Inelastic Scattering of Low Speed Electrons from a Copper Single Crystal

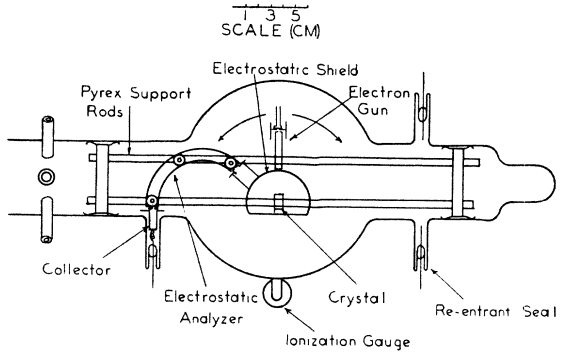
PAUL P. REICHERTZ*,** AND H. E. FARNSWORTH
Brown University, Providence, Rhode Island
(Received December 13, 1948)

The energy distribution of inelastically scattered electrons from a (100) face of a copper single crystal has been investigated by the electrostatic deflection method. Using normal incidence of the primary electrons, observations were made in the neighborhood of two strong diffraction peaks in the (100) azimuth, one at 59.5-ev primary energy and colatitude angle 60°, and one at 114.5 ev and 40.5°. Discrete loss peaks were observed at about 3.0-, 6.0-, 12.3-, and 20.0-ev energy loss with the intensities depending on both primary energy and colatitude angle. An excess of inelastic scattering occurs near the elastically scattered diffraction beams so that maxima are observed in the curves giving the intensity of inelastic scattering as a function of primary energy for constant values of energy loss. Near the 59.5-ev diffraction beam the maxima of the curves for different values of energy loss occur at a constant value of primary energy. This suggests that the inelastic scattering takes place after diffraction, but the fact that the maxima occur at 56 ev instead of 59.5 ev is not understood. For inelastic scattering near the 114.5-ev diffraction beam the results are complex but are approximately explained by assuming (1) inelastic background scattering followed by diffraction, for energy losses below 10 ev, (2) the same as (1) plus diffraction followed by inelastic background scattering, for energy losses above 10 ev. Possible reasons are given for the fact that the maxima for the latter process occur 3.5 ev above the energy for the diffraction maximum.

INTRODUCTION

PREVIOUS investigations on inelastic scattering of low speed electrons from outgassed metal surfaces may be divided into two groups: (1) those using polycrystalline metals, and (2) those using metal single crystals. Results in the first group[1] indicate that there are certain discrete energy loss peaks, corresponding to more probable values of energy loss, superposed on a general background of inelastic scattering. The positions of the discrete loss peaks are a function of the metal although both the positions and intensities are observed to be independent of angle of incidence and energy of the primary electrons. These observations for copper have been accounted for by Rudberg and Slater[2] by deriving an expression for the probability of excitation by electron bombardment as a function of the two electronic levels involved in the transition. Results in the second group obtained with a silver crystal by Turnbull and Farnsworth[3] show that the intensities of both the discrete loss peaks and of the background scattering are a function of primary energy and angle of incidence when the measurements are made in the vicinity of the critical values of angle and voltage for a diffraction beam of elastically scattered electrons. The results also show that the excess background scattering which accompanies the elastic scattering of the diffraction beams, for a given solid angle, increases as the energy-loss is decreased. Further, when inelastic scattering for a constant energy loss is plotted against secondary energy rather than primary energy, the maxima in the curves for different values of energy loss occur at the same values of secondary energy. This result is to be expected if the primary electrons are first inelastically scattered without appreciable change in their direction of motion and are then diffracted by the crystal lattice. However, the discrete loss peaks appear to attain their maximum values in the neighborhood of the primary voltages required for the diffraction of electrons which would indicate that the energy loss in this case occurs after diffraction rather than before. Thus the order of the two processes, diffraction and energy loss, does not appear to be the same for the background and discrete-loss inelastic scattering. Because these observations were confined to the region of only two diffraction beams more observations are required before general conclusions can be drawn.

The purpose of the present investigation is to extend the above observations to other diffraction



a

* Part of a dissertation presented for the degree of Doctor of Philosophy in Brown University.

