PHYSICAL REVIEW A VOLUME 37, NUMBER 3 FEBRUARY 1, 1988

Density effect in K-shell ionization by relativistic electron impact

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(Received 15 September 1987)

A measurement of the cross section for K-shell ionization by 10- and 20-MeV electrons in Mg and Al has been made. These results, together with previous measurements at 50 MeV by Hoffmann *et al.* and at 70 and 230 MeV by Kamiya *et al.*, allow the increase of the cross section with energy to be defined. The results are found to support the claim of a density effect by Kamiya *et al.*, although the extent of the saturation is not as pronounced as first believed.

I. INTRODUCTION

For relativistic electron impact, the theoretical cross section for the inner-shell ionization of isolated atoms is predicted to rise logarithmically[1,2] with energy. However, in general the atoms of a target are not isolated from each other. To correct for the influence of the atoms surrounding the target atom, it becomes necessary to modify the virtual photon model that describes the ionization process, as was done by Dangerfield.[3] Such effects are readily incorporated by ascribing to the target medium a general frequency-dependent complex dielectric constant. The ionizing electron then induces a polarization of the medium surrounding the target atom.

The predicted influence of this polarization on the cross section is negligible at low energies up to 50 MeV for atomic numbers less than 14. However, at incident energies of several hundred MeV the influence of the polarization becomes dominant and a saturation of the cross section is predicted. This phenomenon is called the density effect. Experimental studies have been reported by several authors,[4–9] using targets of relatively high atomic number $29 < Z < 82$. The incident energies have ranged from threshold up to 0.9 GeV, yet, no evidence of a density effect was reported.

The first evidence of a density effect was reported by Kamiya *et al.*[8] for the light elements: Na, Al, and Cl, in measurements made only at 70 and 230 MeV. A comparison between these measurements and the theoretical predictions,[1] for the case of an isolated atom, show the experimental values to lie systematically lower. It is evident from these measurements that the agreement is improved when one allows for the influence of the polarization of the target medium.

In a more recent measurement by Genz *et al.*[9] the incident energy was extended from 0.9 to 2.5 GeV with targets of Ag, Ni, Cu, and Au. These cross sections were still found to exhibit a rising behavior as described by the low-energy scaling law and do not show any sign of the saturation, predicted by Dangerfield, and observed by Kamiya in the lighter elements $Z < 17$. The absence of a density effect in the measurements by Genz *et al.* was investigated in a paper by Amundsen,[10] which indicated that a density effect should not be expected to appear for x-ray energies greater than approximately 1.5 keV (i.e., $Z > 13$). The explanation of Amundsen was subsequently disputed by Bak *et al.*,[11] who claimed to find such a density effect in K-shell ionization in Al and Cu by pions of momentum 2 GeV/c. These authors postulated that the failure to observe the density effect in electron-induced K-ionization as due to "target thickness effects in connection with transition radiation."

It is evident from the published work on K-shell ionization cross sections that there is a shortage of relativistic data for low-Z target elements, with which to define accurately the shape of the cross section for the targets used by Kamiya. The present paper therefore reports measurements of the K-shell ionization cross section for the elements Mg and Al at the bombarding energies, of 10 and 20 MeV. The results obtained are compared with the theoretical calculations of Kolbenstvedt,[1] and finally, with previous measurements of Hoffmann *et al.*[6] at 50 MeV and Kamiya *et al.*[8] at 70 and 230 MeV, thereby permitting the rising section of the cross section to be established. Deviations from this rise at higher energies could then be interpreted as evidence of a density effect.

II. EXPERIMENTAL DETAILS

The experiment consisted of bombarding thin foils of magnesium and aluminum with a beam of electrons from the University of Melbourne betatron at energies of 10 and 20 MeV. The energy spread in the beam has been measured to be less than 10 keV. Beam currents of electrons extracted from the betatron were of the order 10^{-12} A at the target. The electron beam is deflected through 15° by a single-dipole bending magnet and transported to the target chamber, being focused with a system of quadrupole lenses. To minimize the bremsstrahlung background radiation detected extensive shielding, as well as a counting gate of 40 μs, was employed. The accumulated charge was collected in a Faraday cup. Loss of charge due to scattering of the electron beam outside the entrance aperture to the Faraday cup by the targets was corrected for and found to be approximately 2% and 3% for magnesium and aluminum, respectively, at 10 MeV.

The characteristic atomic deexcitation K x rays were observed with an Ortec model SPL-06165 lithium-drifted silicon x-ray detector with an active diameter of 6 mm. The detector face was coupled directly to the vacuum of the target chamber reducing the number of absorbers in the path of the low-energy x rays. The attenuation of the K x rays which occurred in the target itself and in the entrance of the Si(Li) detector was calculated from known x-ray absorption coefficients. It has been found that the detector efficiency can vary significantly from the low-energy x-ray region up to 3 keV, since ice buildup on the detector face causes attenuation of the K x rays. To determine the detector efficiency for the x rays of interest a procedure described by Cohen[12] was used, and gave an absolute detector efficiency of 42% and 58% for the magnesium and aluminum K x rays, respectively.

