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Enhancement of Dielectronic Recombination by External Electromagnetic Fields

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Abstract. The enhancement of the dielectronic recombination rate of lithiumlike Ne^{7+} and O^{5+} ions by external electromagnetic fields has been measured at the storage ring CRYRING. The energy range covered all $1s^2 2pnl$ dielectronic recombination resonances attached to the $2s \rightarrow 2p$ core excitation. Electric fields up to 1436 V/cm were applied in the Ne^{7+} experiment and the saturation of the enhancement with increasing electric field could clearly be seen. In the O^{5+} experiment the enhancement was studied as a function of the Rydberg quantum number n.

Key words: dielectronic recombination enhancement.

Dielectronic recombination (DR) of an ion and an electron is a resonant two-step process. In the first step, the dielectronic capture, a continuum electron is captured into a bound state with simultaneous excitation of a bound electron. In the second step the resulting doubly excited state decays by the emission of a photon to a bound state below the first ionization limit. For the present case, DR can be approximately represented as

$$e^- + A^{q+}\big(1s^2 2s\big) \rightarrow A^{(q-1)+}\big(1s^2 2pnl\big) \rightarrow A^{(q-1)+}\big(1s^2 2snl\big) + h\nu.$$

The weakly bound highly excited intermediate Rydberg states are easily perturbed by external influences, such as electromagnetic fields. The experimental investigation of dielectronic recombination in external fields (DRF) at heavy ion storage rings is an ongoing effort. Here we report on experiments with Ne^{7+} [5] and O^{5+} [6] ions, that extend a series of measurements on lithium-like ions (Si^{11+} [2], Cl^{14+} [3], Ti^{19+} [4] and Ni^{25+} [8]) towards lower values of the nuclear charge Z. High resolution zero field DR of Ne^{7+} and O^{5+} has been measured previously by Zong *et al.* [10] and Andersen *et al.* [1], respectively.

The experiments have been performed at the heavy-ion storage-ring CRYRING of the Manne Siegbahn Laboratory in Stockholm. For the measurements $^{20}Ne^{7+}$

($^{16}O^{5+}$) ions were injected into the ring, accelerated, and cooled by merging the ion beam with a beam of cold electrons. Inside the electron cooler the electron beam is guided by a magnetic field denoted by $B_\parallel$ in the following. For the subsequent DR measurement the electron cooler was used as an electron target. To obtain a DR spectrum the electron energy was ramped. In order to study field effects, external motional electric fields ($E_\perp = vB_\perp$) were introduced in the cooler by applying a defined transverse magnetic field $B_\perp$ using the steering coils of the cooler. With this technique the complete energy range of the resonances attached to the $2s \rightarrow 2p$ core excitation was scanned for different electric fields.

In storage ring experiments, the maximum Rydberg quantum number of resonant states contributing to the detected signal is limited by field ionization. As the recombined ions travel towards the detector, they encounter three regions with different transverse magnetic fields and hence different motional electric fields. These regions are (1) the toroid which guides the electron beam out of the overlap with the ion beam ($\approx 4 \times 10^4$ V/cm), (2) a dipole magnet ($\approx 1 \times 10^5$ V/cm) just behind the cooler that corrects for the ion beam displacement by the toroidal fields in the cooler, and (3) the bending dipole magnet in which the detector is placed and which is used as the charge analyzing magnet ($\approx 5 \times 10^5$ V/cm). The values of the electric fields given in brackets correspond to 11.4 MeV/u Ne^{7+} ions. These fields ionize Rydberg states with quantum numbers n higher than some cutoff value that can be expressed as $n_F = (q^3/9F)^{1/4}$ where F is the electric field in atomic units (1 au $= 5.142 \times 10^9$ V/cm). For 11.4 MeV/u Ne^{7+} ions in the CRYRING, i.e. with the electric fields given above, one obtains $n_F = 46$ in the toroid, $n_F = 35$ in the correction magnet, and $n_F = 24$ in the charge analyzing dipole. Only recombined ions with $n < n_F$ can reach the detector. Since the simple formula for n_F does not consider radiative decay of Rydberg states on the way from the cooler to the different field ionization zones, it is only indicative. In a more detailed field ionization model [9] we have considered all three field ionization regions mentioned above to obtain nl-dependent Rydberg detection probabilities.