** Now with the Magnolia Petroleum Company, Dallas, Texas.

[1] E. Rudberg, Phys. Rev. **50**, 138 (1936); **45**, 764 (1934); Proc. Roy. Soc. **A127**, 111 (1930); K. Svenska Vet. Akad. Handl. 7_1 (1929); L. J. Haworth, Phys. Rev. **48**, 88 (1935); **42**, 906 (1932).

[2] E. Rudberg and J. C. Slater, Phys. Rev. **50**, 150 (1936).

[3] J. C. Turnbull and H. E. Farnsworth, Phys. Rev. **54**, 509 (1938).

beams and also to another crystal. The previous work was done by magnetic analysis in which the angle between the incident and reflected beam is necessarily restricted to 90 degrees and hence to angles of incidence other than normal. In the present work an electrostatic analyzer is used with which it is possible to extend the observations to diffraction beams for the case of normal incidence.

APPARATUS AND PROCEDURE

The apparatus consists of two essential units. The first is the electron gun and the crystal in its housing with provision for varying the colatitude angle of the observed scattered electrons. The second is the electrostatic analyzer and Faraday collector, which determines the energy distribution of the scattered electrons.

Figure 1a shows a diagrammatic sketch of the apparatus. The electron gun is mounted so that the primary electrons are incident normally on the crystal face, and the electron gun and crystal can be rotated as a unit by means of the magnetic control, thus changing the colatitude angle. The analyzer is placed so that scattered electrons enter it normal to the entrance slit. The whole apparatus is assembled so that the plane of rotation of the gun and crystal coincide with the plane of the analyzer. Thus the electrons travel in a plane as they move from the gun filament to the collector. The colatitude angle is measured by a scale and pointer within the tube, which permit estimates of position to 0.2°. The whole structure is assembled as a unit on a rigid frame of Pyrex rods with sheet molybdenum supports. The bulb in which the electron gun and crystal move is 16 cm in diameter and has a semi transparent film of gold evaporated onto its inner surface for purposes of electrostatic shielding. The electrical leads to the gun are connected to re-entrant seals in a small tube at the top of the main bulb which is located directly above the axis of rotation of the gun and crystal. The leads to the gun filament consist of three braided strands of No. 29 copper wire, while the leads to the accelerating chambers of the gun are one strand of the same wire. Because these leads exert an appreciable torque opposing the motion of gun and crystal, a friction arrangement is attached to the magnetic control as a means of maintaining any desired angle. Most of the metallic parts are made of molybdenum, although small amounts of nickel are used at welded joints. The apparatus was assembled with clean tools, after all parts had been cleaned chemically.

The copper crystal is one previously used by Farnsworth.[4] The front face is parallel to the (100) set of crystal planes and observations are taken in

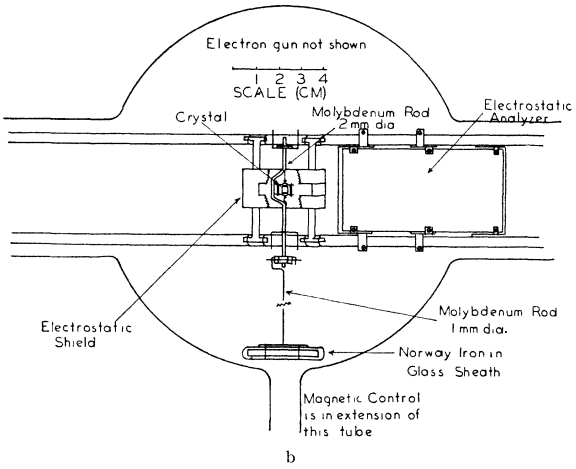


FIG. 1 (a). Schematic diagram of apparatus showing relative positions of electron gun, crystal, and electrostatic analyzer. (b). Diagram of crystal mounting and magnetic control.

the (100) azimuth. The crystal and its mounting are shown in Fig. 1b. A molybdenum plate is attached to the crystal mount so that it makes good thermal contact with the side of the crystal. The plate extends beyond the back face of the crystal and is heated by electron bombardment to outgas the crystal. The crystal can be rotated so that the separation of the plate and a fixed tungsten filament is of the order of two mm. This method of heating decreases the probability of recrystallization of the target during the bombarding process.

