

REFLECTED AND SECONDARY ELECTRONS FROM AN ALUMINUM TARGET

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ABSTRACT

Velocity distributions of secondary electrons from an aluminum target, bombarded with homogeneous streams of primary electrons, were examined with a magnetic analyser. The secondaries examined were those coming off approximately at right angles with the primary beam. The range of primary velocities used was from 5 volts to 175 volts. Sharply defined peaks, consisting of electrons reflected without loss of energy, constitute 2 percent of the whole distribution at 175 volts, 10 percent at 35 volts, 90 percent at 12 volts, and 95 percent at 7 volts. The coefficient of reflection at right angles is of the order of 10^{-3} to 10^{-2} per unit solid angle, increasing over twenty fold between 100 volts and 8 volts, attaining a maximum at 7 or 8 volts and decreasing sharply below that.

J. A. BECKER¹ and E. L. Rose,² using a magnetic velocity analyser, found evidence for the existence of a very sharply defined, true reflection of electrons without energy loss when a metal target is bombarded with a primary electron stream. Since the present work was started, C. F. Sharman³ and D. Brown and R. Whiddington⁴ have reported the same phenomenon. Other observers, notably A. Becker⁵ and H. E. Farnsworth,⁶ using total current and retarding potential methods, had shown the existence of a considerable fraction of the secondary electrons having a velocity at least very close to that of the primary stream. C. Davisson and C. H. Kunsman,⁷ had investigated the angular distribution about the target, of the secondaries having velocities 90–100 percent of that of the primaries and had assumed, in interpreting their results, that they were dealing with electrons reflected by single atoms. The present work was undertaken with a view to securing quantitative data on the intensity of such reflection.

The apparatus used had been set up by Mr. O. Ritzmann and was originally intended to study soft x-rays by magnetic analysis of the photoelectrons ejected from an aluminum target. It consisted essentially, see Fig. 1, of an analyser, *A*, with the aluminum target, *T_a*, before the first slit, and a Faraday collector, *C*, behind the last slit; together with a straight tungsten filament, *F*, and copper target, *T_c*, enclosed in a cylindrical shield, *G*, having a window and wire grid between the two targets.

¹ J. A. Becker, Phys. Rev. **24**, 478–85 (1924).

² Rose, Phys. Rev. **25**, 883(A) (1925).

³ Sharman, Proc. Cambr. Phil. Soc. **23**, 523–30 (1927).

⁴ Brown and Whiddington, Nature **119**, 427 (1927).

⁵ A. Becker, Ann. d. Physik. **78**, 209 (1925).

⁶ Farnsworth, Phys. Rev. **25**, 41–57 (1925).

⁷ Davisson and Kunsman, Phys. Rev. **22**, 242–58 (1923).

The whole was enclosed in Pyrex and could be evacuated by means of a two-stage mercury condensation pump backed by a Cenco Hyvac. Besides the usual vapor trap between pump and apparatus, there was a large charcoal trap near the aluminum target. The whole could be enclosed in a furnace and baked out at a temperature of 450°C before using. It was thus possible to get a vacuum of 1.5 to 2.0×10^{-6} mm of mercury as measured on an ionization gauge.

A large solenoid, with its axis vertical, could be lowered over the whole apparatus to supply the magnetic field for the analyser. A small earth inductor, mounted as indicated in the figure, gave a ready means of determining the correction to be applied for the vertical component of the earth's

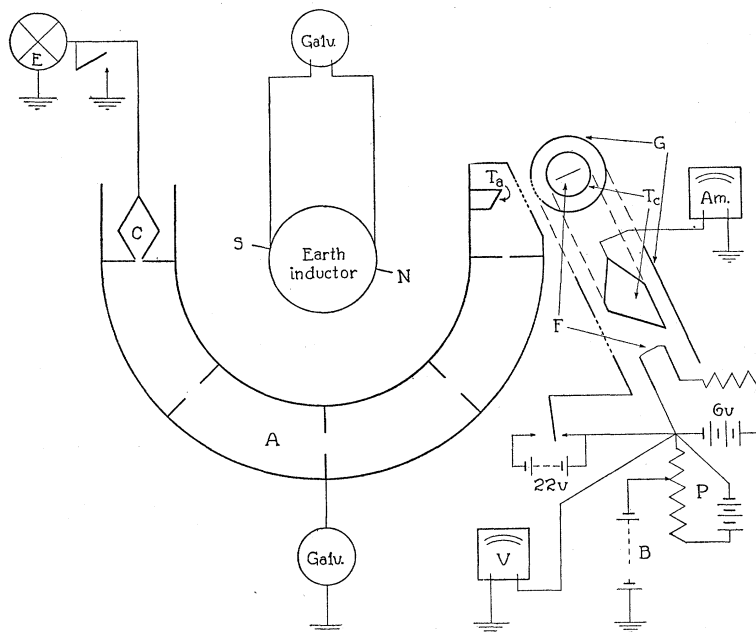


Fig. 1. Diagram of apparatus.

field by merely observing the reverse current through the solenoid needed to reduce the galvanometer throw to zero when the coil was flipped over.

