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K-shell ionization by relativistic electron impact

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K-shell ionization induced by relativistic electron impact has been studied for eleven elements of $22 \leqq Z \leqq 52$ in the incident-electron energy region of 300—380 MeV. The $I(K\beta)/I(K\alpha)$ intensity ratios and the ionization cross sections have been measured. The values of the intensity ratio are in agreement with those of previous experiments and the theoretical calculations of Scofield. Our results, along with those of previous experiments, prove the assumption that the intensity ratio is independent of the incident energy. The values of the cross section decrease with increasing Z. The decreasing tendency can be explained by Scofield's theory, but the experimental values lie systematically lower than the calculated values. The cross sections follow a power-law dependence, $\sigma \sim Z^{-\alpha}$, and the exponent α is evaluated to be 2.51 ± 0.13 for 300-MeV electron impact. As for the incident-energy dependence of the cross section, our results suggest a density effect in the inner-shell ionization process.

I. INTRODUCTION

There have been several experimental studies of inner-shell ionization induced by relativistic electron impact,[1-6] and a good review on this subject is the recent article by Genz.[7] In the relativistic energy region, one expects saturation in the ionization cross sections, called the density effect, because of polarization of the target medium caused by the electromagnetic field of the incident electrons. The density effect for inner-shell ionization processes has been predicted theoretically for relativistic impact electrons.[2,6,8,9] In experimental studies, however, Middleman *et al.*[1] and Ishii *et al.*[3] have not observed the density effect in the energy regions of 150—900 MeV and 70—270 MeV, respectively. In 1980, Kamiya *et al.*[5] measured the difference in increase of the cross section from 70—230 MeV for a pair of elements and they found that the rate of increase for the cross section for lighter elements is smaller than that for heavier elements. They considered their results as proof of the density effect in the inner-shell ionization process. In order to search for the density effect, Genz *et al.*[6] extended the measurement range of the ionization cross sections to the $0.9 \leq E \leq 2.0$ GeV. But their results showed that the cross sections exhibit a rising behavior with increasing impact electron energy, and they would not appear to have seen the density effect.

In the present paper, we study K-shell ionization processes in relativistic electron impact for 11 elements with $22 \leq Z \leq 52$ in the energy region of 300—380 MeV, and measure the $I(K\beta)/K(K\alpha)$ intensity ratio and the cross section for K-shell ionization. The results obtained are compared with those of theoretical calculations and other experiments.

II. EXPERIMENTAL

The experiment consists of bombarding a target with an electron beam and observing the K-shell ionization process by the detection of K x rays emitted from the target. The electron beam was obtained from the 500-MeV electron linear accelerator of the Electrotechnical Laboratory (ETL). A detailed description of the accelerator is given in Ref. 10. The electron beam impinged on the target, set in the center of the vacuum scattering chamber, and was collected in the Faraday cup. In order to reduce a pile-up effect, the beam current was kept below 1 nA.

Characteristic x rays produced in the target were measured through a 15-μm Be window in the scattering chamber with a 10 $\text{mm}^2 \times 3$ mm Si(Li) detector surrounded by lead blocks. The resolving power of the detector was 178 eV (full width at half maximum) at 5.9 keV with the 6-μs shaping time of the spectroscopy amplifier. The efficiency of the detector was determined by using standard radioactive sources such as ^{55}Fe, ^{57}Co, ^{109}Cd, and ^{241}Am.

The targets of Ti, Mn, Cu, Ag, and Sn were self-supporting foils and those of Cr, Ni, Zn, Ge, Y, and Te were prepared by vacuum evaporation on 5-μm aluminum foils. Their typical thickness was a few hundred $\mu\text{g/cm}^2$.

