State-Selective Dielectronic-Recombination Measurements for He-Like Oxygen Ions in an Electron Cooler

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(Received 15 December 1988)

We report on high-resolution, state-selective dielectronic-recombination measurements for metastable, He-like O^{6+} ions. The measurements were performed with a merged-beam configuration in an electron cooler. The energy resolution was found to be as low as 0.135 eV. Dielectronic recombination associated with excitations of the $1s2s(^1S)$ and $1s2s(^3S)$ cores are reported. The data demonstrate strong effects of configuration interaction between different intermediate states with almost identical energy.

PACS numbers: 34.80.Kw, 31.50.+w

In large parts of the physics community, the newly developed techniques of confinement of heavy ions in traps or storage rings have attracted great attention. To achieve long-time storage in the latter case, it is necessary to apply some mechanism for continuous reduction of the beam phase space to counteract the inherent beam heating. One such cooling scheme is electron cooling,[1] where a beam of electrons with little momentum spread and with the same velocity as the ions is merged with the stored ion beam.

Currently, a heavy-ion storage ring, ASTRID, is under construction at the University of Aarhus.[2] As a part of this project, an electron cooler has been built at one of the beam lines at the EN-tandem accelerator in a single-pass geometry. The purpose of this cooler is twofold. First, it serves as a prototype for the electron cooler at ASTRID. Thus, tests on electron-beam quality and vacuum have been performed. Second, the electron cooler is used as an electron target to study electron-ion recombination processes.

If an originally free electron is to end up bound to an ion, its excess energy and momentum has to be given off to some kind of a third "particle." In dielectronic recombination, to be considered here, the incoming free electron loses energy when it excites a core electron of the ion. In doing so, it becomes captured to some state nl which depends on the excitation energy ΔE and the kinetic energy of the free electron E_r (relative to the ion rest frame) according to

$$\Delta E = E_r + E_{nl} , \tag{1}$$

where E_{nl} is the binding energy of the state nl. When ΔE is small compared to the total binding energy of the core electron, n becomes high, and the core excitation (ΔE) is normally unaffected by the Rydberg electron. As will be shown in this Letter, the presence of the Rydberg electron, however, may play a crucial role under certain circumstances. If the doubly excited state decays by photon emission, the dielectronic-recombination (DR) process is fulfilled. If not, elastic scattering has occurred.

In the present Letter, we report on measurements of DR with metastable He-like oxygen ions. The following reactions were considered:

$$\begin{aligned} e^- + O^{6+}(1s2s\,{}^1S) &\rightarrow O^{5+}(1s2p\,{}^1P\,nl) , \\ e^- + O^{6+}(1s2s\,{}^3S) &\rightarrow O^{5+}(1s2p\,{}^1S\,nl) , \\ &\rightarrow O^{5+}(1s2p\,{}^3P\,nl) , \\ &\rightarrow O^{5+}(1s2p\,{}^1P\,nl) , \end{aligned} \tag{2}$$

where the $1s2s$ and $1s2p$ configuration forms either a singlet or a triplet state. The excitation energies of the ${}^1S \rightarrow {}^1P$, ${}^3S \rightarrow {}^1S$, ${}^3S \rightarrow {}^3P$, and ${}^3S \rightarrow {}^1P$ transitions are 5.06, 7.83, 7.59, and 12.89 eV, respectively. The ${}^3P$ energy is averaged over the fine structure.[3]

Theoretically, the DR process has attracted a great deal of attention, primarily because it is a challenge to treat all the intermediate states with their individual decay rates properly. Comparison between theory and experiment constitutes a basis for testing the approximations used in these extensive calculations. In particular, great attention has recently been paid to the influence of external fields. Due to mixing of high Rydberg states with angular momenta, external fields cause a considerable enhancement of the DR cross section.[4-6] An entry to references on DR is given by Dittner.[7]

The experimental setup is shown schematically in Fig. 1. Beams of 1.25 MeV/amu O^{6+} were provided by the 6-MV EN-tandem accelerator at the University of Aarhus. Immediately in front of the interaction region, the ion beam was cleaned for unwanted charge-state components by a 15° bending magnet. After the interaction region of 1 m, the ions were charge-state analyzed by an electric field perpendicular to the beam direction. This field of 8.5 kV/cm sets an upper limit (n_{max}) for the main quantum number of states which survive through the analyzer. Finally, the main beam was collected in a Faraday cup, and the small fraction of ions which had captured an electron was detected by a