The important dimensions of the apparatus were as follows: width of entrance and exit slits, 0.065 cm; mean radius of path between slits, 6.313 cm; width of middle slit (limiting angular width of beam), 1.4 cm; length of all slits, 1.4 cm; solenoid length, 126.95 cm; solenoid circumference, 87.9 cm; solenoid total turns, 1346.

The negative end of the filament was maintained accurately at a fixed negative potential relative to ground by a main battery, B , and an auxiliary potentiometer device, P , as indicated in Fig. 1, this potential being read on a voltmeter, V . The potential drop across the filament varied between 1.6 and 1.9 volts with heating currents of 6 to 8 amperes as read on a voltmeter and an ammeter not shown in figure.

The copper target was connected to ground through a microammeter and the whole metal body constituting the analyser and containing the aluminum target was connected to ground through a galvanometer.

The cylindrical shield, *G*, was usually connected to the negative end of the filament. Electrons from the filament were thus accelerated to the copper target; some of them, after suffering full velocity reflections at this target, passed against a retarding potential to the window in the shield, reaching this window with very little velocity; they were there again accelerated to the analyser and those passing through the second window and grid struck the aluminum target. A narrow beam of the resulting electrons from this target could pass through the first analyser slit and their velocity distribution be determined by observing the rates of drift of the electrometer for various solenoid currents.

The Dolezalek electrometer *E*, together with the leads had a capacity of 110 cm. It was generally used at a sensitivity of about 2000 mm per volt at a scale distance of 2 meters. There was usually a slight but fairly steady electrometer drift of unknown cause which was corrected for by frequent readings with the shield, *G*, put at 22 volts more negative than the negative end of the filament, thus preventing any electrons from reaching the analyser. This zero drift was subtracted from the observed drifts to get the true electrometer current for each setting. For consistent results, it was found highly important to maintain the filament temperature as nearly constant as possible; hence the use of the above method for getting the zero drift. In spite of the use of a very large capacity storage battery for the filament heating current, there was always a slow deterioration in the filament emission, so the procedure followed was to set the filament rheostat for a convenient upper limit value of the analyser current and allow this current to decrease during a series of drift readings, observing its value for each reading.

As is well known, the mere ratio of electrometer current to analyser current will not give the true velocity distribution, since the effective width of the slits in this type of apparatus varies directly with the velocity of the electrons passing through. These ratios must therefore be reduced to their values per unit effective slit width. Fig. 2 shows several of the velocity distribution curves obtained with various accelerating potentials on the primary electrons. They are plotted on a velocity scale, expressed for convenience in terms of amperes of solenoid current corrected for the earth's field. The unit slit width chosen is 10^{-2} amperes on this scale. The auxiliary voltage scale below is computed from the apparatus constants.

Each distribution shows two main features: a full velocity peak whose position and intensity vary with the primary potential; and a broad distribution of lower velocity electrons having a maximum whose position varies little but whose intensity varies greatly with the primary potential. This accords with Sharman's³ results. Also the almost complete separation of the two features at the higher primary potentials agrees with Brown and Whiddington's⁴ brief report. Observations on the lower velocity distributions were much less accurately reproducible than those on the full velocity peaks,

owing probably to varying surface contamination of the target. The position of the maximum varied erratically over a range of 10 volts or so but usually appeared at 5 or 6 volts. As A. Becker and Sharman both suggest, the position and magnitude of this maximum must be influenced by image forces in the surface and hence also be a function of the angle of emission, so that it should be studied at varying angles, which was not possible with the present apparatus.

