REACTIONS OF COOLED IONS WITH COLD ELECTRONS IN CRYRING*

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Cooler-storage ring facilities offer unique experimental possibilities for the study of electron-ion recombination processes at low relative energies by employing the electron cooler as a target. Through the use of an adiabatically expanded electron beam in the cooler of CRYRING, reactions down to 10^{-4} eV relative energies can be measured at an energy resolution in the order of 10^{-2} eV FWHM with ions stored in the ring at around 10 MeV/amu energies. A review of our measurements of radiative recombination, laser stimulated recombination, and dielectronic recombination is presented.

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1. Introduction

Until recently, it was difficult to study reactions between free electrons and ions with accurate control over their collision velocity. Electron cooling in storage rings opened up new possibilities to measure electron-impact ionization and recombination with unprecedented resolution and luminosity. These collisions produce a large number of interesting phenomena with important applications in fusion and astrophysical plasmas and the chemistry of interstellar clouds [1–3]. Indeed, in these plasmas and media, much of the energy transport and reactions occur as electrons collide with atomic and molecular ions. In such collisions, the ions can be excited or further ionized, or the electrons can recombine leading to emission of photons or dissociation of molecules. Studies of recombination can also be important for our understanding of fundamental problems in few-electron atomic systems. Accurate transition and binding energies, autoionization rates, and radiative rates of singly resolved states can be compared with atomic structure calculations. The basic processes are radiative, dielectronic, and three-body recombination of atomic ions, and dissociative recombination of molecular ions.

Radiative recombination (RR), where a free electron is captured simultaneously with the emission of a photon, is the most fundamental process in the interaction of free electrons with ions. It is the key process through which atoms are formed, when the universe evolved from the "photoionization era" into the "recombination era". One currently proposed application of this process is to mediate the recombination of positrons with antiprotons for antihydrogen production in traps. At storage rings RR is of importance for the lifetimes of stored beams during cooling with electrons and is often used as a diagnostic tool for electron cooling. This process is useful, because during cooling zero average relative electron-ion velocity is enforced, and the RR rate reaches its maximum at low relative energies. However, the measured recombination rates deviate increasingly with the ion charge q from the calculated radiative recombination rates. There are speculations that this could be caused by distortions of the free-electron continuum (by *e.g.* Debye screening of the ion charge and three-body recombination (TBR) in the presence of the magnetic guiding field).

In dielectronic recombination (DR) a free electron is captured simultaneously with the excitation of a bound electron in the projectile. Due to energy conservation, the binding energy plus the kinetic energy of the captured electron must equal the excitation energy of the bound electron. The resulting doubly excited state will have a very large probability to autoionize and lose the electron again. It may, however, emit a photon and end up in a singly excited state. This last step completes dielectronic recombination. RR and DR can be viewed as the time reverse of photoionization and of the

Auger effect, respectively. In general these processes are described by:

$$e^- + A^{q+} \longrightarrow A^{(q-1)+} + h\nu \ .$$

DR is only permitted when $q < Z$, where Z is the nuclear charge.

Processes investigated in the experiments reported here are RR with bare ions (D^+ and Ne^{10+}), laser induced RR with D^+, dielectronic recombination in B-like Ar, and the contribution of recombination to the lifetime of electron-beam cooled stored beams.

2. Experiment

The experiments were performed at the ion storage ring CRYRING at the Manne Siegbahn Laboratory. The D^+, Ne^{10+} and Ar^{13+} ions, produced from a plasmatron (MINIS) or an electron-beam ion source (CRYSIS), were injected into the ring at 300 keV/amu via an RFQ and accelerated to typically 10-20 MeV/amu prior to storage. In the experiments, about 10^8 D^+ ions and about 10^6 heavy ions were stored in the ring. During electron cooling, the ions were merged over an effective interaction length of $l = 0.8$ m with a velocity matched electron beam, confined by a solenoid magnetic field of 0.03 T to a diameter of 40 mm. Using the expanded electron beam of the electron cooler [4] very low electron beam temperatures could be reached for the measurements. The temperatures of the electron beam of $T_\perp = 10$ meV$/k_B$ and $T_\parallel = 0.1$ meV$/k_B$ were determined by cooling force measurements. From fitting DR resonances we find an electron beam temperature of $T_\perp \simeq 20$ meV$/k_B$ and $T_\parallel \simeq 0.15$ meV$/k_B$.

