Dielectronic Recombination of Hydrogenlike Oxygen in a Heavy-Ion Storage Ring

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State-resolved cross sections for the dielectronic recombination of hydrogenlike oxygen ions with free electrons have been measured for the first time using the electron cooling device in the heavy-ion Test Storage Ring in Heidelberg. Energies and cross sections for individual terms of the configuration $2l2l'$ were determined. Two-electron resonances $2lnl'$ with $n \geq 3$ contribute 90% to the total dielectronic-recombination cross section. Energies and cross sections are in reasonable agreement with available calculations.

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When performed with sufficient energy resolution, dielectronic-recombination[1,2] (DR) measurements on hydrogenlike ions should constitute an ideal tool for the spectroscopic investigation of heliumlike doubly excited ions. The properties of these two-electron systems are of great interest for testing theories of atomic resonances and correlated electron motion, which find wide application in atomic physics such as for systems of three or more electrons, negative ions, and complex exotic atoms like Ps^-. Moreover, the DR cross sections obtained at well defined electron energies are relevant to the study of thin, high-temperature plasmas[1] and for x-ray laser research.[3]

In this Letter, we report on the first measurement of DR of hydrogenlike ions in the electron cooler of a heavy-ion storage ring. The DR of a positive ion with a free electron of a kinetic energy ϵ is a two-step process composed of the formation of a doubly excited state by time-reversed autoionization and the spontaneous emission of a photon (γ), which stabilizes the recombined system. For hydrogenlike oxygen, this process can be represented by

$$O^{7+}(1s)+e^-(\epsilon)\rightarrow O^{6+**}(Nlnl')\rightarrow O^{6+*}(1snl')+\gamma\,,$$

with the principal quantum numbers $N=2,3,\ldots$ for the "inner" electron, $n=N,N+1,\ldots$ for the "outer" electron, and with the angular momenta l,l' of the hydrogenic orbitals. The cross section $\sigma_\alpha(\epsilon)$ and its integral S_α for a DR resonance via a state α are given by[2]

$$\sigma_\alpha(\epsilon)=S_\alpha L_\alpha(\epsilon)=\frac{2\pi\hbar}{\epsilon/R_\infty}\pi a_0^2\frac{g_\alpha}{2g_i}\frac{A_\alpha A_r}{A_{\text{tot}}}L_\alpha(\epsilon)\,, \quad (1)$$

where A_α is the autoionization rate of α, A_r its radiative decay rate into a bound ($1s\,nl'$) state, A_{tot} its total decay rate, $L_\alpha(\epsilon)$ the normalized line-shape function (a Lorentzian), R_∞ the Rydberg energy, $g_i=2$ the statistical weight of the initial O^{7+} state, and g_α that of the doubly excited state.

Cross sections of DR as a function of the incident electron energy have been measured until now for ions with three or more bound electrons in several single-pass, crossed and merged beam experiments[4] by detecting ions which change their charge state in the overlap region. The sensitivity of these experiments was mainly limited by the electron energy spread, the available electron- and ion-beam intensities, and by the background caused by electron-capture processes in the residual gas. In particular, the DR cross sections of hydrogenlike ions and of those resonances in other ions, which imply the excitation of a core electron to a higher shell ($\Delta N>0$), have not yet been measured with the high-energy resolution possible by merged-beam methods. In a merged-beam experiment[5] the electron-beam quality could be considerably improved such that high-resolution studies of strong $\Delta N=0$ resonances of heliumlike ions became possible. In another experiment[6] performed using a novel ion-trap technique, $\Delta N\geq 1$ resonances in the DR of heliumlike ions could be detected but none of the doubly excited (Nn) multiplets could be resolved. Both high sensitivity and high resolution are achieved by the present experiment performed at the Heidelberg Test Storage Ring[7] (TSR) using stored and cooled O^{7+} ions of relatively high energy and intensity, and an intense electron beam overlapping the ion beam, provided by the electron cooling[8] device installed in the TSR. Furthermore, the low average pressure in the storage ring ensured a low background rate of residual-gas electron capture.

