BACHELOR

Penning ionization and the development of spatial correlation in a molecular ultracold plasma

Kruyen, A.H.J.

Award date:
2012

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

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
Penning Ionization and the development of Spatial Correlation in a Molecular Ultracold Plasma

A.H.J. Kruyen

Augustus, 2012

Supervisors:
prof. dr. Edward Grant
dr. ir. Joshua Gurian
prof. dr. Gerrit Kroesen
Abstract

Most plasmas have a thermal kinetic energy which is higher than the average Coulomb potential energy. When the opposite is true, the plasma is called a correlated plasma. Ultracold plasmas with high density of particles can reach a state of correlation. Ultracold plasmas provide an important way to study the collision physics of Coulomb systems in or near correlated states. An Ultracold high density plasma has difficulty reaching a state of ion correlation from the spatial distribution of a random gas, because the ion-ion repulsion heats the gas. The ratio between potential and thermal energy decreases and with this the correlation.

The strategy in this report for achieving states of higher correlation is by imposing order in the gas before ionization, to decrease the ion-ion repulsion heating. This order is achieved by employing the spatial selectivity of Penning ionization in a frozen molecular Rydberg gas. By Penning ionization nearest neighbors will be depleted, leading to a Penning lattice, and after the electron avalanche a spatially correlated plasma is formed.

In this report the dependence of the formation of a plasma on the Rydberg state and the density is tested. The strength of the formed plasmas for different Rydberg states are researched by applying electric fields on the plasma. It can be concluded that the intermediate Rydberg state gasses form the most stable cold and high densities plasmas. These plasmas are formed with a high spatial correlation, by depletion of the nearest neighbors by Penning ionization. This spatial correlation is called the Penning lattice. The range of formation of stable Penning lattices dependence on the density of the Rydberg gas, for a lower the density the range for Rydberg numbers where a Penning lattice is formed broadens and shifts to a higher Rydberg number.
# Contents

1 Introduction ............................................. 1

2 Ryberg states ........................................... 7
   2.1 Rydberg states ..................................... 7
      2.1.1 The Rydberg states of nitric oxide .......... 8

3 Penning ionization ..................................... 11
   3.1 Penning fraction .................................. 11
   3.2 Prediction of spatial correlation for different quantum numbers .................................. 12
      3.2.1 The distribution for low Rydberg states .... 12
      3.2.2 The distribution for high Rydberg states ... 14
      3.2.3 The distribution for a moderate Rydberg state ... 14
      3.2.4 Variation of spatial correlation with density ... 14

4 Setup ...................................................... 15
   4.1 The laser setup .................................... 15
   4.2 The vacuum chamber ................................. 16
   4.3 The detection system ................................ 17

5 Results .................................................... 21
   5.1 First-photon spectrum ............................... 21
   5.2 The typical plasma signal ........................... 21
   5.3 Second-photon resonances in the plasma signal ... 23
   5.4 Durability of plasmas formed via different Rydberg states .................................... 23
   5.5 Density effects on spatial distribution for different Rydberg states in a plasma ... 24

6 Discussion and conclusion .............................. 27
   6.1 Stability at intermediate Rydberg states ........ 27
      6.1.1 Density dependence ................................ 28
   6.2 Conclusion and recommendations ................... 28
Plasmas are very important in our universe and in our technology. More than 99% of our universe is plasma \[^{[1]}\]. Plasmas form in the process of and it is the source of nuclear fusion, which represents the energy source of the universe, and likely the energy source for human beings in the future \[^{[2]}\]. Plasma interacts with material surfaces for the fabrication or modification of materials for a wide range of applications, like solar cells, nano-electronics, energy storage, functional coatings, flexible electronics and solar fuels \[^{[3]}\]. The knowledge of elementary plasma processes and the physics of plasmas is important for designing medical applications, stimulating skin growth and disinfecting wounds \[^{[4]}\]. Ultracold atomic plasmas provide sources of ultracold electrons and ions that suffer less from space-charge effects, these can be used for high-resolution electron diffraction \[^{[5]}\].

