The synthesis of fluorinated disc 1 is based on the same considerations as those adopted in the synthesis of C\textsubscript{5}-symmetrical disc 2. The synthesis of fluorinated disc 1 is depicted in Scheme 1. First, methyl gallate (1) was reacted with commercially available fluorinated iodide 5 to obtain fluorinated gallic ester 6 in good yield by adopting a combination of several literature procedures.\textsuperscript{52-54} A hydrocarbon spacer length of at least three carbons between the aryl-oxygen and the fluorinated part is necessary: When a -CH\textsubscript{2}- spacer is present, aromatic ether formation could not be accomplished, which is rationalized by the repulsive character of the nearby -CF\textsubscript{2}- group\textsuperscript{55} and in the presence of a -C\textsubscript{2}H\textsubscript{4}- spacer, severe elimination was observed in Williamson ether synthesis conditions.\textsuperscript{56} Fluorinated ester 6 was saponified to give carboxylic acid 7 after neutralization and the latter was easily converted into acid chloride 8.\textsuperscript{45} According to previous syntheses the next logical step would be a direct, selective amidation of 3,3-diamino-2,2-bipyridine\textsuperscript{40,57} in which the
desired monoamino product 11 indeed was formed in up to 90% yield, while the expected bisamide side-product was observed for 5%. However, due to the presence of fluorinated tails, the symmetrical bisamide could not be separated from product 11 by column chromatography. Therefore, mono-BOC protected diamine 9 (Chapter 2, Scheme 4) was employed, which is accessible on a multigram scale. In the subsequent amidation, BOC compound 10 was easily isolated in pure form, while the solubility of the fluorinated components in the reaction mixture was ensured with methoxynonafluorobutane (MNFB) as a co-solvent. Then, removal of the BOC group afforded mono-amine 11 after neutralization. Importantly, considering multigram-scale synthesis, no column chromatographic separation was needed to purify fluorinated compounds 10 and 11. In the final reaction step three molar equivalents of fluorinated amine 11 were reacted with trimesyl chloride to afford target disc 1. Purification was achieved by recrystallization from mixtures of chloroform and fluorinated solvents followed by column chromatography over silica gel with a mixture of chloroform and fluorinated solvents as eluent. Hexafluoroisopropanol proved to be a convenient polar component during chromatographic separation: It is prone to dissolve fluorinated compounds and at the same time it suppresses aggregation of discotic 1 on the column. Purity of the product was guaranteed by a combination of 1H-NMR, MALDI-TOF MS and elemental analysis, while the assignment of its 1H-NMR spectra was done with the aid of gCOSY 1H-1H 2D NMR. The synthesis of discotic 1 shown here enables to afford multigram quantities of disc 1 and its precursors. The latter might be deployed to afford desymmetrized bipyridine discotics possessing potential appealing phase separation and amphiphilic properties.

**Scheme 1:** Synthesis of fluorinated disc 1. During the amidation of acid chloride 8 with amine 9 and in the subsequent reactions the fluorinated solvent MNFB has to be present to ensure solubility. TBAB = tetrabutylammonium bromide, MIBK = methyl isobutyl ketone, TEA = triethylamine, MNFB = methoxynonafluorobutane.
6.3 Columnar mesophase behavior of fluorinated disc 1

The mesophase properties of discotic 1 were investigated like described for hydrocarbon and oligo(ethylene oxide) analogs. Fluorinated disc 1 is a sticky compound at room temperature which is an indication for liquid crystallinity in this kind of compounds. The thermal stability of disc 1 was determined using thermal gravimetric analysis (TGA) because perfluorination is known to increase transition temperatures, possibly above the compound’s degradation temperature. TGA measurements did not show loss of mass upon heating till 350 °C if performed under a nitrogen atmosphere. However, severe decomposition starting from 300 °C was observed when TGA was performed under an oxygen-rich atmosphere. Therefore, DSC and POM were conducted under a nitrogen atmosphere to ensure reliable results.

6.3.1 DSC and polarizing optical microscopy analysis

Phase transitions were determined using differential scanning calorimetry (DSC) and polarizing optical microscopy (POM) under a nitrogen atmosphere. A glass transition instead of a melting point was observed for fluorinated disc 1 below 0 °C. This glass transition was confirmed by modulated DSC analysis. Glass transitions are not often observed for columnar liquid crystals, exceptions are e.g. discotic-functionalized polymers, columnar self-assembling fluorinated crown ethers, ester functionalized triphenylenes and bipyridine based discotics with nine oligo ethylene oxide side tails. Usually the high order of the discotics in the columnar mesophase favors a transition to a crystal state instead of simple freezing of disordered side-tails. Probably, the rigidity of the perfluorinated tails of discotic 1 prevents the reorganization of 1 into an ordered crystal state. Besides the glass transition, no other transitions were observed in DSC. Hence, disc 1 is liquid crystalline over a more than 350 K window. The absence of an isotropization temperature for 1 unfortunately prevented the growth of typical textures by slow cooling. These textures are considered as a strong proof for liquid crystallinity and give information about the type of mesophase. However, the liquid crystalline nature of discotic 1 was proven by shear aligning of a sample on a glass slide at elevated temperatures (Figure 3). Under cross-polarizers, a highly birefringent sample was observed which was sensitive to pressure changes (Figure 3a). When the sample was rotated 45° in the cross polarizer, almost no birefringence was visible indicating an aligned sample (Figure 3b). Finally, by rubbing the sample between two glass slides rather undefined textures were obtained (Figure 3c).
6.3.2 Wide and small angle X-ray diffraction

The structure of disc 1 in the mesophase was studied with wide (WAXD) and small angle X-Ray diffraction (SAXD). WAXD was used to study interdisc conformal parameters while SAXD will give information about intercolumn parameters assuming that disc 1 is present in columnar stacks. Measurements were performed at 50 °C and 250 °C only, regarding the absence of any transitions in DSC above room temperature. Increasing the temperature above 250 °C will result in significant thermal degradation of the sample because the XRD measurement could not be conducted under a nitrogen atmosphere. Considering its molecular structure and C$_3$-symmetry we expected the same kind of columnar mesophase to be present as for its hydrocarbon-tail analogs to which a helical columnar rectangular lattice was assigned.$^{48}$ Samples were prepared in 0.7 mm quartz glass capillaries. Shear alignment was performed (if possible) by rubbing the sample inside the capillary at 250 °C inside a melting point apparatus.$^{67}$ At this temperature, the mesophase is fluid enough to be processed by shearing without destroying the fragile capillary. An aligned sample may give valuable information about the helical self-assembly of the bipyridine discotics as has been shown for other helical systems and as is depicted in Chapter 3, section 3.2.2.$^{48,68}$ Surprisingly, the reflexions in the WAXD region indicated an aligned sample, but the corresponding SAXD reflections appeared as complete, homogeneous rings indicating the absence of alignment. The presence of reflexions belonging to a regular organization of disc 1 in its axial direction together with a diffuse diffraction belonging to disordered side-tails are a strong evidence for

Figure 3: POM micrographs of disc 1. a) Discotic 1 sheared on a glass plate at 200 °C, b) The same sample, but rotated 45°, c) Textures obtained after considerable rubbing at 160 °C.
liquid crystalline behavior. The results subtracted from the WAXD and SAXD measurements are collected in Table 1. In WAXD at 50 °C, the alkyl halo represents a distance of 0.54 nm that corresponds to the fluorinated alkyl tails and this distance is slightly larger than that of hydrophobic alkyl tails (0.40-0.47 nm) (Figure 4a).¹⁶,⁴⁰ This difference may be caused by the larger rigidity of the perfluorinated tails of disc 1 and by the slightly larger size of the fluor atoms compared to the hydrogen atoms resulting in a larger Van der Waals radius (1.47 Å for F and 1.20 Å for H).²⁷ Two reflections at 0.35 nm and 0.33 nm were observed, both assigned to the interdisc distance. The distance of 0.33 nm can be attributed to the distance between the central phenyl moieties while the distance of 0.35 nm probably belongs to the distance between the bipyridine units. This is in correspondence with a rotation of less than 20° of the bis(acylamino)bipyridine unit around the central phenyl moiety which is responsible for the propeller shape of disc 1 in the helical aggregate.⁴⁸,⁶⁹ When the sample is heated to 250 °C, only one reflection at 0.35 nm and the halo belonging to the alkyl tails were observed (Figure 4a). At these high temperatures still an ordered columnar structure is present but the presence of only one reflection belonging to the interdiscs distance may suggest that the discs are present in an on average flat conformation instead of the propeller conformation, thus the absence of helicity.

Table 1: X-ray results on the mesophases of fluor discotic 1.

