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Energy spectra of secondary electrons from Al induced by heavy-ion impact

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Energy distributions of secondary electrons (SE's) emitted backward from a thick Al target were measured in the SE energy region below 170 eV for the impact of purely charged He^{2+}, N^{6+}, Ne^{8+}, and Ar^{12+} ions with the same velocity (1.1 MeV/amu). From the ratios of SE yields for these heavy-ion impacts to those for He^{2+} impacts, it was found that (1) above the energy of the Al *LVV* Auger electrons, 65 eV, the SE yields for the N^{6+}, Ne^{8+}, and Ar^{12+} impacts were given by q^2 scaling, (2) they decreased from the values given by q^2 scaling to those given by stopping-power scaling in the energy region from 20 to 60 eV, and (3) they became much smaller than those expected from stopping-power scaling in the energy region below 20 eV, where such decrease was more pronounced when SE energies became smaller and the projectile's q became larger. The decrease was explained in terms of the screening of the projectile's charge by polarized target electrons for distant collisions.

Total yields of secondary electrons (SE's) γ for the impacts of light projectiles such as protons and α particles are well proportional to their stopping powers S_p, and γ/S_p are only dependent on target materials over the very wide range of their incident energy.[1] However, for heavy projectiles (HP's) with $z_1 > 6$, γ/S_p are dependent on incident energy,[2] or decrease with z_1,[3,4] where z_1 is the atomic number of the HP's. According to the experiment by Pferdekamper and Clerc, the yield of low-energy SE's from a carbon foil induced by the impact of fission products (heavy ions or atoms) shows a prominent decrease relative to that expected from the stopping-power scaling.[5] Such features in the total yields of SE's and in the yield of low-energy SE's will be induced by the strong interaction of HP's with materials. For example, because of the strong electric fields of HP's, HP's can transfer their energies to target electrons, which will have energies large enough to overcome the surface barrier even for large impact parameter. However, in metal targets the interaction potential between the projectile and target electrons is considered to be screened in distant collisions by the polarization of target electrons.[6] In this case, such a dynamic screening may play an important role for the decrease of the primary excitation of SE's relative to q^2 or stopping-power scaling.

The energy spectra of SE's emitted from Al were measured for the impact of He^{2+}, N^{6+}, Ne^{8+}, and Ar^{12+} ions with the same velocity, and these spectra were compared with one another. Observed SE yields for HP's were found to be anomalously low in the energy region below 20 eV compared with those expected from q^2 and stopping-power scaling. From experimental results a mechanism for the decrease will be discussed.

The energy distributions of SE's were measured with a pulse-counting method in an ultrahigh-vacuum system, described elsewhere.[7] After charge stripping the He^{+}, N^{2+}, Ne^{2+}, and Ar^{4+} ions by making them pass through a carbon foil of 10 $\mu g/cm^2$, He^{2+}, N^{6+}, Ne^{8+}, and Ar^{12+} were produced as main charge states and were selected by using an analyzing magnet. These ions have the same velocities, i.e., $v^2/2 = 1.1$ MeV/amu. The electric charges selected here are equal to the respective equilibrium ones at this velocity. Therefore their mean charges after penetrating a thin surface layer whose thickness is comparable to the SE escaping depth ($\leqq 50$ Å) will be the same as their original electric charges. The acceptance angle of the electron spectrometer is about 1 sr, and the angle between its optical axis and the incident beam is 137°. The target surface was set perpendicular to the optical axis of the analyzer, and was at an angle of 53° relative to the beam direction. The target was an *in situ*–vacuum–evaporated Al film on a stainless-steel substrate at a pressure lower than 1×10^{-8} mbar. The pressure of the analyzing chamber was kept at about 2×10^{-10} mbar when the beam was incident on the target. No systematic changes in the spectra due to the contamination could be observed during measurements. In order to obtain high counting rates for low-energy SE's, a potential of -9 V was applied to the target. The scatter of the data from run to run is about ±10%.

