Measurement of Cu K-Shell and Ag L-Shell Ionization Cross Sections by Low-Energy Positron Impact

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Inner shell ionization cross sections by low-energy positron impact have been measured. Development of an x-ray detector with thin Si(Li) crystals has enabled the first measurements of the absolute cross sections for the positron impacts in the energy range below 30 keV. Threshold behavior of the measured cross sections for the Cu K shell and Ag L shell are compared with the theoretical results of Gryzinski and Kowalski [Phys. Lett. A **183**, 196 (1993)] and Khare and Wadehra [Can. J. Phys. **74**, 376 (1996)]. Good agreement has been found for the Cu K shell, while the experimental values for the Ag L shell were found to be smaller than the corresponding theoretical results.

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When electrons with energies higher than the threshold energy are incident on a target, characteristic x rays are emitted by inner-shell ionization. A number of experimental and theoretical investigations have been carried out to determine inner-shell ionization cross sections [1–6]. Recently, large discrepancies between experimental results and the values predicted by the binary encounter approximation theory [2] and the atomic rearrangement theory [3] have been reported for the In and Sn L x-ray production cross sections in the electron energy range from near threshold to tens of keV [6].

Inner shell ionization by positron impact have also been studied actively [4,5,7–17]. Schneider *et al.* [16] have measured the absolute cross sections for Ag K-shell and Au L-shell ionization observing a different behavior of positron and electron impact near the threshold.

The ionization process for positron impact differs from electron impact because of the change in the sign of the Coulomb interaction and the absence of the exchange interaction. These effects are more pronounced at lower energies. Thus, the information on the threshold behavior for positron impact in the energy range below tens of keV will provide information on Coulomb interaction and exchange interaction which are crucial but not yet understood completely in this energy range. It will be further useful to investigate whether the discrepancies between theories and experiments in the L x-ray production cross sections by electron impact also exist. The cross sections measured to date are, however, restricted to impact energies above 30 keV [16]. (Measurements of the cross section ratios have also been restricted to above 20 keV [12,13].) This is because the γ rays emitted from positron annihilation in the targets deposit part of their energy in the x-ray detector crystal and produce a background in the x-ray spectra [13]. Even in the case where the target thickness is comparable to or smaller than the mean-free path of the incident positrons so that most of the positrons pass through the target, a small number of positrons annihilating in flight through the target produce the background. At lower positron impact energies, more positrons annihilate in the target and thus the background becomes higher.

The background can be suppressed if an x-ray detector with a thin crystal is used [18]. In the present work, this kind of detector has been developed. It was employed to measure the ionization cross sections of Cu K-shell and Ag L-shell electrons in the positron energy range below 30 keV by detecting the characteristic x rays from thin film targets. We have also measured the x rays emitted from thick targets and estimated the cross sections using theoretical values of positron stopping power in these materials [19].

The experimental system used was a magnetically guided slow positron beam apparatus with a trochoidal $E \times B$ filter. The positrons from a 2 mCi ^{22}Na positron source were moderated in a high-efficiency electropolished tungsten mesh moderator [20] and transported to the target chamber.

The beam intensity was determined by detecting the annihilation γ rays from a thick target using a high-purity Ge detector. The intensity was $3.2 \times 10^4 e^+/\mathrm{s}$ and was almost constant in the energy range investigated in this experiment. The diameter of the beam at the target position was about 3 mm.

The x rays emitted from the targets were detected using a Si(Li) detector with crystals of 0.25 mm thickness, 1 order of magnitude thinner than those in conventional Si(Li) detectors [18]. With an energy resolution of 300 eV at 5.9 keV and effective area of 40 mm^2, the detector viewed the target perpendicularly to the incident positron beam. The detection efficiency was calibrated by counting the x rays from a ^{55}Fe standard source which was placed at the target position.

The targets were Cu and Ag thin films deposited on 10 μg/cm^2 (40 nm) carbon films supported by an aluminum holder with an aperture of 8 mm in diameter. The thicknesses of the deposited films were 6.7 $\mu g/cm^2$ (7.5 nm) for Cu and 7.6 $\mu g/cm^2$ (7.2 nm) for Ag. These thicknesses are similar to or smaller than the mean-free paths of 10 keV positrons in the targets used [19]. The targets were mounted at an angle of 30° to the incident beam direction. Tilting the sample increases the effective thickness of the foil. But if the angle is smaller than 30°, the x rays emitted in the direction of the detector placed at a right angle to the beam direction are blinded by the sample holder. The average energy loss of the 10 keV positrons while passing through the tilted targets was less than 1%. The fraction of positrons annihilating in the films was less than 3%.

