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Z_2 dependence of peak energies of loss electrons backscattered from metal targets for He^+ impact

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Energy distributions of secondary electrons emitted backward from Au, Ag, Cu, Al, and Be targets were measured in the energy range from 100 to 1000 eV for impacts of He^+ and He^{2+} ions with velocities corresponding to 1.1 MeV/amu. Energies, E_p, at which electron loss peaks for He^+ impact take maximum values are found to show pronounced target dependence. The order of E_p for these targets is Au>Cu>Ag>Al>Be This dependence of E_p is explained in terms of energy loss of loss electrons in their transportation to the surface.

Loss electrons (LE's) are produced through ionizing collisions of projectiles with target atoms, and form a significant peak in the secondary electron spectrum.[1] In case of gas targets, the energy E_p at which the peak takes its maximum is nearly equal to that of electrons with the velocity of the projectiles. E_p shows projectile dependence but no target dependence.[2,3]

In case of solid targets, the electron-loss process has been much discussed in relation to the mechanism of convoy electron excitation.[4] However, studies on broad loss peaks for large emission angles are rather few. E_p for solid targets shows a pronounced ejection-angle dependence.[5] It also shows the projectile dependence;[6] however, Z_2 dependence has not yet been studied, where Z_2 is the atomic number of a target.

In the present paper, we report on the first observation of significant Z_2 dependence of E_p of LE's backscattered from thick solid targets. Such Z_2 dependence of E_p is explained in terms of Z_2 dependence of energy loss of produced LE's during their transportation up to the surface. That is, in a target with a long mean free path for electron loss, LE's are produced in a deep region and lose much energy before they escape from the surface compared to those produced in a target of a short mean free path for the electron loss.

The experiment was carried out by using the linear accelerator in the Institute of Physical and Chemical Research. The experimental set up with an ultrahigh vacuum system has been described previously,[7] and only a brief description of experimental conditions will be given here. He^+ and He^{2+} ions were selected by using a magnetic analyzer. They had nearly the same velocities corresponding to 1.1 MeV/amu. The beam direction was 53° relative to the normal of the target. The acceptance angle of the parallel-plate electron spectrometer is about 1 sr. Its optical axis was set to be perpendicular to the surface of a target and 137° relative to the incident beam. Therefore only secondary electrons (SE's), normally emitted from the surface of a target, were energy analyzed and detected by a channel electron multiplier. Spectra were taken by a pulse counting method. Targets were *in situ* vacuum evaporated on stainless-steel substrates. Surface contamination could not be detected during measurements.

Figure 1 shows the electron spectra differential in energy and ejection angle multiplied by the electron energy E, $E\,d^2n/dE\,d\Omega$, for He^+ and He^{2+} impacts. Spectra for He^{2+} show only slight shoulders or low peaks; however, those for He^+ impact show very pronounced peaks due to LE's. It should be noted that the energies E_p at which the loss peaks take their maxima are different from target to target. This Z_2 dependence of E_p can be seen more clearly in Fig. 2, where peak heights are normalized to unity. E_p for Al is almost the same as that for Ag, and the spectrum for Al is omitted in order to avoid tangling of curves. E_p is highest for Au, and lowest for Be. It should be noted that E_p for Cu is higher than that for Ag, which indicates that E_p is not necessarily high simply because Z_2 is large. The pronounced Z_2 dependence of E_p has been represented, within the author's knowledge, for the first time in the present experiment.

In order to see the Z_2 dependence of only LE's, the background should be subtracted. For the background subtraction, it is assumed that (1) the spectrum of background SE's for He^+ has the same shape as that for He^{2+} and (2) in the energy region higher than 1000 eV the contribution of LE's to total SE's is negligibly small. Then the background will be given by the spectrum of SE's for He^{2+} with its magnitude normalized to that for He^+ in the energy region above 1000 eV. LE spectra, $d^2n_l/dE\,d\Omega$, are obtained from $Ed^2n/dE\,d\Omega$ for He^+ by subtracting background according to this method and dividing the background subtracted spectra by energy E.

Figure 3 shows $d^2n_l/dE\,d\Omega$ with heights of maxima normalized to unity. E_p are 540 eV for Au, 480 eV for Cu, 420 eV for Ag, 390 eV for Al, and 260 eV for Be, respectively. In Table I these values of E_p are listed with those obtained by the calculations which will be described later. Also in the background subtracted spectra, E_p is higher for Cu than that for Ag.

