Dielectronic Recombination on Heliumlike Argon

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We have used the electron-energy dependence of yields of heliumlike and lithiumlike argon ions from the Kansas State University electron-beam ion source (EBIS) to measure the ratio of the cross section for $\Delta n=1$ dielectronic recombination on heliumlike argon to that for electron ionization of lithiumlike argon. By normalizing to the latter cross section we obtain absolute dielectronic recombination cross sections and find good agreement with theoretical calculations for the lower-energy resonances.

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Dielectronic recombination (DR) of a free electron with an ionic target is the process whereby an electron of the core is collisionally driven to an excited orbit, with a change in principal quantum number hereafter designated by Δn, while the incident electron is itself captured into an excited orbit on the core, thus forming a doubly excited ion (atom). If the excited ion (atom) decays radiatively, the charge state of the system has decreased by one unit and recombination of ion and electron is accomplished. Since the doubly excited state has a discrete energy, the process is resonant in electron energy. It was shown by Burgess[1] in 1964 that DR generally proceeds at a higher rate than radiative recombination in hot plasmas, and it has come to be widely recognized[2-4] that this process plays a dominant role in determining the charge-state balance in the state of matter found in many fusion and astrophysical settings. In spite of the importance of this process, the first experimental measurements of DR cross sections for well-defined target ion and electron energy were not reported until 1983,[5-7] and all previous rates were based on theoretical calculations. While these and subsequent measurements[8,9] on $\Delta n=0$ transitions have led to valuable increased understanding of the DR process, the comparison between theory and experiment is complicated in these cases by the fact that the experimental cross sections measured receive large contributions from unresolved resonances which encompass a Rydberg series for the captured electron. The resonances lying near the series limit are substantially affected by the electric fields present in the experimental apparatus, and indeed the experiments have served to show in the laboratory that DR rates can be substantially enhanced by the presence of external electric fields.[8] Only very recently have experiments on $\Delta n=0$ transitions been able to obtain a resolution high enough that a clean comparison between theory and experiment for nearly isolated resonances may become possible.[10]

For $\Delta n=1$ transitions the DR resonances are sufficiently well separated that individual groups containing a small number of resonances are easily isolated and Stark mixing problems are reduced. Such transitions have been the object of study through resonant transfer and excitation (RTE) collisions,[11] which involve the replacement of the incident free electron by a loosely bound quasifree one in a light target atom. Agreement between RTE experiments and DR theory has been fair but rendered somewhat uncertain by the presence of competing processes and the fact that RTE and DR are, at base, not identical processes. Very few $\Delta n=1$ DR experiments have been reported to date. Briand *et al.*[12] detected DR on berylliumlike argon in an EBIS (electron-beam ion source). Knapp *et al.*,[13] using the LLNL EBIT (electron-beam ion trap), detected the stabilizing radiation from DR resonances in lithiumlike nickel to identify DR and obtained absolute cross sections for the *KLL* resonances by normalizing to the calculated cross section for radiative recombination off resonance. Although some uncertainty is introduced by the possibility of nonisotropic emission of the resonant radiation, excellent agreement with theory was obtained. Very recent results on DR on heliumlike oxygen have been obtained[14] at the Heidelberg heavy-ion storage ring.

The present experiment is in many respects similar to that of Knapp *et al.*,[13] but differs from it in one important way. We have observed the direct influence of $\Delta n=1$ DR resonances on the relative equilibrium abundances of heliumlike and lithiumlike argon ions trapped in the plasma. The effect of DR is not small; on the contrary, it changes the equilibrium balance in a major way. Indeed, that the DR effect can be so large is the reason why understanding of this process and its influence on charge-state equilibria in hot plasmas has been such a center of activity in recent years. By ejecting the ions from the plasma periodically, we measure the equilibrium inventory of the two ion species directly. An extremely simple and clean analysis of the equilibrium equations for this two-component system allows us to extract from these yields the relevant DR cross sections if the ionization cross section for lithiumlike Ar is treated as known. The analysis is free of complications from nonisotropic angular distributions of the stabilizing radiation and from potentially uncertain charge-state fractions in the source. To our knowledge, this is the first time that the direct measurement of the relative numbers of ions in charge-state equilibrium in a plasma maintained by a monoenergetic electron beam has been used to obtain DR cross sections.

