PHYSICAL REVIEW A VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Measurement of the *LMM* dielectronic recombination resonances of neonlike gold

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(Received 19 June 1991)

The *LMM* dielectronic recombination resonances of a neonlike ion (Au^{69+}) have been observed. The ions were produced and held in an electron-beam ion trap. The intensity of the $n=3\rightarrow 2$ x rays resulting from dielectronic recombination was measured as a function of electron-beam energy with sufficient resolution to distinguish the structure of the *LMM* resonances. The measured resonance strengths for *LMM* resonances with a $2p_{3/2}^{-1}$ core are in good agreement with theoretical predictions, but there is some disagreement for the $2p_{1/2}^{-1}$ and $2s_{1/2}^{-1}$ core configurations.

PACS number(s): 34.80.Kw, 32.80.Hd, 52.25.−b

Dielectronic recombination (DR) is the resonant capture of electrons by ions. An intermediate state is formed when the energy gained by capturing an electron from the continuum resonantly excites one of the ion's electrons. DR occurs when the ion, now with one less charge, decays by emitting a photon. DR is an important process in fusion plasmas, solar flares, and astrophysical systems because it strongly influences their ionization balance and emitted x-ray spectra. In addition, measurements of DR in highly charged ions are of fundamental interest because they can test multielectron atomic physics models in the high-*Z*, highly relativistic limit.

The resonance strengths $S(d,f)$ for nonoverlapping DR resonances can be expressed in terms of the Auger and radiative rates of the resonances [1]:

$$S(d,f)=\int_{-\infty}^{\infty}\sigma(d,f,E)dE = \frac{2\pi^2}{k_i^2}\frac{g_d A_r(d\rightarrow f)A_A(d\rightarrow i)}{2g_i\left[\sum_{r'}A_{r'}+\sum_{A'}A_{A'}\right]}\,, \qquad (1)$$

where *i*, *d*, and *f* refer to the initial, intermediate, and final states, respectively, A_r and A_A are the radiative and Auger rates, g_i and g_d are statistical weights, and k_i is the initial electron wave number. For transitions in which the stabilizing radiative decays have a change of principal quantum number, $\Delta n \geq 1$, $A_r \propto Z_{\rm eff}^4$ for an isoelectronic sequence, where $Z_{\rm eff}=(Z+q)/2$ and Z and q are the nuclear and total charge of the ion. The Auger rates remain roughly constant as a function of $Z_{\rm eff}$. For the DR of neonlike ions, A_r and A_A become comparable in size at about $Z\approx 45$ [2]. The present experiment explores the region for which $A_r \gg A_A$.

Among resonances involving the same radiative transition, in the limit $A_r \gg A_A$, the lower *n*-shell resonances are the strongest because $S(d,f)\propto A_A$ and A_A scales as n^{-3} as a result of the bound-state wave function normalization. The strongest resonances are the *KLL* ($1s2l2l'$) resonances for heliumlike target ions, and the *LMM* ($2p^5 3l3l'$) resonances for neonlike target ions. For DR onto neonlike gold the *LMM* resonances are expected to have about 70% of the total DR resonance strength.

DR can be measured by detecting either the intensity of the DR x rays or the ion abundance as a function of the interaction energy between the ion and the electron. X-ray techniques have been used to measure the *KLL* DR resonances of heliumlike Ni^{26+} [3,4] and Mo^{40+} [4]. The cross sections were normalized to those of radiative recombination (RR), the nonresonant recombination of electrons with ions. The second technique has been used to measure the Ar^{16+}-to-Ar^{15+} abundance ratio of ions extracted from an electron-beam ion source [5]. In this case, the DR cross sections were normalized to those of electron-impact ionization. DR has also been indirectly measured in resonant transfer and excitation (RTE) experiments where ions move through a gas target and interact with the target electrons. Recently, the RTE equivalent of the *KLL* resonances of heliumlike U^{90+} onto H_2 was observed [6]. All three experiments for heliumlike target ions have been in good agreement with theory.