The electron gun is similar to that used by Farnsworth.[5] It consists of a platinum ribbon filament coated with oxides of barium, strontium, and calcium, an accelerating electrode, and a barrel containing diaphragms with rectangular openings to define the beam. The filament is shaped in the

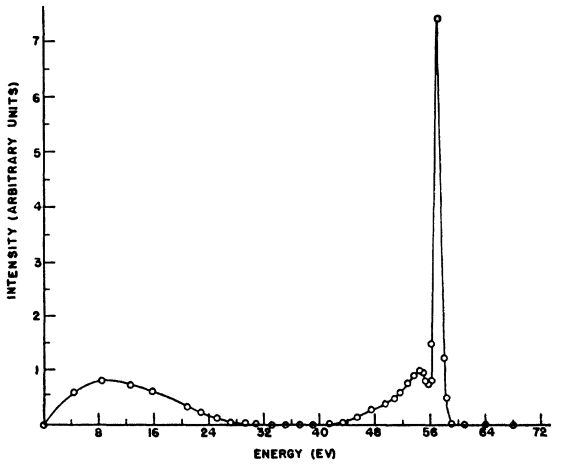


FIG. 2. Complete energy distribution curve at colatitude angle of 56° for primary energy of 57 ev.

[4] H. E. Farnsworth, Phys. Rev. **40**, 684 (1932).

[5] H. E. Farnsworth, Phys. Rev. **34**, 679 (1927).

form of a "T" to reduce the magnetic field. Three evenly spaced small tungsten wires placed over the opening in the diaphragm of the accelerating electrode decrease the field distortion in the neighborhood of the filament. The output of the gun, as measured by the total current to the crystal, is held constant for a set of readings. The defining cylinder of the electron gun, the target, and the entrance and exit slits of the analyzer are all at ground potential so that the electrons after leaving the gun and before entering the analyzer travel in a field-free space. This path is further protected by metallic shields. The distance between the exit slit of the gun and the crystal face is 40 mm.

The electrostatic analyzer is similar to that described by Hughes and McMillen[6] and has been treated theoretically by Rojansky.[7] The radii of the plates are 3.5 cm and 4.5 cm and the dimensions of the entrance and exit slits are 4×0.470 mm and 4×0.480 mm, respectively. This gives a theoretical