The experiment was performed in the Kansas State University EBIS which has been described in detail elsewhere.[15] Briefly, a 17-mA electron beam of energy (E_e) between 2.0 and 3.5 keV is magnetically compressed and confined with a resulting current density near a thousand A/cm^2. The beam travels through a series of coaxial drift tubes before being allowed to expand into an axially symmetric collector at the exit of the source. Argon gas is injected by a continuous flow into one drift tube at one end of the source. Following a brief ionization period, low-charged ions are electrostatically injected into a 66-cm-long containment region in the center of the source. The injection region is nearly isolated from the containment region by the slow pumping speed through and cryogenic pumping by the drift tubes. In the containment region, the argon ions are driven, by collisions with the electrons, to successively higher charge states until the ionization potential exceeds the energy of the electron beam, at which point the charge state ceases to increase. In the present case, for E_e between 0.92 and 4.1 keV, the process ends at Ar^{16+}. The ions so formed are trapped radially by the space charge of the electron beam and longitudinally by voltages applied to the drift tubes. After some containment time the drift-tube voltages are raised so that the ions are ejected axially from the exit of the source and emerge through an aperture in the collector, to be focused, analyzed in charge-to-mass ratio by a 90° magnet, and detected by a channel-plate detector. Charge-state equilibrium was obtained after roughly 300 msec, and was observed not to change appreciably for several seconds thereafter. A typical argon-ion inventory contained Ar^{16+}, Ar^{15+}, and Ar^{14+} in the abundances of 84%, 14%, and 2%, respectively, for an off-resonance electron-beam energy of 2.5 keV. In order to ensure that no nonequilibrium conditions persisted, the source plasma was maintained for a total containment time of 1 to 1.5 sec, at which time the trap voltages were raised, the ions ejected, and the charge-state inventory measured. The electron-beam energy was varied by changing the voltage on the drift tubes surrounding the containment region, with the electron-beam current remaining fixed.

Figure 1 shows the raw yields of Ar^{16+} and Ar^{15+} ions from the source as a function of the electron-beam energy. The latter energy was taken to be that given by the voltages applied to the electron gun and drift tubes plus a space-charge contribution caused by the electron beam itself. The last can be calculated accurately only if the radius of the electron beam is known, and we chose instead to evaluate it from the observed location of the *KLL* resonance whose energy is well known theoretically. The space-charge potential so obtained, approximately

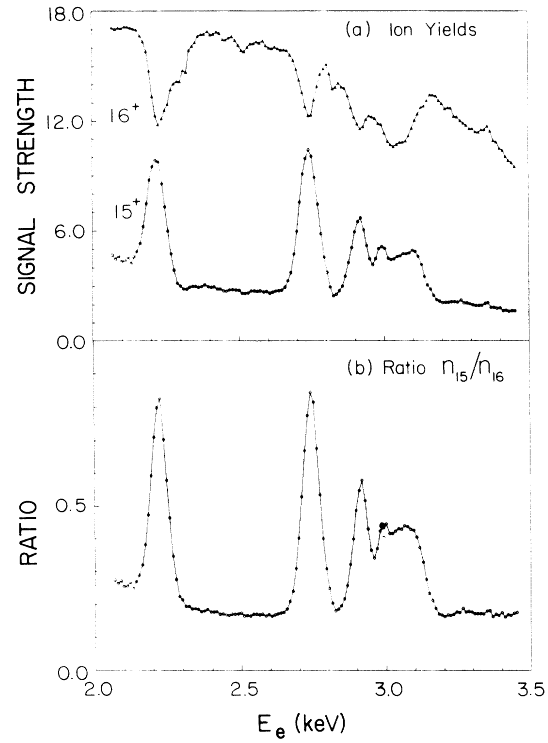

FIG. 1. Plots vs electron energy of (a) the yields of $Ar^{16+}(n_{16})$ and $Ar^{15+}(n_{15})$, and (b) the ratio n_{15}/n_{16}.

