Dielectronic Recombination: A Crossed-Beams Observation and Measurement of Cross Section

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(Received 26 October 1982)

Dielectronic recombination has been directly observed with use of crossed beams of electrons and Mg^+ ions. Measurements were made of delayed coincidences between the stabilizing photon near 280 nm and the resultant neutral atom, and cross sections were determined. Theoretical cross sections are more than a factor of 5 smaller than those measured.

PACS numbers: 34.80.-i, 35.80.+s

This Letter describes unambiguous observation and direct cross-section measurements of the esoteric atomic collision process known as dielectronic recombination (DR). The process can be visualized with the help of Fig. 1. In Fig. 1(a) an electron is incident on a target Mg^+ ion, a sodiumlike structure with a single $3s$ electron in the outer shell. At infinity the incoming electron has ϵ less energy than $\Delta E = 4.43$ eV, the energy needed to excite the bound $3s$ electron to the $3p$ level. However, in the Coulomb field of the ion, the electron gains kinetic energy, so that at small distances it has more than enough energy to excite the $3p$ level. Having excited the $3p$ level, the incident electron no longer has enough energy to leave the ion, and is trapped in a Rydberg level nl, with an energy ϵ below the continuum, resulting in an intermediate doubly excited neutral atom Mg^{**} [Fig. 1(b)]. The doubly excited atom can autoionize, leaving a ground-state ion and a continuum electron; or it may radiatively stabilize [$\tau_{3p} \sim 3.7$ ns] as shown in Fig. 1(c), leaving an atom in a Rydberg level and a photon, completing the DR process. The competition between these two processes is n dependent; for large n's, radiative stabilization dominates. For the largest n's (e.g., $n > 500$), however, the capture probability itself becomes small. Dielectronic recombination is strongly resonant, since the incident electron must have just the precise energy to excite the $3p$ level and be left in a specific Rydberg level. However, there are clearly very many Rydberg levels, so there are many closely spaced resonances. The process can be written $e + Mg^+(3s) \rightarrow Mg(3pnl) \rightarrow Mg(3snl) + h\nu$, or in general $e + X^{+n} \rightarrow X^{+(n-1)**} \rightarrow X^{+(n-1)*} + h\nu$.

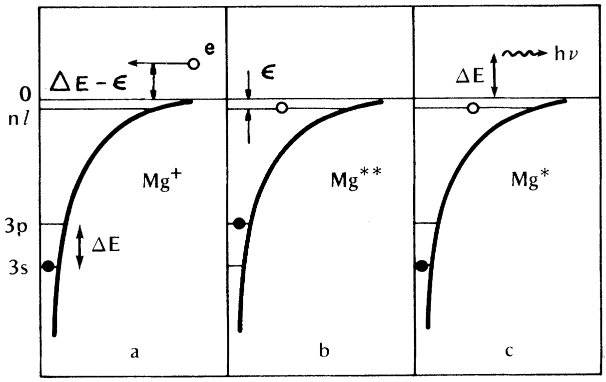

FIG. 1. Sequence of events in $e + Mg^+$ dielectronic recombination.

Since 1964 when Burgess[1] showed that inclusion of this process in models of the solar corona explained some long-standing discrepancies in temperature measurements, DR has been invoked in the modeling of essentially all high-temperature plasmas—most notably astrophysical[2] and controlled fusion[3,4]—and a very extensive literature has developed. The reader is referred to one of the reviews[2,5,6] in the field.

Despite the fact that for hot plasmas "the importance of dielectronic recombination can hardly be overemphasized,"[4] nearly all data on the process itself are theoretical. There have been several observations,[2-13] including some rate measurements,[8-11] of phenomena associated with DR, and an extensive literature has been built around these observations. In one case[13] a cross section was recently measured for the analogous ion-atom process of resonant transfer excitation. Until now, however, because of the associated experimental difficulties, there have been no direct cross-section measurements for DR.[14]

The present experiment is outlined schematically in Fig. 2. A beam of 2-keV mass-selected $^{24}Mg^+$ ions (~ 1 μA) is crossed by a magnetically confined (0.02 T), variable-energy beam of electrons (~ 10 μA; ~ 300 meV full width at half maximum). Photons from the $3p$-$3s$ stabilizing transi-

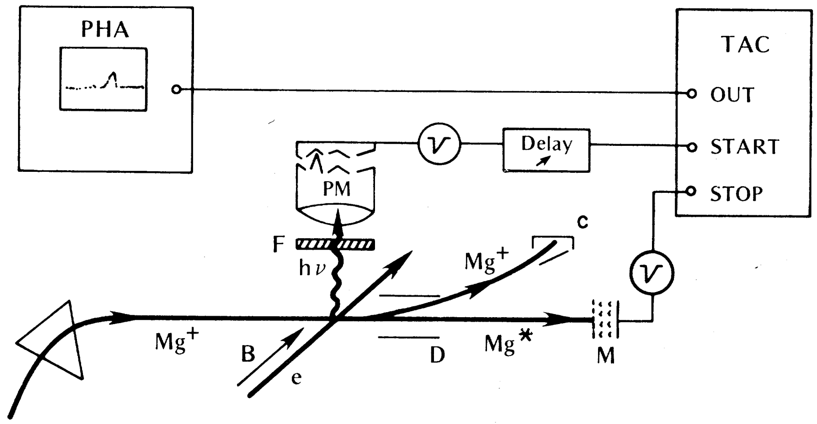

FIG. 2. Schematic representation of the experimental apparatus.

