Secondary Electron Production from Metals by 1-Mev Protons

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Be, Al, Cu, and Au targets were bombarded with 1-Mev protons. The resulting secondary electrons were investigated in respect to their intensity, energy distribution, and energy distribution as a function of angle of emission. The results show that, contrary to previous investigations, electrons with energies higher than those corresponding to the so-called "local-heating" effect contribute considerably to the total yield. About 75% of the secondaries are emitted at low energies, and the remaining part is emitted with high energies (up to 2000 ev for 1-Mev protons). The electron spectrum decreases rapidly toward the high-energy end. The high-energy component is not emitted isotropically, but preferably backwards in the direction from which the protons arrive.

INTRODUCTION

THE secondary-electron emission by heavy particles has been thoroughly studied in the past; however, most of the investigations were concerned with primary particles of several kev energy, and only few papers are available for the case where the primary particles were protons in the Mev range.[1–7] Recently interest has been aroused in the secondary-electron emission by protons in the Mev range by problems in plasma physics, outer-space physics, and by fast-neutron dosimetry at high dose rates. Experiments were performed using secondary electrons emitted from the hydrogenous wall of a vacuum chamber by recoil protons. The electrons were attracted to a centrally located electrode. It was found that, to attract all secondary electrons, collecting voltages of about 1000 v had to be applied.[8] This result indicated that there may be a significant amount of secondary electrons with several hundred ev energy, contrary to the results obtained by previous investigators, according to which only low-energy secondaries contribute considerably to the total yield.

Therefore, measurements were made to investigate the yields, energy distribution, angular distribution, and energy spectra as a function of the angle of emission of the secondary electrons.

EXPERIMENTS AND RESULTS

To find the yields and estimate the energy distribution of secondary electrons, we used the apparatus shown in Fig. 1. After passing through a set of collimators which assured that no electrons coming from sources other than the target could be counted, the protons hit the target and produced secondary electrons. The targets used in this experiment were thick, and only electrons emitted backwards were considered. These electrons moved against an opposed field and only those with sufficient energy arrived at the collector. If the secondary electrons have energies of only a few ev, as assumed in the previous investigations, there is no problem of production of tertiary electrons from the collector surface. However, when the secondary-electron energy is of the order of several hundred ev, the probability of tertiary-electron release becomes close to one.[9] The tertiary electrons are then repelled by the applied field from the collector to the target, and the net current through the collecting electrode becomes close to zero. This effect may give the erroneous result that the maximum energy of secondary

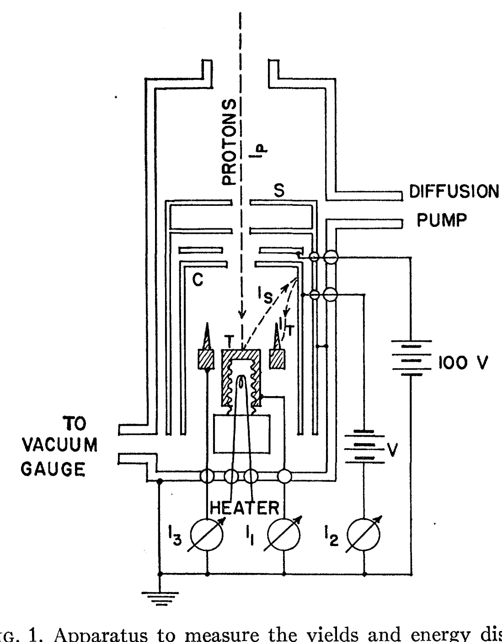

Fig. 1. Apparatus to measure the yields and energy distributions of secondary electrons using a three-electrode system. The application of the ring electrode with corona points proved to be more reliable than the use of a suppressor grid.

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[2] A. G. Hill, *et al.*, Phys. Rev. **55**, 463 (1939).
[3] X. Aarset *et al.*, J. Appl. Phys. **25**, 1365 (1954).
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[8] S. Kronenberg, and H. Murphy, U. S. Army Signal Research and Development Laboratory Report TM-2070, 1959 (unpublished).

[9] See, for example, Sanborn C. Brown, *Basic Data of Plasma Physics* (Massachusetts Institute of Technology Press, Cambridge, Massachusetts, 1959), p. 202.

