Field Enhanced Dielectronic Recombination of Si^{11+} Ions

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The enhancement of dielectronic recombination by applied electric fields has been observed and measured for the first time in a wide range of controlled and measurable fields using multiply charged ions. The heavy ion storage ring CRYRING at Stockholm University was used to store a beam of Si^{11+} and collide it with a cold electron target. Rydberg resonances up to $n = 25$ are resolved for both the $2p_{3/2}$ and $2p_{1/2}$ series. The observation of a substantial monotonic increase of the rate coefficient for the group of higher Rydberg states is in puzzling disagreement with theoretical calculations of electric field enhanced dielectronic recombination. [S0031-9007(97)04040-4]

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Dielectronic recombination (DR) plays an important role in plasma dynamics and is also a subject of interest in studies of atomic structure. In spite of intense ongoing theoretical and experimental research on DR, the knowledge about effects of omnipresent external electromagnetic fields on this fragile process is still very limited. In this work field enhancements of cross sections for DR of Li-like Si^{11+} ions and electrons have been determined for nine different strengths of an applied electric field. The field enhancement has been measured under particularly well controlled conditions by employing—for the first time—a wide-range field-scanning technique. Moreover, this is the first such experiment with a multiply charged ion. Calculations have been made for the electric field enhancement, and puzzling disagreement is found upon comparing experiment and theory.

DR can, for the present case, be represented by

$$e + \mathrm{Si}^{11+}(1s^2 2s) \rightarrow \mathrm{Si}^{10+}(1s^2 2p_j n\ell)$$
$$\mathrm{Si}^{10+}(1s^2 2p_j n\ell) \rightarrow \mathrm{Si}^{10+}(1s^2 2sn\ell) + \text{photon}, \quad (1)$$

where $j = \frac{1}{2}$ or $\frac{3}{2}$. In the presence of electric fields this resonant process (DRF) is quantitatively and qualitatively different from DR in the absence of fields. Burgess and Summers [1] and Jacobs *et al.* [2] recognized early that electric fields could mix ℓ states and thus strongly influence DR. Very briefly, the effect arises because states of high ℓ have low autoionization rates, and by detailed balancing also low capture rates, so that they contribute negligibly to DR. Electric fields mix these high ℓ states with low ℓ states associated with high autoionization rates, and this increases the counting of states contributing to DR.

Measurements on singly charged Mg^+ ions at JILA [3] demonstrated a clear dependence of the DR cross sections on known electric fields, and the agreement between theory [4,5] and experiment could be considered quite reasonable. However, inconsistencies were found for multiply charged ions in first-generation merged-beam experiments at Oak Ridge Laboratory. Measured DR rates were interpreted in terms of similar field mixing by treating the unmeasured field as a free parameter to obtain agreement with theoretical calculations. For Be-like [6] and B-like [7] ions studied there, good agreement with theory could be imposed by adjusting the field to a reasonable magnitude. However, using a nearly identical apparatus configuration for the Li-like ions B^{2+}, C^{3+}, N^{4+}, and O^{5+} [8], agreement with theory [9,10] could not be obtained with like fields, and in fact, fields required to obtain agreement were unrealistically large. An attempt was made at Harvard [11] using Li-like C^{3+} and a known applied field in an inclined-beams experiment to resolve the inconsistencies. Again, values larger than DRF theory were obtained; though within the large experimental uncertainties there was agreement. Thus, the precision and limited scope of these experiments left ambiguities. Effects of unknown external electric fields on DR were also invoked in the interpretation of results obtained in a second generation of merged-beam experiments on Li-like ions, C^{3+} and O^{5+} [12,13], N^{4+}, F^{6+}, and Si^{11+} [14], and Ar^{15+} [15]. By adjusting the field values (a bit) larger than estimated, agreement of DRF theory and the experiment could be obtained.

Thus, with only one clear-cut experiment on DRF, and that for a singly charged ion, there remains a serious need for definitive DRF experiments on multiply charged ions using known fields. In the face of past history with multiply charged ions, experiments on Li-like ions seem most valuable.