60 eV on the *KLL* resonance, is consistent with that expected. For other electron energies, this value was scaled with the inverse velocity of the electron beam, since the electron current remained fixed. The dielectronic resonances originating from an Ar^{16+} $1s^2$ target and with configurations $1s2lnl'$ are seen as depletions of Ar^{16+} yields, and complimentary enhancements of Ar^{15+} yields, near energies of 2.2, 2.73, and 2.9 keV, corresponding to $n=2$ (*KLL*), 3 (*KLM*), and 4 (*KLN*), respectively. The series limit ($n=\infty$) is seen at 3.13 keV, the threshold for direct excitation of the heliumlike target to its first excited state. Above this electron energy, the $n=2$ excitation is accompanied by an inelastic projectile electron in the continuum rather than recombination. Similar scans of the Ar^{14+} yields show DR resonances on an Ar^{15+} target which occur at slightly higher energies than those for the heliumlike target. In Fig. 1, small dips in the Ar^{16+} and Ar^{15+} yields near 2.3 keV, just above the *KLL* resonance on Ar^{16+}, are caused by *KLL* DR onto the Ar^{15+} target which depletes the population of both 15+ and 16+.

We confine our quantitative analysis to the Ar^{16+}-Ar^{15+} system. The Ar^{16+} charge state is fed by electron ionization from Ar^{15+}, while it is destroyed by DR and RR (radiative recombination) on Ar^{16+} and by capture collisions with residual gas in the EBIS. In equilibrium, the rate equation for n_{16} becomes

$$n_{15}\sigma_i J_e/e = n_{16}[(\sigma_{RR}+\sigma_{DR})J_e/e+\sigma_c n_0\bar{v}]\,, \qquad (1)$$

where n_{15} and n_{16} are the numbers of 15+ and 16+ ions, J_e is the effective electron current density, σ_c is the capture cross section on the residual gas, n_0 is the density of the residual gas, $\bar{v}$ is the mean velocity of the Ar^{16+} ions, e is the magnitude of the electron charge, σ_i is the cross section for ionization of lithiumlike argon,[16] σ_{RR} is the cross section for radiative recombination, and σ_{DR} is the cross section for DR. Only the last of these is strongly energy dependent. Solving for σ_{DR} in terms of the ratio n_{15}/n_{16}, Eq. (1) gives

$$\sigma_{DR} = \sigma_i n_{15}/n_{16} - [\sigma_{RR} + \sigma_c n \bar{v} e/J_e] . \quad (2)$$

Since the second term on the right-hand side of Eq. (2) is slowly varying with E_e, σ_{DR} is simply given by $\sigma_i n_{15}/n_{16}$ minus a slowly varying background. In Fig. 2 we show a plot of σ_{DR} deduced by subtracting a smooth background, obtained from a polynomial fit to nonresonant parts of the spectrum, from the experimental $\sigma_i n_{15}/n_{16}$ and normalizing to σ_i calculated from Ref. 16.

We note that, while similar equilibrium equations for other charge states would reveal couplings of, for example, Ar^{15+} to Ar^{14+}, the two-component equation (1) remains exactly correct, relying only on the fact that $dn_{16}/dt = 0$. Further, the simplicity of the result of Eq. (2) does not depend on the identification of all processes which might deplete Ar^{16+}, such as electron-beam heating of the ions out of the trap. Any such process will be nonresonant in E_e, and would only give rise to an additional background term in Eq. (2).

Comparison with theoretical calculations requires that the theoretical resonance strengths be folded into the experimental resolution function for E_e and summed over all resonances. The expression is

$$\sigma_{DR} = \sum_i [A_i/(2\pi)^{1/2}\sigma] \exp[-(E_e - E_i)^2/2\sigma^2] , \quad (3)$$

where i denotes a particular DR resonance occurring at energy E_i and A_i is the resonance strength (see Ref. 17). If σ_{DR} is in cm^2 and σ in eV, A_i has units of $cm^2 eV$ and is the integral of the DR cross section over the very small natural width of the resonance. We have taken the experimental resolution function to be Gaussian in shape. The FWHM of this function, $2.35\sigma = 61$ eV, was adjusted to provide the optimum fit to the *KLL* resonance and was taken to be constant over the entire range in E_e.