After cooling the ion beam with an velocity matched electron beam, ($E_e = E_i(m_e/m_i)$), the electron energy is changed by a certain amount ΔE which results in a center-of-mass energy: $E \approx \Delta E^2/4E_e$. The exact relativistic expression is:

$$E = \left[(E_e + E_i + m_e c^2 + m_i c^2)^2 - \left(\sqrt{E_e^2 + 2m_e c^2 E_e} + \sqrt{E_i^2 + 2m_i c^2 E_i} \right)^2 \right]^{1/2} - m_e c^2 - m_i c^2 \ .$$

That small collision energies can be measured with high resolution can be seen from the example: If a 12 keV electron beam (for cooling a 20 MeV/amu ion beam) is detuned by $\Delta E = 500$ eV, the resulting collision energy is only about 3 eV.

The recombined ions, formed in the cooler, are separated from the circulating beam in the first bending magnet downstream from the cooler, and are detected by a surface barrier detector inserted on a manipulator. As the recombined ions pass through the bending magnet, electrons bound above a certain n-level given by

$$n > n_{\max} = \sqrt[4]{\frac{6.2 \times 10^8 \, q^3}{v_i B}}$$

are stripped by the motional electric field in the bending magnet. After cooling the beam for typically 3 sec., the relative velocity between the ion and electron beam is tuned through the resonances. The rate coefficients are determined in the experiments by

$$\alpha^{\text{expt.}} = \frac{\gamma^2 R^{\text{det}}}{n_e N_i} \left(\frac{L}{l} \right),$$

where γ is the Lorentz factor, R^{det} is the background corrected counting rate of recombined ions, n_e is the electron density, N_i is the number of ions stored in the ring and L is the ring circumference. At a vacuum of 10^{-11} Torr, the electron capture background is in the percent level of the total detected charge exchanged particles under cooling conditions. The systematic experimental uncertainty is about 15%: 10% from the absolute stored ions, and 5% from the effective interaction length. The rate coefficients are measured in this work at an electron density of about $n_e = 2 \times 10^7$ cm^{-3}, and at a relative energy difference between electron and ion beams ranging from 10^{-6} to around 30 eV by detuning the cathode voltage.

At very low temperatures the electron beam introduces a strong drag force on the ions at small detuning velocities, disturbing the transformation from laboratory to CM energies. For its correction, we have calculated the change of the velocity of the ions as a function of time during the measurements by numerical solution of the differential equation describing the beam acceleration due to repeated Coulomb collisions in the electron beam (for details see Ref. [5]). With the inclusion of this acceleration we have transformed the energy scans from the laboratory system into the center-of-mass system. This was checked by saw-tooth scans of the electron velocity around the velocity matching point at cooling (see below). With this approach one obtains four spectra; two, where the electrons move faster and two where they move slower then the ions. By using the resonance lines in the four spectra the transformation and correction can be checked and an absolute energy accuracy of 10 meV is obtained for center-of-mass energies below 1 eV (see below).

The energy resolution that can be achieved in such measurements is limited by the energy spread of the two beams, and the lateral spread of the ion beam in the space charge distribution of the electron beam. At small collision energies the transverse energy spread will usually dominate since it remains unaffected by the transformation to the center-of-mass system. On the other hand, due to the mass difference the velocity spread of the ion beam is small compared to that of the electron beam. This is generally verified in storage ring experiments. With the expanded electron beam *e.g.* one expects an energy resolution δE_{cm} of 0.01 eV to 1 eV at collision energies from 1 eV up to roughly 1 keV. A value of that order was obtained in dielectronic recombination experiments at CRYRING. An energy resolution of about 0.03 eV was, for example, reached at around 4 eV center-of-mass energies (see below).

3. Radiative recombination

The RR cross section is related to the photoionization cross section through the principle of detailed balance:

$$\sigma_{nl}^{RR}(E) = 2\,(2l+1)\,\frac{E_\gamma^2}{2m_e c^2 E}\,\sigma_{nl}^{i}(E)\,,$$

where E_γ is the energy of photon. A widely used form is the Kramers cross section corrected by the Gaunt factor $g(\epsilon)$ to give the quantum mechanically correct Stobbe result [6, 7]; which we also used for a theoretical estimate:

$$\sigma_{nl}^{RR}(E) = \left(2.11\times 10^{-22}\mathrm{cm}^2\right)\,\frac{E_{1s}^2}{n(E_{1s}+n^2E)E}\,g_{nl}(E)\,,$$

where E_{1s} stands for the ground-state ionization energy of the hydrogen-like ion. For most cases the l averaged Gaunt-factor

$$g_n = \frac{1}{n^2}\sum_l (2l+1)g_{nl} = 1 + 0.1728n^{-2/3}(x-1)(x+1)^{-2/3} - 0.0496n^{-4/3}(x+1)^{-4/3}(x^2+4x/3+1)+\cdots\,,$$

where $x = E_r/E_{nl}$, from Ref. [8], is a useful approximation (deviation from Stobbe $< 1\%$). The cross section for non-bare ions can be estimated using the screening correction proposed in Ref. [9].

