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Projectile Structure Effects on Neon K X-Ray Production by Fast, Highly Ionized Argon Beams*

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An already large yield of neon K x-rays produced by a high-energy (60–80 MeV) stripped argon beam has been observed to undergo a tenfold increase when the *projectile* charge state is changed from +6 ($2p$ shell full) to ~ +14 ($2p$ shell empty). This increase may be understood qualitatively in terms of a transfer of $1s$ neon electrons to the empty $2p$ shell of the more highly stripped ions during collisions. Other possible interpretations are also discussed.

The production of K-shell vacancies in heavy-target atoms (nuclear charge Z_T) during collisions with light charged particles (nuclear charge Z_P) is well understood as a Coulomb ionization process. Both a plane-wave Born-approximation[1] model and a classical, binary-collision model[2] yield universal curves which fit existing data reasonably well so long as the structure of the bombarding projectile can be ignored. The projectile is assumed to be either a fully stripped ion, or an ion or atom whose electrons are loosely bound compared to the binding of the target K electrons, i.e., $Z_P \ll Z_T$.

The structure of the projectile becomes important when its nuclear charge is comparable to that of the target. For suitable projectile energies, a quasimolecule is formed during deeply penetrating collisions; under the appropriate circumstances, greatly enhanced K x-ray yields can be observed in the lighter collision partner, especially when energy-level matching occurs. These large yields are often due to a transfer of a K-shell electron in the lighter collision partner to an unoccupied level in a shell of higher principal quantum number (often the L shell) in the heavier collision partner. This electron promotion concept has had remarkable success in providing qualitative understanding of many collision phenomena in both symmetric[3] and asymmetric[4] collisions. It is usually assumed that the velocity of the bombarding projectile is small compared with the velocity of a K-shell electron in the target atom ($v_P < Z_T \alpha c$, where α is the fine-structure constant and c the speed of light) so that a molecular aggregate may exist for an appreciable time.

In this Letter we report some observations of K x-ray production in neon due to collisions with fast, highly stripped argon ions. The large body of data on argon + anything collisions (see work cited in Refs. 3 and 4) does *not* extend to the high-energy or high-charge states considered here. The experimental system falls outside the scope of the plane-wave Born approximation because $Z_P > Z_T$, and because the projectile contains tightly bound electrons. The experiment probes the electron promotion model in the region $v_P \sim Z_T \alpha c$, where there may be some doubt about its validity. We find that the K x-ray yield is strongly dependent upon the charge state of the projectile. The difference in yields probably results from a combination of effects, but changes in the number of $2p$ vacancies and in energy-level matching are thought to be important. In addition, a significant change in target fluorescence yield might occur if many valence-shell electrons are also lost during the collision.

Beams of Ar^{6+} at 60 and 80 MeV ($v/c = 0.057$ and 0.065, respectively) from the Oak Ridge isochronous cyclotron were passed through a differentially pumped gas cell containing neon at a few milliTorr pressure. The beam then passed into a Faraday cup where the total collected charge was measured. A carbon foil (~20 μg/cm^2) could be placed upstream from the gas target to significantly increase the average incident charge state. A Si(Li) detector viewed the target area at right angles to the beam. Detected x rays were energy analyzed and the counts stored in a multichannel analyzer. The neon K x-ray yield was measured as a function of gas pressure, projectile energy, and incident charge state.

Yield data, corrected for attenuation in the detector window and dead layers but not for solid-angle factors, are shown in Fig. 1. The full width at half-maximum (~230 eV) represents the instrumental resolution. The peak in the spectrum occurs at a slightly higher energy than where the neon K lines are expected to appear (~channel 30). This shift (see Fig. 1) may represent the detection of unresolved K x-rays from ionized neon, which are expected to have greater energy than the neutral neon x ray.[5] This peak did not appear in spectra taken with gas targets of H_2, He, and Ar.

In order to reduce uncertainties in window absorption factors and to suppress the effects of x rays observed in lower-energy channels, we take

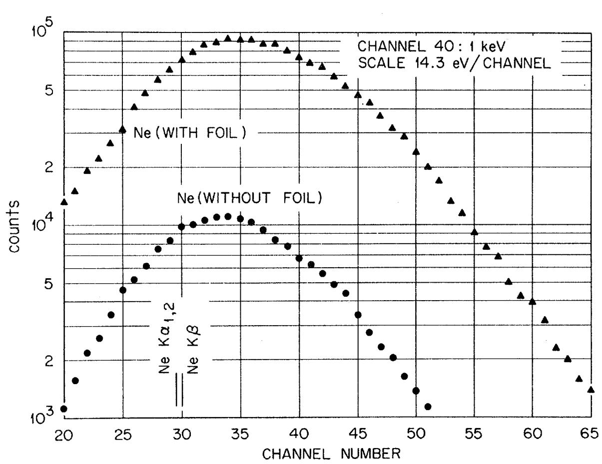

FIG. 1. X-ray spectra of neon excited by a highly stripped 60-MeV argon beam. The data have been corrected for detector-window attenuation but not for solid angle.

