Experimental Evidence for Magnetic Field Effects on Dielectronic Recombination via High Rydberg States

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We report the first experimental observation of magnetic field effects on dielectronic recombination (DR) via highly excited Rydberg levels. Crossed static electric and magnetic fields E_y and B_z were imposed on the collision region in high resolution DR measurements with Li-like Cl^{14+} ions at the heavy ion storage ring TSR in Heidelberg. Enhancement of DR rate coefficients α for the group of high Rydberg states attached to the $2p_{1/2}$ and $2p_{3/2}$ series limits was observed when motional electric fields E_y up to 380 V/cm were introduced. The associated enhancement rate $d\alpha/dE_y$ which we found to be constant at least for $E_y \leq 100$ V/cm decreased by almost a factor of 2 when the longitudinal field B_z was increased from 20 to 69 mT. [S0031-9007(99)09107-3]

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This work for the first time experimentally demonstrates that a magnetic field crossed with an electric field substantially affects the cross sections and rates for dielectronic recombination (DR), in particular through the effect it has on the expected electric field enhancement of this process. DR is a fundamental electron-ion reaction well known to be important in plasma environments. One can view it as a two step process beginning with the excitation of an ion by an electron which is simultaneously captured into a level $n\ell$ (n and ℓ denoting the principal and the angular momentum quantum numbers); this first step is the time inverse of autoionization. In the second step the new ion is stabilized by photon emission from the intermediate doubly excited state. Realizing that high Rydberg levels are particularly relevant, Burgess found DR to be the dominating recombination mechanism in the solar corona [1]. Since then DR has received much theoretical attention, and calculated DR rate coefficients constitute an essential ingredient of plasma modeling codes. First measurements of rate coefficients were conducted [2,3] employing well characterized plasmas, but most of the experimental progress in understanding the numerous facets of DR has been achieved since then by using colliding beams techniques [4,5].

It is well known by now that external electric fields can strongly influence cross sections and rates of DR. This was recognized early by Burgess and Summers [6] and Jacobs *et al.* [7]. Electric field enhancement of DR was subsequently found in numerous theoretical calculations [8]. Huber and Bottcher investigated theoretically possible effects of pure static magnetic fields on DR [9]. Up to 5 T no effects were found. For higher fields up to 100 T, however, DR rates were calculated to fall off slowly with increasing magnetic field. Experiments on DR employing controlled and measurable external motional electric $\vec{v} \times \vec{B}$ fields in the electron-ion collision region have been scarce but have clearly established the enhancement of DR by electric fields [10–12]. Also, measurements in which the external fields had not been controlled [13–16] appeared to be understandable on the basis of the theoretical concept of electric field enhancement of DR, although the comparisons left ambiguities (see, e.g., Ref. [8]).

Electric field enhancement of DR arises from the Stark mixing of ℓ states and the resulting influence on the autoionization rates which, by detailed balancing, determine the capture of the free electron. Autoionization rates strongly decrease with increasing ℓ and, therefore, only low ℓ states significantly contribute to DR. Electric fields mix the low ℓ and high ℓ states, increasing the autoionization rates of the higher-ℓ states, and therefore the contributions of Rydberg states to the DR process.

Our previous storage-ring experiment on field enhanced DR of Si^{11+} ions [12] provided detailed results for a wide range of external electric fields. Although the theoretical calculations were in reasonable agreement with the experiment as to the magnitude of the observed enhancement effect, significant disagreement was found regarding the change in the magnitude of the effect as a function of electric field strength. The theory was subsequently extended to include the magnetic field perpendicular to the external electric fields in that experiment. A model calculation [17] indicated for the first time that a magnetic field causes a change in the mixing of m states and can thus influence the counting of states contributing to DR. This speculation was supported by subsequent more detailed calculations [18,19]; however, the experimental proof remained to be found.

In the present experiment we studied possible effects of magnetic fields on the DR of Li-like Cl^{14+} ions. The processes investigated can be represented by

$$\begin{aligned} e + Cl^{14+}(1s^2\,2s) &\rightarrow Cl^{13+}(1s^2\,2p_j\,n\ell), \\ Cl^{13+}(1s^2\,2p_j\,n\ell) &\rightarrow Cl^{13+}(1s^2\,2s\,n\ell) + \text{photon}, \end{aligned} \qquad (1)$$

