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MULTIPLE ELECTRON CAPTURE IN CLOSE ION-ATOM COLLISIONS

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Collisions in which a fast highly charged ion passes within the orbit of K electrons of a target gas atom are selected by emission of a K x-ray from the projectile or target. Measurement of the projectile charge state after the collision, in coincidence with the K x-ray, allows measurement of the charge-transfer probability during these close collisions. When the projectile velocity is approximately the same as that of target electrons, a large number of electrons can be transferred to the projectile in a single collision. The electron-capture probability is found to be a linear function of the number of vacancies in the projectile L shell for 47-MeV calcium ions in an Ar target.

I. INTRODUCTION

Charge transfer in ion-atom collisions is a fundamental process of considerable interest. The probability of capturing an electron in a collision is a function of the impact parameter for the collision, as well as a function of projectile velocity and charge state. Collisions in which a fast ion projectile passes close to a target atom, e.g., within the K or L shell, can be selected by measuring the angle through which the projectile is scattered in the collision: the projectile is scattered through a larger angle in a close collision than in a more distant one.¹⁻⁵ A less direct method of selecting close collisions is coincident detection of highly charged target recoil ions: a highly charged recoil ion implies that a close collision has taken place.⁶⁻⁹ The impact-parameter dependence of inner-shell vacancy production has also been studied by measuring coincidences between charge transfer and x-ray emission.¹⁰

We have measured¹¹ cross sections for electron capture in coincidence with Ca or Ar K x-ray emission for 47-MeV $\text{Ca}^{17+} + \text{Ar}$, and showed that the cross

section for capturing several electrons in a close collision can exceed that for capturing only one electron. The only previous report of the cross section for multiple-electron capture being larger than that for single-electron capture, determined by ion-x-ray coincidence, is the observation of double K-to-K transfer in collisions of bare 4.5-MeV/u Si ions in Ar.¹² The results of reference 11 were recently extended to measure capture of up to eight electrons, and the projectile velocity has been varied.¹³ New results are presented here for varying the projectile charge state, which varies the number of initial vacancies in the projectile L shell.

II. APPARATUS AND METHOD

The apparatus and methods employed are similar^{11,13,14} to those previously used. The apparatus is shown schematically in Fig. 1. A beam of fast Ca ions from the LBL SuperHILAC accelerator was passed through a thin foil, and ions in a given charge state were selected by a magnet. Calcium ions

in charge states from $17+$ (lithium-like) to $10+$ (neon-like) were collimated and then passed through a differentially pumped gas cell. The magnetically-analyzed Ca ions were measured after the collision using a Faraday cup and electrometer for those ions which did not change charge in the target, while ions which captured one to eight electrons were counted with solid-state detectors. A $\text{Si}(\text{Li})$ x-ray detector viewed the gas cell. Coincidences between x-rays and projectiles which captured electrons were measured by starting time-to-digital or time-to-amplitude converters (TDCs or TACs) with an x-ray signal, and stopping them with delayed signals from the particle detectors. The data were corrected for absorption of x-rays in the detector window and for the detector solid angle. Errors were minimized by using a very thin target relative to all relevant electron-capture and -loss cross sections and by correcting for background effects. The relative uncertainties in the cross sections reported here are $\pm 25\%$, the systematic uncertainty is $\pm 30\%$, for an absolute uncertainty of approximately $\pm 40\%$.

FIG. 1. Schematic diagram of the apparatus, shown for Ca^{17+} projectile; eight particle detectors were used (only five are shown). Each particle detector goes to a separate time-to-amplitude converter (TAC). The $\text{Si}(\text{Li})$ detector is used to detect x-rays.

III. CLOSE COLLISIONS OF 47-MeV Ca^{17+} IN Ar

A 47-MeV Ca ion has a velocity (1.5×10^9 cm/s) which is close to the velocity of the L-shell electrons of the Ar target (1.0×10^9 cm/s), and is slower than the K-shell electrons¹⁵ of the projectile (4.2×10^9 cm/s) and target (3.4×10^9 cm/s). K-vacancy production in either partner is therefore expected to be appropriately described in the molecular-orbital picture. The relevant MO diagram for the relevant states of the $\text{Ca} + \text{Ar}$ system is shown in Fig. 2. An Ar K electron can be transferred to the L shell of the Ca^{17+} ion at an internuclear separation of about the K-shell radius (approximately $0.08a_0$) via $2p\sigma$ - $2p\pi$ rotational coupling.¹⁶ The resulting vacancy in the Ar K shell can be shared with the outgoing Ca ion by subsequent $2p\sigma$ - $1s\sigma$ radial coupling¹⁷ at a distance of several times the K-shell radius, giving rise to a Ca K vacancy. Simultaneous with the K-K transfer is the transfer of target L- and M-shell electrons to the projectile L shell, which has a high probability of occurrence over a range of several times the L-shell radius (see Fig. 2).

FIG. 2. Schematic molecular-orbital diagram for the $\text{Ca} + \text{Ar}$ system showing the relevant levels. Rotational coupling creates an Ar K vacancy at small internuclear separations; radial coupling (vacancy sharing) at larger internuclear separations can lead to a Ca K vacancy. L-L transfer occurs over a still larger range of internuclear separations (indicated schematically by the cross hatching).

Cross sections for L- and M-shell electron capture coincident with a Ca K or Ar K x-ray are

shown in Fig. 3 for 47-MeV Ca^{17+} in Ar. The cross sections for coincidence with an Ar K and Ca K x-ray have essentially the same shape, and in fact, coincide, if the cross sections for coincidence with an Ar K x-ray are shifted one charge state lower, as shown in Fig. 3. This shift is needed because an Ar K vacancy (Ar K x-ray emission) resulting from transfer of an Ar K electron to the Ca L shell appears as a capture event by the Ca ion (Fig. 4a). For the case of emission of a Ca K x-ray, however, an electron has been returned to the Ar by K-vacancy sharing (Fig. 4b), resulting in no net change of charge for the Ca ion. The cross sections are thus compared in terms of capture of target L- and M-shell electrons only.