The plasmas in the universe and those used in different application vary in temperature and density (see for examples figure \[^{[1.1]}\]) as well as in atoms or molecules used. The characteristics of a plasma completely depend on these properties. Most plasmas can be described with fluid-model equations of state and are called thermal plasmas. Such plasmas are said to be uncorrelated. However, for plasmas with high density and low temperature, this is not the case. The average kinetic energy in these plasmas is smaller than their electrostatic potential energy, these systems are correlated \[^{[7]}\]. The degree of correlation can be expressed in a dimensionless ratio, called the Coulomb coupling parameter $\Gamma$,

\[
\Gamma = \frac{e^2}{4\pi\varepsilon_0a} \frac{1}{kT}
\]  \hspace{1cm} (1.1)

where $e$ is the charge, $T$ the ion or electron temperature for either the ion of electron coulomb coupling and $a$ is the Wigner-Seitz radius, which relates to the particle density, $\rho$, by
Chapter 1 Introduction

Figure 1.1: Overview of the occurrence of neutral plasmas. Examples for neutral plasmas are shown at their respective position in the density-temperature plane. The $\Gamma = 1$ line separates thermal plasmas from plasmas in the correlated regime.[6]

For the condition $\Gamma > 1$, the plasma falls in the correlated regime. In figure 1.1 this condition is satisfied for the plasmas under the $\Gamma = 1$ line.

It is important to experimentally characterize and understand Coulomb correlation in high density and low temperature plasmas to model the dense astrophysical plasmas at the cores of dwarf stars, non-Fermi metals and quantum semiconductors[7]. A good way to study correlated systems is with ultra cold plasmas. One of the first attempts to experimentally study a plasma in the correlated regime was in a cryogenic afterglow experiment. The initial gas temperature was 4.2K, the electron temperature was 10 K and the density was around $10^{24} m^{-3}$ [8]. More recent studies of correlation cooled atoms at a density of $10^{16} m^{-3}$ in a MOT below 100 $\mu$K and ionized the atoms with a laser to form a plasma [6]. In these plasmas, the spatial properties of disordered gases heats the plasma. Electrostatic interactions cause displacements of ions (ion-ion repulsion), this increases the kinetic energy i.e. the temperature. Reducing this heating and keeping a strong Coulomb coupling in the system requires spatial correlation in the initial system [9].

$$a = \sqrt[3]{\frac{3}{4\pi \rho}}$$

(1.2)
Clever strategies have been proposed to have a high spatial correlations. For instance, optical lattices have been suggested to trap atoms and ionize them to achieve a spatial pre-correlation \cite{9}. So far this method has had no success. Another strategy seeks a lattice that not necessary regular in space, but rather regular in the distribution of nearest neighbors. This can be achieved by selective pairwise interactions that deplete the nearest neighbors. The random initial distribution is replaced by distribution which misses a part of its population. In figure 1.2 this change in distribution is shown, where the random distribution of nearest neighbors for particles is given by the Erlang distribution \cite{10}. This report shows how to achieve this regularity and demonstrates the experimental consequences of this effect.

In this research an ultracold molecular plasma is created by Penning ionization between NO molecules in a high Rydberg state. The molecules are in a molecular beam, with a density of $10^{18} m^{-3}$, that is cooled to 700 mK by supersonic expansion and brought to a Rydberg state by multi-photon excitation. The Rydberg molecules interact with their neighbors to Penning ionize. The Penning ionization of the Rydberg molecules leads to a regular distribution of nearest neighbors depending on the Rydberg state. The left over Rydberg molecules ionize in the electron avalanche and these, together with the ions from the Penning ionization, form a spatially correlated plasma. In figure 1.3 the steps to the spatially correlated plasma is shown.

Chapter 2 discusses the theory of Rydberg states and considers the Rydberg states of NO in particular. Chapter 3 describes the change in the nearest neighbor distribution due to Penning ionization as a function of the initial Rydberg state and the density. Depending on this distribution there may be a sufficient spatial distribution for a Coulomb correlated plasma. Next, the setup of the experiments is shown in chapter 4. In chapter 5 all experiments and their results are given. These results are discussed in Chapter 6 and a
Chapter 1 Introduction

Figure 1.3: A 2D cartoon of forming a spatial correlated plasma by penning ionization in a ultracold molecular plasma. Some of the ultracold Rydberg molecules are ionized by Penning ionization and some are brought to the ground level. The last ones will dissociate and nearest neighbors are depleted. After the electron avalanche a spatial correlated plasma is formed.
conclusion is given in addition to this. The chapter ends with some future recommendations.
Chapter 2

Ryberg states

In this part of the report the basic theory of Rydberg states is shown. The later will focus on nitric oxide and the formation of its Rydberg states.