The positron beam was directed onto the film but not onto the aluminum holder using the steering coils. The incident positron energies were set at an interval of 5 keV in the energy range below 30 keV.

The x-ray signals from Cu and Ag thick targets (0.1 mm in thickness) were also measured. The x rays were emitted from atoms which exist at sites deeper than the thicknesses of the thin films. In order to reduce the absorption of the x rays in the targets, the tilting angle of the targets were increased to 45° to the beam direction. The incident energies were set at an interval of 1 keV in the energy range below 30 keV.

Typical x-ray spectra obtained at 15 and 30 keV positron impact for both thin and thick Cu and Ag targets are shown in Fig. 1. The data for the thin film targets [1(a) and 1(b)] were acquired over a period of 1.6×10^5 s, and those for the thick targets [1(c) and 1(d)] were accumulated for 1×10^4 s. In the case of the thin films, the background signals of the spectra at 15 keV are higher than those at 30 keV due to the larger fraction of positrons annihilating in the film at the lower energy.

If we assume that the emission of the characteristic x rays is isotropic, the inner-shell ionization cross section, Q, is obtained from the following equation:

$$N_x = nlQN_0\varepsilon\omega, \quad (1)$$

where N_x is the x-ray count rate, n is the number density of the target atoms, l is the target thickness, N_0 is the beam intensity, ε is the detection efficiency of the x ray, and ω is the fluorescence yield. The K-shell fluorescence yields for various elements have been measured by many authors and reliable values have been obtained. Here the "best fitted values," compiled by Bambynek *et al.* ($\omega_K^{Cu} = 0.443$) [21], are employed. Unfortunately, no such reliable values are available for the mean L-shell fluorescence yield. Therefore, we have used the value obtained by fitting a polynomial to a set of selected values for various elements for Ag L shell, i.e., $\overline{\omega}_L^{Ag} = 0.062 \pm 0.009$ [22]. The values of Q thus determined are plotted in Fig. 2 against the positron impact energy.

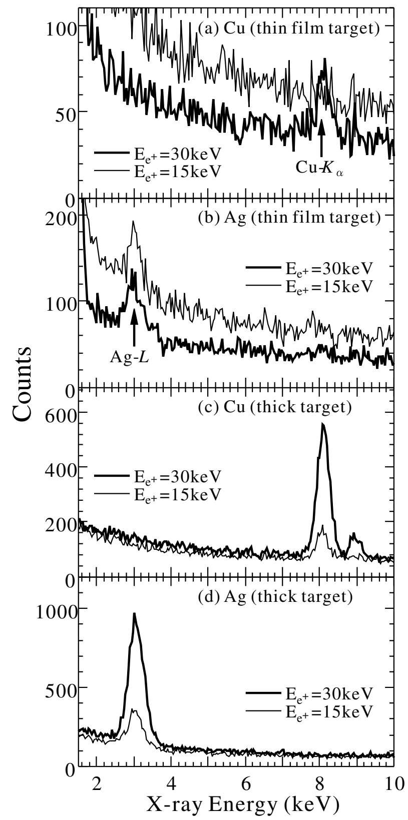

FIG. 1. X-ray energy spectra for (a) Cu thin film, (b) Ag thin film, (c) Cu thick target, and (d) Ag thick target. Spectra taken at 15 and 30 keV positron impact energies are shown.

The errors of the present results for Cu K shell are mainly due to statistical error, error in the estimation of the efficiency of the x-ray detector, and error in the determination of the target thickness. For Ag L shell, the uncertainty in fluorescence yield also contributes to the total error.

