Magnetic Spectra of Secondary Electrons from Silver

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By means of a magnetic analyzer and electrometer, the spectra of secondary electrons from silver, when bombarded with cathode rays of energies in the range of 2.1 to 30 equivalent k.v., were determined. Each of the kinetic energy distribution curves shows one prominent peak the location of which varies somewhat with the primary voltage. For voltages up to about 10 k.v. it is located between 0.6 and 0.7 eV_0, where eV_0 is the primary energy; for voltages between 15 and 30 k.v. it is located between 0.7 and 0.8 eV_0. The slopes of the curves on the high energy side of the peaks increase with increasing primary voltages, becoming discontinuous at a point which, within experimental error, corresponds to the primary energy. On the low energy end the peaks decrease less rapidly, reaching half maximum values around 0.3 eV_0 for voltages up to 10 k.v. and around 0.5 eV_0 for the higher primary voltages. The curves have a shape similar to that of the continuous x-ray spectrum curves.

I. INTRODUCTION

WHEN x-rays strike a substance they give rise, among other phenomena, to an electronic radiation. This so-called x-ray photoelectric effect, has been placed upon a secure basis by the experiments of M. de Broglie.[1] His work established the fact, that when a monochromatic beam of x-rays of frequency ν is incident on a substance, a number of groups of secondary electrons are expelled, the energies of which are given by Einstein's equation,

$$\tfrac{1}{2}mv^2 = h\nu - h\nu_0 \qquad (1)$$

where $h\nu_0$ stands for the quantities $h\nu_K$, $h\nu_{L_3}$, $h\nu_{L_2}$ $\cdots$, the work of extraction for the corresponding levels K, L_3, L_2, etc., of the atom. Knowing v, the velocity of each group of electrons, the several values of $h\nu_0$ and from them the absorption limits ν_K, ν_{L_3}, ν_{L_2} $\cdots$, can thus be obtained. The different groups of electrons were isolated by the magnetic spectrograph.

de Broglie's experiment and other similar experiments provided an almost direct method of proving that electrons exist at various energy levels and that there are one K level, three L levels, five M levels, etc.

It is also known, since the work of Lenard[2] and his collaborators, that electrons striking a metal surface cause an emission of secondary electrons.[2] The early work in this field is full of contradictory statements. Since ionization, characteristic radiations etc., are produced by electron bombardment as well as by x-rays, one might expect to find magnetic spectra of secondary electrons such as those observed by de Broglie in the case of the x-ray photoelectrons. Such spectra have actually been observed in the case of certain

[1] M. de Broglie, Comptes Rendus **1**, 274, 527, 746 and 806 (1921).

[2] P. Lenard, *Quantitatives über Kathodenstrahlen*, 1925 Ed. The name "secondary" electrons is used by Lenard and his school in a very restricted sense. In this article we mean by secondary all those electrons that issue from a target when it is bombarded by primary electrons.

gases, for instance, by Dymond,[3] Harnwell[4] and others for helium, and by Eldridge[5] for mercury vapor. In the case of solids no such clear-cut results have been obtained. One might think the reason for this to be partly due to the use of the electric counterfield method of analysis, which was used by the early investigators in this field. This method gives essentially integrated results and hence the existence of any special groups of electrons should be indicated merely by bends or inflections of the velocity distribution curves. The author[6] applied the magnetic analyzer method which is described in detail below. Lorenz[7] made an indirect study of secondary electrons from a tungsten target by comparing the spectra of the focal spot and the so-called stem radiations. The stem radiation is supposed to be produced by the electrons which leave the target and fall back on it due to the negative field of the glass walls and the positive field of the target. The two spectra are similar but that of the stem radiation is displaced towards longer wave-lengths. The difference between the short wave-length limits of the two types of radiation Lorenz identifies as corresponding to the work of extraction of the electrons from definite levels within the atom. Reasoning in this manner he concluded that the secondary electrons were electrons that had been knocked out from the different atomic levels by the primary electrons. Wagner[8] criticized these conclusions and by a photographic magnetic spectrum analysis showed that no such groups of electrons as Lorenz had found, actually existed. He studied the magnetic spectra of high-speed secondary electrons emitted by gold, silver and aluminum targets when bombarded with cathode rays of 16 to 40 k.v. He found the velocity distribution curves to be everywhere continuous except possibly at the high velocity end; also that most of the secondary electrons had speeds close to those of the primary electrons, as the author[6] had found for silver in the range of 5 to 20 k.v. These electrons were evidently of the type that in Lenard's old terminology were named "re-diffused," that is, those electrons which issue from the solid after undergoing deflections by a penetration of relatively few atomic layers.