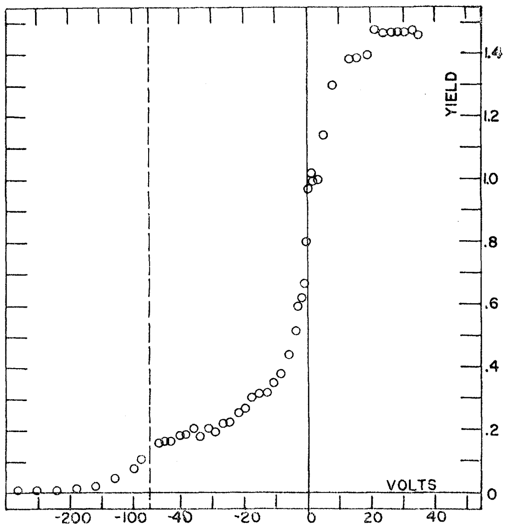

FIG. 2. Integral energy distribution of secondary electrons obtained with the three-electrode, opposed-field method for 0.96-Mev protons on beryllium.

electrons corresponds to the repelling potential at which the collector current vanishes. To avoid this error, we placed a third electrode in the assembly. This electrode was at the same potential as the target, surrounded it as a ring, and had four sharp corona points. Thus, electrons repelled by the retarding field on the collector returned to the target, whereas the tertiary electrons emitted from the collector were most likely to reach the corona points of the outer electrode.

If $J_{1,2,3}$ denotes the current measured by the readout meters 1, 2, and 3 in Fig. 1, J_p is the proton current, J_S and J_T secondary and tertiary electron currents, and V the applied voltage, the following relationships apply:

$$J_1(V)=J_p+J_S,$$
$$J_2(V)=-J_S+J_T,$$
$$J_3(V)=-J_T,$$

and

$$Y(V)=J_S/J_p=(-J_2-J_3)/(J_1+J_2+J_3). \qquad (1)$$

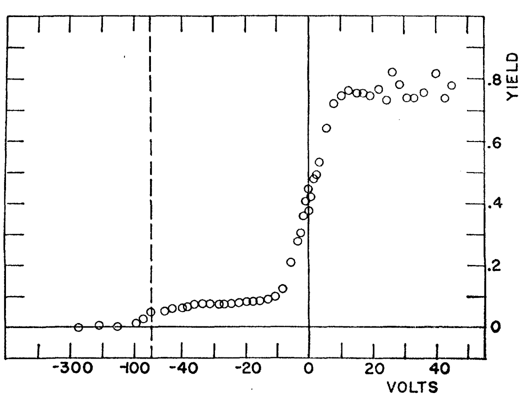

FIG. 3. Same as Fig. 2 but for 1.034-Mev protons on aluminum.

For positive voltages Y is the total yield, and for negative voltages it is the number of electrons per incident proton with energy greater than V ev. The measurements were made using Be, Al, Cu, and Au as target materials. The metals were mounted on a modified soldering iron tip to make outgassing by heat possible. The outgassing was accomplished by heating the materials in vacuum to 400°C for 15 min. The vacuum during the measurement in the vicinity of the target was 4×10^{-7} mm Hg. Figures 2–5 show the results of the measurement. If one adds J_2 and J_3 in the above measurement and calls the sum J_{2+3} one obtains the expression

$$Y_{2+3}(V)=(-J_{2+3})/(J_1+J_{2+3}). \qquad (2)$$

This is the yield of a two-electrode-system arrangement, which was used in earlier investigations by different authors. An example is shown in Fig. 6. This

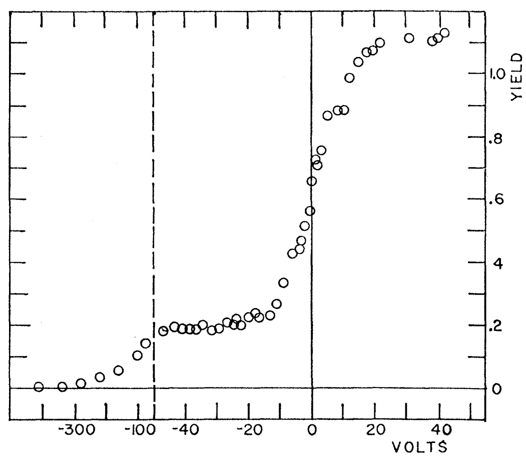

FIG. 4. Same as Fig. 2 but for 0.94-Mev protons on copper.

curve agrees very closely with the typical yield-versus-energy measurements obtained in the earlier experiments. The three-electrode system of measurement shows that a high-energy component up to several hundred ev exists, and gives reliable total yields for positive collector potentials. The quantitative energy-spectrum analysis of the secondary electrons cannot be done very reliably with this method, because some secondaries that approach the collector but do not quite reach it are repelled to the corona points and so distort the measurement. Also the sensitivity of the method is not sufficient to establish the maximum energy of the secondary electrons.