<table>
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<th>Phaseᵃ</th>
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ᵃ Col₁₀₀ = ordered columnar rectangular phase. Col₁₀₀ = ordered columnar hexagonal phase.ᵇ br. = broad maximum. h = interdisc distance from WAXD. p = distance along one column for a 120°-turn of the helix. ρcalc(Col₁₀₀) = (10 × Z × M_w)/(a × b × h × 6.02), where M_w is the molecular weight and Z the number of discs per unit cell. ρcalc(Col₁₀₀) = (20 × M_w)/(a² × h × √3 × 6.02).
SAXD gives information about the two-dimensional organization of disc 1 in the columnar mesophase. At 50 °C a rectangular lattice could be assigned with $p2gg$ symmetry (Figure 4b) according to the extinction rules (see also Chapter 3, Figure 1 and Table 1 for the rectangular lattices). This implies that the column which is located in the center of the rectangular unit cell differs from the others, probably due to a vertical shift between the columns. Although no aligned sample was achieved, the powder pattern is analogous to previously studied bipyridine discotics and a helical pitch of 76.5 Å was determined corresponding to 23 discotics and a rotation of 16° between superimposed discs. This is in line with the assignment performed for disc 2, its achiral analog and desymmetrized derivatives. Probably, the larger steric demands of the perfluorinated tails causes the helical pitch of disc 1 to be smaller than its hydrocarbon analog that possesses nine dodecyloxy tails (pitch: 95.4 Å), like is the case for chiral disc 2 that possesses nine branched alkoxy tails (pitch: 76.5 Å). The calculated density is in agreement with that of other reported fluorinated discotics. The mesophase at 250 °C is clearly hexagonal (Figure 4b). The structural difference between the Col$_{ro}$ and Col$_{ho}$ mesophases is small regarding the ratio between lattice a and b parameters of the Col$_{ro}$ lattice which amounts to 1.78 ($\sim \sqrt{3}$) and the angle $\alpha$ which amounts 60.6° (Table 1). This small difference may explain the absence of a detectable transition in DSC between the Col$_{ro}$ and Col$_{ho}$ mesophases. An increase in temperature and dynamics is expected to gradually erase the helicity and the small vertical difference between the columns and hence increase the symmetry of the unit cell. Overall, disc 1 displays very stable columnar mesophases with a mesophase window of almost 400 K and intracolumnar order still present at elevated temperatures.
6.4 Self assembly of fluorinated discotic 1 in solution

Self-assembly studies of heavily fluorinated compounds in solution are very rare due to their limited solubility in common organic solvents. Concentration-dependent self-assembly of hexabenzocoronenes equipped with six perfluorinated tails in trifluorotoluene was observed. However, discotic 1 is completely insoluble in trifluorotoluene. As discussed in the synthesis section, disc 1 is soluble in mixtures of methoxynonafluorobutane (MNFB), chloroform and hexafluoroisopropanol (HFIP) and appeared to be soluble in pure MNFB, perfluorononane, trifluoroacetic acid and hexafluorobenzene as well.

6.4.1 $^1$H-NMR spectroscopy

$^1$H-NMR spectroscopy is a convenient tool to show the presence of intramolecular hydrogen bonding and preorganization in bipyridine discotics which is responsible for their appealing self-assembly properties (See Chapter 2, section 2.4). Fortunately, discotic 1 can be dissolved in a mixture of 20 vol-% HFIP in CDCl$_3$. To ensure the visibility of the exchangeable amide N-H protons a 1:1 mixture of HFIP/HFIP-D$_2$ was used (Figure 5a).

![Figure 5](image)

**Figure 5:** a) $^1$H-NMR spectrum of discotic 1 in HFIP/HFIP-D$_2$/CDCl$_3$ (20 vol-% HFIP/HFIP-D$_2$ (1:1)-CDCl$_3$, 3.8 mM). Only the aromatic and hydrogen bonding regions are shown. $^1$H = OC$_3$H$_6$C$_6$F$_{17}$. b) The three possible deuterated states of the 3,3'-(bisacylamino)-2,2'-bipyridyl wedge.

The downfield shifted protons a and b point to strong intramolecular hydrogen bonding of the amide N-H with the bipyridine nitrogens which is remarkable in the presence of HFIP, a strong hydrogen bond breaking solvent. Surprisingly, protons a and b are split while their integration value is about 50% of the value of the other protons, indicating that partial H-D exchange took place (Figure 5b). Due to the weaker acidity of an amide N-D compared to an amide N-H, the intramolecular hydrogen bond of the former will be weaker which is communicated to the other amide N-H resulting in a little upfield shift. Bipyridine protons c and e are positioned downfield (9.2 and 9.0 ppm, respectively) as a result of anisotropic deshielding by the nearby amide carbonyls indicating in-plane conformation of the amide and bipyridine moieties. Bipyridine proton f is shifted more downfield than similar proton g due to a deshielding influence of the amide carbonyl of the neighboring wedge. This indicates an
on average rather planar conformation of the whole compound, which is important to enable columnar stacking.

6.4.2 UV/Vis spectroscopy

Columnar stacking in the mesophase was discussed in Section 6.3 but disc 1 is expected to self-assemble in non-solvents analogs to its hydrocarbon and oligo(ethylene oxide) analogs. This has been studied by means of UV/Vis spectroscopy which is a convenient method to study the self-assembly of bipyridine discs in dilute solution. Discotic 1 was sonicated in fluorinated solvent methoxynonafluorobutane or perfluorononane to give highly fluorescent solutions. The absorption spectra are shown in Figure 6.

![Figure 6: UV/Vis absorption spectra of discotic 1 in a) C9F20 (5.5 μM), b) MNFB (5.7 μM) at three temperatures. Spectra are normalized to the absorption maximum at 292 nm.](image)

As can be seen in Figure 6, four distinguished absorption maxima are present. The broad band at 292 nm belongs to the peripheral trialkoxyphenyl and the bipyridine chromophore while the typical splitted pattern with maxima at 362 nm and 381 nm and the shoulder at 346 nm belong to the bipyridine chromophore only. This typical splitting pattern was observed before for hydrocarbon analogs of disc 1 and was attributed to the presence of helical stacks. Thus, fluorinated disc might be present in helical self-assemblies in these fluorinated solvents. When the temperature was raised from 15 °C to the highest temperature possible almost no changes in the UV/Vis spectra were observed, suggesting that the assemblies of disc 1 are very stable in these solvents even at a concentration of 5 μM. This contrasts with solutions of hydrocarbon-tail discs like disc 3 in dodecane in which a blue shift together with a hyperchromic shift indicate melting of the helical aggregates upon heating. The only way to obtain the molecularly dissolved state of disc 1 is to add a highly competitive solvent for stacking like HFIP or TFA. In Figure 7, the UV/Vis absorption curves are depicted of a titration of a solution of disc 1 in HFIP to a solution of disc 1 in MNFB in which the total disc concentration was kept constant.
Helical self-assembly of fluorinated, preorganized discotics and their co-assembly with chiral discotics

In Figure 7a a large hyperchromic effect and fading of the typical splitting pattern in the bipyridine chromophore region can be observed with increasing HFIP content. Surprisingly, already 0.5 vol-% of HFIP is able to disrupt the helical self-assembly of disc 1 as illustrated by the large difference of the curves belonging to 0 vol-% and 0.5 vol-% HFIP. The latter curve resembles an absorption spectrum of hydrocarbon discotics in chloroform where the molecularly dissolved state is assumed. When more HFIP was added, these absorptions merge into a broad shoulder around 330 nm. The change in absorption levels off after addition of 20 vol-% of HFIP (Figure 7b) indicating that only the molecularly dissolved state is present above 20 vol-% HFIP. According to the course of the graphs in Figure 7b, the interaction of HFIP with disc 1 probably consists of a two-state process. Besides the transition from the self-assembled state to the molecularly dissolved species this other process might involve hydrogen bonding of HFIP to bipyridine nitrogens or amide carbonyls. HFIP is not believed to be able to protonate basic nitrogens in the core of disc 1 and to disrupt the preorganization and disc-shaped conformation of 1 (Figure 5). In contrast, upon addition of a small amount of TFA to a solution of molecule 1 in HFIP complete vanishing of the absorption bands belonging to the preorganized bipyridine moiety was observed due to pyridine-N protonation (Figure 7, black, dashed line). Summarizing, disc 1 forms stable self-assemblies of equal amounts of left and right handed helices in fluorinated solvents which can be disrupted by the addition of highly competitive solvents like HFIP. The former result justifies an attempt to bias the helical sense of the self-assemblies of discotic 1 with a chiral discotic in fluorinated media.

6.5 Co-assembly of fluorinated and non-fluorinated discs in solution

Because achiral, fluorinated disc 1 is supramolecularly aggregated into equal amounts of left and right handed helices, amplification of chirality is expected to happen by the addition of chiral discotics 2 or 3 (Figure 2b). These mixtures may give rise to a Cotton effect comparable in size to that of the pure chiral compound. Therefore, achiral disc 1 was mixed with chiral discs 2 or 3 which required a solvent in which both discs are soluble and helically aggregated. Both discs 1 and 3 were found to be soluble in a 1:10 v:v mixture of methoxynonafluorobutane (MNFB) and 1,1,2-trichloro-1,2,2-trifluoroethane (Freon 113) (abbreviated as F1:10), fluorinated...
disc 1 up to approximately 0.25 mM and non-symmetric chiral disc 3 up to approximately 0.75 mM. When the 1:10 v:v ratio of the solvent mixture was changed either disc 1 or disc 3 became insoluble. Surprisingly, C₃-symmetrical chiral disc 2 is insoluble in this solvent mixture, even at micromolar concentrations. However, disc 2 is solubilized upon addition of at least 10 mol-% of fluorinated disc 1 up to a concentration of about 0.4 mM in F1:10. This observation offers strong evidence for the presence of fluorinated disc 1 and apolar disc 2 in the same aggregates.