The present work was undertaken with a view of settling the question of whether or not energy relations exist between the primary and secondary electrons analogous to those that de Broglie found in the case of x-rays and photoelectrons. It was decided to study the electronic emission proceeding in a definite direction from a silver target bombarded with electrons of speeds in the range of 2 to 30 k.v., which region contains all of the critical potentials necessary to excite the various x-ray spectra of silver. It is well known that a certain minimum potential is necessary to excite the K-series spectrum of an element. An increase in the primary potential beyond that minimum might be supposed to detach a K-electron which should then issue with an

[3] E. G. Dymond, Phys. Rev. **29,** 433 (1927).
[4] G. P. Harnwell, Phys. Rev. **33,** 559 (1929).
[5] J. A. Eldridge and H. F. Olson, Phys. Rev. **28,** 1151 (1926).
[6] S. Chylinski, Phys. Rev. **28,** 429 (1926).
[7] E. Lorenz, Zeits. f. Physik **51,** 71 (1928).
[8] P. B. Wagner, Phys. Rev. **35,** 98 (1930).

energy equal to the difference between the energy of the primary electron and that required for K-ionization, the thermionic work function being negligible. The same should be true for the other levels. For instance, with a primary potential of 2 k.v. all of the N and M levels of silver should be excited and we might expect groups of secondary electrons given by the following relations:

$$P - W_{N_7} = 2000 - 106,\ P - W_{M_5} = 2000 - 723, \text{ etc.}$$

where P stands for the primary potential and the W's represent the energy in electron-volts corresponding to the different absorption limits. In addition to the removal of these electrons by inelastic collisions, one might expect photoelectrons to be released from higher levels, due to the x-rays originating in the deeper levels of the same atom or other atoms. Thus, if the analysis is correct, there should appear on the velocity distribution curves distinct peaks, some of which, namely those due to electron impact, should shift their position towards the high velocity end with increasing primary potentials, while those due to x-ray photoelectrons should remain fixed. After a primary potential of about 4 k.v. is reached new peaks should appear, since the L absorption limits of silver correspond to about 3.8 k.v. The K-excitation would not be reached until a voltage of 25.5 k.v. was passed. The intensity of x-ray lines is known to vary approximately as $(V_0 - V)^2$, where V_0 is the primary voltage and V is the minimum voltage required to excite a given series. Hence one might expect the N, M and L electrons to be continuously more numerous as the K-voltage is approached.

Webster,[9] in his studies of the production of characteristic x-rays from silver concludes that they are largely of direct origin, that is produced by the ejection of K-electrons from atoms by the impact of the primary electrons on those atoms, rather than of indirect origin, which may be ascribed to the ejection of K-electrons by the photoelectric effect of continuous x-rays excited by cathode rays in other atoms. The ratio of direct to indirect rays he finds equal to about 2 at 50 k.v. for silver.

Certain considerations are rather discouraging as far as the expectation of the appearance of definite groups of secondary electrons is concerned. Chief among them is the very low line-emission efficiency of cathode rays. This amounts to only a fraction of one percent. Also, as Wagner[8] has pointed out, most of the atoms from which, for example, the L electrons are ejected are not at the surface of the target, and hence there are energy losses along the paths of both the primary and secondary electrons; and that the probability of a cathode ray transferring all of its energy to a given orbital electron is small.