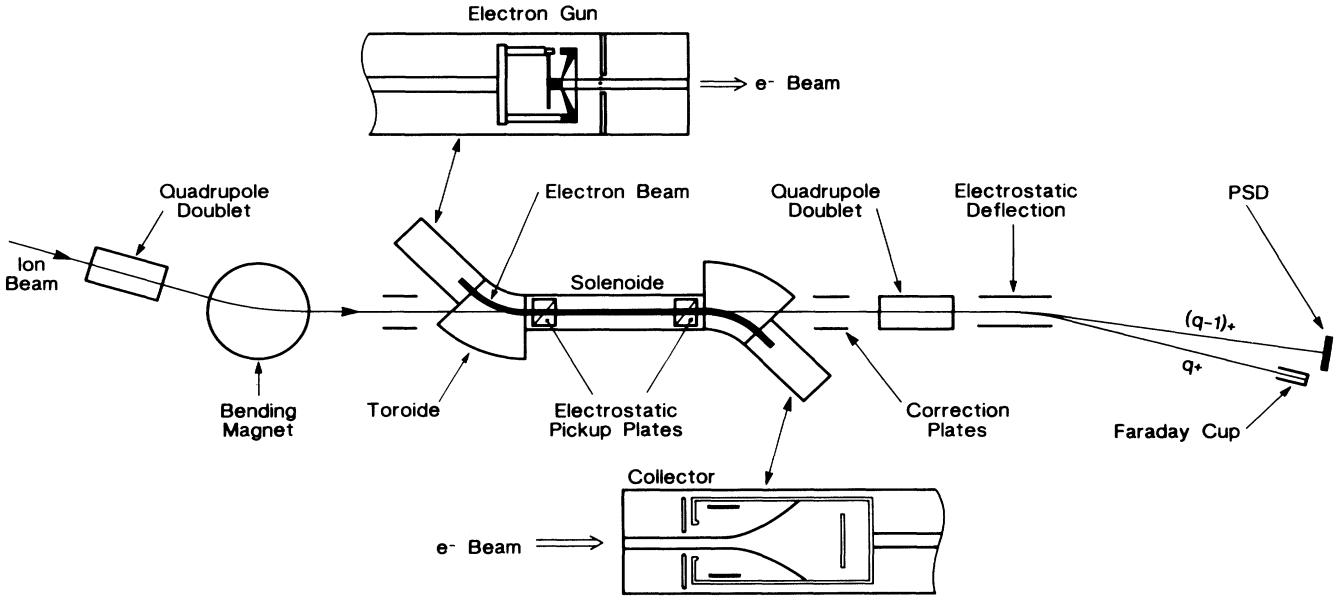

FIG. 1. Schematic diagram of the experimental setup.

position-sensitive channel-plate detector (PSD). With both ion and electron beams on, the pressure in the interaction region was about 2×10^{-11} Torr.

The electron beam had a diameter of 1 cm. It was verified by measurements with a Faraday probe that the intensity variation within the electron beam was typically less than 5%. The electron current was between 5 and 10 mA. Three solenoids and two toroids guided the electrons from the gun through the interaction region to the collector. The magnetic field of about 150 G was applied to compensate for the space-charge field in the electron beam. We estimate that this field in the interaction region was 1 to 2 V/cm.

The position of the two beams in the merge section was measured by two sets of electrostatic pickup plates. By modulating the beam intensity at a frequency of 2 MHz, it was possible to control both the vertical and the horizontal positions of the two beams to ensure that the ion beam was fully embedded in the electron beam.

The actual energy of the electrons is given by the formula (in the laboratory frame)

$$E_e=(V_c+V_s)e\,, \tag{3}$$

where V_c is the cathode potential, V_s is the space-charge potential in the electron beam, and e is the elementary charge. In the rest frame of the ion the energy of the electron, E_r, is obtained as

$$|E_r|=E_e+(m/M)E_i-2(E_iE_em/M)^{1/2}\,, \tag{4}$$

where E_i is the ion energy and m and M are the electron mass and ion mass, respectively. We use the convention that negative E_r corresponds to $v_e<v_i$ and positive E_r to $v_e>v_i$, where v_e and v_i are the electron and the ion laboratory velocities, respectively.