where $j = 1/2$ or $3/2$. The experiments were carried out at the heavy ion storage ring TSR of the Max-Planck Institute for Nuclear Physics in Heidelberg. Beams of $^{35}Cl^{14+}$ ions with intensities up to almost 1 mA were stored in the ring at energies of 250 and 110 MeV. The ion beams were cooled by interaction with a velocity-matched cold beam of electrons which was confined by a magnetic field $\vec{B}$; the direction of $\vec{B}$ defines that of the electron beam. The electron-beam diameter was 30 or 36 mm, while that of the cooled ion beam was of the order of 2 mm. First, as in the standard tuning procedure of the electron cooler, the electron beam was steered so that, along the straight interaction region of 1.5 m length, the ion beam traveled on the electron-beam center line and the guiding field $\vec{B}$ pointed exactly along the ion beam; this minimized the electric field in the frame of the ions originating from space charge and motional ($\vec{v} \times \vec{B}$) fields. A reasonably "electric-field free" measurement of the DR rate coefficient (with an estimated residual field of at most ± 10 V/cm) could then be obtained at high energy resolution by switching the energy of the electrons in the cooler to different values. The energy range thus covered in the center-of-mass frame includes all $Cl^{13+}(1s^2 2p_j n\ell)$ DR resonances ($n \geq 10$). Recombined Cl^{13+} ions were magnetically separated from the parent Cl^{14+} beam and detected with an efficiency $\geq 95\%$ down beam from the cooler behind the first bending magnet.

Controlled motional electric fields in the frame of the ions were then applied by superimposing in the interaction region a defined transverse (horizontal) magnetic field $B_x \ll B_z$ in addition to the unchanged longitudinal field B_z along the ion beam direction (z). This field was generated by the electron-beam steering coils along the complete straight section of the electron cooler and created a motional electric field $E_y = vB_x$ in the frame of the ions at a beam velocity v. Progressively different electric fields were produced by varying the transverse magnetic field strength B_x. At a given transverse field B_x the electron and the ion beam are misaligned by the small angle B_x/B_z so that the distance of the ion beam from the center of the electron beam varies along the interaction region. This leads to unwanted effects due to the electron space charge: (I) a variation of the (temperature average) relative velocity between electrons and ions along the interaction path, resulting in a degraded energy resolution; (II) creation of an additional electric field E_x which, in contrast to the imposed field E_y, varies along the interaction region. Low electron densities were chosen in order to keep these effects small. With electron currents of 20–50 mA, measurements were performed at electron densities either in a "low" range near 0.5×10^7 cm^{-3} (an order of magnitude lower than in our previous experiment [12]) or in a "high" range of $(0.8\text{–}1.2) \times 10^7$ cm^{-3}. The cooler was operated at longitudinal field strengths B_z of 20–69 mT. Transverse fields of $|B_x| \leq 1.07$ mT (measured with an uncertainty of $\pm 3\%$) were applied, corresponding to controlled motional electric fields $|E_y|$ up to 395 V/cm; in all measurements the misalignment angle was kept below $|B_x/B_z| \lesssim 0.02$. The ratio E_x/E_y of the unwanted electric space charge field and the applied motional field is expected to vary linearly along the interaction region with $|E_x/E_y|$ remaining always below 0.07 for all measurements with different experimental parameters.

Before each energy scan with an imposed electric field E_y, ions were injected into the ring, accumulated by stacking [20], and then cooled for 1 s. After that, the cathode potential of the cooler was offset from cooling by about 800 V (corresponding to 35 eV in the center-of-mass frame), and then the steering coils were set to produce a defined transverse magnetic field. Next, the center-of-mass energy was ramped down from about 35 to 1 eV within 4 s thus completing a first mini cycle. After new ion injection and cooling, the next transverse field B_x was automatically set and a new energy scan started. The mini cycles, covering one complete energy scan each, were repeated for a set of prechosen magnetic steering fields. A grand cycle through typically 20 values of E_y thus took about 2 min and such cycles were repeated until a satisfying level of statistical uncertainty (below 3% per channel) had been reached.

Sets of recombination rate measurements were made for different longitudinal fields B_z, electron densities, and ion beam energies. Using measured beam currents the spectra were calibrated, reaching an uncertainty of $\pm 20\%$ for absolute and $\pm 5\%$ for relative rate coefficients. The center-of-mass energies were determined (with uncertainties below $\pm 1\%$) from the average relative velocities of electrons and ions, accounting for the angle between the electron and the ion beam due to the applied transverse field B_x. A typical set of measurements is presented in Fig. 1 and shows the two series of Rydberg resonances converging to the $2p_{1/2}$ and $2p_{3/2}$ core excitation limits. A significant enhancement of the rate coefficient with increasing electric field E_y is observed for high Rydberg states $n \gtrsim 25$, while for the lower-lying resonances the integrated rate coefficient remains constant.