III. RESULTS AND DISCUSSION

A typical K x-ray spectrum of Mn bombarded by 350-MeV electrons is shown in Fig. 1, which shows sufficiently a low and flat background. After the spectrum is fitted to a Gaussian peak plus a linear background, the peak area which indicates the number count of detected x rays is corrected for self-absorption inside the target, for ab-

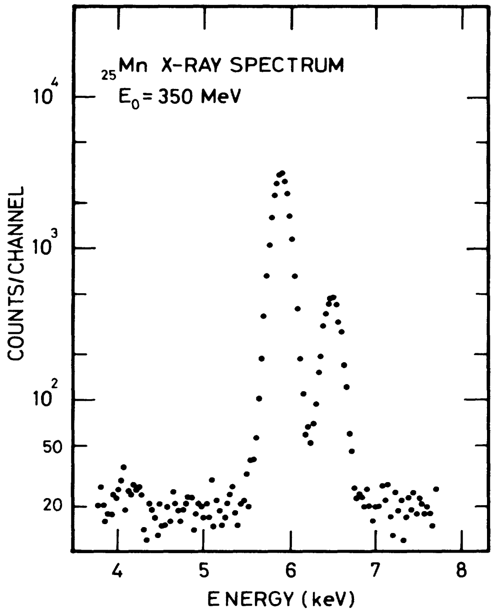

FIG. 1. Typical x-ray spectrum detected with the Si(Li) after bombarding manganese with 350-MeV electrons.

sorption in the 15-μm Be window and the 3.2-cm air path, and for the pile-up effect.

A. $I(K\beta)/I(K\alpha)$ intensity ratio

From the corrected areas of the K_α and K_β peaks, the $I(K\beta)/I(K\alpha)$ intensity ratio can be estimated. The results obtained are shown in Fig. 2 together with the theoretical curve calculated by Scofield.[11] From this figure, it can be seen that our results are in good agreement with the Scofield theory within experimental accuracy. But, the experimental values seem to be a little higher than the theoretical ones above on atomic number of 39.

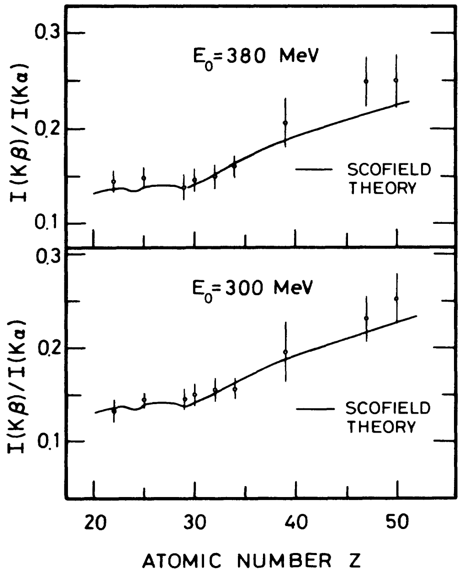

FIG. 2. $I(K\beta)/I(K\alpha)$ intensity ratio for electron impact as a function of the atomic number. The solid curve is the theoretical prediction of Scofield (Ref. 11).

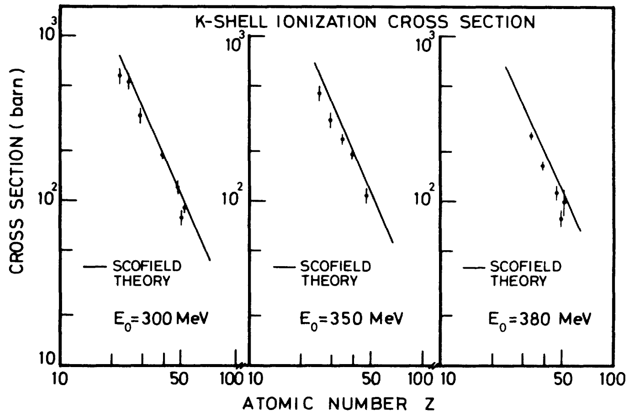

FIG. 3. K-shell ionization cross section as a function of the atomic number for 300-, 350-, and 380-MeV electron impact. The theoretical curve is calculated by Scofield (Ref. 9).

