Characteristic x-ray production by electron bombardment of argon, krypton, and xenon from 4 to 10 keV

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As part of an experiment to study atomic-field bremsstrahlung produced by electron bombardment of rare-gas atoms in the 4- to 10-keV energy range, we have determined the characteristic x-ray production cross section for the K shell of argon and the L shells of krypton and xenon. We compare our results for the inner-shell ionization cross section with the Bethe theory, the plane-wave Born approximation of McGuire, and the classical binary encounter theory as well as with previous experiments. Using the observed validity of classical scaling over this energy range, and the known average K-shell fluorescence yield for argon, we have determined the average L-shell fluorescence yield for xenon and krypton.

INTRODUCTION

The production of characteristic x rays by the bombardment of an atom by an electron can be treated as a two-step process: first, the ionization of the inner shell by the electron; and second, the emission of a characteristic x ray as the inner-shell vacancy is filled by the transition of an atomic electron from an outer to the inner shell. The first process is characterized by a total cross section for inner-shell ionization σ; the second process by the fluorescence yield ω, which is defined as the ratio of the rate of x-ray emission to the sum of all possible atomic deexcitation processes. Hence the total x-ray production cross section σ_p can be written as $\sigma_p=\sigma_n\omega_n$, where n designates the particular inner shell in question. In this experiment, we measure σ_p for the K shell of argon and the L shell of krypton and xenon. Depending on whether one assumes σ_n or ω_n is the better known quantity, it is possible to deduce the other. So, if we assume we know ω_n, we can deduce inner-shell ionization cross sections for comparison with various theoretical models. Even if ω_n is not known it is still possible to determine the energy dependence of σ_n, since ω_n can generally be assumed to be independent of bombarding energy at least to the extent that multiple ionization of the atom by a single incident electron can be neglected. On the other hand, if we have a good model for σ_n or if we can show that it follows some scaling law, such as the classical scaling law,

$$\sigma T I_n = F(T/I_n) ,$$

where T is the bombarding energy and I_n is the ionization potential of the nth shell, then we can determine the average fluorescence yield of one shell in terms of a known, independently measured fluorescence yield.

Previous work on inner-shell ionization, the bulk of which has been on solid targets, has been reviewed by Powell.[1] There is also the work of Tawara *et al.*[2] on argon and the recent work of Hippler *et al.*[3] on xenon. Fluorescence yield measurements have been reviewed by Bambynek *et al.*,[4] and recently, the K-shell yields have been reviewed by Langenberg and Van Eck.[5] Because of the lack of a detailed theory for inner-shell ionization by electron bombardment, much of the data has been analyzed using the Bethe theory.[6] The simple Bethe formula obeys classical scaling and can be written following Powell,[1] as

$$\sigma_n T I_n = 6.51\times10^{-14} n_e b_n \times[\ln(T/I_n)+c_n]\ \text{eV}^2\,\text{cm}^2 ,$$

where n_e is the number of electrons in the nth shell, and b_n and c_n are the so-called Bethe parameters. In addition to the Bethe theory, predictions of the classical binary encounter approximation (BEA) of Vriens[7] and the plane-wave Born approximation (PWBA) of McGuire[8] are available for comparison with data at bombarding energies near threshold, although the simple Born approximation without exchange is not expected to be particularly applicable for low electron bombarding energy.

EXPERIMENT

The results of x-ray production cross sections reported here were obtained as part of an experiment to measure atomic-field bremsstrahlung or the continuous x-ray spectrum in the electron bombardment of rare-gas atoms in the energy range of 4–10 keV. Some of the initial bremsstrahlung results have been reported, and the experimental set-up has been described.[9] Essentially, the apparatus consists of a triode electron gun mounted in a vacuum chamber at right angles to a gas inlet. The gas is introduced through a 50-μm capillary array, and during operation the background gas pressure is kept at less than 2×10^{-5} Torr. The x rays produced at 90 degrees to the electron beam-gas beam interaction region are viewed by a Si(Li) photon detector through a 0.25-mil Mylar window. In addition, in the x-ray path there is a 0.3-mil Be detector window and a 0.25-mm air space between windows. Typical results for electron bombarding energy of about 6 keV are shown in Fig. 1. We have plotted scaled x-ray production cross sections versus emitted x-ray energy. The spectrum consists of an x-ray peak on the relatively flat bremsstrahlung continuum. The endpoint of the bremsstrahlung spectrum is seen at about 6 keV, which corresponds to the kinetic energy of the bombarding electrons. The data shown in Fig. 1 have been corrected for x-ray attenuation effects in the absorbers before the detector. This process has been described[10] and consists of determining the attenuation in absorbers of known thickness using a fit to the photoionization cross section data of Storm and Israel.[11] The solid lines shown in Fig. 1 are the prediction of bremsstrahlung theory of Pratt *et al.*[12] The theory, expected to be the best available, is first order in quantum electrodynamics and treats the bremmstrahlung process as a single electron transition in a relativistic self-consistent screened atomic potential. The lines shown in Fig. 1 come from an interpolation of Pratt's theory.[13] The data have been normalized to the theory in a one-parameter fit which minimizes the chi-square between theory and data.