The present measurements have been performed with Li-like Si^{11+} ions in the heavy-ion storage ring (CRYRING) at Stockholm University [16]. During recent years, merged beams in heavy ion storage rings have proven to be the "method of choice" for electron-ion recombination studies. The rings provide superior energy resolution, high detection efficiency, relaxed internal states, high beam and target densities, and a wide choice of reactant species. Different from the earlier Mg^{+} experiment, intermediate states populated by DR(F) can now be identified directly by their resonance energy.

In CRYRING a beam of Si^{11+} ions was accelerated and stored with typically 3 μA at 10 MeV/u. In one section of the ring a high-intensity (about 240 mA, radius 2 cm) magnetically confined electron beam "cooled" the ions. After optimizing the alignment of the ion beam with the electron beam, and hence also with the longitudinal magnetic field of the cooler, the ions traveled in the bottom of the electron space-charge well so there were no transverse fields from space charge and the Lorentz ($\vec{v} \times \vec{B}$) fields in the frame of the ions were minimized. A reasonably "field free" measurement of DR (with an estimated residual electric field of at most ± 5 V/cm) could then be obtained by switching the energy of the electrons in the cooler to different values, covering an energy range of approximately $1 \leq E_{\mathrm{c.m.}} \leq 25$ eV in the electron-ion center-of-mass frame. Recombined Si^{10+} ions were magnetically separated from the parent Si^{11+} beam and detected with a solid state detector downbeam from the cooler behind the first bending magnet. External motional electric fields were then introduced in the cooler of CRYRING by applying a defined transverse magnetic field $B_{\perp}$ using the steering coils available at the ring cooler. This transverse field was varied to give progressively different fields in the collision region.

For the measurements a scanning technique was applied in order to minimize relative uncertainties in the field and energy dependence of the data. After injection, acceleration and cooling of the ions in the ring ($\approx$2 s), the complete energy range of the resonances with $9 \leq n \leq \infty$ [see Eq. (1)] was scanned (1335 energies) for five different settings of the steering coils in *one* cycle ($\approx$26 s) with *one* filling of the ring. Before each energy scan ($\approx$4 s), the ion beam was cooled ($\approx$1 s) and the steering coils were set to produce a defined transverse magnetic field. The scans were made for $B_{\perp} = 0$, and 1.05, 2.09, 3.14, and 4.18×10^{-4} T (measured with an uncertainty of 3%) corresponding to the motional electric fields $E_x = 0.0$, 46.0, 91.5, 137.5, and 183.1 V/cm. The remaining ions were then dumped, and the whole cycle started over—this being repeated about 1500 times. Likewise, a second set of spectra for $E_x = 0.0$, 9.20, 18.4, 32.0, and 68.8 V/cm was measured. The relative ion currents were inferred from the recombination rate at cooling, and this was used to calibrate the spectra with respect to each other. An absolute calibration with an uncertainty of $\pm 20\%$ was achieved by normalization to data of Kenntner *et al.* [17], who measured recombination of Si^{11+} at $E_x = 0$ on the Test Storage Ring (TSR) at Heidelberg.

In all such experiments, the maximum Rydberg quantum number of contributing resonant states is limited by field stripping. As the recombined $Si^{10+}(1s^2 2sn\ell)$ ions travel toward the detector, they encounter the 0.966 T field of one of the dipole magnets causing a Lorentz field of $F = 4.2 \times 10^5$ V/cm. This field ionizes Rydberg states with quantum numbers n greater than some cutoff value which can be expressed [3] as $n_c = [(7.3 \times 10^8) q^3/F]^{1/4}$, where F is the field in V/cm. Thus only recombined ions with $n < n_c$ would reach the detector. The simple formula gives $n_c = 39$, but, of course, there is radiative decay of Rydberg states in the 2.15 ± 0.51 m between the cooler (1 m interaction length) and the detector position, so that the formula for n_c is only indicative. Using hydrogenic Rydberg lifetimes to estimate the decay of Rydbergs to all lower states in the flight between the center of the cooler and the front edge of the dipole magnet, we obtain $n_c = 47 \pm 4$ (depending on where in the cooler the ions have recombined).