2.1 Rydberg states

Rydberg atoms and molecules are atoms and molecules in states of high principal quantum number \( n \). To understand why Rydberg atoms (and molecules) are so interesting, consider the Bohr’s model of the H atom, where an electron moves classically in a circular orbit around the positive core \([11]\).

The radius of the orbit of a Bohr atom is given by

\[
 r = \frac{n^2 \hbar^2}{e^2 mk}
\]  

(2.1)

where \( e \) the electric charge, \( m \) the mass of the electron and \( k = \frac{1}{4\pi\varepsilon_0} \). For a given \( n \) state, the potential plus kinetic energy is

\[
 W = \frac{-k^2 e^4 m}{2n^2 \hbar^2}
\]  

(2.2)

So high \( n \) hydrogenic Rydberg states have electron binding energies that decrease as \( \frac{1}{n^2} \) (equation 2.2) and orbital radii that increase as \( n^2 \) (equation 2.1). For atoms with a higher atomic number, or for molecules where an electron is excited in a Rydberg state, the system can be approximated as a hydrogen atom. The electron is far enough from the center so this center can be seen as a uniform charged core with approximately charge \( e \). Only a small correction, referred to as the quantum defect, \( \delta \), is needed to express the energy levels of a non-hydrogenic atom or molecule in a Rydberg state, as that the positive core with all other electrons around is not a perfectly
uniform charged e that leads to a non-Coulombic potential well. The energy levels for large principal quantum numbers \( n \) are given by

\[
E_n = EI - \frac{n}{(n - \delta)^2}
\]

(2.3)

Here \( EI \) is the ionization energy of the molecule and \( R \) is the Rydberg constant which has a value of approximately 13.6 eV.

Ways to produce Rydberg atoms include photo-excitation, electron impact and charge exchange. In this section we will focus on the first. After the excitation, the electrons decay radiatively to low lying states, emitting light, or the atoms ionize. The last outcome is very easy to achieve because the electron is weakly bound in a large orbit. This process can happen by collision or field ionization.

For optical excitation to a Rydberg state an exciting photon is absorbed by the target atom. By specifying the energy, wavelength, of this absorbed photon the Rydberg state produced is specified. The resolution of the excitation is determined by the Doppler effect and the the finite linewidth of the laserbeam.

### 2.1.1 The Rydberg states of nitric oxide

In this research, NO molecules in Rydberg states are used to create a molecular ultracold plasma. The molecule NO has three positive features. Firstly, only two photons from the ground state are needed to get the molecule in the vicinity of its ionization potential. Secondly, for NO the spectroscopy is well known for easily analyzing data. Finally, the ground state of NO\(^+\) has a total spin quantum number of zero, therefore the coupling with the Rydberg electron is simple.[12]

The two-photon absorptions mentioned earlier are needed, because the transition directly to the long-lived Rydberg states of interest requires more photon energy than can be easily provided by a single laser. Further, the use of two photons gives the opportunity to select a specific rotational state. In this report, the first molecule is excited from the ground state, \( X^{2}\Pi_{\frac{1}{2}} \), to the ground rovibronic level, of the electronically excited \( \Lambda^{2}\Sigma^{+} \) state. For this transition the photon has a wavelength of 226 nm or equivalently wavenumber of 44250 cm\(^{-1}\). After this transition the NO molecule can absorb another photon and go in a Rydberg state, see figure 2.1. Depending on the wavenumber of this photon the principal quantum number \( n \) of the Rydberg state is determined. The difference in energy between the different states is given by equation 2.3 and so the difference in wavenumber between two Rydberg state \( n_1 \) and \( n_2 \) is known by
2.1 Rydberg states

\[ \Delta \tilde{v}_{21} = \frac{E_{n_2}}{\hbar c} - \frac{E_{n_1}}{\hbar c} = \frac{R}{\hbar c} \left( \frac{1}{n_2^2} - \frac{1}{n_1^2} \right) \]  

(2.4)

where the correction term \( \delta \) is neglected for clarity.