The x-ray production cross sections obtained were converted into the ionization cross sections using the values of fluorescence yield of Bambynek *et al.*[13] The adopted fluorescence yields are consistent with those of previous experiments. Total errors of the absolute cross section were calculated to be 15%. Errors in the fluorescence yield have not been included.

III. RESULTS AND DISCUSSION

The measured values of the cross sections are summarized in Table I. In Fig. 1 the cross sections for K-shell ionization are plotted as a function of incident electron energy. Previously measured values at 50 MeV by Hoffmann *et al.* and 70 and 230 MeV by Kamiya *et al.* are displayed; also shown is the theoretical calculation of Kolbenstevdt, the dashed line is the predicted saturation effect that results when one considers the possible dielectric properties of the target medium. The Stobbe photoelectric cross section[14] has been used to calculate the contribution to the cross section from the distant collisions.

It is evident from these measurements that the theoretical predictions for the cross section are consistently higher than the experimental values. This discrepancy can be readily reduced if one considers the relatively arbitrary choice of the free parameter b_0 (b_0 being the parameter defining the interaction boundary between the distant and close collisions in the virtual photon theory; this is usually taken to be the K-shell radius). The effect of b_0 on the cross section has been investigated by Dangerfield.[15] For energies greater than 1 MeV the variation in the cross section is approximately a constant additive correction to the magnitude, with the slope of the cross section with energy being larger for larger b_0. This is consistent with the present experimental results.

TABLE I. Experimental details and results.

Target	Thickness (μm)	Fluorescence yield	σ (barns) (10 MeV)	σ (barns) (20 MeV)
Mg	2.78	0.0272	874±140	1186±190
Al	2.85	0.0357	885±142	1256±201

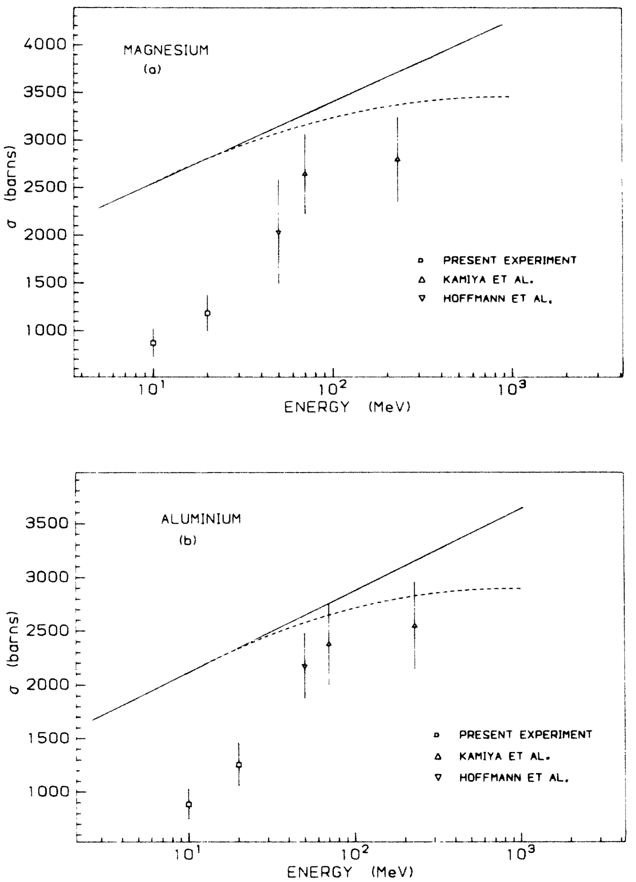

FIG. 1. The K-shell ionization cross sections for (a) Mg and (b) Al. The solid line is the theoretical calculation of Kolbenstvedt reported by Kamiya *et al.* The dashed line includes the density effect using the dielectric constant given by Kamiya. The experimental points are at 10 and 20 MeV, with previous measurements at 50 MeV by Hoffmann *et al.*, 70 and 230 MeV by Kamiya *et al.*

Figure 1 shows that the rise of the cross section with energy has been established with the present measurements. There is a deviation of the 230-MeV measurement from the rise defined by the lower energy points. The fact that the deviation is consistent in both the Mg and Al measurements is evidence indicating the possible beginnings of a density effect. The results are therefore found to be in agreement with the conclusions reported by Kamiya *et al.*, although the extent of the saturation is not as pronounced as first believed.

Clearly, the situation remains indefinite, with the present conclusions depending solely on the 230-MeV measurements of Kamiya. Further work, both experimental and theoretical, is required in order to resolve the problem. In particular, experimental studies are needed in the region above 200 MeV for light atoms where the saturation becomes dominant and departures from the logarithmic rise will be more readily identifiable.

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