Crystal engineering of melamine - imide complexes: tuning the stoichiometry by steric hindrance of the imide carbonyl groups

Citation for published version (APA):

Lange, R. F. M., Beijer, F. H., Sijbesma, R. P., Hooft, R. W. W., Kooijman, H., Spek, A. L., Kroon, J., & Meijer, E. W. (1997). Crystal engineering of melamine - imide complexes: tuning the stoichiometry by steric hindrance of the imide carbonyl groups. *Angewandte Chemie - International Edition*, 36(9), 969-971.
<https://doi.org/10.1002/anie.199709691>

DOI:

[10.1002/anie.199709691](https://doi.org/10.1002/anie.199709691)

Document status and date:

Published: 01/01/1997

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.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

- [9] a) B. Hille, *Ionic Channels of Excitable Membranes*, 2nd ed. Sinauer, Sunderland, MA, USA, 1992; b) P. Langer, *Angew. Chem.* **1985**, 97, 939–959; *Angew. Chem. Int. Ed. Engl.* **1985**, 24, 905–923; c) B. A. Suarez-Isla, K. Wan, J. Lindstrom, M. Montal, *Biochemistry* **1983**, 22, 2319–2323.
- [10] G. A. Woolley, A. S. I. Jaikaran, Z. Zhang, S. Peng, *J. Am. Chem. Soc.* **1995**, 117, 4448–4454.
- [11] The analog of **1** lacking the crown ethers, Boc-(L-F-L₃-F-L)₃-OMe, was inactive in the same bilayer experiment but led to perturbations in bilayer stability.
- [12] a) N. Voyer, J. Lamothe, *Tetrahedron* **1995**, 51, 9241–9284; b) N. Voyer, *Top. Curr. Chem.* **1996**, 184, 1–37.
- [13] C. D. Bain, S. D. Evans, *Chem. Br.* **1995**, 31, 46–48.
- [14] L. A. Bumm, J. J. Arnold, M. T. Cygan, T. D. Dunbar, T. P. Burgin, L. Jones II, D. L. Allara, J. M. Tour, P. S. Weiss, *Science* **1996**, 271, 1705–1707.
- [15] N. Voyer, *J. Am. Chem. Soc.* **1991**, 113, 1818–1821.

Crystal Engineering of Melamine–Imide Complexes; Tuning the Stoichiometry by Steric Hindrance of the Imide Carbonyl Groups**

Ronald F. M. Lange, Felix H. Beijer, Rint P. Sijbesma, Rob W. W. Hooft, Huub Kooijman, Anthony L. Spek, Jan Kroon, and E. W. Meijer*

The proposed infinite, two-dimensional lattice, formed by complexation of melamine with cyanuric acid through triple hydrogen bonds,^[1] has been a unique inspiration to supramolecular chemists.^[2] Various model studies have been performed to mimic this triple hydrogen bond formation.^[3–9] Whitesides et al. reported the formation of a well-defined complex of six melamine and six cyanuric acid derivatives, linked together by 36 hydrogen bonds.^[3] Using substituted melamines and barbituric acid derivatives, they were also able to prepare molecular tapes, crinkled tapes, and rosettes.^[4] A variation of the linear tape was described by Lehn et al.^[5] Furthermore, helical^[6] and tube-like^[7] nanostructures are formed by complexation of dialkyl-substituted melamines with a diimide, whereas Rebek et al. reported on a trisimide which could act as a molecular “tool chuck” for melamine.^[8] Until now, only two crystalline complexes containing melamine have been reported in literature.^[9]

Here, we present the formation of supramolecular 1:1, 1:2, and 1:3 complexes of melamine with imides. We show that the availability for hydrogen bonding of the carbonyl groups in the imide is strongly influenced by subtle differences in its molecular structure. The result that the stoichiometry of the supramolecular complexes can be tuned represents a distinct step forward towards crystal engineering.^[10]

Cocrystallization of melamine with succinimide from water or DMSO in a molar ratio between 1:10 and 1:1 resulted in the formation of a supramolecular 1:1 complex of melamine and

succinimide. When a molar excess of melamine was used, crystals of pure melamine were formed together with crystals of the 1:1 complex. X-ray analysis^[11] of the complex revealed a 1:1 sheetlike structure (Figure 1). In both molecules, every donor