The quality of the electron beam was characterized by two temperatures $T_\perp$ and $T_\parallel$. In the rest frame of the ion, the electron-velocity distribution was described as

$$f(\mathbf{v})=\frac{m}{2\pi kT_\perp}e^{-mV_\perp^2/2kT_\perp}\left(\frac{m}{2\pi kT_\parallel}\right)^{1/2}e^{-m(V_\parallel-\Delta)^2/2kT_\parallel}\,, \tag{5}$$

where $V_\perp$ and $V_\parallel$ are the electron-velocity components perpendicular and parallel to the ion beam, respectively, and Δ is the detuning velocity determined by $\frac{1}{2}m\Delta^2=E_r$. Since the DR resonances are narrow,[8] we used a δ function to describe a single DR resonance. Figure 2 shows the fit to the $1s2p(^1P)11l$ DR resonance of O^{6+} at 1 eV relative energy. From the fit, we obtained $kT_\perp$

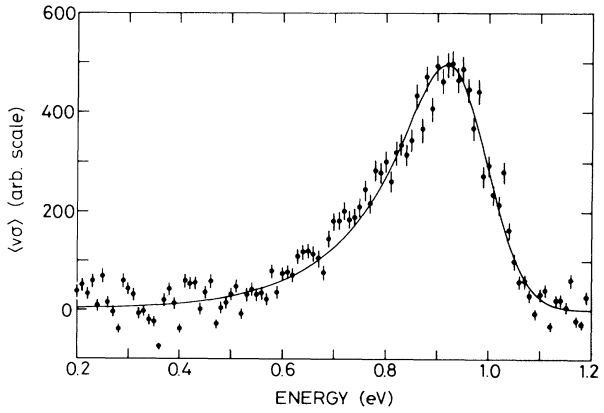

FIG. 2. Fit to the $1s2p(^1P)11l$ DR resonance.

$=0.135\pm0.010$ eV and $kT_{\parallel}=(10\pm5)\times10^{-4}$ eV. If the width of the resonant state cannot be neglected, we have overestimated $T_{\perp}$ and $T_{\parallel}$; thus the values are to be considered as upper limits. Evidently, $kT_{\parallel}\ll kT_{\perp}$, as expected due to the kinematic reduction of the longitudinal energy spread. The transverse energy spread in our cooler is close to the temperature expected on the basis of the cathode temperature which was about 1000 K. It must be emphasized that any contribution from the energy spread in the ion beam is included in the values above.

We choose to represent our data in the form of the rate defined as

$$\langle v\sigma(v)\rangle=\frac{1}{\epsilon}\frac{N^{(q-1)+}}{N^{q+}}\frac{v_i}{\rho_e L}, \tag{6}$$

where ϵ is the ion detection efficiency, N^{q+} is the number of incoming ions $(q+)$, and $N^{(q-1)+}$ is the number of ions with charge $(q-1)+$ corrected for the nonresonant background contribution due to electron capture from the rest gas. ρ_e is the electron density and L is the interaction length.

Figure 3 shows our result for O^{6+}. Since there are no DR resonances in the present energy range for the ground state $(1s^2)$, the recombination occurred due to metastable $1s2s$ ions through the reactions (2). The lifetimes of the $1s2s(^1S)$ and $1s2s(^3S)$ states are longer than or comparable to the ion flight time from the place of production to the region where the beams merge.[9]

To obtain absolute rates for the reactions (2), one must know the fraction of metastables in each state.