FIG. 3. Cross sections for electron capture in coincidence with an Ar or Ca K x-ray for 47-MeV Ca^{17+} in Ar, as a function of the number of L- and M-shell electrons captured. The upper scale shows the projectile final charge state for coincidence with a Ca K x-ray. The Ar K x-ray coincidence data have been shifted one charge state to the left to account for the promotion of an Ar K electron to the Ca L-shell for the case of emission of an Ar K x-ray (see text).

FIG. 4. Schematic diagram of energy levels for $\text{Ca}^{17+} + \text{Ar}$, showing (a) electron promotion and (b) vacancy sharing.

The electron-capture charge-state distribution can be described¹⁸ by a binomial distribution if we assume that the L- and M-shell electrons are captured due to electron-nucleus interactions and that electron-electron interactions can be neglected, i.e., the electrons are captured without correlation. The binomial distribution for capture of n electrons with a probability p is written:

$$P_n = \binom{t}{n} p^n (1-p)^{t-n}$$

where t is the number of places into which electrons may be captured and $\binom{t}{n}$ is the binomial coefficient.

The measured relative probability distributions for electron capture in coincidence with an Ar K x-ray (shifted one charge state lower) and with a Ca K x-ray are shown in Fig. 5, along with a binomial distribution which has been fit to the experimental data for $t=7$, giving an electron-capture probability $p = 0.45$ for the Ar K x-ray data and $p = 0.49$ for the Ca K x-ray data. The good agreement of the measured charge-state distribution with a binomial distribution is consistent with independent electron-capture events, and argues against significant electron correlation effects.

FIG. 5. Relative electron-capture probabilities for 47-MeV Ca^{17+} in Ar as a function of the number of L- and M-shell electrons transferred for coincidence with a Ca K or Ar K x-ray. The distribution for coincidence with an Ar K x-ray has been shifted to the left by one charge state (see text). Solid bars show the experimental results; shaded bars show the binomial distribution for an electron-capture probability of 0.47 (assuming 7 electrons can be captured). The experimental probabilities have been normalized by a factor determined by the fit to the binomial distribution.

Experimental K-vacancy-sharing probabilities, w_{exp} , can be calculated from the observed cross sections for electron capture in coincidence with a Ca or Ar K x-ray, corrected by neutral-atom fluorescence yields. Agreement of experimental values, w_{exp} , with the theoretical¹⁷ value $w_{\text{th}} = 0.30$ is good for capture of up to four electrons, where neutral-atom K binding energies have been used. The values of w_{exp} for a larger range of number of electrons captured shows that w_{exp} increases with increasing number of electrons captured (Fig. 6). Possible explanations for this dependence are that the K-vacancy-production process is not truly independent of the electron-capture mechanism for collisions in which many

electrons are captured, or that the use of neutral-atom fluorescence yields is inadequate.

FIG. 6. K vacancy-sharing probabilities as a function of the number of L- and M-shell electrons captured. Experimental probabilities, w_{exp} , are calculated from the experimental results; w_{th} is the theoretical value.¹⁷

IV. CLOSE COLLISIONS OF 47-MeV Ca IONS IN Ar: VARYING THE NUMBER OF VACANCIES IN THE Ca L SHELL

Close collisions of 47-MeV Ca ions in Ar have been further investigated by varying the number of initial vacancies in the L shell of the Ca-ion; ions in charge states 10, 13, 15, 16, and 17 were used. Results are shown in Fig. 7, as a function of the number of L-shell electrons captured. Note that the abscissas are offset to emphasize that the cross-section distributions have the same shape. This suggests that cross sections for electron loss in coincidence with a Ca or Ar K x-ray might be appreciable.

FIG. 7. Cross sections for electron capture in coincidence with an Ar or Ca K x-ray for 47-MeV Ca^{q+} in Ar, for $q = 13, 15, 16$ and 17 , as a function of the number of L-shell electrons captured. The upper scale shows the projectile final charge state for coincidence with a Ca K x-ray. The Ar K x-ray coincidence data have been shifted one charge state to the left.

The cross sections shown in Fig. 7 can be fit with a binomial distribution, as has been done in Fig. 5 for Ca^{17+} ions. The result in each case is an electron-capture probability. These electron-capture probabilities are shown in Fig. 8 as a function of the number of initial vacancies in the L shell of the Ca-ion projectile. This electron-capture probability is seen to be linear with the number of Ca-ion L-shell vacancies.

FIG. 8. Electron-capture probability as a function of the number of vacancies in the Ca L shell for close collisions of 47-MeV Ca^{9+} in Ar ($q = 13, 15, 16$, and 17).

V. TOTAL ELECTRON CAPTURE: 47-MeV Ca IONS IN Ar

Total electron-capture cross sections for 47-MeV Ca^{17+} in Ar are shown in Fig. 9. A total cross section for capture of up to eight electrons in a single collision is observed. These cross sections, unlike those for close collisions (coincidence with a Ca or Ar K x-ray), which are also shown in Fig. 9, are a monotonically decreasing function of the number of electrons captured. We note that close collisions are only a small fraction of the total number of collisions, although this fraction is found to increase with increasing number of electrons captured, a result which might arise from greater interpenetration of the projectile and target L shells for collisions in which a greater number of electrons are captured.

FIG. 9. Total and x-ray coincident (sum of Ar and Ca K x-rays) electron-capture cross sections for Ca^{17+} in Ar as a function of the number of electrons captured.

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