For the transition spectrum between the ground state and the first excited state in NO the theoretical predictions for Resonance Enhanced Multi-Photon Ionization (REMPI) scans are known. The spectrum changes with temperature, when the temperature is higher the molecule will have more rotational energy levels. The NO spectrum will have more peaks, due to the higher amount of possible transitions. In figure 2.2

the theoretical predictions for a REMPI scan are show for 2.5K, 5K and 10K.
Figure 2.2: Rotational temperature of nitric oxide. The plots are theoretical predictions for a REMPI scan, for temperatures of 2.5K, 5K and 10 K, of the transition spectrum between ground state, $X^2\Pi_{1/2}$, to the first excited state in NO, $A^2\Sigma^+$. 
Chapter 3

Penning ionization

In this chapter the penning ionization of Rydberg molecules is viewed for different Rydberg principal quantum numbers, \( n \). For various values of \( n \) the Penning fraction changes and this predicts a different degree of final spatial correlation of ions in the formed plasma. Together with the Rydberg state, the density influences this spatial correlation as well.

3.1 Penning fraction

For molecules in a random distribution, the nearest neighbor distribution depend on the density \( \rho \) as described the Erlang distribution \[10\]

\[
f(d) = 4\pi d^2 e^{-\frac{4}{\pi} d^3 \rho} \tag{3.1}
\]

where \( d \) is the distance to the nearest neighbor.

When a molecular gas is excited to a Rydberg state, the molecules will Penning ionize. When two molecules Penning ionize, one Rydberg electron drops to a more deeply bound level while the other Rydberg electron is ionized. This reactions creates a distribution of initial ions and Rydberg molecules. This alters the distribution of nearest neighbors for the Rydberg molecules unaffected by Penning ionization. These Rydberg molecules ionize by an avalanche. The fraction of molecules that Penning ionize depends on the Rydberg number \( n \). The maximum separation distance for 90\% ionization is \( r \sim 1.8 \cdot 2n^2 a_0 \) for 800 Rydberg periods \[13\]. Integrating the Erlang distribution (3.1) from \( r = 0 \) to this maximum separation distance and multiplying this value with 0.9 gives the fraction \( F \) of all molecules that Penning ionize for a given \( n \). Half of these yield ions. The other half have an electron in a lower energy level and are likely to dissociate. The Penning fraction
Table 3.1: The penning factor of the gas depending on the Rydberg number $n$.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$f_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.008</td>
</tr>
<tr>
<td>40</td>
<td>0.04</td>
</tr>
<tr>
<td>50</td>
<td>0.15</td>
</tr>
<tr>
<td>60</td>
<td>0.40</td>
</tr>
<tr>
<td>70</td>
<td>0.70</td>
</tr>
<tr>
<td>80</td>
<td>0.81</td>
</tr>
</tbody>
</table>

gives the number of molecules that initially ionize compared to the number of molecules that are ions after the avalanche and is given by

$$f_p = \frac{F}{\frac{F}{2} + (1 - F)}$$

Table 3.1 gives the Penning fraction for different values of the principal quantum number $n$, for a density of $2.5 \cdot 10^8 \text{cm}^{-3}$.

3.2 Prediction of spatial correlation for different quantum numbers

The Penning fraction for different Rydberg states of a gas predicts a range of spatial correlation in the ionized gas. Penning ionization forms a distribution of initial ions for which neighbour Rydberg molecules have been lost. Rydberg molecules lose their nearest neighbor. This leaves a depleted distribution of the Rydberg molecules for the electron avalanche, where all remaining Rydberg molecules are ionized. This distribution, together with the distribution of the initial ions, can be predicted for different Rydberg states $n$. In figure 3.1 the statistical distributions of the sum of initial ions and Rydberg molecules is shown in blue and the distribution of the same number of particles ionized randomly in green. The simulations are done with 30000 particles and for Rydberg states $n = 30, 40, 50, 60, 70, 80$. The statistical results in these figures will help to explain the expected spatial correlation separately for low, high and moderate Rydberg states.