Figure 1(a) shows DR spectra of Ne^{7+} ions for five selected electric fields. Clearly the measured DR rate coefficient in the energy region 11.65–15.9 eV increases with increasing electric field strength. For a longitudinal magnetic field $B_\parallel$ of 180 mT the electric field was varied between 0 and 1436 V/cm in 25 different steps. For a second set of measurements $B_\parallel$ was set to 30 mT and the electric field was varied between 0 and 144 V/cm in 15 different steps.

The enhancement of the DR via high Rydberg states is quantified by extracting rate coefficients I_{hi} integrated over the energy range 11.65–15.9 eV for Ne^{7+} and 9.4–12 eV for O^{5+}, respectively. For normalization purposes we also monitored the integral I_{lo} at low energies where the electric field has no significant influence on the recombination rate (4.5–8.5 eV and 1.3–7.25 eV, respectively). The high Rydberg contributions I_{hi} monotonically increase with the electric field, while the lower-n contribution I_{lo} remains constant when the electric field is

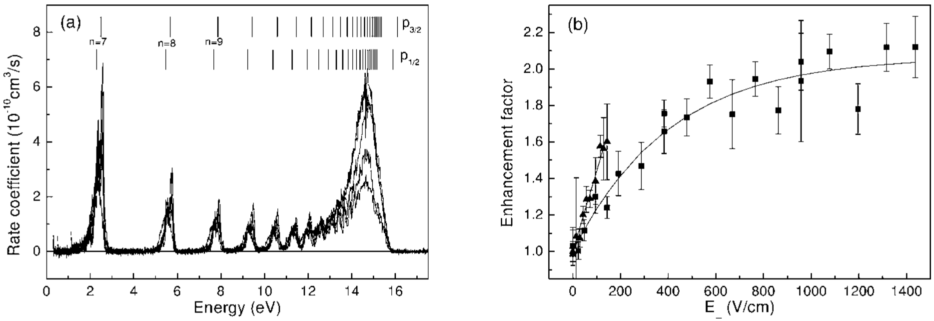

Figure 1. (a) Ne^{7+} DR, spectra for 5 different electric fields 0, 144, 479, 1077, 1316 V/cm ($B_{\|} = 180$ mT). (b) Electric field enhancement factors for Ne^{7+}-ions for 2 different longitudinal magnetic fields, 180 mT (squares) and 30 mT (triangles).

changed. In Figure 1(b) we have plotted the electric-field enhancement factor [4, 8]

$$r(E_\perp, B_\|) = C(B_\|)\frac{I_{\rm hi}(E_\perp, B_\|)}{I_{\rm lo}(E_\perp, B_\|)} \tag{1}$$

with the constant $C(B_\|)$ chosen such that fits to the data points (see below) yield $r^{(\rm fit)}(0, B_\|) = 1.0$. The formula

$$r^{(\rm fit)}(E_\perp, B_\|) = 1 + s(B_\|)E_{\rm sat}(B_\|)\left\{1 - \exp\left[\frac{-E_\perp}{E_{\rm sat}(B_\|)}\right]\right\}, \tag{2}$$

that we have fitted to the measured enhancement factors (full lines in Figure 1(b)), provides an easy parameterization of our data. The parameter $E_{\rm sat}(B_\|)$ is the saturation field and $s(B_\|)$ is the initial slope, that is, the tangent to $r^{(\rm fit)}(E_\perp, B_\|)$ at $E_\perp = 0$. The enhancement factor first grows linearly and then saturates for high electric fields. This saturation was already indicated by other measurements [3] but was not seen previously as clearly as in the experiment with Ne^{7+} ions.

