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Projectile-charge-state dependence of K-x-ray production

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K-x-ray production cross sections have been measured in (nearly symmetric) ${}_{16}S + {}_{18}Ar$ and (very asymmetric) ${}_{16}S + {}_{2}He$ collisions as a function of the projectile charge state q ($q = 3$–16) at low incident energies of 10 and 20 MeV. The charge-state dependence is very similar in the two cases, confirming results obtained at higher incident energies. The sensitivity of such studies to different K-vacancy-production mechanisms is discussed.

We show in this paper that K-x-ray production cross sections for 10- and 20-MeV sulfur ions in nearly symmetric (${}_{16}S^{(3-16)+} + {}_{18}Ar$) and very asymmetric (${}_{16}S^{(3-16)+} + {}_{2}He$) collisions exhibit a similar dependence on the charge state of the projectile. The results are consistent with a previous study[1] at higher incident beam energy. The measured cross section is constant as long as the projectile $2p$ shell is fully occupied, then increases nearly linearly with the number of projectile $2p$ vacancies, and finally increases abruptly when the K shell begins to empty. This characteristic projectile-charge-state dependence has been observed in symmetric and nearly symmetric collisions for both light[2–4] ($A < 40$) and heavy[5–8] ($A > 60$) atomic systems and the nearly linear increase per $2p$ vacancy had been generally interpreted as both a manifestation and a signature of the $2p\pi$-$2p\sigma$ rotational-coupling model.[9]

In the previous study[1] using 70-MeV S ions and 95-MeV Ti ions, however, a qualitatively similar charge-state dependence was observed for the very asymmetric collisions: ${}_{22}Ti + {}_{8}O$, ${}_{16}S + {}_{8}O$, and ${}_{16}S + {}_{2}He$. These results suggested that charge-state dependence is not a unique signature of a particular K-vacancy production mechanism since the $2p\pi$-$2p\sigma$ rotational coupling cannot operate in a very asymmetric collision system.

In the past, it has been necessary to use high-energy projectiles in order to produce appreciable quantities of high charge-state ions. In the present study we are able to use much lower collision velocities for the same range of charge states because of the recent development of the tandem four-stage "accel-decel" method for producing low-velocity, highly charged ions.[10] This method is based on the use of two tandem van de Graaff accelerators to first accelerate ions to high energy, then strip to high charge state and finally decelerate to low energy. This makes possible the use of substantially lower ion energies where the adiabaticity conditions necessary for the application of the molecular orbital model are better fulfilled than at the higher energy of the previous experiment.

The charge-state dependence of characteristic K-x-ray production was measured in $S^{q+} + Ar$ and $S^{q+} + He$ collisions at $E_{lab} = 20$ MeV for incident charge states of $q = 3$–16 and at $E_{lab} = 10$ MeV for $q = 3$, 7, and 10. The experiments were performed at the Brookhaven National Laboratory MP Tandem Van de Graaff Facility. The low charge-state ($q = 3$–7) beams were obtained from a single MP tandem accelerator, while the high charge states ($q = 9$–16) were obtained from the dual MP tandem facility operated in the four-stage accel-decel mode.[10]

The experimental arrangement was similar to that described by Tserruya, Johnson, and Jones,[1] except that a gas-target cell replaced the gas jet used earlier. A three-stage differential pumping system was used in order to ensure single-collision conditions and to preserve the charge state of the incoming beam. The x rays were detected at 90° with respect to the beam direction with a Si(Li) detector. Typical pulse-height spectra for the 20-MeV $S^{13+} + He$ and $S^{13+} + Ar$ collisions are shown in Fig. 1. For each incident charge state, the x-ray yield was measured as a function of the pressure in the gas cell. A linear dependence was found in the normalized yield versus gas cell pressure, as expected for single-collision conditions. The relative x-ray production cross section is given by the slope of the linear portion of the yield versus pressure curve.