The *LMM* dielectronic recombination resonances in neonlike ions have not previously been seen. There have been two observations [7,8] of some of the higher-order, weaker resonances, but with either poor resolution [8] or no analysis [7]. We report the first measurements of the *LMM* resonances in a neonlike system, Au^{69+}. We used the electron-beam ion trap (EBIT) at the Lawrence Livermore National Laboratory to measure the intensity of the $n=3\rightarrow 2$ DR x rays as a function of the initial energy of the recombining electrons.

The *LMM* resonances in neonlike ions differ from the

KLL resonances in heliumlike ions in severals ways: (a) the energy threshold for ionization to a neonlike state is 2–3 times the energy of the *LMM* resonances, whereas the threshold for ionization to a heliumlike state is below the energy of the *KLL* resonances, (b) the *LMM* resonance strengths are at least an order of magnitude larger than the *KLL* resonance strengths, and (c) the *LMM* resonances for neonlike target ions have 237 intermediate states whereas the *KLL* resonances for heliumlike target ions have only 16. These factors make it difficult to observe the *LMM* resonances without destroying the population of neonlike ions.

The EBIT employs a precisely tuned, 70-μm-diam electron beam with an energy spread of about 60 eV full width at half maximum (FWHM) to trap, ionize, excite, and recombine with highly charged ions [7,9]. X rays from these interactions are observed at 90° to the electron-beam direction. In this experiment, low-charge-state gold ions were injected into the EBIT and successively ionized for 2 s at an electron energy of 18 keV and a beam current of 150 mA, a procedure that maximized the amount of neonlike gold (the ionization potential of Au^{69+} is 18.07 keV). To avoid perturbing the ionization stage balance, the DR resonances were probed by reducing the beam current to 50 mA and linearly ramping the beam energy from 18 to 2 keV and back in 10 ms. The current was then returned to 150 mA and the beam energy to 18 keV for 70 ms to regenerate the equilibrium ionization balance. The cycle was repeated 200 times, and then the trap was dumped.

When an x ray was detected in a solid-state Ge detector, its photon energy, the electron-beam energy, and the time of the event were recorded. The data were self-normalized because the same amount of time was spent at each voltage.

The data from a typical run can be displayed as a scatter plot, as shown in Fig. 1. The *LMM* resonances occur at electron energies between 1 and 6 keV. An excitation function was constructed by summing all the $n=3\rightarrow2$ photons plus the RR to $n=3$ photons at each electron-beam energy and correcting for dead time. Exactly one $n=3\rightarrow2$ photon is emitted for each dielectronic recombination event because the intermediate state of the ion has only one hole in the $n=2$ core. The measured excitation function for the strongest region of the *LMM* resonances is shown in Fig. 2. Much of the structure results from the presence of several ionization stages.

The data in Fig. 2 were compared to multiconfiguration Dirac-Fock (MCDF) calculations of the resonance strengths for recombination onto four ionization states, neonlike to aluminumlike gold. The ions were assumed to be initially in their ground state because the electron density was so low ($<3\times10^{12}$ cm^{-3}) that the time between an electron-ion collision was longer than the lifetime of any metastable state of the ion. The atomic energy levels and bound-state wave functions were calculated using the MCDF model in the extended average-level scheme [10]. The effects of quantum-electrodynamic corrections, the finite nuclear size, the transverse Breit interaction, and relaxation were included in the calculations of the transition energies. The relativistic Auger and radiative rates for each intermediate state were calculated using first-order perturbation theory. The effect of the electric field in the EBIT, 8000 V/cm at its maximum, was ignored because the electric field from the nucleus at these tightly bound orbitals ($n=2,3$) is so huge. Because the DR resonances have much narrower widths than the beam resolution, they were treated as δ functions normalized to the energy-averaged cross sections as defined by Lagatutta and Hahn [1]. The cross sections for emission of x rays at 90° to the electron beam were expressed as resonance strengths averaged in energy bins of 1 eV. A more complete presentation of the techniques used is given in Ref. [11].

