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Enhanced radiative Auger emission from lithiumlike $_{16}S^{13+}$

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The radiative Auger emission (RAE) from 0.94–6.25-MeV/u $_{16}S^{13+}$ (lithiumlike) projectiles excited in collisions with He target atoms has been measured. For these highly stripped ions the intensity of RAE photons relative to $K\alpha$ x-ray emission is enhanced by about a factor of five compared with theoretical calculations and an earlier experimental measurement for S ions with few electron vacancies. The enhancement of RAE for S^{13+} is qualitatively similar to results reported previously for lithiumlike $_{23}V^{20+}$; however, some differences between S and V are evident.

I. INTRODUCTION

The radiative Auger effect[1,2] (RAE) is a second-order multielectron decay mode of inner-shell vacancies in atoms and ions. In the RAE process an electron transition to a lower-energy state is accompanied by simultaneous emission of a photon and the ejection of a second electron into the continuum. For example, *K-LL* RAE occurs when a 2*p* or 2*s* electron fills a 1*s* vacancy while a second 2*p* or 2*s* electron is ejected from the ion along with photon emission. Figure 1 shows a schematic energy-level diagram illustrating a *K-LL* RAE transition in lithiumlike $_{16}S^{13+}$. Since the total energy difference between the discrete initial and final atomic states is shared between the emitted electron and photon, the RAE photon spectrum is nonmonoenergetic.

RAE has been observed following *K*-shell vacancy production created by photons,[1,3] electrons,[4–6] protons,[7] and α particles[7,8] in atomic targets ($8 \leq Z \leq 22$). In these experiments the measured intensities of RAE for *K-LL* transitions relative to $K\alpha$ emission are less than 1% for atoms with $Z \geq 16$, in agreement with theoretical calculations.[3,9]

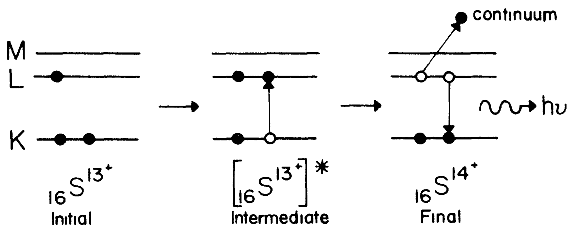

FIG. 1. Schematic energy-level diagram illustrating a typical *K*-shell excitation event in lithiumlike $_{16}S^{13+}$ with subsequent decay by a *K-LL* radiative Auger transition.

A large enhancement of the probability of RAE transitions compared to characteristic x-ray emission was recently reported[10] for 3.5–9.0-MeV/u lithiumlike $_{23}V^{20+}$ ions which were excited in collisions with a He gas target. The measured ratio of *K-Ln* ($n \geq 2$) RAE emission compared to $K\alpha$ emission[11] of $(8.2 \pm 0.9)\%$ was more than an order of magnitude larger than the expected value of about 0.4% based on theoretical calculations[3,9] and previous experimental results for ions (atoms) which had relatively few electron vacancies.[1,4–8] It was suggested[10] that the large relative RAE transition rate was related to the small number of electrons in the lithiumlike V^{20+} ions.

The present paper reports RAE transition rates for 0.94–6.25-MeV/u lithiumlike $_{16}S^{13+}$ projectiles excited in collisions with a He target. For this collision system the average value of the ratio of *K-Ln* ($n \geq 2$) RAE emission to $K\alpha$ emission was measured to be 4.3%. This result can be compared to the value[3] of 0.8% obtained from an experimental measurement for S ions (atoms) with few electron vacancies, which is in good agreement with theoretical calculations[3,9] for the few-vacancies case. Thus the observed relative RAE rates for lithiumlike $_{16}S^{13+}$ ions excited in collisions with He atoms are enhanced by about a factor of 5 relative to the rate for few-vacancies ions. This enhancement of RAE emission for S^{13+} is qualitatively similar, although somewhat smaller than that obtained[10] for lithiumlike V^{20+} projectiles.

