Test of predicted $\Delta n \geq 1$ L-shell dielectronic-recombination cross sections

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The predicted charge-state dependence of dielectronic-recombination cross sections involving $\Delta n \geq 1$ L-shell excitation has been tested by measurements of resonant transfer and excitation (RTE) for ${}_{41}Nb^{q+}+H_2$ ($q=28$ to 32) collisions at 3.7 and 4.0 MeV/u. The measured RTE cross sections increase significantly with increasing charge state and thus disagree substantially with theoretical calculations that predict essentially equal cross sections for Nb^{29+}, Nb^{30+}, and Nb^{31+}. This disagreement is contrary to the good agreement previously found between theory and experiment for K-shell RTE.

Recombination of ions in collisions with free electrons involves fundamental interaction mechanisms and is a subject of considerable interest. Dielectronic recombination[1] (DR) is a resonant process in which electron capture is accompanied by simultaneous excitation of the ion due to the electron-electron interaction followed by radiative stabilization. DR is, in fact, the principal mechanism by which free electrons recombine with ions. DR has been identified as an energy-loss mechanism in magnetically confined nuclear-fusion plasmas since impurity ions (such as C, O, Fe, etc.) in the plasma can recombine by this mechanism.[2] The cross sections and spectral properties of the DR process are also of interest in plasma diagnostics[3] and in the study of astrophysical plasmas and soft x-ray lasers.[4] Therefore DR has been the subject of intense experimental and theoretical investigations. However, measurements[5–7] of cross sections for DR have proven to be a formidable task since either crossed-beam or merged-beam techniques are required.

A mechanism closely related to DR occurs in ion-atom collisions when projectile excitation is accompanied by simultaneous capture of a weakly bound target electron, a process known as a resonant transfer and excitation[8,9] (RTE). RTE and DR proceed through an inverse Auger transition and, hence, are resonant processes. If the projectile velocity is large compared to the target electron velocity, then RTE can be treated in the impulse approximation[10] with the resonant maxima being broadened by the momentum distribution of the target electrons. In the last few years a number of experimental[9,11–15] and theoretical studies[2,16,17] of RTE have clearly demonstrated that RTE closely approximates DR. These RTE studies, done principally for $1s$ (K-shell) excitation, have shown that the measured RTE cross sections are in good agreement both in magnitude and peak energy location with calculations based on theoretical DR cross sections. Of particular significance to the present work is the fact that excellent agreement between experiment[9,13] and theory[2,17] was obtained for the projectile charge-state dependence of K-shell RTE for $Ca^{q+}+H_2$, $Ca^{q+}+He$, and $V^{q+}+He$ collisions. Furthermore, for RTE involving K-shell excitation there is considerable variation with incident charge state of the cross sections even when the incident projectiles differ only by the presence of one or two additional electrons.[13] For example, with an H_2 target, the cross sections[13] at the RTE maxima for incident Ca^{18+} projectiles are 2.5 to 3 times larger than the values at the maxima for incident Ca^{16+}. These results, which were in good agreement with theory, provided a quantitative test of the charge-state dependence of DR for 1*s* excitations.

At present the only existing data[6,7] for DR involving 2*s* or 2*p* (*L*-shell) excitations are for cases where the principal quantum number *n* of the excited electron does not change (i.e., $\Delta n = 0$). Furthermore, only limited data exist[18,19] for RTE involving excitation of projectile *L*-shell electrons to $n \geq 3$ ($\Delta n \geq 1$). Previously, detailed measurements using coincidence techniques for *L*-shell RTE with $\Delta n \geq 1$ for ${}_{41}Nb^{31+}$ (neonlike) ions incident on H_2 have been reported.[18] These experimental *L*-shell RTE cross sections are about an order of magnitude larger than those for 1*s* excitation, and also are in reasonably good agreement (to within about 25%) with calculated values obtained using theoretical DR cross sections[20] as seen in Fig. 1(a).