Measurements of the K x-ray intensity ratio for electron impact ionization have been performed in the energy regions of about a hundred keV[12,13] and about a hundred MeV.[1,14] In these energy regions, no dependence of the intensity ratio on the bombarding energy has been found. Our results are found to be in good agreement with the previous experimental results[12,14] and prove the assumption that the intensity ratio is independent of the incident-electron energy.

B. Cross section

The K-shell ionization cross section is obtained by the following equation:

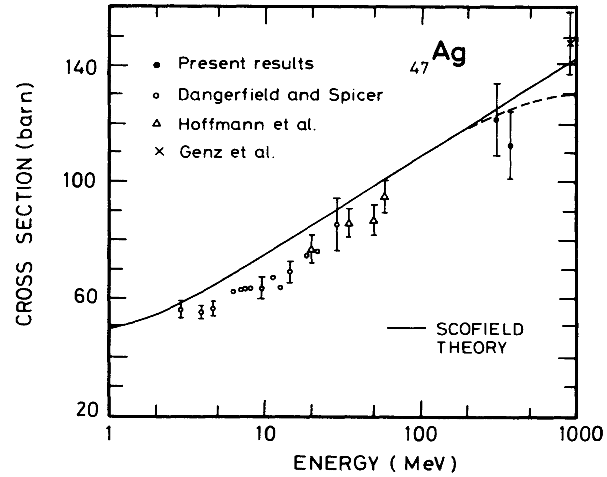

FIG. 4. Comparison of experimental values for K-shell ionization cross section by electron impact for silver targets. The solid curve is the theoretical prediction without the density effect and the dashed curve includes the density effect (Ref. 9).

$$\sigma_K=\frac{N_K}{(Q/e)(t/\sin\theta)(N_A/A)\epsilon\omega_K}\ , \tag{1}$$

where N_K is the number of detected x rays corrected for absorption and pile-up effect, Q is the total charge transmitted to the target (coulomb), e is the elementary charge: 1.602×10^{-19} (coulomb), t is target thickness (g/cm^2), θ is the angle between the target and beam direction (45°), N_A is the Avogadro number: 6.02×10^{23} (mol^{-1}), A is the atomic weight (g/mol), ϵ is the overall detection efficiency, and ω_K is the K fluorescence yield.[15]

In Fig. 3 the cross sections for the K-shell ionization are plotted as a function of atomic number Z for the incident-electron energies of 300, 350, and 380 MeV. The theoretical curves by Scofield[9] are also shown in Fig. 3. Our results show that the cross section decreases with increasing atomic number Z, that the decreasing tendency is in agreement with the Scofield theory, but that the experimental values are a little smaller than the theoretical predictions. The Z dependence of the ionization cross section is found to be a power law $\sigma\sim Z^{-\alpha}$. The exponent α is determined by a linear-squares fit of the data plotted in a double logarithmic representation. We have obtained the value of $\alpha=2.51\pm0.13$ for 300-MeV electron impact. Middleman *et al.*[1] reported that the exponent is approximately 2.70 and is constant over the incident-electron region of 150—900 MeV. According to Hoffmann *et al.*,[4] the exponent is estimated to be 2.45 ± 0.02 for 50-MeV electron impact. Our result agrees well with the previous results within the experimental accuracy. From these experimental results, it can be concluded that the exponent α is independent of the incident-electron energy.

Figure 4 displays experimental and theoretical values for the K-shell ionization cross section for silver targets. The sources of the experimental points are given in Refs. 2, 4, and 6. The solid curve is the theoretical calculation without the density effect and the dashed curve includes the density effect.[9] Experimental results show that the cross section increases with increasing incident energy, that the increasing tendency is explained by the Scofield theory, but that the theoretical values are slightly higher than the experimental values. The values of the cross section seem to be overestimated by the theory. A comparison between the experimental and theoretical values calculated with the density effect shows that our results seem to confirm the density effect in the inner-shell ionization process. However, because the experimental errors, mainly ascribed to uncertainties of the total charge transmitted to the target and the target thickness, are not small, more detailed studies of the ionization cross section are necessary in order to confirm the density effect.

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