

Characteristic Energy Losses of Electrons Scattered from Incandescent Solids

Erik Rudberg

Proc. R. Soc. Lond. A 1930 **127**, 111-140

doi: [10.1098/rspa.1930.0046](https://doi.org/10.1098/rspa.1930.0046)

Email alerting service

Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click [here](#)

Characteristic Energy Losses of Electrons Scattered from Incandescent Solids.

By ERIK RUDBERG, Nobel Institute, Stockholm, Sweden.

(Communicated by O. W. Richardson, F.R.S.—Received January 13, 1930.)

Introduction.

The electron emission produced when solid conductors are bombarded with electrons of controlled speed has formed the subject of a great number of investigations. It is now generally recognized that this emission consists of three different parts: (1) Primary electrons, truly reflected without loss of energy; (2) electrons scattered back with reduced energy; and (3) secondary electrons proper, with very low velocities, which would seem to be produced from the atoms of the target by the same collision processes that give rise to the second group. In recent years considerable attention has been paid to the reflected electrons, the angular distribution of which reveals their wave character, if the target is a definitely orientated crystal of the substance in question.* Some time ago I made some measurements on the velocity spectrum of the emission produced by electron bombardment, using a magnetic deflection apparatus of fairly high resolving power.† The principal object of this investigation was to look for evidence of groups of electrons with characteristic velocities related to the soft X-ray levels of the substance. From certain theoretical considerations such electrons might be expected to be present in the emission.‡ Targets of lithium, beryllium, boron, carbon and aluminium were tried, but in no case was there any evidence of electrons of the kind in question. These results are discussed in the paper mentioned. The distribution curves obtained for different targets and bombarding voltages ranging from 40 to 900 volts were all similar in shape. The reflected electrons produced a sharp and narrow peak, separated from the rest of the curve by a very deep minimum. The curve then rapidly rose to a maximum, corresponding to scattered electrons which had lost an energy equivalent to 25

* Davisson and Germer, 'Phys. Rev.,' vol. 30, p. 705 (1927); vol. 33, p. 760 (1929); 'Nat. Acad. Sci. Proc.,' vol. 14, p. 317 (1928); Davisson, 'J. Franklin Inst.,' vol. 205, p. 597 (1928), and vol. 208, p. 571 (1929); D. C. Rose, 'Phil. Mag.,' vol. 6, p. 712 (1928).

† Rudberg, 'K. Svenska Vet. Akad. Handl.,' vol. 7, No. 1 (1929).

‡ Richardson, 'Roy. Soc. Proc.,' A, vol. 119, p. 531 (1928); Rudberg, 'Roy. Soc. Proc.,' A, vol. 121, p. 421 (1928), and *loc. cit.*

volts in the collision. In addition to these, some experiments were made with targets of platinum and carbon, which could be kept at incandescence also when readings were taken. It was found that new maxima appear at high temperature, nearer to the reflected peak, and that the 25 volt maximum becomes very faint but reappears after some time on cooling. These changes were repeated several times. It was concluded that the 25 volt maximum was produced by an adsorbed layer formed on the cold target in the high vacuum, whilst the new maxima with hot targets should probably be regarded as characteristic of the target substance itself. Somewhat similar effects have been observed by Brown and Whiddington using a photographic method.*

The present investigation is a continuation of these experiments with heated targets. The influence of the magnetic field set up by the heating current for the targets in the earlier apparatus made it necessary to work with fairly high bombarding voltages, and owing to the limited resolving power in this region the characteristic features of the curves near the reflected peak could not be traced accurately. The apparatus used in the present work is essentially an improved form of the earlier one. To avoid complications I have only studied targets of non-magnetic material; these are copper, silver, gold, platinum, and the oxides of magnesium, calcium, strontium and barium.

Description of Apparatus.

The various parts of the experimental arrangement employed are all mounted on a large glass stopper, provided with a tube of large bore, joined to the pumping system, and several narrow tubes for wire connections. A long, 80 mm. wide glass tube, closed at one end, surrounds the whole; it is joined to the stopper by hard sealing-wax. The inside construction consists of three parts: the electron gun, the small box containing the target, and the large deflexion box, to which the tube shielding the electron collector is directly attached. These are all shown in fig. 1, *a*; *b* represents a horizontal section through the plane of the slits in the deflexion box; *c* gives vertical sections showing details of the mounting of the target box and the target holder. All metal parts are made of pure copper, silver soldered or bolted together by copper screws. The particular shape of the target holder was chosen in order to reduce the magnetic field of the heating current to a minimum. For this purpose connexion to the ends of the thin strip used as a target is made through strips of sheet copper in the plane of, and parallel to the target, the direction

* Brown and Whiddington, 'Leeds Phil. Lit. Soc. Proc.', vol. 1, p. 162 (1927); Whiddington, *ibid.*, vol. 1, p. 242 (1928).

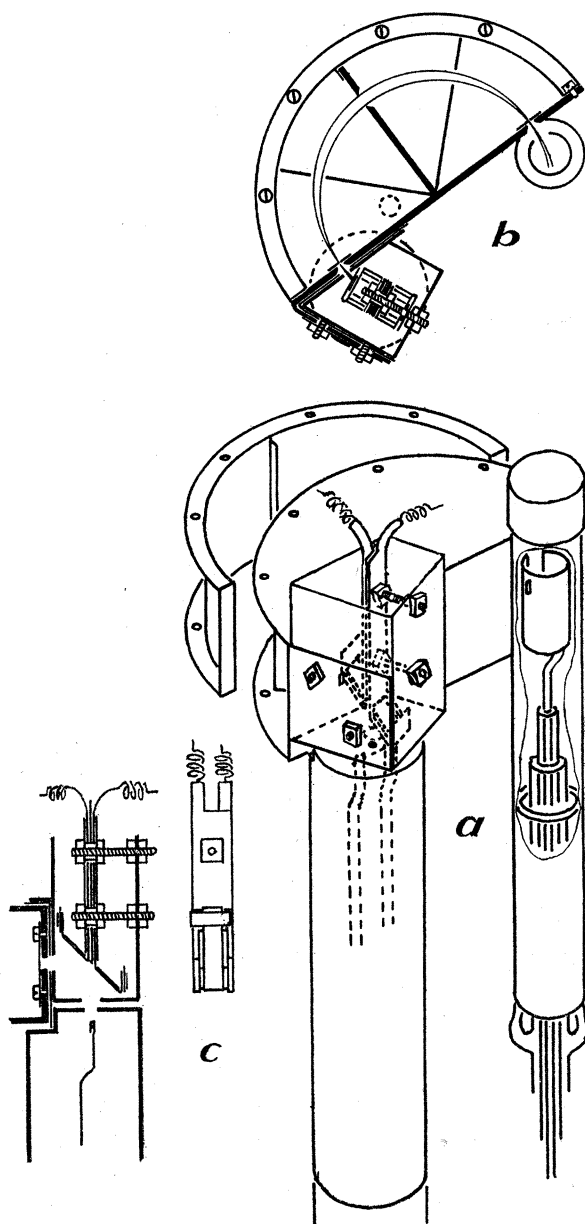


FIG. 1.

of the current in these strips being opposite to that in the target. The leads for the heating current are insulated from each other and from the target box by thin pieces of mica and very short bits of quartz tubing. The target box is insulated from the deflection chamber by sheets of mica.

