Dielectronic recombination in He^+ ions

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Dielectronic recombination involving $1s + e^- \to nln'l'$ transitions has been investigated for He^+ ions. This work was done using the ion storage ring and electron cooler at the Indiana University Cyclotron Facility. Resonant maxima from DR were observed, but the energy resolution was insufficient to identify individual transitions. The magnitude of the measured cross sections appears to be about a factor of two lower than theory.

Dielectronic recombination (DR) [1] occurs in an electron–ion collision when capture of the electron is accompanied by simultaneous excitation of the ion, resulting in the formation of a doubly-excited intermediate state, followed by subsequent radiative stabilization, i.e.,

$$A^{q+} + e^- \to [A^{(q-1)+}]^{**} \to A^{(q-1)+} + h\nu, \qquad (1)$$

where A^{q+} represents an ion of initial charge q, and the double asterisk denotes a doubly-excited state. The formation of the intermediate state, which is mediated by the electron–electron interaction, proceeds via the inverse of an Auger transition, and, hence, is resonant for relative velocities corresponding to outgoing Auger-electron energies.

DR is the principal mechanism by which free electrons recombine with ions, and has been of considerable interest in recent years [2,3]. Apart from its fundamental interest, DR is important to astrophysical studies [4] and to the development of nuclear fusion plasmas [5]. Cross sections for DR have been calculated [2,6–8] extensively, and measurements of DR were first carried out by groups at JILA [9], the University of Western Ontario [10] and Oak Ridge National Laboratory [11]. Recently, three powerful new techniques for investigating DR have been reported. The electron beam ion trap (EBIT) at Livermore has been successfully used to obtain DR cross sections for Ni^{26+} ions [12]. Intense electron beams designed for ion cooling in storage rings were used to study DR in O^{6+} at Åarhus [13] and O^{7+} at Heidelberg [14]. And, at Kansas State University, a cryogenic electron beam ion source (CRYEBIS) was used to measure DR for Li-like Ar^{15+} ions [15].

In the earlier experiments [9–11] the small size of the cross sections limited the study of DR to collisions for which ionic excitation occurs via $\Delta n = 0$ excitation, e.g., $2s \to 2p$ or $3s \to 3p$ transitions. The more intense ion and electron beams in the later works (including the present one) [12,14,15] permitted measurements for $\Delta n = 1$ excitation, i.e., $1s \to 2p$. All of these studies point to the intense level of interest and activity in the investigation of DR.

An important ion in the investigation of DR is He^+. In addition to its fundamental interest as the lowest Z ion for which DR is possible, it provides a significant test of theory [16,17]. For He^+ the electron–electron interaction which mediates the DR process is stronger compared to the electron–nucleus interaction between the ion and free electron than for any other ion. This makes the calculation of DR more difficult for He^+, thereby posing a stringent and important test of theory [16,17].

We have conducted a preliminary investigation of DR for He^+ ions at the Indiana University Cyclotron Facility (IUCF) using the ion storage ring and its associated electron cooler. Specifically, the reaction measured was

$$He^+(1s) + e^- \to [He^0(2pnl)]^{**} \to He^0(1snl) + h\nu, \qquad (2)$$

i.e., excitation of the He$^+$ takes place via a $1s \rightarrow 2p$ ($\Delta n = 1$) transition accompanied by simultaneous (resonant) capture. Subsequent radiative stabilization of the doubly-excited neutral He atom completes the recombination process. The threshold for $\Delta n = 1$ DR for He$^+$ occurs for a relative energy [18] (in the rest frame of the ion) of about 33 eV and the series limit for $\Delta n = 1$ transitions occurs near 41 eV. To resolve transitions involving individual intermediate resonance states, the electron beam energy resolution must be less than about 0.5 eV [19].

The measurements were conducted using the ion storage ring and the electron cooler in a "single pass" mode as shown in fig. 1. The ions circled the ring once, passed through the electron cooling region, were deflected by a ring dipole magnet, and then collected in a Faraday cup (fig. 1a). The ring thus serves as a long beamline with the cooler providing the electron "target". By collecting the ion beam in a Faraday cup, a very accurate measure of the incident He$^+$ beam current can be obtained. A beam of 44 MeV $^3He^+$ ions (current ~ 300 nA) from the cyclotron was merged with the electron cooling beam (current ~ 0.2 A) over an interaction length of ~ 2.8 m. By varying the electron energy relative to the ion energy, events resulting in DR were detected by observing neutral He atoms produced in the electron Cooler (fig. 1b). These atoms, which exited through a 0° port following the cooler region, were observed with solid-state detectors in a dE/dx arrangement thereby allowing particle identification to separate the He atoms from background events. When the electron beam was turned off, essentially no background events were observable.

