Dielectronic Recombination Cross Sections of Neonlike Xenon

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High-resolution measurements of dielectronic recombination cross sections for neonlike xenon (Xe^{44+}) are presented. The experimental method consists of the formation and interaction of ions with electrons in an ion trap followed by an analysis of the extracted ions to determine relative yields. Low beam currents are used to obtain an energy resolution of 16 eV FWHM. Reductions in the number of initial ions of more than 3 orders of magnitude are observed as the strongest resonances are scanned. The relative contributions of the *LMM*, *LMN*, *LMO*, *LMP*, and *LMQ* groups of resonances are compared to theoretical calculations. The agreement with theory is excellent.

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The availability of highly charged ions for direct interaction with free electrons has been a significant development in the study of dielectronic recombination (DR). Although highly charged ions have been available at accelerators for decades only recently have methods of studying their interactions with free electrons under well-controlled conditions been achieved [1-5]. We report here the first high-resolution measurements of dielectronic recombination on a high Z neonlike system through direct analysis of the population of such ions present within an ion trap under specified interaction conditions.

Dielectronic recombination [6] is a resonant capture process in which a free electron is captured into a bound state of a multielectron ion. This process is the inverse of autoionization and the resonant DR energies correspond to those of the electron emitted in that process. This two-electron recombination process is completed when the resulting doubly excited system decays below its ionization threshold through x-ray emission.

Dielectronic recombination onto a neonlike system is represented schematically as

$$A(1s^22s^22p^6)+e\rightarrow A^{**}(1s^22s^22p^5nln'l')\rightarrow A^*(1s^22s^22p^6n'l')+h\nu \quad (1a)$$

or as

$$A(1s^22s^22p^6)+e\rightarrow A^{**}(1s^22s2p^6nln'l')\rightarrow A^*(1s^22s^22p^6n'l')+h\nu. \quad (1b)$$

In this experiment we do not excite the K-shell electrons. We use Auger transition notation to represent the resonant capture process, for example, a $2p$ (L-shell) electron excited to fill a vacancy in the M shell as the free electron is captured into a vacancy in the N shell is denoted by *LMN*. Many studies of dielectronic recombination in highly charged ions have been reported in the last few years [7,8]. However, only within the last year have measurements of DR on neonlike high Z ions been made [8]. In this paper we report the use of a new method to extend these measurements to include higher energy resonances through the *LMQ* groups. Through the exploitation of novel values of several trap parameters we are able to measure the DR cross sections with much higher energy resolution than other experiments performed using ion traps [7]. In this method direct observation of the ion population allows us to study the behavior of individual charge states thus eliminating the contributions of adjacent charge states to the total cross section as seen in the x-ray experiments. The present technique therefore features several advantages over ion trap experiments using x rays [9].

The neonlike xenon ions are formed in an electron beam ion trap (EBIT) [10,11]. A 20-mA electron beam is compressed to approximately 70 μm diam in a 3-T magnetic field and accelerated to 7 keV as it approaches the drift tubes which form the trap. The trap consists of a three segment drift tube assembly biased to form a shallow axial electrostatic well for positive ions. The ions are trapped radially by the beam's space charge. Xenon gas, which is continuously fed into the trap region, is ionized until an equilibrium distribution of neonlike xenon ions is reached.

Once equilibrium is established the electron beam current is lowered to 5 mA and the drift tube voltage is switched to a particular value which defines the electron beam probe energy. After the ions are probed for a set period of time the beam is turned off and the ions ejected. The ions are then extracted [12,13] and magnetically analyzed and counted. This cycle of ionization, probe, counting is repeated for probe energies between 1 and 4 keV at 5-eV intervals. Figure 1 shows a scan of neonlike xenon ion yield as a function of the probe energy. At each energy the ions were probed for 200 msec for two cycles. The equilibrium distribution of ions is reproduced at the beginning of each cycle of the experimental scan of probe energies and therefore serves as normalization. This is shown by the roughly flat ion yield of approximately 1300 particles at off-resonance points which extends across the energy range.