At low energies one has the condition $E \ll E_{nl}$ for not too high n states. Within such limits a low energy approximation, valid for cooling conditions and recombination into the lower bound states, analytical formulas for radiative recombination cross sections, rates and photon angular distributions have been derived [10].

Recombination studied from light to heavy ions has shown reasonably good agreement for protons [11] and deuterons [12, 13], however, increasing deviation have been found for heavier ions when compared to radiative recombination theory [11, 14]. In all cases of deviations reported so far the experimental rates were lower then expected from calculations, and in some cases of non-bare heavy ions deviations from RR theory by one to two orders of magnitude have been reported. In cooling tests with lead ions of a charge around $q = 53+$ large variations in the beam lifetime due to recombination were observed [15]. In a recent case, Ar^{13+} DR resonances at very low relative energy ($E \leq 10$ meV) were identified to cause an increased rate for electron-ion recombination. With bare ions, however, an enhancement by DR is excluded.

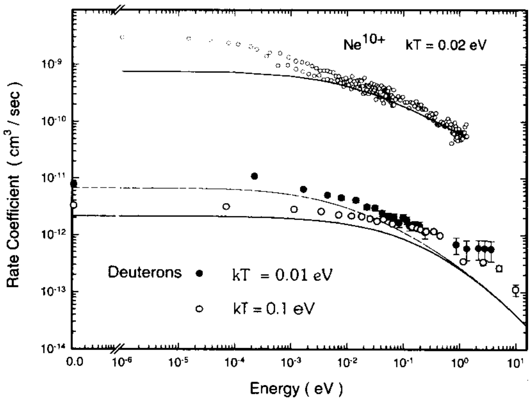

Fig. 1. Radiative recombination rate as a function of electron-ion relative energy E_r measured with deuterons stored at 6 MeV/amu Ref. [13], and Ne^{10+} stored at 11 MeV/amu Ref. [14] in CRYRING (full lines represent the calculated radiative recombination coefficients).

In Fig. 1 we show as an example the radiative recombination rates, as a function of E_r, measured with deuterons at 6 MeV/amu and Ne^{10+} stored at 10 MeV/amu in CRYRING [12–14]. The experimental results for D^+, which fall off steeply from a maximum at $E_r = 0$, compare well with the curves calculated by integrating the Kramers cross-section corrected by the Gaunt factor up to $n_{\max} = 9$ for two different transversal temperatures. The electron beam temperatures of $T_\perp = 0.1$ eV$/k_B$, $= 0.01$ eV$/k_B$ and $T_\parallel = 10^{-4}$ eV$/k_B$ were chosen to calculate the rates. A small enhancement of 50 % is seen for D^+. Deviations of this size could be within present systematic errors of such a measurement. Fig. 1 also shows the measured rate coefficient of Ne^{10+}. The full curve represents the calculated RR rate with $k_B T_\perp = 10$ meV and $k_B T_\parallel = 10^{-4}$ eV. One sees that the measured rate coefficient is enhanced by a factor of 3 below $E = 10^{-3}$ eV over the calculated RR rate coefficient. Possible reasons for the measured enhancement could be: (i) transverse temperature below 10 meV, (ii) local density increase within the Debye sphere radius, (*iii*) field effects, and (*iv*) three-body recombination. Although the measured rate coefficient can be approximately fitted by assuming a transverse temperature of 1 meV, is such a low temperature not realistic. The value of $k_B T_\perp = 10$ meV is the lower limit, obtained by expanding the initially $k_B T_\perp = 100$ meV electron beam by a factor of 10. A temperature of $k_B T_\perp = 10$ meV was confirmed by a cooling force measurement and a higher value of $k_B T_\perp \simeq 20$ meV was obtained by fitting DR resonances of Ne^{7+}, measured under the same experimental conditions. The widths of measured DR resonances with Ar^{13+} and laser induced RR with D^+ are compatible with the same value. An estimate for an electron beam with 10 meV isotropic temperature distribution shows that the density variation by Debye shielding is negligible at these low densities. Also, the enhancement is unlikely due to field effects because $n_{\max} = 9$ is rather low, as are the external fields.