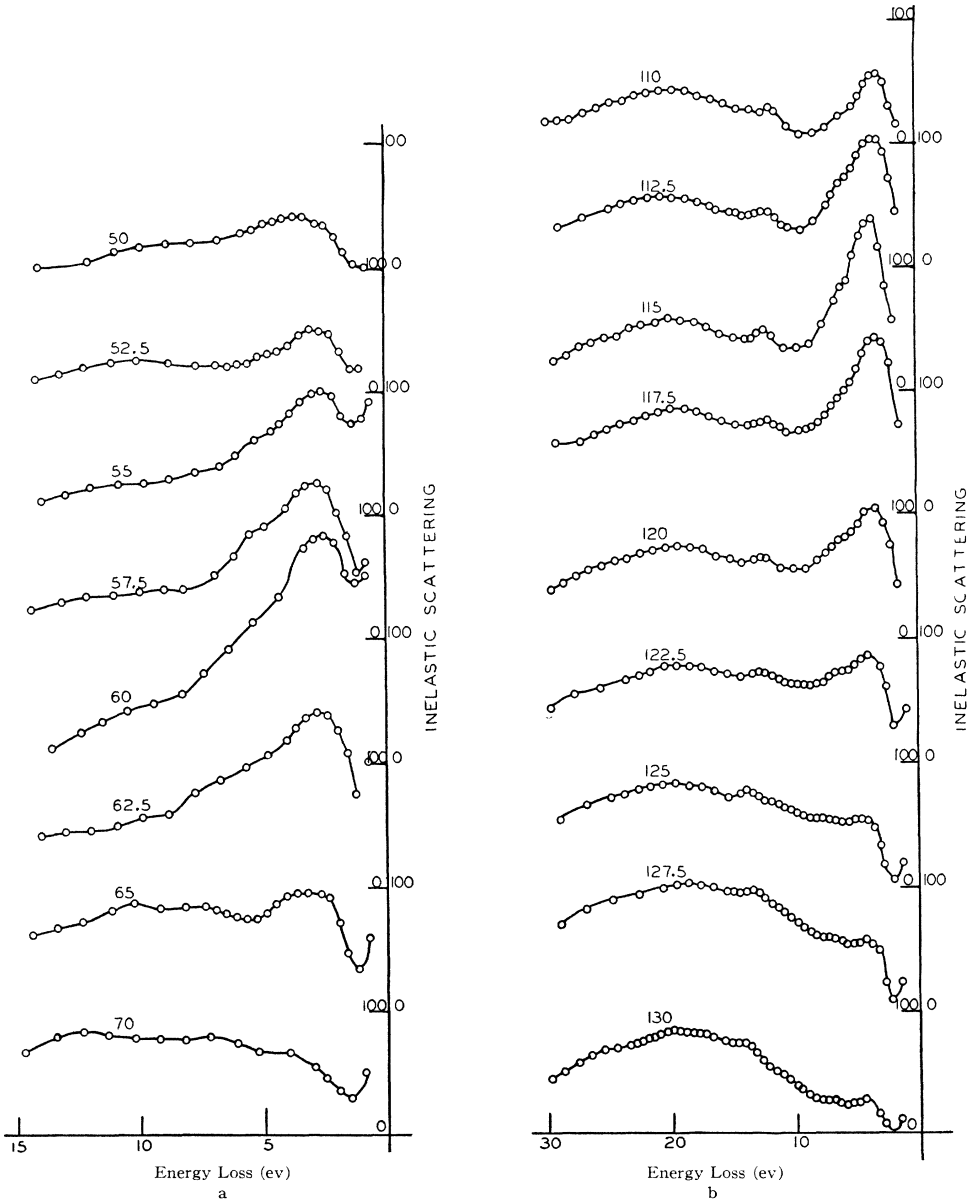


FIG. 3. Energy distribution curves of inelastically scattered electrons for the primary voltages given on the individual curves. The scattering or colatitude angle is 60° for all curves in Fig. 3a, and 40.5° for curves in Fig. 3b. The peaks for elastically scattered electrons at zero energy loss are not shown.

[6] A. L. Hughes and J. A. McMillen, Phys. Rev. **34**, 291 (1929).
[7] V. Rojansky, Phys. Rev. **34**, 284 (1929).