Hydrogenlike oxygen ions of 142.96 MeV were produced by the Heidelberg MP Tandem/Postaccelerator. Approximately 4×10^7 O^{7+} ions were filled into the TSR by multiturn injection such that the current circulating in the ring was a factor of up to 40 higher than the output current of the accelerator. The mean beam lifetime was about 7 min at an average pressure of about 1×10^{-10} mbar reached in TSR during this experiment. The diameter of the stored ion beam was about 2 mm when electron cooling was applied. A movable ion detector was installed behind the first bending magnet following the electron cooling device. It intercepted the trajectories of O^{6+} ions produced by charge-changing processes in the straight section containing the electron cooler. The detector was a 20-mm-diam, single anode microchannel plate (MCP). The maximum count rate for the most prominent DR resonance was about 10^4 s^{-1} and the background count rate was typically 3000 s^{-1}. For each counting interval of 0.2 s the ion count, the electron acceleration voltage and current, and the value of the ion current were stored in a computer.

After the O^{7+} beam was cooled down, O^{6+} ions produced by the nonresonant radiative recombination with electrons from the cooling beam could be observed. Subtracting the background, which was measured for detuned electron energy as described below and assuming the detector efficiency to be $\eta=0.8$ for fast heavy ions,[9] a recombination rate coefficient of $\alpha_r=(3.0\pm0.3)\times10^{-10}$ $cm^3 s^{-1}$ is determined from the measured rate. The value of α_r is consistent within 20% with an estimate obtained by scaling a theory for electron-proton recombination in a storage ring,[10] and using an average transverse electron energy of 0.10 eV as expected from the cathode temperature of 1200 K. The measured value of α_r thus serves as a convenient check on the reliability of our absolute rate measurements.

For DR measurements the energy of the electrons in the center-of-mass (c.m.) frame of the circulating ions was adjusted to that of the O^{6+} resonances above the $N=1$ threshold (> 460 eV) by increasing the electron acceleration voltage to 8.4–9.6 kV. Having increased this voltage from the value of 5.0 kV set during the cooling, it was varied in small steps and the counting was performed as described above. After about 20 s, the voltage was lowered again in order to recool the ion beam. A new beam was injected after some two or three cycles of DR measurement and cooling. The energy of the circulating ions was monitored continuously by observing the revolution frequency spectrum generated by the Schottky noise of the ions passing a current pickup unit. During the measurement it was verified that the average ion energy changed by less than 3×10^{-4}, corresponding to 0.5-eV c.m. energy at $\epsilon=500$ eV. The energy spread was about $\pm4\times10^{-4}$ (±0.6-eV c.m. energy).

Since the ion-beam energy was well known from the frequency spectrum of the Schottky noise, the calibration of the c.m. energy scale depended mainly on a precise determination of the electron energy in the overlap region with the ion beam. This determination was based on an accurate absolute measurement of the electron acceleration voltage; the main error of the c.m. energy arose from the correction for the electron space charge, which caused a potential difference of about 650 V between the grounded vacuum tube, surrounding the electron beam, and its center. The space-charge correction was calculated from the known beam geometry and electron current (0.73–0.95 A, beam diameter 50.8 mm). The accumulation in the electron beam of slow positive ions, produced by electron impact in the residual gas, was minimized by using clearing electrodes outside the overlap region; a remaining c.m. energy shift of <0.3 eV is calculated from the estimated production rate of these ions. The maximum systematic error of the absolute electron energy after the space-charge correction is estimated to be ±3 eV, corresponding to an uncertainty of ±1 eV for the overall c.m. energy calibration in the region of the measured DR resonances.

The spectrum of dielectronic resonances observed in this experiment for c.m. energies ϵ from 450 to 870 eV is shown in Fig. 1 where the background due to collisions with the residual gas has already been subtracted. The Rydberg series converging to the $N=2$ hydrogenlike excitation energy is resolved up to the $N=2$, $n=7$, doubly excited states, and a significant contribution of states with even higher n to the total DR cross section is observed. Furthermore, two small structures are observed at higher energies, which are likely to belong to the

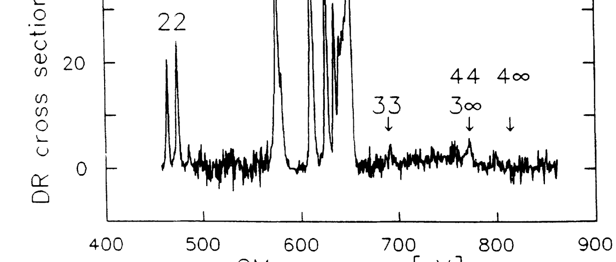

FIG. 1. Dielectronic resonances corresponding to O^{6+} doubly excited states. (a) Observed spectrum with indication of principal quantum numbers (Nn). (b) Simulated spectrum from Ref. 11.