About 20 *LMM* DR resonances onto the neonlike ion make significant contributions to the DR cross section

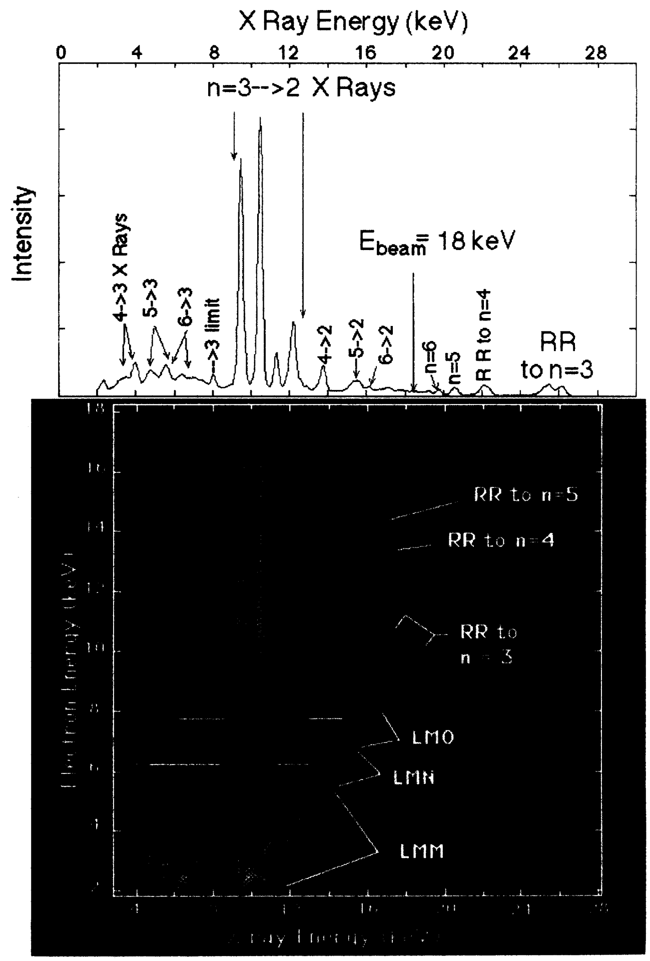

FIG 1. Neonlike gold x-ray data. Top: Direct excitation spectrum at an electron energy of 18 keV. The strongest excitation lines are from two $E1$ transitions: $(2p_{3/2}^{-1}\ 3d_{5/2})_{j=1}$ $\rightarrow$ground state (g.s.) near 10.5 keV and $(2p_{3/2}^{-1}3s_{1/2})_{j=1}$ $\rightarrow$g.s. near 9.5 keV. The other strong $n=3\rightarrow2$ transitions involve the $2p_{1/2}^{-1}$ core. Bottom: x-ray intensity distribution vs x-ray energy and electron energy. The DR resonances are the bright spots at the intersections of the excitation x rays in the vertical bands and the RR x rays in the diagonal bands.

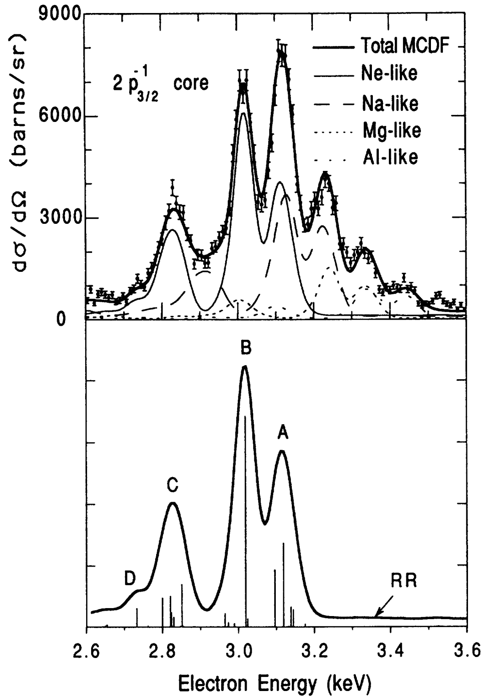

FIG. 2. Top: DR excitation function data and MCDF theory for the $2p_{3/2}^{-1}$ core region. The background is from RR to $n=3$. Bottom: Theoretical resonance strengths for neonlike gold target ions (vertical bars) and calculated cross sections given the resolution of this experiment (solid line). The peaks *C*, *B*, and *A* correspond to the second DR electron in the $3p_{3/2}$, $3d_{3/2}$, and $3d_{5/2}$ subshells, respectively. The theory for target ionization states beyond aluminumlike were not available, but siliconlike ions were in the trap, as evidenced by the peak in the data at 3.52 keV where the *B* peak in siliconlike gold target ions is expected.