Based on the model for TBR [16], with an isotropic temperature distribution of 10 meV the calculated TBR rate coefficient is only 10^{-12} cm^{3}s^{-1}. This is three orders magnitude lower than the observed rate coefficient. The TBR contribution seems thus to be negligible. However, this model may be too simple to describe the flattened temperature distribution of a cooler's electron beam, where a very low longitudinal temperature of 0.1 meV may play some role in enhancing the recombination rate. The TBR contribution to the recombination rates should increase for increasing ion charge. It should also have a quite different electron density and temperature dependence than RR. A study of the rates as function of the electron density [14] did not show the dependence expected from TBR. However, there is an additional difficulty with the interpretation of a TBR contribution in this case. TBR mainly populates high Rydberg states which are stripped by the motional electric field in the bending magnet, preventing detection unless the electrons reach a lower n-state by collisional and radiative cascading, which is found to be unlikely within a time of a few ns. Thus, a clear explanation for the measured enhancement with the bare ion Ne^{10+} cannot be given at present.

4. Laser induced recombination

Laser-induced radiative recombination has been performed with merged beams of ions, electrons, and laser photons in the cooler section of CRYRING [17]. In the experiment intense laser light pulses at the Balmer series limit are sent into the overlap region of electrons and deuterons (at an energy of 21 MeV) in the cooler, and the formation of hydrogen in the quantum state $n = 2$ is measured. The light pulses of 450.46 nm from a tunable dye laser, pumped by an excimer laser, were 20 ns long and had a peak power of 1 to

3 MW; it focussed to a typical power density of 10 MW/cm^2 in the cooler region.

The time spectrum from the coincidences between deuterium atoms reaching the detector and the laser pulses has a flat background of spontaneous recombination and a peak from the induced process. The width of the peak is given by the laser pulse length and the overlap time between laser photons and protons in the cooler. The ratio between the counts in the time window of the peak and the background represents the gain factor. In Fig. 2 the gain factor, normalized to a laser intensity of 10 MW/cm^2, is shown as a function of the photon energy in the c.m. system (the $n = 2$ binding energy subtracted). A surprising result from these experiments is that the gain factor starts to rise already at $E_\gamma = -5$ meV, clearly below the threshold given by the $n = 2$ binding energy. Above the maximum it falls off slowly, which is well described by the electron velocity distribution in the moving frame.

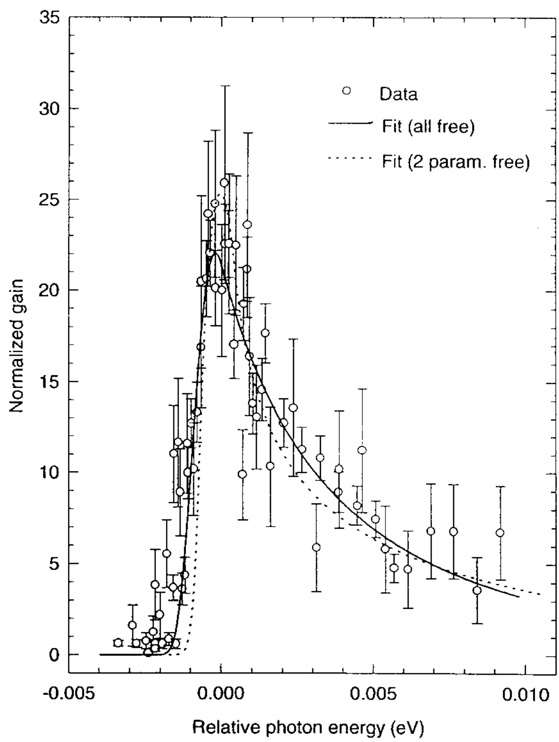

Fig. 2. Normalized gain factor for laser-induced recombination into the hydrogenic $n = 2$ state as a function of the c.m. photon energy minus the $n = 2$ binding energy Ref. [17]. The full line is the best fit, the dashed lines were calculated for the external field of 2 V/cm and 20 meV resp. 10 meV transverse energy.

The calculated gain factor for recombination into the $2p$ state is around 100, for a laser power of 10 MW/cm^2. This value is nearly a factor 3 above the measured value (shown in Fig. 2). A possible photo re-ionization of the recombined ions by the same laser pulse is negligible for the $2p$ state, but nearly 100% for the $2s$ state. The deviations, both in the maximum gain and position of the threshold might be explained by the influence of external electrical fields on the electronic states at the hydrogen ionization limit (Stark states at the ionization limit) [18]. This requires a displacement between electron and deuteron beam so that an electric field of around 35 V/cm from the electron beam space charge can be deduced. The linear potential of this field exceeds the Coulomb potential at a distance of $\sim 1\mu$m from the proton. It would lead to a saddle point of the potential at about -5 meV which reduces the ionization threshold of the hydrogenic $n = 2$ level by this amount. In a model which combines the classical motion of the electrons in the Stark potential with the quantum mechanical description of radiative recombination, the curves in Fig. 2 are calculated. This model is in good agreement with the measured shift towards energies below threshold and explains the reduction of the gain by binding and anti-binding Stark states, *i.e.* the Stark potential allows only certain electron trajectories to recombine with the protons. The problem is, however, that much larger shifts of the ion beam with respect to the center of the electron beam are needed than reasonable from a machine operation point of view. This leaves the intensity below threshold still unexplained.