II. Apparatus

The principal parts of the apparatus are shown diagrammatically in Fig. 1. B is a brass cylinder two inches long and of eight inches outside diameter. The cover is fitted to it by means of a ground joint. A little sealing wax around the outside edge makes it air tight. Soldered to the cover is a

[9] D. L. Webster, Proc. Nat. Acad. Sci. **14**, 330, 339 (1928).

small brass pipe having a ground taper into which is fitted the glass cone which supports the cathode. The bottom of B consists of a brass plate which is permanently soldered to it. This plate holds the water-cooled silver target T, an amber plug through which passes the connection to the Faraday cylinder F and a brass pipe leading to the vacuum pumps.

Electrons from the hot cathode pass through a small circular hole in the cover and strike the target. The silver is 2 cm in diameter and 2 mm thick. The target surface is located at 45 degrees with the plane of the drawing, the normal to the surface making an angle of 45 degrees with the primary beam. Electrons escaping from the target at right angles to the primary beam and

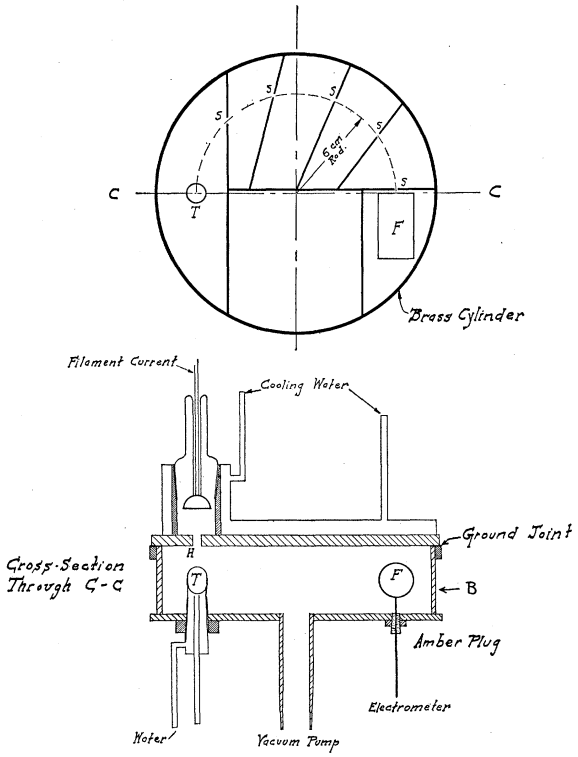

Fig. 1. Diagram of apparatus.

the normal to the target are bent into a semi-circle by means of a uniform magnetic field, which is parallel to the primary rays. The circle has a radius of 6 cm. The beam that enters the Faraday cylinder is reduced by a series of five slits S to a cross section much less than 1 mm^2.

The distance between cathode and cover was 3 cm and that between cover and target was 2 cm. The accelerating potentials were applied between cathode and cover, which, together with the rest of the brass cylinder and the target, was at ground potential. The target is thus located in a space that is practically free from electrostatic disturbances, especially so since the electron current was small, not greater in most instances than 1 m.a. Measure-

ments were made by means of a Dolezalek electrometer, having a sensitivity of 500 divisions per volt. To reduce stray (tertiary) electrons, the walls of the brass chamber were covered with a layer of soot.

The vacuum was obtained by mercury diffusion pumps. These were in continuous operation during the progress of the work. The vacuum was at all times less than 10^{-5} mm of mercury. Preliminary experiments showed no evidence of any ionizing effects due to residual gas. Before use, the apparatus was strongly heated to drive out all occluded gases; the target was heated by electron bombardment lasting several days. To insure steady conditions the apparatus was in operation for about four hours before any measurements were taken.

The magnetic field was supplied by a solenoid which slipped over the vacuum chamber, the latter being mounted on a wooden pedestal. The solenoid was 36 inches long, having about 2700 turns of insulated copper wire. In the middle of the solenoid, where the vacuum chamber was located, the field was found to be very uniform. It was calibrated by means of the usual search-coil ballistic galvanometer method. For any given magnetic intensity H, the voltages equivalent to kinetic energies of the electrons entering the Faraday cylinder could then be computed from the relation

$$V = \tfrac{1}{2}e/mr^2H^2 \qquad (2)$$

where the symbols have the usual signification. The solenoid current was supplied by a large storage battery.