The semi-cylindrical wall of the deflexion box is made removable to allow adjustment of the inside parts; it is provided with flanges which fit very closely to the other walls of the box, to which it is fastened by 10 screws. The entrance and exit slits are cut by a sharp razor in thin sheet copper and examined under the microscope. They are attached by screws to the inside of the box in such a way that they cover the corresponding wider slits in the rigid base plate of the box. The correct adjustment of the slits is checked and their distance apart measured with the aid of a dividing machine. The width of the electron beam which is analysed in this apparatus, is determined by a third slit in the central partition of the box, the two extra screens merely serving the purpose of cutting down the effect of stray electrons. The dimensions of the slits used in the present research are: entrance slit 2.5×0.083 , exit slit 2.5×0.073 , central slit 2.5×3.5 , all in millimetres. The slit in the target box is 3.0×0.7 mm. The distance between entrance and exit slit was found to be 49.95 mm., the mean radius hence very nearly 25.0 mm. From these data the greatest relative interval of velocity $\Delta v/v$, within which electrons are collected for a given value of the deflecting field, may be calculated*; the smallness of this quantity measures the resolving power. In the present case, maximum $\frac{\Delta v}{v} = 0.6$ per cent.

After a good many readings had been taken with this apparatus, in which only electrons scattered in a direction at right angles to the primary beam are studied, it was thought desirable to try similar experiments for electrons scattered in other directions. For this purpose the apparatus was altered in such a way as to allow measurements of the velocity distribution among the scattered electrons to be taken for a series of different angles in succession, keeping other conditions constant. The change in the former design consists essentially in the introduction of a new construction, which replaces the electron gun and the target box and which is rigidly attached to the deflexion chamber in the same way as the latter. The new construction is shown in position in fig. 2, *a* and *b*; in *a* the nearest corner of the apparatus is to be imagined cut open, as indicated, in order to show the interior parts; *b* is a top view. Fig. 2, *c*, represents a vertical section through the centres of the two wheels to be seen in fig. 2, *b*. The upper one of these wheels, the axis of which coincides with the axis of the whole tube, merely serves the purpose of transmitting a rotating motion to the similar pulley attached to the electron gun and target to be rotated. A simple coupling enables the first pulley to be turned from the

* Rudberg, *loc. cit.*

outside, when the tube is mounted in position, by acting on a ground joint at the top; this joint is lubricated by a special vacuum oil* of a very low

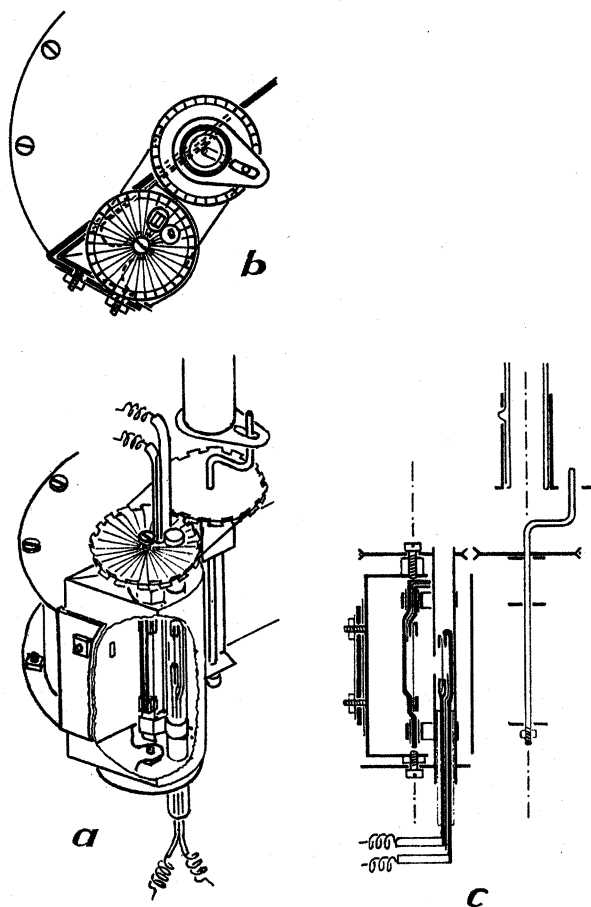


FIG. 2.

vapour pressure made by the Metropolitan-Vickers Electrical Company. When lubricated in this way the joint worked very satisfactorily.

The long, very narrow electron gun of this apparatus constitutes a rigid stem to which the other revolving parts, particularly the target holder, are attached. It is fixed to the pulley with its upper end and to another wheel with its lower part in such a way that it remains parallel to the slit, when it is made to pivot round the common axis of these two wheels, which is also

* C. R. Burch, 'Roy. Soc. Proc.,' A, vol. 123, p. 271 (1929). I am much indebted to Prof. Siegbahn of Upsala, who very kindly let me have some of the oil given to him.

parallel to the slit. The target is a narrow strip, stretched as nearly as possible along the axis of rotation. The target holder is insulated by strips of mica, and the construction is such as to reduce the magnetic field due to the heating current to a minimum. The same precaution has been taken in the construction of the hot filament source, which is insulated by a quartz tube fitting snugly into the gun tube. Electrical connexion is made to the foil at the top, and to the filament at the bottom, by means of very soft copper springs, which do not impede the motion appreciably. The position of the gun with respect to target and slit can be read from the outside by the aid of a fixed index and a circle divided in 24 parts, which is drawn on the top wheel.

Methods.

Keeping the bombarding voltage constant, there are two different methods which may be used to obtain the velocity distribution of the fast electrons from the target. In the first of these, the target box and the target are directly connected to the deflexion chamber. The magnetic field, parallel to the slits, is varied by small steps over the region corresponding to the velocities in question according to the relation

$$v = erH/m, \quad (1)$$

where v is the velocity an electron must possess to be able to follow the semi-circular path of radius r defined by the three slits, when the deflecting field is H . For each setting of the slit, the current to the collector behind the exit slit is measured. This method, which was the one adopted in the previous work referred to, will be called the method of the varied field. Since the energy of the electrons is proportional to the square of the velocity, and the latter proportional to the first power of the field and hence to the coil current, it is necessary to plot the results against the square of the current in the magnetic coils to obtain the distribution with respect to energy. A further disadvantage with this method is that the magnitude of the velocity interval selected by the slits is proportional to the velocity, which means that the electrometer readings must be divided by a quantity proportional to the square of the coil current to give the actual number of electrons of the corresponding energy in the distribution.

The second method consists in keeping the deflecting field fixed at a value slightly higher than that which would focus the fastest—truly reflected—electrons on to the exit slit, and lowering the potential of the entire system, target box and electron gun, by small, measured steps. In this way the

Energy Losses of Electrons.

