Multiple Inner-Shell Ionization of Aluminum Atoms by 3-15-MeV/amu Proton and $^3\text{He}^{2+}$-Ion Bombardments

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A formula of L-shell ionization probability $P_L$ is derived in terms of PWBA theory, and a scaling law based on this theory is compared with experimental results for light-ion bombardments obtained heretofore; rather good agreement is obtained. In order to compare with the PWBA calculation, intensity ratio of the satellite lines for Al-K shell $\sigma^{KL^1}_L/\sigma^{KL^0}_L$, produced by proton and $^3\text{He}^{2+}$-ion bombardments, has been measured over the projectile-energy region 3-15 MeV/amu with a crystal spectrometer.

Recently, many high-resolution studies of characteristic x rays produced by heavy-charged particle and heavy-ion bombardments have been reported, and K- and L-x lines from multiply-ionized states have been observed. Taking K-x ray lines for example, satellite lines from states accompanied with vacancies in the L-shell have been well separated. In a case of heavy-ion bombardments with a velocity equal to that of the L-shell electrons, intensities of highly L-shell ionized lines, such as KL$^4$-, KL$^5$-lines, become much more higher than that of KL$^0$ line. This fact shows the high probability of multiple ionization in a single ion-atom collision.\(^1\)

Several theories on the mechanism of multiple ionization have been published. The statistical model-binomial distribution model-proposed by Hansteen and Mosbeek has been most widely used in analyses of the satellite-line spectra.\(^2\) Many experimental results support this statistical model. In contrast to the statistical model, Russek proposed "evaporation model", where the multiple-ionization process has thermodynamically treated.\(^3\) This theory can be applied to a heavy-ion bombardment where the interaction between the projectile and the target atom is comparatively strong and the velocity of incident ion is nearly equal to that of outer-shell electrons.

While the theories of SCA\(^4\), BEA\(^5\), and PWBA\(^6\) have been developed for inner-shell ionizations, it seems that no theoretical calculations of multiple ionizations has been carried out in terms of PWBA. On the basis of PWBA, we have recently derived the cross section for KL$^1$-ionization, which is expressed by\(^7\)

$$\sigma^{KL^1}_L \approx \sigma^i_K \cdot 8P_L,$$

and

$$8P_L = (\frac{Z_T}{Z_L})^2 \times f(\frac{\delta^2_L}{\delta^2_L}, \gamma_L),$$

where $Z_T$ is the target-charge number, $f$ is a function of $\delta^2_L/\delta^2_L$ and $\gamma_L$. The other notations have been given by Merzbacher.\(^6\) Thus the value of the L-shell ioniza-
tation probability $P_L$ must approximately be scaled by plotting $P_L \cdot (Z_T \cdot \sigma_L / Z_P)^2$ versus $\sqrt{4n_L / Z_P}$. The scaling behavior of $P_L$ has been experimentally obtained by Watson and by Awaya et al. on the basis of BEA. Our present calculation cannot predict the intensity distribution of the K-x ray satellite spectrum. However, this theory is applicable to a case where the multiple-ionization probability is very small. The scaling plot based on Eq. 2 is shown in Fig. 1 for cases of $Z_P = 1-3$ and $Z_T = 13-26$. It is seen in this figure that the experimental data are well scaled except those of aluminum in low projectile-energy region.

In a case of very small $P_L$, where higher order terms in the PWBA calculation can be neglected, the ratio of cross section for $KL^0$ line to that for $KL^1$ line can be approximately given by

$$\frac{\sigma_{KL^1}}{\sigma_{KL^0}} = 8P_L.$$  \(3\)

In order to study this relation based on PWBA theory, we have measured the K-shell ionization of aluminum. An aluminum target of 150 $\mu g/cm^2$ thickness was bombarded with beams of 3-15 MeV/amu protons and $^3He^{2+}$ ions, and the X rays produced were analysed with a curved-crystal spectrometer of energy resolution of 1/650. Results obtained on $\sigma_{KL^1}/\sigma_{KL^0}$ are shown in Fig. 2, where the open circles and solid circles stand, respectively, for $^3He^{2+}$ ions and protons. The crosses are the results obtained by Watson et al. with $\alpha$-particle beams, and the dot and dashed curve is for the x-ray excitation. The results for proton bombardments are nearly constant. This fact shows that the $KL^1$-satellite line is mostly produced by shake-off process, and the results for proton bombardment are in good agreement with those for x-ray excitation. The results for $^3He^{2+}$-ion bombardment converge to those for the shake-off process with increase in the projectile energy. There is a difference of about 30% between the results for $\alpha$ particles obtained by Watson et al. and the present ones for $^3He^{2+}$ ions. This difference can not be explained from self-absorption in the target and the detection efficiency.

Assuming the dependence of the ratio $\sigma_{KL^1}/\sigma_{KL^0}$ on the shake-off effect by

$$\frac{\sigma_{KL^1}}{\sigma_{KL^0}} = \frac{8P_L + f}{1 - f},$$  \(4\)

we derived the value of $8P_L$ from the experimental ratios and the results are shown in Fig. 3. It is well seen that the L-shell ionization probability decreases with increase in the incident energy. (The point $\bullet$ in Fig. 1 shows the scaled value of $P_L$ for Al obtained from this analysis.) The calculation of $P_L$ for Al in terms of PWBA theory is now in progress.

References
7) Ishii K. and Morita S. et al., in preparation.

Fig. 1. Scaled representation of $F_L$ on the basis of the FWBA theory.
Fig. 2. Ratios of $\sigma_{K,L} / \sigma_{K,L}^0$ for Al.

Fig. 3. Projectile-energy dependence of $P_L$ for Al.