3.2.1 The distribution for low Rydberg states

A low principal quantum number $n$ yields a small Penning fraction (table 3.1). In this case the Penning ionization has a neglectable effect on the
3.2 Prediction of spatial correlation for different quantum numbers

Figure 3.1: Statistical calculation of the ion nearest neighbor distribution after Penning ionization and the avalanche in blue and the distribution of the same number of ions when ionized randomly in green. The calculation is done with 30000 particles in a density of $1 \mu m^{-3}$ for Rydberg states $n = 30, 40, 50, 70, 80$. [14]
distribution of the Rydberg gas as can be seen in the calculated distributions for \( n = 30 \) in figure 3.1. The distribution of final ions remains highly random and the spatial correlation is low.

### 3.2.2 The distribution for high Rydberg states

For a very high quantum number \( n \) the Penning fraction is very high (table 3.1). The Penning ionization creates a gas in which Rydberg molecules will Penning ionize within all nearest neighbor distances. This gives no selectivity. Furthermore, the energy required to ionize a Rydberg molecule is too small to de-excite the partner molecule to the degree that causes it to be lost by dissociation. For example, the ionization energy for a Rydberg molecule in \( n = 80 \) is approximately 0.002 eV and this equal to the energy of an electron going from \( n = 80 \) to \( n = 57 \) (2.2). Falling back to such a high Rydberg state, leads to little depletion of the nearest neighbors, the Rydberg molecules with a lower \( n \) ionize as well. This and the absence of selectivity in Penning ionization causes no alteration in the spatial distribution in the formation of the plasma.

### 3.2.3 The distribution for a moderate Rydberg state

In a certain range of principal quantum numbers \( n \), Penning ionization yields a non-random spatial distribution which we call a Penning lattice. The gas forms a spatial distribution depleted in nearest neighbors, which leads to a spatial correlation. The processes sketched in figure 1.3 take place.

### 3.2.4 Variation of spatial correlation with density

The Rydberg state alone does not determine when a spatial correlation can be expected. The particle density also influences the degree of spatial correlation. The initial random Erlang distribution for nearest neighbors shifts to larger distances and broadens for lower densities. The maximum separation distance for 90\% ionization stays the same, so the Penning fraction decreases for lower densities at a fixed \( n \). For lower densities the range in \( n \) for where a spatial correlation is expected is larger and shifts to higher values of \( n \). Although, there is a limit in density for the formation of a correlated plasma, for a lower density the desired correlation becomes weaker.
Chapter 4

Setup

In this part of the report the experimental setup is described. The goal of the setup is to detect spatial correlation within the formation of the plasma. In order to detect this, the setup needs lasers to excite NO molecules to a Rydberg state, a ultracold molecular beam and finally a detection system.

4.1 The laser setup

For the excitation of the NO molecules to a Rydberg state, we use two pulsed Nd:YAG dye lasers, the $\omega_1$ - and $\omega_2$-lasers, see figure 4.1.

The first laser excites the NO molecule to the $A^2\Sigma^+$ state with a wavelength of 226 nm. We call this laser the $\omega_1$-laser. The light from the YAG laser is tripled to 355 nm and pumps the dye laser with Coumarin 460 in methanol as a dye solution. The output of this tunable dye laser is around 452 nm (see figure 4.2) and is sent through an auto tracker and is doubled. The intensity of the $\omega_1$-laser is controlled by two polarization crystals and send into the vacuum chamber. By comparing the REMPI scan of the transition between the ground state and the first excited state in NO to the theoretical predictions, (figure 2.2), the wavelength can be tuned to the right transition $[2.1.1]$. In order to get a plasma, the intensity of $\omega_1$ should be low enough that it will not ionize all the NO molecules by a second excitation with this wavelength of the NO molecule in the $A^2\Sigma^+$ state.