117

bombarding voltage remains the same all the time, but the electrons emerging from the slit in the target box are accelerated in the narrow space between this and the entrance slit, so that they enter the deflexion chamber with an energy which is greater than their initial energy by an amount equivalent to the applied potential difference. If the total energy of the electron on entering the deflexion box corresponds to the particular velocity which satisfies equation (1) for the value of the fixed magnetic field in question, the electron is captured by the collector. As the applied potential difference is increased, electrons which have lost a greater amount of energy in the collision are directed to the collector, for the gain of kinetic energy in the accelerating field makes up for the loss in the target. Obviously the applied potential difference provides a measure of the energy loss, and it is only necessary to determine the true zero of the energy scale. This is done by observing the value of the applied potential for which the truly reflected electrons are directed to the collector. This method, which will be referred to as the method of accelerating potential, has another advantage besides that of the linear scale. It is obvious that the electrometer readings give a direct measure of the number of electrons which have suffered the corresponding energy loss, since the magnetic field remains the same all the time. But there is also a disadvantage with this method. In the method of the varied field, the emission which is analysed derives exactly from the same spot of the target, whatever the value of the field; this is easily recognised, if the two limiting trajectories in fig. 1, *b*, are extended back into the target box. In the second method this is no longer the case, for whereas the path inside the deflexion chamber is the same for all electrons analysed, the trajectories in the target box are more curved the lower the initial energy of the electrons. Hence an electron, if it is to be counted, must start from a point nearer to the axis of the apparatus the greater the energy loss. In the first apparatus the bombardment is sufficiently uniform over the area of the target required by the differences in speed in the region investigated; for the rotating target, however, the area bombarded is so narrow that this shift often produces a considerable distortion of the distribution curves obtained by the method of accelerating potential. For this reason I have used both methods alternately. As regards the first of the two, the range of velocities of the scattered electrons which is studied in the present case is so small relatively, that the readings may be plotted directly against the coil current without recalculation and the corresponding voltage scale marked down.

Experimental Procedure.

As a support for the different substances investigated, strips of platinum foil, 0.003 mm. thick, have been used throughout. When targets of the other metals were studied, small rectangular pieces were cut from a thin foil of the metal; two parallel slits were made in the small piece and the platinum strip passed through; finally the projecting edges were turned back and the whole was pinched tight together. Such a platinum strip, with a coating of a less refractory metal in the middle, is easy to heat and does not burn through if overheated for a moment, as does a simple strip of the metal in question. The oxides were deposited on a platinum surface, roughened with a piece of emery paper, by evaporating solutions of the nitrates in the usual way.

After assembly the tube received a heat treatment in an electric furnace, the temperature of which was raised to 400° C. A cooling mixture—carbon dioxide and acetone—was then applied to the mercury trap and the filament and the foil heated for some time; then the bombardment was started with the foil still kept at incandescence. In general the experiment with any particular target extended over a period of 4 days at least, during which time readings were taken several hours every day; sometimes an experiment would last more than a week. In these experiments, not only were the pumps and the mercury trap maintained in operation during the whole time, but both the filament and the foil were kept glowing continuously, day and night. It would therefore appear that the targets must have been rather well degassed in these experiments. As a matter of fact, the McLeod—of the large type, calibrated down to 10^{-5} mm.—always indicated “sticking pressure” under these conditions. A few runs taken with pressures considerably higher than this, of the order 10^{-5} mm., did not reveal any change in the curves due to the increased pressure. It should also be mentioned, that in no case was there any trace of a tungsten deposit to be found on the targets when removed at the end of an experiment. As a matter of fact a deposit of this kind soon formed on the inside of the target box, and in such a position as to suggest that the particles of sputtered tungsten from the filament were largely specularly reflected at the hot surface of the target. In some of the experiments with copper and silver the temperature in the first degassing was raised to such a point that the metal evaporated freely, forming a bright deposit on the surrounding walls, but when readings were taken it was tried to use such a heating current that the vapour pressure in front of the surface of the target could be neglected.

box R_2 R_3 ; G_1 is a galvanometer. The accelerating potential difference used in the second method is supplied by a battery of small accumulators, adjusted by a sliding resistance potentiometer and measured by the precision voltmeter V_2 .

The first measurements of the current to the collector were made by timing the motion of the electrometer needle as the quadrants charged up (electrometer sensitivity, 3000 mm./m. for 1 volt). Later this method has only been used in the region of the true reflection, where the currents become very large. For the rest of the distribution curves the quadrants are shunted with a high resistance R_4 —a quartz fibre with a thin film of sputtered platinum—and the steady deflection of the needle is observed.

To supply the magnetic field I have used the pair of Helmholtz coils previously employed, giving 56.52 gauss per ampere. A precision ammeter is included in the circuit, but the current is measured with a higher accuracy by employing the usual method of balancing the potential drop across a small resistance in series with the coils. R_5 R_6 is a potential divider of the dial pattern, and G_2 a galvanometer, used to check the balance. The earth's magnetic field I have compensated in all experiments by means of a large pair of Helmholtz coils, mounted in the appropriate position. They have been omitted in the diagram.

Results.

I have confined the investigation to such scattered electrons for which the energy lost in the collision does not exceed 50 volts. A typical curve is shown in fig. 4 for a platinum target; this was obtained by varying the magnetic field and timing the swing of the electrometer. The dots represent the measured points. The sharpness of the peak due to reflected electrons and its height compared with that of the rest of the distribution curve should be noticed. In all the other curves reproduced in the following, the ordinates of the part due to reflected electrons have been plotted in a scale which is roughly 1/10 of that of the rest of the curve, for the sake of convenience. Of the two further maxima exhibited by the platinum curve the one corresponding to the smaller energy loss is fairly sharp. Sometimes this maximum is accompanied by one for a 3 volts greater loss, which may become so large that it almost suppresses the first one.

The curve in fig. 5, for copper, was obtained in the same way as that for platinum. There are maxima at 7.0 and 25.4 volts loss, and indications of similar features at 3.5 and, although very feeble in this curve, at about 12 and 35 volts.

