Projectile-charge Dependence of K-shell Ionization Cross Section of Al

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Cross sections for K-shell ionization by heavy charged particles have extensively been studied in a region of projectile velocity lower than the velocity of an electron to be ionized. Simple theories of inner-shell ionization, such as PWBA1) or BEA2), predict that the ionization cross section for projectiles of same velocity should be proportional to square of the projectile charge $Z_1$. It has been found, however, that experimental results on the ratio of ionization cross sections $R = Z_2^2/2 Z_1^2 Z_2^0/2 Z_1^0$, where $Z_1$ and $Z_2$ are the projectile charge, deviate from unity. This behavior has been interpreted by Brandt et al.3), 4) in terms of effects of the Coulomb deflection, the increase in binding energy, the polarization and the charge transfer. On the other hand, Reading et al.5) calculated the contribution from the Glauber effect in a region of projectile velocity larger than the electron velocity and obtained the value of $R$ smaller than unity in this region. In the present experiment, the behavior of $R$ is measured in the high-projectile-energy region and the contribution from the Glauber effect is studied.

Beams of protons and $^3$He-ions of 7, 9, 12, 16 and 21 MeV/amu have been obtained with our cyclotron. An Al target of ~100 µg/cm², prepared by vacuum evaporation, and an ORTEC Si(Li) x-ray detector were set at 90° and 135°, respectively, with respect to the beam. Energy resolution of the detector was 160 eV for 6.4-keV x rays. Typical spectra obtained at 21 MeV/amu are shown in Fig. 1, where the counts are normalized by the square of projectile charge and the projectile number. It is seen in this figure that the Al K-x-ray peaks are in complete agreement for the two kinds of projectile. Assuming a Gaussian shape for the x-ray peak and polynomials of the 6-th order for the background, the peak counts separated from the background were obtained by least-squares method. Since the measurements for protons and $^3$He-ions have been carried out under just same geometrical condition, the ratio $R$ is determined solely from the ratio of counts per projectile and the errors come only from the statistical ones — < 0.5 %. The ratio $R$ was therefore determined with uncertainties less than 1 %. In estimating the value of $R$, change in the fluorescence yield depending on the projectile has been neglected as it has been found to be quite small.

In accordance with Reading et al.5), the K-shell ionization cross section is expressed by
\[ \sigma_K = \frac{Z^2}{\eta_K} \int_{\theta_K} \int_{Q_m} dW dQ F_K(W,Q) \{ 1 - Z \int f(W,Q,\eta_K) \}, \]

where the notations should be referred to Merzbacher and Lewis\(^1\).

The experimental values of \( R \) are nearly equal to unity in the region above 12 MeV/amu as are shown in Fig. 2, and the results are compared with the theoretical predictions in Fig. 3, where the solid curve is obtained from the above equation. As seen in Fig. 3, the theory of Reading et al. predicts the value of \( R \) about 5 % smaller than unity in contrast to the experimental result. On the other hand, Doolen et al.\(^6\) have pointed out an importance of charge transfer to continuum states of the projectile, which had been neglected in the calculation of Reading et al. The results of calculation by Doolen et al. taking into account the charge-transfer process are represented by the dotted line in Fig. 3. At the highest energy shown in Fig. 3, the G öber effect is just cancelled out by the charge-transfer process and the calculation agrees with the experimental result, whereas, at lower energies, the calculation overestimates the contribution from the charge-transfer process as has been expected by Doolen et al.

As a conclusion, it was experimentally found that the K-shell ionization cross section in a high-projectile velocity region is quite well proportional to the square of projectile charge, and a more precise theoretical treatment of the charge-transfer process is desirable.

References

Fig. 1. Al K x-ray spectra for proton- and $^3$He-ion bombardments at 21 MeV/amu. The counts are normalized by the projectile number and the square of projectile charge.

Fig. 2. The values of $R$, experimentally obtained, are plotted as a function of projectile energy.

Fig. 3. The solid curve shows the result of calculations of the Glauber effect by Reading et al., and the dotted curve calculated by Doolen et al. takes into account further the charge-transfer process.