Therefore, the measurement has been repeated using the magnetic spectroscopy method in which no electric fields can affect the path and energy of the secondary electrons. The experimental arrangement is shown in Fig. 7. Also, in this design the collimators were made so that only the electrons emitted from the target alone could be registered. The receiver was a tubular

collimator with a Faraday cup at the end, all surrounded by metallic shielding except for a small opening in the front. The receiver part could be placed at different angles to the surface of the target. Between the target and the receiver, a magnetic field of variable strength could be applied perpendicular to the path of the electrons, so that secondary electrons below a certain energy, determined by the strength and geometry of the magnetic field, would miss the Faraday cup and the electrons above this energy could be collected. Special care was taken to avoid exposed insulators that could charge up, produce an electric field, and affect the path of electrons. The absolute calibration of the effect of the magnetic field on the electrons was made by replacing the metal target with an electron gun taken from an old cathode-ray tube, shooting the electrons of known energy through the collimators into the Faraday cup, and establishing the necessary current through the magnet coil to prevent

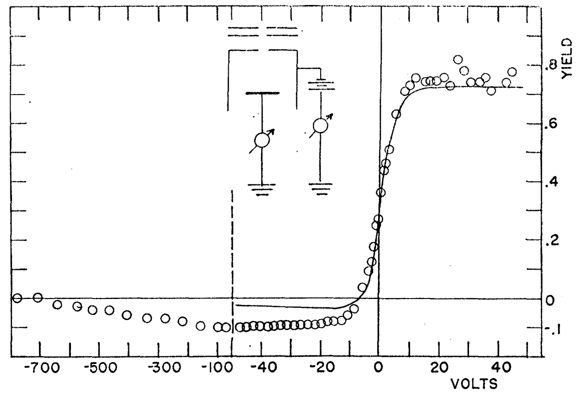

FIG. 6. Yield and integral energy distribution of secondary electrons emitted from aluminum. The points represent the measurement obtained for 1.035-Mev protons with the three-electrode system but evaluated for the two-electrode system according to formula 2. The solid curve is reproduced from reference (3) for 2-Mev protons on Al. The two curves are comparable because beyond 1 Mev the yield varies slowly with the proton energy.

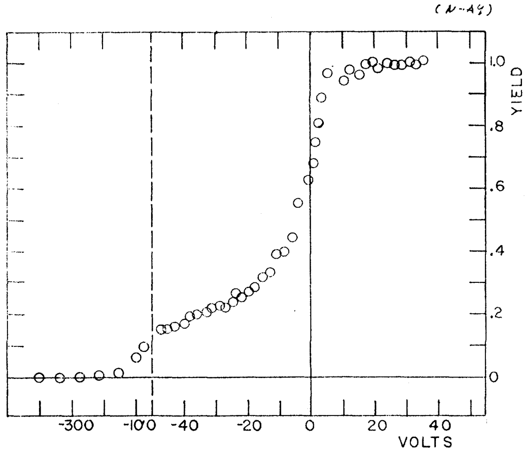

FIG. 5. Same as Fig. 2 but for 0.95-Mev protons on gold.

the electrons from reaching the cup. The calibration was repeated by measurement of the shape and intensity of the magnetic field and computation from the results of the path of electrons with a given energy. Results obtained with both methods agreed within 2.5%.

Two electrometers were used to detect the currents through the target and the Faraday cup. Under bombardment, they charged up with time to a small voltage (0.5 v), which did not distort the path or energy of the secondary electrons. The electrometer on the target was shunted with a 6-μf capacitor. The electrometer on the detector side detecting only about one millionth of the target current had an input capacity of 78 $\mu\mu$f. Both instruments had an open input with the resistance to ground above 10^{14} ohms. The voltages on the electrometers were recorded as a function of time. From this data, plus the known geometry of the arrangement and the collimator, one can compute the "differential yield"

$$Y(E,\gamma)=\left[1+Y(0,\gamma)\right]\bigg/\left|\frac{\Delta V_T}{\Delta V_C(E,\gamma)}\right|\frac{C_T}{C_C}\Omega \qquad (3)$$

where ΔV_T and $\Delta V_C(E,\gamma)$ are the voltage rises on the target and Faraday cup electrometer, C_T and C_C are the corresponding input capacitors, and $2\pi\Omega$ the solid angle of the collimator. This expression is defined here as the number of secondary electrons per incident proton with energies higher than E emitted under an angle γ with respect to the incident protons, for the

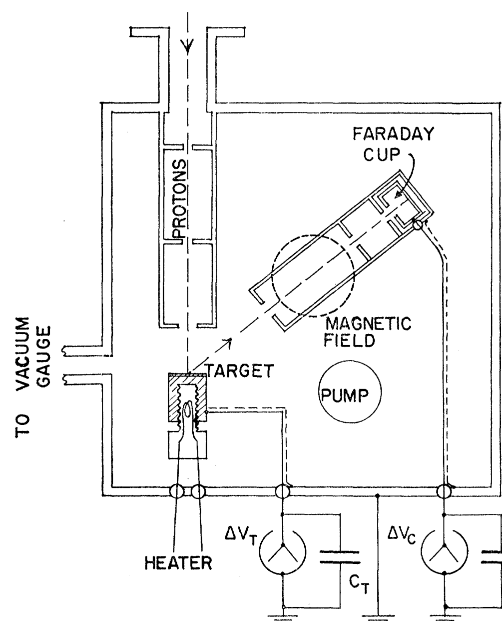

FIG. 7. Apparatus used to measure the differential yield of the high-energy component of the secondary electrons.