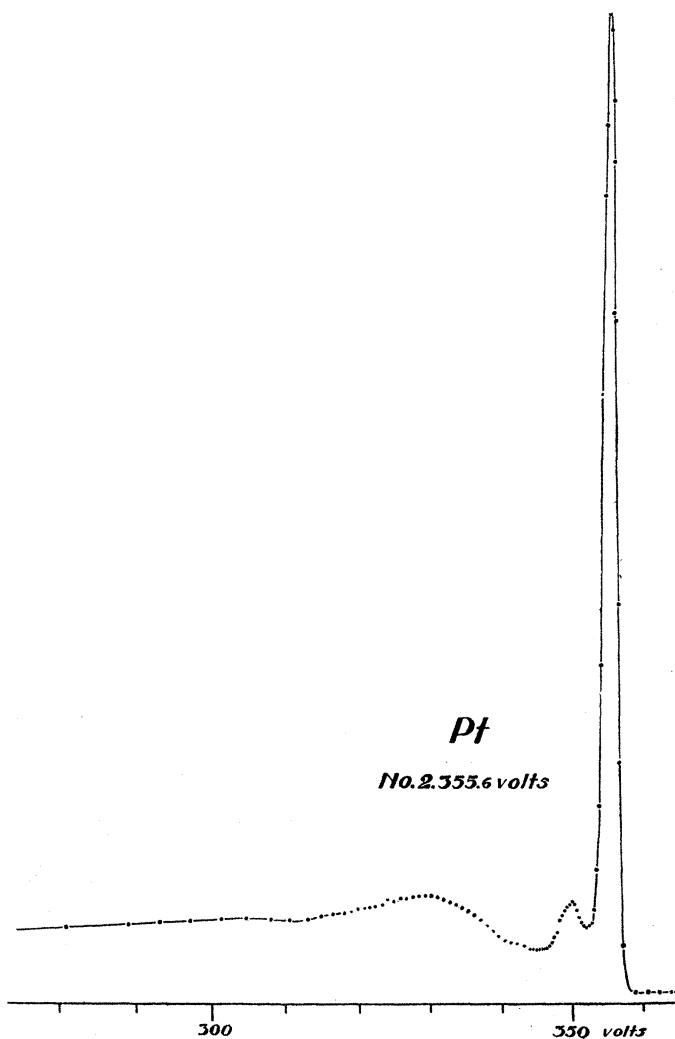


FIG. 4.

The curve for a silver target, shown in fig. 6, was obtained by the method of accelerating potential, as indicated by the manner in which the voltage scale is marked off in this case. Since this curve was taken with the rotating target apparatus, it is believed to come down a little too quickly on the side of higher energy losses, for the reasons mentioned in the discussion of the method. There are three maxima in this curve, and the rise to the first one is remarkably steep.

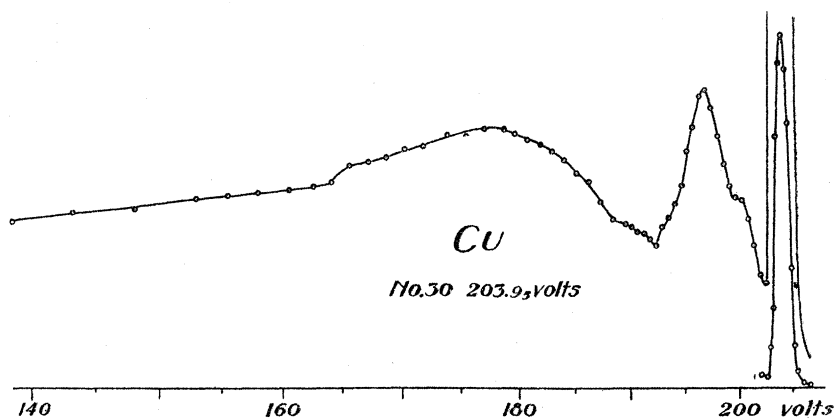


FIG. 5.

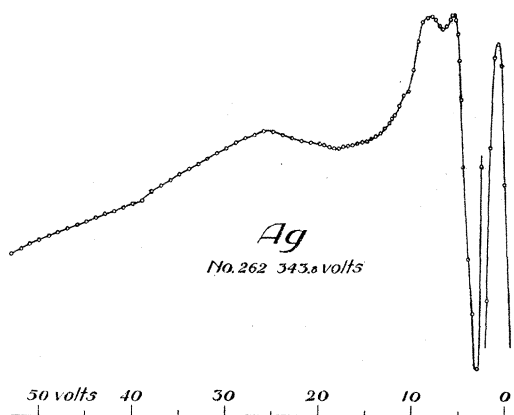


FIG. 6.

Two different specimens of gold have been tested (fig. 7). The first contained 96 per cent. of pure gold, the rest being presumably copper. The second held 99.9 per cent. of the pure metal. On the whole there is a fair agreement between the curves for the first specimen, which like the upper curve in fig. 7 were all obtained with a fixed target and accelerating potential, and the results for the pure metal, secured in the second form of apparatus and using a varied magnetic field. In the former case, however, there is near the first maximum a further hump for a somewhat higher energy loss, which will be seen to be competing with the first maximum in the curve.

Still more salient features are exhibited by the curves rendered by the oxides, particularly those of the metals calcium, strontium and barium. With calcium oxide, for example, four different deposits have been tested and the different

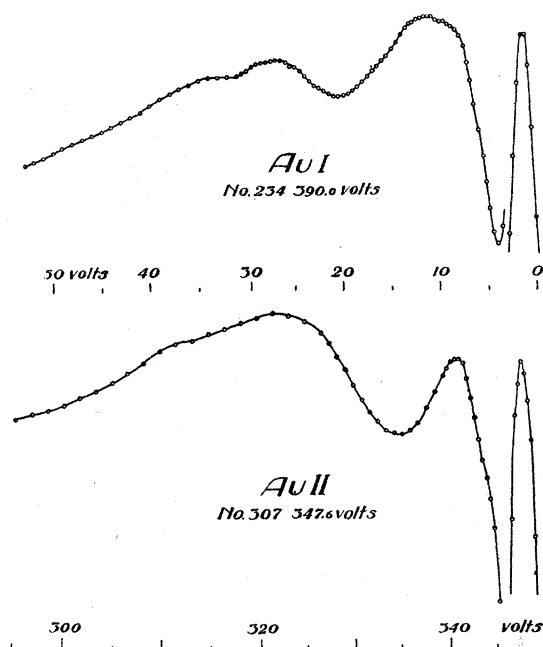


FIG. 7.

methods employed, using both types of apparatus. Altogether more than 30 distribution measurements have been secured with this substance, all of which show the same kind of curve. In figs. 8 and 9 distribution curves are given for the oxides of the four metals mentioned. They were all obtained with the method of accelerating potential. Each of the three oxides CaO, SrO and BaO gives rise to two conspicuous maxima, which appear to shift in the same direction from one element to the next in proceeding down the series. Besides these main maxima, there appears to be several small ones, particularly in the case of calcium oxide. The curve for magnesium oxide in fig. 9 has at least one well-developed maximum at 22.7 volts. Of the others, the one in the neighbourhood of 17 volts is usually brought out fairly well in the curves.

