Simultaneous Electron Capture and Excitation in S + Ar Collisions

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Electron capture accompanied by simultaneous K-shell excitation has been observed for 70-MeV S^{13+} + Ar collisions. This process is analogous to dielectronic recombination for the case of free electrons incident on highly charged ions. In addition, radiation following capture into high-n states without accompanying excitation is measured for charge states $q = 14+$ to $16+$. The results are used to determine the fraction of capture events which result in K-shell radiation, and the fraction of K x rays resulting from capture events.

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Dielectronic recombination occurs when an ion in charge state q captures a continuum electron and simultaneously excites an electron from the ground-state configuration, resulting in a doubly excited state. This process is just the inverse of the Auger effect. Dielectronic recombination is a process not only of fundamental interest but also is thought to be an important energy-loss mechanism in thin high-temperature plasmas.[1-3] Measurement of dielectronic recombination cross sections is difficult, however, due in part to similar processes taking place at the same time such as collisional excitation and ionization.

A process analogous to dielectronic recombination should occur in ion-atom collisions. In this Letter we report the first identification of such a process, which we call *capture with excitation,* in which a highly stripped ion captures a weakly bound electron from a neutral target atom simultaneous with the excitation of an inner-shell electron in the ion. In this work, sulfur K x-ray emission following electron capture has been measured for 70-MeV S^{q+} ($q = 13-16$) ions incident on argon. K radiation resulting from capture was isolated by detecting coincidences between S K x rays and electron-capture events. In addition to capture with excitation, probabilities for K radiation following capture into a high-n state ($n \geq 2$) without accompanying K-shell excitation have also been determined.

This work was performed at the Triangle Universities Nuclear Laboratory (TUNL) using the FN tandem Van de Graaff accelerator. Sulfur ions from the TUNL sputter ion source were accelerated to 70 MeV and poststripped to achieve high charge states. Following magnetic analysis, the selected charge-state beam was passed through a differentially pumped gas cell containing typically 100–200 μm of Ar as measured with a capacitance manometer. Target gas pressures were such that $\lesssim 15\%$ of the incident beam changed charge state in passage through the target and for S^{13+} this fraction was $\lesssim 7\%$. Beam-line pressures were such that $\lesssim 2\%$ of the beam changed charge between the analyzing magnet and the target cell. After emerging from the gas cell, the beam was electrostatically analyzed into its charge-state components. Ions which underwent single capture were detected in a silicon surface-barrier detector. X rays emitted from the target were detected with a Si(Li) detector mounted at 90° to the beam. X rays were viewed through a 6.4-μm Mylar window which sealed the gas cell.

Collimation of the incident beam was such that

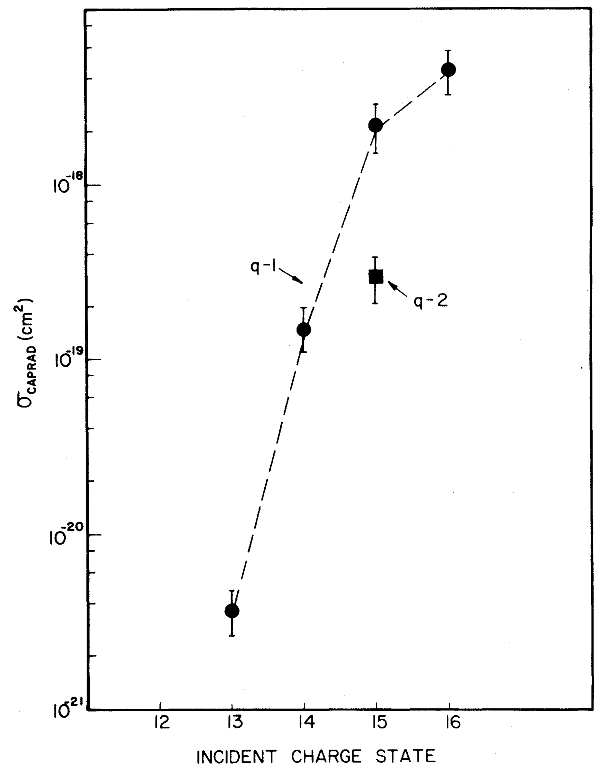

FIG. 1. Total cross section for projectile K-shell radiation following single $(q-1)$ or double $(q-2)$ capture for 70-MeV S^{q+} ions $(q = 13-16)$ incident on Ar. This cross section is the sum of the K radiative cross sections resulting from simultaneous capture and excitation events and capture into high-n states without accompanying excitation. The line is drawn to guide the eye.

ions with impact parameters $\gtrsim 1.3\times10^{-11}$ cm would be seen by the detection system. From Cocke *et al.*[4] we infer that essentially all K vacancies are produced for impact parameters *greater* than this. Hence all K-vacancy events were viewed by the detection system.