The initial slope of the enhancement factor for the measurements at 30 mT is much higher than the slope at $B_\| = 180$ mT, i.e. the magnetic field reduces the effect of the perpendicular electric field on DR. This B field dependence of DR rates was theoretically predicted [7] and experimentally verified [3, 4] only recently.

Compared to other measurements where the detected enhancement of the recombination rate due to an electric field increased when going from Ni^{25+} ($Z = 28$) to Si^{11+} ($Z = 14$) the enhancement of the detected recombination rate decreases again in the present experiments with lower Z ions. This decrease is caused by field ionization of high Rydberg states that for low Z sets in at relatively low n. The results of the Ne^{7+} experiment have been reported in detail previously in [5].

In the O^{5+} experiment DRF was studied as a function of the Rydberg quantum number n. This was done by utilizing the unavoidable field ionization described above which limits the maximum detected Rydberg state to a value $n_F =$

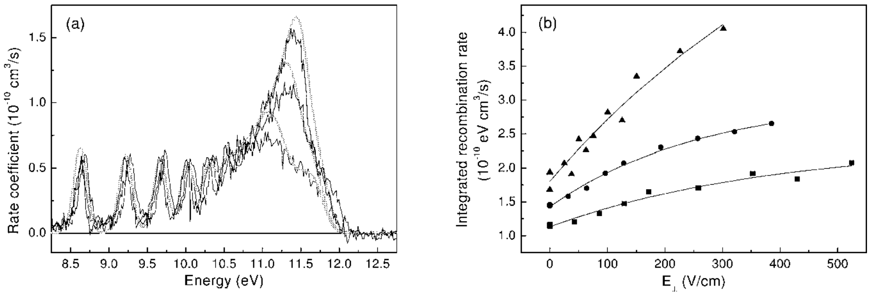

Figure 2. (a) O^{5+} DR spectra for three different ion energies with no electric fields applied to the interaction region. Included are the theoretical results obtained by AUTOSTRUCTURE to which our field ionization model has been applied (thick lines), (b) Integrals I_{hi} from 9.4–12 eV for all three ion energies (9.4 MeV/u squares, 5 MeV/u circles, and 3.26 MeV/u triangles).

$(q^3/9F)^{1/4}$. The field F depends on the ion velocity. As the ion velocity is decreased the magnetic field of the bending dipole magnets can be reduced and therewith the motional electric field $F = vB$. This shifts the cutoff quantum number n_F to higher values.

Three different ion energies (9.4, 5 and 3.26 MeV/u) were used in the O^{5+} experiment. The corresponding cutoff quantum numbers n_F are 19, 22, and 25, respectively. The effect of this increase of n_F is seen in Figure 2(a). As the ion energy is decreased and n_F grows, the recombination rate coefficient in the high energy part of the spectra increases.

The experimental spectra are compared to theoretical results from Badnell obtained by the AUTOSTRUCTURE atomic structure code to which our field ionization model has been applied. The thick lines in Figure 2(a) show the results which agree very well with the experiment. From this we conclude that field ionization is sufficiently well understood in our experiments.

The enhancement of the DR via high Rydberg states has been quantified by extracting the integrated recombination rate of the high energy part of the spectra (9.4–12 eV) as described above. These integrals I_{hi} are shown in Figure 2 for all three ion energies. The difference between these curves is due to the bandwidths of n states added by lowering the ion energy ($n = 19$–22 and $n = 22$–25). By subtracting the curves from one another one gets the integrated recombination rate only due to these two bandwiths. The increasing difference between these curves as the electric field increases shows that the higher Rydberg states ($n = 22$–25) are much more sensitive to external fields then the lower ones ($n = 19$–22). The analysis of the n differential DR data has not been completed yet but it is obvious that this technique allows us to investigate n differential DRF.

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