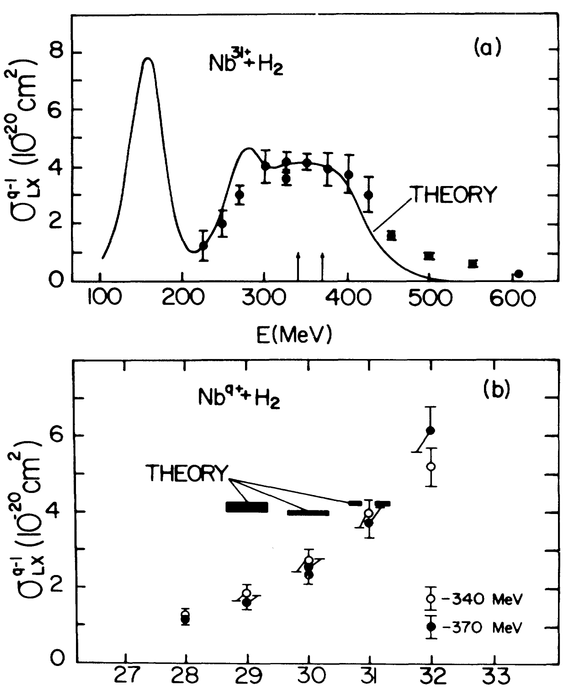

FIG. 1. (a) Energy dependence of the cross sections for Nb *L*-shell x rays (contributions from $L\alpha$, $L\beta$, and $L\gamma$ are summed) coincident with projectiles that have captured an electron, σ_{Lx}^{q-1}, for ${}_{41}Nb^{31+}$ (neonlike) incident on H_2. The data and theoretical curve are taken from Ref. 18. Note the insensitivity of the cross section to the incident beam energy for the values of 340 and 370 MeV (indicated by arrows) used in the present work. (b) Charge-state dependence of the coincidence cross sections σ_{Lx}^{q-1} at 340 and 370 MeV. Theoretical predictions (Ref. 20) for charge states 29+, 30+, and 31+ are shown by the horizontal bands. The upper and lower edges of the bands give the calculated cross sections at 340 and 370 MeV, respectively. Relative experimental uncertainties are indicated by the error bars in both (a) and (b).

Explicit calculations of DR cross sections for Nb^{29+}, Nb^{30+}, and Nb^{31+} ions for 2*s* and 2*p* excitations with $\Delta n \geq 1$ are given in Ref. 20. Although the theoretical DR calculations were made for Mo ($Z = 42$), the DR cross sections for the corresponding isoelectronic charge state for Nb differ[20] by only 1.2% from the Mo values. In calculating RTE cross sections for Nb from the Mo DR cross sections, the excitation transition energies given[20] for Mo were reduced by the ratio of the squares of the atomic numbers for Nb and Mo (4.9%). An unexpected result of the theoretical calculations was that, within the estimated uncertainty of ±20% in the calculation, the DR cross sections are nearly the same for the Nb charge states 29+, 30+, and 31+. It was argued[20] that, while the 2*s* and 2*p* excitations are expected to behave in a similar manner for each of these charge states, the presence of one or two 3*s* electrons on the recombining ion should change the statistics and widths resulting in rather different DR (and hence RTE) cross sections. Thus the finding[20] that the calculated DR cross sections were essentially independent of charge state was rather surprising, and it is of interest to test this prediction experimentally. The present experiment was designed to accomplish this test by measuring the charge-state dependence of *L*-shell RTE with $\Delta n \geq 1$ for various incident charge states in $Nb^{q+} + H_2$ collisions.

The measurements reported here were carried out at the Lawrence Berkeley Laboratory using the SuperHILAC accelerator. The experimental technique consisted of measuring niobium *L*-shell x rays coincident with single electron-capture events. Niobium projectiles in a given charge state passed through a differentially pumped gas cell. X rays produced in collisions with the target gas were detected with a Si(Li) detector mounted at 90° to the beam axis. The beam, after emerging from the gas cell, was magnetically analyzed into its charge-state components and the ions which underwent electron capture in the target gas were detected with a solid-state detector. The non-charge-changed component of the emerging beam was collected in a Faraday cup. Coincidences between *L*-shell x rays and projectile ions which captured or lost an electron were recorded with a time-to-digital converter. The total x-ray and coincidence yields were measured as a function of gas pressure to obtain the desired cross sections and to ensure that single-collision conditions prevailed. A capacitance manometer was used to measure the absolute pressure in the target gas cell.