Coincidences between single-capture events and S K x rays were detected with a time-to-amplitude converter (TAC). An energy window was set on the S K x rays using a single-channel analyzer (SCA) so that only *projectile* x rays in coincidence with capture events would be recorded.

Singles spectra for both particles and x rays as well as the coincidence spectrum were recorded. Measured x-ray yields were corrected for detection efficiency and subtended solid angle. Normalization of the incident beam intensity was accomplished in two ways: (1) measurement of the analyzed ion intensity in each of the charge states and (2) from the measured S and Ar total K x-ray production cross sections in a separate experiment. The total absolute error in the coincidence K x-ray cross sections obtained is estimated to be ±30%. Sufficient counts were obtained in the TAC spectrum so that statistical errors were less than 3% for $q = 14+$ to $16+$ and less than 10% for $q = 13+$. The counting time to obtain sufficient statistics for $q = 13+$ was about four to five hours.

Cross sections for K x-ray emission following capture as well as total cross sections for single and double capture were obtained for incident sulfur charge states $q = 13+$ to $16+$. The results are shown in Table I and Figs. 1 and 2.

In Fig. 1 we show the total cross section for K-shell radiation following capture, which we denote by σ_{CAPRAD}. This is just the sum of the cross section for K radiation resulting from capture with excitation and the cross section for K radiation following capture into a high-n state without accompanying excitation. Only for S^{13+} (Li-like sulfur) can the cross section be attributed totally to capture with excitation since the initial three-electron state of the beam is $1s^2 2s$. For He-like S ($q = 14+$), there is a significant metastable fraction $1s2s$ ($^3S_1$) in the beam for which K radiation following high-n-state capture becomes possible. Unfortunately, the metastable fraction of the beam is unknown. For ground state S^{14+}, only the capture-with-excitation process is possible. For S^{15+} nearly all of the K radiation is believed to result from high-n-state capture, while for S^{16+} this is the *only* possible K-radiative decay mode. Thus, it is seen that σ_{CAPRAD} increases by more than three orders of magnitude (primarily due to high-n-state capture) in going from $q = 13+$ to $16+$.

Two processes which compete with capture with excitation and which cannot be distinguished from the measured coincidences in this experiment are (1) single capture following excitation in the same collision and (2) double capture following ionization in the same collision. We have estimated the probabilities for these two-step competing processes and find that single capture following excitation is by far the biggest competitor accounting for *at most* 15% of the coincidence events of interest.

Also shown in Fig. 1 is the cross section for K radiation following double capture by S^{15+} ions. This cross section is seen to be about an order of magnitude lower than that following single capture. This double-capture radiative recombination mechanism was measured only for inci-

TABLE I. Cross sections for K x-ray emission following electron capture and total cross sections for single and double capture by 70-MeV S^{q+} ions incident on Ar.

Incident	σ_{CAPRAD} (kb)		$\sigma_{q,q-n}$ (10^{-18} cm^2)		Y_{COINC}/Y_{SINGLE}	
q	$q-1$	$q-2$	$q-1$	$q-2$	$q-1$	$q-2$
13	3.7± 1.1	···	9.55±0.96	1.67±0.17	0.17±0.02	···
14	150± 45	···	18.2±1.8	3.64±0.36	0.43±0.03	···
15	2200± 660	300±90	16.7±1.7	3.33±0.33	0.52±0.02	0.24±0.01
16	4500±1350	···	15.2±1.5	7.27±0.73	0.67±0.05	···

dent S^{15+} ions.

We know of no theoretical calculations with which to directly compare our measured capture-with-excitation cross section for 70-MeV S^{13+} ions. If we assume, however, that this process approximates dielectronic recombination then we can get an order-of-magnitude comparison with theory from the calculations of Hahn[5] for Li-like Ar ions. A 70-MeV sulfur ion has a velocity of 2.06×10^9 cm/sec which corresponds to an electron energy of 1.2 keV. From Hahn[5] the dielectronic recombination *rate* for 1s excitation of Ar^{15+} is 2.5×10^{-13} cm^3/sec. This gives an *average* cross section for dielectronic recombination of 1.2×10^{-22} cm^2. This is the cross section for a single electron. If we assume that all eight M-shell electrons in the Ar target atom contribute equally, then the expected cross section would be ~9.6×10^{-22} cm^2. This is to be compared with the experimental value of 3.7×10^{-21} cm^2 obtained in this work. This comparison should be considered only qualitative, of course.