Before proceeding to give the numerical results of the different experiments to fix the position of these maxima in the curves, a few words must be said about the question how the distribution depends on the angle of scattering. This has been studied with the apparatus where the target and electron gun could be rotated, in the case of targets of copper, silver, gold and calcium oxide. It should be mentioned that the angle at which the bombarding electrons

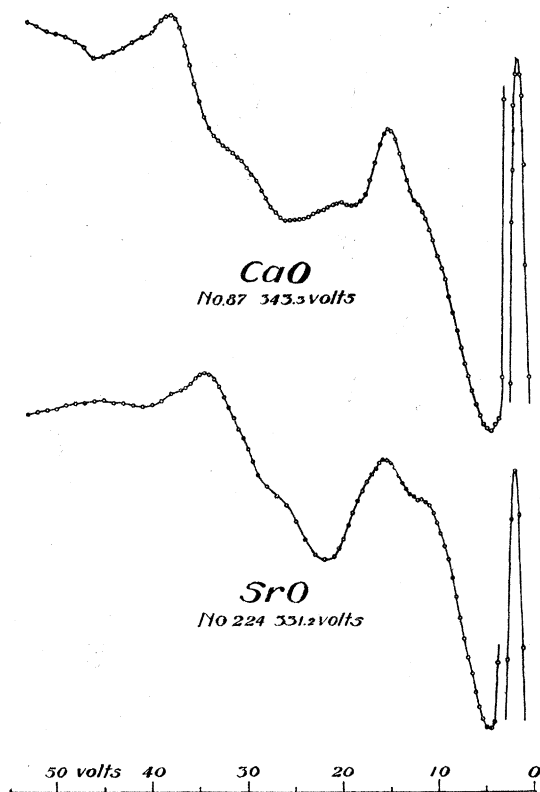


FIG. 8.

strike the plane surface of the target remains constant in these experiments, since the latter rotates together with the gun. This angle was about 30° in all the measurements. A typical series of distribution curves for different angles of scattering, measured from the initial direction of the primary electrons, is shown in fig. 10. These seven curves were all obtained by the method of varying the magnetic field, using a copper target. The bombarding voltage was the same in all seven cases; the very slight shifts of the scale which some of these curves exhibit, when compared with the others, are probably due to a small error in the adjustment of the rotating system, with the effect that the scattering studied does not take place at exactly the same points of the target for different settings. This may produce a small change in the energy of the bombarding electrons, on account of the voltage drop across the strip and the filament. The inclusive potential drop, measured between the leads outside the tube, was generally about 1 volt for the strip, and about 1.5 volts for the filament.

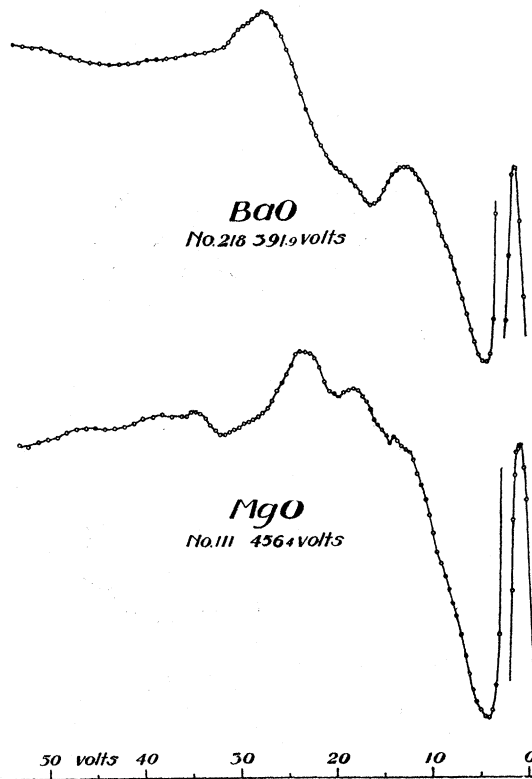


FIG. 9.

Fig. 10 clearly shows that the position of the maxima is independent of the angle of scattering, at any rate for this range of some 70° . All the other measurements support this conclusion. In fact, the shape of the distribution curve is almost exactly the same for all angles. It is doubtful if any meaning should be attached to the variation of the relative intensities of the maxima, which may be found in these curves, and which sometimes occurred in other experiments of the same kind. Such changes would frequently take place for the metal targets also in the measurements where the scattering angle remained fixed, owing to uncontrollable changes in the conditions.

In my first paper on this subject, I was able to show that, if the distribution is plotted as a function of the energy, maxima of this kind retain a fixed position with respect to the reflected peak over a considerable range of the bombarding voltage. In the present experiments I have hence mostly restricted the range of the bombarding potential to such values as were favourable for a determination of the position of the characteristic humps in the curves. Notwithstand-

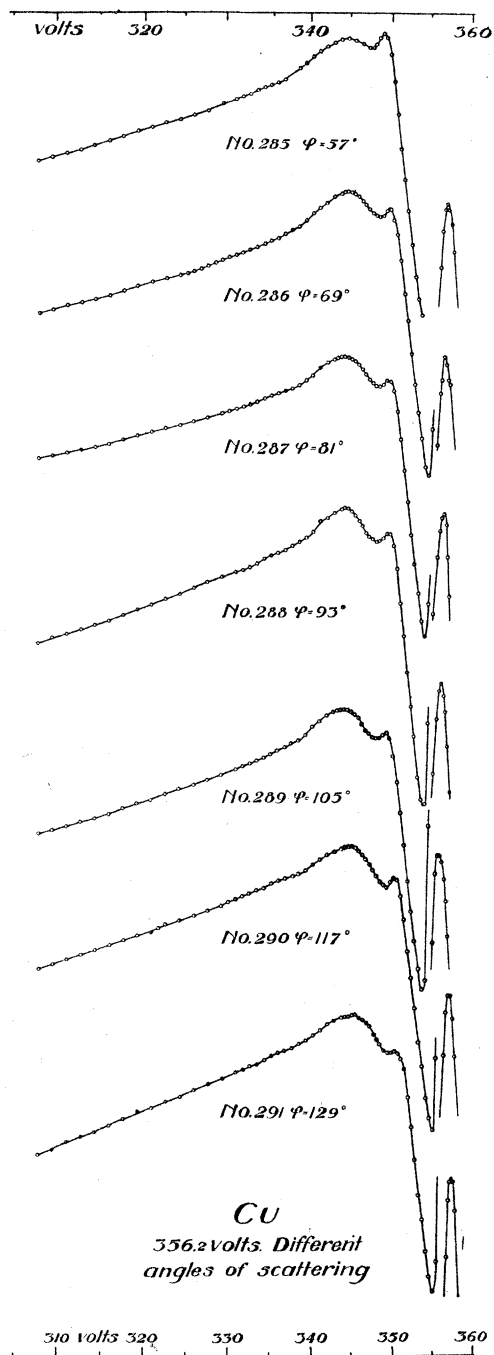


FIG. 10.

Energy Losses of Electrons.

127

ing, the data presented in the following tables supply valuable additional proof of this statement.

Numerical Data.

The following tables give the position of the different maxima, or indications of maxima, in the curves, measured in volts from the centre of the peak due to reflected electrons. The bombarding voltage and the kind of method employed are also stated. The different curves are numbered in chronological order. Where several targets of the same substance have been tested, they are distinguished as I, II, etc. The symbol Pt' refers to a silver target backed with platinum, from which the silver had been distilled off completely, before the measurements were started.

Table I.—Copper.