6.5.1 UV/Vis spectroscopy
According to UV/Vis spectroscopy discs 1, 2, and 3 are helically aggregated (Figure 8) in F1:10, as indicated by the splitted absorption pattern around 360 nm. Concentration dependent UV/Vis spectroscopy (Figure 8) might give an indication of the stability of assemblies in F1:10.

![Figure 8: Concentration dependent UV/Vis absorption spectra of a) disc 1 between 0.30 and 0.0056 mM, b) disc 3 between 0.50 and 0.0010 mM, c) disc 2 with 10 mol-% disc 1 between 0.30 and 0.0059 mM. Spectra were obtained at RT with MNFB:Freon113 1:10 v:v (F1:10) as solvent. The arrows indicate the effect of lowering the concentration (b).](image_url)

As can be deduced from Figure 8a, the extinction coefficient of disc 1 is independent of the concentration; suggesting that fluorinated disc 1 is completely aggregated at all concentrations. Disc 3 however, displays a small concentration dependence thus indicating incomplete aggregation at lower concentrations. The 1:9 molar mixture of discs 1 and 2 barely displays concentration dependence (Figure 8c). However, no shift of absorption maxima was observed for discs 1, 2 and 3, indicating that the fraction of non-aggregated species is small.
6.5.2 Optical spectroscopy of mixtures and detection of alternating stacks

Mixtures of fluorinated disc 1 and chiral disc 3 can be made by simply adding equimolar solutions of the pure components in F1:10 to each other and subsequent annealing by fast heating to 45 °C and cooling. CD and UV/Vis spectroscopy were performed to probe the presence of helices of biased helical sense. Mixing experiments were performed at several concentrations, of which the spectra are shown in Figure 9.

Figure 9: CD and UV/Vis spectra from the mixing experiments. a) Mixing of a solution of chiral disc 2 containing 10 mol-% disc 1 with a solution of fluorinated disc 1. b) Mixing of a solution of chiral disc 3 with a solution of fluorinated disc 1. Total concentration = 15 µM, solvent: F1:10. All samples were annealed before measuring.

A clear increase of the CD effect with increasing amount of chiral disc can be observed. Surprisingly, after addition of 50 mol-% chiral disc added, the Cotton effect did not increase anymore but rather diminished. This small decrease can be explained by a more efficient packing of achiral discs 1 compared to that of chiral discs 3 which are equipped with branched side tails. Apparently, the bias of helical sense of the assemblies of discs 1 and 2 or 3 is maximal after addition of 50 mol-% chiral disc. The absolute value of the Cotton effect (app. -45 M M⁻¹ cm⁻¹ at 387 nm) is in correspondence with values observed for pure chiral discs in apolar solution. Thus, probably all helices are biased at this point. The absorption spectra depicted in Figure 9 point to the presence of similar type of helices during the mixing experiments, although a small decrease of the extinction coefficient was observed, especially in Figure 9b, together with a red shift. In Figures 10 and 11 are depicted the dimensionless g-factors as function of the amount of chiral disc present at 15 µM and 100 µM or 150 µM. The non-linear relationship between the observed CD effect and the amount of chiral disc 3 in the solutions described in Figure 10a,b are a clear evidence for transfer of chirality from discs 3 to achiral discs 1 in one type of aggregate. The maximum Cotton effect reached at about 50 mol-% chiral disc 3 is in agreement with an amplification of chirality by a factor of two. This, together with an almost linear increase of the CD effect depicted in the first half of the mixing curve and the subsequent rather sharp transition, may be indicative for a preference for alternating stacking of chiral disc 3 and fluorinated disc 1.
Figure 10: Results of the mixing experiments of equimolar solutions of discs 1 and 3. a) Total concentration = 15 µM and b) Total concentration = 100 µM. Measurements were performed at room temperature after annealing in a 1 cm and 1 mm quartz cuvette, respectively. Solvent: F1:10. Shown is the g-value as function of the amount of chiral disc 3 present at two representative wavelengths corresponding to two maxima in the CD spectra.

Figure 11: Results of the mixing experiments of a solution of disc 1 with a solution of C₇-symmetrical disc 2 containing 10 mol-% disc 1. a) Total concentration = 15 µM and b) Total concentration = 150 µM. Measurements were performed at room temperature after annealing in a 1 cm and a 1 mm quartz cuvette, respectively. Solvent: F1:10. Shown is the g-value at two representative wavelengths corresponding to two maxima in the CD spectra.

The results from the mixing of chiral disc 2 with fluorinated disc 1 (Figure 11) are similar to the results displayed in Figure 10 although the transition at 40-60 mol-% chiral disc is less pronounced. Only, the measuring point of 100 mol-% chiral disc 2 cannot be reached due to the insolubility of disc 2 in F1:10 in the absence of fluorinated disc 1. Evidence of increased stack stability for the mixed system of discotics 1 and 3 and of discs 1 and 2 was gained from fluorescence spectra (Figure 12). Discotics 1, 2, and 3 and their previously reported analogs are known to luminesce around 513 nm after excitation if they are present in the self-assembled helical state. The fluorescence of hydrocarbon discs is strongly quenched upon melting of the aggregates. This, together with a blue shift in UV/Vis upon melting of the helix, is an indication for the formation of J-aggregates.⁷⁷,⁸²
Figure 12: a) Fluorescence spectra of discs 1, 2 (in the presence of 10 mol-% disc 1) and 3 and their 1:1 mixtures in F1:10. Measurements performed at room temperature in a 1 cm quartz cuvette, concentration = 1 µM, excitation at 365 nm. Graphs were normalized to the absorption of the mixtures at 365 nm (data obtained from Figures 8 and 9) b) Simplified representation of the types of helical assemblies of discs 1 and 2 or 3 present in the mixtures in F1:10 assuming there is a preference for alternating assembly. Note that the final state cannot be reached for discs 1 and 2 in F1:10. Dark disc = fluor disc 1, light disc = chiral disc 2 or 3. A = helices of biased sense, B = unbiased helices (equal amounts of left- and right-handed helices).

From Figure 12a, it can be deduced that the solutions of disc 1 and the 1:1 mixtures of discs 1 and 2 or 3 display the highest fluorescence intensity and solutions of chiral discs 3 and 2 (in the presence of 10 mol-% disc 1) display the lowest intensities. This is in correspondence with the concentration dependent UV/Vis absorption results from Figure 8: discs 2 and 3 are probably less aggregated compared to fluorinated disc 1 and the 1:1 mixtures. This also may suggest that the mixed aggregate is more stable compared to chiral discs 2 and 3 alone and that the formation of the former is preferred rather than phase separation between aggregates composed of only disc 1 and only of disc 3 or 2. The latter is confirmed by calculating the fluorescence of the corresponding 50:50 mixture from the pure solutions, which is smaller than the real fluorescence observed. Finally, the preference for alternating assembly between the fluor and chiral discs is represented schematically in Figure 12b. In real time, the presence of these alternating and pure assemblies is not a black-and-white phenomenon due to the dynamics in the supramolecular assemblies. Of course, also the presence of other types of mixed stacks can be assumed, like supramolecular block copolymers or randomly organized mixed columns. But these are less likely. The presence of phase separation between assemblies of fluor disc 1 and those of chiral disc 2 or 3 is not presumable because of the proved interaction present between the fluor and hydrocarbon discs. When fluor disc 1 is present in excess (i.e. less than 50 mol-% chiral disc), alternating aggregates and pure fluor disc-columns may be present, while the presence of an excess of chiral disc 2 or 3 may result in the presence of only alternating and pure chiral disc-columns. Because the chiral disc is able to transfer its chirality to neighboring discs, the alternating stacks are assumed to be of one handedness. Thus in the two latter cases in Figure 12b, only helices of one handedness are present explaining the more or less horizontal course of the curves in Figures 10 and 11.
6.6 Conclusions

The successful synthesis of novel C₃-symmetrical 3,3’-bis(acylamino)-2,2’-bipyridine discotic 1 possessing three peripheral fluorinated 3,4,5-trialkoxyphenyl wedges has been described. Their appealing self-assembly in the mesophase and in solution could be demonstrated. Discotic 1 possess three peripheral fluorinated 3,4,5-trialkoxyphenyl wedges and thus allows to take advantage of the ‘fluorophobic effect’ i.e. increased phase separation between the disc’s aromatic core and a heavily fluorinated aliphatic periphery to achieve appealing self-assembly properties. By applying slightly adapted established synthetic methods, multigram amounts of a fluorinated wedge were obtained in which only straightforward syntheses and purification steps were involved. This fluorinated wedge was converted into the desired fluorinated disc 1, but may also serve as a precursor for desymmetrized discotics containing a single fluorinated wedge with potential intriguing phase separation behavior. Teflon disc 1 displays very stable columnar mesophase behavior which is only matched by a few other discotic systems. X-ray diffraction showed a low temperature helical rectangular and a high temperature hexagonal mesophase for disc 1. However, DSC revealed only a glass transition below 0 °C, suggesting that the transition between the two columnar mesophases is gradual and accompanied by slow disappearance of the helical organization upon increasing the temperature. This helical organization is originating from the self-assembly of propeller-shaped discotics, the latter conformation enabled by very stable intramolecular hydrogen bonding within the aromatic amide core. Temperature-stable helical self-assemblies of disc 1 were detected in fluorinated solution which could be disrupted by the addition of the strong competitive solvents HFIP or TFA, the latter of which is also able to break the intramolecular hydrogen bonds. Mixing of fluor disc 1 with chiral hydrocarbon discotics in solution could be performed by dissolving them into a mixture of methoxynonafluorobutane and 1,1,2-trichloro-1,2,2-trifluoroethane. The fact that C₃-symmetrical disc 2 dissolved only in the presence of fluor disc 1 proves an interaction between these discs in solution. Mixing experiments of fluor disc 1 with chiral discs 2 and 3 revealed amplification of chirality via the ‘Sergeant and Soldiers effect’. On top of that, a rather linear increase of the Cotton effect up to 50 mol-% chiral disc indicates the preference for alternating chiral and fluorinated discs. This is unprecedented since the difference between the discs in the mixture is related only to the presence of hydrocarbon or fluorocarbon tails.
6.7 Experimental section