5. Dielectronic recombination

Recently, high resolution measurements of dielectronic recombination were made at CRYRING [5, 19]. Measurements of DR resonances in heavy ions with high resolution can serve as benchmark tests for relativistic structure calculations and for quantum electrodynamical corrections. For center-of-mass energies of the first $1s^22p_{1/2}nl$ and $1s^22p_{3/2}nl$ resonances at around 1 eV in Ne^{6+} and Ar^{14+}, for example, a resolution on the order of 10 meV can be expected with the lower transverse temperature of $k_BT_\perp = 10$ meV of the cooler's expanded electron beam. Above this energy the resolution is determined to a larger extent by the longitudinal temperature of $T_\| \simeq 10^{-4}$ eV$/k_B$, through the relation $\delta E = k_BT_\perp + k_BT_\| + 2\sqrt{E_{cm}k_BT_\|}$. For reaching the required accuracy we developed a method (described below), which takes care of most of the space-charge uncertainties, and the correction for the drag force on the ions from the electron beam during the scanning of resonances. This drag correction seems to be a major factor in DR measurements with heavy ions and cold electrons, when measurements are done at low energies.

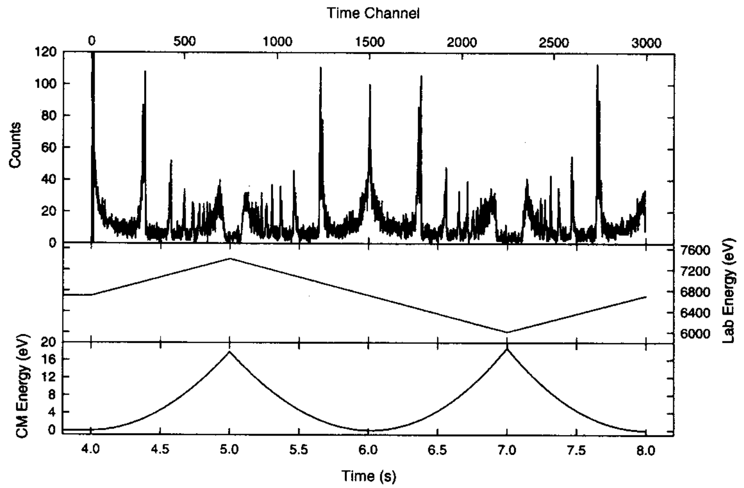

Fig. 3. Scans of the recombination rates for the stored lithium-like Ne ions. Top: counts of recombined ions, middle: variation of cathode voltage, bottom: CM energy as function of scanning time.

The ions of Ne^{7+} and Ar^{15+}, which have a lithium-like $1s^2 2s$ ground state configuration, were accumulated, accelerated, and cooled before scanning the resonances. Saw-tooth scans of the electron velocity around the cooling velocity were performed. Thus we get four spectra of DR resonances which should be identical in the CM system: two where the electrons moved faster and two where they move slower then the ions. With the inclusion of a correction for the drag force acceleration we have transformed the energy scans from the laboratory system into the center-of-mass system. In Fig. 3 (middle) the detuning of the cathode voltage from cooling is shown. The lower part of this figure displays the corresponding CM energies for the case of Ne^{7+}; at the top the four spectra are displayed. By checking these corrections for the transformation by the four spectra an agreement of the spectra to better then 20 meV was possible. From fitting DR resonances with Ne^{7+} we find an electron beam temperature of $k_B T_\perp \simeq 20$ meV and $k_B T_\| = 0.15$ meV.

A comparison with theory of DR resonances in Ne^{6+} is shown in Fig. 4. The calculations of the $2p_j - 2s$ splittings includes electron correlation [20], the Breit interaction, and a first order estimate of radiative corrections. The high n-electron is assumed to be moving in the frozen Hartree-Fock potential of the three inner electrons.