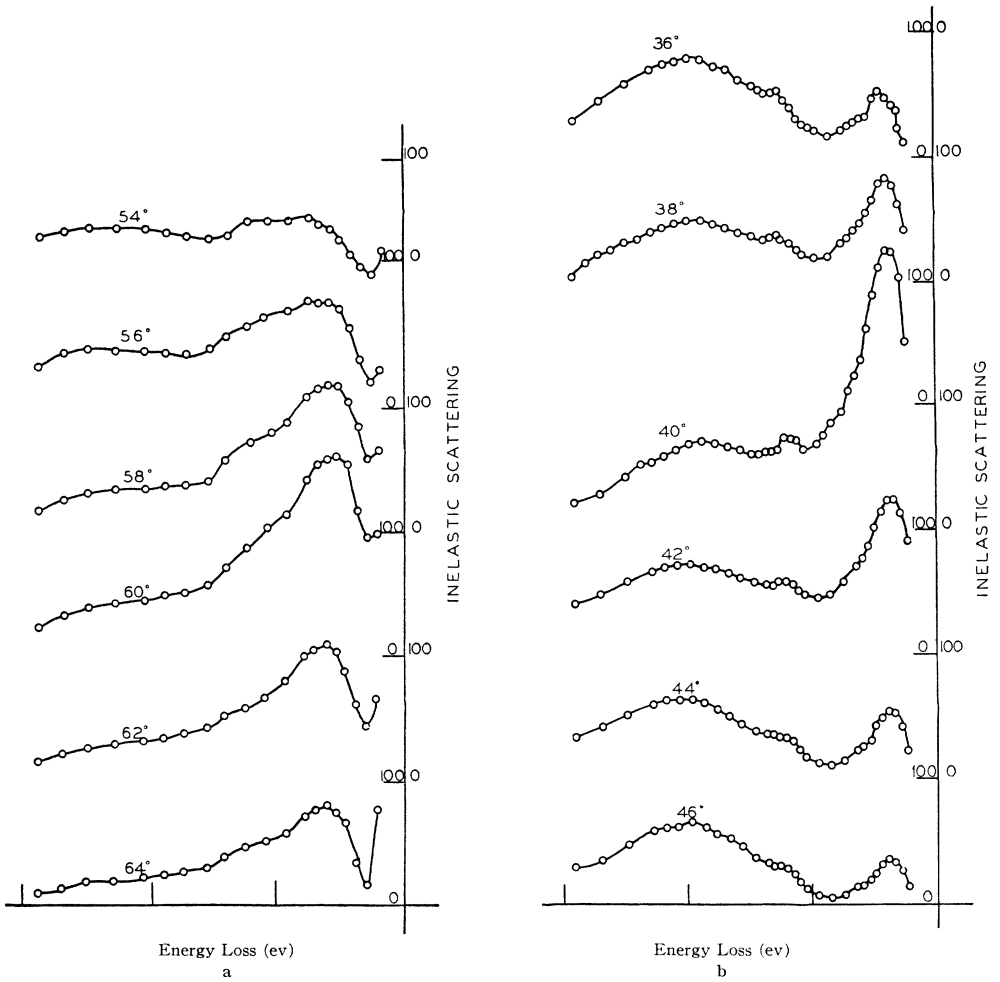


FIG. 4. Energy distribution curves of inelastically scattered electrons for the colatitude angles given on the individual curves. The primary voltage is 59.5 for all curves in Fig. 4a and 114.5 for curves in Fig. 4b.

resolving power of $\Delta V/V=0.0273$ as compared with 0.0265 for the magnetic analyzer used by Turnbull and Farnsworth and 0.009 for the electrostatic analyzer used by Rudberg. All parts of the analyzer are made of molybdenum, with the exception of platinum-iridium foil slits. The various components of the analyzer are insulated electrically from one another by thin strips of mica.

The collector is of the double wall type, with fused silica insulation between the walls. The current to the collector is measured by a balanced bridge direct current amplifier with a FP-54 tube. Used in conjunction with a galvanometer of sensitivity 10^{-10} ampere per millimeter, the amplifier has a maximum sensitivity of approximately 10^{-16} ampere per millimeter. This maximum sensitivity is required for most of the observations. The earth's magnetic field is compensated by Helmholtz coils of 1-meter diameter, and 0.5-meter separation.

During the initial period of alternate bombardment of the crystal and experimental observations on the elastic scattering, the experimental tube was pumped continuously. Pressures obtained at this point were of the order of 10^{-8} mm of mercury as measured by an ionization gauge. When the crystal had been outgassed sufficiently so that strong diffraction beams of elastically scattered electrons appeared, the tube was gettered, using RCA type Barium getters, and sealed off. Further outgassing of the crystal at dull red heat was continued at intervals during the period of making observations.

Figure 2 shows a typical energy distribution curve obtained at a colatitude angle of 56° for electrons having a primary energy of 57 ev. The elastically scattered electrons are represented by the sharp peak at the extreme right of the curve. The position of this peak serves to establish the zero on the energy loss scale for all subsequent figures. The intensity of the reflection peak is such that it cannot be plotted on the scales chosen for

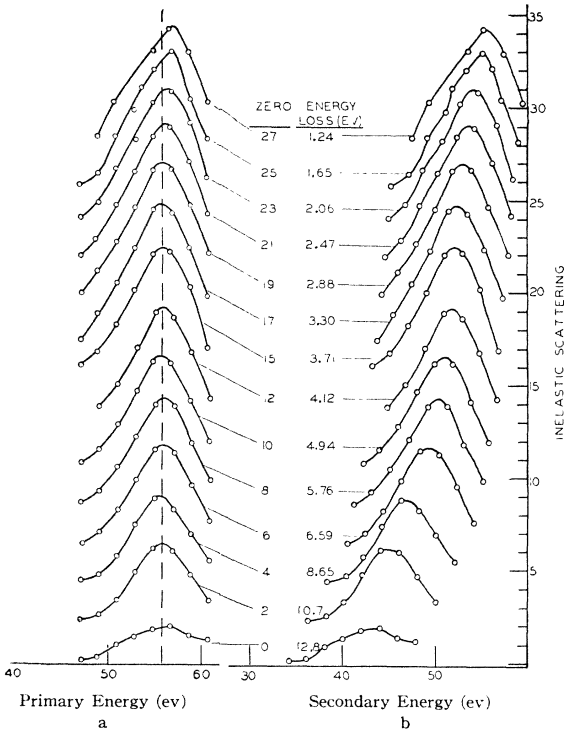


FIG. 5. Inelastic scattering for constant values of energy loss about the diffraction peak at 59.5 ev. Successive curves are shifted vertically; the zeros and energy losses are given in the figure. The same data are used for the two sets of curves but are plotted with different abscissas.

