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Projectile Charge-State Dependence of Ne K-Shell Ionization and Fluorescence Yield in 50-MeV Cl^{n+} + Ne Collisions*

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Ne K x-ray and Auger-electron production cross sections have been measured in 50-MeV Cl + Ne collisions for incident charge states of 5+ to 15+. The ionization cross section and mean fluorescence yield were derived from the data. A factor 20 rise in the x-ray cross section over the charge-state range studied is primarily due to a factor 7.2 increase in the mean fluorescence yield. The factor 2.8 rise in the ionization cross section can be explained by a decreased screening of the projectile nuclear charge.

Macdonald *et al.*[1] and Mowat *et al.*[2,3] have recently reported that x-ray production cross sections in heavy-ion collisions at a fixed energy increase rapidly with the projectile charge state: In 80-MeV Ar + Ne and 50-MeV Cl + Ne collisions the x-ray cross sections rise exponentially with the incident charge state above 6+. This important discovery clearly showed the need for more detailed studies of the ionization mechanisms in heavy-ion collisions, and placed severe limitations on the interpretation of solid-target x-ray studies since they measure only the effects of an equilibrium charge-state distribution. Related studies of multiple ionization in Ne have recently been reported by Kauffman *et al.*,[4] Burch *et al.*,[5] and Brown *et al.*[6]

A test of any ionization theory, however, requires a measurement of the total ionization cross section $\sigma = \sigma^x + \sigma^A$ ("x" for x ray, "A" for Auger) or equivalently, of the mean[7] fluorescence yield $\bar{\omega} = \sigma^x/\sigma$. The exponential rise observed in σ^x can be the result of a change in σ and/or $\bar{\omega}$. An increase in σ would require a modification of direct *inner*-shell ionization models, which to first order are independent of the charge state, or the inclusion of additional mechanisms such as electron capture. An increase in $\bar{\omega}$, on the other hand, could be due to a charge-state dependence of the *outer*-shell cross sections alone since $\bar{\omega}$ is a strong function of the number of electrons available to fill the inner vacancy.

To test this we have measured σ^x and σ^A, and consequently σ and $\bar{\omega}$, for the Ne K shell in 50-MeV Cl + Ne collisions at incident charge states of 5+ to 15+. Partial results of this work are summarized as follows: (1) Both σ and $\bar{\omega}$ increase with increasing charge state. From 5+ to 15+, σ increases by a factor of 2.8 and $\bar{\omega}$ increases by a factor of 7.2 showing that the factor 20 (2.8×7.2) rise in σ^x is primarily due to the rise in $\bar{\omega}$. The relative importance of the fluorescence yield change observed here is the opposite of that deduced previously[6] from a semiempirical analysis, based on theoretical fluorescence yields, of the charge-state dependence of the Ne x-ray spectrum. We emphasize, however, that there is no discrepancy between the present measurements and the x-ray data of Brown *et al.*[6]; the two experimental results are consistent with regard to the fraction of x-ray transitions which must originate from states having $\omega = 1$. (2) Very large L x-ray emission cross sections from the

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Cl projectile were found to be nearly independent of charge state. (3) Increase of multiple ionization of Ne with increasing Cl charge state is observed as a shift in the centroid energy of the Auger electron peak. (4) The charge-state dependence of σ can be accounted for in terms of projectile screening.

The experiment was carried out using a crossed-beam apparatus and electron spectrometer which was temporarily transported from the Hahn-Meitner-Institut Berlin to the FN tandem Van de Graaff accelerator laboratory of the University of Washington. A detailed description of the analyzer, scattering chamber, and absolute cross section measurement appears elsewhere.[8] The target gas enters the scattering chamber containing the spectrometer in the form of a jet crossing the incident projectile beam. The collision region of ~(3 mm×13 mTorr) was determined relative to measurements using a uniform pressure of 2×10^{4} Torr measured with a Baratron capacitance manometer. In the presence of the target beam, a pressure of 5×10^{-5} Torr was maintained in the region of the analyzer by a 3000-l/sec diffusion pump located below the chamber. The scattering region and analyzer were inside a Mumetal shield. Electrons emitted at $150\pm1.5°$ to the beam direction were energy analyzed with a parallel-plate spectrometer with a resolution of 2.6% full width at half-maximum and detected with a windowless electron multiplier (EMI 9603B). The transmission function of the analyzer and the efficiency of the multiplier were determined previously with a calibrated electron gun.[8] Single-collision conditions were guaranteed by the short path length and low density of the target gas. The experimental uncertainty in the absolute cross sections (± 25%) arises primarily from three roughly equal sources: electron detection efficiency, determination of the crossed-beam target density, and the absolute pressure measurements.