The measurements with Ar^{15+} were done in a similar way, except the need for space charge corrections to the electron velocity were eliminated by running the following cycles: The cooler was set to a DR resonance energy and the ion beam was then accelerated or decelerated and cooled at

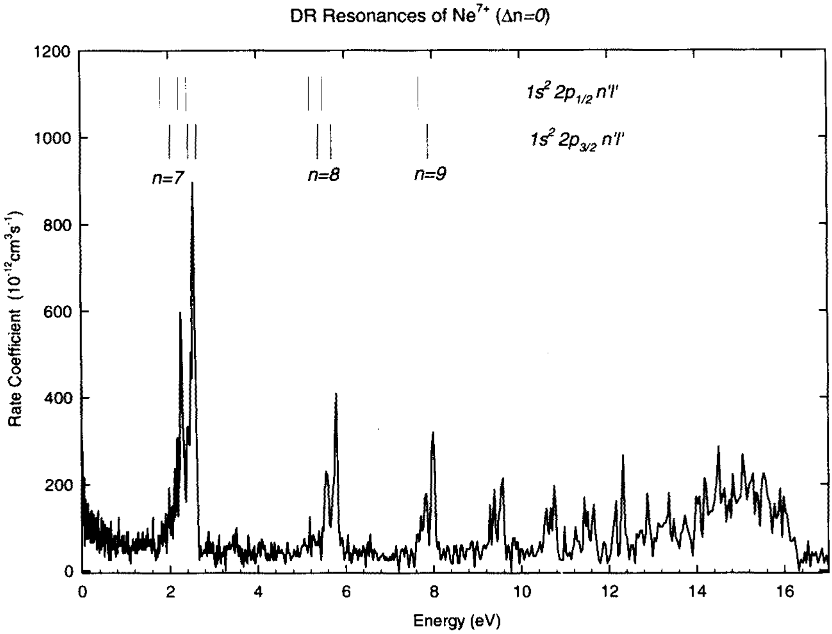

Fig. 4. Recombination rate coefficient for Ne^{7+} vs. relative energy. The vertical lines represent an estimate of the resonance positions, as obtained when the outer electron is moving in the Hartree-Fock potential from the frozen core.

this energy. The Schottky signal was analysed again and the trajectory of the ions determined by scrapers. The difference in electron velocities is thus equal to the difference in ion velocities. The main source of inaccuracy in this procedure comes from an uncertainty in the trajectory of the ions at the two different cooling energies. This enters when transforming from the Schottky frequencies to the matched ion and electron velocity. The DR resonances with Ar^{15+} after transformation into CM energies and corrections for space-charge effects and drag force line up well within the width of the lines of 10^{-2} eV. This gives us an estimate of the present uncertainty in these measurements.

A comparison of the presently analysed $1s^2 2p_{1/2}(10l)$ and $1s^2 2p_{3/2}(10l)$ Ar^{14+} resonances with a calculation of the $2p_{1/2} - 2p_{3/2}$ fine structure splitting is demonstrated in Fig. 5. The different levels of the approximation in calculating this splitting are shown in the graph. The difference in energy derived from the fit to the lines (inset, full line) gives a value for $1s^2 2p_{1/2}(10l) - 1s^2 2p_{3/2}(10l)$ of 3.24 ± 0.02 eV which is quite close to the calculated value of the fine structure splitting. An analysis of the line intensities for higher n values is in progress. Previous measurement of the Rydberg series of doubly excited states in Ar^{14+} formed by DR were mea-