subsequent figures. However, its position was always measured in order to determine the zero on the energy loss scale.

Immediately to the left of the reflection peak is the portion of the distribution curve associated with inelastic collisions. This research is confined to a study of the character of the structure in this region of the distribution curve. The relatively broad maximum in the curve which appears at low energies is due to secondary emission. Some evidence of structure has also been found in this region for molybdenum by Haworth.[1]

The following evidence indicates that the measurements on inelastic scattering are not due to elastically scattered primaries which have reached the collector. The absence of any measurable current on the high energy side of the main reflection peak is an indication of the resolution of the analyzer. The positions of the energy loss peaks observed for the copper single crystal correspond reasonably well to similar peaks for polycrystalline copper observed by Rudberg[2] using magnetic rather than electrostatic analysis.

THE INELASTIC SCATTERING

A. The Discrete Loss Peaks

Observations were made in the neighborhood of the two diffraction peaks in the (100) azimuth which were observed to occur at 59.5-ev and 114.5-ev primary energies, with colatitude angles of 60° and 40.5°, respectively. The curves in Figs. 3a and 3b show the distribution of energy of the inelastically scattered electrons for various values of the primary voltage near two different diffraction peaks. Each curve represents the energy distribution of the secondary electrons which are inelastically reflected from the crystal, for a constant value of primary energy and of colatitude angle. A comparison of these curves for either peak shows the variation of results as the primary energy is changed from the critical value for the diffraction peak in question. The curves in the neighborhood of the peak at 59.5-ev primary energy, and shown in Fig. 3a, show clearly the presence of one discrete loss peak indicating a most probable energy loss of about 3 ev. The presence of two other discrete loss values at approximately 6 and 11 ev may also be detected, but these are not pronounced or sharp. The curves taken in the neighborhood of the second diffraction peak at 114.5-ev primary energy, Fig. 3b, show four discrete loss values at approximately 3.6, 6.0, 12.3, and 20 ev, respectively.

Both sets of curves indicate a decided dependence of intensity of the first discrete loss peak on the primary energy of the electrons. In each case this peak attains its maximum value at or near the primary voltage for the main diffraction peak. Because of the broadness, overlapping, and low intensities of the other discrete loss peaks occurring near the 59.5-ev diffraction beam, changes of their intensities with changes in primary energies are not pronounced. In the neighborhood of the other main diffraction peak at 114.5-ev primary energy the discrete loss peak at 20.0-ev energy loss attains a maximum value at two different primary energies; one at about 117.5 ev and the other at about 127.5 ev. The intensity variation of the peak at 12.3 ev is difficult to determine, but it appears that this peak also attains a maximum at two primary energies which are approximately the same as those for the 20-ev peak. These observations check with other results which are considered later.

The curves in Figs. 4a and 4b show the change in the distribution of energy of the inelastically scattered electrons as the colatitude angle is varied. Each of the curves shows the energy distribution in the inelastically scattered electrons for a constant value of primary energy and particular colatitude angle. A comparison of these curves in the vicinity of either diffraction peak shows that the first discrete loss peak is most pronounced at the colatitude angle for the diffraction peak in question.

The variations of the other weaker discrete loss peaks with colatitude angle are not well defined but appear in approximate agreement with that of the first discrete loss peak.

B. Total Scattering with Energy Loss

Examination of the curves of Figs. 3a and 3b and of Figs. 4a and 4b indicates that, disregarding the structure appearing in the curves, the background scattering is largest where the elastic scattering is largest. This is most pronounced for small values of energy loss, where the amount of extra background scattering increases with decreasing energy loss. For larger values of energy loss it is difficult to separate the background scattering from the discrete loss scattering. Accordingly, the following observations include both types of scattering.