Figure 1. X-ray crystal structure of the 1:1 complex between melamine and succinimide (PLUTON plot).

and acceptor site available for hydrogen bonding is used. Surprisingly, when glutarimide was crystallized with melamine from water or DMSO in melamine:imide ratios between 1:10 and 1:2, a 1:2 complex of melamine and glutarimide was obtained. X-ray analysis^[12] showed a 1:2-herringbone structure (Figure 2). In this complex, one of the four carbonyl acceptor sites of the imide is not involved in hydrogen bonding. Therefore, by masking two of the four carbonyl acceptor sites of an imide, it should be possible to obtain a 1:3 cocrystal with melamine. To verify this hypothesis, we co-crystallized melamine with a variety of imides (adipimide, 2,3-diphenylmaleimide, phthalimide, diphenylimide, and 1,8-naphthalimide) in various ratios of DMSO, DMF, ethanol, or NMP as solvent. However, crystallization did not result in single crystals of the desired 1:3 melamine–imide complex. This is possibly due to the large solubility difference between the imides and melamine.^[13]

However, cocrystallization of melamine with the water-soluble 1-*N*-propylthymine from water or 96% ethanol in initial

[*] Prof. Dr. E. W. Meijer, F. H. Beijer, Dr. R. P. Sijbesma
Laboratory of Organic Chemistry
Eindhoven University of Technology
P. O. Box 513, 5600 MB Eindhoven (The Netherlands)
Fax: Int. code + (40) 2451036
e-mail: tgtoelm@chem.tue.nl

R. F. M. Lange
DSM Research, Geleen (The Netherlands)
Dr. R. W. W. Hooft, Dr. H. Kooijman, Dr. A. L. Spek, Prof. J. Kroon
Bijvoet Center for Biomolecular Research, University of Utrecht (The Netherlands)

[**] The authors acknowledge the fruitful discussions with many colleagues at DSM Research and the University of Eindhoven. Dr. B. Coussens is acknowledged for her contributions in molecular modeling.

Figure 2. X-ray crystal structure of the 1:2 complex between melamine and glutarimide (PLUTON plot).

molar ratios between 1:2 and 1:5 resulted indeed in the crystallization of the desired 1:3 melamine–imide complex. X-ray analysis^[14] showed a 1:3 C_3 -symmetrical structure with disordered propyl groups and small quantities of disordered solvent in infinite channels perpendicular to the plane of molecules (Figure 3).

The crystal structures of the complexes show that all hydrogen-bond lengths and angles agree well with values in other melamine complexes^[4, 5, 9] and support the triple hydrogen-bond motif. In the 1:1 melamine–succinimide crystal structure the molecules are paired through three anti-parallel hydrogen bonds (Figure 1).^[15a] Two independent pairs are present in the unit cell, and a two-layer zigzag sheet is formed. Intermolecular hydrogen bonds within the two-layer zigzag sheet connect the different pairs parallel to the a,c plane (Figure 1). No hydrogen bonding occurs between different two-layer zigzag sheets along the b axis. Detailed analysis of this complex crystal structure reveals that each succinimide molecule uses all four H-bond acceptor sites and its H-bond donor site, while melamine uses three H-bond acceptor and all its six H-bond donor sites. This results in a 1:1 complex with seven donors and seven acceptors per pair.

In the 1:2 melamine–glutarimide crystal structure, each melamine molecule is connected to two glutarimide molecules by three anti-parallel hydrogen bonds.^[15b] These units, located

Figure 3. X-ray crystal structure of the 1:3 complex between melamine and 1-*N*-propylthymine (PLUTON plot).

on a crystallographic twofold rotation axis, are connected in a one dimensional hydrogen-bonded chain, forming an α -network in which the arrangement of the molecules resembles a herringbone structure. No specific interactions between the α -networks are detected. All molecules in the complex leave one of their H-bond acceptor sites unused. Assuming that one of the four imide carbonyl acceptor sites is not available due to steric hindrance, it is obvious that a 1:2 stoichiometry gives an optimal balance of donor and acceptor sites.