Projectile L and target K x rays were detected at 90° simultaneously with the electrons using a gas-flow proportional counter. The detector entrance window was 2-μm Makrofol which has a measured transmission for Ne K x rays of (44 ± 4)% and was independent of incident charge state to within these limits.

The Cl beams were produced in two charge-state regions reflecting, respectively, the equilibrium charge-state distributions at the accelerator-terminal stripper foil and at an additional stripper foil placed before the beam analyzing magnet. The 5+ to 8+ beams were obtained without the additional foil by varying the terminal voltage, with intensities on target of ~100 nA. The 12+, 13+, and 15+ beams were obtained from the 50-MeV 7+ beam by use of the extra foil, with intensities of 2 to 10 nA. At 50 MeV, 4+ or lower charge states are prohibited by the terminal voltage requirement of ≥ 10 MV; states higher than 15+ were prohibited by the present extra-foil technique since contaminant Cl beams with the same magnetic rigidity were produced. Intermediate (9+, 10+, and 11+) beams lacked sufficient intensity.

Auger-electron and x-ray spectra are shown in Fig. 1. The Auger spectra consist of two groups, one representing single K-shell plus multiple L-shell vacancies and a second, at higher energies, which is tentatively attributed to a combination of double K-shell ionization and excitation to bound states. At 15+ the intensity of the high-energy group is 23% of the total K spectrum.[9] The more prominent group is seen to move to lower energies as the Cl charge state is increased, reflecting the increase in the degree of multiple ionization. At 15+ the transitions are predominantly from Ne ions having only two or three remaining L-shell electrons.

The x-ray spectra show the Ne K x rays, which are ~60 eV higher than the normal $2p$-$1s$ transition in Ne, in addition to the intense projectile L-shell transitions. Energy shifts with increasing charge state could not be discerned with the low resolution of the proportional counter. At low charge states the origin of the projectile L

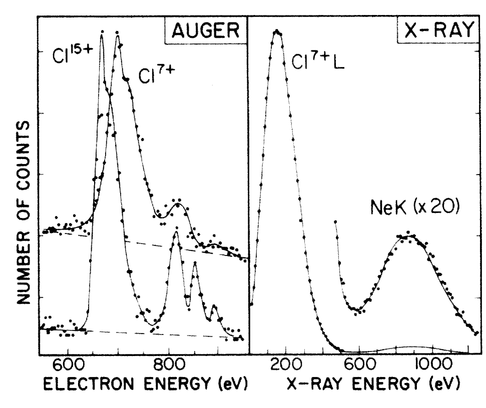

FIG. 1. Auger-electron and x-ray spectra from 50-MeV Cl + Ne collisions. The highest point in the Auger spectra corresponds to 300 counts and in the x-ray spectra to 6×10^{4} counts. The base line of the Cl^{7+} Auger spectrum is displaced for display. In the Cl^{15+} Auger spectrum the four peaks occur at energies of 682, 818, 855, and 897 eV.

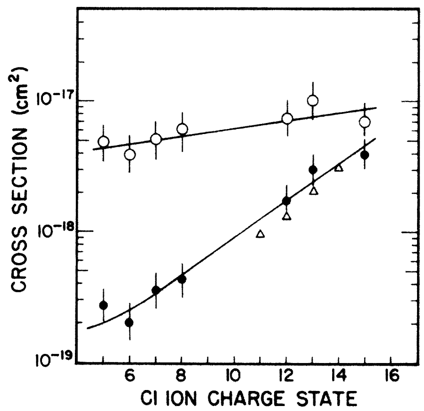

FIG. 2. Auger-electron (open circles) and x-ray (filled circles) production cross sections in 50-MeV Cl + Ne collisions versus Cl ion charge state. The open triangles are the results of Mowat *et al.*, Ref. 3.

x rays is probably L-to-M Coulomb excitation since the M shell is otherwise empty and the L shell filled (7+). For higher charge states, on the other hand, their origin must be capture into the M shell and subsequent decay to the L shell (15+). The former cross section decreases with increasing charge state while the latter increases giving rise to the nearly charge-state-independent x-ray yields. The increasing capture cross section accounts for the increasing degree of L-shell ionization of the target atoms which in turn results in an increasing K-shell fluorescence yield.

Auger-electron and x-ray production cross sections are presented in Fig. 2; the charge-state dependence of the Ne fluorescence yield is shown in Fig. 3. The value for 5-MeV proton excitation was also determined from our measurements of $\sigma^x = 1.4\times10^{-21}$ cm^2 and $\sigma^A = 86.0\times10^{-21}$ cm^2. The resulting $\omega = (16\pm2)\times10^{-3}$ agrees identically with the calculations of Bhalla, Folland, and Hein[10] verifying the lack of multiple ionization in this collision.