In this experiment the directly measured quantity is the number of neonlike ions remaining in the trap following recombination with an electron beam of fixed energy. Since the initial number of ions is constant as the electron

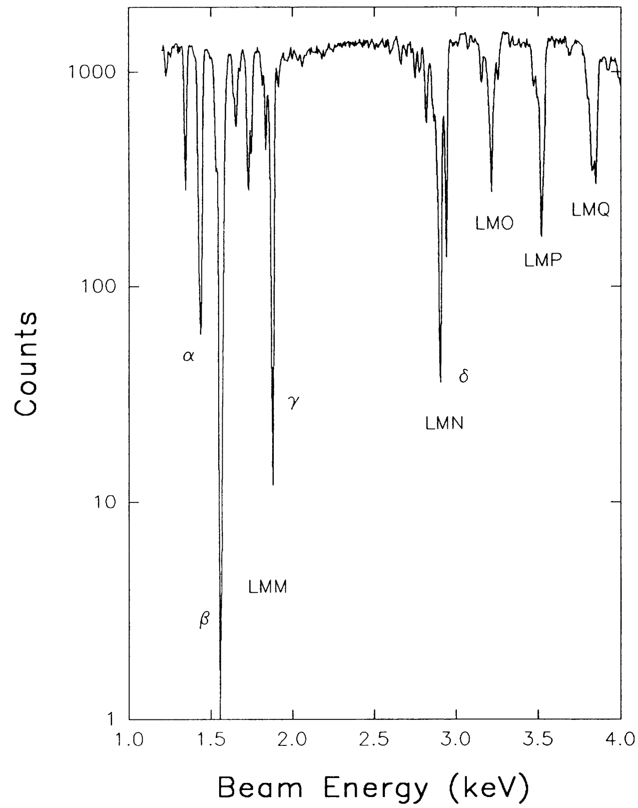

FIG. 1. Yield of neonlike xenon ions as a function of energy. The initial content of neonlike ions is represented by the flat background of approximately 1300 counts. As the electron energy sweeps through the resonances these ions are sharply reduced. The *LMM* group of resonances lies between 1 and 2 keV. The *LMN* group is located at about 2.8 keV and so on. For the scan shown the beam was applied for a probe time of 200 msec.

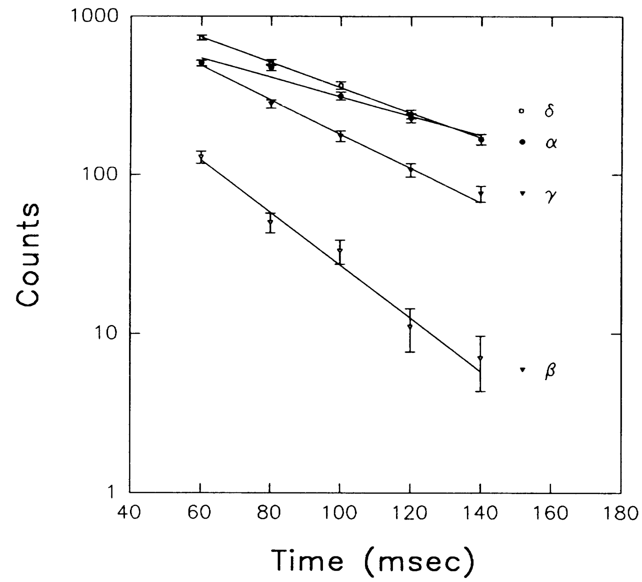

FIG. 2. Linear fits to the logarithm of the time decay for the four energy values with the greatest reductions. α, β, γ, and δ are identified in Fig. 1. The error bars represent 1 standard deviation as given by Poisson statistics for the number of counts in each point. The slope of the line is directly proportional to the total dielectronic recombination cross section at that energy.