for the data in Fig. 2. The dominant contribution is from high angular momentum intermediate states with a $2p_{3/2}^{-1}$ core and at least one DR electron in the $3d_{5/2}$ subshell. The theoretical predictions of the resonance strengths for neonlike ions are shown in Fig. 2. Also shown are the calculated cross sections for the energy resolution of this experiment. All the ionization stages have a similar three-peak structure.

The excitation function in Fig. 2 was fitted for an ionization-stage distribution and an electron-beam energy resolution. The fit to the data is shown in Fig. 2 (top), along with the separate contributions from the different ionization stages (44% Ne-like, 35% Na-like, 12% Mg-like, and 9% Al-like target ions). The Gaussian FWHM of the electron energy was 59 eV, consistent with previous measurements [3,4]. The energy axis was adjusted to correct for the space charges of the electron beam and ion cloud and the time lag between the actual and measured electron-beam energies by comparing the data and theory over a wide electron energy range (2.2 to 5.5 keV).

The DR resonance strengths were derived by normalizing the data to the measured intensity of RR photons to $n=3$, 4, and 5 using calculated RR cross sections. Care was taken in the normalization to avoid regions in which the RR x rays might be contaminated by x rays produced by other processes. The RR cross sections for x rays emitted at 90° to the electron beam for each ionization stage were calculated using a relativistic distorted-wave code [12] from 2 to 8 keV at every 0.5 keV. Cross sections at intermediate energies were determined by interpolation.

The final value for the DR cross-section scale, shown in Figs. 2(a) and 3, is quite insensitive to the ionization balance used in the normalization process because the RR cross sections of the four ionization stages are so similar.

The measured total resonance strength for DR onto neonlike gold between 2.6 and 3.6 keV is $(1.0\pm0.15)\times10^{-17}$ $cm^2\,eV$; the theoretical value is 0.95×10^{-17} $cm^2\,eV$. The principal source of error comes from the possibility of contamination of the RR x rays.

Data taken with 40-, 50-, and 60-mA beam currents during the DR measurement had the same ionization balance, indicating that ionization-stage depletion by DR during the measurement was insignificant. Using the measured resonance strengths, we estimate the depletion of neonlike ions during one sweep through the *LMM* resonances to be 2.5%.

LMM resonances at incident-electron energies above 3.6 keV involve intermediate states with $2p_{1/2}^{-1}$ and $2s_{1/2}^{-1}$

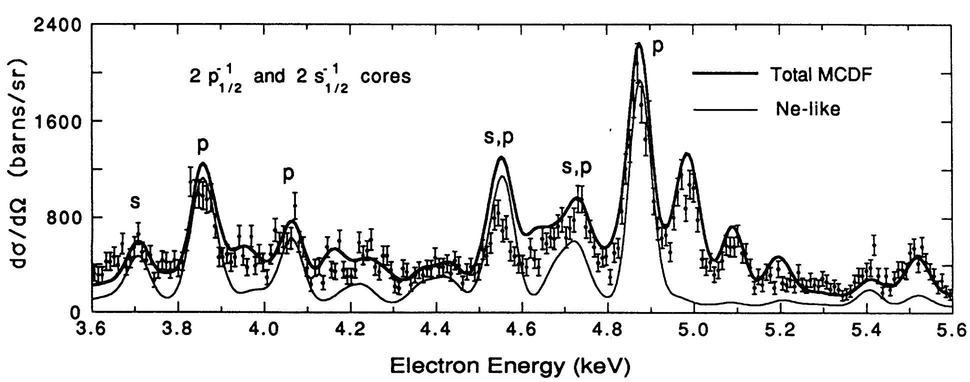

FIG. 3. DR excitation function data for the $2s_{1/2}^{-1}$ and $2p_{1/2}^{-1}$ core region. The theory uses the parameters from Fig. 2. The major neonlike peaks are identified by *s* for the $2s_{1/2}^{-1}$ core or by *p* for the $2p_{1/2}^{-1}$ core.