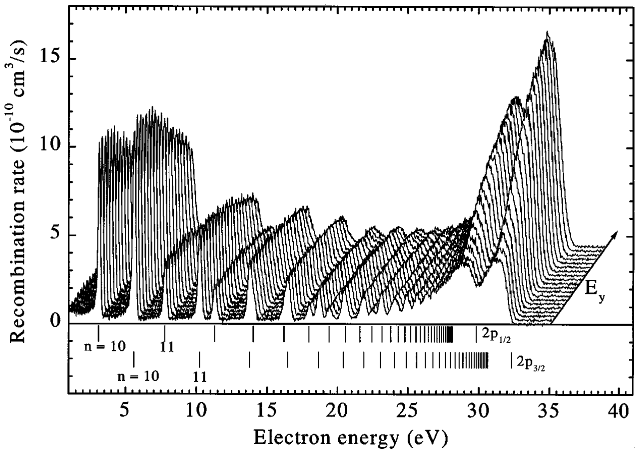

FIG. 1. Absolute recombination rate coefficients measured for 250 MeV Cl^{14+} ions at applied motional electric fields E_y increasing nearly linearly from 0 to 380 V/cm; longitudinal magnetic field $B_z = 69$ mT, electron density 0.5×10^7 cm^{-3}. Energetic positions of the $2p_{1/2}\,nl$ and $2p_{3/2}\,nl$ resonances according to the Rydberg formula are indicated.

A slight degradation of the energy resolution, caused by the space charge in connection with the beam misalignment as discussed above, is visible through the decreasing height (and increasing width) of the low-lying resonances ($n = 10, 11$).

The enhancement of the DR via high Rydberg states is quantified by extracting rate coefficients integrated over different energy regions of the measured spectra. The energy range of 24.6–35 eV, yielding the integral $P_>(E_y)$ at a given field E_y, is used to represent the high-Rydberg contribution, while the range of 2–15 eV, yielding the integral $P_<(E_y)$, describes the contribution from lower n. The smooth background caused by radiative recombination of ions with cooler electrons is subtracted. As shown by the typical set of rate integrals in Fig. 2, the high-Rydberg contribution $P_>(E_y)$ monotonically increases with $|E_y|$, while the lower-n contribution $P_<(E_y)$ remains constant. In order to provide a quantity for the following discussion that is independent of the normalization of the individual spectra, we consider ratios $P_>(E_y)/P_<(E_y)$ of the high-n to the low-n contribution in a single DR spectrum. The electric-field enhancement factor

$$\kappa = \frac{P_>(E_y)/P_<(E_y)}{P_>(0)/P_<(0)} \tag{2}$$

then directly measures the influence of the external electric field on the DR rates via high Rydberg states. It should be noted that zero applied field $E_y = 0$ still implies a residual electric field $\lesssim 10$ V/cm so that the measured dependence of κ near $E_y = 0$ is washed out to some extent.

The field enhancement factors as a function of $|E_y|$ found for the smallest and the largest longitudinal magnetic field used in the present study ($B_z = 20$ and 69 mT, respectively) are shown in Fig. 3. The enhancement factors turn out to be independent of the sign of E_y, as expected. Starting from $|E_y| \gtrsim 10$ V/cm and reaching up to field strengths of the order of 100 V/cm, the results for κ indicate a linear increase with $|E_y|$, with a clear dependence of the slope $d\kappa/d|E_y|$ on the magnetic field strength B_z.

The results for the slope as obtained in measurements at different electron densities and with different ion energies are summarized in Fig. 4. At an ion energy of 250 MeV the data obtained with electron densities in the low and the high ranges as specified above consistently

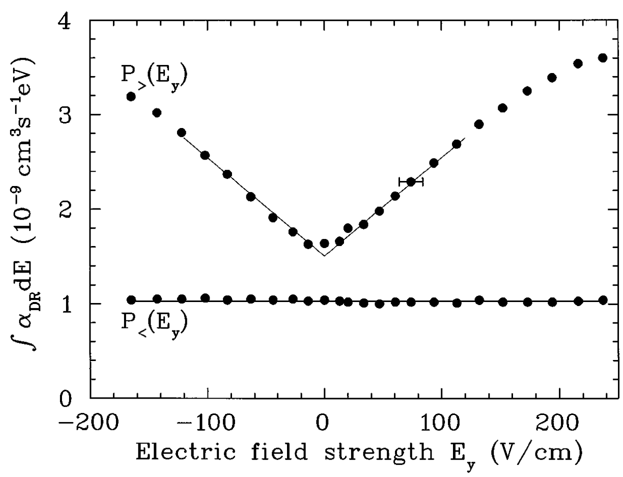

FIG. 2. Integrals $P_>(E_y)$ and $P_<(E_y)$ of the rate coefficients associated with high and low Rydberg states, respectively, as a function of the applied motional electric field E_y; longitudinal magnetic field $B_z = 42$ mT, electron density $(0.46-0.48) \times 10^7$ cm^{-3}, ion energy 250 MeV. Straight lines fitted to the rate integrals and the size of the residual space charge field for vanishing applied field strength E_y are indicated.