The main results of this experiment are shown in Fig. 2. Since the purpose, here, was to study the charge-state dependence of K-x-ray production, and not to measure absolute cross sections, no provision was made to determine either absolute gas-target thickness or the product of solid angle and x-ray detection efficiency for the Si(Li) detector. Absolute cross-section values were, however, established by normalizing the data at two points to previous independent experiments.[11,12] The two normalization constants obtained by comparison with absolute K-x-ray production cross sections for 10-MeV $S^{3+} + Ar$ and 30-MeV $S^{10+} + Ar$ agreed to

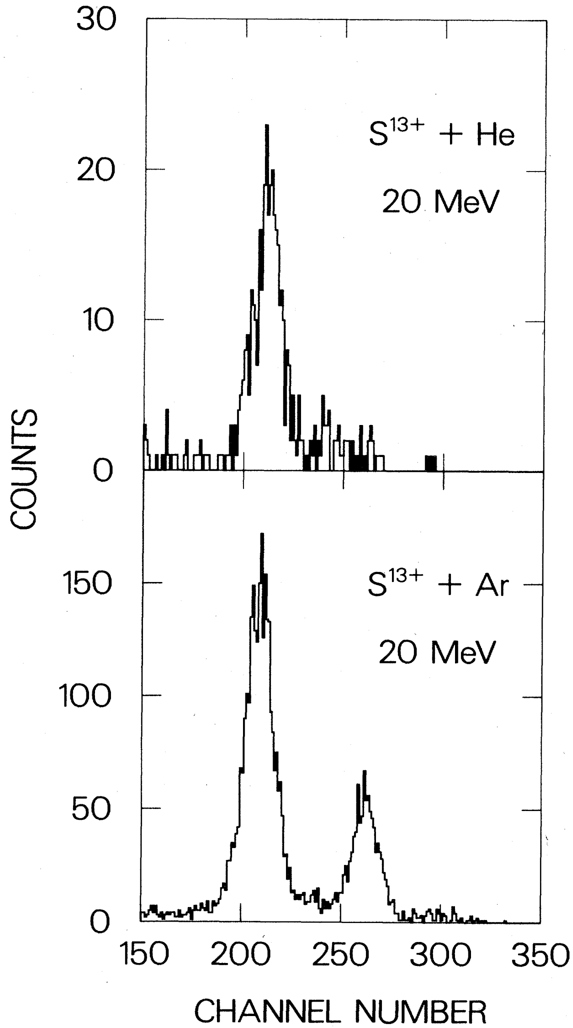

FIG. 1. Typical K-x-ray energy spectra for $_{16}S^{13+} + _{2}He$ and $_{16}S^{13+} + _{18}Ar$ collisions at 20 MeV.

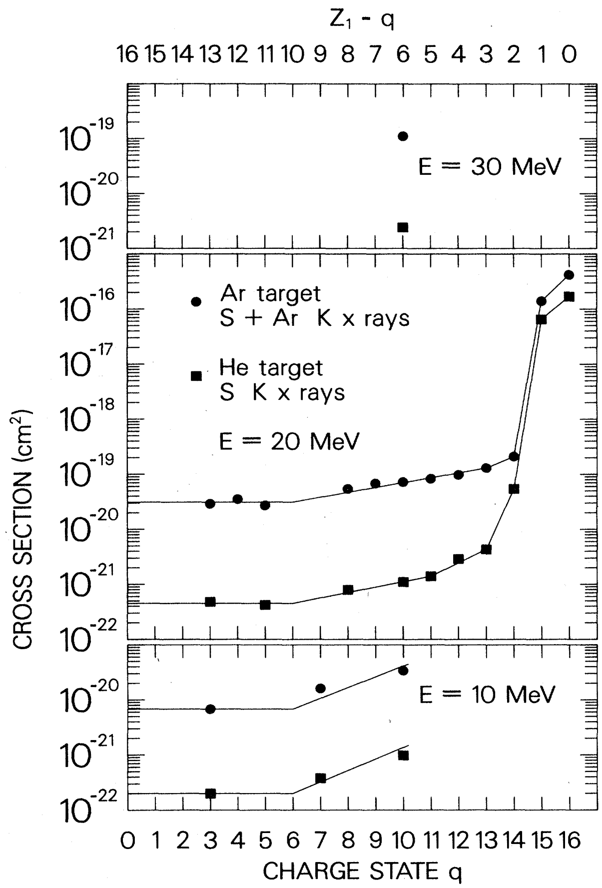

FIG. 2. K-x-ray production cross sections for $_{16}S^{q+}$ on $_{18}Ar$ and $_{16}S^{q+}$ on $_{2}He$ at $E = 30$, 20, and 10 MeV as a function of the projectile charge state q or the projectile electron number $Z_1 - q$. The curves are to guide the eye.

within 3%. Because the charge-state dependence of the fluorescence yields is not known, and neutral atom fluorescence yields are inappropriate, no attempt was made to convert to K-vacancy production cross sections.