Hereafter the Z_2 dependence of E_p will be discussed. An experiment by Duncan and Menendez showed no Z_2 dependence of E_p for H_2^+ impact on Ne, Ar, and Kr gas targets in the range of scattering angle of LE's $\theta=0°-10°$.[2] Spectra represented by Schneider *et al.* also showed no Z_2 dependence of E_p for Ne^{4+} and Ar^{6+} impacts on Ne, Kr, and Xe gas targets at the scattering angle $\theta=30°$, 90°, and 150°.[3] Now we assume that E_p for

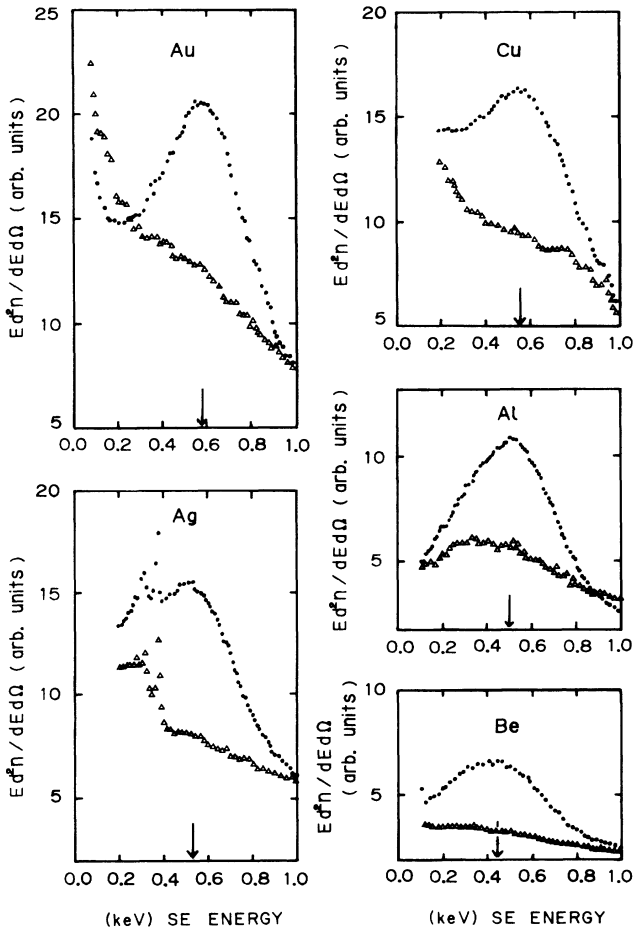

FIG. 1. Differential energy spectra multiplied by electron energy E, $E\,d^2n/dE\,d\Omega$, for secondary electrons emitted backward from thick targets induced by the impacts of He^+ and He^{2+} with velocities corresponding to 1.1 MeV/amu. Pronounced loss peaks are seen for He^+ impact. Arrows indicate the energies, E_p, at which loss peaks take maxima. ●: He^+, Δ: He^{2+}.

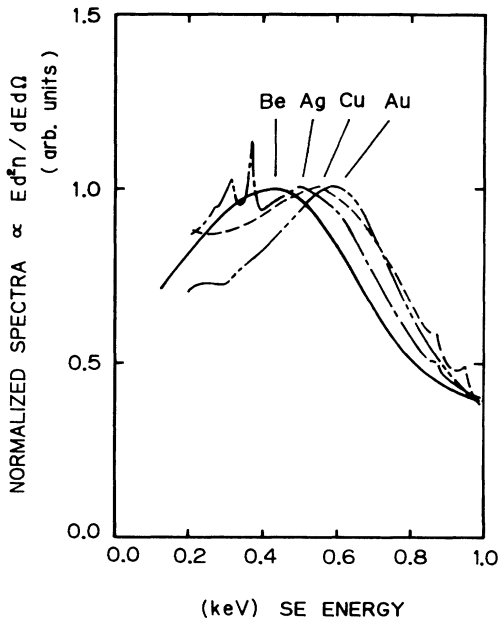

FIG. 2. Differential energy spectra of secondary electrons for He^+ impact multiplied by electron energy E, $E\,d^2n/dE\,d\Omega$, with heights of loss-electron peaks normalized to unity. (—··—): Au; (---): Cu; (—·—): Ag; (——): Be.

primarily excited loss electrons also has no Z_2 dependence in solid targets. An experiment on electron backscattering from thick metal targets carried out by Sternglass showed clear Z_2 dependence of energies of peaks of backscattered fast electrons, which resulted from Z_2 dependence of transport processes of them inside the target.[8]