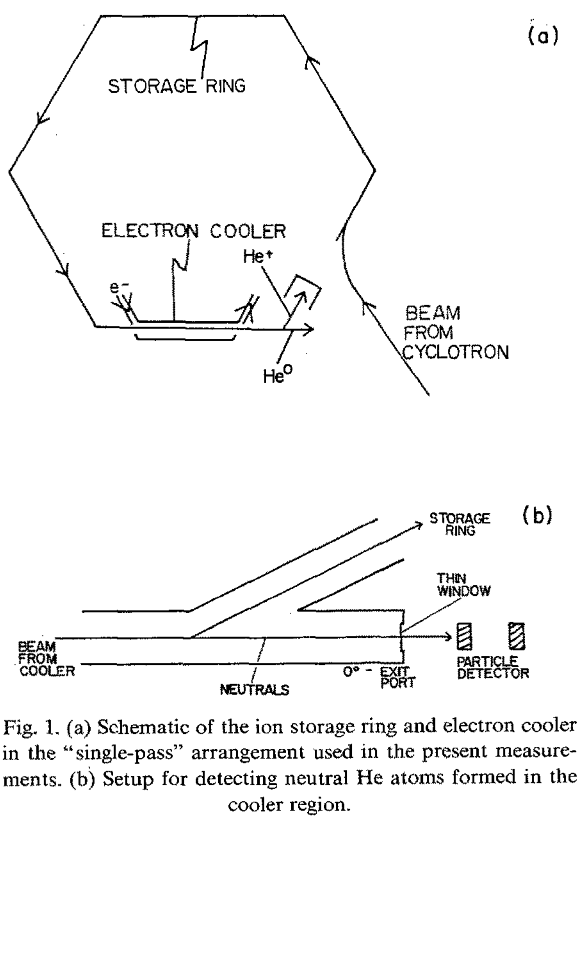

Fig. 1. (a) Schematic of the ion storage ring and electron cooler in the "single-pass" arrangement used in the present measurements. (b) Setup for detecting neutral He atoms formed in the cooler region.

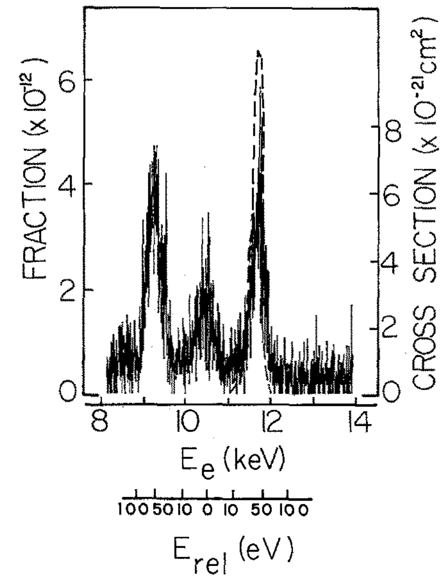

Fig. 2. Fraction of neutral He atoms formed in the electron cooler as a function of the laboratory electron energy E_e and the relative (in the projectile rest frame) electron energy E_{rel}. The central maximum is due to radiative recombination while the other two maxima correspond to DR for electron velocities less (left) and greater (right) than the ion velocity, respectively. The dashed curve is the calculated (see ref. [20]) DR cross section, divided by two, for a 20 eV (in the projectile frame) FWHM electron energy resolution.

As stated above, DR is expected to occur in He$^+$(1s) ions for relative energies of 33–41 eV between the ion and electron. It is not important whether the electron moves faster or slower than the ion. For 44 MeV $^3He^+$ (equal to an electron energy of 7988 eV) the laboratory electron energy was ramped from ~ 6.8–9.3 keV to include both negative and positive values of relative velocity within the relative energy span of 0–50 eV. Fig. 2 shows the measured He^0 fraction as a function of the energy between the electrons and the He$^+$ ions. Both laboratory E_e and relative E_{rel} electron energy scales are shown. DR maxima were observed for electron velocities less and greater than the ion beam velocity, respectively, and between the DR maxima, a peak due to radiative recombination at $E_{rel} = 0$ was observed. ($E_{rel} = 0$ was defined as the centroid of the radiative recombination peak.) Maximum counting rates at the DR maxima were about 10 Hz and the signal to noise ratio was about 18 : 1.

There are two problems with the measured spectrum: (1) there is a large (~ +2.5 keV) laboratory energy offset, and (2) the electron beam energy resolution is about 20 eV FWHM (in the projectile frame) rather than the ~ 0.5 eV expected. In the case of the energy shift, only about 300 eV can be attributed to the space charge of the electron current. The poor energy resolution makes it impossible to resolve individual transitions due to DR. Both of these problems were apparently due to a hardware problem in which one of the drift electrodes in the electron cooler was inadvertently left "floating" and thus became charged when some of the high intensity electron beam struck it. It should be emphasized, however, that by defining the central maximum to occur for $E_{rel} = 0$, the maxima on either side occur at the expected centroid energies for DR in He^+.

In view of the experimental difficulties encountered in the present measurements, a meaningful comparison between theory and experiment is difficult. However, the magnitude of the present data appear to be about a factor of two lower than a calculation [20] of the DR cross section for He^+ ions assuming a projectile frame electron energy resolution of 20 eV as shown for the $E_{rel} > 0$ portion of the spectrum in fig. 2. Furthermore, the shape of the curve rather accurately reflects the data. But, it is emphasized that a more quantitative assessment of the accuracy of the theory must await better experimental data.

In summary, in this first effort to investigate DR at IUCF, resonances were observed for $He^+ + e^-$ collisions. Due to an unfortunate hardware problem leading to a large energy shift and poor electron energy resolution, the resonant energies could not be determined, nor could individual DR transitions be identified. Because the He^+ beam current was accurately measured, however, the experimental DR cross section is believed to be fairly accurate. It is planned to repeat this experiment with the hardware problem fixed.

Acknowledgements

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