the observed yield to be twice the number of counts under the high-energy half of the peak. The total yield is derived by accounting for the solid angle subtended by the detector window (assuming the x-ray emission to be isotropic). The total yield, quoted per incident argon ion, per milliTorr target gas pressure, per centimeter of path is (a) 6×10^{-4} with foil, (b) 6×10^{-5} in its absence. There was no significant difference between yields obtained at 60- and 80-MeV beam energy. Corresponding cross sections could be derived if appropriate fluorescence yields were known.

These absolute yields could be in error by as much as a factor of 2 because of uncertainties in density, thickness, and mass absorption coefficient of the detector window and dead layers, and because of uncertainties in the factor connecting heavy-particle current and Faraday-cup electrical current. Even so, the yields quoted above are larger than the yield $\sim 2\times10^{-5}$ expected from a geometrical cross section $\sigma \sim \pi(r_1 + r_2)^2$, where r_1 is the neon K-shell radius and r_2 is the neutral argon L-shell radius,[6] and from the (probably inappropriate) fluorescence yield[7] of *neutral* neon (0.018). It should be pointed out that the yield obtained with foil *relative* to that obtained without foil is independent of window attenuation and solid-angle factors. Clearly, there is a large change in the target K x-ray yield when the projectile charge state is changed. To our knowledge, this is the first time such a charge-state-dependent K x-ray yield has been directly observed for the case $Z_P > Z_T$.

At these beam energies the most probable charge state emerging[8] from a carbon foil of sufficient thickness to establish charge-state equilibrium is $\sim +14$. Hence, the projectiles emerging from the foil are primarily Ar^{14+} ($2p$ shell empty) with significant numbers of Ar^{13+} and Ar^{15+} present also. With the foil removed the projectiles are nearly all Ar^{6+} ($2p$ shell full), excepting small charge-changing effects in the cyclotron beam line. Because of reduced screening, L-shell electrons in these ions are much more tightly bound than L-shell electrons in neutral argon. In fact, an unoccupied $2s2p^3P$ state of Ar^{14+} is estimated to be bound by 840 ± 5 eV, which is close to the 867-eV binding energy of the neon K shell and the 855-eV energy of the united atom (nickel) L_{III} shell.[9]

Strong electron promotion effects are often known to occur when energy levels of projectile and target happen to coincide.[4] In addition, K-

electron promotion of the lighter atom occurs when there is a vacancy in the L shell of the *heavier* collision partner prior to the collision.[4,10] Both of these conditions are met in the case Ar^{14+} on neon. Neither condition is met when Ar^{6+} is the projectile, since then the L shell of the heavier collision partner is completely filled (neglecting metastable excited ions and high charge-state beam contaminants). Furthermore, the Ar^{6+} L shell lies well above the neon K shell in energy. K-electron promotion is still possible in this case, but is probably much less likely.

A similar charge-state–dependent effect has been reported, at much lower energies, for the symmetric case Ne^{+} or Ne^{++} on Ne. Energy loss[10] and Auger electron spectra[11] rather than x-ray yields were observed in these experiments.

Recently, several groups have reported promotion effects in solid targets which do not occur in gas targets.[12-16] They attribute these effects to two-step collision processes which can occur in solids but not in gases. Because of the relatively high density of a solid as compared to a gas, it is possible for projectile inner-shell vacancies created in one collision to persist until the next collision. In the second collision these vacancies are filled by promoted electrons from the target atoms, thereby transferring the vacancy. The experiment reported here demonstrates the possible magnitude of such effects and can be interpreted as a direct observation of this two-step process.

Collisionally induced K x-ray yields are proportional to the product of the K-shell ionization cross section and the fluorescence yield. Since the latter is a property of the target, not of the projectile, and since it is a change in the charge state of the projectile which leads to the tenfold increase in yield reported above, we have suggested an interpretation based on an enhancement of K-shell ionization due to electron promotion. An alternate interpretation could be based on a possible large change in fluorescence yield of the target. Presumably such a change could occur if the neon outer shell were heavily ionized during the same collision that produced the inner-shell vacancy. (Indeed, the channel shift noted above may be evidence for this.) It is conceivable that the probability of removing some other electrons could be highly dependent upon the charge state of the projectile, but the observed channel shift appears to be approximately independent of projectile charge state. New experiments are needed to clarify these strongly charge-state–dependent effects.

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