Figure 1 shows the energy spectra of SE's for He^{2+}- and

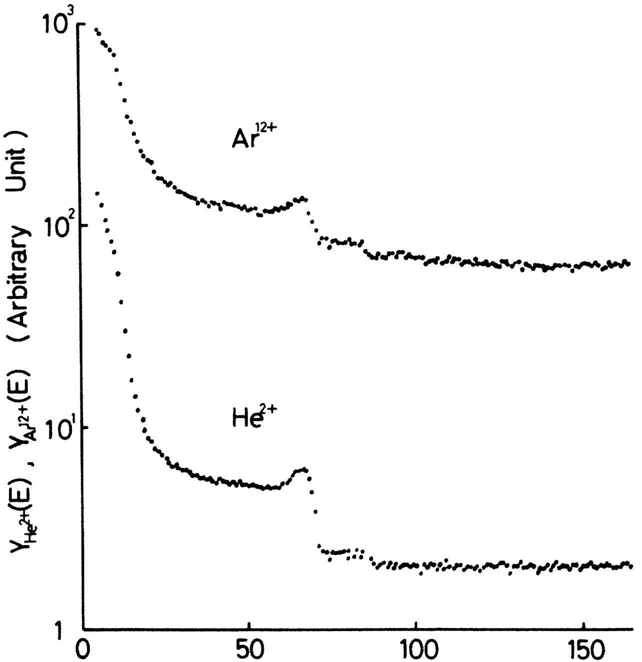

FIG. 1. Semilogarithmic plots of energy spectra of secondary electrons from Al induced by He^{2+} and Ar^{12+} ion impacts. Velocities of these projectiles are 1.48×10^9 cm/sec (1.1 MeV/amu).

Ar^{12+}-ion impacts, $Y_{He^{2+}}(E)$ and $Y_{Ar^{12+}}(E)$. Peaks of Al *LVV* Auger electrons can be seen at the energy of 65 eV. The fraction of the yield of low-energy SE's in the total yield is very low for Ar^{12+} impact compared with that for He^{2+} impact. In order to examine this trend more quantitatively, the ratios of the SE yields induced by heavy ions to those induced by He^{2+} ions,

$$R_{Ar,He}(E)=Y_{Ar^{12+}}(E)/Y_{He^{2+}}(E)\ ,$$

$$R_{Ne,He}(E)=Y_{Ne^{8+}}(E)/Y_{He^{2+}}(E)\ ,$$

$$R_{N,He}(E)=Y_{N^{6+}}(E)/Y_{He^{2+}}(E)$$

are plotted in Fig. 2. In the energy region above 70 eV, $R_{Ar,He}(E)\approx37$, $R_{Ne,He}(E)\approx17$, and $R_{N,He}(E)\approx8.5$, respectively. These values are nearly equal to the respective values of the ratios of the squared charges of the ions, $12^2/2^2=36$, $8^2/2^2=16$, and $6^2/2^2=9$. Near the energy of the Auger peak 65 eV, stepwise decreases can be seen. The values of the ratios in the energy range from 20 to 60 eV are nearly constant, and are about 25 for $R_{Ar,He}(E)$, 13.5 for $R_{Ne,He}(E)$, and 7.5 for $R_{N,He}(E)$, respectively. These values are near to the respective values of the ratios of their stopping powers: $18.1(Ar)/0.652(He)\approx28$, $9.03(Ne)/0.652(He)\approx14$, $5.48(N)/0.652(He)\approx8.4$,[8] where those stopping powers are given in units of MeV/(mg/cm^2). Here the stopping powers for equilibrium charge states were used, because these He^{2+}, N^{6+}, Ne^{8+}, and Ar^{12+} ions have charges equal to the respective equilibrium ones. Below 20 eV, the ratios show pronounced decreases with decreasing SE energies. For example, $R_{Ar,He}(E)\approx5$, $R_{Ne,He}(E)\approx4$, and $R_{N,He}(E)\approx2.4$ at low energies near 0 eV. The ratios of these values, 5:4:2.4, are nearly equal to those of the respective charges of these projectiles, 12:8:6. Thus at energies near 0 eV the yields of SE's for heavy projectiles with equilibrium charges are approximately given by q^1 scaling. The yield of SE's for He^{2+} impact is considered to be proportional to the squared charge 2^2. Then the ratio of the