In the 1:3 melamine–(1-*N*-propylthymine) crystal structure four molecules are connected by nine H-bonds to form a planar C_3 -symmetrical structure.^[15c] Here, two carbonyl acceptor sites are not used, because they are masked by the methyl and the *N*-propyl group. This 1:3 arrangement of molecules around melamine resembles the hydrogen-bonding motif of the cyanuric acid–melamine lattice.

These results show that it is possible to influence the ratio of the components of the complex of melamine with succinimide (1:1), glutarimide (1:2), and 1-*N*-propylthymine (1:3). The availability of the imide carbonyl acceptor sites affords a handle to tune the supramolecular crystal structure with melamine. Because of the hydrophobic interactions, water seems to be the best medium from which the different crystals can be grown. The 1:3 melamine–imide structure is consistent with the arrangement of cyanuric acid around melamine in the 1:1 com-

plex of melamine and cyanuric acid.^[11] It also supports the 1:3 complexation of melamine with an alternating copolymer of maleimide and styrene, in which the polymer backbone is presumed to mask two carbonyl acceptor sites of the maleimide.^[16] The present results suggest that uncovering assembly rules that govern the crystallization of a restricted group of related complexes is a useful approach to the design of crystalline solids.^[10, 13] Further research to extend these new insights into the formation of supramolecular lattices is in progress.

Experimental Section

Typical procedure for the cocrystallization of melamine and succinimide: melamine (99.1 mg, 0.79 mmol) and succinimide (78.7 mg, 0.79 mmol) were dissolved in water (5 mL) under reflux and slowly cooled to ambient temperature. After filtration 136.9 mg (0.61 mmol, yield 77%) of the 1:1 melamine-succinimide cocrystals were obtained. The 1:2 melamine-glutarimide and the 1:3 melamine-(1-*N*-propylthymine) complexes were obtained in a similar manner.

Received: October 4, 1996 [Z 96141E]

German version: *Angew. Chem.* 1997, 109, 1006–1008

Keywords: crystal engineering · hydrogen bonds · imides · supramolecular chemistry