The present DRF calculations were carried out in a manner previously described in detail [10]. The intermediate-coupled field mixed eigenvectors for the $2p_j n\ell$ Rydberg states of Si^{10+} were determined by diagonalizing a Hamiltonian matrix for each n which includes the internal electrostatic and spin-orbit terms, as well as the Stark matrix elements. The DRF cross section is evaluated in the isolated resonance approximation using autoionization and radiative rates calculated with the field mixed eigenvectors.

The total absolute recombination rate coefficients for the process of Eq. (1) are shown in Fig. 1. Both experimental and theoretical results are included, but barely distinguishable in the figure. The energy resolution is

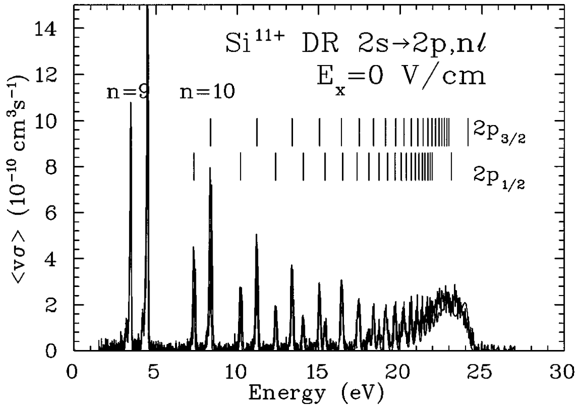

FIG. 1. Absolute total recombination rates for dielectronic recombination of Si^{11+} ions at zero imposed external electric field in the collision region. The CRYRING measurements were normalized to absolute data from the TSR [17]. The theoretical rate coefficient is indicated by a solid line (which can hardly be distinguished from the experiment).

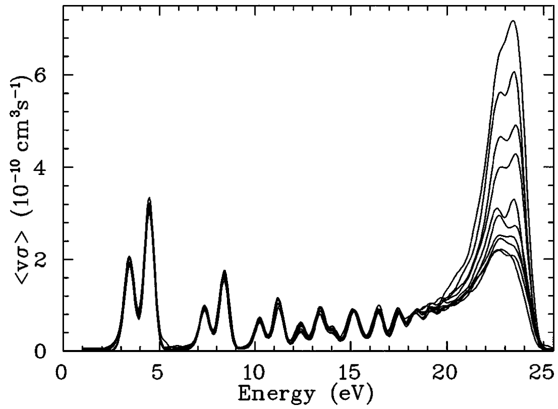

FIG. 2. Comparison of all data sets for nine different external electric fields. The imposed fields are $E_x = 0.0$, 9.2, 18.4, 32.0, 46.0, 68.8, 91.5, 137.5, and 183.1 V/cm. For this comparison, the resonances were artificially broadened in order to simulate equal energy resolution of all spectra. The experiment clearly shows an increase of the rate coefficient with increasing E_x. (Separate curves are displayed for the two measurements at $E_x = 0$.)

determined by the velocity distribution of the electrons characterized by an anisotropic temperature distribution with $kT_\perp = 10$ meV and $kT_\parallel = 0.1$ meV. Hence, the theoretical cross section was adapted for this distribution. Two distinct Rydberg sequences are seen, belonging to $2p_{1/2}n\ell$ and $2p_{3/2}n\ell$ states with $n \geq 9$. The energy resolution is such that even fine structure within the $n = 9$ Rydberg states can be observed and up to $n = 15$ Rydberg states can be seen as separate peaks in the spectrum. States up to $n = 25$ can be distinguished. The maximum principal quantum number observable in this experiment can be inferred from the half-height position of the experimental energy cutoff of the DR spectrum in Fig. 1. The Rydberg formula expressing this energy as $E(2s \to 2p_{3/2}) - 13.6 \text{ eV} \times (11)^2/n_c^2$ gives $n_c = 50 \pm 5$. This is consistent with the cutoff at $n_c = 47 \pm 4$ expected on the basis of lifetimes for radiative decay. Accordingly, the theoretical calculations in Fig. 1 have been truncated in principal quantum number. Since field ionization does not set in abruptly for a given n but starts gradually, depending on the symmetries of the substates, we have adopted a "soft cutoff," representing the detection probability of Rydberg states by a Fermi function $f(n, \Delta n)$ centered at $n = n_c = 50$, with a width $\Delta n \approx 10$.