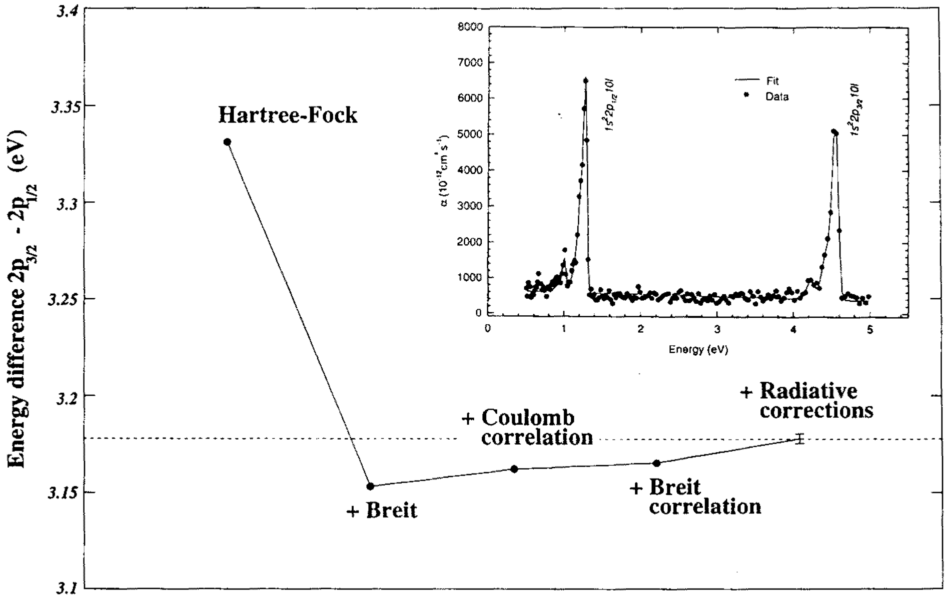

Fig. 5. Calculated results for the $2p_{1/2} - 2p_{3/2}$ fine-structure splitting for different levels in the hierarchy of approximations. The uncertainty indicated in the last point is due to the simple estimate of the self-energy screening effect used here. Insert shows the Ar^{14+} $1s^22p_{1/2}10\ell$ and $1s^22p_{3/2}10\ell$ resonance lines with fits to them resulting in an energy difference of 3.24 +- 0.02 eV.

sured with the electron target at GSI [21]. In those experiments a resolution of about 1 eV and an uncertainty of 2.5 eV in the region of 30 eV was obtained. Significant discrepancies to the AUTOSTRUCTURE calculation by Badnell *et al.* were reported. With the accuracy reached in the present experiments a more crucial test of such calculations should be possible.

6. Recombination enhancement and beam lifetimes

The types of ions where the strong recombination enhancement and beam lifetimes under electron cooling were found previously had very complex electronic structures for the possible excited states. For investigating this question we selected here an ion with enough electrons to allow for resonances at close to zero relative energy, but not having the complexity which prevents reasonable description by atomic structure calculations. The contribution of DR resonances at low energies can be determined from the shape of the resonance curve. With the very low electron beam temperature of $k_BT_\perp \simeq 10$ meV of the electron cooler in CRYRING, we can expect to resolve resonances even at center-of-mass energies below 10^{-2} eV. For these reasons we chose boronlike (Ar^{13+}) argon and performed high resolution measurements of recombination rates close to zero relative energy. The aim was to test whether $\Delta n = 0$ resonances for such a many electron system could contribute to the recombination rate under cooling conditions. In order to reveal more clearly other contributions to the recombination rates we also performed measurements with a bare ion of about the same charge (Ne^{10+}), where DR cannot occur. Here we use the shape of the measured Ne^{10+} rate, along with an overall scaling factor, as a background for the Ar^{13+} rates, where additionally DR can occur. This approach is used to study the difference in recombination rates between bare and non-bare ions near zero relative energy.

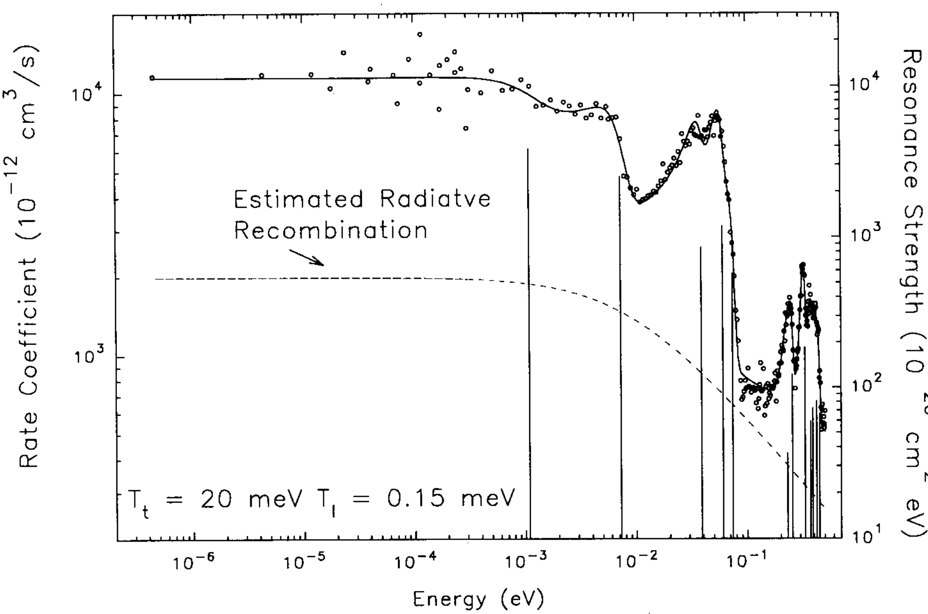

Fig. 6. Averaged measured recombination rates with fits of DR resonances (the lines indicate calculated resonance energies) and the estimated radiative recombination rates.