TABLE I. Observed energies ϵ and integrated cross sections S of the $2l2l'$ resonances in comparison to calculations.

		ϵ (eV)				S (10^{-20} cm^{2}eV)		
Configuration	Term	Expt.[a]	Theor.[b]	Theor.[c]	Theor.[d]	Expt.[e]	Theor.[b]	Theor.[c]
$2s^2$	$^1S^e$	461.9(9)	461.9	461.7	462.3	0.45(36)	0.268	0.260
$2s2p$	$^3P^o$	463.9(1)	464.2	463.9	464.4	4.30(63)	4.897	4.736
$2p^2$	$^3P^e$	470.7(4)	470.9	469.8	471.0	0.48(10)	0.138	0.31
$2p^2$	$^1D^e$	474.1(1)	475.2	473.2	474.8	5.65(90)	5.911	6.026
$2s2p$	$^1P^o$	476.5(12)	476.7	474.8	476.0	0.93(43)	1.810	1.868
$2p^2$	$^1S^e$	485.8(1)	487.7	485.8	487.0	0.61(10)	0.741	0.747

[a]Statistical errors only.
[b]Reference 11.
[c]Reference 12.
[d]Reference 14.
[e]An additional error of $\pm 25\%$ has to be added for absolute cross sections.

$N=3$, $n=3$ configuration and the corresponding Rydberg series, possibly influenced by overlapping $N=4$, $n=4$ terms. It appears that the observed FWHM of ≈ 2 eV in Fig. 1 is dominated by the electron energy spread of ± 5 eV (± 1.2 eV c.m.) caused by the variation of the space-charge effect over the diameter of the ion beam (6 mm during the DR measurement).

The measured recombination rate $R(\epsilon)$, which represents the intrinsic rate folded with the electron energy distribution, and the corresponding folded cross section, $\bar{\sigma}(\epsilon)$, are related by

$$\bar{\sigma}(\epsilon)=R(\epsilon)C/L_e v_{\text{c.m.}}(\epsilon)n_e N_i \eta ,$$

where C is the storage-ring circumference, L_e is the electron beam length, $v_{\text{c.m.}}(\epsilon)$ is the c.m. electron velocity, n_e is the electron density, and N_i is the number of stored O^{7+} ions. The overall uncertainty on the absolute cross section is estimated to be $\pm 25\%$ and includes the systematic error on efficiency η and on ion current measurement used to determine N_i; the relative error in comparing cross sections of different resonances is $\leq 5\%$.

A prediction of absolute cross sections for the case studied here has been made recently by Griffin and Pindzola.[11] Recombination rates were obtained from standard configuration-mixing intermediate-coupling atomic structure calculations and then folded with an electron energy spread of 2 eV at 460-eV c.m. energy, varying like $\sqrt{\epsilon}$. Their predictions are shown in Fig. 1(b) and seem to reproduce all details of the experimental spectrum. In these calculations no influence of an external electric field up to 100 V/cm on the DR cross section was found. Calculations for low-lying states ($n\leq 3$) were made earlier using Z-expansion[12] and multiconfiguration Hartree-Fock methods.[13] Recently, term energies were also predicted by group-theoretical arguments.[14]

A more quantitative comparison of term energies and cross sections is presented for the $2l2l'$ states in Table I (see also Fig. 2). Independent of an overall shift of the energy scale, small but significant deviations of the measured energy *differences* from the predicted ones are observed. Thus, the difference between $2s2p\,^3P^o$ and $2p^2\,^1S^e$ is smaller by about 1.6 eV compared to the recent calculation of Ref. 11. The experimental integrated cross sections, at least for the large and well separated resonances, are in reasonable agreement with theory, with the exception of the value of Ref. 11 for the $2p^2\,^3P^e$ term.