The second laser excites the NO molecules to a Rydberg state. We call this laser the $\omega_2$-laser. The dye laser is pumped by 532 nm doubled light from the YAG laser. The dye used is DCM in methanol, the output wavelength is set around 652 nm (see figure 4.2). After the auto tracker the light is doubled to 326 nm. This light is sent into the vacuum chamber shortly after the $\omega_1$-laser ($\sim$ 5ns). The delay is increased for the density dependence
4.2 The vacuum chamber

A room temperature high-pressure pulsed valve for supersonic expansion is placed in the beginning of the chamber, which is separated into two compartments. The valve creates a supersonic jet of nitric oxide, seeded with 10% helium, with a repetition rate of 10 Hz and duration of 400 µs in the first compartment of the vacuum chamber. This supersonic expansion cools the beam by conversion of the thermal energy into directional kinetic energy. 25 mm behind the valve opening, a skimmer of 1 mm diameter lets the coldest part of the beam enter the second compartment of the vacuum chamber. Here the beam, with a density of $\sim 1 \cdot 10^{14}$ particles per cubic centimeter, will overlap with the the lasers and a part of the NO molecules is excited to a specific Rydberg state. The transverse temperature around this point is around 700 mK \cite{16}. A REMPI scan is used to determine the rotational temperature which is optimized by the aligning of the valve with respect to

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.1.png}
\caption{The excitation of NO from the ground state to a Rydberg state with excitation by a $\omega_1$- and $\omega_2$-laser.}
\end{figure}
4.3 The detection system

Figure 4.2: Range of wavelengths for ND:Yag pumped laser dyes. [13]

the skimmer, and by timing the lasers. The alignment of the lasers also has an effect on this temperature, for in the center of the beam the rotational temperature is the lowest. For a cold signal and with this a cold plasma, the lasers should excite only this coldest part of the beam. This is achieved by crossing the laser beams in the center of the chamber.

4.3 The detection system

Figure 4.3 shows a schematic diagram of the detection system of the setup. Figure 4.4 gives a picture of this system. The cold molecular beam enters the detection system by passing the repeller (G1). During the experiment the repeller has a pulsed voltage with an adaptable positive value, a fixed duration of 130 µs and a fixed delay of 2 µs with respect to the excitation of the molecules to a selected Rydberg state. This voltage establishes an electric field between the repeller and the extractor (G2), which accelerates electrons in the opposite direction of the molecular beam.

The plasma propagates hitting G2, which disrupts the charge distribution. In front of G2 the field free tube (G3) is charged to a positive voltage of 300 V. Electrons from the disrupted plasma accelerate towards G3 and drift in the tube. After the field free region the electrons are accelerated further
Figure 4.3: The detection system, first the molecular beam will pass G1, the repeller, the NO molecules are excited and a plasma is formed between G1 and G2. The plasma will pass through G3 and the cylinder and hit the MCP grid which is directly followed by a MCP plate.

Figure 4.4: The detection system of the setup.
4.3 The detection system

toward the grid of the MCP, which is charged up to 350 volts. The electrons are detected with the MCP with a gain of 2500 volts. The signal on the MCP is detected and averaged using a digital oscilloscope. This signal is triggered by the pulses from the $\omega_1$-laser, as measured by a photodiode.
Chapter 5

Results

In this part of the report the experiments are described and the results are shown. Firstly, a REMPI scan of the $\omega_1$-laser is made. Secondly, a typical plasma signal is taken. Further, the $\omega_2$-laser spectrum is scanned for the resonance in the plasma signal. This spectrum is analyzed for different field strengths between the repeller and extractor. Next, the effect of the field change is reported at different Rydberg peaks. Finally, the $\omega_2$-laser spectrum is taken for different densities of the molecular beam.

