Physica Scripta. T92, 395–397, 2001

Influence of Electromagnetic Fields on the Dielectronic Recombination of Ne^{7+} and O^{5+} Ions

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Received July 31, 2000; accepted September 12, 2000

PACS Ref: 34.80.Lx

Abstract

Within a series of measurements of the dielectronic recombination (DR) of lithium-like ions we have determined the enhancement of the recombination rate in the presence of crossed electric and magnetic fields for Ne^{7+} and O^{5+} ions. In both cases the electron energy range covers all DR resonances attached to $2s \rightarrow 2p_{1/2}$ and $2s \rightarrow 2p_{3/2}$ $\Delta n = 0$ core excitations. For increasing field the enhancement factor first increases linearly with the electric field and then saturates. In order to investigate the field effect on high-n Rydberg states the ion energy in the O^{5+}-experiment was changed from 9.4 MeV/u to 5 MeV/u and 3.26 MeV/u. With the variation of the ion energy the field ionization of Rydberg states in the analyzing magnet is influenced. This enabled us to study the field enhancement for a narrow bandwidth of n-states.

1. Introduction

Dielectronic recombination (DR) of an ion and an electron is a two-step process in which the dielectronic capture of the projectile electron into a doubly exited intermediated state is followed by the radiative decay of this state to a bound configuration. As a consequence of this scheme the final result of the recombination is susceptible to external influences on the short lived intermediate state. Such influences could be collisions with other particles, interactions with a laser or even with static external electromagnetic fields. In weak external electric fields Stark-mixing of states within one $n\ell m$-Rydberg manifold occurs (with m being still a good quantum number). This yields autoionization rates which are lower for low-ℓ and higher for high-ℓ states as compared to the field free situation. The net effect is an increase of the number of states participating in DR, i.e., an increase of the DR cross section. An additional magnetic field mixes the m-states which further influences the recombination rate. At low magnetic fields m-mixing typically enhances the electric-field effect. At a higher magnetic field the rate decreases again, because of the increasing energetic splitting of the m-levels, which hampers the mixing of these states. More detailed discussions can be found in recent publications [1–4].

2. Experiment

The experiments have been performed at the heavy-ion storage-ring CRYRING at the Manne-Siegbahn Laboratory in Stockholm. Beams of $^{20}Ne^{7+}$ ($^{16}O^{5+}$) ions were stored in the ring with intensities of about 2 μA. In one section of the ring a high intensity 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, such that transverse fields from space charge were negligibly small and the Lorentz ($\boldsymbol{v} \times \boldsymbol{B}$) fields in the frame of the ions were minimized. A reasonably "field free" measurement of DR could then be obtained by switching the energy of the electrons in the cooler to different values, covering the energy range of the $2s \rightarrow 2p_{1/2}$ and $2s \rightarrow 2p_{3/2}$ resonances. Behind the first bending magnet the recombined ions were separated from the primary beam and detected with a surface barrier detector. In order to study field effects, external motional electric fields $E_\perp$ were then introduced in the cooler by applying a defined transverse magnetic field $B_\perp$ using the steering coils of the cooler. Further details of the experimental procedure are described in Ref. [5].

In storage ring experiments, the maximum Rydberg quantum number of contributing resonant states is limited by field stripping. As the recombined ions travel towards the detector, they encounter the magnetic field of the bending magnet (≈ 1 T for an ion energy of 10 MeV/u) causing a Lorentz field of about 4×10^5 V/cm. This field ionizes Rydberg states with quantum numbers n higher than some cutoff value which can be expressed as $n_c = [Z^3/9F_c]^{1/4}$ where F_c is the electric field in atomic units ($1\,\text{au} = 5.142 \cdot 10^9$ V/cm) [6]. Thus, only recombined ions with $n < n_c$ would reach the detector. This simple formula does not consider radiative decay of Rydberg states between the cooler and the detector, so that the formula for n_c is only indicative. Here we estimate n_c by using a formula [7] also taking radiative decay of high n states into account.