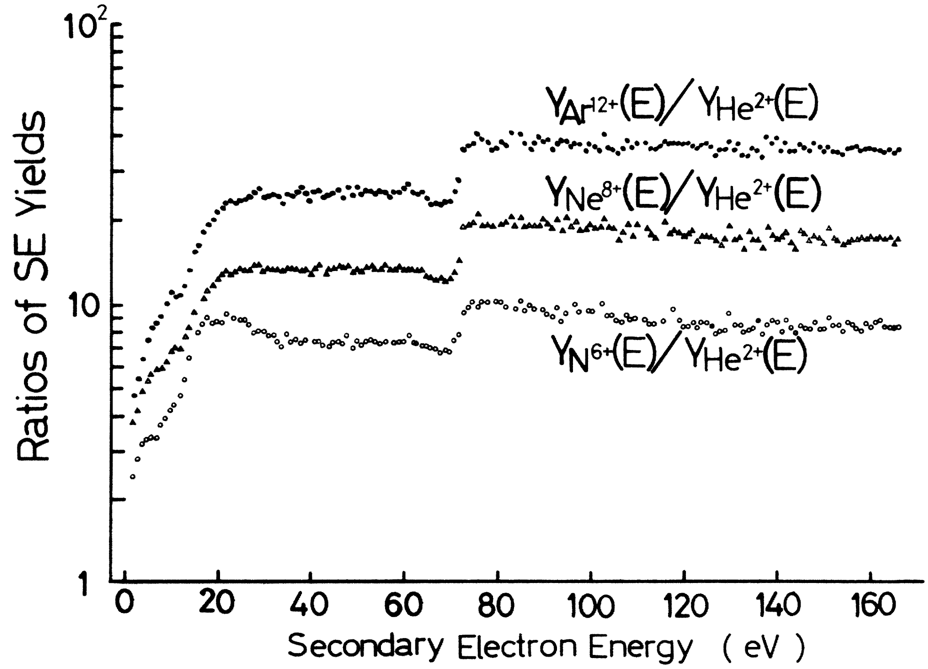

FIG. 2. Ratios of yields of secondary electrons from Al induced by heavy-ion impacts to those induced by He^{2+} impacts, $R_{Ar,He}(E)=Y_{Ar^{12+}}(E)/Y_{He^{2+}}(E)$, $R_{Ne,He}(E)=Y_{Ne^{8+}}(E)/Y_{He^{2+}}(E)$, $R_{N,He}(E)=Y_{N^{6+}}(E)/Y_{He^{2+}}(E)$.

yields of SE's with energies near 0 eV for HP impacts to those for He^{2+} impacts can be written as

$$R(q,2)=\alpha q/2^2 , \tag{1}$$

where q is the charge of the HP's and α a numerical factor. From the comparison of this equation with the experimental values 5, 4, and 2.4, α for each HP can be estimated as $\alpha_{\mathrm{Ar}}=1.7$, $\alpha_{\mathrm{Ne}}=2$, and $\alpha_{\mathrm{N}}=1.6$. Thus the factor α is almost independent of the species of HP's and is equal to 1.8 on average.

Hasselkamp, Hippler, and Scharmann[9] showed that the ratio of the yields of SE's from a Au target for the impact of He^+ and H^+, $Y_{\mathrm{He}^+}(E)/Y_{\mathrm{H}^+}(E)$, decreased with decreasing energy from 4 at 150 eV to 2.4 below 5 eV.[9] The decrease was explained in terms of the screening of the nuclear charge by electrons bound to the He^+ ions. The mechanism of the screening by the projectile's electrons may be useful for the explanation of the q^2 scaling of the excitation probability of low-energy SE's. However, the low-energy SE yields observed here were much smaller than the values expected from the q^2 and stopping-power scalings. Now we have to consider another mechanism.