Data were taken in the following manner to determine the dependence of the total inelastic scattering on the secondary energy of the electrons. The position of the crystal and electron gun with respect to the analyzer was set at the critical angle for the main diffraction peak. Then, starting with a primary energy below the critical value for the main peak, the potentials on the plates of the electrostatic analyzer were adjusted so that only electrons of some definite energy loss were measured. Then the primary energy was changed and the potentials on the plates of the analyzer were changed correspondingly so that again only electrons of the same energy loss were measured. In this manner points for one curve were obtained, and those for succeeding curves resulted by repeating this procedure for other values of energy loss. The experimental curves are shown in Figs. 5 and 6. Figures 5a and 5b contain curves of the total inelastic scattering plotted against both primary and secondary energy in the vicinity of the diffraction beam at 59.5 ev.

The curves in Fig. 5 show that the maxima in the neighborhood of the first diffraction peak are essentially constant in primary energy, except for several of the lower energy-loss curves, and occur at about 56 ev, instead of 59.5 ev, the value for the first diffraction peak. The fact that the maxima occur at a constant primary energy suggests that the primary electrons are diffracted before suffering energy losses of varying amounts corresponding to the background scattering. But if this were the complete explanation the maxima should occur at 59.5 ev instead of 56 ev. One possible interpretation of this discrepancy is that the effective inner potential of the crystal is greater for electrons which are first diffracted and then suffer inelastic collisions as they leave the crystal than it is for elastically diffracted electrons. There is ample evidence[8] that the effective inner potential is not constant,[9] at least in the range of primary energies below 150 ev. Also, as the energy loss becomes smaller, one would expect the process to approach that for elastically scattered electrons so that the maximum should shift toward 59.5 ev as the energy loss decreases. This shift is exhibited by the uppermost curves corresponding to energy losses less than about 2.5 ev, in Fig. 5a. However, if diffraction occurs before inelastic scattering it is difficult to understand why the diffracted electron, which later suffers an inelastic collision, should be subject to a higher value of inner potential.

Reference to the curves in Fig. 6 show that in the neighborhood of the 114.5-ev diffraction peak the results are more complicated than those just discussed. The following characteristics are to be noted. The maxima for different energy losses are not constant in either primary or secondary energy. For the larger energy-loss curves there are two maxima. For several of the curves in limited ranges of energy loss the maxima are constant in primary energy and a similar statement applies for secondary energy. For energy losses below about 10 ev, the maxima are essentially constant in secondary energy, suggesting inelastic background scattering followed by diffraction. Furthermore, the maxima occur at a secondary energy of about 114.5 ev, which is that of the second diffraction peak, as one expects for the above double process. Even in the two lowest curves, corresponding to larger energy losses, one notes maxima at approximately the above value of secondary energy. However, in the curves for energy losses greater than about 10 ev, there is a shift and then a splitting of the maxima as the energy loss increases. While one set of maxima is nearly constant in primary energy, the other set is nearly constant in secondary energy (with one exception in each case). That which is

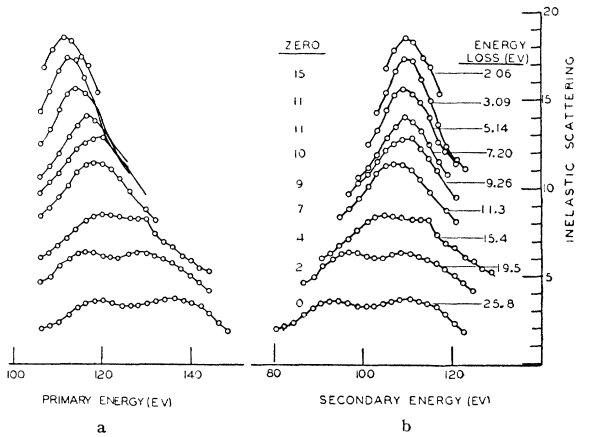


FIG. 6. Inelastic scattering for constant values of energy loss about the diffraction peak at 114.5 ev. Successive curves are shifted vertically; the zeros and energy losses are given in the figure.

[8] H. E. Farnsworth, Phys. Rev. **34**, 690 (1929).