Fig. 6 shows the average of the four scans and the fit. The fit curve consists of two parts: the smooth experimental (enhanced) background of nonresonant recombination which was taken from a fit to the measured rate coefficient of Ne^{10+}, and the convolved DR resonances. The width of the fitted resonances is less than 30 meV FWHM. After drag force correction the absolute resonance positions could be determined with better then ± 10 meV [22]. The fitting indicates that at least half of the factor of 10 enhancement of the rate coefficient of Ar^{13+} measured near zero relative energy could be attributed to DR. We would also like to point out that by comparing the fit with and without a DR resonance at $E_{rel} \simeq 1$ meV, we cannot exclude the possibility of this additional DR resonance. If there exists a DR resonance near 1 meV, the observed enhanced intensity at zero relative energy for Ar^{13+} would be dominated by this DR resonance. Comparison with theory is not yet possible for Ar^{13+} in this ultra low energy region. The theoretical description of resonances near zero with the desired accuracy for the Ar^{12+} system still out of reach for atomic structure calculations.

Even for bare ions, where DR is obviously not possible, enhancements of the RR rates at nearly zero relative velocities have also been observed [13, 14, 23]. It has been speculated that this could be caused by TBR populating high-n states [24]. It has also been suggested that it could be caused by external fields in the interaction region [25]. We have recently made a new attempt at studying electron-ion recombination into high-n states of D^+ [26]. In that work we have simultaneously measured the lifetime of the coasting ion beam and the rate of recombined particles leaving the cooling section of the ring. Because of field stripping at the main dipole, the measured yield is limited to D^0 in states of $n \leq 5$. The lifetime includes the contributions of recombination into considerably higher values of n. From an appropriately built difference between the measurements made for each of these quantities, we were able to obtain some information on recombination into high-n states of deuterium. As an illustration, we present in Fig. 7a

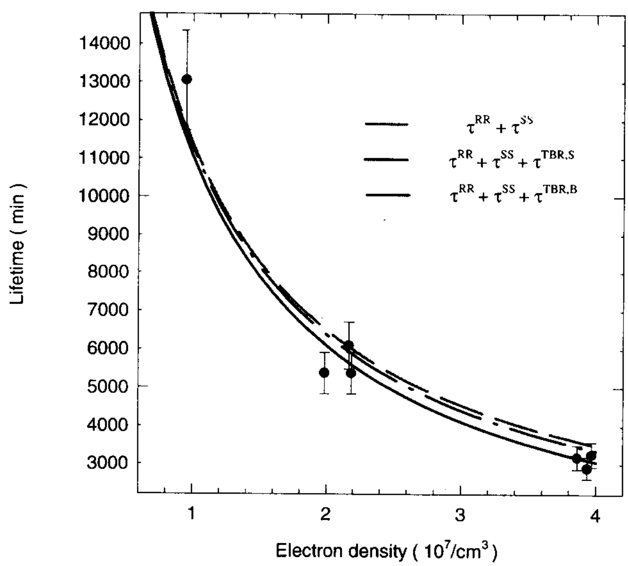

Fig. 7. Lifetime of 21 MeV/amu D^+ as a function of the electron density at the cooler. The dashed curve shows the contributions from radiative recombination, and single elastic scattering. The solid and dash-dotted lines show the effect of TBR.

plot of the D^+ beam lifetime as a function of the electron density in the cooler. In this experiment, performed with electron-cooled ions stored at 21 MeV/amu, the overall beam decay results from several factors. Mainly it is caused by RR and single elastic scattering (SS) of the stored ions by rest gas particles (dashed line). Better agreement at high electron densities is obtained when the contribution of TBR following either the description in Ref. [27] (full line) or that of Ref. [16] (dash-dotted line) is included.

7. Conclusion

We have shown that electron-ion collision reactions can be studied with high resolution in CRYRING by using energetic stored ion beams and an expanded electron beam for cooling and as a target. In studies of radiative recombination for bare ions of charge 10 a factor of 3 enhanced rate coefficient near zero relative energy ($< 10^{-3}$ eV) was measured. The explanation of this effect awaits further investigation. It was shown that dielectronic recombination resonances in Li-like systems can be measured with an accuracy in the order of 10^{-2} eV. A correction for the drag force and its control is essential for obtaining accurate absolute resonance positions at low energies. The results are compared to many-body calculations of the $2p_j, 2s$ splittings which include correlation, Breit interaction, and first order estimates of radiative corrections. The strong enhancement of recombination rate coefficients at very small relative energy observed for highly charged ions with several electrons, such as Ar^{13+}, was found to be due to very low-lying dielectronic recombination resonances.

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