tion are collected in a lens system, passed through an interference filter F (12 nm full width at half maximum, 278 nm peak), and focused onto the cathode of a photomulitplier, PM. Pulses from the PM are delayed (typically 3.9 μs) and they then initiate the start gate of a time-to-amplitude converter (TAC). The stabilized neutral atom travels 54 cm to a particle multiplier in about 4.2 μs, generating a pulse which stops the TAC. The output of the TAC is fed into a pulse-height analyzer (PHA) yielding a coincidence spectrum[15] like the example shown in Fig. 3. Background photons ($\sim 30\ \mathrm{s}^{-1}$) primarily from electron-ion excitation and neutrals ($\sim 10^5\ \mathrm{s}^{-1}$) primarily from charge transfer give rise to the accidental coincidence background. A least-squares fit to this background is subtracted from the spectrum.

The number of coincidences in the peak at 4.2 μs is used to calculate the DR cross section

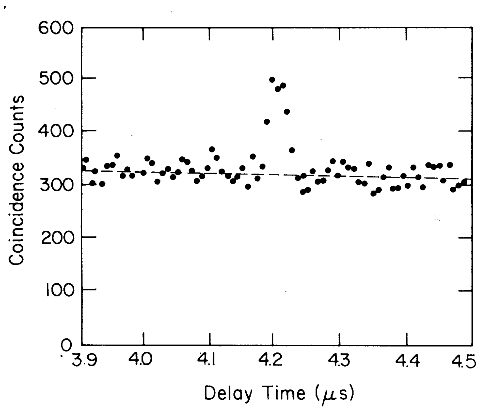

FIG. 3. Dielectronic recombination coincidence spectrum; dashed line is least-squares fit to background.

from the relation[16] used in crossed-beams work

$$\sigma_{\mathrm{DR}} = \frac{(N_c/T)e^2 v_i v_e \mathfrak{F}}{\xi_\lambda \xi_n i_e i_i (v_i^{\,2} + v_e^{\,2})^{1/2}}, \qquad (1)$$

where N_c is the number of coincidences in the peak, T the time of observation, v_e, v_i and i_e, i_i, are the electron and ion velocities and currents, respectively, $\mathfrak{F}$ the form factor defining the beam overlap,[16] and ξ_λ and ξ_n the efficiencies for detecting photons and Rydberg-atom products, respectively.

In the present experiment, excitation measurements were made contiguous to the DR measurements and used to determine the photon-detection sensitivity ξ_λ. The stabilizing satellite photons from DR do not have precisely the same wavelengths as the ion resonance lines used in the calibration. With use of resonances of $\mathrm{Mg}^+ + e$ calculated by Mendoza[17] and known energy levels of Mg, wavelengths of the stabilizing photons ($3pnl \rightarrow 3snl$) have been calculated[18] for $n \leq 7$. Detection efficiencies compared to the ion resonance line have then been calculated, making use of the calculated wavelengths and the measured filter transmission curve. The relative efficiencies rapidly approach 1.0 as n increases, and the overall efficiency for satellite lines compared to the calibration line is estimated to be 0.98.

The excitation measurements were also used to determine the exact electron energy and to determine the electron energy distribution. Figure 4 shows a typical excitation measurement at threshold. The peak excitation cross-section value[19] of $2.3 \times 10^{-15}\ \mathrm{cm}^2$ is within 15% of both distorted wave[20] and close-coupling[21] calculations of the excitation cross section. Since the excitation cross section rises with an infinite slope at threshold, the derivative of the experimental

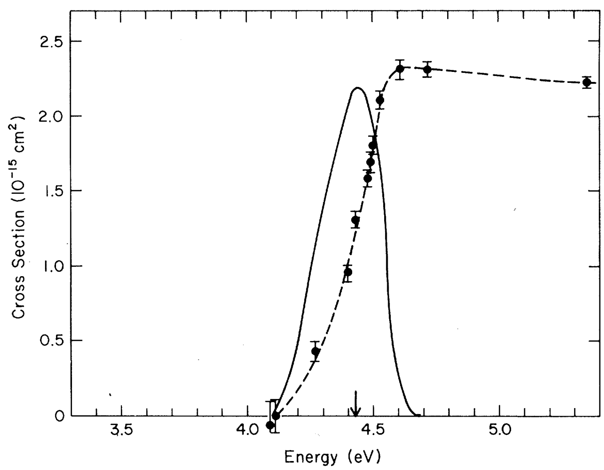

FIG. 4. Threshold cross section for $Mg^+(3s \rightarrow 3p)$ excitation (experimental points and dotted curve). Solid line is first derivative representing the mirror image of electron beam energy distribution. Arrow indicates excitation threshold energy.