- [1] a) G. Ostragorich, R. Bacaloglu, *Acad. Repub. Pop. Rom. Fil. Chuj Stud. Cercet. Chim.* 1962, 18, 273; b) A. I. Finkel'shtein, O. S. Rukevich, *Zh. Prikl. Spektroskop.* 1983, 38, 327.
- [2] Reviews on supramolecular chemistry: a) J.-M. Lehn in *Supramolecular Chemistry*, VCH, Weinheim, 1995; b) G. R. Desiraju, *The Crystal as a Supramolecular Entity*, Wiley, 1996; c) D. Philp, J. F. Stoddart, *Angew. Chem.* 1996, 108, 1242; *Angew. Chem. Int. Ed. Engl.* 1996, 35, 1154; d) H. Ringsdorf, B. Schlarp, J. Venzmer, *ibid.* 1988, 100, 117 bzw. 1988, 27, 113.
- [3] J. P. Mathias, C. T. Seto, E. E. Simanek, G. M. Whitesides, *J. Am. Chem. Soc.* 1994, 116, 1725.
- [4] a) J. A. Zerkowski, C. T. Seto, G. M. Whitesides, *J. Am. Chem. Soc.* 1992, 114, 5473; b) J. A. Zerkowski, G. M. Whitesides, *ibid.* 1994, 116, 4298; c) J. A. Zerkowski, J. P. Mathias, G. M. Whitesides, *ibid.* 1994, 116, 4305; d) J. P. Mathias, E. E. Simanek, J. A. Zerkowski, C. T. Seto, G. M. Whitesides, *ibid.* 1994, 116, 4316; e) J. P. Mathias, E. E. Simanek, G. M. Whitesides, *ibid.* 1994, 116, 4326.
- [5] a) J.-M. Lehn, M. Mascal, A. DeCian, J. Fischer, *J. Chem. Soc. Chem. Comm.* 1990, 479; b) *J. Chem. Soc. Perkin Trans.* 1992, 461.
- [6] N. Kimizuka, S. Fujikawa, H. Kuwahara, T. Kunitake, A. Marsh, J.-M. Lehn, *J. Chem. Soc. Chem. Comm.* 1995, 2103.
- [7] N. Kimizuka, T. Kawasaki, K. Hirata, T. Kunitake, *J. Am. Chem. Soc.* 1995, 117, 6360.
- [8] J. Rebek, Jr., *Pure Appl. Chem.* 1989, 61, 1517.
- [9] a) J. A. Zerkowski, J. C. MacDonald, G. M. Whitesides, *Chem. Mater.* 1994, 6, 1250; b) M. M. Chowdhry, D. M. P. Mingos, A. J. P. White, D. J. Williams, *Chem. Comm.* 1996, 899.
- [10] a) G. R. Desiraju, *Angew. Chem.* 1995, 107, 2541; *Angew. Chem. Int. Ed. Engl.* 1995, 34, 2328; b) J. D. Dunitz, *Pure Appl. Chem.* 1991, 63, 177; c) M. C. Etter, *J. Phys. Chem.* 1991, 95, 4601.
- [11] Crystal data for 1:1 melamine-succinimide: $C_3H_6N_6 \cdot C_4H_5NO_2$, $M_r = 225.21$ g mol⁻¹, colorless, block-shaped crystal (0.25 × 0.62 × 0.75 mm), monoclinic, space group $P2_1/c$ (no. 14), $a = 10.1648(8)$, $b = 14.0935(6)$, $c = 14.5361(5)$ Å, $\beta = 106.253(5)^\circ$, $V = 1999.2(2)$ Å³, $Z = 8$, $\rho_{\text{calc}} = 1.4964(1)$ g cm⁻³, $F(000) = 944$, $\mu(\text{CuK}\alpha) = 9.4$ cm⁻¹. Of 5187 reflections measured, 4126 were independent; $R_{\text{int}} = 0.050$, $(3.1^\circ < \theta < 75.0^\circ)$, $\omega/2\theta$ scan, $T = 295$ K, $\text{CuK}\alpha$ radiation, Ni filter, $\lambda = 1.54184$ Å on an Enraf-Nonius CAD4-F diffractometer in a sealed tube. Data were corrected for Lp effects, extinction, and for a linear instability of 2% in three reference reflections during 59 h of X-ray exposure time; no absorption correction applied. The structure was solved by automated direct methods (SHELXS86). Refinement on F was carried out by full-matrix least-squares techniques (SHELXL96); final R value 0.043, $wR = 0.056$, $w = 1/\sigma^2(F)$, for 3836 data with $I > 2.5\sigma(I)$ and 357 parameters. Hydrogen atoms were located on a difference Fourier map and subsequently included in the refinement. All non-hydrogen atoms were refined with anisotropic thermal parameters; the hydrogen atoms were refined with one overall isotropic thermal parameter. A final difference Fourier showed no residual density outside -0.09 and 0.09 e Å⁻³.
- [12] Crystal data for 1:2 melamine-glutarimide: $C_3H_6N_6 \cdot 2C_5H_7NO_2$, $M_r = 352.36$ g mol⁻¹, colorless, block-shaped crystal (0.25 × 0.25 × 0.50 mm), monoclinic, space group $C2/c$ (no. 15), $a = 14.5430(3)$, $b = 8.5816(3)$, $c = 13.2400(4)$ Å, $\beta = 97.697(3)^\circ$, $V = 1637.49(8)$ Å³, $Z = 4$, $\rho_{\text{calc}} = 1.4292(1)$ g cm⁻³, $F(000) = 744$, $\mu(\text{CuK}\alpha) = 8.8$ cm⁻¹. Data collection and re-

duction was performed as described in ref. [11]. Of 3041 reflections measured, 1699 were independent; $R_{\text{int}} = 0.011$, $(3.4^\circ < \theta < 75.0^\circ)$. The structure was solved by automated direct methods (SIR92). Refinement on F^2 was carried out by full-matrix least-squares techniques (SHELXL-93); no observance criterion was applied during refinement. Hydrogen atoms were located on a difference Fourier map and subsequently included in the refinement. All non-hydrogen atoms were refined with anisotropic thermal parameters; hydrogen atoms were refined with individual isotropic thermal parameters. Refinement converged at $wR_2 = 0.095$, $1/[\sigma^2(F^2) + (0.0412P)^2 + 0.57P]$, $P = (\text{Max}(0, F_o^2) + 2F_o^2)/3$, $R_1 = 0.033$ (for 1598 reflections with $I > 2\sigma(I)$), $S = 1.11$, for 156 parameters. A final difference Fourier showed no residual density outside -0.15 and 0.22 e Å⁻³.