Neglecting excitation to higher shells and the coupling terms of open shells, the Ne configuration with the highest possible ω (less than exactly 1) is $1s^1 2s^1 2p^1$. The Hartree-Fock-Slater results of Bhalla, Folland, and Hein[10] predict that $\omega = 0.084$ for this configuration. For incident Cl^{15+}, however, the measured value of $\bar{\omega}$ is 0.36. This implies that this mean value must be made up of some components having $\omega = 1$ or, for example, configurations of the type $1s^1 2s^0 2p^1$. The measured $\bar{\omega}$ for Cl^{15+} collisions together with the

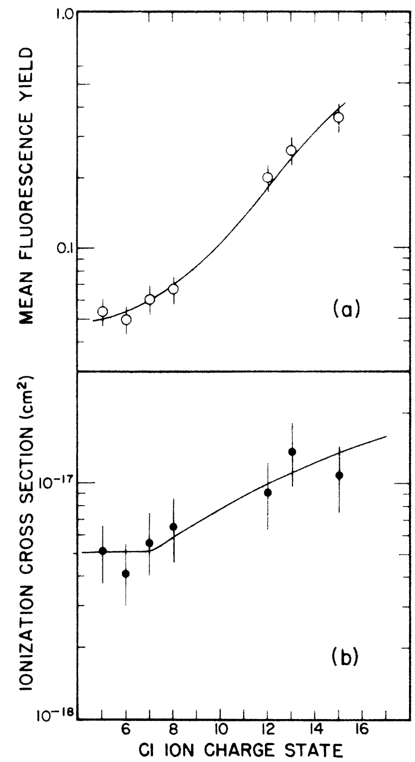

FIG. 3. (a) Mean fluorescence yield and (b) K-shell ionization cross sections of Ne in 50-MeV Cl + Ne collisions versus Cl ion charge state. The uncertainties in $\bar{\omega}_K$ are smaller than in σ_K, since $\bar{\omega}_K$ is a ratio of cross sections measured simultaneously. The solid line in (b) is the screening prediction discussed in the text. The line in (a) is an assumed interpolation to charge states not measured.

calculations of Bhalla, Folland, and Hein (made under the assumptions indicated) requires that *at least* 30% of the K-shell ionization events are accompanied by such high degrees of simultaneous L-shell ionization that Auger decay is not possible ($\omega = 1$).

The charge-state dependence of the K-shell ionization cross section is also shown in Fig. 3. Several authors[1,11] have pointed out the possible importance of inner-shell electron capture to the total ionization cross section. In 50-MeV Cl + Ne collisions the increase of σ with projectile charge state might alternatively be accounted for in terms of a change in the screening of the projectile nuclear charge.

The binary-encounter-approximation impact-parameter calculations of Hansen[12] predict that for 50-MeV Cl the Ne K-shell ionization takes place predominantly at impact parameters of

~0.15 Å. This distance is nearly equal to the Cl ion L-shell radius which is twice the Ne K-shell radius. Under these circumstances and at these large internuclear distances it is reasonable to expect electron screening to play a role. For the lower charge states the projectile M electrons do, however, overlap considerably with the target K shell and therefore would have less influence in the screening.

Neglecting contributions from the M shell, the screening effect can be tested by fitting the experimental cross sections with $\sigma_0(Z_1 - \alpha n_{KL})^2/Z_1^2$, where n_{KL} is the number of K and L electrons on the projectile and α is an effective screening constant for the nuclear charge $Z_1 = 17$. The result is shown in Fig. 3 for $\alpha = 0.75$ and $\sigma_0 = 1.6 \times 10^{-17}$ cm^2. It is interesting that σ_0 agrees with the binary-encounter–approximation prediction[12] for $Z_1 = 12$, the average equilibrium charge of Cl at 50 MeV; a similar result was observed by Macdonald *et al.*[1] The value of α is consistent with what might be expected from the Slater screening rules. An apparent change of slope at the projectile L shell is in agreement with the screening predictions. Although the screening effect cannot always be described as simply as under the present collision conditions, the results indicate that under these circumstances a direct Coulomb ionization process might itself account for a significant charge-state dependence.

We emphasize that any theoretical comparison with charge-state–dependent x-ray cross sections must include the mean fluorescence yield changes which can be expected to be nearly maximum in some cases. Estimating the effect of this change on the x-ray or Auger-electron cross sections is complicated by the necessity of knowing the fraction of the transitions having $\omega = 1$. High-resolution x-ray and Auger spectra cannot directly provide this information but combined with mean fluorescence yield measurements can be used to test theoretical predictions for specific defect configurations.

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