Figure 2 shows 10 DRF spectra for the nine applied fields ($E_x = 0$ was measured twice). The data have been modified to accommodate the fact that with increasing $B_\perp$ the energy resolution of the measurements deteriorates because of increased misalignment of the electron and ion beams. Thus, all data have been artificially broadened by convoluting with a Gaussian function such that the worst energy resolution is realized for all spectra. While for $E_{\text{c.m.}} < 20$ eV it is not possible to see a clear effect of the field, a comparison of the spectra shows a dramatic increase of DRF rates for $n \geq 20$ ($E_{\text{c.m.}} > 20$ eV) with increasing external electric field strength in the interaction region. In this range of principal quantum number, the Rydberg states are unresolved, and it is most meaningful for comparison purposes to consider the sum or integral of contributions over some energy range.

Figure 3 shows the integral between 20 and 25 eV of the rate coefficients for each of the field strengths E_x investigated. Experimental data are the solid points and the bars on the points represent the relative uncertainty of normalization. Statistical uncertainties are inconsequential. The DRF calculations are presented in Fig. 3 with a soft cutoff at $n_c = 50$ and—considering the uncertainty of the cutoff—also at $n_c = 45$. The result for a sharp cutoff at $n_c = 39$ (i.e., Rydberg states up to $n = 38$ are included) is also displayed. In magnitude, the experiment and theory differ at most by 24% for $n_c = 50$, and the average difference for the nine field values is only 11%, bringing reassurance that the theoretical models for DRF are also reasonable for multiply charged ions. However, a more striking feature of the data compared with theory is that the experimental DRF integrated collision strength continues to climb at a roughly constant slope for all fields investigated, in conspicuous contrast to the theoretical curves which are relatively flat beyond 50 V/cm, independent of whichever cutoff is supposed. Clearly, any further studies should pursue investigation to high-enough imposed fields that saturation is achieved; higher fields were not instrumentally accessible at the time of these studies, but will be in the future.

Several speculations may be made on the puzzling disagreement between theory and experiment found in Fig. 3. First, there is some underlying uncertainty in the transverse magnetic field, resulting in a small motional electric field even at the experimental zero. A steep rise from zero as suggested by the theory with $n_c = 50$ could thus