We also point out that simultaneous capture with excitation is expected to be a resonant process for projectile velocities corresponding to the energy of an exiting Auger electron in the inverse process. For S^{13+} this resonant electron energy is about 1.76 keV.[6] The sulfur beam energy corresponding to this electron resonance energy (assuming the captured electron to be at rest) is then 3.2 MeV/amu $\simeq$ 100 MeV. However, calculations[7] based on the Compton profile of the target electrons[8] indicate that the width of the resonance is such that the measured cross section for 70-MeV S+Ar is about 5% of the maximum expected cross section.

The single- and double-capture cross sections for 70-MeV S^{q+} ions in Ar gas were determined from the charge-changed fractions and are listed in Table I. From these capture cross sections and the data of Fig. 1 we can obtain the ratio $\sigma_{CAPRAD}/\sigma_{q,q-n}$ which is the fraction of single- or double-capture events which result in K radiation. This fraction increases rapidly from 0.0004 to 0.3 for charge states q = 13+ to 16+. For S^{15+} we see that 13% of the single-capture events result in K radiation, while 9% of the double-capture events result in K radiation.

Finally, in Fig. 2 we show the fraction of S projectile K x rays which result from capture events as opposed to those which result from *excitation* or *ionization* events. This is just the ratio of coincidence K x rays to singles K x rays. For single capture, this ratio varies from 0.17 to 0.67 for q = 13+ to 16+. For S^{16+}, all of the x rays must result from electron capture and hence the ratio Y_{COINC}/Y_{SINGLE} should equal unity. The result plotted for S^{16+} is for single capture only, and hence K x rays following double capture are not included. The double-capture fraction was measured to be about half that found

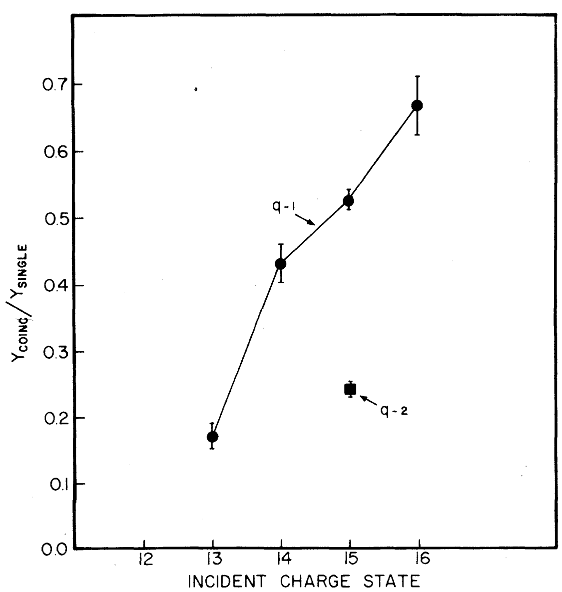

FIG. 2. Yield of S projectile K x rays which result from capture events (Y_{COINC}) compared to total S K x-ray emission (Y_{SINGLE}) which includes x rays from excitation and ionization events.

for single capture, and so we conclude that if the x rays following double capture were included, this ratio would be nearly unity.

The present results indicate that the simultaneous capture-with-excitation process can be a significant contributor to K-shell vacancy production and subsequent K x-ray emission in highly stripped projectiles. For 70-MeV Li-like S ions incident on Ar, about 15–20% of the K x-ray events occur as a result of this process.

As mentioned previously, dielectronic recombination is expected to be an important recombination mechanism for highly stripped impurity ions in a plasma. To date, there exists no direct experimental measurement of dielectronic recombination. If the capture interaction in the present work is with the loosely bound electrons in the neutral target atom, then it may be possible to simulate to some extent the recombination of free electrons in fusion or astrophysical plasmas with the corresponding processes in ion-atom collisions. Evidence for the fact that capture of loosely bound target electrons is approximately equivalent to capture of a free electron has already been obtained[9-11] in the case of radiative electron capture. This is also similar to the case of Compton scattering in which the target electrons are considered "free." If capture with excitation does approximate free-electron recombination, then this process could be used as a benchmark for comparison with theoretical calculations of individual dielectronic recombination transition probabilities.

Furthermore, if the coincidence K x rays do indeed result from interactions with the loosely bound target electrons, then the remaining K x rays can be attributed mostly to interactions with the target nucleus (see Fig. 2). This suggests the possibility that K-radiative events due to target ions and electrons may be separately determined. If a target such as H or He were used in which *all* of the target electrons may be considered "free" with respect to the fast projectile, the coincidence x rays would represent radiative transitions due to electron capture, while the remaining x rays would represent radiative transitions resulting from excitation or ionization by the positive nucleus.

In summary, we have reported the first observation of simultaneous electron capture and excitation in ion-atom collisions. In addition, K-radiative cross sections following high-n-state capture have been determined for charge states for which this mechanism dominates over capture with excitation. These results were used to determine the fraction of capture events which results in K-shell radiation, and the fraction of K x rays which result from capture events.

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