5.1 First-photon spectrum

In order to determine the rotational temperature of the gas, and to set the laser on the right transition from the ground state, $X^2\Pi_{1/2}$, to the ground rovibronic level, of the excited $A^2\Sigma^+$ state of NO, the $\omega_1$-laser is scanned. While scanning $\omega_1$, the $\omega_2$-laser is fixed on 655.200 nm, a wavelength above ionization threshold. A 20 times averaged signal is taken for (non-calibrated) $\omega_1$ wavelengths with steps of 0.0005 nm. The second peak, the plasma peak, in figure 5.2 is integrated for every averaged signal to determine the intensity of the electron signal. In figure 5.1 the REMPI scan is shown in the upper graph. In the lower graph the theoretical transition spectrum is shown for 2K, the upper graph is shifted for -4.7807 cm$^{-1}$ to fit the expected graph. For the other experiments the $\omega_1$-laser is set to the $A^2\Sigma^+$ state with the lowest rotational energy, this transition is indicated with an arrow in figure 5.1.

5.2 The typical plasma signal

In figure 5.2 a typical 20 times averaged electron signal from the MCP on
Figure 5.1: REMPI scan of $\omega_1$-laser at the top, this spectrum is $-4.7807 \text{ cm}^{-1}$ shifted compared to the theoretical predicted transition spectrum for 2K on the bottom. The arrow indicates the transition peak to $A^2\Sigma^+$ with the lowest rotational energy.

Figure 5.2: Typical plasma signal, the signal is averaged 20 times, taken at a $\omega_2$ wavelength of 655.54 nm and the electric field between G1 and G2 is 5 V/cm.
5.3 Second-photon resonances in the plasma signal

The resonance in the plasma signal is observed by scanning $\omega_2$. Every peak in the electron signal corresponds to an excitation to a specific $n$ Rydberg state. Figure 5.3 shows the result of such a scan. The scan is taken with steps of 0.004 nm in the wavelength of $\omega_2$, every signal is averaged 20 times, the plasma peak is integrated to yield an intensity measure. During the measurement the pulse field between G1 and G2 had a value of 5 V/cm.

The Rydberg state of every peak is determined by the distance between the different peaks by equation 2.4.

5.4 Durability of plasmas formed via different Rydberg states

In this experiment the $\omega_2$-laser is scanned for different pulse fields strengths between G1 and G2 of 5, 50, 100, 150, 200 and 250 V/cm, as described in section 5.3. In figure 5.4
Chapter 5 Results

Figure 5.4: The resonance $\omega_2$ scans for pulsed fields of 5, 50, 100, 150, 200 and 250 V/cm normalized on the highest signal of the 5 V/cm scan.

The result is shown for the different electric fields, the scan signals are normalized on the highest peak in the 5V/cm scan. In order to rule out the effects changing in time by other factors on the spectrum, the field strength during this experiment is changed in a random order.

Figure 5.5 shows for four different values of $n$, the relative intensity of the plasma peak for different pulsed field strengths. For this experiment the $\omega_2$ wavelength is kept constant on four different peaks and again the voltage on G1 is changed in random order to 0, 50, 100, 150, 200 and 250 V/cm.

5.5 Density effects on spatial distribution for different Rydberg states in a plasma

For this experiment a different setup is used [6], this setup is in general the same as the setup described above. The difference in this setup is the distances between the grids, the distance between G3 and the MCP is smaller. The signal on the oscilloscope shows three peaks, the prompt peak, a plasma peak on G2 and a plasma peak on G3.

To create different densities of the Rydberg gas the delay between the arrival of the $\omega_2$-laser compared to the $\omega_1$-laser is delayed, the density decreases as $\rho = 10^{18}e^{-\Delta t/\tau_{\text{m}}}$. Where $10^{18}$ is the original density in cubic meters,
5.5 Density effects on spatial distribution for different Rydberg states in a plasma

Figure 5.5: The relative intensity of four peaks belonging to the Rydberg states $n=36, 41, 45$ and $54$ for pulsed field strengths of 5, 50, 100, 150, 200 and 250 V/cm.
150 ns the lifetime of the intermediate states and \( \Delta t \) the delay between the arrival of the two lasers in nanoseconds. In this experiment this delay is set in randomly order on 0, 300, 600 and 900 ns which is comparable to a density of \( 10^{18} \), \( 1.4 \cdot 10^{17} \), \( 1.8 \cdot 10^{16} \) and \( 2.5 \cdot 10^{15} \) \( \text{m}^{-3} \) respectively. For each of these densities the \( \omega_2 \)-laser is scanned and the plasma peak on G3 in integrated, the results is shown in figure 5.6.

