1.005 for both He I and He II near the λ-point, the relative change in the adiabatic compressibility should be very nearly the same as that in the isothermal value. This should cause an increase in the velocity of sound of about 2.5 percent. However it will be seen from Fig. 3 that the change at the λ-point, if any, is not more than 0.5 percent. It will be seen, further, that the measured velocity is a maximum in He I at 2.5°K. Such a maximum is not predicted by calculations based on the published data for liquid helium, and there may be some significance in the fact that the increase from the value in He II at the λ-point to the maximum in He I is approximately equal to the increase predicted by Ehrenfest's relations.

Wave Form

As the reflector was moved, there appeared in addition to the main maxima of the galvanometer deflection, smaller secondary peaks. These peaks maintained the same positions relative to the primary maxima as the reflector was moved, and were the same for all liquids used, with the exception of liquid He II. Hence they could not be attributed to different velocity or frequency components. It is thought that they are due to some discontinuity in the activity of the crystal. In liquid helium, there was a distinct change in the form of these secondary peaks on passing from He I to He II. However, their form remained constant throughout the motion of the reflector in both liquids, and hence the measurements of the wave-length should not be affected. This change in wave form may be related in some way to the peculiar physical properties of He II.

In conclusion, the authors wish to thank Dr. E. F. Burton for his kindly interest and guidance in this research.

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The Inelastic Scattering of Slow Electrons From a Silver Single Crystal

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The energy distribution of electrons inelastically scattered from a (111) face of a silver single crystal has been studied by the method of magnetic deflection. At about 45° incidence primary electrons are regularly reflected into the analyzer, and diffraction beams are observed at primary energies of 7.7, 23.2, and 83.2 ev. The structure in the energy distribution shows two discrete loss peaks at 3.9 and 7.3 ev, respectively, in general agreement with that found by Rudberg for polycrystalline silver. However, the relative intensities of the two discrete loss peaks depend on both the primary voltage and the target angle in the neighborhood of the diffraction beams, while Rudberg has found that for polycrystalline targets the peaks are independent of these variables. The energy distribution curves are also distorted by an extra inelastic scattering which accompanies the elastic scattering of the diffraction beams, and which extends down to an energy loss of 10 to 15 ev. Thus, maxima are observed in the curves giving the amount of inelastic scattering as a function of the primary energy for the constant values of energy loss. The maxima occur at secondary energies equal to the critical voltages of the diffraction beams. This indicates the existence of a double process consisting of inelastic scattering of the incident electrons followed by diffraction of the scattered electrons by the crystal lattice.

Introduction

Previous measurements[1] of the energy distribution of electrons scattered from an outgassed metal target in high vacuum have shown that certain discrete energy loss peaks are superposed on the general background of inelastic scattering. For polycrystalline silver there are two such peaks at 3.9 and 7.8 ev

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

[1] Rudberg, Phys. Rev. **50**, 138 (1936); **45**, 764 (1934); Proc. Roy. Soc. **A127**, 111 (1930); K. Svenska Vet. Akad. Handl. **7**, 1 (1929). Haworth, Phys. Rev. **48**, 88 (1935); **37**, 93 (1931); **42**, 906 (1932).