We have performed explicit calculations of x-ray and Auger rates and obtained corresponding values of E_i and A_i for doubly excited Li-like argon for the following cases; $1s2pnp$ ($n = 2$–8), $1s2pns$ ($n = 2$–8), $1s2pnd$ ($n = 3$–6), $1s2pnf$ ($n = 4,5$), and $1s2snp$ ($n = 2$–8). The Hartree-Fock atomic model was used in this work and the details of the theoretical formulation are given elsewhere.[17] The satellite intensity factors were obtained by using the n^3 scaling for n larger than listed above.

The agreement between theory and experiment for the *KLL* and *KLM* groups appears good but discrepancies arise for higher E_e. Comparing area ratios, thus excluding any influence from our choice of σ, we find that the ratio of experiment to theory is 1.08, 1.19, and 1.68 for the *KLL*, *KLM*, and *KLN* groups, respectively. On the basis of possible errors in background, reproducibility, and relative detector efficiency, we estimate an error bar of 8% on the experiment, exclusive of any error in σ_i. One should expect problems near the series limit, since the number of contributing states, some of which are excluded from the theory, becomes infinite. For the *KLN* group, however, the major contributing resonances are taken into account in the theory.

We have chosen to discuss the results of the experiment as if the ionization cross section σ_i were well known. For an Ar^{15+} target, only a single experimental measurement of σ_i has been reported.[18] This result is in agreement with the Lotz[19] formula and slightly larger than that calculated by Younger,[16] but bears a substantial error bar. It is possible that some of the disagreement between the present experiment and theory is due not to an error in the DR cross sections but in the ionization cross section used. Excitation followed by ionization, which is well known to contribute to the ionization of lithiumlike ions above the threshold for $1s$ excitation,[20] cannot contribute for E_e below 3.08 keV, the threshold for excitation of a $1s$ electron in Ar^{+15} to $n = 2$. The cross sections of interest here lie below this threshold.

It is not impossible that electric fields inside the EBIS, which could be as high as 10^4 V/cm, could affect the resonant strengths.[8] We suspect that this is not important for the relatively low-lying *KLN* resonances, but evaluation of this possibility awaits theoretical attention. We

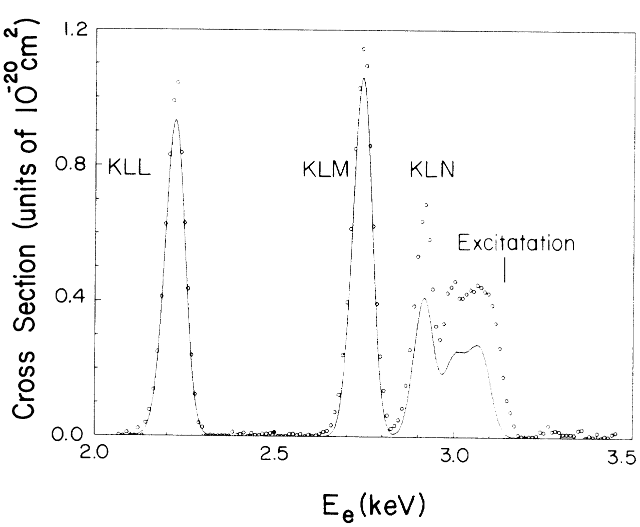

FIG. 2. Cross sections for dielectronic recombination on heliumlike Ar derived from the data of Fig. 1. The data are normalized to the ionization cross sections of Younger (Ref. 16). The solid line is the theoretical calculation, as discussed in the text.

point out that we do not expect to have electronically excited targets since the time between electron-ion collisions in the EBIS is long (typically hundreds of msec).

In conclusion, we have observed the influence of DR directly on the equilibrium balance between heliumlike and lithiumlike ions in an electron-beam–maintained plasma, and have quantitatively interpreted the energy dependence of this balance to extract cross sections for DR. The normalization of the absolute cross section is to that for electron ionization of lithiumlike Ar, and is thus quite different from the normalization to the radiative recombination cross section used by Knapp *et al.*[13] in nickel. That both experiments are in near agreement with theoretical DR calculations for the lower-energy resonances suggests that the theory is on solid footing for the lower $\Delta n = 1$ DR cross sections. The lack of agreement between theory and experiment for the *KLN* resonances remains unexplained.

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