The Z_2 dependence of E_p found in the present experiment will also reflect the Z_2 dependence of transport processes of LE's. Based on this assumption, simulation calculations of energy losses of LE's were carried out for Au, Ag, Cu, and Al by using the Monte Carlo method. It is assumed that LE's are produced with an energy E_0 (velocities equal to those of projectiles) and an ejection angle 0° at the depth of $\lambda_{loss}\cos(\beta)$, where λ_{loss} is the mean free path of electron loss for He^+, and β is the incident angle of the He^+ relative to the perpendicular to the target. In accordance with the experiment, E_0 is 600 eV, and β is 53°. LE's will suffer many elastic and inelastic collisions before they escape from the surface. The probability of

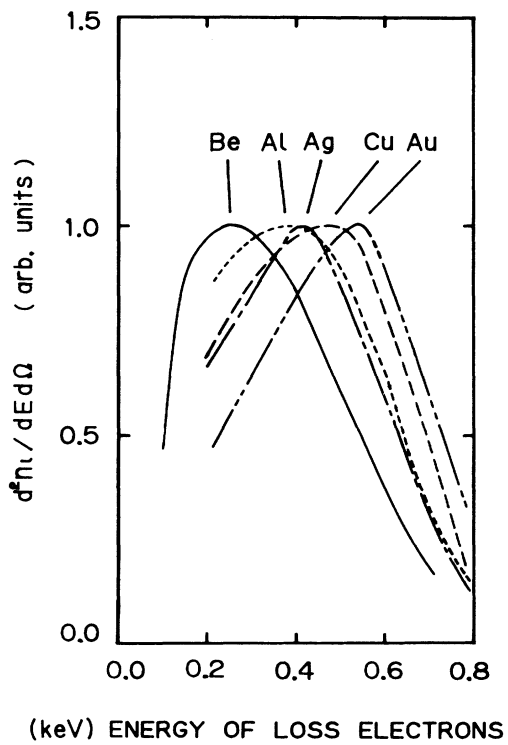

FIG. 3. Differential energy spectra of loss electrons, $d^2n_l/dE\,d\Omega$, with peak heights normalized to be unity. (—··—): Au; (---): Cu; (—·—): Ag; (....): Al; (——): Be.

TABLE I. Experimental values of energies E_p at which loss peaks take maxima are listed and compared with those deduced from the present calculation.

Target	E_p (eV) Expt. (± 40 eV)	Calculation
Au	540	540
Ag	420	470
Cu	480	490
Al	390	420
Be	260	

inelastic scattering is given by

$$P_{\text{in}}=\lambda_{\text{in}}^{-1}/\lambda^{-1} , \tag{1}$$

where λ is given by

$$\lambda^{-1}=\lambda_{\text{in}}^{-1}+\lambda_{\text{el}}^{-1} , \tag{2}$$

with the inelastic and the elastic mean free path λ_{in} and λ_{el}. If a uniform random number A_1 $(0\leqq A_1\leqq 1)$ is smaller than P_{in}, inelastic scattering occurs, and if A_1 is larger than P_{in}, elastic scattering does occur. A path length from scattering to scattering R or a scattering angle θ is determined by using the next equation:

$$A_2=\int_{x_{\min}}^{x} f(x)dx/\int_{x_{\min}}^{x_{\max}} f(x)dx , \tag{3}$$

where A_2 is a random number distributed uniformly between 0 and 1 and $f(x)$ gives some distribution of random number x; that is, R or θ here.[9] The distribution function for R is given by $f(R)=e^{-R/\lambda}$, and that for θ is given by the angular distribution of inelastic or elastic scattering. Values of inelastic mean free paths are taken from the paper by Tung, Ashley, and Ritchie[10] and the angular distributions of inelastic scattering are given according to Amelio.[11] Cross sections σ_{el} and angular distributions of elastic scattering are given by Mott and Massey.[12] λ_{el} is calculated from σ_{el} by using the relation $\lambda_{\text{el}}=1/n\sigma_{\text{el}}$ with the density of lattice atoms n. Values of λ_{el} for Cu, Ag, and Au are shorter than diameters of respective lattice atoms, which may be unrealistic. However, it is assumed that several virtual scattering events in a path length comparable to the diameter of the lattice atom approximately express the real scattering. Only electrons emitted perpendicularly from the surface are counted according to the experiment. It is assumed that the energy loss of LE in passing the length R is given by $R\,dE/dx$. Then the total energy loss inside the target is obtained by multiplying