In Fig. 2, the sharp increase observed in the cross sections for $q \geqslant 14$, when the K shell begins to empty, is attributed to electron-capture processes followed by K-vacancy decay. This aspect of the data will not be discussed, since, here, we are concerned with the charge-state dependence for $q < 13$. For these charge states the results of Fig. 2 show the characteristic $2p$-vacancy dependence; that is, the cross section is constant as long as the projectile $2p$ shell is filled and then increases monotonically with the number of $2p$-shell vacancies in the projectile. We also stress the striking similarity between the nearly symmetric S + Ar and the very asymmetric S + He collision systems.

The charge-state dependence shown in Fig. 2 could, in principle, result from the combined effect of two independent factors: the first is a dependence of the K-vacancy production mechanism on the projectile charge state; the second is the possible relative variation of the mean fluorescence yield of the post-collision ions for the different incident charge states. This second factor was considered in detail in Ref. 1, and it cannot account for the charge-state dependence shown in Fig. 2. The results are, therefore, attributed to the first factor, namely, the dependence of the K-vacancy production mechanisms on the incident charge state.

For the energies used here, 10 and 20 MeV, the adiabatic condition[9] necessary for application of the molecular orbital model is fulfilled. At $E_{\text{lab}} = 20$ MeV, $v_0/v_K \simeq 0.3$, and $v_0/v_{2p} \approx 1$, where v_0, v_K, and v_{2p} are the velocities of the projectile, K, and $2p$ electrons, respectively. The $2p\pi$-$2p\sigma$ rotational-coupling model is, therefore, expected to be valid for the nearly symmetric collisions S + Ar. As mentioned above, this model predicts a variation of the K-x-ray production cross section with the number of $2p$ vacancies carried into the collision by the projectile. This mechanism is not applicable to the very asymmetric S + He collisions. In this case the vacancy production should be dominated by the direct Coulomb ionization and excitation mechanisms. Nevertheless, the data for the two systems, shown in Fig. 2, are qualitatively similar. This confirms the previous results obtained for the same systems at higher incident energy.[1]

Similar dependences were observed by Lennard, Mitchell, Ball, and Mokler[8] for the heavier systems Cu+He, Ne, Kr, Zn, and Br+Kr at $E_{\text{lab}}=0.87$ and 1.4 MeV/amu, and they argued that differences in the magnitudes of the absolute cross sections were caused by the predominance of different excitation mechanisms in symmetric and asymmetric collision systems. For closed $2p$-shell configuration $(q < Z-10)$ the cross sections indeed differ by orders of magnitude (see Fig. 2 and Ref. 8). These differences, however, may be adequately accounted for by the approximate Z^2 scaling which is predicted by direct Coulomb processes, neglecting binding energy effects.[13] The cross-section increase per $2p$ vacancy relative to the cross section for the closed $2p$ shell is very similar in the two cases. A precise comparison of the measured cross sections with those predicted by the two models is problematic. Predictions of the rotational-coupling model depend on an accurate knowledge of the number of $2p\pi$ vacancies, which is uncertain because they can be either already present because of the charge state selected for the projectile and/or dynamically produced at an early stage of the collision. Coulomb excitation model calculations suffer from uncertainties in the binding-energy effect.

The present and previous study[1] both demonstrate that measurements of projectile-charge-state dependence are insensitive monitors of differences in K-vacancy-production mechanisms. The behavior of symmetric and asymmetric collision systems is similar, and it is difficult to compare the predictions of the two relevant models, rotational-coupling and Coulomb excitation. More sensitve experimental tools, such as the measurement of impact parameter (b) dependent probabilities, are necessary to differentiate between the different mechanisms which contribute to the K-vacancy-production cross section. Indeed, recent measurements of b-dependent K-vacancy-production probabilites $P_K(b)$, in near symmetric systems[14,15] (similar to those studied here and in Ref. 8) show clearly the operation of two alternative mechanisms. At large impact parameters the values of $P_K(b)$ were found to agree with the predictions of the $2p\pi$-$2p\sigma$ rotational-coupling model. Smaller impact parameters show the contributions from Coulomb excitation processes. Determinations of $P_K(b)$ should allow the investigation of the relative importance of the different K-vacancy-production processes.

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