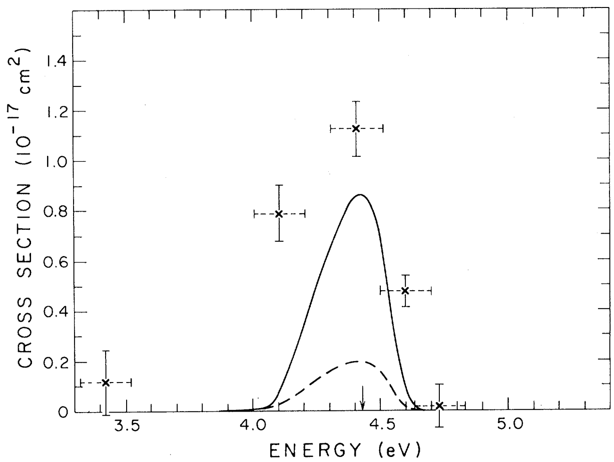

FIG. 5. DR cross section vs energy for $e + Mg^+$; crosses, experiment; dashed curve, convolution of theory (Ref. 23) for $n \leq 64$ with experimental electron energy distribution; solid curve, same as dashed curve, including all n. Arrow indicates excitation threshold energy. Bars are relative uncertainty only. The absolute uncertainty in cross section is $\pm 58\%$ (see text).

rise gives the electron energy distribution, and the midpoint of the rise locates the threshold energy.

The determination of the neutral-particle detector (M, Fig. 2) efficiency ξ_n is the most uncertain part of the quantitative measurement of σ_{DR}. Considering contributions from Auger surface ejection, kinetic ejection, and field ionization of Rydberg atoms in the detector, we have arrived at a value $\xi_n = 0.65 \pm 0.35$ for these early measurements. The very conservative limits of uncertainty allow ξ_n to have the absolute maximum value of 1.0, and the minimum value 0.3 equal to that measured for 2-keV ions.

When the above uncertainty in ξ_n is added in quadrature to the estimated 15% uncertainty in ξ_λ, appropriate small uncertainties for i_e and i_i, and (typically) 15% statistical uncertainty in N_c, one obtains an uncertainty of $\pm 58\%$. We believe this is a very conservative estimate and gives a firm lower limit on the experimental cross section, but a less firm upper limit.

Before reaching the neutral detector, some of the product Rydberg atoms $Mg(3snl)$ will be field ionized by the 36 V/cm deflecting field that separates Mg^+ and Mg^*. To estimate the quantum number n_f above which field ionization occurs in an electric field E, we use the relation,[22]

$$n_f = [6.2 \times 10^8 / E\,(\mathrm{V/cm})]^{1/4}. \qquad (2)$$

Thus, the measurements we made on DR were for $n < 64$.

For the largest coincidence peaks, coincidence rates were about 0.05 s^{-1}. Counting times of several hours were needed to obtain individual coincidence spectra of adequate precision. Possible contributions to the signal from excitation of neutrals in the beam or charge transfer to excited states were tested for and shown to be negligible.

To date measurements have been made at only five electron energies. The resulting measured cross sections are shown in Fig. 5. The error bars here represent relative uncertainty only. The dashed curve in the figure shows calculated cross sections of LaGattuta and Hahn[23] modified to account only for contributions from $n < 64$, and convoluted with our electron energy distribution. There is more than a factor of 5 difference between the measured peak value and that calculated. Even considering the lower uncertainty limit of the measurements, there is still a factor of $3\frac{1}{2}$ discrepancy.

We have already noted that we consider the lower limit firm, i.e., there are possible systematic errors which could lead to a larger cross section, but we can think of none that we have not tested for to make it smaller. To show the effect of field ionization, we include the solid curve in Fig. 5 which gives the results of LaGattuta and Hahn with no field-ionization adjustments, but convoluted with our electron energy distribution. The experimental results at the peak are larger than even these.[24] It is clear that more experimental results are needed and that the formulation of the theory of DR should be reevaluated.

The authors acknowledge the close collaboration of Dr. J. Kurepa during part of this work. Helpful comments from many colleagues have helped in the work. This work was supported through the Office of Fusion Energy, U. S. Department of Energy.

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[24]W. A. Huber and C. Bottcher [J. Phys. B 13, L399 (1980)] calculated effects of high B field (2–100 T) on DR, and found a cancellation of effects leading to unaltered total DR rates. However, the n state distribution is altered to lower values. While detailed calculations are needed, it is possible that the 0.02 T field of our electron gun will enhance the cross section for $n < 64$; and in the extreme case, our experiment should be compared with the solid curve of Fig. 5.