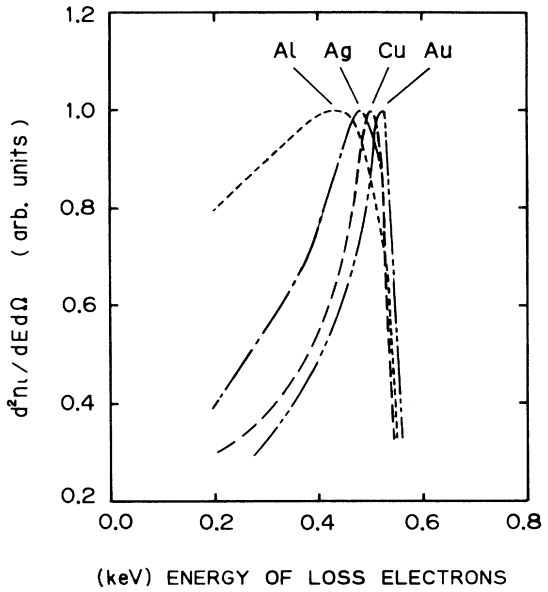

FIG. 4. Calculated differential energy spectra of loss electrons, $d^2n_l/dE\,d\Omega$, with peak heights normalized to be unity. (— · · —): Au; (---): Cu; (— · —): Ag; (....): Al.

dE/dx with the total path length, where the energy dependence of dE/dx is neglected for simplicity and only the value at $E=600$ eV is used. Values of dE/dx are also taken from the paper by Tung *et al.*[10] Energy distributions of backscattered LE's are thus obtained from counted numbers of LE's and their energies. E_p is higher for shorter λ_{loss} and λ_{el}, for longer λ_{in}, and for smaller dE/dx, respectively. Values of λ_{loss} are determined to give proper values of E_p.

In Table II, adopted values of λ_{loss} are listed with fixed parameters λ_{el}, λ_{in}, and dE/dx. λ_{loss} for Cu should be shorter than that for Ag in order to give a higher value of E_p for Cu than for Ag. Cross sections of electron loss, σ_{loss}, are calculated from λ_{loss} by using the relation $\sigma_{\text{loss}}=1/n\lambda_{\text{loss}}$. Calculated values of σ_{loss} are also listed and compared with semiempirical ones which are interpolated from experimental values for gas targets according to theoretically deduced Z_2 dependence of σ_{loss}.[13] The calculated σ_{loss} are nearly equal to those semiempirical ones. Therefore values of λ_{loss} adopted here should be near real ones. Though λ_{loss} for Cu is shorter than that for Ag, σ_{loss} for Cu is smaller than that for Ag because of the

TABLE II. Used values of λ_{loss}, λ_{in}, dE/dx are listed. λ_{loss} are determined so as to give proper values of E_p in the calculation. σ_{loss} calculated from λ_{loss} are also listed and compared with semiempirical ones.

Target	λ_{loss} (Å)	$10^{16}\sigma_{\text{loss}}$ (cm^2) Present calc.	Semiemp.	λ_{in} (Å)	λ_{el} (Å)	$\frac{dE}{dx}$ (eV/Å)
Au	6.3	2.7	2.2	10.5	0.33	7
Ag	12	1.4	2.0	11	0.68	6
Cu	10	1.2	1.7	11	0.9	6
Al	20	0.8	1.0	14	3.7	3

difference in the atomic densities n. This is consistent with the Z_2 dependence of experimental values of σ_{loss} for gas targets.[13] Figure 4 shows the energy spectra obtained by using these values of mean free paths and dE/dx, where peak heights are normalized to unity. Using only a fixed energy E_0, a fixed angle 0°, and a fixed creation depth $\lambda_{loss}\cos(\beta)$, we obtained energy distributions for emitted LE's that are narrower than the experimental spectra. Values of E_p obtained from Fig. 4 are listed in Table I. Agreement between the experimental and the calculated values of E_p is fairly good, in spite of the ambiguities in the background subtraction for the experimental spectra and in the λ_{el} numeration for the calculation. That is, experimental values of E_p are reproduced in the present calculation by using the values of λ_{loss} which give the values of σ_{loss} near those for gas targets. Therefore, it is concluded that the Z_2 dependence of E_p comes from that of energy loss of LE's during their transportation to the surface. Then it is reasonable that E_p for Cu is higher than that for Ag: As shown in Table II, λ_{in}, λ_{el}, and dE/dx are almost the same for Cu and Ag. Further, λ_{loss} for Cu is shorter than that for Ag. Then, LE's in Cu are produced in a thinner surface layer, and consequently lose less energy in the transportation to the surface than those in Ag. That is, E_p for Cu is higher than that for Ag.

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