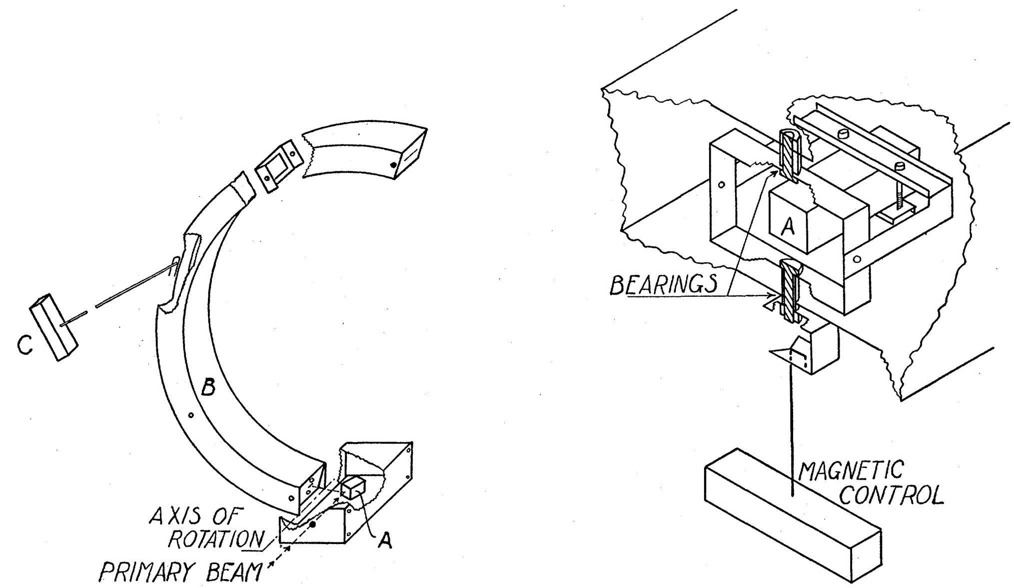

FIG. 1. Diagram of apparatus showing (a) (left) magnetic analyzer, (b) (right) detail of crystal mounting.

energy-loss. The intensities of these discrete loss peaks were found to be independent of the energy of the incident electrons and also of the angle of incidence.

The present experiments show that for a single crystal of silver the intensities of the discrete loss peaks are a function of both the energy of the incident electrons and the angle of incidence. Such a variation might be expected in the neighborhood of the intense diffraction beams which issue from the single crystal surface. A recent theoretical treatment by Slater[2] shows that inelastic scattering of the incident electrons should modify a diffraction beam by lowering and broadening the theoretical maximum. Agreement with the experimental maximum is obtained when considerable inelastic scattering is assumed. Consequently, the presence of a diffraction beam may be expected to modify the inelastic scattering. Davisson and Germer[3] observed a change in the background inelastic scattering in the neighborhood of a diffraction beam. In the present paper a more detailed study of this has been made, in addition to an investigation of the effect of a diffraction beam on the discrete loss peaks.

[2] Slater, Phys. Rev. **51**, 840 (1937).
[3] Davisson and Germer, Phys. Rev. **30**, 705 (1927).

Apparatus and Procedure

The apparatus and procedure are similar to Rudberg's.[1] Most of the metallic parts are made of molybdenum. As shown in Fig. 1a the primary electrons move parallel to the magnetic analyzing field, and the analyzer B gives the distribution in energy of the secondary electrons leaving a 2 mm spot on the surface of the target A in a direction perpendicular to the magnetic field. The analyzer contains stops which limit the spread in angle of the collected electrons so that sharp diffraction beams are obtained. Consequently the slit widths must be large enough to give measurable collector currents, thus producing a relatively low resolving power ($\Delta V = 0.027\,V$) as compared with $\Delta V = 0.012\,V$ obtained by Rudberg and $\Delta V = 0.006\,V$ obtained by Haworth.

The crystal is one which was formerly used by H. E. Farnsworth in experiments on diffraction of low speed electrons. Its target face is cut, ground and etched parallel to the (111) planes.[4] The crystal is turned by a magnetic control about a vertical axis (Fig. 1b) which lies in this face and which is perpendicular to the axis of the electron gun and to the initial direction of motion of the electrons going through the analyzer. The

[4] Farnsworth, Phys. Rev. **49**, 602 (1936).

target angle is measured between the normal to the crystal face and the axis of the gun. A second magnetic control C rotates the analyzer through a small angle about an axis parallel to its slits, thus slightly moving the spot on the crystal face from which secondary electrons are collected. In this way the normal to the crystal face may be brought accurately into the plane in which the primary and secondary electrons under consideration move by maximizing the elastic scattering when the other variables are adjusted for a diffraction beam. The output of the gun is constant during the experiment, and in order to permit the above adjustment (of the normal) the primary beam diverges from a hole in the end of the gun so that primary electrons strike the entire face of the crystal. The target and analyzer are at the same potential, and the distribution in energy is obtained by varying the magnetizing current of the Helmholtz coils (radius 7 inches) producing the magnetic field. This current, which passes through a standard resistance, and the primary voltage are obtained with a type K potentiometer. The current to the collector of the analyzer (10^{-13} to 10^{-14} ampere) is measured as a direct deflection by the single tube FP-54 balanced amplifier circuit. The target is outgassed at a dull red heat by bombardment of the mounting on the back side. The system is pumped continuously, and during the final stages of the outgassing pressures of about 5×10^{-8} mm were recorded. At this time a curve could be repeated for several hours after outgassing the target. The pumping system consists of two Apiezon oil vapor pumps backed by a Cenco Hyvac pump. The condensing traps between the experimental tube and vapor pumps, and between the Hyvac pump and vapor pumps are cooled with CO_2 snow in acetone.