Target.	No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .	V ₅ .
I	33	91.6	var. field	3.3	6.9		27.5	
	29	137.2		3.1	7.1		26.8	
	35	166.4		3.0	7.2		28.0	
	30	204.0		3.5	7.0		25.4	
	27	232.4		3.5	7.1		26.1	
	32	275.3		3.8	7.0		25.2	
	34	305.3		3.3	6.7		24.2	
	28	340.7		3.8	7.5		24.9	
	31	411.8			6.3		24.1	
						3.4	7.0	
II	172	303.7	acc. pot.		8.1			
	171	325.6			8.1			
	170	346.9			8.6			
					8.3			
III	179	280.9	acc. pot.		7.0	12.8	24.5	34.9
	186	375.6			6.5	12.6	24.7	33.7
	185	395.9			6.8	12.7	24.7	34.4
	183	434.4			6.8	12.6	25.1	35.1
					6.8	12.7	24.8	34.5
IV	280	254.0	acc. pot.					
	279		45°		6.5	12.9		
	277		69°		6.1	11.9		
	281		81°		6.7	12.8		
	282		93°		6.6	13.0		
	276		105°		6.6	13.1		
	278		117°		6.5	12.9		
	137°		6.8	13.0				
					6.5	12.8		

Table I.—(continued).

Target.	No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .	V ₅ .
	284	254.0	var. field		6.3	10.7		
	283		57°		6.4	12.7		
	285	356.2	137°		6.5	11.0		
	286		57°		6.8	11.8		
	287		69°		6.8	12.2		
	288		81°		6.6	12.0		
	289		93°		6.5	11.8		
	290		105°		6.8	12.2		
	291		117°		6.9	12.0		
			129°					
Mean of all measurements				3.4	6.6	11.8	25.5	34.5

Table II.—Silver.

No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .
		acc. pot.			
258	261.8	69°	4.3	7.2	
257		81°	4.3		
260		93°	4.4	7.3	
256		105°	4.4		
261		117°	4.6	7.1	
259		136°	4.7	7.0	
265	343.8	69°	4.6	7.4	
264		81°	4.6	7.5	
267		93°	4.8	7.6	
263		105°	4.7	7.6	
268		111°	5.0	8.0	25.1
266		117°	4.6	7.4	
262		136°	4.8	7.2	24.6
			4.6	7.4	24.8

Energy Losses of Electrons.

129

Table III.—Gold.

Target.	No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ '.	V ₃ .	V ₃ '.	V ₄ .				
I	229	298.9	acc. pot.	8.1		24.6	25.6	27.1	35.1				
	228	316.0		8.1					24.3	34.6			
	227	336.1		8.2					24.7	34.6			
	237	348.8		8.7		25.2	35.2						
	226	356.4		7.4	9.2	24.9	34.6						
	236	365.1		8.9		25.0	25.9	25.8	34.2				
	225	376.1		7.1	11.0				34.7				
	235	377.9		7.5	9.8	25.6	34.5						
	234	390.0		7.3	10.3	25.6	35.4						
	233	401.9		7.2	10.7	25.0	27.6	35.0					
	232	417.5		7.2	8.4	24.5	27.4	27.3	34.8				
	231	438.6		7.3	9.4								
	230	458.9		8.6		24.8	25.7	25.5	26.6				
	II	301		256.8	var. field	7.3	10.1	26.4	26.4	27.3	36.0		
		300				7.0	26.3					26.3	27.1
		299				7.2							
		302		69°		7.3	24.3	26.0	26.3	27.1	36.5		
		303		81°		7.0	27.1						
		304		93°		7.5	27.3	26.3	26.6	27.1	35.9		
307		347.6	69°	7.1		26.6	36.8						
306		81°	7.8	26.0		27.1	27.7	27.7	35.4				
305		93°	8.0	26.3									
308		375.8	69°	6.9		24.6	27.1	35.0					
309		81°	7.4	27.1		27.7	36.3						
310		93°	7.5	27.7		27.7	36.3						
Mean of all measurements				7.3	10.1	25.9	26.4	27.3	35.2				

Table IV.—Platinum.

Target.	No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .	
I	3	93.0	var. field	6.3				
	9	135.1		6.3				
	1	190.1		5.8		26.2		
	5	256.6		6.4		25.9		
	2	355.6		5.9		25.7		
	4	540.2		5.9		25.9		
II				6.1		25.9		
	125	203.6	acc. pot.	6.5				
	124	224.6			9.1			
	115	240.0		5.9	9.7			
	116	262.0		6.5	9.8			
	117	283.4		6.7	9.5	23.8		
	118	304.0		7.0	9.3	24.3		
	119	324.8		6.8	9.4	24.2		
	120	344.1		6.3	8.9	24.3		
	122	385.2		6.4	9.3	24.1		
	123	416.0			8.9	24.2		
	126	437.3		6.6				
	III					6.8	9.3	24.1
164		260.0		acc. pot.	6.1	8.7	25.4	33.1
154		270.3	6.2		10.3	24.5	33.7	
163		282.2	6.8		9.4	25.5		
153		296.5	6.5		10.0	24.1	34.1	
162		317.1	7.0		9.4	25.5	33.9	
156		332.9	7.6		9.7	24.1	33.8	
155		359.9	6.8		9.4	23.8		
161		370.1	7.4		9.4	25.6	33.9	
160		385.0			9.3	24.6	33.3	
159		410.8			9.6	24.8	33.4	
158		435.3	6.9		9.6	25.0	33.2	
157		458.7	7.1		9.7	25.1	34.5	
			6.8		9.5	24.8	33.7	
Mean of all measurements				6.5	9.4	24.8	33.7	

Energy Losses of Electrons.

131

Table V.—Pt'.

No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .	
198	242·3	acc. pot.	6·5	11·5	23·8	33·8	
197	259·0		6·9	11·5	24·1	35·2	
196	273·8		6·3	11·4	24·0	35·7	
193	335·9		6·7	11·5	24·1	34·9	
192	356·7		6·6	11·4	25·0	35·1	
201	400·0		6·7	11·9	25·7	34·2	
200	422·9		6·7	12·0	25·3	35·1	
199	443·9		6·6	12·3	26·1	34·2	
				6·6	11·7	24·8	34·8

Table VI.—Magnesium Oxide.

No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .	V ₅ .	
107	202·2	acc. pot.	6·8		17·6	22·8		
106	222·7		7·8		17·3	22·7	34·6	
105	243·6		6·9		17·9	22·8	33·8	
98	261·0			11·5	17·8	22·7	34·2	
104	280·6		7·0	11·5	16·7	23·0	33·4	
100	300·6		6·6		17·9	22·4	33·3	
109	319·3		6·9		17·4	22·6		
101	339·9		6·5	12·2		22·7	33·6	
102	368·5		6·3	11·9	17·1	22·8	33·8	
110	388·5			11·7	17·8	23·0		
103	415·0				17·7	22·8		
111	456·4		7·1	11·6	17·3	22·7	33·9	
				6·9	11·7	17·5	22·7	33·8

Table VII.—Calcium Oxide.