3. Results and discussion

Figure 1 shows DR spectra of Ne^{7+} ions for 5 different electric fields. The $2p_{1/2}$ and $2p_{3/2}$ series could only be resolved for small values of n where the recombination rate is not influenced by the electric field. For a longitudinal magnetic field $B_\parallel$ of 1800 G the electric field was varied between 0 and 1436 V/cm in 25 different steps. For another set of

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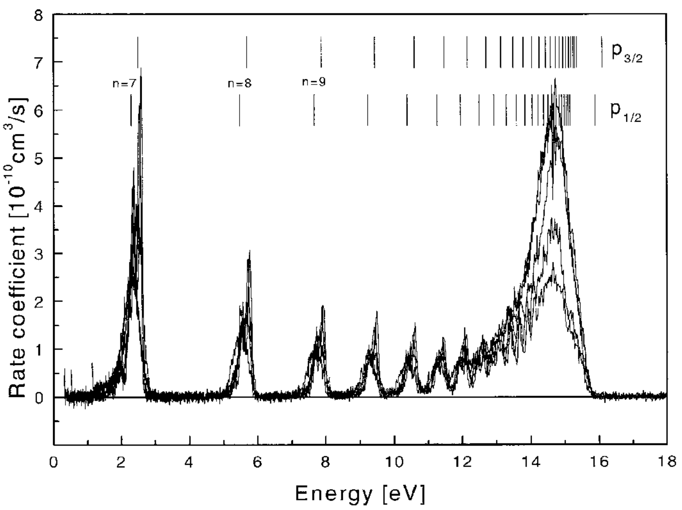

Fig. 1. Ne^{7+} DR spectra for 5 different electric fields 0, 144, 479, 1077, 1316 V/cm. The magnetic field was $B_{\|} = 1800$ G. The DR rate coefficient for high n-states increases with increasing electric field.

measurements the longitudinal magnetic field was set to 300 G and the electric field was varied between 0 and 144 V/cm in 15 different steps. Only resonances up to $n_c = 28$ contribute to the recombination rate. All higher n-states are lost due to field ionisation.

The enhancement of the DR via high Rydberg states is quantified by extracting rate coefficients I_j integrated over the energy range of 11.65– 15.9 eV of the measured spectra covering Rydberg states of both p_j series with n between 13 and 28. For normalization purposes we also monitored the integral I_0 (4.5–8.5 eV) comprising DR contributions from $n = 8 - 9$. The high Rydberg contributions I_j monotonically increase with the electric field, while the lower-n contribution I_0 remains constant when the electric field is changed. In order to provide a quantity characterizing the field effects we use the electric-field enhancement factor

$$r_j(E_y, B_z) = C_j(B_z)\frac{I_j(E_y, B_z)}{I_0(E_y, B_z)}. \qquad (1)$$

The constants $C_j(B_z)$ have been chosen such that fits to the data points (see below) yield $r_j^{(\mathrm{fit})}(0, B_z) = 1.0$. The result for the Ne^{7+}-experiment is shown in Fig. 2. The formula

$$r_j^{(\mathrm{fit})}(E_y, B_z) = 1 + s_j(B_z)E_j(B_z)\left\{1-\exp\left[\frac{-E_y}{E_j(B_z)}\right]\right\} \qquad (2)$$

which we have fitted to the measured enhancement factors, provides a parameterization of our data. The parameter $E_j(B_z)$ is the saturation field and $s_j(B_z)$ is the initial slope. The enhancement factor first grows linearly and then saturates for high electric fields. This saturation was already indicated by other measurements but was not seen as clearly as in this experiment. For the smaller longitudinal magnetic field of 300 G we could not apply as high transverse magnetic fields $B_\perp$ as for 1800 G. The reason for this limitation is the tilt angle ϑ between the electron and ion beams. Since the electrons follow the magnetic field lines, the electron beam is tilted with respect to the cooler axis (the ion beam direction) by the angle $\vartheta = \arctan(B_\perp/B_\|)$. If ϑ becomes too large the beams will no longer fully overlap. The initial slope of the enhancement factor for the measurement at 300 G is much higher than the slope for 1800 G, i.e. the magnetic field reduces the effect of the perpendicular electric field on DR. This confirms previous findings for Cl^{14+} [2] and Ti^{19+} [3,8] ions.

