V. 27  \( K-, L-, \) and \( M \)-shell Ionizations by 3-40-MeV Proton Impact

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Introduction

Inner shell ionizations in the energy region \( E/\lambda U < 1 \), where \( E \) is the projectile energy, \( \lambda \) is the mass ratio of the projectile to the electron, and \( U \) is the ionization energy, have extensively been studied by many researchers. On the other hand, systematic measurements of the ionization process in the energy region \( E/\lambda U > 1 \) are still scarce.\(^1\) It had been considered that, in the region \( E/\lambda U < 1 \), the ionization occurs by the Rutherford scattering between the projectile and an orbital electron which is regarded as free, namely the close collision. In the region \( E/\lambda U > 1 \), however, detailed discussions on the ionization mechanism have not been done.

We have measured the production cross sections of Al-K, Cu-K, Y-L, Sn-L, Au-M and Bi-M x rays for proton impact over the incident energy range 0.5-40 MeV and the results are compared with calculations of the plane-wave Born approximation (PWBA) and the binary-encounter approximation (BEA). It is found that, in the high energy region, distant collisions become effective in addition to close collisions. The former process can be treated as a photo-ionization by virtual photons induced by the projectile. In the present work, the ionization cross sections for distant collisions are separated from those for close collisions on the basis of the PWBA theory, and the results of calculation are found to be quite consistent with the experimental results.

Theoretical

In accordance with the PWBA theory, the inner-shell ionization cross section is given by

\[
\sigma_n = 8\pi z^2 \frac{a^2}{z_S} \frac{1}{\eta_S} \int \frac{dW}{W} \int \frac{dQ}{Q} P_n(W, Q) .
\]

Here \( Z \) is the projectile charge, \( z_S \) is the effective atomic number, \( a \) is the Bohr radius, and \( \eta_S, W, Q \) are defined by

\[
W = \frac{\Delta E}{Z_S^2 \Theta} , \quad Q = \left( \frac{\hbar q}{2m} \right)^2 \frac{1}{Z_S^2 \Theta} , \quad \eta_S = \frac{me}{\hbar^2} \frac{E}{Z_S^2 \Theta} ,
\]

where \( E \) is the energy transfer and \( \hbar q \) is the momentum transfer. The generalized oscillator strength (GOS) is defined by
\[ F_n(W, Q) \equiv \sum_{n'} \langle n' | e^{-i\mathbf{Q} \cdot \mathbf{P}_j} | n \rangle, \]

where \( \mathbf{P}_j \) is the position vector of the j-th electron. Information about the target atom is involved in GOS, and the quantity can generally be expressed by \(^2,3\) \( \)

\[
F_n(W, Q) = 3^4 W \frac{\exp\left(-\frac{\tan^{-1}\left(\frac{2K/n}{Q-W+2/n}\right)}{1-\exp(-2\pi/K)}\right)}{\sqrt{\frac{(W-Q)^2+(2/n)^2}{(2n+1)}}} \times \prod_j A_j^n(Q)(W-Q)^j.
\]

(3)

where \( K \) is the wave number of the ejected electron, \( n \) is the principal quantum number, and \( A_j^n(Q) \) is a polynomial of \( Q \). The GOS for a \( K \)-shell is shown in Fig. 1 as a function of \( \log Q \) together with that obtained from BEA, which includes only close collisions. It is found from this figure that the peak appearing at high momentum transfer near \( Q = W \), known as the Bethe ridge, corresponds to close collisions. On the other hand, the plateau in the low-\( Q \) region comes from the fact that \( F_n(W, Q) \) can be approximated by an optical oscillator strength and the ionization is produced by the photoelectric effect, namely, distant collisions. It is expected from the kinematics, from which the integration limits are determined, that this low-\( Q \) component would become effective to the ionization in the energy region \( E/\lambda U > 1,4,5 \)

To investigate the contribution of these two processes to the ionization cross section, we divided the polynomial \( A_j^n(Q) \) into

\[
\sum_j A_j^n(Q) : \text{distant collisions} \quad \sum_j (A_j^n(Q) - A_j^n(0)) : \text{close collisions}.
\]

(4)

The physical meaning of this condition is given in reference (5). The functions \( FC.C. (W, Q) \) and \( FC.C. (W, Q) \) thus obtained are represented in Fig. 2. By using \( FC.C. (W, Q) \) and \( FC.C. (W, Q) \), inner-shell-ionization cross sections corresponding these two mechanisms can be calculated from eq. (1).

Comparisons between the experiment and the theories

Theoretical results thus obtained for Al-K are shown in Fig. 3, together with the experimental results. The general experimental setup is described in references (4) and (5). The experimental K-shell-ionization cross sections agree well with the prediction from the PWBA, especially in the region \( E/\lambda U > 1 \), whereas the BEA prediction shows a systematic deviation. This discrepancy can clearly be understood by the contribution from the distant collision. For Cu-K shell ionization, we have the similar result to that for Al-K.

The data on Y-L and Au-M are shown in Figs. 4 and 5, respectively.
Considering these two mechanisms, it is predicted\(^5\) that the ratio \(\sigma^\text{D.C.}/\sigma^\text{C.C.}\) is approximately proportional to \(1/n\). The experimental results, including those for Sn-L and Bi-M, clearly show this tendency; the ratio \(\sigma^\text{D.C.}/\sigma^\text{C.C.}\) becomes smaller as the principal quantum number is larger.

Summary

K-, L- and M-shell ionization cross sections for proton impacts have been measured over the wide projectile-energy range for several elements, and the results were found to be in good agreement with the PWBA. Dividing the generalized oscillator strength of the PWBA into two parts corresponding to close and distant collisions, the ionization cross section from PWBA was separated into contributions from these two kinds of collisions. A good agreement between the experimental results and the PWBA, especially in the region \(E/\lambda U < 1\), reveals the important role of distant collisions in this region.

References

Fig. 1. The generalized oscillator strength for K shell — $F_K(w,Q)$ — obtained from PWBA and BEA is shown as a function of log $Q$; $w$ and $Q$ are the transfer energy and the transfer momentum, respectively.

Fig. 2. The generalized oscillator strength — $F_{PWBA}^k(w,Q)$ — is divided into the dashed lines — $F_{PWBA}^{C.C.}(w,Q)$ — and the dot and dashed lines — $F_{PWBA}^{D.C.}(w,Q)$ — corresponding to close and distant collisions, respectively.
Fig. 3. Theoretical calculations for the K-shell ionization of Al by proton impacts are compared with the experimental results. The dotted and the dot and dashed curves, respectively, stand for the cross sections of close and distant collisions: $\sigma^c_K$ and $\sigma^d_K$. The triangles were obtained with a Van de Graff generator and the circles were with the AVF Cyclotron.

Fig. 4. The total L X-ray production cross sections of Y for proton impact are compared with the PWBA calculation (the solid line) and the BEA (the dashed line). The dot and dashed line and the dotted line are, respectively, the PWBA cross sections decomposed into that for close and that for distant collisions.
Fig. 5. The experimental M-shell ionization cross sections of Au for proton impact are compared with theoretical predictions from the BEA and PWBA. The PWBA cross sections are decomposed into the cross sections for close and distant collisions. The circles represent the present data and the triangles show the previous experimental results of reference (6).