Target.	No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .	V ₅ .	
I	42	105.0	var. field		13.0			36.1	
	47	138.9			15.1			38.4	
	43	170.3			13.8				
	40	200.8			13.0			35.9	
	46	232.2			13.5				
	44	267.2			13.4			35.1	
	41	322.9			13.0			36.1	
	48	362.0			13.6			35.0	
	45	413.9			12.5			34.7	
II			acc. pot.		13.4			35.9	
	80	143.0		9.1	13.8		29.0	37.1	
	81	170.4		9.7	14.0		29.0	36.3	
	82	204.0		9.5	13.8	20.6		36.5	
	83	227.0		9.8	13.9	19.3	28.9	36.4	
	79	245.9		9.2	14.1		29.2	36.3	
	86	316.2		9.6	13.9	19.7	29.2	36.8	
	87	343.3		9.6	13.7	19.8	29.5	36.7	
	88	370.4		9.4	13.9	20.9	28.5	36.5	
	89	392.6		9.0	14.0	20.8	29.1	36.5	
	91	460.6		9.2	13.8	19.8	29.4	36.8	
	90	472.1		9.1	13.9	19.2	29.0	36.8	
	92	481.5		9.3	13.9	19.5	29.2	37.1	
	93	504.2		9.3	13.8	19.8	29.3	36.9	
	III				acc. pot.	9.4	13.8	19.9	29.1
214		314.1	9.9	14.2			29.9	37.5	
213		335.0	9.6	14.2			29.9	37.4	
	212	354.7		9.9	14.2		30.4	37.5	
IV			acc. pot.	9.8	14.2		30.1	37.5	
	246	244.1		81°	9.7	13.9		29.7	36.3
	245			99°	9.1	14.3		29.6	37.0
	244			137°	9.8	14.1	20.6	29.8	37.3
	247	467.3		74°		13.8		30.0	36.5
	248			99°		14.3		29.3	37.8
	249			137°		14.4	20.5	29.9	37.9
						9.5	14.1	20.5	29.7
Mean of all measurements				9.4	13.8	20.0	29.4	36.7	

Energy Losses of Electrons.

133

Table VIII.—Strontium Oxide.

Target.	No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .	V ₅ .
I	65	268.0	acc. pot.	6.4	9.7	13.9	25.6	31.6
	66	306.0				9.7		13.3
	67	336.0		7.4	10.1	13.7		31.7
	68	360.0		7.5	9.9	13.1	24.6	31.4
	69	380.4		7.3	9.6	13.1	24.7	31.6
	70	404.4		7.6	9.8	12.8	25.3	31.4
	71	439.9		7.8	9.9	13.1		31.7
				7.3	9.8	13.3	25.1	31.6
II	74	153.9	acc. pot.		9.7	13.4	24.1	
	72	467.2		7.2	8.9	12.8	25.3	30.7
	73	490.3			9.1	12.4	25.7	30.5
				7.2	9.2	12.9	25.0	30.6
III	76	239.0	acc. pot.	6.8	9.7	13.4	24.5	31.7
	75	273.9			9.3	13.5		31.5
	78	286.0		7.3	9.5	12.7	25.3	31.4
	77	313.8		7.5	9.9	13.0		31.3
				7.2	9.6	13.2	24.9	31.5
IV	224	331.2	acc. pot.		9.3	13.6	24.0	32.5
		352.2			9.5	13.8	24.8	32.5
					9.4	13.7	24.4	34.5
Mean of all measurements				7.3	9.6	13.2	24.9	31.6

Table IX.—Barium Oxide.

Target.	No.	Voltage.	Method.	V ₁ .	V ₂ .	V ₃ .	V ₄ .
I	61	94.0	acc. pot.		17.0	25.2	
	62	125.9		10.1	18.1	24.8	
	54	216.3		10.3			
	55	262.8		10.4	16.6	25.0	
	51	269.2		10.5	16.2	24.2	32.7
	56	282.8		10.1	16.2	24.6	32.4
	57	308.1		10.6	16.8	25.8	32.7
	58	347.3		10.6	17.1	25.5	33.2
	59	376.1		10.5	16.5	25.5	32.8
	60	414.8		10.6	16.4	25.5	
					10.4	16.7	25.1
II	219	328.0		11.4	26.5		
	218	391.9		11.5	17.3	26.1	
			11.4	17.3	26.3		
Mean of all measurements				10.6	16.8	25.3	32.7

It may seem strange to take a simple mean of all the values in the vicinity of 25 volts for gold. Several of the curves for the first target give fairly definite evidence of two maxima in this region. The corresponding maxima for the second target, however, have not been separated, although there is a considerable spreading of the individual values, and a separation of these values into two groups, with respect to their magnitude, would be very arbitrary. This is the reason why I have treated this part of the curves as a single maximum.

In many of the cases where several targets of the same substance have been tested it will be found that the mean values for the different targets do not show such a close agreement among themselves as would be expected from the magnitude of the individual deviations within each group. Hence there would seem to be a systematic difference in these cases. It is fairly certain that the position of these maxima is influenced to a certain extent by conditions not controlled in the experiments, the nature of which remains unknown. In some cases, the temperature of the heated target may be of some importance, although several experiments in which this factor was varied failed to reveal any influence of this kind. The changes in relative intensity and the disappearance of some of the maxima should probably be connected with the same change in conditions, which is responsible for the shift in position. Under these circumstances one might be inclined to regard the mean of the average positions of the maximum for each separate target as the best value to represent this position. I have chosen, however, to use the simple mean of all determinations. The difference is usually not very large; where the number of measurements is the same for the different groups, the two methods obviously lead to the same result. The mean positions of the maxima thus calculated, together with the error in these mean values obtained in the usual way, are summarized in Table X.

Table X.

Copper	3.4 ± 0.11	6.9 ± 0.10	12.3 ± 0.15	25.5 ± 0.31	34.5 ± 0.31
Silver	4.6 ± 0.06	7.4 ± 0.08	24.8 ± 0.26	—	—
Gold	7.3 ± 0.07	10.1 ± 0.29	25.9 ± 0.21	35.2 ± 0.19	—
Platinum	6.5 ± 0.09	9.4 ± 0.08	24.8 ± 0.16	33.7 ± 0.14	—
Pt'	6.6 ± 0.06	11.7 ± 0.12	24.8 ± 0.30	34.8 ± 0.23	—
Magnesium oxide	6.9 ± 0.10	11.7 ± 0.11	17.5 ± 0.11	22.7 ± 0.05	33.8 ± 0.13
Calcium oxide	9.4 ± 0.07	13.8 ± 0.07	20.0 ± 0.17	29.4 ± 0.10	36.7 ± 0.13
Strontium oxide	7.3 ± 0.13	9.6 ± 0.08	13.2 ± 0.11	24.9 ± 0.17	31.6 ± 0.12
Barium oxide	10.6 ± 0.14	16.8 ± 0.19	25.3 ± 0.20	32.7 ± 0.14	—

The data of this table are shown graphically in fig. 11, where each value is represented by a pointed, vertical wedge. The height of the wedge should give a

rough idea of the relative importance of the corresponding maximum for each particular substance, *i.e.*, the weight given to the corresponding value. This was determined by the product of the number of curves showing this maximum, and a second weight factor from 0.5 to 1.0, to take account of the shape of the maximum in the curves (whether there was a real maximum or merely an outstanding change of slope). In order that this figure should give at least a rough idea of the relative accuracy in the different values, the "Halbwertsbreite" of the wedges was made equal to the calculated mean errors from Table X. The shape of the wedges has, of course, very little to do with the shape of the actual maxima in the curves. For the sake of brevity I shall use the term "(energy) loss spectrum" for a representation like those in fig. 11.

