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Recombination and Ionization Measurements at the Heidelberg Heavy Ion Storage Ring TSR

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ABSTRACT

Knowledge of the charge state distribution (CSD) of astrophysical plasmas is important for the interpretation of spectroscopic data. To accurately calculate CSDs, reliable rate coefficients are needed for dielectronic recombination (DR), which is the dominant electron-ion recombination mechanism for most ions, and for electron impact ionization (EII). We are carrying out DR and EII measurements of astrophysically important ions using the TSR storage ring at the Max-Plank-Institute for Nuclear Physics in Heidelberg, Germany. Storage ring measurements are largely free of the metastable contamination found in other experimental geometries, resulting in more unambiguous DR and EII reaction rate measurements. The measured data can be used in plasma modelling as well as for benchmarking theoretical atomic calculations.

1. Introduction

Reliable ionization balance calculations are needed to analyze spectra from a wide range of cosmic sources including photoionized objects such as Active Galactic Nuclei and X-ray binaries and electron ionized objects such as stars, supernovae, galaxies, and clusters of galaxies. In order to calculate the ionization balance, accurate ionization and recombination rate coefficients are needed for all ion charge states of all astrophysically relevant elements, typically taken as hydrogen through zinc.

EII is the main ionization mechanism for collisionally ionized plasmas. There are several channels through which EII can occur. In direct ionization a free electron collides with an ion transferring energy to, and freeing, a bound electron. The most common indirect process is excitation-autoionization (EA) in which an incident electron excites an inner-shell electron forming a doubly-excited state that stabilizes by ejecting an electron.

The main recombination processes for both collisionally ionized and photoionized plasmas are radiative recombination (RR) and dielectronic recombination (DR). In RR a free electron is captured by an ion and the excess energy is released by emitting a photon. DR occurs when a free electron collides with an ion exciting a bound electron and is simultaneously captured. The resulting doubly-excited state lies in the continuum of the recombined system. The excited state may decay by emitting a photon, in which case DR is complete, or it may autoionize leaving the ion in its original charge state. DR is the dominant electron-ion recombination mechanism for most ions.

2. Measurements at TSR

We are carrying out ionization and recombination measurements at the TSR heavy ion storage ring of the Max-Plank-Insitute for Nuclear Physics in Heidelberg, Germany. The ion beam is prepared in a tandem accelerator and injected into TSR (Figure 1). There are separate cold electron beams located in two portions of the ring. These can be merged with the stored ion beam within the ring. Initially the energy of both electron beams is set to a “cooling energy” where the relative velocity between the electrons and ions is zero. Beam-beam collisions reduce the energy spread of (phase space cool) the ions and define the average ion energy. The initial phase lasts several seconds during which metastable levels within the ion beam radiatively decay producing a well defined ground state ion beam.

Measurements are performed by varying the energy of one of the electron beams in small steps while the other provides simultaneous phase space cooling of the stored ions. The ionized and recombined products are separated from the parent ion beam by the first dipole magnet downstream of the interaction region. There they are counted by particle detectors positioned to intersect the product beams. After each measurement step the count rate is measured at a fixed reference energy in order to determine the background count rate from collisions between the ions and the residual gas.

The largest source of uncertainty comes from the ion current measurement, which is needed to normalize the recombination and ionization count rates and to calculate absolute cross sections and rate coefficients. The 1σ systematic error due to the ion current measurement is about 15%. The uncertainty from counting statistics is typically only a few percent. More details about the experiments can be found in Lestinsky et al. (2009) and Hahn et al. (2010) and in the references listed in each. TSR has been used extensively to study DR of cosmically abundant ions. A recent review of this work has been given by Schippers et al. (2009).

3. Recent Results

DR and EII were recently measured for initially Mg^{7+} ions (Hahn et al. 2010). This ion has a long-lived metastable state with a lifetime of about 3 s, making the storage ring technique necessary in order to measure ground state ions. The DR results are still being prepared for publication.

The EII cross section for Mg^{7+} forming Mg^{8+} over the energy range from 200 to 2000 eV is shown in Figure 1. This energy range includes channels for direct ionization of the $2p$, $2s$, and $1s$ electrons at threshold energies of 265.96 eV, 283.37 eV, and 1587.32 eV, respectively (Ralchenko et al. 2008). It also includes EA from excitation of a $1s$ electron, which can occur at energies above 1291 eV (Safronova & Shlyaptseva 1996). The cross section is compared to a calculation with the Flexible Atomic Code (FAC) reported by Dere (2007) and a calculation using the Los Alamos Atomic Physics Code (Magee et al. 1995). The measured cross section is in agreement with both calculations to within the experimental uncertainties. This is the first experimental measurement of EII for Mg^{7+}.

4. Future Directions

Future potential DR and EII measurements include Fe^{12+} and Fe^{6+}. Additional future EII work could involve measurements in iso-electronic sequences for which no storage ring data exist.

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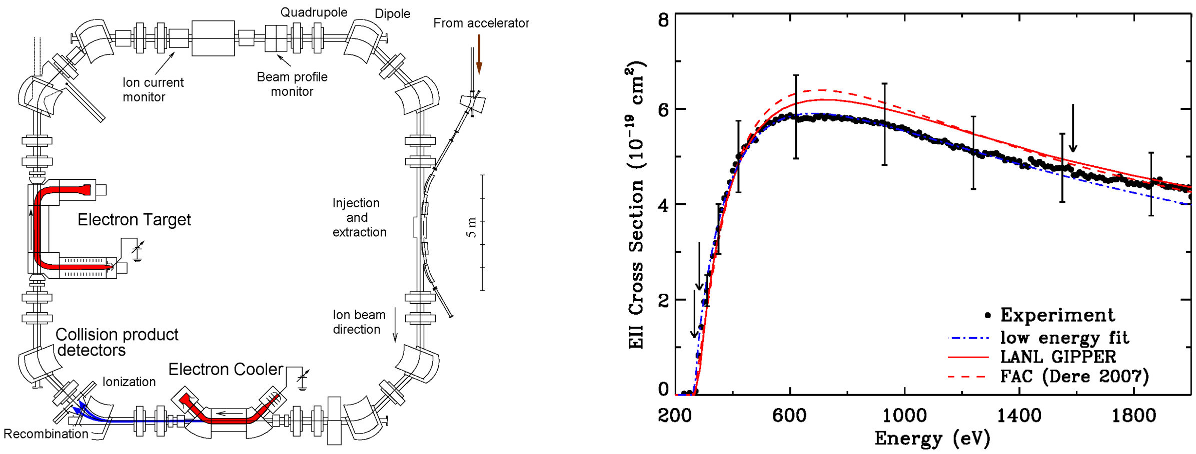

Fig. 1.— (Left) Schematic of the TSR ion storage ring showing the two electron beams. These beams are labeled "Electron Cooler" and "Electron Target", but their roles of continuously cooling the ion beam or serving as a variable energy target are interchangeable. (Right) The EII cross section for Mg^{7+} forming Mg^{8+}. The estimated 1σ experimental uncertainty is illustrated by error bars at selected points. Arrows indicate energy thresholds for the various direct ionization channels ($2p$,$2s$,$1s$). The dot-dashed line shows a fit to the experimental data below 1100 eV using the Lotz formula in order to illustrate the change of shape at high energies that may be caused by EA and direct ionization of a $1s$ electron. Also shown are theoretical results from the LANL Atomic Code and FAC.

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