In a further experiment at CRYRING DRF of $^{16}O^{5+}$-ions was studied. In order to investigate the influence of field ionisation we changed the ion energy from 9.4 MeV/u to 5 MeV/u and 3.26 MeV/u in this experiment. Lowering the ion energy means, that the ion velocity is reduced and the magnetic field in the bending magnets can be lowered. As a result the motional electric field $\boldsymbol{F}_c = \boldsymbol{v} \times \boldsymbol{B}$ seen by the ions is smaller. This shifts the field ionization quantum number n_c from 19 at an ion energy of 9.4 MeV/u to 22 for 5 MeV/u to 24 at 3.26 MeV/u. Correspondingly, as shown in Fig. 3 (all spectra taken at $E_\perp = 0$ V/cm) an increase of DR resonance strength is observed with decreasing ion energy. Further lowering of the ion energy below 3.26 MeV/u was not possible, because of the very

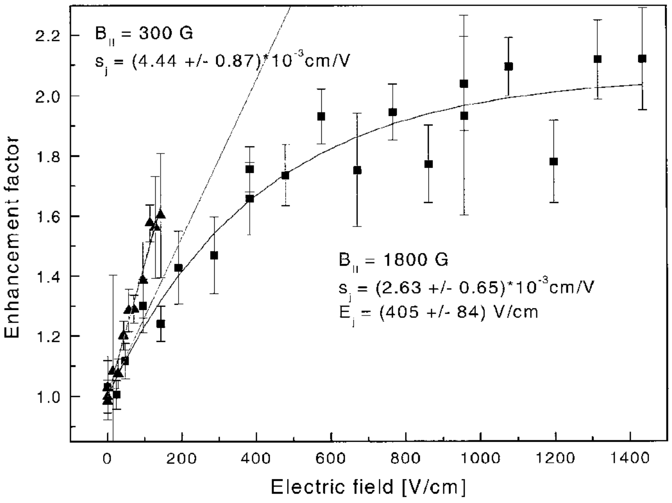

Fig. 2. Electric field enhancement factors for Ne^{7+}-ions for 2 different longitudinal magnetic fields. The error bars represent the uncertainty in the relative ion current calibration and the statistical error. s_j is the initial slope and E_j the saturation field.

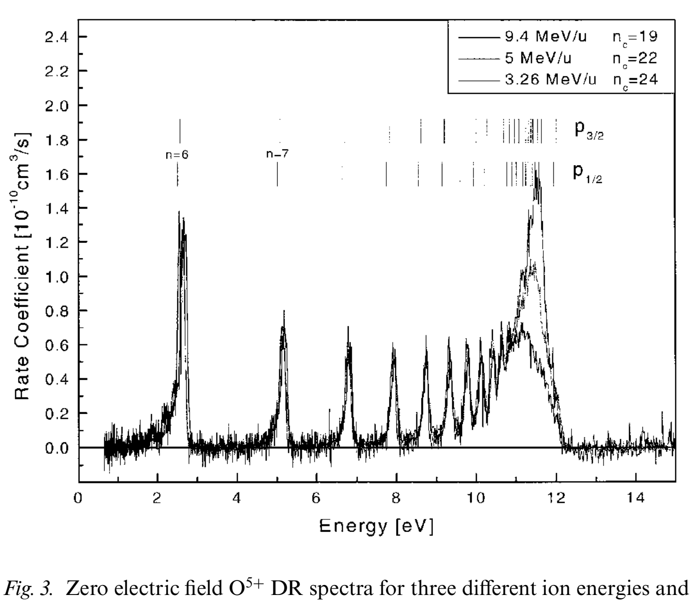

Fig. 3. Zero electric field O^{5+} DR spectra for three different ion energies and corresponding field ionisation cutoff Rydberg quantum numbers n_c.