II. EXPERIMENTAL TECHNIQUE

Since the RAE process involves the emission of an electron, those S^{13+} ions which are excited and decay by RAE will change their charge to 14+. Thus the RAE photon spectra for S^{13+} were obtained by measuring x rays coincident with single electron loss in the $S^{13+}+\mathrm{He}$ system. Characteristic $K\alpha$ and $K\beta$ x rays associated with electron loss occurring *during* the collision were also detected in the same coincidence spectra. In addition to measuring x rays coincident with electron loss, the total $K\alpha\beta$ emission along with $K\alpha+K\beta$ x rays coincident with electron capture were measured.

These experiments were conducted using the tandem Van de Graaff facilities at the Brookhaven National Laboratory (BNL) and at Western Michigan University (WMU). The acceleration-deceleration capability of the two coupled model MP tandems at BNL was utilized in order to span the large energy range (30–200 MeV) of the S^{13+} ions. Measurements at 40 and 48 MeV were made at WMU. Briefly, the experimental technique[12] for measuring x rays associated with electron loss and capture is as follows. Projectiles in a given charge state pass through a differentially pumped gas cell. After emerging from the cell, the beam is electrostatically (BNL) or magnetically (WMU) analyzed into its charge-state components. Ions which undergo electron loss or capture in the target gas are detected in a solid-state particle detector, while the x rays are detected with a Si(Li) detector mounted at 90° to the beam. The BNL measurements were made using a 200-mm^2 area x-ray detector with a 5.08×10^{-3}-cm-thick Be window, while at WMU a 30-mm^2 area detector with a 7.62×10^{-4}-cm-thick Be window was used. Coincidences between ions and x rays are measured with a time-to-amplitude converter. The non-charge-changed component of the emerging beam is collected in a Faraday cup. A capacitance manometer is used to measure the absolute pressure in the target gas cell. Data were obtained for pressures in the range 0–100 μ for each beam energy. The total x-ray yields and the coincidence yields were found to be linear with gas pressure in the range studied, indicating that single collision conditions prevailed.

Relative uncertainties in the cross sections obtained are estimated[12] to be $\pm3\%$ for the total projectile x-ray production, $\pm(5-7)\%$ for the $K\alpha\beta$ x rays associated with electron loss, and $\pm(10-15)\%$ for the RAE photons. Systematic uncertainties in target thickness and x-ray detector efficiency and solid angle lead to an additional uncertainty of $\pm25\%$ in the absolute cross sections.

III. RESULTS AND DISCUSSION

A typical x-ray spectrum coincident with incident S^{13+} projectiles which have lost an electron is shown in Fig. 2. This spectrum was taken with the thinner window x-ray detector at WMU. The nonmonoenergetic band of x rays on the low energy side of the $K\alpha$ line is attributed to K-LL RAE transitions. The vertical lines in the figure indicate the calculated positions of the high-energy edges of the K-LL and K-LM photon spectra, neglecting the resolution of the detector.

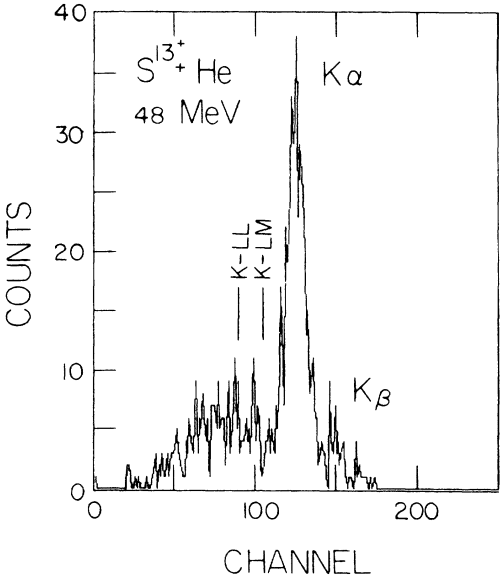

FIG. 2. X-ray spectrum coincident with single electron loss for 48-MeV $_{16}S^{13+}+\mathrm{He}$ collisions. The calculated positions (neglecting detector resolution) of the high-energy edges for K-LL and K-LM RAE photons are indicated by the vertical lines.