For other experimental conditions, see Chapter 2, 3, 4 and 5. The synthesis of 3'-tertiary-butoxycarbonylamino-2,2'-bipyridine-3-amine (9)\(^6\) has been described in Chapter 2. All solvents were of AR quality if not stated otherwise and were purchased from Biosolve (www.biosolve.nl). Tetrabutylammonium bromide, potassium carbonate and methyl isobutyl ketone were purchased from Acros (www.acros.be). 1-iodo,1H,1H,2H,2H,3H,3H-perfluoroundecane (5) was purchased from Fluka (www.aldrich.com). Sodium hydroxide was purchased from Merck (www.merck.nl). Methoxynonafluorobutane, hexafluoroisopropanol (≥99.8 %, spectroscopic grade) and 1,1,2-trichloro-1,2,2-trifluoroethane (HPLC grade) were purchased from Aldrich (www.aldrich.com). 1-Iodo,1\(^\text{H}\),1\(^\text{H}\),2\(^\text{H}\),2\(^\text{H}\),3\(^\text{H}\),3\(^\text{H}\)-perfluoroundecane (5) was purchased from ABCR (www.ABCR.de). Perfluorononane was purchased from Fluorochem (www.fluorochem.co.uk). Methoxynonafluorobutane was dried over 4 Å molsieve before use. Potassium carbonate was powdered and dried in a vacuum oven before use. Dichloromethane was distilled over Merck P_2O_5. All spectroscopy and chromatography were performed at room temperature unless stated otherwise. \(^{19}\)F-NMR spectra were recorded on a Varian Mercury Vx 400 MHz (375 MHz for \(^{19}\)F), a Varian 400-MR 400 MHz (375 MHz for \(^{19}\)F), or a Varian Mercury Plus 200 MHz (188 MHz for \(^{19}\)F) NMR spectrometer. \(^{19}\)F chemical shifts were calculated by the Varian software based on CCl_3F as standard. A one cm quartz cuvette was used for the optical measurements in the 0.01 mM range and a 1 mm quartz cuvette for measurements in the 0.1 mM range, wavelengths are given in nm and absorptions (extinction coefficients, \(\epsilon\)) in l/mol/cm. For temperature dependent measurements, a screw-cap sealed quartz cuvette was used. The CD effect is given in \(\Delta\epsilon\) (L/mol/cm) and is calculated by: \(\Delta\epsilon = (\text{CD effect})/(c \times l \times 32980)\), where CD effect = measured CD effect in mdeg, \(c\) = disc concentration in mol/L and \(l\) = cuvette path length in cm. Solutions were made by addition of the appropriate amount of solvent to the weighted sample and subsequent dissolution by gentle heating and sonication. Mixtures are made by addition of two solutions to each other followed by a heating and cooling step (annealing). The stability of the mixtures was verified with time dependent CD and UV/Vis spectroscopy. During optical measurements with CD spectroscopy especially the concentrated solutions were checked for the presence of linear dichroism, because this can influence the apparent CD signal.\(^{53}\)

The samples for wide angle X-ray diffraction (WAXD) and small angle X-ray diffraction (SAXD) have been prepared in 0.7 mm Lindemann glass capillaries. The samples were analyzed on a Bruker-Nonius D8-Discover X-ray diffractometer with a 0.154 nm Cu radiation source, equipped with a home-build sample oven (TU Delft, group of prof. dr. S.J. Picken). The scattering data were recorded on a 2D detector (1024×1024) and the sample-to-detector distance was 8.4 cm (WAXS) or 34 cm (SAXS). The capillary was placed inside a vertically aligned graphite tube with a transversal hole, which allows the incident X-ray beam to cross freely. The temperature of the graphite tube was controlled by a system formed by a thermocouple connected to a proportional integral-derivative (PID) controller and power supply, which acts as a fast-response online oven ranging from room temperature to 350 °C.

Methyl 3,4,5-tris(1H,1H,2H,2H,3H,3H-perfluoroundecyl-1-oxy)-benzoate (6)\(^{52,53}\)

Under argon, methyl gallate (4) (1.49 g, 8.10 mmol), 1-iodo,1H,1H,2H,2H,3H,3H-perfluoroundecane (5) (15.0 g, 25.5 mmol), tetrabutyl ammonium bromide (0.130 g, 0.47 mmol) and finely powdered, dry K_2CO_3 (6.77 g, 48.6 mmol) were mixed in MIBK (21 mL) at room temperature under vigorous stirring. Under argon, the beige reaction mixture was heated under reflux and vigorous stirring for 6 h after which TLC and \(^1\)H-NMR showed the presence of product and excess iodide only. The yellow suspension was cooled to room temperature, MIBK (25 mL) was added and the yellow suspension was filtered using a glass filter. The off-white residue was washed with MIBK (2× 25 mL). Methanol (300
mL) was added to the combined yellow filtrates resulting in the formation of a white precipitate. Subsequently, the suspension was heated to reflux till complete dissolution. The beige solution was allowed to reach room temperature slowly giving rise to a white precipitate. The precipitate was filtered over a Büchner funnel and the obtained white residue was washed with methanol-MIBK 3:1 (v:v) (2 × 100 mL). Drying of the residue in a vacuum-oven yielded ester 6 as a white powder (10.8 g, 6.90 mmol, 85 %). Rf = 0.41 (silica gel, ethyl acetate-heptane 1:3 (v:v)); m.p. 88.5 °C (Lit. 87-88 °C);\textsuperscript{33} \(^1\)H NMR (400 MHz, CDCl\(_3\), 25 °C): \(\delta = 7.29\) (s, 2H, 2), 4.12 (t, 4H, 2, \(\gamma\)(H,H) = 5.7 Hz), 4.06 (t, 2H, 6, \(\gamma\)(H,H) = 5.8 Hz), 3.91 (s, 3H, OCH\(_3\)), 2.43-2.26 (6H, 10), 2.19-2.09 (m, 4H, 8);\textsuperscript{34} \(^1\)C NMR\textsuperscript{35} (100 MHz, CDCl\(_3\), 25 °C): \(\delta = 166.4, 152.2, 141.5, 125.6, 108.3, 71.9, 67.6, 52.3, 27.8\) (t, \(\gamma\)(C,F) = 22.1 Hz), 21.5, 20.6 ppm; \(^{19}\)F NMR (375 MHz, CDCl\(_3\))\textsuperscript{36} \(\delta = -80.9\) (t, 6F, \(\delta\)(F,F) = 10.2 Hz, 16), -81.0 (t, 3F, \(\delta\)(F,F) = 10.2 Hz, 16), -114.5 (tt, 4F, \(J = 16.7\) and 15.5 Hz, 11);\textsuperscript{37} -114.8 (tt, 2F, \(J = 16.6\) and 15.3 Hz, 11), -121.8--122.0 (18F, 13), -122.9 (6F, 14), -123.6 (6F, 12), -126.2--126.3 ppm (6F, 15), FT-IR (ATR): \(\nu\) (cm\(^{-1}\)) = 2957, 2888, 1712 (C=O), 1587, 1502, 1479, 1441, 1432, 1382, 1373, 1344, 1197, 1144, 1114, 1060, 1031, 1010, 973, 937, 902, 865, 830, 769, 748, 740, 721, 705, 685, 656; MALDI-TOF MS: \(m/z\): calced for: 1564.07; found: 1563.94 (M\(^+\)), 1586.90 (M+Na\(^+\)); Analysis: calcd (%) for C\(_{41}\)H\(_{22}\)F\(_3\)O\(_5\): C 31.48, H 1.48; found: C 31.38, H 1.39.