core configurations. Figure 3 shows the data in this region compared to the MCDF theory with the ionization balance, beam width, and normalization factor from the data in Fig. 2. There is a large discrepancy for the peak at 4.55 keV. The MCDF theory predicts this peak to be composed of two neonlike $J=\frac{5}{2}$ DR resonances: 80% from an intermediate state composed mainly of the $(2p_{1/2}^{-1}3p_{3/2}3d_{3/2})$ configuration and 20% from an intermediate state composed mainly of the $(2s_{1/2}^{-1}3s_{1/2}3d_{5/2})$ configuration. It is likely that perturbation approximations in the theory overestimate the mixing between these two configurations, making the resonance of the mainly $2s_{1/2}^{-1}$ state too large.

In summary, we have measured the *LMM* dielectronic recombination resonances of a highly charged neonlike ion. Detailed structures in the resonances for neonlike to aluminumlike target ions have been resolved and compared to MCDF theory in the high-Z limit. Significant disagreements [13] have been seen only in the $2p_{1/2}^{-1}$ and $2s_{1/2}^{-1}$ core region. The resonance strength between 2.6 and 3.6 keV, relative to that of radiative recombination, is 1.05 ± 0.16 times the theoretical MCDF value for neonlike target ions.

We wish to thank A. Hinz, E. Magee, and D. Nelson for their assistance in these measurements. We thank Dr. M. J. Eckart and Dr. R. J. Fortner for their encouragement and support. Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

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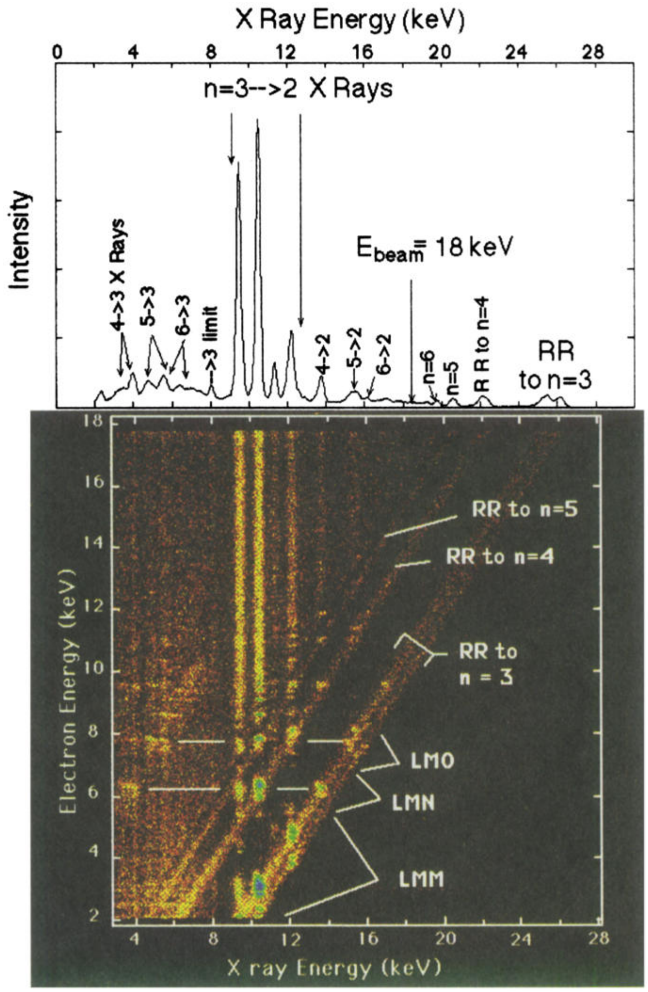

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