In metal targets the interaction potential is considered to be fairly screened by the polarization of target electrons toward a positively charged projectile at a distance larger than $d_p=v/\omega_p$, where v is the ion velocity and ω_p is the plasmon frequency.[6] d_p is estimated to be about 6 Å in this experiment, where $v\approx 14.8\times 10^8$ cm/sec and $\omega_p\approx 2.3\times 10^{16}$ sec. The ionization cross section of gas targets for Ar^{12+} impact at a velocity corresponding to 1.1 MeV/amu is nearly equal to 10^{-14} cm^2.[10] This means that low-energy SE's are excited by the ion-atom collision with a large impact parameter, i.e., $p\approx\sqrt{10^{-14}/\pi}\approx 6$ Å, which is comparable to d_p. Then the screening due to target electrons is considered to be effective, by which the excitation probability of low-energy SE's is reduced compared to the case with no screening. The screening becomes more effective with the increase of the impact parameter p, i.e., with the decrease of SE energy for fixed q, and with the increase of q for fixed SE energy. Such tendencies were consistent with the experimental results obtained here.

Let us estimate the ratio of the primary excitation probabilities of low-energy SE's for He^{2+} and Ar^{12+} impacts. For He^{2+} impact, p should be smaller than d_p and then the interaction potential can be approximated by the Coulomb potential. The differential cross section to transfer an energy T from a projectile to a target electron is given by

$$d\sigma=\frac{4\pi a_0^2 E_R^2 q^2}{E_e}\frac{dT}{T^2} , \tag{2}$$

where a_0 is the Bohr radius, E_R the Rydberg energy, q the charge of the projectile (i.e., 2), and $E_e=\frac{1}{2}mv^2$ with the electron mass m. For the velocity corresponding to 1.1 MeV/amu, E_e is about 600 eV. T is related to the energy of SE's E by

$$T=\varphi+E , \tag{3}$$

where φ is the work function, and $\varphi=4.3$ eV for an Al target.

On the other hand, for the case of Ar^{12+} impact, a screened potential should be used as the interaction potential for a low-energy electron excitation, which may be approximated by the inverse square potential,

$$V(r)=-qe^2\frac{a}{r^2}\mathrm{e}^{-1} , \tag{4}$$

where a is the screening parameter, and e is the natural number, and $q=12$. For this inverse square potential, the differential cross section for the transfer of energy T is approximated by

$$d\sigma=q\,2\pi a_0 a\frac{E_R\,\mathrm{e}^{-1}}{T^{3/2}E_e^{1/2}}dT , \tag{5}$$

for $T\ll E_e$. Equation (5) shows that the primary excitation probability of low-energy SE's is not proportional to q^2, but proportional only to q^1. The ratio of the yield of low energy SE's primarily excited by Ar^{12+} to that by He^{2+} is written by use of Eqs. (2), (3), and (5) as

$$R_{\mathrm{Ar,He}}(E)\approx 0.33\frac{a}{a_0}(\varphi+E)^{1/2}\frac{12}{2^2} , \tag{6}$$

where $E+\varphi$ is given in units of eV. Equation (6) shows that the ratio becomes smaller as E is lowered. This is consistent with the experimental results. According to Pines,[11] $a\approx 2/k_{\mathrm{FT}}$, with the Fermi-Thomas screening wave vector k_{FT} and is equal to 1.7 Å for Al. For $E=0$ eV, $\varphi=4.3$ eV, and $a=1.7$ Å, Eq. (6) is written as $R_{\mathrm{Ar,He}}(0)\approx 2.2\times 12/2^2$. By comparing this equation with Eq. (1), the value of α is estimated to be 2.2, and is nearly equal to the experimental average value of 1.8. The observed yields of low-energy SE's induced by the projectiles with high electric charges can be well explained by this mechanism of the screening of the projectile's charge by polarized target electrons in distant collisions.

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