3,4,5-Tris(1H,1H,2H,2H,3H,3H-perfluoroundecyl-1-oxy)-benzoic acid (7)

Under argon, methyl ester 6 (10.0 g, 6.39 mmol) was suspended in ethanol (50 mL) under vigorous stirring at room temperature after which a solution of NaOH (0.760 g, 19.0 mmol) in water (2 mL) was added. The white suspension was refluxed under stirring and argon for 5.5 h after which TLC and FT-IR showed the absence of starting material. Subsequently, ice-water was added which caused the formation of a thick suspension. Then, aqueous HCl (3 M, 7 mL) was added to the suspension under vigorous stirring to adjust the pH at 1-2. Then, the thick, white suspension was filtered over a Büchner funnel and the residue was washed thoroughly with water (4 × 30 mL) and water-methanol 1:1 (v:v) (3 × 30 mL). Drying of the residue in a vacuum-oven yielded benzoic acid 7 as a white powder (9.55 g, 6.16 mmol, 96 %). Rf = 0.29 (silica gel, ethyl acetate-heptane 1:3 (v:v)); m.p. 187-198 °C;\textsuperscript{38} \(^1\)H NMR (400 MHz, CDCl\(_3\) + HFIP-D\(_2\), 25 °C): \(\delta = 7.27\) (s, 2H, 2), 4.15-4.10 (6H, 6+, 7), 2.38-2.26 (m, 6H, 10), 2.20-2.10 (m, 4H, 8), 2.09-2.00 ppm (m, 2H, 9);\textsuperscript{39} \(^1\)C NMR (100 MHz, CDCl\(_3\) + HFIP-D\(_2\), 25 °C): \(\delta = 171.5, 152.6, 141.2, 126.0, 108.6, 73.2, 68.0, 27.9\) (t, \(\gamma\)(C,F) = 22.5 Hz), 21.3, 20.6 ppm; \(^{19}\)F NMR (375 MHz, CDCl\(_3\) + HFIP-D\(_2\)): \(\delta = -81.9\) (t, 6F, \(\delta\)(F,F) = 10.2 Hz, 16), -82.0 (t, 3F, \(\delta\)(F,F) = 10.1 Hz, 16), -115.0 (tt, 6F, \(J = 23.3\) and 15.6 Hz, 11),\textsuperscript{40} -122.4--122.6 (18F, 13), -123.5 (6F, 14), -124.1 (6F, 12), -127.0 ppm (6F, 15); FT-IR (ATR): \(\nu\) (cm\(^{-1}\)) = 2960, 2888, 1691 (C=O), 1589, 1506, 1478, 1433, 1372, 1333, 1199, 1146, 1135, 1115, 1029, 1006, 972, 866, 828, 777, 747, 739, 722, 704, 686, 656; MALDI-TOF MS: \(m/z\): calced for: 1550.06; found: 1550.01 (M\(^+\)), 1573.99 (M+Na\(^+\)); Analysis: calcd (%) for C\(_{40}\)H\(_{21}\)F\(_3\)O\(_5\): C 30.99, H 1.37; found: C 30.90, H 1.19.

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Helical self-assembly of fluorinated, preorganized discotics and their co-assembly with chiral discotics

3,4,5-Tris(1H,1H,2H,2H,3H,3H-perfluoroundecyl-1-oxy)-benzoyl chloride (8)
Under argon, benzoic acid 7 (6.00 g, 3.87 mmol) was suspended in distilled dichloromethane (36 mL) and MNFB (48 mL) at room temperature after which oxalyl chloride (0.55 mL, 0.81 g, 6.4 mmol) and DMF (4 drops) were added under the escape of gases from the mixture. The bubbling suspension was stirred for an additional 2 h at room temperature during which the beige suspension dissolved. After confirmation with FT-IR spectroscopy of complete product formation, the solution was concentrated in vacuo and dried thoroughly on a high vacuum line to remove volatile residues yielding a beige residue (6) (6.07 g) that was used as such. FT-IR (ATR): ν (cm⁻¹) = 2961, 2890, 1746 (C=O), 1590, 1499, 1475, 1451, 1431, 1382, 1372, 1332, 1198, 1144, 1135, 1115, 1060, 1030, 1004, 974, 918, 864, 820, 790, 769, 740, 721, 704, 656.

3′-Tertiary-butoxycarbonylamino-3-[3,4,5-tris(1H,1H,2H,2H,3H,3H-perfluoroundecyl-1-oxy)]benzoylamino]-2,2′-bipyridine (10)
Under argon, a solution of acid chloride 8 (6.07 g, 3.87 mmol) in dichloromethane (10 mL) and MNFB (30 mL) was added dropwise to a solution of 3′-tertiary-butoxycarbonylamino-2,2′-bipyridine-3-amine (9) (1.33 g, 4.64 mmol) and triethylamine (0.67 mL, 0.47 g, 4.64 mmol) in dichloromethane (30 mL) and MNFB (10 mL) under stirring at room temperature. The obtained thick yellowish suspension was refluxed for an additional 2 h and then stirred overnight at room temperature. Then, acetone (150 mL) and methanol (100 mL) were added followed by reflux³⁰ of the obtained yellowish suspension for 30 min. Subsequent cooling of the suspension to room temperature yielded more precipitate. The suspension was filtered over a Büchner funnel and the obtained residue was washed with acetonemethanol 2:1 (v:v) (2 × 75 mL) yielding BOC protected 10 (6.27 g, 3.45 mmol, 90 %) as an off-white, sticky product after drying in a vacuum-oven. Rf = 0.71 (silica gel, ethyl acetate:MNFB:CHCl₃ 1:2:5 (v:v:v)); m.p. 133.4 °C; ¹H NMR (400 MHz, CDCl₃ + HFIP-D₂ + CDCl₃F痘, 25 °C): δ = 14.08 (s, 0.1H, 7), 14.05 (s, 0.2H, 7), 12.27 (s, 0.1H, 7), 12.23 (s, 0.2H, 7), 9.06 (d, 1H, 4, 3J(H,H) = 8.3 Hz), 8.73 (d, 1H, 4, 3J(H,H) = 8.3 Hz), 8.45 (s, 1H, 6), 8.23 (s, 1H, 6), 7.46-7.43 (dd, 1H, 3J(H,H) = 8.5 Hz and 3J(H,H) = 4.5 Hz), 7.37-7.35 (dd, 1J(H,H) = 8.3 Hz and 2J(H,H) = 4.4 Hz, 1H, 5), 7.20 (s, 2H, 10'), 4.16-4.12 (6H, 13′+14′) 2.39-2.29 (m, 6H, 17′), 2.22-2.14 (m, 4H, 15′), 2.11-2.03 (m, 2H, 16′), 1.54 ppm (s, 9H, BOC-H); ¹³C NMR (100 MHz, CDCl₃ + HFIP-D₂, 25 °C): δ = 167.9, 154.5, 152.7, 143.5, 142.9, 140.6, 140.4, 136.2, 134.9, 131.2, 130.5, 130.3, 124.5, 124.4, 106.0, 82.7, 72.6, 67.8, 27.8, 27.5 (t, 3J(C,F) = 21.2 Hz), 21.1, 20.4 ppm; ¹⁹F NMR (188 MHz, CDCl₃ + HFIP-D₂): δ = 81.6 (t, 6F, 3J(F,F) = 9.9 Hz, 23'), -81.7 (t, 3F, 3J(F,F) = 9.9 Hz, 23'), -115.0-115.1 (6F, 18'), -122.4 (18F, 20′), -123.3 (6F, 21′), -124.0 (6F, 19′), -126.8 ppm (6F, 22′); FT-IR (ATR): ν (cm⁻¹) = 2968, 1723 (C=O carbamate), 1660 (C=O amide), 1584, 1569, 1495, 1452, 1438, 1371, 1336, 1295, 1199, 1147, 1115, 1046, 1030, 1014, 976, 905, 856, 842, 805, 769, 750, 733, 722, 704, 685, 658; MALDI-TOF MS: m/z: calcd for: 1818.19; found: 1818.10 (M⁺); 1819.11 (M⁺H⁺), 1841.09 (M⁺Na⁺), 1857.07 (M⁺K⁺); Analysis: calcd (%) for C₂₉H₂₅F₇N₂O₂: C 36.32, H 2.05, N 3.08; found: C 36.18, H 1.81, N 3.04.
3′-[3,4,5-Tris(1H,1H,2H,2H,3H,3H-perfluoroundecyl-1-oxy)benzoylamino]-2,2'-bipyridine-3-amine (11)

Under argon, BOC compound 10 (6.00 gram, 3.30 mmol) was dissolved in TFA (46 mL) and the yellowish solution was then stirred under bubbling of argon at room temperature until all starting material was converted according to TLC. The reaction mixture was concentrated in vacuo at room temperature\(^{32}\) to give a yellow residue which was suspended in acetone (150 mL) and chilled in an ice-bath. Triethyl amine (30 mL) dissolved in acetone (50 mL) was added dropwise to the yellow suspension under vigorous stirring giving a sticky, beige suspension. After stirring for an additional 30 min, the beige suspension was filtered over a Büchner funnel and the residue was washed in acetone (150 mL) and refluxed for 30 min under stirring. Then, the beige suspension was allowed to reach room temperature and filtered over a Büchner funnel and the residue was washed with acetone (2 × 50 mL). Drying of this residue in a vacuum-oven yielded amine 11 (5.01 g, 2.91 mmol, 88 %) as a beige compound. \(R_t = 0.57\) (silica gel, ethyl acetate:MNFB:CHCl\(_3\) 1:2:5 (v:v:v)); m.p. 125.9 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\) + HFIP-D\(_2\), 25 °C); \(\delta = 12.16\) (bs, 1H, 7 N-H), 8.74 (d, 1H, 4', \(^3\)J(H,H) = 8.4 Hz), 8.43 (d, 1H, 6', \(^3\)J(H,H) = 4.6 Hz), 8.00 (d, 1H, 6, \(^3\)J(H,H) = 4.4 Hz), 7.49 (dd, 1H, 5', \(^3\)J(H,H) = 8.2 Hz and 4.8 Hz), 7.31-7.23 (m, 2H, 14+), 7.08 (s, 2H, 10'), 4.12 (t, 6H, 13+14', \(^3\)J(H,H) = 5.8 Hz), \(^{19}\)F NMR (75 MHz, CDCl\(_3\) + HFIP-D\(_2\)); \(\delta = -81.4\) (t, 6F, \(^3\)J(F,F) = 10.2 Hz, 23'), -81.5 (t, 3F, \(^3\)J(F,F) = 9.9 Hz, 23'), -114.8--115.1 (6F, 18'), -122.1--122.4 (18F, 20'), -123.2 (6F, 21'), -124.0 (6F, 19'), -126.7 ppm (6F, 22'), FT-IR (ATR): \(\nu\) (cm\(^{-1}\)) = 3403 and 3288 (NH\(_2\)), 2961, 2886, 1647 (C=O), 1585, 1573, 1522, 1498, 1472, 1454, 1428, 1400, 1372, 1336, 1296, 1199, 1146, 1114, 1066, 1029, 1010, 975, 933, 916, 865, 827, 796, 748, 733, 722, 704, 686, 658; MALDI-TOF MS: \(m/z\): calc for: 1718.14; found: 1718.08 (M\(^+\)), 1719.08 (M+H), 1741.06 (M+Na); Analysis: calc (%) for C\(_{95}H_{129}F_{15}N_{21}O_{17}:\ C 34.94, H 1.70, N 3.26; found: C 34.93, H 1.47, N 3.26.