Cross sections for *L*-shell x rays coincident with projectiles that have captured an electron σ_{Lx}^{q-1}, (contributions from $L\alpha$, $L\beta$, and $L\gamma$ were summed) were obtained for $Nb^{q+} + H_2$ ($q = 28$, 29, 30, 31, and 32) at 340 and 370 MeV (3.7 and 4.0 MeV/*u*). The corresponding translational electron kinetic energies as viewed from the rest frame of the projectile are 2008 and 2184 eV, respectively. Figure 1(b) shows the measured values of σ_{Lx}^{q-1} as a function of incident charge state. Relative uncertainties in the data are shown by the error bars. The uncertainty in the absolute cross sections is estimated to be ±30%. Also shown in Fig. 1(b) are the predicted cross sections obtained from the calculations of Ref. 20.

The previous measurements[18] and calculations[20] for $Nb^{31+} + H_2$ are shown in Fig. 1(a). In agreement with theory, the experimental values of $\sigma \xi_{L_x}^{-1}$ exhibit a broad flat-topped maximum in the energy range from about 230 to 500 MeV. This structure, which is rather wide compared to peaks observed for RTE involving 1*s* excitation, is due to the contributions from a large number of intermediate resonant states each of which is broadened[10] by the momentum distribution of the target electrons. A nearly identical structure is predicted from the theoretical DR cross sections[20] for the RTE cross sections for incident Nb^{29+} and Nb^{30+}. The earlier Nb^{31+} studies[18] [Fig. 1(a)] showed that essentially all of the *L*-shell x rays coincident with projectiles which have captured an electron for energies near 350 MeV could be attributed to the RTE process. Based on this result a similar behavior is expected for Nb^{29+} and Nb^{30+}. Thus the present measurements at 340 and 370 MeV should provide an accurate representation of the charge-state dependence of the *L*-shell RTE cross sections, and, hence, provide a quantitative test of the predicted DR cross sections for these charge states.

The cross sections measured in the present experiment, which are shown in Fig. 1(b), are nearly the same for each individual charge state at 340 and 370 MeV in agreement with the theoretical energy dependence predicted[20] for $Nb^{29+,30+,31+}$ at these energies. However, the experimental cross sections show a significant increase as the incident charge state is increased. The cross sections for Nb^{31+} are about a factor of 2 larger than the values for Nb^{29+}, a result which is in substantial disagreement with the theory. No calculations currently exist for $q = 28+$ and $32+$. Furthermore, since incident Nb^{32+} ions have an initial *L*-shell vacancy, values of $\sigma \xi_{L_x}^{-1}$ for this charge state may be considerably larger than the actual RTE cross section due to contributions from direct electron capture to an excited state ($n \geq 3$) followed by radiative decay.

The experimental results show, in contrast to the theoretical predictions, that the pressure of one or two 3*s* electrons on the projectile appears to have a significant effect on the transition rates for $\Delta n \geq 1$ *L*-shell RTE and DR excitations. Also, it is noted that the observed decrease in RTE cross sections for Nb ions with 3*s* electrons is quantitatively similar to the measured decrease in *K*-shell RTE cross sections[13] for calcium ions with 2*s* electrons. In this latter case, however, the theory was in rather good agreement with the data. The reason for the large difference between the present experimental results and the theory is not known. Additional theoretical calculations of *L*-shell DR cross sections for Nb^{29+} and Nb^{30+} are apparently needed to resolve the discrepancy. A possibility is that perturbations due to the electric field of the target nucleus are large enough to significantly change the RTE cross sections for *L*-shell excitation with $\Delta n \geq 1$. Such electric-field effects have been invoked[2,21] in the case of $\Delta n = 0$ measurements to explain enhanced DR cross sections. Recent calculations[22] of *L*-shell DR with $n \geq 1$ indicate that the effect of external electric fields may also decrease the cross sections; however, the electric-field effect was found to be relatively small for Fe^{23+}.

In summary, we have tested the predicted charge-state dependence of $\Delta n \geq 1$ *L*-shell dielectronic recombination cross sections for highly charged Nb^{q+} ions using measurements of resonant transfer and excitation. The measured cross sections are found to increase substantially with increasing charge state contrary to the theoretical cross sections which were predicted to be essentially independent of charge in the range $q = 29+$ to $31+$. The present results are in sharp contrast to previous studies of the charge-state dependence of RTE (and, hence, for DR) cross sections for $\Delta n \geq 1$ *K*-shell excitation in which it was found that theory and experiment were in rather good agreement. The resolution of the discrepancy reported here is important not only from a fundamental point of view, but also from the standpoint of providing an accurate theoretical description of DR for the purpose of understanding and predicting total DR rates in laboratory and astrophysical plasmas.

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