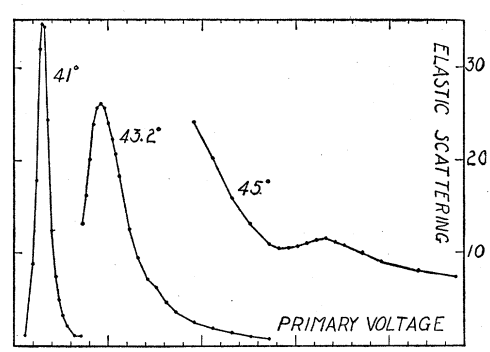

FIG. 2. Elastic scattering as a function of the primary voltage. The values of target angle for regular reflection on the (111) planes are indicated.

RESULTS AND DISCUSSION

The elastic scattering

The energy distribution curve of the secondary electrons has a sharp peak due to electrons reflected from the crystal. The height of this peak is taken as a measure of the elastic scattering. Fig. 2 gives the elastic scattering as a function of the primary energy, which is corrected for contact potential difference. There are maxima at 7.7, 23.2, and 83.2 ev which represent diffraction beams from the (111) planes. The target angle (indicated beside each curve) is set for maximum collector current with the primary energy adjusted on the maximum in the voltage curves. The angle for the 83.2-volt beam is assumed to be 45°. The angle of the 23.2-volt beam is then 43.2°, and of the 7.7-volt beam 41°. Inaccurate alignment could account for only about one-half of the observed variation of 4° in the critical angle. This variation is probably real since Farnsworth[5] has observed a similar

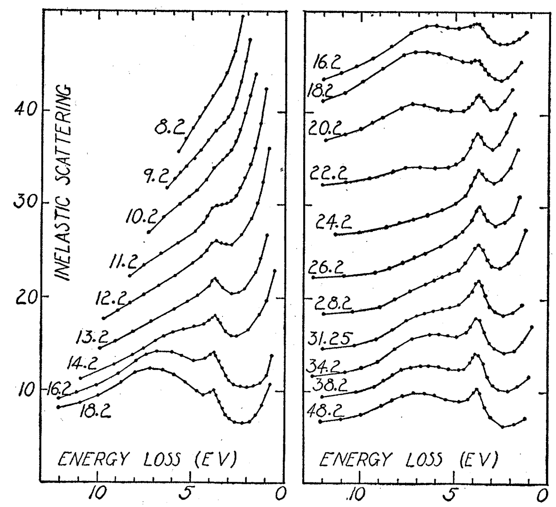

FIG. 3. Distribution curves for the primary voltages given on the curves. The target angle was set at 41° for (a) left), and at 43.2° for (b) (right). The curves are normalized so that the intensity of scattering is 10 at the peak at about 3.7 ev energy loss. Beginning with the lowest curves, the ordinate zeros are at 0, 4, 8, 12, etc., units.

[5] Farnsworth, Phys. Rev. **40**, 684 (1932).

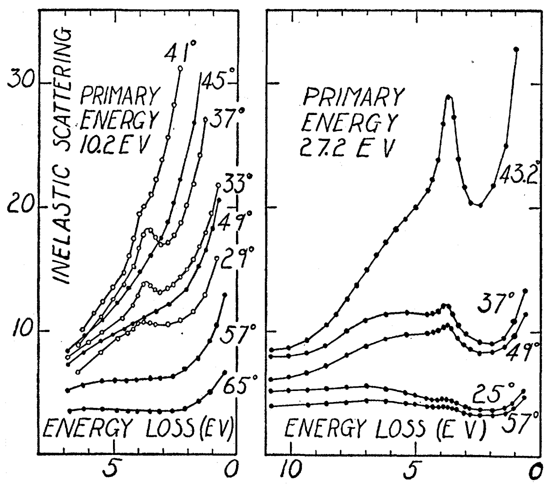

FIG. 4. Distribution curves as a function of the target angle, for values of primary voltages near two diffraction beams.

change in the angle for regular reflection from a silver crystal. Possibly this variation is connected with the nonsymmetrical colatitude curves found by Farnsworth[4] which indicate the existence of beams other than those corresponding to Bragg reflection. The intensities of the beams increase to constant values as the outgassing proceeds. The data given in Fig. 2 were taken immediately after outgassing and were repeated within 10 percent over a period of a month. The beams are not due to a lattice of gas atoms since Farnsworth[5] has found that the gas beams from a silver crystal are weak and disappear rapidly when the target is outgassed.