\(N,N',N''\)-Tris(3′-[3,4,5-tris(1H,1H,2H,2H,3H,3H-perfluoroundecyl-1-oxy)benzoylamino]-2,2′-bipyridyl)benzene-1,3,5-tricarboxamide (1)

Under argon, a solution of trimesyl chloride (0.162 g, 0.610 mmol) in distilled dichloromethane (6 mL) was added dropwise to a well-stirred suspension of amine 11 (3.16 g, 1.84 mmol) and triethylamine (0.40 mL, 0.29 g, 2.87 mmol) in dichloromethane (8 mL) and MNFB (55 mL). A white precipitate was formed. Then, the well-stirred, gray suspension was refluxed under argon for 4 h after which all acid chloride was converted according to FT-IR spectroscopy. After cooling to room temperature, methanol (50 mL) and acetone (50 mL) were added while stirring. The formed precipitate was filtered over a Büchner funnel and the residue was washed with acetone-methanol 1:1 (v:v) (2 × 25 mL) and redispersed in CHCl\(_3\) (90 mL), triethyl amine (5 mL) and MNFB (30 mL) followed by reflux for 30 min. Subsequently, the beige suspension was allowed to reach room temperature and filtered over a Büchner funnel. The beige residue was washed with CHCl\(_3\)-MNFB 3:1 (v:v) (2 × 15 mL). This procedure was repeated once more to yield a sticky, beige residue (2.3 g) that contained predominantly desired product 1 according to \(^1\)H-NMR. The crude product was further purified by repetitive recrystallisations from a hot mixture of chloroform (10 mL), acetone (10 mL) and MNFB (35 mL) and subsequent column chromatography.
Helical self-assembly of fluorinated, preorganized discotics and their co-assembly with chiral discotics

(6.8 References)


Fluorinated calamitic liquid crystals display improved mesophase properties as well as important physical properties (see ref. [26]).

References:


Helical self-assembly of fluorinated, preorganized discotics and their co-assembly with chiral discotics


This low-boiling fluorinated solvent is harmless, inflammable and miscible with almost any common organic solvent. Also, the commercially available MNFB is very transparent in UV/Vis making it suitable for spectroscopic measurements. Methoxynonafluorobutane is readily commercially available as a mixture of isomers under the name HFE-7100 or Novec Engineering Fluid.


a) A Büchi Melting Point B-540 device.


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The extinction coefficients of the mixtures are stable in time.

The annealing step is necessary to reach the thermodynamically most stable state; the optical spectra of the non-annealed mixture change slowly in time to reach a final state while the optical spectra of the annealed mixtures are stable in time at this final state.

Please remind that chiral, C₃-symmetrical disc 2 needs to be mixed with at least 10 mol% of fluorinated disc 1 to achieve complete dissolution.


For these protons a quintet was expected but six lines were observed; probably because of an additional ¹J(H,F) coupling or because of the coupling with two different neighboring CH₂ groups resulting in a triplet out of a triplet.

The perfluorinated carbons can be observed as multiplets between 105 and 125 ppm, but can not be resolved due to their coupling with the ¹⁹F nucleus.


Surprisingly, the CF₃⁻ is the least shielded resonance while the CF₃-CF₂⁻ is the most shielded resonance.

These fluorines are coupled with a neighboring- CH₂- and -CF- group, however assignment of the coupling constants is not possible.

Instead of two triplet-triplets as observed for ester 6, a single triplet-triplet is observed, probably because of the presence of a fluorinated solvent that is able to solvate the perfluor chain.

Due to the fast formation of a lot of foam from boiling solutions of BOC protected 10 or amine 11 care has to be taken during recrystallization steps or concentration in vacuo.

Due to the partial exchange of the acidic amide and cabamate protons with deuterium splitting of the N-H protons is observed together with a reduced intensity of the signal in proton NMR.

Heating of a TFA salt of an amine can cause the formation of a TFA amide.

In this case HFIP induces a significant upfield shift of the N-H proton and proton 4' and vanishing of the NH₂ protons compared to the monoacylated compounds as reported in ref. [41].

Surprisingly, only one triplet is observed, but it can actually exist of two superimposed triplets belonging to protons 13’ and 14’ respectively.

Due to the partial exchange of the acidic amide protons with deuterium, splitting of the N-H protons is observed together with a reduced intensity of the signal in ¹H-NMR.
In the field of supramolecular chemistry control over self-assembly is one of the main targets. This might be accomplished by adaptation of the environment of organic assemblies by allowing their interaction with other molecules or substrates. To do so, the assembling component has to be equipped with a functional site, which requires derivatization. Also, derivatization in itself may result in enhanced, beneficial supramolecular behavior. In this thesis, derivatization of disc-shaped molecules at their periphery is described with the goal of introducing functionality into the discotic systems and of allowing the discotics to perform desirable, programmed interactions with other molecules. The discotics are composed of a central trimesic core and radially equipped with three 2,2'-bipyridinyl-3,3'-diamine moieties that in turn are linked to three gallic moieties decorated with peripheral alkyl tails.

In Chapter 1, an overview of functionalized and desymmetrized discotics is given, with the focus on single-core discotics like triphenylenes, hexabenzocoronenes, phthalocyanines, porphyrins and benzene-1,3,5-tricarboxamides. The synthesis of the desymmetrized derivatives as well as their enhanced supramolecular and material properties is described. It is clear that desymmetrization and functionalization of the originally symmetrical discotics allows programmed interaction with other molecules or gives rise to functional materials besides the original focus on one-dimensional assembly and columnar liquid crystals.

In Chapter 2, two synthetic strategies to replace one of the 3,4,5-trialkoxyphenyl units of 3,3'-bis(acylamino)-2,2'-bipyridine discotics with a phenyl (disc 1, Figure 1) or 4-pyridyl (disc 2, Figure 1) unit are proposed. The first synthetic strategy is based on a statistical approach and the second one on a step-wise approach involving protective-group chemistry. Both strategies afforded the desired non-symmetrical discotics but the second strategy has many advantages over the first one, like easier purification steps and accessibility to multigram amounts of the desired discs and their valuable precursors. Importantly, the desymmetrization does not affect significantly the preorganized hydrogen-bonded structure of the discotics.

The self-assembly properties of desymmetrized discotics 1 and 2 are reported in Chapter 3. Both discotics display helical self-assembly in the mesophase and in apolar solution. Importantly, this assembly of discs 1 and 2 is similar to that of their C3-symmetrical analogues showing that desymmetrization and functionalization of the discotics is feasible without undoing their self-assembly capabilities.

In Chapter 4, the interaction of disc 2, possessing a peripheral 4-pyridyl group, with chiral acids is described as well as the supramolecular transfer of chirality. Several acids were screened to reveal which acids bind selectively with the discotic without disrupting its supramolecular properties. Apparently, acids of intermediate strength like phosphonic and tartaric acids satisfy this requirement. The appropriate chiral acids were used to induce chirality into the helical assemblies of disc 2 in solution. Apparently, the efficiency of the transfer of chirality is not only determined by the strength of the chiral acid, but also by steric
Summary

Chapter 5 deals with the incorporation of a functionalized discotic in methacrylate based polymers. Desymmetrized discotic 3 (Figure 1) carrying a dangling hydroxy group was synthesized that may act as a starting point for a wide variety of functionalized discotics. This was illustrated by transforming disc 1 into a polymerizable disc carrying a methacrylate group. This disc was then copolymerized under ATRP conditions to afford a disc-functionalized poly(butyl methacrylate) copolymer. The latter may serve as a novel material for supramolecular, fluorescent polymeric nanoparticles.

In Chapter 6, a novel, C₅-symmetrical, heavily fluorinated disc (teflon star 4, Figure 1) was introduced. Replacing the originally hydrophobic hydrocarbon periphery by a fluorophilic fluorocarbon periphery (disc 4, Figure 1) allows helical self-assembly in fluorinated media. Teflon star 4 forms very stable columnar mesophases in which helicity may be present. Surprisingly, a proper choice of solvent combination allowed the formation of mixed assemblies in which both discotics possessing a chiral, hydrocarbon periphery and fluorinated discotics 4 are present. This allows transfer of chirality from the former to the latter with concomitant amplification of chirality.