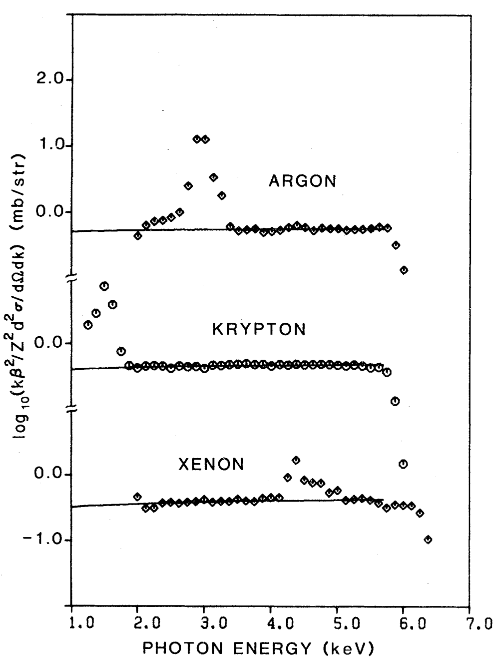

FIG. 1. Typical spectra for 6-keV electrons on argon, krypton, and xenon. In each case, $\log_{10}(k\beta^2/Z^2 d^2\sigma/d\Omega\, dk)$ is plotted versus photon energy. Endpoint of the spectrum is seen at about 6 keV. Peaks are characteristic x rays. Solid lines are Pratt's theory for the bremsstrahlung continuum.

The absolute cross section for the characteristic x-ray production is determined by normalizing to the bremsstrahlung cross section. Essentially,

$$\sigma_n = \frac{N_x}{N_B}\frac{4\pi}{\omega_n}\int_{k_1}^{k_2}\frac{d^2\sigma}{d\Omega\, dk}dk ,$$

where N_x is the number of characteristic x rays, N_B is the number of bremsstrahlung counts in the photon energy region k_1 to k_2, and $d^2\sigma/d\Omega\, dk$ is the theoretical bremsstrahlung cross section.

RESULTS AND DISCUSSION

In order to compare the results with the Bethe theory we present Fano plots of $\sigma U I_n^2$ vs $\ln(U)$ in Fig. 2, where $U = T/I_n$ for the argon K shell, the krypton L shell, and the xenon L shell. The data are well described by a straight-line fit.

The error bars are shown on the individual cross-section values where they are larger than the plotted symbol and are compounded of statistical error in the number of x-ray counts and the number of counts in the region of the bremsstrahlung spectrum used for normalization. For argon, the latter is the larger uncertainty since the bremsstrahlung rate is lower, while for xenon, the former is the larger uncertainty since there is a larger bremsstrahlung rate and smaller characteristic x-ray rate. Not included here is a $\pm10\%$ uncertainty estimated by Pratt[12] in the theoretical value of the bremsstrahlung cross section used for normalization.