We have also estimated Q using the x-ray spectra from the thick targets. If we neglect the inner-shell ionization by secondary electrons emitted in positron impact and backscattered positrons, Q is related to N_x for the thick targets as follows:

$$N_x\left(E + \frac{\Delta E}{2}\right) - N_x\left(E - \frac{\Delta E}{2}\right) = nl'QN_0\varepsilon\omega, \quad (2)$$

where l' is the path length over which the positrons lose their energies from $E + \frac{\Delta E}{2}$ to $E - \frac{\Delta E}{2}$. This is equal to $\Delta E/P$, where P is the positron stopping power in the materials. The values for Q determined with the theoretical results for P [19] are shown by open circles in Fig. 2. Negative values for Q resulting from the statistical uncertainty of N_x are not visible in this figure.

Theoretical inner-shell ionization cross sections for the positron impact have been calculated in the binary encounter formalism by Gryzinski and Kowalski [4] and in the plane-wave Born approximation with Coulomb and

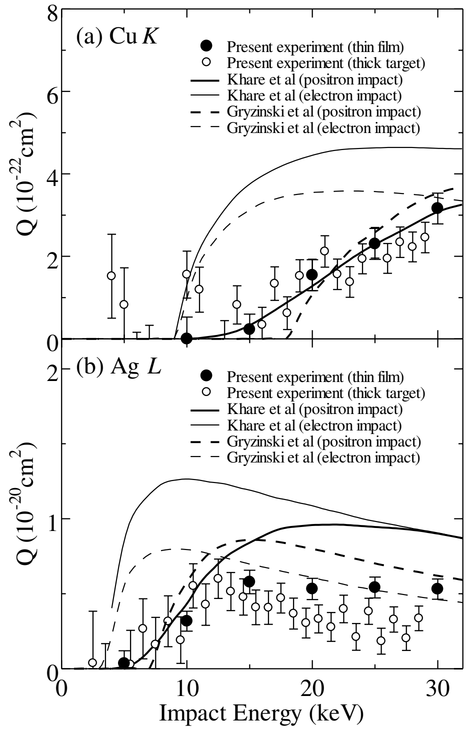

FIG. 2. Cu K-shell and Ag L-shell ionization cross sections plotted against the positron impact energy. Results for thin films and thick targets are plotted. Theoretical values for positron impact and electron impact calculated in the binary encounter formalism [4] and the plane-wave Born approximation with Coulomb, relativistic, and exchange corrections [5] are also shown.

relativistic corrections by Khare and Wadehra [5]. Their results are also plotted in Fig. 2.

A good agreement is obtained between the present results for Cu K shell using the thin film target and the theoretical results. The thick target results, though less reliable, also agree with the thin target data and the theoretical results.

For Ag L shell, although the data for the thick target shown in Fig. 2 are shifted slightly from those for the thin target, the value range is almost the same. The difference might be due to errors in the theoretical calculation for the positron stopping power, P, used in the analysis of the thick target data. A remarkable feature is that both experimental results are smaller than the theoretical predictions of Khare and Wadehra [5]. Although the deviation from the theoretical values by binary encounter formalism of Gryzinski and Kowaleski [4] is smaller, our experimental values are even smaller than their values. This might suggest that the theoretical approximation is increasingly inadequate with decreasing threshold energy and increasing target atomic number. This trend is also observed in the electron impact cross sections by Tang *et al.* [6] where the experimental cross sections for In and Sn L shell do not follow the prediction by the binary encounter formalism [2], although the values for Re are almost consistent with the formalism. The experimental data for low-energy positron and electron impacts for other targets are necessary in order to investigate the discrepancy.

In the data analysis, we have assumed that the emission of the characteristic x rays is isotropic. The discrepancy between the present results and the theoretical values for Ag L shell appears too large to be attributable to the anisotropic angular distribution of characteristic x rays following an inner-shell vacancy with quantum number $j > \frac{1}{2}$ [23]. Several authors have reported experimental and theoretical results for the angular distribution and polarization of characteristic x rays for electron impact [24–31]. All the results for the anisotropy measured thus far are less than 10%.

In conclusion, we have measured absolute Cu K-shell and Ag L-shell ionization cross sections by positron impact in the energy range below 30 keV. The results for Cu K-shell ionization are in good agreement with the theoretical results calculated in the binary encounter formalism and those in the plane-wave Born approximation with Coulomb corrections. The results for Ag L-shell ionization are, however, smaller than both of the theoretical results. Further investigation is necessary, both experimentally and theoretically, for a better understanding of the inner-shell ionization processes by low-energy lepton impacts.

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