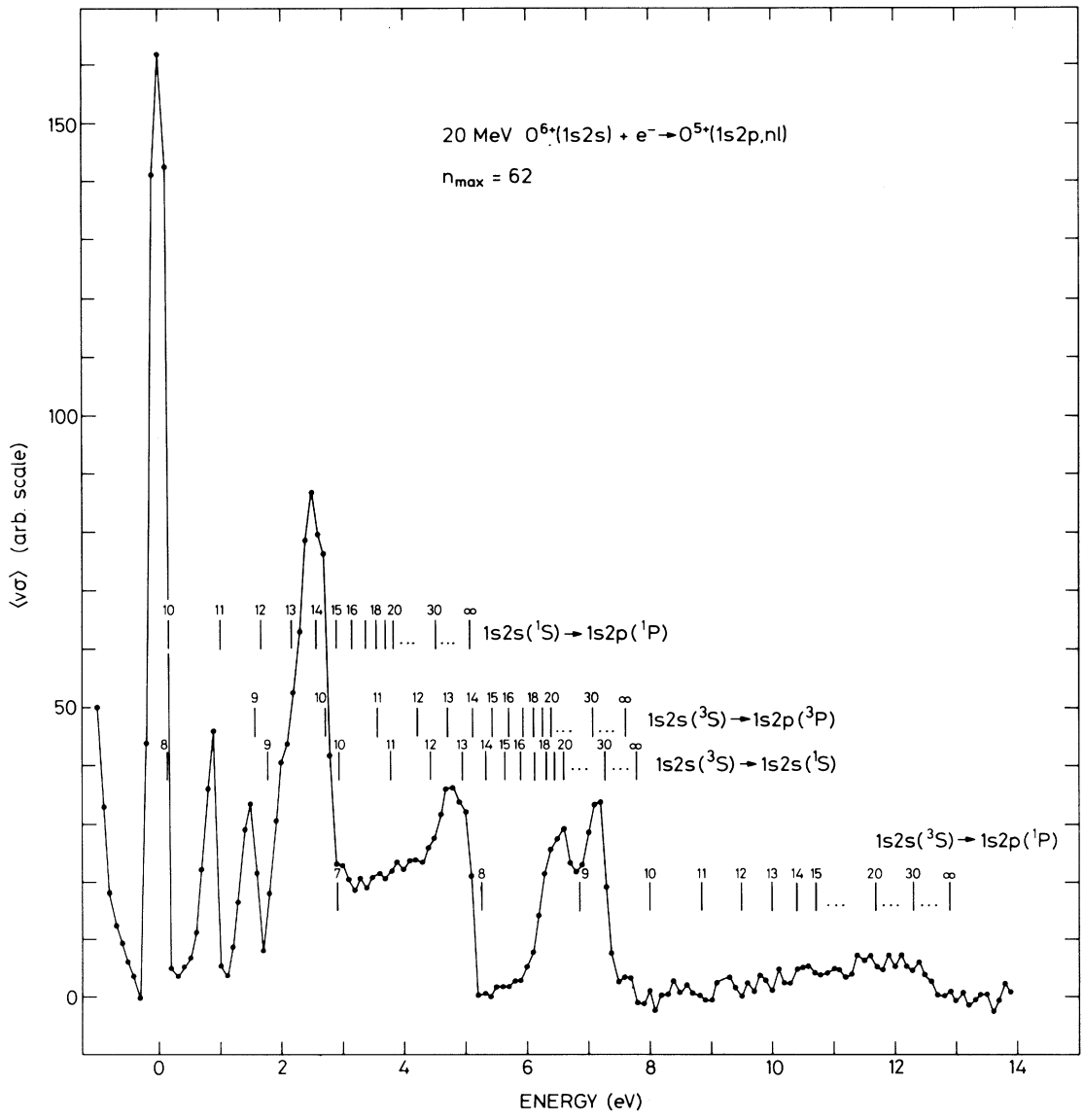

FIG. 3. The rate coefficient $\langle v\sigma\rangle$ as a function of relative electron energy for O^{6+}. To obtain a lower limit for the rate coefficient, multiply the ordinate by 10^{-11} cm^3/s.

These fractions are not known, and the rates quoted here are to be considered as *lower* limits since we used the total number of ions (in any state) as N^{q+} in formula (6).

For convenience, we show the expected resonance position according to

$$E_n = \Delta E - \frac{q^2 \times 13.6}{n^2}, \quad (7)$$

where we neglect the quantum defect. When inspecting the data displayed in Fig. 3, the series corresponding to core excitations $^3S \rightarrow {}^1P$, $^3S \rightarrow {}^1S, {}^3P$, and $^1S \rightarrow {}^1P$ are recognized. The very large peak at around zero energy is probably due to DR with $n=10$ of the ^1S-to-^1P excitation and possibly with $n=8$ of the ^3S-to-^1S excitation. The rate for radiative recombination[10] was calculated to be only 12×10^{-11} cm^3/s at zero energy with the present electron temperatures. Moreover, calculations show that the observed sharp structure cannot be due to radiative recombination because of the relatively weak energy dependence of the cross section of this process.

Several striking features related to the excitation of the ^3S core are revealed. For example, when the $1s2p(^1P)nl$ intermediate resonances lie below the series limits of the $1s2s(^1S)$- and $1s2p(^3P)$-core states, unusually large rates are observed (at 2.5, 4.4, and 6.5 eV). This happens close to the DR resonances with $n=7$, 8, and 9 of the $^3S \rightarrow {}^1P$ series. It is argued[11] that this is due to the configuration interaction between three-electron states (core-nl), closely spread in energy, belonging to the different core configurations. Thus, mixing of the $1s2s(^1S)nl$ and $1s2p(^3P)n'l'$ states with the $1s2p(^1P)n''l''$ states increases the DR rate due to the strong radiative transition $1s2p(^1P) \rightarrow 1s^2(^1S) + h\nu$ which completes the DR process. On the other hand, the rate associated with the $^3S \rightarrow {}^1P$ excitation above the ^1S and ^3P threshold at around 7.5 eV is decreased due to the opening of the Auger decay channel to these states.[11]

The good energy resolution of the present experiment has revealed structures in the DR process which clearly call for calculations which take into account the specific structure of the ion with three open shells in the intermediate state.

This work was supported by the Danish Natural Science Research Council, the Carlsberg Foundation, and the Ib Henriksen Foundation. We wish to thank K. Taulbjerg and J. Macek for communicating their results to us.

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