If we assume a constant fluorescence yield for argon of 0.1214 ± 0.002,[5] we obtain the Bethe parameters

$$b_k = 0.634\pm0.026$$

and

$$c_k = 0.821\pm0.015$$

for the argon data, excluding the lowest U point,

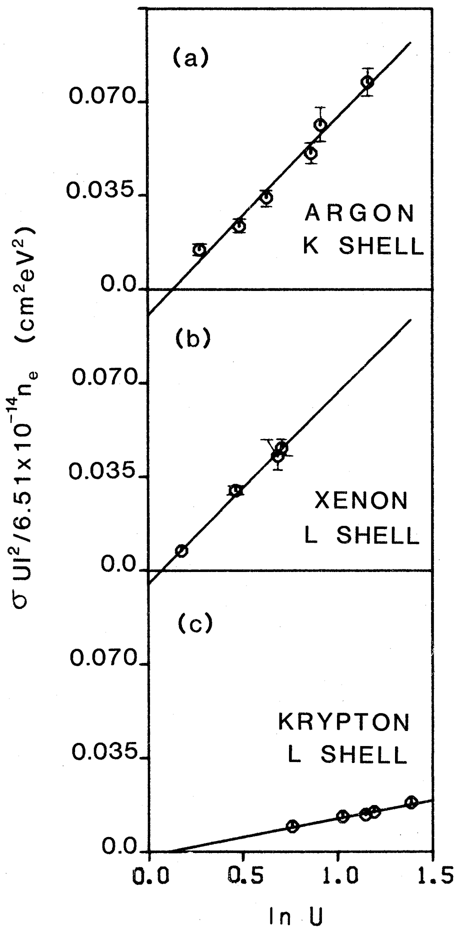

FIG. 2. Fano plots of $\sigma U I^2/6.51\times10^{-14}n_e$ vs $\ln U$ for the argon K shell (a), xenon L shell (b), and krypton L shell (c). Straight lines are least-square fits to the data. Error bars shown where larger than the plotted symbol are compounded from the statistical error in the characteristic x-ray peak and the region of the bremsstrahlung spectrum used for normalization.

which is about $2\frac{1}{2}$ standard deviations from the straight line. The chi-square for this fit was 1.2 for 3 degrees of freedom. These results are in good agreement with the typical values of Bethe parameters obtained in theories and experiments at higher U for other atoms. However, it should be noted that the agreement of the parameters may be fortuitous, since it is not likely that the asymptotic values would be obtained at such low U. Nevertheless, it is perhaps somewhat surprising that the Bethe theory continues to be a good description of the data down to values of U so near threshold. This suggests that deviations from the Bethe theory seen in experiments with solid targets[1] may be due to insufficiently thin targets. The value of b_k decreases by 21% if the data point for the lowest value of U is included in the straight-line fit. Hence higher precision data and data for U nearer to threshold would be desirable to determine the limit of applicability of the Bethe theory.

For krypton and xenon, the linearity of the data shown in Fig. 2 over the same energy region as that of argon suggests the validity of classical scaling. For xenon, the chi-square was 1.2 for 2 degrees freedom; for krypton, the chi-square was 3 for 3 degrees of freedom. Hence we have scaled the measured cross sections to that for argon and determined the average fluorescence yields. The result for xenon is

$$\omega_L = 0.112 \pm 0.006 \, .$$

While this is not in agreement with either the early result of 0.25 of Auger[14] or with 0.2 of Bower,[15] it is in very good agreement with the more recent values of 0.10 ± 0.01 of Fink *et al.*[16] and 0.11 ± 0.01 of Hohmuth.[17] The result for krypton is

$$\omega_L = 0.0205 \pm 0.0009 \, .$$

This appears to be the first modern measurement of ω_L for krypton. Previous measurements include the 1925 result of Auger[14] of 0.13 and the 1936 result of Bower[15] of 0.075. While the present value is not in agreement with these early results, it is in reasonable agreement with interpolation of measurements for neighboring atoms[18,4] and with the value expected from theoretical calculations.[19]

In Fig. 3 we plot the inner-shell ionization cross section, determined by using the above fluorescence yields versus U in order to compare with various theoretical models. The error bars shown in this case have added in quadrature the 10% uncertainty in the theoretical bremsstrahlung cross section, the statistical errors previously shown, and the uncertainty in the fluorescence yields. Also shown in Fig. 3 is data for argon by Tawara *et al.*,[2,20] which is reported with 13% errors, and data for xenon by Hippler *et al.*,[3] reported to have 15% errors. The experiments are in reasonable agreement within the errors. For comparison, we have plotted the prediction of the plane-wave Born approximation (PWBA) of McGuire[8] and the classical binary encounter approximation (BEA) of Vriens.[7] Above U of 2.0 the PWBA seems to overestimate the cross section. Perhaps it is not surprising that the agreement is poor in this energy range since the simple Born approximation without the inclusion of exchange effects is not really expected to be valid. The BEA prediction is in better agreement with the data, especially for the L shells. The formula used for BEA is