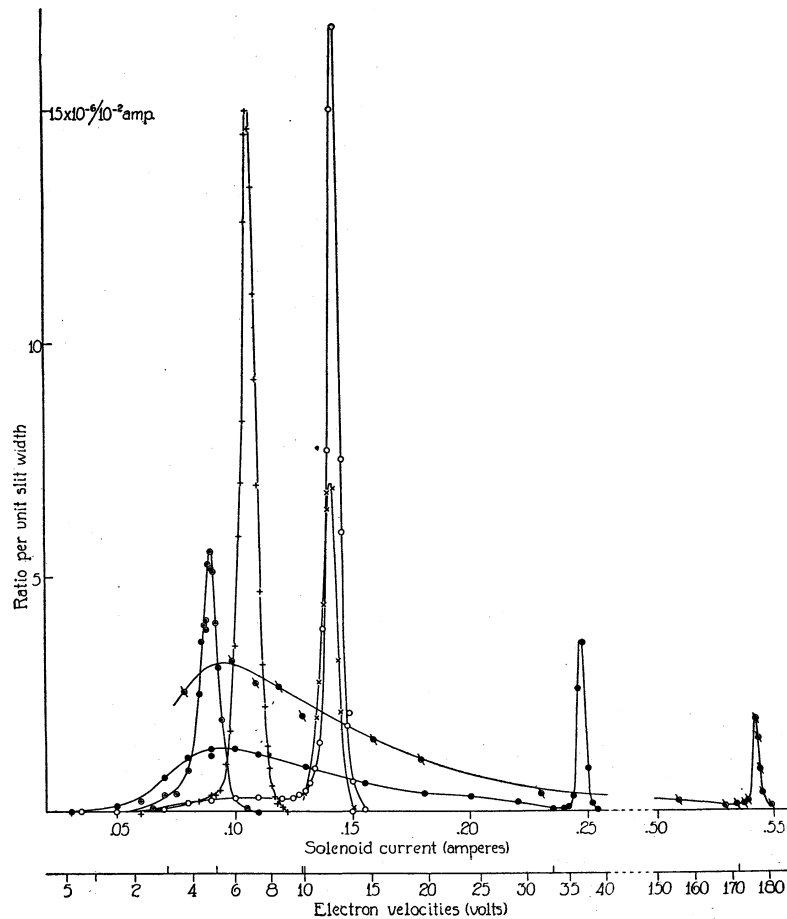


Fig. 2. Velocity distributions of secondary electrons.

That the full velocity peaks consist of electrons truly reflected without appreciable energy loss is clearly shown by their extreme sharpness, the whole observed width down to about 10 percent of the total height being fully accounted for by the effective slit width and the potential drop in the filament. The toeing off at the bottoms is presumably due to scattering in the analyser rather than to appreciable energy losses, since this toeing off is as marked on the high velocity as on the low velocity sides of the peaks.

It will be noticed that each peak comes at a voltage somewhat higher than the primary potential at the center of the filament, the latter being indicated by short lines above the voltage scale. This is undoubtedly due largely to the emission of the primary electrons from the hot filament with a finite velocity which is added to the velocity produced by the accelerating potential. The observed discrepancy averaged 1.95 volts for all observations below 30 volts primary energy with lowest and highest values of 1.36 and 2.52 volts respectively. Above 30 volts it averaged 3.9 with lowest and highest values of 1.5 and 6.8 respectively. The filament was run at bright white heat so that the initial finite velocity of emission is enough to account for the discrepancy in the lower range. In the upper range, any slight errors in calibration, in the setting of the solenoid or in the value of the earth's field

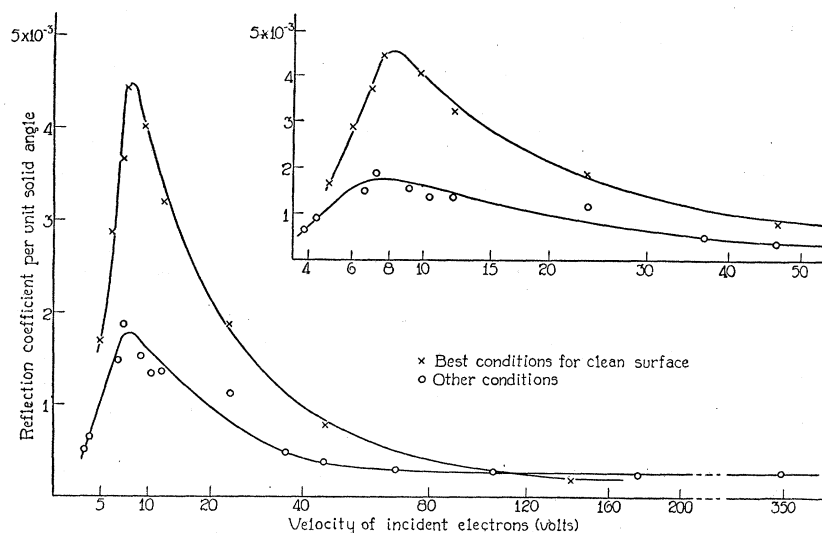


Fig. 3. Fraction of analyser current reflected per unit solid angle as function of primary velocity.

correction would produce more discrepancy on the voltage scale than would the same errors on the lower range.

Measurements of the areas under the full velocity peaks and under the rest of the distribution curves give the percentages stated in the abstract at the beginning of this article. Fig. 3 shows the collected results of all observations on the magnitude of the reflected peak alone for the range of primary velocities examined. The abscissas are observed positions of the peaks on the velocity scale of Fig. 2. The ordinates are the areas under these peaks each divided by the solid angle of the electron beam in the analyser. To get the true coefficient of reflection, one would need to know what fraction of the analyser current struck the target proper within the area effective for passage of secondary electrons through the analyser. From the construction and dimensions of the apparatus, a value somewhere between $\frac{1}{4}$ and $\frac{1}{2}$ seems

to be a reasonable estimate for this fraction. To eliminate the scattering effect, the areas were taken to be those of triangles; of heights equal to the observed heights of the peaks and bases equal to the combined slit-width and filament drop. The plotted points are each averages of from one to three sets of observations taken at the same accelerating potential.