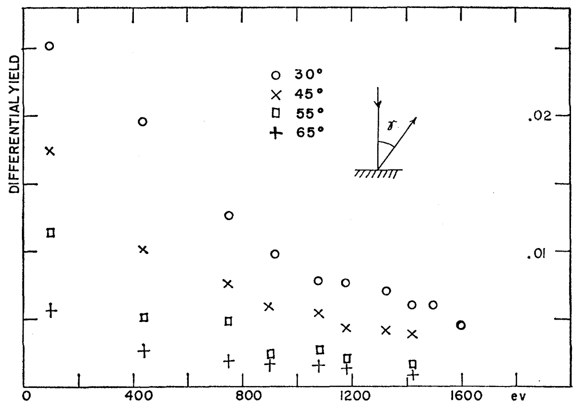

FIG. 8. High-energy component of secondary electrons. Differential yield as functions of integral energy distribution for different angles of emission. The measurement was obtained with 0.96-Mev protons on aluminum.

solid angle $4\pi/2$. From this expression the total yield as given by (1) is:

$$Y(E)=\int_0^{\pi/2} Y(E,\gamma)\,\sin\gamma d\gamma. \tag{4}$$

The results of this measurement reconfirmed the existence of the high-energy component. The energy-spectrum measurements at different exit angles gave a surprising result: The high-energy electrons are emitted preferably within a small angle γ, while the electrons with lower energy have the tendency to be emitted more isotropically.

Figures 8 and 9 show the secondary-electron spectra given by formula (3) for different exit angles. Only electrons with energies higher than 100 ev could be recorded with the above method, because the stray field of the analyzer magnet of the Van de Graaff accelerator in the target area (~0.5 gauss) was already sufficient to prevent most electrons below 100-ev energy from traversing the collimator and reaching the Faraday cup. The same reason seems to account for the fact that in the opposed field method (Figs. 2–7), the saturation took place at about +10 v rather than at 0 v as one would expect. Some of the electrons below 10 ev seem to be deflected to the bottom of the apparatus by the stray magnetic field, and escape without being recorded.

DISCUSSION

In Figs. 8 and 9, we see that the maximum energy of the secondary electrons is about 2000 ev for 0.96-Mev incident protons. This value corresponds closely to the maximum energy a proton can deliver to an electron due to Coulomb scattering. In the laboratory coordinate system, this energy is given by

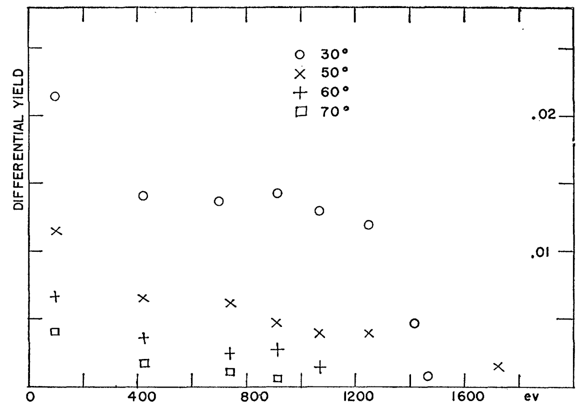

FIG. 9. Same as Fig. 8 but for 0.96-Mev protons on gold.

$$E_{\max}=4(m_e/m_p)E_p$$

or for 0.96-Mev protons,

$$E_{\max}=2092 \text{ ev}. \tag{4}$$

The data for dependence of energy on emission angle also confirm the explanation of the high-energy component by Coulomb scattering. Electrons escaping from the target must be the product of at least two consecutive scattering processes to comply with the law of conservation of momentum. The energy transfer is highest for electrons that were first scattered in the direction of the incoming proton, and then suffered a second collision which reversed their momentum. These electrons traverse the shortest distance in the target, lose least energy, and therefore the probability that they escape with high energy is big. The quantitative explanation of the phenomena described here seems to be similar to the one reported in the paper by Sternglass,[10] and a theoretical paper on this subject will be published in the future.

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