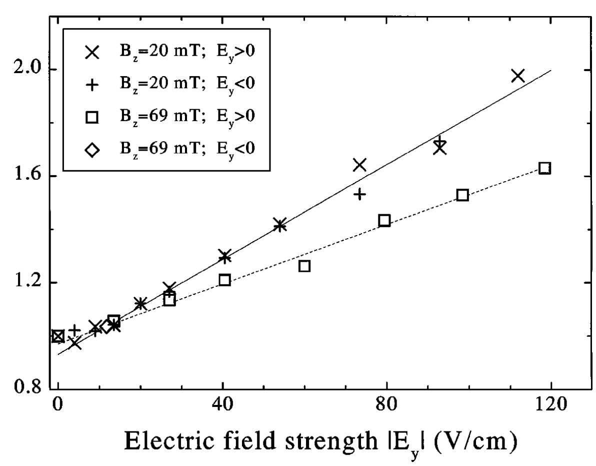

FIG. 3. Measured field enhancement factor κ according to Eq. (2) as a function of the applied motional electric field strength $|E_y|$; electron density $(0.46-0.48) \times 10^7$ cm^{-3}, ion energy 250 MeV. Results are shown for the largest and the smallest longitudinal magnetic field B_z as indicated.

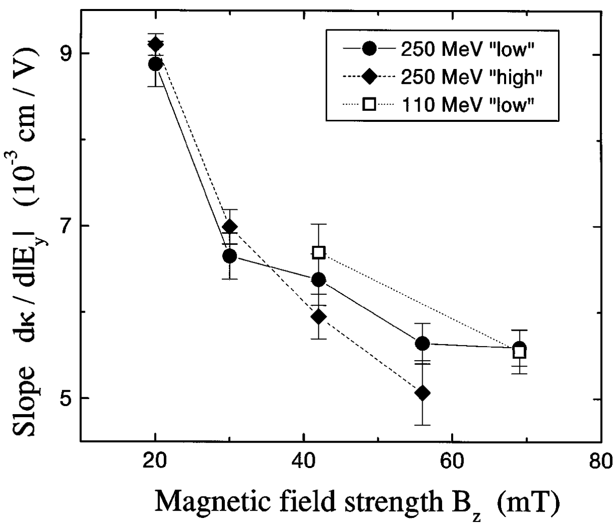

FIG. 4. Dependence of the slope $d\kappa/d|E_y|$ representing the electric field enhancement for $|E_y| \lesssim 100$ V/cm as a function of the longitudinal magnetic field strength B_z. Circles: "Low" electron density [$(0.46-0.48) \times 10^7$ cm^{-3}], ion energy 250 MeV. Diamonds: "High" electron density [$(0.8-1.2) \times 10^7$ cm^{-3}], ion energy 250 MeV. Squares: Low electron density (0.45×10^7 cm^{-3}), ion energy 110 MeV.

indicate a decrease of the slope $d\kappa/d|E_y|$ with increasing magnetic field strength B_z. A relative decrease of the electric field enhancement by a factor of about 1.8 is found over the range of magnetic field strengths covered here. Also the results for two values of B_z obtained at an ion energy of 110 MeV follow this trend. It should be noted that the maximum quantum number of Rydberg resonances contributing to the measured recombination rate is calculated to be $n_c = 79(87) \pm 4$ for 250 MeV (110 MeV) ion energy. This accounts for field ionization of recombined $Cl^{13+}(1s^2\,2s\,n\ell)$ ions in the strong motional electric field of the first down beam storage-ring dipole, affecting only those ions (with $n > n_c$) which are not able to radiatively stabilize their $n\ell$ Rydberg electron before reaching the dipole. Hence, the observed field enhancement factors reflect a specific range of Rydberg resonances with a slightly larger upper limit for 110 MeV as compared to 250 MeV ion energy.

The set of data obtained in this measurement provides clear evidence for the influence of magnetic fields on DR rates involving high Rydberg levels in the presence of perpendicular electric fields. The observed decreasing trend of the electric-field enhancement at magnetic fields rising from 20 to about 70 mT is consistent with the model predictions for the effective number of substates contributing to DR via a high-n Rydberg resonance by Robicheaux and Pindzola (Fig. 2 of Ref. [17]), obtained under simplifying assumptions for tenfold charged lithiumlike ions and $n = 30$. Thus, our measurements provide the first experimental proof for the recent theoretical hypothesis of magnetic field effects on DR in crossed external electric and magnetic fields. Our data emphasize the relevance of the effect of small magnetic fields on DR via high Rydberg levels in conjunction with the well-known electric-field enhancement. This result bears important implications upon the charge state balance of ions in astrophysical and laboratory plasmas where both electric and magnetic fields are ubiquitous.

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