energy is scanned the number of ions remaining is a function of the beam intensity, the combined strength of the interactions which deplete these ions, and the interaction time. We therefore measure the number of ions remaining as a function of time. The data are analyzed by assuming that the rate at which the neonlike Xe^{44+} ions in the trap decay is

$$\frac{dn}{dt} = -\frac{J'}{e}[\sigma^{DR}(\epsilon)+\sigma^{RR}(\epsilon)]n - \frac{n}{\tau}, \qquad (2)$$

where n is the number of neonlike (Xe^{44+}) ions, σ^{DR} and σ^{RR} are the total dielectronic recombination and radiative recombination cross sections, respectively, τ is the characteristic decay time for nonresonant losses such as charge exchange with neutral atoms, and J' is the effective electron beam current density. The effective current density is dependent on many complex factors such as the distribution of times which the ions spend within the beam. The rate equation contains terms involving the neonlike ions only because there is no feeding through radiative recombination (RR) since the 7-keV ionization energy is below the ionization threshold of the Xe^{44+}. The range of energies scanned does extend beyond the 3.3-keV ionization threshold energy of the sodiumlike ions but this contribution is negligible since the product of the ionization cross section and the number of Xe^{43+} ions is small.

To evaluate the data we solve Eq. (2) for the total DR cross section,

$$\sigma^{DR}(\epsilon) = -\frac{e}{J'}\frac{d\ln(n)}{dt} - \left[\sigma^{RR}(\epsilon)+\frac{e}{J'\tau}\right]. \qquad (3)$$

Here the total DR cross section, $\sigma^{DR}(\epsilon)$, is formed by convoluting the theoretical resonance strengths with a Gaussian energy resolution whose deviation is $w = (\mathrm{FWHM})/2.35$. The term in large parentheses is a slowly varying background which contains no resonances. Our method is to compare the total theoretical cross section with the normalized logarithmic derivative of the experimental data. The normalization of the intensities is facilitated by J'. Scans of ion yield similar to that shown in Fig. 1 were taken for probe times of 60, 80, 100, 120, and 140 msec. Figure 2 shows linear fits to the time decay for the peaks of the four strongest resonances. The slope of each line is directly proportional to the total DR cross section at that probe energy. The slope was determined at each of the 600 points in the 1–4-keV energy range scanned.

The theoretical DR resonance strength from the initial state i via intermediate state d to the stabilized final state

f can be written as a product of dielectronic capture strength multiplied by the fluorescence yield and is given in atomic units by

$$S_i(d,f) = \frac{\pi^2}{E_i}\frac{g_d}{2g_i}\frac{A_A(d\to i)A_r(d\to f)}{\sum_k A_r(d\to k)+\sum_m A_A(d\to m)}, \quad (4)$$

where g_d and g_i are the statistical weight factors, E_i is the resonance energy, and A_r and A_A are the radiative and Auger rates, respectively. In the present work the Auger and radiative rates for each autoionizing state were explicitly calculated from the first-order perturbation theory using the multiconfiguration Dirac-Fock model (MCDF) [14,15]. The energy levels and bound-state wave functions were evaluated in intermediate coupling with configuration interaction from the same complex using the MCDF model in extended average-level scheme [14]. The Breit interaction and quantum electrodynamic corrections were included in the calculations of transition energies. The calculated Auger and radiative rates were then employed to compute the DR strength according to Eq. (4). The width of the theoretical DR cross sections is more than 2 orders of magnitude smaller than our experimental energy width. The resonance strengths are therefore obtained by integrating over the narrow width of the theoretical cross section. The resulting strengths are convoluted with a Gaussian function for comparison with the experimental data.

In order to compare the data to theory the values of J' and w were found using a least-squares fit with the *LMM* group of resonances. The values obtained were $J'=23.5$ A/cm^2 and $w=6.9$ eV, which gives an energy resolution of 16.2 eV FWHM. This resolution is considerably better than any thus far obtained in measurements of DR using ion traps [7,8]. The fit was made only to the *LMM* group of resonances. Figure 3 shows the result. The relative amplitudes of the different peaks are in excellent agreement with theory.

To obtain an independent comparison to the theory for the higher resonances we used the same J' and w determined for the *LMM* resonances. Figure 4 shows the data obtained for the higher resonances after normalization with the value of J' found for the *LMM* group. The theoretical resonance strengths for these groups is convoluted with a Gaussian energy resolution function using the same deviation parameter and is overlaid with the experimental data; the agreement is excellent.