A diagram of the principal electrical connections is given in Fig. 2. The 60-cycle alternating current was rectified by the two kenotrons K and smoothed out by the condenser C, which had a capacity of 0.32 microfarads. The high potential was measured by means of a specially constructed electrostatic voltmeter. This was calibrated against a spark gap. The cathode filament was heated by a current from the secondary of a 110 volt 60-cycle transformer. Throughout each run the current to the target, as measured by a milliammeter, was kept constant by a rheostat. In the case of the 2.1 k.v. run the potential was supplied by a storage battery.

III. Experimental Procedure and Results

The procedure consisted in applying a definite potential to the cathode and obtaining readings on the electrometer for different values of the solenoid current, everything else being kept constant. From these data curves were plotted, of which that shown in Fig. 3 is a typical example. The crosses represent experimental points for a primary voltage of 5 k.v. The electrometer readings are plotted as ordinates, against abscissas that are proportional to the magnetic field intensities and consequently to the square root of the energy. From these, by an application of relation (2) another set of curves was constructed, the abscissas now being proportional to voltages equivalent to kinetic energies. To get the velocity distribution or kinetic energy distribution curves, such as those shown in Figs. 4 and 5, each ordinate of the intermediate curve was divided by the corresponding value of V. This had to be

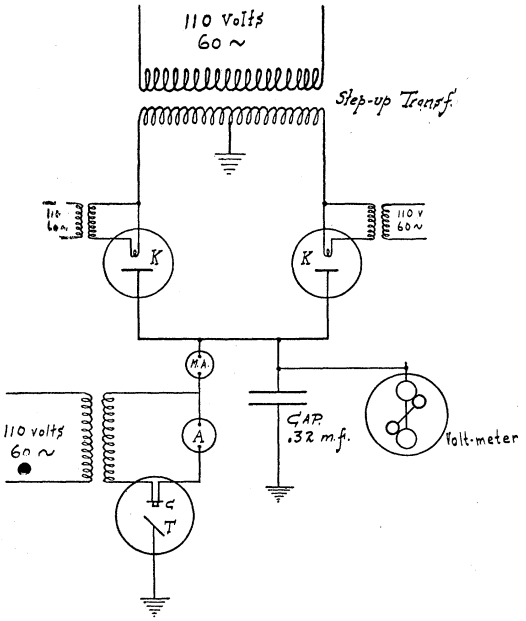

Fig. 2. Diagram of connections.

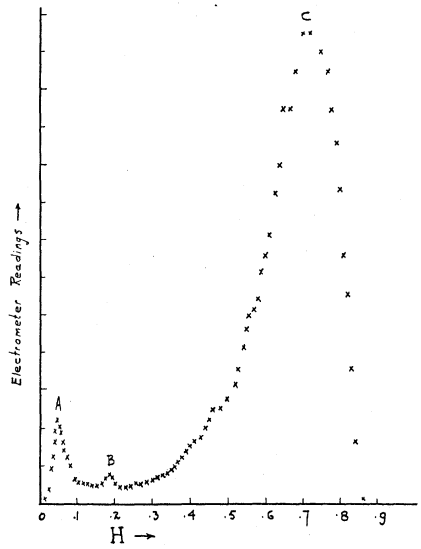

Fig. 3. Experimental curve for primary voltage of 5 k.v.