The discrete loss peaks

The curves in Fig. 3 show distributions in energy losses for various primary voltages. The target angle is set at the critical value for the nearest diffraction beam, 41° for Fig. 3a and 43.2° for Fig. 3b. Except for the lowest values of primary energy, the energy distribution curves have two maxima in addition to the peak due to the elastically scattered electrons which is not shown in the figures. In Fig. 3a, the peak at about 3.7 ev energy loss first appears at a primary voltage of 10.2 volts and increases in intensity relative to the background scattering as the primary voltage is increased. The observed energy loss for this peak increases from about 3.7 ev at 10 ev primary energy to the value given by Rudberg (3.9 ev) at primary energies above 50 ev. In the neighborhood of the second diffraction beam (Fig. 3b) the relative intensity of the first energy loss peak is nearly constant. The second peak at about 7.3 ev energy loss first appears at a primary voltage of 14.2 volts. It disappears (Fig. 3b) at a primary voltage of about 23, but reappears rapidly as the primary voltage is increased above this value. Corresponding results in the neighborhood of the third diffraction beam indicate that, when the primary voltage is varied, the intensities of the discrete loss peaks change by about the same relative amount as the elastic scattering.

Figure 4 gives the distribution in energy losses as a function of the target angle, in the neighborhood of the diffraction beams at 7.7 and 23.2 ev, respectively. Fig. 4a, taken for a primary voltage of 10.2, shows that the development of the first discrete loss peak at about 3.7 ev energy loss depends strongly on the target angle. This peak is strongest at an angle of about 37°. The angle for its maximum development increases as the primary voltage increases, and approaches the critical angle for diffraction at about 20 ev primary energy. At 7.2 ev primary energy these angles differ by about 10°, so that the change in the first angle (about 10°) is much larger than the change in the critical angle (about 2°) in this range of primary voltage. In Fig. 4b, taken for a primary voltage of 27.2, the intensity of the first peak increases to a maximum at a target angle of 43.2°, which is also the critical angle of the diffraction beam. The development of the peak is nearly symmetrical about this value of target angle. The intensity of the second peak is also greatest at the critical angle, but the relative intensities of the two peaks vary with the target angle. The results observed about the third diffraction beam are similar to those in Fig. 4b except that the discrete loss peaks retain about the same relative intensities as the target angle is varied.

Background scattering with energy loss

If one neglects the structure in the curves of Figs. 3 and 4, it becomes evident that the inelastic scattering for energy loss up to 10 or 15 ev is large when the elastic scattering is large. In Fig. 4a, for example, the curve for 41° rises

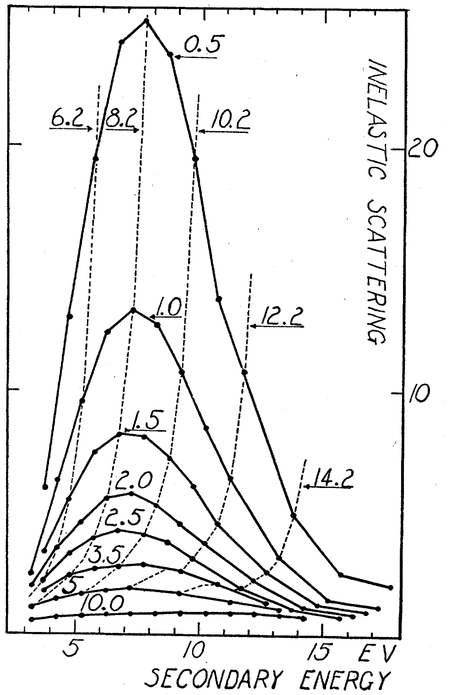

FIG. 5. Inelastic scattering about the diffraction beam at 7.7 ev. The dotted lines are parts of the distribution curves, on which the primary voltages are indicated. The full lines give the inelastic scattering for constant values of energy loss, which are also given on the curves.

faster at low values of energy-loss than the curve for 57°. The same behavior can be seen in Fig. 3 as the primary voltage is varied. Thus, there is an extra amount of inelastic scattering for small values of energy-loss, which accompanies the large elastic scattering of the diffraction beams, and which increases as the energy-loss is decreased.