- [13] C. B. Aakeröy, K. R. Seddon, *Chem. Soc. Rev.* 1993, 397.
- [14] Crystal data for 1:3 melamine-(1-*N*-propylthymine): $C_3H_6N_6 \cdot 3C_8H_{12}N_2O_2$, $M_r = 1261.41$ g mol⁻¹, colorless, block-shaped crystal (0.1 × 0.2 × 0.5 mm), hexagonal, space group $P6_3/m$ (no. 176), $a = 17.212(2)$, $c = 6.3697(5)$ Å, $V = 1634.2(3)$ Å³, $Z = 2$, $\rho_{\text{calc}} = 1.282$ g cm⁻³, $F(000) = 672$, $\mu(\text{MoK}\alpha) = 1.0$ cm⁻¹. All data, where relevant, are given without disordered solvent contribution (*vide infra*). Of 4825 reflections measured, 1366 were independent; $R_{\text{int}} = 0.14$, $(1.37^\circ < \theta < 27.5^\circ)$, ω scan, $T = 100$ K, $\text{MoK}\alpha$ radiation, graphite monochromator, $\lambda = 0.71073$ Å on an Enraf-Nonius CAD4 Turbo diffractometer on rotating anode. Data were corrected for Lp effects and for a linear decay of 4% of three reference reflections during 59 h of X-ray exposure time; no absorption correction was applied. The structure was solved by automated direct methods (SHELX86). Refinement on F^2 was carried out by full-matrix least-squares techniques (SHELXL-93); no observance criterion was applied during refinement. The *N*-propyl moiety is disordered over four positions, two of which are generated by space-group symmetry. The occupancy ratio of the two unique conformations was included as a parameter in the refinement. The unit cell contains a channel parallel to the *c* axis and passing through the origin, filled with disordered solvent (probably water). This density was modeled by introducing two partially occupied oxygen sites in the channel. Hydrogen atoms were located on a difference Fourier map and subsequently included in the refinement. All non-hydrogen atoms were refined with anisotropic thermal parameters except for the carbon atoms in the disordered *N*-propyl moiety. Hydrogen atoms were refined with a fixed isotropic thermal parameter related to the value of the equivalent isotropic displacement parameter of their carrier atoms by a factor of 1.5 for the methyl, disordered methylene, and amine hydrogen atoms, and by a factor of 1.2 for the other hydrogen atoms. Refinement converged at $wR_2 = 0.179$, $w = 1/[\sigma^2(F^2) + (0.0483P)^2 + 1.81P]$, $R_1 = 0.065$ (for 690 reflections with $I > 2\sigma(I)$), $S = 1.07$ for 113 parameters. A final difference Fourier showed no residual density outside -0.26 and 0.28 e Å⁻³. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-100114. Copies of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: int. code + (1223) 336-033; e-mail: deposit@chemcrs.cam.ac.uk).
- [15] a) The NH...O hydrogen bonds are of comparable length (3.125(2), 3.048(2), 3.120(2), and 3.150(2) Å), while the NH...N hydrogen bond is shorter (2.812(2) and 2.814(2) Å). The hydrogen bonds connecting the pairs range from 2.913(2) to 3.054(2) Å. b) The length of triple anti-parallel hydrogen bonds is the same within 0.063 Å (2.941(1), 2.961(1), and 3.005(1) Å), while the other hydrogen bond is somewhat longer (3.095(1) Å). c) The three triple anti-parallel hydrogen bonds range from 2.881(6) Å (NH...N distance) to 2.867(5) and 2.881(1) Å (NH...O distance).
- [16] a) R. F. M. Lange, E. W. Meijer, *Macromolecules* 1995, 28, 782; b) *Macromol. Symp.* 1996, 102, 301.