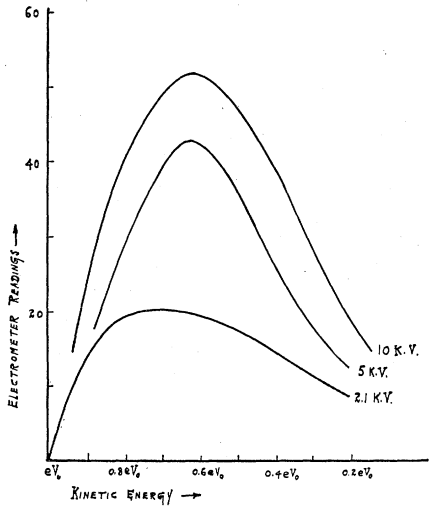

Fig. 4. Velocity distribution of secondary electrons for primary voltages V_0 of 2.1, 5 and 10 k.v.

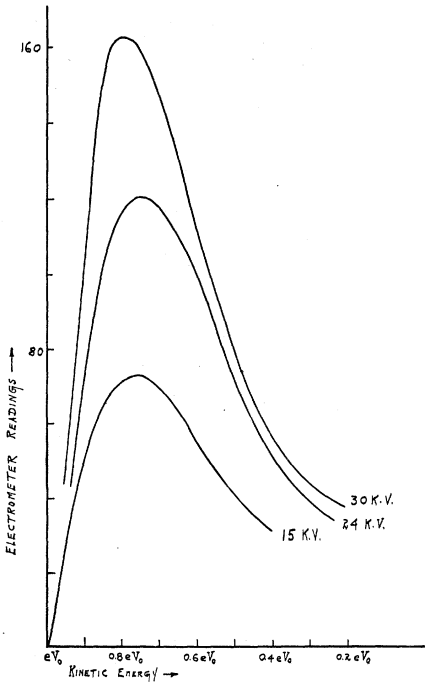

Fig. 5. Velocity distribution curves for primary voltages V_0 of 15, 24 and 30 k.v.

done in view of the change of resolving power of the magnetic analyzer from one part of the scale to another. For any given value of H the electrons entering the collector have values of V in the range of $V \pm \Delta V$, and ΔV is not a constant, but proportional to V.

In this manner the kinetic energy distributions of secondary electrons for primary potentials ranging from 2.1 to 30 k.v. have been investigated. This was done in steps of about 2.5 k.v., but only six representative distributions are shown in Figs. 4 and 5, the rest having exactly similar characteristics.

IV. Discussion

An examination of the curves in Figs. 4 and 5 reveals no such discontinuities as might have been expected if there had been energy relations between the primary and the secondary electrons of the type discussed in the introduction. For voltages up to about 10 k.v. there appear two small peaks, A and B in Fig. 3, which grow less prominent with increasing primary voltages, until at 12.5 k.v. they can no longer be detected. They appear at practically the same places in all curves, A at 8 volts and B at 220 volts. Little if any importance should be attached to the peak at 8 volts. The method of analysis is unreliable for values of V near zero. The low speed electrons do not get away from the target because of the space charge field, or if they do get away they are dispersed by their mutual repulsions and fail to reach the collector. It is not clear what the meaning of the B peak is.

All curves are characterized by the prominent peak at C. For primary voltages up to 10 kilovolts the location of this peak is, in terms of kinetic energy of the primary beam eV_0, between 0.6 and 0.7 eV_0; for voltages between 15 and 30 kilovolts it is located between 0.7 and 0.8 eV_0. The slopes of the curves on the high energy side of the peaks increase with increasing primary voltages, seemingly becoming discontinuous at a point which, within experimental error, corresponds to the primary energy eV_0. On the low energy end the peaks decrease less rapidly, reaching half maximum values around 0.3 eV_0 for the set shown in Fig. 4 and around 0.5 eV_0 for those in Fig. 5. The curves show plainly that most of the secondary electrons have very high speeds.

In conclusion one may say that, while undoubtedly some of the secondary electrons must have come from the inner orbits, their number must also be relatively so small as to be of no detectable influence upon the shape of the velocity distribution curves. The general shape of these curves merits perhaps a remark. They are of the same form as the continuous x-ray spectrum curves. It is not clear, however, what significance, if any, should be attached to this similarity.

It is a pleasure to express my appreciation of the kind interest and help extended to me by Professor Arthur H. Compton during the course of this work.