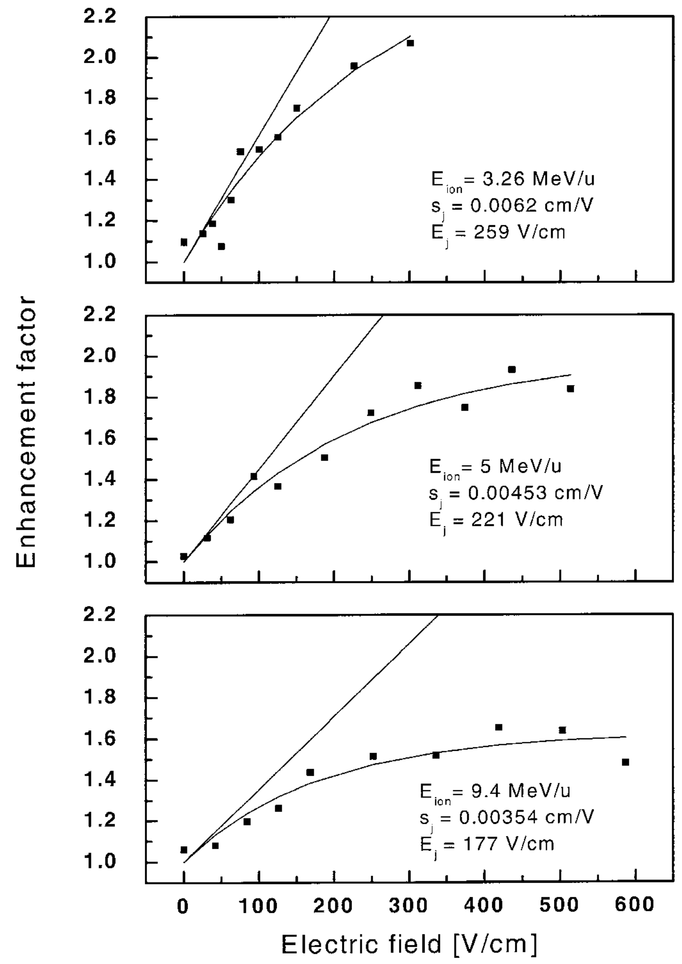

Fig. 4. Field enhancement factor r_j for O^{5+}-ions at 3 different ion energies.

strongly increasing background from electron capture of the ions in the residual gas in the ring.

The longitudinal magnetic field has been set to 1000 G this time and the highest electric field imposed on the interaction region was $F = 692$ V/cm. Figure 4 shows the field enhancement factor r_j and the initial slope s_j for the three different ion energies. As the ion energy decreases the slope s_j grows from 0.00354 cm/V at an ion energy of 9.4 MeV/u to 0.0062 cm/V at 3.26 MeV/u. Thus, the influence of the electric field on the n-states increases with increasing n in the range of Rydberg quantum numbers investigated here. By comparing the integrals I_j for two different ion energies the recombination rate for a narrow bandwidth of n-states can be deduced.

4. Summary and conclusions

DRF-measurements have been extended towards elements with lower nuclear charge. Taking advantage of the high magnetic fields in the CRYRING electron cooler higher electric fields as in previous experiments could be applied. This enabled us to see the saturation of the field enhancement very clearly in DRF of Ne^{7+}. In the O^{5+}-experiment we made a step towards investigations of field ionization of high n Rydberg states by varying the ion energy. The resonance strength of high n Rydberg states has been found to increase with decreasing ion energy interpreted as a shift of the corresponding field-ionization cutoff quantum number n_c towards higher values. This allows us to determine the recombination rate for a bandwidth of n-states and its dependence on the electric field, i.e. to obtain DRF data differential in n. A detailed analysis is currently being performed.

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