Figure 1: Discotics described in this thesis. Desymmetrized discotics 1 and 2 figure as the main topics in Chapters 2, 3 and 4. Hydroxy-disc 3 is applied in Chapter 5 and teflon star 4 is the key molecule in Chapter 6.
Samenvatting

3,3'-Bis(acylamino)-2,2'-bipyridine discoten: desymmetrisatie en functionalisatie

In het gebied van de supramoleculaire chemie is de controle over zelf-assemblage één van de hoofddoelen. Dit doel kan worden bereikt door de omgeving waar deze zelf-assemblages zich in bevinden te veranderen of door interactie met andere moleculen of substraten. Hiervoor moet de assemblerende component worden voorzien van een functionele groep en dit vereist derivatisering. Derivatisering op zich zelf kan ook resulteren in beter supramoleculair gedrag. Het onderwerp van dit proefschrift is de derivatisering van de buitenkant van schijf-vormige moleculen met als doel om functionaliteit te introduceren in de discotische (discoot = schijf-vormig molecuul met vloeibaar-kristalline eigenschappen) systemen en om de discoten gewilde, voorgeprogrammeerde interacties met andere moleculen te laten ondergaan. Deze discoten bestaan uit een centrale trimesische kern waaraan drie 2,2'-bipyridine-3,3'-diamine groepen zijn gekoppeld die op hun beurt weer zijn gekoppeld aan perifere 3,4,5-trialkoxybenzoyl eenheden. In hoofdstuk 1 is een overzicht van gefunctionaliseerde en gedesymmetriseerde discoten gegeven waar de nadruk ligt op één-kernige discoten zoals trifenylenen, hexabenzocoronenen, ftaalocyanines, porfyrenes en benzeen-1,3,5-tricarboxamiden. Zowel de synthese van de gedesymmetriseerde derivaten en hun verbeterde supramoleculaire- en materiaaleigenschappen zijn beschreven. Desymmetrisatie en functionalisatie van discoten maakt voorgeprogrammeerde interacties met andere moleculen mogelijk, net zoals de vorming van functionele materialen. In hoofdstuk 2 zijn twee synthetische strategieën beschreven om één van de 3,4,5-trialkoxyfenyl groepen van 3,3'-bis(acylamino)-2,2'-bipyridine gebaseerde discoten te vervangen door een fenyl (discoot 1, Figuur 1) of 4-pyridyl (discoot 2, Figuur 1) groep. De eerste strategie is gebaseerd op een statistische benadering en de tweede op een staps-gewijze benadering waarbij beschermende-groep chemie een belangrijke rol speelt. Beide strategieën geven de vereiste niet-symmetrische discoten, maar de tweede heeft veel voordelen ten opzichte van de eerste, zoals eenvoudigere zuiveringstappen en de synthese van multigram hoeveelheden van de niet-symmetrische discoten en hun precursoren. Belangrijk is dat de desymmetrisatie de gepreorganiseerde waterstof-gebrugde structuur van de discoten intak gaat. De zelf-assemblage eigenschappen van niet-symmetrische discoten 1 en 2 zijn beschreven in Hoofdstuk 3. De helische zelf-assemblages van discoten 1 en 2 in oplossing toonden helische zelf-assemblage in de mesofase en in apolaire oplossing wat vergelijkbaar is met het gedrag van hun C₃-symmetrische analogen. Dus desymmetrisatie en functionalisatie van de discoten is mogelijk zonder hun zelf-assemblage eigenschappen te verhinderen. In Hoofdstuk 4 is de interactie van discoot 2, die een perifere 4-pyridyl groep bevat, met chirale zuuren beschreven alsmede de supramoleculaire overdracht van chiraliteit. Verschillende zuuren waren getest om te bepalen welke zuuren selectief binden aan de discoot zonder de supramoleculaire eigenschappen aan te tasten. Blijkbaar voldoen zuuren van gemiddelde sterkte aan deze voorwaarde. De geschikte chirale zuuren waren vervolgens gebruikt voor de introductie van chiraliteit in de helische zelf-assemblages van discoot 2 in oplossing. De efficientie van de chiraliteitsoverdracht blijkt niet alleen bepaald te zijn door de sterkte van het
Samenvatting

gebruikte chirale zuur, maar ook door sterische effecten. Tevens is de stabilitéit van het chirale complex erg gevoelig en hangt af van de stabilitéit van de helix, de sterkte van het zuur-base complex en de oplosbaarheid van de componenten. Hoofdstuk 5 heeft als onderwerp de inbouw van een gefunctionaliseerde discoot in methacrylaat gebaseerde polymeren. Gedesymmetriseerde discoot 3 (Figuur 1), die een vrije hydroxygroep bezit, was gesynthetiseerd en deze kan dienen als reactant voor een familie van gefunctionaliseerde discoten. Dit was aangetoond met de conversie van discoot 3 in een polymeriseerbare discoot die is uitgerust met een methacrylaat groep. Deze discoot was vervolgens gecopolymeriseerd onder ATRP (Atoom Transfer Radicaal Polymerisatie) condities waarbij een poly(butyl methacrylaat) copolymer met bengelende discoten was verkregen. Dit copolymer zou als grondstof kunnen dienen voor supramoleculaire, fluorescerende nanodeeltjes. In Hoofdstuk 6 is een nieuwe, C₃-symmetrische, sterk gefluoreerde discoot (teflonster 4, Figuur 1) geïntroduceerd. Doordat de oorspronkelijk hydrofobe koolwaterstof periferie is vervangen door een fluorofiele fluorkoolstof periferie wordt helische zelf-assemblage mogelijk in gefluoreerde oplosmiddelen. Discoot 4 vormt erg stabiele columnaire, mogelijk helische mesofasen. In oplossing is de vorming van gemengde helices mogelijk waarin zowel discoten met een chirale koolwaterstof buitenkant als gefluoreerde discoten aanwezig zijn door de juiste oplosmiddel combinaties te gebruiken. Dit zorgt naast overdracht van chiraliteit van eerstgenoemde naar laatstgenoemde ook voor amplificatie van chiraliteit.

**Figuur 1:** Discoten die beschreven zijn in dit proefschrift. Gedesymmetriseerde discoten 1 en 2 zijn de cruciale moleculen in Hoofdstukken 2, 3 en 4. Hydroxy-discoot 3 is gebruikt als sleutel-precursor in Hoofstuk 5 en teflonster 4 is het belangrijkste molecuul in Hoofdstuk 6.
Curriculum Vitae


Michel van Houtem was born on 5 March, 1981 in Heerlen, the Netherlands. After completion of his secondary education at the Sophianum grammar school in Gulpen, he started studying Chemical Engineering and Chemistry at the Eindhoven University of Technology in 1999. His master was completed with a graduation project in the Laboratory of Macromolecular and Organic Chemistry (MST at the moment), under the supervision of Prof. Dr. E.W. (Bert) Meijer. From September 2005, he worked as a PhD student in the same laboratory, under the supervision of Dr. Jef A.J.M Vekemans en Prof. Dr. E.W. (Bert) Meijer. The aim of this research was the desymmetrization and functionalization of 3,3'-bis(acylamino)-2,2'-bipyridine based discotics, of which the most important results are presented in this thesis.
Dankwoord/Expression of gratitude

De afgelopen vier jaar waren, net als tijdens mijn afstudeerperiode daarvoor, een fijne en leerzame ervaring. Graag wil ik in deze laatste paragraaf de mensen bedanken die daaraan hebben meegeholpen en hopelijk ben ik niemand vergeten, anders mijn excuses hiervoor.

Als eerste wil ik mijn promotor, Prof. Bert Meijer bedanken voor mijn begeleiding, enthousiasme en het overzicht houden van mijn onderzoek. Bedankt voor alle hulp, discussies en waardevol commentaar op manuscripten. Ik heb veel bewondering voor de kennis die je hebt over de chemie dat varieert van π-conjugated systemen tot eiwitten en het belang dat je hecht in de groei en ontwikkeling van je AIO's en postdocs. Tevens waardeer ik hoe je leiding geeft aan de vakgroep en de professionele en gezellige sfeer in MST die vrij uniek is. Uiteraard gaat mijn waardering hiervoor ook uit naar Prof. René Janssen, Prof Rint Sijbesma, Prof. Luc Brunsveld en de andere staafleden.

Graag wil mijn copromotor, Dr. Jef Vekemans bedanken voor de vele discussies, hulp en uitleg bij de vele organisch/synthetische problemen, NMR spectra en bij het opstellen van manuscripten en presentaties. Jouw kennis van de organische chemie is ongeëvenaard en vaak heb ik je kantoor met nieuwe ideeën en moed verlaten. Ook heb ik veel profijt gehad van jouw secure correcties en waardevolle suggesties van rapporten, manuscripten en hoofdstukken die daardoor een stuk beter zijn geworden.