We note that using a 5-mA beam during the probe reduces its intrinsic energy spread by more than 3 eV FWHM as compared to scans which use a 2-mA beam. Experiments which rely on the measurement of x rays produced as the doubly excited ions decay typically use currents of 70–150 mA or more [6] in order to achieve reasonable interaction rates. The effective electron beam current density is reduced by a factor of approximately 4 by a similar reduction in current. However, as Fig. 1 shows, the effective current density is high enough to completely deplete the neonlike ions within 200 msec at the energy of the strongest DR resonance, designated β in the figure. This reduction by more than 3 orders of magnitude occurs at a cluster of resonances which includes, for example, the $2p_{3/2}^{-1}3d_{3/2}3d_{5/2}$ $J=\frac{5}{2}$ transition which

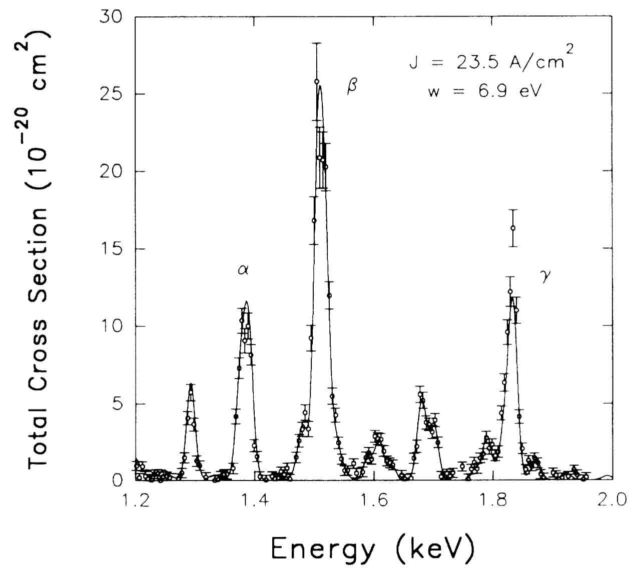

FIG. 3. Fit of experiment to theory for the *LMM* group of resonances. The values of w, the experimental energy resolution, and J', the effective electron beam current density, were found using a weighted least-squares fit of the experimental data by the total theoretical cross section. Only the *LMM* resonances were used in the fit.

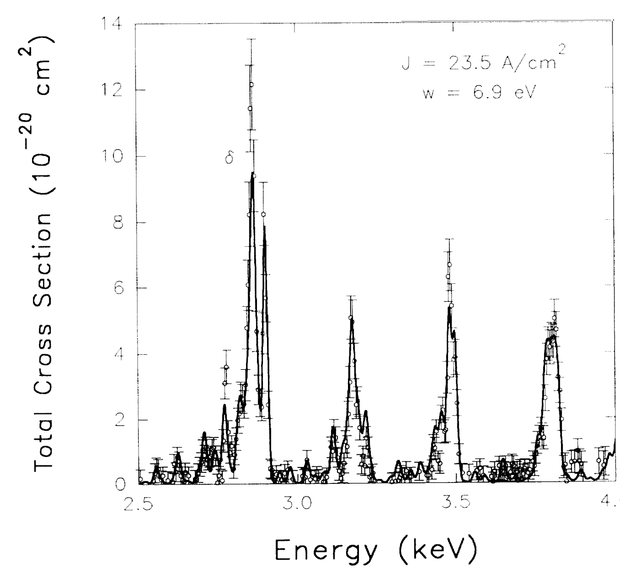

FIG. 4. Overlay of the normalized experimental data for the *LMN*, *LMO*, *LMP*, and *LMQ* resonance groups onto the convoluted theoretical resonance strengths. The values of w and J' used are those found in the fit to the *LMM* group.

has a calculated resonance strength of 2.37×10^{-18} cm^2eV.

In conclusion, we have measured relative dielectronic recombination cross sections in neonlike xenon using an electron beam ion trap. Our energy resolution is 16.2 eV FWHM. Comparison of the relative contributions of the *LMM*, *LMN*, *LMO*, *LMP*, and *LMQ* groups of resonances with theory shows excellent agreement between theory and experiment.

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