[9] L. Sturkey (Phys. Rev. **73**, 183 (1948)) has shown that there are double values of the effective inner potential when primary electrons are incident on a set of crystal planes at the Bragg angle.

constant in primary energy suggests diffraction followed by inelastic background scattering as in the first case considered. However, in the present case the maxima occur at about 118 ev which is 3.5 ev greater than the 114.5 ev for the diffraction peak. As in the first case we may associate this difference with a variation in the effective value of inner potential. It may also be attributed to a discrete energy loss of 3.5 ev (which agrees approximately with the value for the first discrete loss peak) which precedes the diffraction. The experimental evidence is not sufficient to justify a definite conclusion. The number of observations was limited by a failure in the experimental tube.

SUMMARY

The following processes have been postulated to interpret the results:

(1) For the results in the vicinity of the 59.5-ev diffraction beam.—Diffraction followed by inelastic background scattering. However, the maxima occur at 3.5 ev below the 59.5 ev of the diffraction beam.

(2) For the results in the vicinity of the 114.5-ev diffraction beam.—(a) Inelastic background scattering followed by diffraction, for energy losses below 10 ev. The maxima occur at the secondary energy of 114.5 ev which checks with the 114.5-ev diffraction peak. (b) The same as (a) plus diffraction followed by inelastic background scattering, for energy losses above 10 ev. The maxima for the latter process occur at 118 ev instead of at 114.5 ev which corresponds to the diffraction maximum.

PHYSICAL REVIEW VOLUME 75, NUMBER 12 JUNE 15, 1949

The Surface Photoelectric Effect

R. E. B. MAKINSON
School of Physics, University of Sydney, Australia
(Received December 20, 1948)

An expression is derived for the photoelectric current produced at the surface of a metal, the conduction electrons being supposed free and the potential barrier of arbitrary shape. The validity of the common assumption that the current arising from conduction electrons of a particular momentum can be expressed as the product of an excitation function and a transmission coefficient is examined. It is concluded that the assumption is in general valid. The production in the photoelectric current of beat frequencies between spectral lines is also briefly discussed.

I. INTRODUCTION

IN discussions of the surface photoelectric effect in metals, particularly in deriving an expression for the threshold frequency at 0°K from data obtained at higher temperatures, it has frequently been assumed that the photoelectric current arising from conduction electrons of given momentum in the metal may be expressed as a product of an excitation function and the transmission coefficient of the surface barrier for the excited electrons. The excitation function is then assumed not to vary rapidly near the threshold frequency.

No general proof of the validity of this factorization appears to have been given in accessible literature, but doubts as to its validity have been expressed.[1,2]

An extension of earlier work[3] is given below in which a formal expression of great generality for the photoelectric current is derived. From this it appears that the factorization mentioned and the smooth variation of the excitation function near the threshold are in general justified. The theory is easily extended to enable discussion of the possible production of beats between spectral lines.

II. ASSUMPTIONS

If we suppose that the conduction electrons are free in the interior of the metal and neglect their interaction, the potential energy of each may be represented near the surface by a potential $V(x)$ which has some such form as shown in Fig. 1(a).

The wave function u for an electron unperturbed by incident light satisfies

$$(h^2/2m)\nabla^2 u + ih\partial u/\partial t - Vu = 0. \quad (1)$$

Putting

$$u = u_k = \psi_k \exp(-iE_k t/h), \quad (2)$$

let

$$\psi_\kappa = \alpha_k \phi_k(x) \exp(ik_2 y + ik_3 z);$$

then

$$\phi_\kappa'' - \{p^2 + (\mu/h)V(x)\}\phi_k = 0,$$

where

$$p = (\mu\nu_a - k_1^2)^{\frac{1}{2}} > 0, \quad \mu = 8\pi^2 m/h,$$

$$k^2 = k_1^2 + k_2^2 + k_3^2 = (8\pi^2 m/h^2)(E_k + h\nu_a).$$

[1] R. H. Fowler, *Statistical Mechanics* (Cambridge University Press, London, 1936), p. 358.
[2] E. Guth and C. J. Mullin, Phys. Rev. **59**, 868 (1941).
[3] R. E. B. Makinson, Proc. Roy. Soc. **A910**, 367 (1937). The same notation is used here. Essentially the present discussion was given in a Dissertation by the author, University of Cambridge, England, 1938.