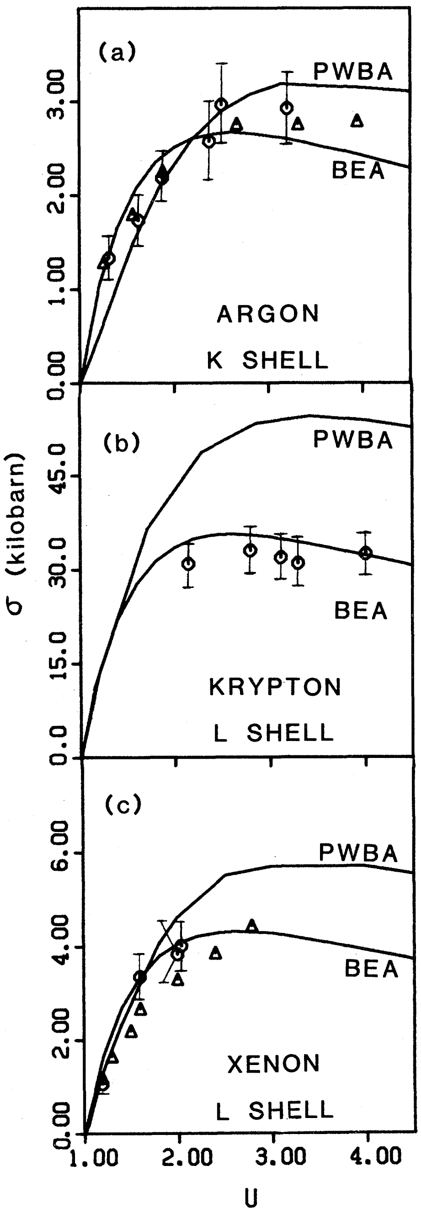

FIG. 3. Total ionization cross section σ vs U. Curves are plane-wave Born approximation (PWBA) and binary encounter approximation (BEA). In (a), circles are current data, triangles are data of Tawara *et al.* (Ref. 2). In (c), circles are current data, triangles are data of Hippler *et al.* (Ref. 3). Error bars shown represent one standard deviation and are compounded of uncertainty in the bremsstrahlung cross section used for normalization, statistical error, and uncertainty in fluorescence yield.

$$\sigma=\frac{6.51\times 10^{-14} n_e}{I^2 U(U+1+E/I)}\left[(U-1)+\frac{2}{3}\frac{E}{I}\frac{(U^2-1)}{U}-\frac{\phi \ln U}{U(U+1)}\right] \mathrm{eV}^2\,\mathrm{cm}^2$$

with $E/I=0.5$ and $\phi=1$. Somewhat different values are obtained with a different choice of these parameters, but this choice seems reasonable. The classical calculation of Gryzinski[21] (not shown) is somewhat lower than the BEA prediction shown here.

The data are also in reasonable agreement with the semiempirical model based on analysis of a large amount of K-shell ionization data mostly at higher U values.[22]

In the case of the argon K shell, the data are not precise enough to distinguish between different theoretical models. However, with a modest improvement in precision such distinction should be possible. For the krypton L shell, the data clearly favors the BEA model; while for the xenon L shell the data would need to extend to larger values of U to make a distinction between the models.

CONCLUSION

In conclusion, we have measured absolute x-ray production cross sections for electron bombardment of free gas atoms from 4 to 10 keV. We find good agreement with the Bethe theory and values of the Bethe parameters for argon in general agreement with those typically found in experiments done at higher U. We find evidence for classical scaling for L and K shells and have used this observation to determine the average L-shell fluorescence yield of krypton and xenon. The xenon result is in excellent agreement with other measurements, and the krypton result is the first modern result available. We have compared our results for the ionization cross section with other experiments and several theoretical models. In general, the data seem to be described better by the classical binary encounter model in this low energy range than by a plane-wave Born approximation.

We hope to apply the technique of normalizing to the bremsstrahlung cross section to measure the inner-shell ionization cross sections and average fluorescence yields for a wide range of atoms.

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