Secondary emission from thin Al, Cu, and Be films induced by a 1-MeV proton beam

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Experiments reveal that the energy spectrum of the secondary electrons emitted at various angles from Al, Cu, and Be targets is a piecewise-power function. The exponents for these materials are essentially identical at energies above 10 eV, regardless of the angle. The experiments reveal the dependence of the secondary-emission yield on the excitation potential. A modification of the Sternglass formula for the secondary-electron-emission yield is proposed.

The theories which are presently being used to describe the kinetic electron emission induced by ions are modifications of theories proposed by Parilis and Kishinevskiĭ[1] for low-energy ions and by Sternglass[2] for high-energy ions. Theories which are refinements of the Sternglass theory[2] are quite successful in explaining the observed proportionality (Refs. 3–8, for example) between the secondary emission yield Δ and the energy loss of the fast particle, dE/dx. On the other hand, we do not yet have a theory capable of describing the energy spectrum of the emitted electrons, nor have there been experimental studies of the actual, rather than integral, energy spectrum of the secondary electrons over a broad energy range (up to hundreds of electron volts), induced by a beam of fast ions. In Ref. 3 the energy spectrum was studied in a narrow energy interval (0–10 eV), and all that was reported was that this spectrum was nonthermal; measurements over a broad electron energy range (0–100 eV) were carried out in Refs. 4 and 5, but not by a spherical analyzer, and the only information furnished on the distribution function of the secondary electrons was an global characteristic. In an earlier work we studied the spectrum of the secondary electrons which appear as α particles from a radioisotope source passed through thin films.[6] Although it was demonstrated in Ref. 4 that the spectrum of secondary electrons emitted from an aluminum target in a "shoot-through" arrangement is a power function over a broad range of the proton energy (20–250 keV), and this function is independent of the energy of the fast particles, we regard the averaging of the energy spectrum over the energy of the bombarding α particles and over the emission angle of the secondary electrons which was carried out in Ref. 6 as a shortcoming.

Our purpose in the present study was to carry out experiments on the energy spectrum of the secondary electrons caused by the bombardment of a target by a proton beam for various emission angles and for Al, Cu, and Be targets. We also studied the secondary emission yield in a shoot-through arrangement as a function not only of the energy loss of the protons in the material but also of other macroscopic characteristics of the target.

The experimental arrangement is shown in Fig. 1. A beam of protons with an energy of 1 MeV from an electrostatic accelerator penetrates target 1 and is detected by Faraday cup 3. The secondary electrons ejected from the target are collected by collector 4. For a retarding-potential analysis of the energy of the secondary electrons we use a small-aperture ($4 \cdot 10^{-4}$-sr) three-grid analyzer 2. The analyzer is placed at various angles (30°,45°,75°) with respect to the beam direction. The ratio of the electron current I_e to the proton current I_p is plotted against the analyzing voltage U on an x, y chart recorder 5. The secondary emission yield is determined from the ratio of the total current of secondary electrons from collector 4 to the proton current. Experiments were carried out with aluminum targets 5.6 μm thick, beryllium targets 9.7 μm thick, and copper targets 1.2 μm thick.

From the experimental results on I_e/I_p as a function of U we can find the exponent (s) of the electron energy distribution, carrying out a single differentiation of these functions, since in the present case, in the region in which the distribution is a power-law distribution, we have

$$\frac{d}{dU}\left(\frac{I_e}{I_p}\right)=A(E_F+\varphi+eU)^{s+1},$$

where E_F is the Fermi energy, φ is the work function, and A is a constant. On a logarithmic scale, expression (1) is thus a straight line with a slope of $s+1$. Figure 2 shows such a plot of $d(I_e/I_p)/dU$ versus U for aluminum (a), beryllium (b), and copper (c) targets for three emission angles. The experimental points for these angles conform well to three straight lines, corresponding to different exponents in the intervals 0–10 eV, 10–40 eV, and 40–100 eV. These exponents agree quite well ($\sim 10\%$) with the exponents which we found with the help of a spherical analyzer for the same targets, bom-

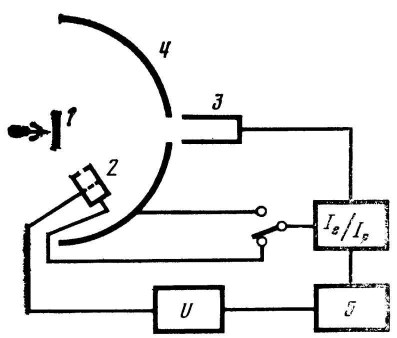

FIG. 1. Experimental arrangement (see the text proper for an explanation).

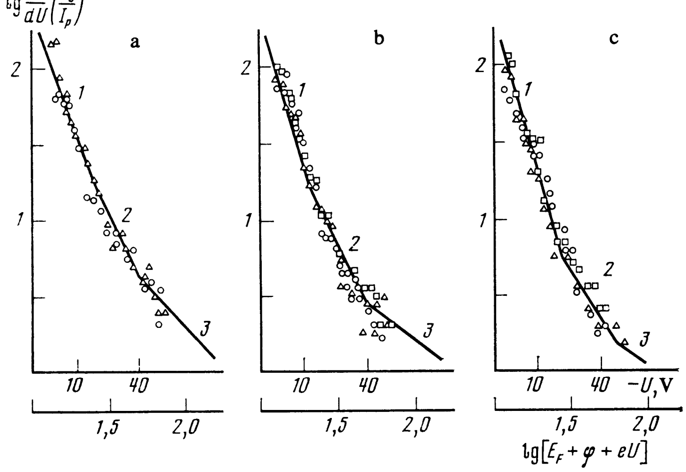

FIG. 2. Experimental results on $d(I_e/I_p)/dU$ versus U for (a) Al, (b) Be, and (c) Cu targets according to measurements at various angles: □—30°; △—45°; ○—75°. For regions 1, 2, and 3 the values of the exponent s are -3.5, -3.05, and -1.92 for Al; -4.5, -3.14, and -1.72 for Be; and -4.66, -2.95, and -1.60 for Cu.

barded by α particles.[6] It was established that the exponents s for the different targets differ only at low energies, 0–10 eV.

In addition to studying the energy spectrum, we obtained values of an global property—the secondary emission yield Δ—for the aluminum, copper, and beryllium targets. The results are 2.5, 1.6, and 4.6, respectively. As we mentioned earlier, Δ is proportional to the energy loss of the fast particle, dE/dx:

$$\Delta = k dE/dx,$$

where k is a proportionality factor, which varies severalfold from one material to another.

According to our experimental results for the three targets, according to experimental data which we had obtained earlier[6] for aluminum and beryllium, and according to the data of Ref. 7 for graphite, the yields Δ for the various targets are inversely proportional to the excitation potential Φ multiplied by $N^{1/3}$ (N is the density of atoms in the material). We therefore propose the following expression for Δ:

$$\Delta = \frac{12 Z_{eff}^2}{\Phi N^{1/3}} \left(\frac{dE}{dx}\right)_p,$$

where $(dE/dx)_p$ is the energy loss of a proton moving at a velocity equal to the velocity of the bombarding ion, and $Z_{\rm eff}$ is the effective charge of the ion in the target. This expression is a modification of the expression proposed for Δ in Refs. 2 and 8. It predicts yield values which agree satisfactorily with the experimental results for aluminum, beryllium, and carbon targets. Although there is a fairly large discrepancy in the case of copper targets, it may be due to imperfections of the surface layer of the copper film which was used.

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