The dependence of this extra inelastic scattering on the secondary electron energy is given in Figs. 5 and 6. Fig. 5 is taken at the critical angle (41°) and for energies near the diffraction beam at 7.7 ev. The dotted lines are parts of the distribution curves. The inelastic scattering for constant values of energy-loss is given as a function of the energy of the secondary electrons by the solid curves, which are obtained from the dotted curves. The maxima in these curves lie within one ev of the critical energy of the first diffraction peak (7.7 ev). The maxima become broader and disappear as the energy-loss is increased. The curves of Fig. 6, taken directly about the second diffraction beam at 23.2 volts, are entirely similar to those of Fig. 5. The small bump in the elastic scattering at 40 ev (Fig. 2) appears in some of these curves at a secondary energy of 40 ev. The results for the third diffraction peak are also like those of Fig. 5. This behavior of the inelastic scattering is not due to scattering within the analyzer, which would produce maxima at constant values of *primary* energy. There is, however, a possible source of error. The primary current density at the spot on the crystal from which the analyzer collects electrons depends on the analyzing field because of magnetic focusing, even though the output of the gun is constant. This would be expected to decrease the scattering for small secondary energy, and thus displace the maxima towards higher values of energy. The magnetic focusing, however, depends on the potentials of the elements of the electron gun, and, since the maxima are unchanged when these potentials are varied, it is thought that the effect of the magnetic focusing is negligible.

Discussion of results

Davisson and Germer,[3] who first observed the extra inelastic scattering by the retarding potential method, suggested that the extra elec-

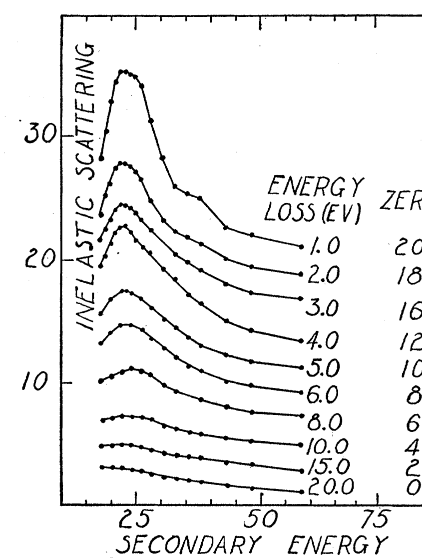

FIG. 6. Inelastic scattering for constant values of energy loss, about the diffraction beam at 23.2 ev. Successive curves are shifted vertically; the zeros and energy losses are given on the curves.

trons were due to a double process consisting of diffraction of the incident electrons followed by energy loss of the reflected electrons as they leave the crystal. Rudberg and Slater[6] have shown that for single collisions the probability of scattering on a crystal should be approximately proportional to some inverse power of ΔK, where ΔK is the change in momentum for the collision. The inelastic scattering thus decreases as the energy loss increases and, for a given energy loss, is a maximum in the original direction of the primary beam. Hence the contribution of the above double process should be a maximum when the elastic scattering is largest. The observed angle for maximum inelastic scattering does in general coincide with the critical angle for diffraction. But, since the maxima in Figs. 5 and 6 occur at constant values of secondary energy, the above double process is inadequate. These experimental results indicate the existence of another double process in which the primary electrons are first inelastically scattered without appreciable change in their original direction of motion, and then reflected from the (111) planes. Thus the reflection of the inelastically scattered electrons should be a maximum at the critical angle, and at a secondary energy equal to the critical energy for diffraction. This is just what is observed.

If the above double process also applies to the electrons responsible for the discrete loss peaks, we should expect that (1) the inelastically scattered electrons would be diffracted in the same direction as that of the elastically scattered electrons, and (2) the secondary energy, i.e., the energy after collision, should be the one which governs the diffraction of these electrons rather than the energy of the incident electrons before collision. As seen from Fig. 4, condition (1) is satisfied by the first discrete loss peak except for the deviation at very low primary energies. Condition (2) requires that the intensities of the discrete loss peaks should be a maximum when the secondary energy equals that for a diffraction beam of elastically scattered electrons, i.e., when the primary energy is that for a diffraction beam plus the energy loss corresponding to the discrete loss peak. Similar reasoning should apply to the minimum intensities as a function of primary voltage. Referring to Fig. 3b, we note that the second discrete loss peak disappears at about 24 volts. By subtracting the energy loss of 7 for this peak we obtain 17 volts which checks well with the minimum at about 17 volts in the curve of Fig. 2. However, there appears to be no minimum in the intensity of the first discrete loss peak at about 21 ev primary energy where it would be expected. The primary voltages for which the discrete loss peaks attain maximum values are less certain, but, as mentioned previously, they do appear to be in the neighborhood of the voltages for diffraction beams of the elastically scattered electrons. However, further experiments are required to determine whether or not a detailed correlation exists. Plans are being made in this laboratory to construct an electrostatic analyzer with which it will be possible to extend the present observations to the neighborhood of many more diffraction beams, particularly for the case of normal incidence.

[6] Rudberg and Slater, Phys. Rev. **50**, 150 (1936).