The integrated cross sections as a function of the principal quantum numbers N and n are listed in Table II. In addition to fitting individual peaks, a special procedure was applied to fit the data between the $N=2$, $n=6$ resonance and the series limit. With reference to the proposed n^{-3} scaling law[15] for the DR resonance strengths S_n, the transition rates in Eq. (1) are written $A_a(n)=b/n^3$ for $l\leq l_0$, $A_a(n)=0$ for $l>l_0$, and $A_r(n)=c$, where b, l_0, and c are constants. This yields the scaled resonance strengths

$$S_n=\frac{8\pi^2\hbar a_0^2}{\epsilon/R_\infty}\frac{b(l_0+1)^2}{n^3+n_0^3},$$

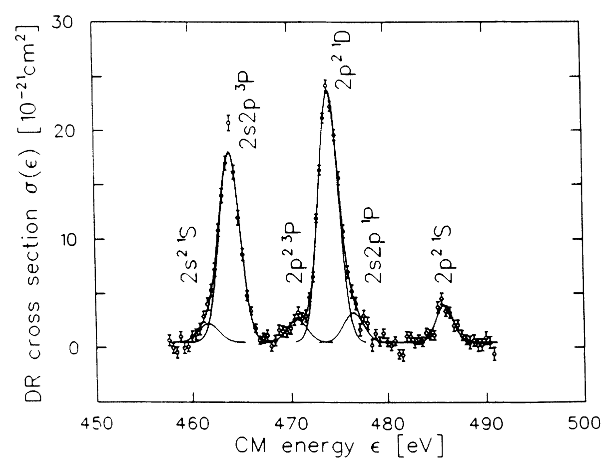

FIG. 2. Region of the $2l2l'$ resonances with fitted Gaussians.

TABLE II. Observed average resonance energies ϵ_n and integrated cross sections S_n in the $N=2$ and $N=3$ Rydberg series.

N	n	ϵ_n (eV)	S_n (10^{-20} cm^{2}eV)
2	2	...	12.3(5)
2	3	576.5(1)[a]	14.4(4)[a]
		580.4(1)[a]	4.4(3)[a]
		Sum	24.5(9)
2	4	611.5(1)	18.0(3)
2	5	626.5(1)	14.3(2)
2	6	634.8(1)	9.6(2)
2	7	639.8(1)	8.8(3)
2	>7	...	34.9(7)
2	∞	653.5(1)[b]	...
3	3	691.5(2)[a]	1.0(2)[a]
3	∞	774.5(2)[b]	...

[a]Strongest individual components.
[b]Edge position.

where $n_0=(b/c)^{1/3}$. The energies were set according to the Rydberg formula, $\epsilon_n=\epsilon_{2\infty}-q^2R_\infty/n^2$. Values of $b(l_0+1)^2=(1.80\pm0.02)\times10^{15}$ s^{-1}, $n_0=6.9\pm0.1$, $q=6.96\pm0.02$, and $\epsilon_{2\infty}$ (Table II) were determined from the fit. Using the theoretical[12] value of $c=2.56\times10^{12}$ s^{-1}, the experiment yields also $l_0=0.48\pm0.02$ and $b=(8.4\pm0.4)\times10^{14}$ s^{-1}.

From the fit of the data close to the $N=2$ series limit, it is seen that states up to a principal quantum $n_{\max}$ of at least 35 contribute to the cross section. The quantum number of observable states is expected to be limited because of field ionization in the motional electric field due to the magnets passed by the ions on their way to the detector. Taking into account the lifetimes of the $1s\,nl$ states of the recombined ions, a limit of $n_{\max}=69$ is estimated for the present experiment.

In summary, the first measurement of separated DR resonances with hydrogenlike oxygen has demonstrated the use of DR for the spectroscopy of heliumlike doubly excited states. For the $2l2l'$ states, the energy differences obtained in the present measurement reached the level of precision of the available predictions. For $N=2$, the integrated cross sections are in good agreement with theory. The cross sections for DR resonances of the Rydberg series can be fitted using a simple scaling law, yielding the autoionization parameter of the series. An improvement of the energy resolution to 0.1 eV or below can be expected by using in parallel an electron target for DR measurements and a separate electron beam for cooling.

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