There are two significant qualitative differences between the x-ray spectra coincident with electron loss obtained in the present experiments for $S^{13+}+\mathrm{He}$ compared to those obtained in the $V^{20+}+\mathrm{He}$ measurements. First, in the V case there were few, if any, $K\alpha\beta$ x rays present, whereas for S the $K\beta$ to $K\alpha$ ratio is consistent with the usual ratio of about 0.15 observed in most situations. Second, for V, in addition to K-LL RAE photons, a comparable intensity of K-LM (and perhaps K-Ln for $n>3$) photons were observed. However, in the present case for S, the existence of K-Ln ($n\geq3$) photons is less evident as seen in Fig. 2.

The relative RAE transition rate can be obtained by comparing the RAE photon intensity to the intensity of characteristic x rays from the same ionic species. As previously noted RAE photons will be coincident with ions one charge state higher than the charge state in which the excitation producing the intermediate state occurred. Thus the K-LL RAE photons observed in the spectrum coincident with electron loss (exiting S^{14+} ions) originate in projectiles which undergo K-shell excitation with no change in charge S^{13+} ions.

The cross section for production of $K\alpha\beta$ x rays from projectiles which do not change charge, $\sigma^{q}_{K\alpha\beta}$, which was not measured directly, can be deduced from the total $K\alpha\beta$ x-ray production cross sections[12] by subtracting the x-ray yields coincident with projectiles which either captured[12] or lost an electron. The x-ray yield coincident with other charge states is negligible in the present case. About 20% of the total characteristic x-ray yield is associated with projectiles which are excited in the collision and change charge.

Figure 3 shows the energy dependence of the cross section for producing RAE photons σ_{RAE} along with $\sigma^{q}_{K\alpha\beta}$,

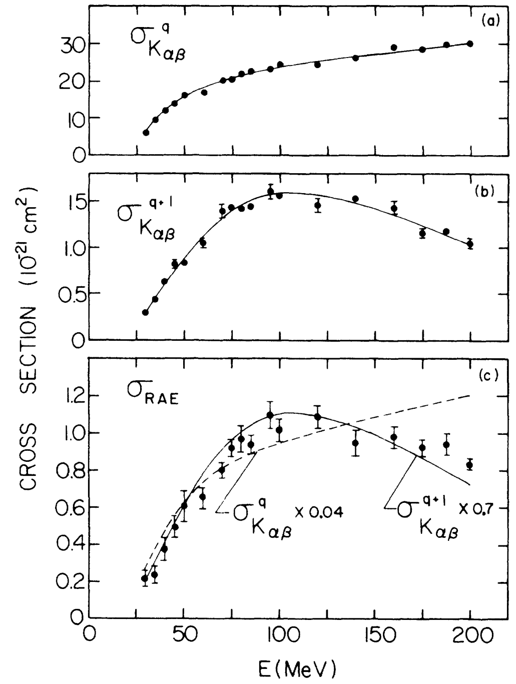

FIG. 3. Energy dependences of the following x-ray cross sections for ${}_{16}S^{13+}+He$: (a) $\sigma^{q}_{K\alpha\beta}$ for $K\alpha\beta$ x rays associated with projectiles, which do not change charge (see the text). The line is drawn through the data. Relative uncertainties are equal to or smaller than the symbols. (b) $\sigma^{q+1}_{K\alpha\beta}$ for $K\alpha\beta$ x rays coincident with single electron loss. The line is drawn through the data. Typical relative uncertainties are indicated. (c) σ_{RAE} for RAE photons coincident with electron loss. Relative uncertainties are indicated. The dashed curve was obtained by taking 4% of the curve for $\sigma^{q}_{K\alpha\beta}$ shown in (a). The solid curve was obtained by taking 70% of the curve for $\sigma^{q+1}_{K\alpha\beta}$ shown in (b).