Graag wil ik Prof. Rint Sijbesma en Prof. Roeland Nolte danken voor hun deelname in de kerncommissie en het lezen van mijn manuscript. I would like to thank Prof. Serrano for reading the manuscript and for participating in my committee. Your work on supramolecular columnar liquid crystals and chirality inspired us a lot and was an inspiration for Chapter 4. Of course, I would like to thank Dr. Rafael Martín-Rapún for participation in my committee. Rafa, you helped me a lot in understanding the world of columnar liquid crystals and X-ray diffraction and your contribution to our Chemistry paper about the GGB and GGP discs and to Chapter 3 and 6 is very important. Muchas gracias! Also, many thanks for the useful discussions and for reading and correcting my manuscripts so carefully. I wish you a lot of success in sunny Tarragona and much happiness with your family. Ook wil ik Dr. Anja Palmans bedanken voor haar deelname in de promotiecommissie. Samen met Jef ben jij begonnen met de C₃-symmetrische bipyridine discoten die de basis vormen voor dit proefschrift en het spijt me dat ik vooral bezig ben geweest met het teniet doen van de C₃-symmetrie. Ik ben er van overtuigd dat onze discoten een belangrijke rol zullen gaan spelen in Bert’s nanoparticle project.

I would like to thank Prof. Dr. Jim Feast and Dr. Erik Berda for reading my manuscript and giving valuable suggestions. Jim, I enjoyed the time when we were going through the chapters a lot, also because of the conversations about English language and history. Your comments on the chapters of the manuscript helped me a lot. I also appreciate your help with contacting the crystallographic experts in Durham. Prof. Judith Howard, Dr. Olga Chetina and Dr. Ehmke Pohl, I greatly appreciate your efforts to solve the crystal structure of the adamantane disc of Chapter 3.
Tijdens m'n promotieonderzoek heb ik verschillende studenten mogen begeleiden, dat erg plezierig was. Faysal Benaskar, samen hebben we de synthese van de Teflonsterren onder de knie gekregen, ondanks hun 'beperkte' oplosbaarheid. Jouw werk heeft aan de basis gestaan van Hoofdstuk 6 waar ook nog een leuk artikel uit zal gaan komen. Veel dank en veel succes met je eigen promotieproject op vloer 1! Axel van Zweeden, jouw afstudeerwerk heeft geleid tot een mooi verslag en tot Hoofdstuk 5. De hydroxy-discoot die je hebt gemaakt heeft nog veel potentieel en je hebt voor de eerste keer een bipyridine discoot gepolymeriseerd. Veel dank en veel succes tijdens je stage!

Jolanda Spiering, veel dank voor de synthese van de '2/3de discoten' die gebruikt zijn in hoofdstuk 2 en 5, ook heb ik dankbaar gebruik gemaakt van andere bouwstenen zoals chirale wedges en 2,2'-bipyridine-3,3'-diamine. Tevens wil ik Bas de Waal en het Spinoza instituut bedanken voor de levering van verschillende bouwstenen.

Veel hulp heb ik gehad van Ralf Bovee, Dr. Xianwen Lou en Joost van Dongen met chromatografische en massaspectrometrische analyses en scheidingen, mijn dank daarvoor! Henk Eding en Ralf, bedankt voor alle element analyses. Verder wil ik Dr. Marcel van Genderen, Dr. Tom de Greef, Thomas Hermans en Marko Nieuwenhuizen bedanken voor hun hulp bij NMR analyses, Dr. Henk Janssen en Carel Fitié voor hulp met DSC analyses en de verse doctoren Maarten Smulders en Martin Wolffs voor hulp met optische spectroscopie. Carel, net als Rafa heb je mij geholpen in de wereld van columnaire vloeibare kristallen en röntgendiffraactie, veel dank voor het meten van de teflonster die liever dood ging dan dat hij isotroop werd en niet netjes wilde alignen zoals de andere sterren wel deden. Ongeveer tegelijkertijd hebben we aan onze proefschriften gezeefd en samen hebben we een review artikel gecomponeerd, vaak kon ik op je steunen als ik weer 'ns in een dip zat! Graag wil ik Dr. Pim Janssen bedanken voor het uitvoeren van AFM metingen en Dr. Koen Pieterse voor het maken van de mooie, rode kaft en het modelleren van de bipy-disc helix die op de kaft en in Hoofdstuk 3 staat. Dr. Martijn Veld wil ik zeker bedanken voor de cartoons van deze helix.

Tevens wil ik graag Otto van Asselen en Pit Theunissen bedanken voor hun hulp met infrarood spectroscopie op vloer 0, Ben Norder van de TU Delft voor hulp met röntgendiffraactie en finally I would like to thank Dr. Michael Debije for performing conductivity measurements on the teflon star of Chapter 6 and Dr. Martin Lutz of the University of Utrecht for measuring crystals with X-ray diffraction.

Veel mensen dragen bij aan een goede werksfeer. Hans, bedankt voor het regelen van alle oplosmiddelen, stofjes, glaswerk en (lab)apparatuur, ook al moet het uit de woestijn in Israël komen! Henk, ook jij helpt vaak met technische problemen en je zorgt altijd voor koffie, een praatje en een opgeruimde koffieruimte. Angela, Joke, Carine, Ingrid, Janna, Hanneke, Nora en Patricia, bedankt voor alle mogelijke secretariële ondersteuning en jullie hulp.

Verder wil ik alle participanten (met uitzondering van de aanwezige computer) danken voor de bijdragen aan en discussies tijdens de helix- en nanoparticlelunchmeeting waarvan ik met plezier voorzitter van ben geweest. Het organiseren van het MST-uitje naar Friesland (Wat's gebird?) heb ik samen met Bert, Joke, Carel, Wencke, Stefan en Johan gedaan en ondanks de korte tijdsspanne die we hadden was het een fantastisch uitje geworden!
Op lab 4 (het Überlab met de beste verzamel-CD’s) is er altijd een leuke werksfeer geweest waarvoor ik m’n labgenootjes Arjan, Axel, Bart, Davide, Ewelina, Faysal, James, Janus, Jianbin, Johan, Juliën, Kars, Karthik, Linda, Maarten, Madeleine, Mark, Martin, Martijn G, Martijn V, Mellany, Melanie, Nicole, Oren, Peter K, Peter Z, Rachid, Ramon, Rob, Robert Rolf, (bedankt voor de citronellolderivaat!), Roxanne, Shahid, Stephanie, Suvarna, Tobias, Veronique, Wencke, Xiao-Yu en Yuko graag wil bedanken. Ook op kantoor STO 4.47 is de sfeer goed geweest; Maarten (excuses voor alle gegrom tijdens pc- en thesisproblemen), Floris, Adrien, Cameron, Jan G, Ronald en Željko bedankt hiervoor!

Naast het werk was er ook tijd voor ontspanning zoals de regelmatige sportieve uurtjes in ’t krachthonk met Carel, Arjan, Tristan, Marko, Martin en Janus en regelmatige lunches met Ewelina, Floris, Lars, Pol, Seda en Tristan. Verder waren er natuurlijk 2 × wintersport (erg leuk, bedankt Jeroen en Frank voor de organisatie!), uitjes, cabaret optredens, pokervonden, (kerst)borrels, stapavonden en onofficiële kerstborrels, ouwhoeren, koffie-, thee- en lunchpauzes, discussies, fruitapjes, film- en bioscoopvonden, huisfeestjes, verjaardagen, uiteraard, en een legendarisch Eddie Wally optreden waarvoor ik Amparo en Thomas, Adrien, Arantxa, Arjan, Axel, Bas, Bram, Carel, Dana, Daniele, Davide, Dirk en Karin, Edith, Erik en Dana, Eva, Ewelina, Floris, Frank, Henk K, Jan G, Jan V en Anna, Jeroen (de Herrik) en Noëlle, Johan B, Johan (Earl), Jolanda, Joris, Jos, Karthik, Katja, Kelly en Sjoerd, Linda, Maarten S en Leonie, Maarten P, Maartje, Mantas, Marie-France, Marcel, Marko, Martin W, Martin S, Martijn G, Martijn V, Matthew and Shanna, Matthijn, Michael, Michel F, Mindaugas, Misha, Melissa, Nicole, Noémie, Oren, Pascal, Patricia, Patrick, Pol, Rachid, René (bedankt voor alles tijdens m’n eerste jaren bij SMO en alles wat ik van je hebt geleerd!) en Anouk, Ronald, Robert, Roxanne en Pablo, Seda, Stefan, Subi, Tristan, Wencke en Edwin, Wilco, Yuko (hee, de "M" is dominant in dit rijtje!, heb ik nu iedereen?) en nog meer mensen wil bedanken. Mijn excuses aan iedereen voor voor m’n neerslachtige, stille en besluiteloze momenten.

Tenslotte wil ik geer mieng familie en vrung i Limburg bedanke veur alle steun, vertroewe en sjpas same, zoe wie peerd-rieje, op vakans goan, thoes op de bank hange, wandele, karte, skieje, vreetje, allerliej oetsjeperfectes en nog veul miedeer dinger. Ut spiet mich dat ik vaak aawezig woar of un bietje mismoodig woar. Bram, Fabiënne en Lukas, Benoît, Jérôme, Karin en Niek, Niels en Peggy, Noach (SG), Jorien en toeomstig SG, Quiryn en Daiverke, Tim en Alma, Niels, Sebastiaan (Bassie), Jim, Veronique, Brenda, Theo, ouch e vung ut erg suin om deer as vrung te han! Mam, Pap, Jo, Angèle en Cyriel, Marietje, Thomas en Jop d’r zut erg belangriek veur mich!

Michel