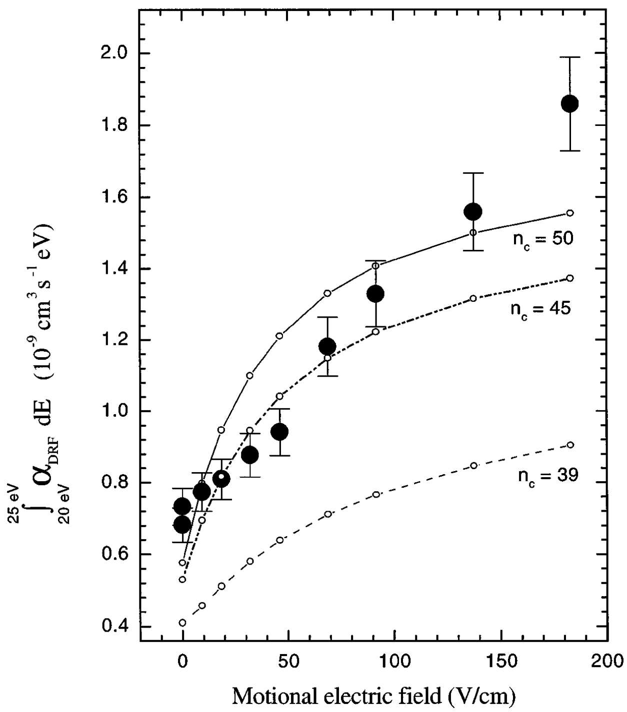

FIG. 3. Comparison between theory and experiment concerning field effects on dielectronic recombination of Li-like Si^{11+} ions. The rate coefficient of DR is integrated from 20 to 25 eV, and the values obtained are displayed vs corresponding electric field strengths E_x. Experimental data are black dots with error bars showing the relative uncertainty of normalization. Theory is given by open circles with connecting lines, depending on the choice of cutoff (see text).

be washed out in the measurements. Second, the calculations are done for a static, purely electric field. In the experiment, the guiding magnetic field of 0.030 T is at right angles to the motional electric field found from Lorentz transforming the transverse magnetic field. This arrangement of crossed electric and magnetic fields in the ion frame may provide additional magnetic sublevel mixing and further enhancement of the cross section [18]. For that reason, work on a more complete theory of dielectronic recombination in the presence of crossed electric and magnetic fields, beyond that of the model calculation of Robicheaux and Pindzola [18], is currently under way.

Finally, a determination of the cutoff of Rydberg states is greatly complicated by the relatively large distance between the cooler and the analyzer in the experimental setup. It is very difficult to determine how the Stark/Zeeman mixed states will decay on route from the interaction region to the stripping magnet, and once they arrive, it is difficult to determine exactly how they are affected by the strong magnetic field. However, to go much beyond the approximate treatment included in this paper would be, in itself, a major theoretical effort.

In summary, the effect of known motional electric fields on DR rates for a highly charged ion has been observed and measured for the first time. The use of a field- and energy-scanning technique in the present experiment has provided data of unprecedented quality with respect to field dependence of DR over a significant range. Reasonable agreement with DRF calculations is found as to the magnitude of the effect. However, puzzling disagreement between experiment and theory is found as to the change in the magnitude of the effect as a function of electric field strength.

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[1] A. Burgess and H. P. Summers, Astrophys. J. **157**, 1007 (1969).
[2] V. L. Jacobs *et al.*, Phys. Rev. Lett. **37**, 1390 (1976); V. L. Jacobs and J. Davis, Phys. Rev. A **19**, 776 (1979).
[3] A. Müller *et al.*, Phys. Rev. Lett. **56**, 127 (1986); Phys. Rev. A **36**, 599 (1987).
[4] K. La Gattuta *et al.*, Phys. Rev. A **33**, 2782 (1986).
[5] C. Bottcher *et al.*, Phys. Rev. A **34**, 860 (1986).
[6] P. F. Dittner *et al.*, Phys. Rev. A **36**, 33 (1987).
[7] P. F. Dittner *et al.*, Phys. Rev. A **38**, 2762 (1988).
[8] P. F. Dittner *et al.*, Phys. Rev. A **35**, 3668 (1987).
[9] K. J. LaGattuta, J. Phys. B **18**, L467 (1985).
[10] D. C. Griffin *et al.*, Phys. Rev. A **33**, 3124 (1986).
[11] A. R. Young *et al.*, Phys. Rev. A **49**, 357 (1994); D. W. Savin *et al.*, Phys. Rev. A **53**, 280 (1996).
[12] L. H. Andersen *et al.*, Phys. Rev. A **41**, 1293 (1990).
[13] D. C. Griffin *et al.*, Phys. Rev. A **40**, 6699 (1989).
[14] L. H. Andersen *et al.*, Phys. Rev. A **45**, 6332 (1992).
[15] S. Schennach *et al.*, Z. Phys. D **30**, 291 (1994).
[16] K. Abrahamsson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **79**, 269 (1993).
[17] J. Kenntner *et al.*, Phys. Rev. A (to be published); J. Kenntner *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **98**, 142 (1995).
[18] F. Robicheaux and M. S. Pindzola, following Letter, Phys. Rev. Lett. **79**, 2237 (1997).