A new method for detecting the contribution of high Rydberg states to electron-ion recombination

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Abstract. A position sensitive detector for measuring field ionized electrons in the fringe field of a dipole magnet is presented. The detector provides a means to study, in a state selective fashion, recombination into high Rydberg states and offers a new method to investigate recombination enhancement effects. Several experimental considerations and possibilities are discussed in the text.

1. Introduction

Electron-ion recombination processes are important to many aspects of astrophysics [1] and laboratory plasma physics [2] and are relevant in the study of basic atomic processes [3]. In the study of astrophysical and laboratory plasmas, elemental abundances, plasma temperatures, column densities, energy transport, and ionization balance can be derived from satellite recombination lines.

Electron-ion recombination in low and medium density plasmas takes place through two major channels. Radiative recombination (RR) is a direct process in which an electron recombines with an ion with the simultaneous emission of a photon. The cross section for RR has a maximum at zero center-of-mass (CM) electron-ion collision energy and has a smoothly decreasing cross section as the CM energy is increased. The second recombination channel to consider is dielectronic recombination (DR), which can be regarded as a two step process. A recombining electron looses energy by exciting a bound electron in the target ion, forming a doubly-excited state. These intermediate doubly excited states are autoionizing, however, a small fraction of them will decay via photon emission to a state below the autoionization threshold. If this occurs, the system will be bound against autoionization, and the recombination process is completed. Consequently, subsequent decay of the system via photon emission is the source of satellite recombination lines.

At low temperatures and high densities, a third recombination process becomes relevant. Three-body recombination (TBR) is a similar process to RR, except that the energy released during recombination is transferred into the kinetic energy of a neighbouring free electron, instead of a photon, and TBR preferentially populates high Rydberg states during recombination, whereas RR preferentially populates low principal quantum states. TBR can be thought of as the time inverse of electron-impact ionization.
Most experiments aimed at measuring recombination rate coefficients cannot detect recombination into high Rydberg states. The electric or magnetic fields, used to separate the charge changed ions, ionize Rydberg electrons above a field specific principal quantum state, thus rate coefficients for recombination into Rydberg states cannot be determined and are often accounted for by theoretical methods. We present a novel approach to investigating recombination into high Rydberg states. We show that by inserting a position sensitive detector into the dipole chamber of the bending (and charge state analyzing) magnet of the CRYRING storage ring, these Rydberg states can be detected.

![Figure 1. Schematic representation of the setup used for detection of field ionized electrons in the dipole magnet of the CRYRING heavy-ion storage ring.](image)

2. Experimental aspects

The coupling of electron coolers and ion storage rings has provided for an unsurpassed accuracy in recombination rate coefficients at low impact energies for a large variety of ion species \[4\]. In the electron cooler of the CRYRING heavy-ion storage ring \[5\], a low temperature electron beam is merged with the stored ion beam over a distance of \(\sim 80\) cm. The electron beam is used to reduce the momentum dispersion of the ions and, subsequently, to study electron-ion recombination. Once the ion beam properties have been improved through electron cooling, the electron energy can be systematically varied and electron-ion recombination measurements can be performed over a desired collision energy range. In these experiments, the dipole magnet after the electron cooler of the storage ring is used to separate the recombined ions from the stored ion beam. As recombined ions leave the electron cooler and pass on their way to the dipole magnet, through regions with weak transverse magnetic fields \(\sim 0.1\) T \[6\] and enter the dipole magnet (up to 1.2 T), they experience increasing \(v \times B\) motional electric fields which successively ionize Rydberg states starting from the high \(n\) states down to an \(n_{\text{cut-off}}\). Only recombined ions having electrons in quantum states below a particular \(n_{\text{cut-off}} \approx [6.2 \times 10^{10} Q^3/(v \times B)]^{1/4}\) value will survive the dipole magnet without being re-ionized. Here \(Q\) and \(v\) represent the ion charge and velocity, respectively, and \(B\) is the magnetic field density in the dipole magnet. The re-ionized ions follow the same trajectory as the stored ion beam and therefore these ions cannot be detected as charge charged ions. Varying the magnetic field strength in the dipole magnets changes the \(n_{\text{cut-off}}\) value, however, this method of studying recombination into Rydberg states is quite rough because it allows only the detection of the total amount of recombined ions having electrons in states below \(n_{\text{cut-off}}\) and it is restricted to low \(n\) states \[7\].

Electrons ionized from the recombined ions in the field of the dipole magnet, on the other hand, can be detected by other methods in order to obtain information about recombination into high Rydberg states. Field ionization of different quantum states varies as a function of
the field strength in the fringe field of the dipole magnet. The strong magnetic field forces field ionized electrons to execute cyclotron motion around the field lines. Electrons in decreasing \( n \) states are stripped off by the increasing magnetic field, and are imaged on a position sensitive detector. Thus, at the entrance fringe field of the dipole magnet, state-selective recombination into high Rydberg states can be studied by detecting field ionized electrons.

A position sensitive detector (figure 1) was constructed and tested at the cryRING heavy-ion storage ring. The detector consists of a stack of 2 microchannel plates (MCP) and a resistive anode, for position readout, mounted in a compact form of only \( \sim 5 \) mm height. It is inserted into the field gap at the entrance of the first dipole magnet following the electron cooler. A negative potential is applied to a metallic plate situated opposite the MCP detector, in order to extract the field ionized electrons and to accelerate them to the surface of the MCP. Further acceleration of the electrons is ensured by an electric field between a grid, located just above the MCP, and the MCP surface.

![Image](image.png)

**Figure 2.** Image of a circulating \( \text{F}^{9+} \) beam, obtained with the position sensitive detector. The arrow shows the direction of the ion-beam.
3. Results and discussion

Figure 2 shows the profile of a stored 6.5 MeV/amu F$^{9+}$ beam passing the detector. The given storage velocity of the ions and the associating magnetic field strength leads to a detectable $n$ range of $\sim 44$–49. The decrease in the number of counts across the detector, in the direction of the ion velocity, is probably due to an efficiency loss of the MCPs with increasing magnetic field. In the detector region, the residual gas pressure was $\sim 10^{-9}$ mbar. A significant background event rate is to be expected, arising from electrons produced by ionization of residual gas molecules in collisions with the circulating ions. The counts shown in figure 2 are mainly due to electrons originating from residual gas ionization. This gives a constant event rate over the beam’s path, independent of the electron beam, which is possible to separate from the collision-energy dependent recombination events during data analysis. While electrons are accelerated by the electric field toward the MCPs, residual gas ions are accelerated toward the metal plate. In order to block the secondary electrons created by the residual gas ion-metal surface collisions, a mesh was installed below the plate. This mesh and improved vacuum conditions will result in a significant increase of the signal-to-background ratio in future measurements.

The method discussed here offers the possibility to further the study of enhancement effects in RR [8]. Toward the series limit, field enhancement of DR becomes more predominant for recombination into progressively higher $n$ states. Because of the experimental resolution and closeness of the DR resonances near the series limit, recombination into these states form overlapping resonances and separate states cannot be resolved. Additionally, because of field ionization, many high $n$ states are lost in the dipole magnet. The detector described here gives the possibility to investigate DR and enhancement of DR [9, 10] into high Rydberg states over a reduced $n$ range, and will also make it possible to partially account for the diminished strength of DR series limits observed in experiments [11]. A comparison of experimental results with calculations [12] will lead to a better understanding of recombination enhancement effects.

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