and the cross section for producing characteristic x rays coincident with projectiles which have lost an electron $\sigma^{q+1}_{K\alpha\beta}$. In Figs. 3(a) and 3(b) the curves for $\sigma^{q}_{K\alpha\beta}$ and $\sigma^{q+1}_{K\alpha\beta}$ are drawn through the data points. The dashed curve in Fig. 3(c) was calculated by multiplying the curve through $\sigma^{q}_{K\alpha\beta}$ by 0.04, and the solid curve in Fig. 3(c) was calculated by multiplying the curve through $\sigma^{q+1}_{K\alpha\beta}$ by 0.7. It is clear that the shape of the energy dependence of σ_{RAE} closely follows that of $\sigma^{q+1}_{K\alpha\beta}$ and does not follow the $\sigma^{q}_{K\alpha\beta}$ shape at the higher energies. However, it should be noted that within the accuracy of the data the three excitation functions shown in Fig. 3(c) are not distinguishable for energies up to about 120 MeV near the maximum in $\sigma^{q+1}_{K\alpha\beta}$. For the V case[10] the measurements only covered the energy range where the excitation functions for $\sigma^{q}_{K\alpha\beta}$, $\sigma^{q+1}_{K\alpha\beta}$, and σ_{RAE} were very similar, that is, up to the expected maximum in $\sigma^{q+1}_{K\alpha\beta}$.

The similarity between the energy dependencies of σ_{RAE} and $\sigma^{q+1}_{K\alpha\beta}$ suggests that there may be a connection between the mechanisms involved in producing these two types of events. One possibility is that 2*s* ionization and 1*s* excitation are the dominant processes which produce the characteristic *K* x rays coincident with electron loss, and that 2*s* excitation and 1*s* excitation are the processes involved in producing the electron configurations which have a high RAE decay probability. If this is the case, the excitation functions for σ_{RAE} and $\sigma^{q+1}_{K\alpha\beta}$ would be very similar, since 2*s* ionization and 2*s* excitation have nearly the same energy dependence. The above interpretation is supported by the fact that in previous investigations[13] of 3.7 to 9 MeV/u $Ca^{17+}+H_2$ and He collisions and in the present measurements (see Fig. 3) $\sigma^{q+1}_{K\alpha\beta}$ is significantly smaller than $\sigma^{q}_{K\alpha\beta}$. This indicates that projectile *K* x-ray production occurs mainly through excitation of a 1*s* electron rather than 1*s* ionization.

Although it is evident from the results shown in Fig. 3 that the ratio of the intensity of RAE photons to characteristic *K* x rays associated with no charge change is not constant over the entire energy range, it is useful to determine the average value of this ratio in order to compare with theoretical calculations and the previous experimental value. The measured average value of the ratio of RAE to $K\alpha$ x rays for S^{13+} is (4.3±0.4)%. This result is a factor of 5 larger than the value of 0.8% measured[3] and calculated[3,9] for few-vacancies S ions.

IV. CONCLUSIONS

Strong enhancement of *K*-shell radiative Auger emission relative to $K\alpha$ emission has been observed for 0.94–6.25-MeV/u S^{13+} ions excited in collisions with He target atoms. However, the enhancement factor of 5 for the ratio of RAE to $K\alpha$ intensities is considerably smaller than the enhancement factor of about 20 obtained for lithiumlike V^{20+} ions in a similar experiment. Furthermore, the RAE photon spectrum for S^{13+} indicates only *K-LL* transitions with no evidence of *K-Ln* ($n>2$) radiation. This latter result also differs from that obtained for V^{20+} where contributions from higher energy *KLn* ($n>2$) RAE transitions appeared to be significant.

The similarity of the shape of the excitation functions for producing RAE photons with that for characteristic $K\alpha\beta$ x rays coincident with electron loss suggests that the electron configurations which lead to enhanced *K*-shell RAE emission result from excitations involving both 1*s* and 2*s* electrons. In Ref. 10 it was shown that the excitation function for the enhanced RAE yield for V^{23+} was similar to that obtained for $\sigma^{q}_{K\alpha\beta}$. However, as noted previously, for the range of energies measured in that case the excitation functions for $\sigma^{q}_{K\alpha\beta}$, $\sigma^{q+1}_{K\alpha\beta}$, and σ_{RAE} have similar excitation functions. Thus the V results are also consistent with the suggestion that the enhanced RAE emission results from both 1*s* and 2*s* excitations.

Theoretical calculations along with additional experimental results are needed to better understand the mechanisms responsible for the enhancement of RAE emission for highly stripped lithiumlike ions. Measurements of RAE emission for lithiumlike $Ca^{17+}+He$ collisions have been made and are currently being analyzed.

ACKNOWLEDGMENTS

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