The points on the upper curve were obtained on three separate occasions after the whole apparatus had been filled with hydrogen and baked at atmospheric pressure at 400 to 450°C for 12 hours, the pumps then started and baking continued for 7 hours, the furnace then removed, liquid air put on the charcoal trap and pumping continued for 24 hours or more with liquid air on the charcoal trap continuously. The lower points were obtained at numerous other times, some after no baking except of the charcoal trap, some after merely rinsing with dry air and baking, some after baking in hydrogen but with chance of contamination by vapor from shellac used to stop a slight leak. The difference between the two curves is therefore ascribable to differences in cleanness of the target surface.

Both curves show clearly that the coefficient of reflection at right angles increases markedly at low primary energies over its value at higher energies, attaining a sharp maximum at 7 or 8 volts. (See upper graph with voltage scale enlarged.) No other magnetic analysis of full velocity reflection at these low voltages seems to have been made previous to this; but the existence of the sharp maximum here shown explains the shapes in this region of the curves obtained by Farnsworth⁶ for the total secondary current in all directions. The rapid rise of his curve for aluminum from zero to six volts is due to the initial rapid increase in the coefficient of reflection; the flat portion is due to a decrease in the reflection balancing an increase in the true secondary emission; and the rise beyond is due to rapidly increasing secondary emission. The fact that the maximum of reflection is found in this work at 7 or 8 volts while Farnsworth's curve has become nearly flat at 6 volts may be due to any or all of several causes: (a) differences in the initial velocity of emission of electrons from the sources in the two experiments, since he found a voltage discrepancy similar to the one above mentioned but of opposite sign; (b) differences in the amount or kind of adsorbed gas on the targets; (c) possible variation in the position of the reflected maximum for different angles of deflection, since his work includes all angles.

Another experimental fact which is related to the present results is the observation by H. E. Hartig⁸ that the secondary current from the far side of a thin aluminum foil, bombarded with primary electrons, reaches a maximum at about 8 volts primary potential. This is perhaps all the more significant here because of Kurchatov and Sinelnikov's⁹ observation that the effect appears only when there are slight perforations in the foil.

The writer has, as yet, no satisfactory theoretical explanation for this maximum in the coefficient of reflection. Davisson's¹⁰ spherical condenser

⁸ Hartig, *Phys. Rev.* **26**, 221-31 (1925).

⁹ Kurchatov and Sinelnikov, *Phys. Rev.* **28**, 367-71 (1926).

¹⁰ Davisson, *Phys. Rev.* **21**, 637-49 (1923).

theory of reflection by a single atom would predict curves of the general type here observed, the maximum occurring for electrons of such velocity as to execute a certain trajectory inside the outer electron shell. To account for the relative heights of the various points on the observed curve, the theory would call for an effective outer shell radius over twice that of the aluminum atom, while to account for the absolute height of the maximum it would call for a shell of radius less than half that of the atom. Thus the quantitative fit is far from satisfactory but perhaps as close as could be expected considering the very approximate character of the theory.

It is possible that the phenomenon may be connected with Davisson and Germer's¹¹ recent observations of a diffraction pattern in the reflection of electrons from a single crystal of nickel. Assuming a random orientation of crystals in the target and diffraction of De Broglie associated waves similar to Hull's powder patterns of x-rays, one can readily compute from Hull's¹² data the electron velocities at which diffraction at right angles would occur from the various crystal planes in aluminum. It appears that there would be a series of such velocities and if the relative intensities corresponded to Hull's observed intensities for x-rays, the distribution would be roughly similar to the present observed distribution but with its peak at 13.8 volts instead of at 7 or 8 volts. So that to make this theory fit the observations, it would be necessary to assume a virtual expansion of the aluminum lattice of about 40 percent instead of Davisson and Germer's virtual contraction of 30 percent in the case of nickel.

To decide between the two suggested types of explanation (or against both), further experimental evidence is needed at other angles of deviation, with other target materials and with improved resolving power; the last because the diffraction pattern explanation would call for a fine structure in and near the reflection maximum. Farnsworth's curves for very clean crystalline copper show slight peaks which he attributes to increased secondary emission accompanying inelastic collisions but which may possibly be evidence of such fine structure.

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¹¹ Davisson and Germer, *Nature* **119**, 558-60 (1927).

¹² Hull, *Phys. Rev.* **10**, 661-96 (1917).