Every scan is normalized on the highest signal in the scan.
Chapter 6

Discussion and conclusion

The previous chapter showed the results of this study. The selection of different Rydberg principal quantum numbers, and the resulting variation in response to different pulsed electric fields provides a means to explore the effects of the final spatial correlation, arising from the Penning lattice, formed in these different Rydberg gasses. The effect of the density on this spatial correlation is discussed with the results in the final section. These results give suggest important conclusions about the stability of the different Rydberg plasmas, but more research can be done to broaden and strengthen this knowledge.

6.1 Stability at intermediate Rydberg states

In figure 5.4 it can be seen that Penning ionization in the higher Rydberg states does not lead to a strongly associated plasma. For higher electric fields, applied after 2 $\mu$s, the plasma is destroyed by the field. Although for higher electric fields the intensities of the plasma peaks belonging to intermediate Rydberg states are lower, the peaks are still detected for the highest fields. Shielding in the plasma blocks the effect of the electric field and spatial correlation retains the expansion of the plasma, the plasma survives. For low Rydberg states distinct peaks are also visible for the highest applied field of 250 V/cm. In order to conclude more about the lower Rydberg states, resonance scans with higher intensities of the lower Rydberg states should be made. This is done by optimizing the alignment, the intensity of the lasers and the voltages on the different grids.

An other way to look at the strength of the plasmas at different Rydberg states is by the fixed peak experiment. In figure 5.5 the change in intensity for four different peaks is measured for the 6 different applied electric fields. It
can be seen that indeed the intensity of the high Rydberg peak around \( n=54 \) drops the fastest for higher electric fields. For the peaks of \( n=41 \) and \( n=36 \) the intensity drop is less steep and for \( n=45 \) this drop seems to be the slowest. It must be noted that for this measurement every peak is only averaged once for the six different electric fields. For a more reliable result and an error bar in the intensity, the averaging for different fields and the different peaks should be done multiple times. It would also be an improvement to broaden the range of the fixed peaks, to compare the intensity change of lower Rydberg numbers as well. So the correlation within these lower Rydberg numbers plasmas can be researched as well.

6.1.1 Density dependence

The results in figure 5.6 show that indeed, as expected in 3.2.4, the range for plasmas formation changes in respect to the density. It can be seen that for lower densities, plasma formation for higher Rydberg states is possible, because of the shift in the nearest neighbor distribution. The penning fraction belonging to these higher Rydberg states is lower. The same for the lower regime of the Rydberg states, for higher densities, stable plasmas can be formed for lower Rydberg principal quantum numbers. It must be noted that the overall intensity of the peaks drops for lower intensities, because of the lower number of particles and therefore lower number of electrons in the plasma which can be detected by the MCP. This low number of particles can effect the correlation as well, the Wigner-Seitz radius will be larger, so \( \frac{1}{1.1} \) will decrease. It would be interesting to do the pulsed field scans of section 5.4 for the different densities to see the change in the range in Rydberg numbers for stable plasma formation.

6.2 Conclusion and recommendations

From the results it can be concluded that the intermediate Rydberg state gasses form the most stable plasmas. These plasmas are formed with a high spatial correlation, by depletion of the nearest neighbors by Penning ionization. This spatial correlation is called the Penning lattice. The range of formation of stable Penning lattices depend on the density of the Rydberg gas. For a lower the density the range broadens and shifts to a higher Rydberg number.

To prove reproducibility and in order to get an error in the fixed peak experiment, this measurement should be repeated multiple times. It would be interesting to measure the intensity of the peaks of Rydberg states in
6.2 Conclusion and recommendations

a bigger range, peaks with Rydberg number above 54 and especially below 36. The decrease in stability in plasmas formed out of gasses with a lower Rydberg states may need more proof. To check the changes in stability in different Rydberg state plasmas for different densities, resonance scans should be made for different pulsed electric fields.

The strategy of using the spatial selectivity of Penning ionization in a frozen molecular Rydberg gas can be used to study the collision physics of Coulomb systems in or near states of charged-particle correlation, when staying in the intermediate Rydberg states.
Bibliography