Discussion.

The smallest values recorded are those for the first maximum in the case of copper and silver. There follows, for all the metals tested, a prominent

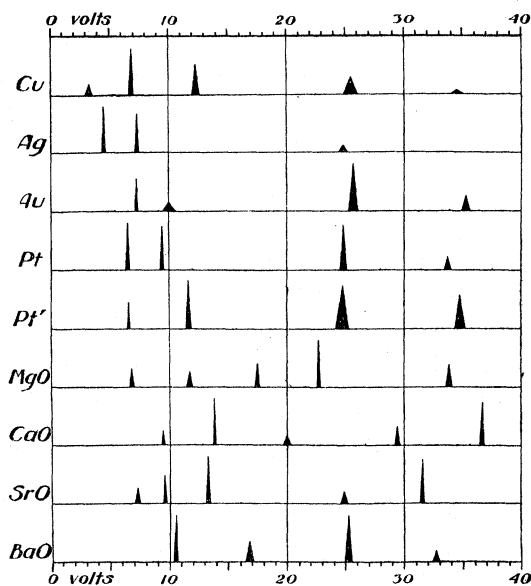


FIG. 11.

maximum in the neighbourhood of 7 volts. Further, the metals will be seen to give a broader hump near 25 or 26 volts, usually fairly obvious, and a rather faint indication of a similar feature not too far from 35 volts. I am inclined to regard the former of these as identical with the maximum always present with cold targets, whatever the substance bombarded. If this maximum is

attributed to some common foreign substance, the possibility of a hump in this part of the loss spectrum characteristic of the metal itself should not be excluded. The behaviour of the curves for gold may have some significance in this connection, but the question requires further experiments. The loss spectrum for Pt' bears a close resemblance to that for platinum, and there is no reason why this target should have differed essentially from the ordinary platinum ones. The prominent platinum maximum at 9.4 volts, however, appears replaced by an equally sharp one at 11.7 volts. This is certainly not an accidental shift. The possibility* cannot be entirely excluded, that this last maximum is due to copper, although it does not seem very likely that the adjustment was so bad that the scattering from the copper leads to the foil was included in the measured emission to a considerable extent. Also, these leads should have been at a comparatively low temperature in the experiments.

As regards the loss spectra for the four different oxides tested, the possibility of the appearance of features pertaining to the backing substance must not be overlooked, since the deposits were sometimes thin and did not cover the entire surface of the strips. Both the position and the general shape of the first maximum in the case of magnesium oxide and calcium oxide are in agreement with the view that these maxima belong to the platinum support. The same is probably true for the first and second maximum in the loss spectrum for strontium oxide, although the value for the former one is rather high. The second maximum for magnesium oxide coincides exactly with the strongest one in the loss spectrum for Pt'. The peaks near 25 volts for strontium oxide and barium oxide are probably not related to the one common to the metal targets, although they fall in the same region.

It is difficult to trace any relations between the different loss spectra as shown in fig. 11. Although the series of substances studied—elements from the first and second column of the periodic table—was chosen partly with the view of looking for such regularities, there is, of course, no binding reason why a relationship should be expected. As regards the metals, however, the gap between 13 and 25 volts should be observed. With the oxides there would seem to be some evidence of sequences in the loss spectra. Thus the values CaO 13.8, SrO 13.2, BaO 10.6, and CaO 36.7, SrO 31.6, BaO 25.3, for the two strongest maxima in each case, show a similar trend; to the first series the fairly prominent maximum at 17.5 for magnesium oxide could perhaps be added at the top. The less important peaks CaO 29.4, SrO 24.9, BaO 16.8 (to which MgO 33.8 may indicate a prolongation at the upper end)

* Prof. O. W. Richardson has very kindly suggested this possibility to me.

Energy Losses of Electrons.

137

form a sequence with a similar trend. I have no theoretical explanation to offer for this behaviour of the maxima in the curves; and it is, of course, possible that it is only a matter of chance, to which no significance should be attached. I think, however, that this particular feature is sufficiently striking in fig. 11, and perhaps still more in the curves, to justify mentioning at the present state of things.

Interpretation.

It does not seem possible to give a detailed quantitative interpretation of the experimental results at present. As to the nature of the phenomenon, the following conclusions may be drawn. The effect is not one of diffraction of electron waves of the usual character, which is related to the crystal structure of the target. This is shown by its independence of bombarding voltage, orientation of the target and scattering angle. It is also difficult to imagine that the often complicated structure of the experimental distribution curves could simply represent the variation of the probability for one single kind of ionisation. The several maxima in the distribution curve for the secondary electrons proper, which would be expected on this view, have not been observed; also, a probability curve of this kind could hardly show such a remarkable independence of voltage and scattering angle. In fact, I believe that the constant position of the maxima measured in terms of energy from the reflected peak constitutes definite proof that their appearance is accompanied by definite energy changes taking place in the bombarded atoms at the surface of the targets. The values obtained should thus represent a kind of critical potentials for the substances in question. Such potentials, secured by a modification of the well-known method of Franck and Hertz, have recently been published by H. B. Wahlin* for the vapours of copper and silver. His curves show a great number of small breaks for potentials in the region from 1 to 11 volts, some of which are not too far from the few values for targets of these metals listed in Table X, but these breaks are in no way outstanding ones and it is very doubtful if any correlation exists. From spectroscopic data, the values for the resonance potential, $1S - 2P_{1,2}$, and the first ionisation potential, $1S$, should be: for copper, 3.80, 3.77 and 7.69; for silver, 3.76, 3.65 and 7.54; for gold, 5.08, 4.61 and 9.25, all in volts.† On the whole it would seem that the two first maxima obtained reproduce, to some extent, the general trend of these values—the resonance doublet could scarcely be expected to be

* 'Phys. Rev.', vol. 31, p. 155 (1928); vol. 32, p. 277 (1928).

† Franck and Jordan, "Anregung von Quantensprüngen durch Stösse," p. 127, Berlin (1926).

resolved—although there are very large individual deviations (for instance gold). The spectroscopically determined values, however, correspond to the free atoms in the gaseous state, and though there may have been some metal vapour present of a very low pressure at the temperatures of the bombarded targets, the greater part of the scattering must have taken place in the solid substance, where the conditions probably were rather different from those governing the reactions of free atoms. Brown and Whiddington,* using oxide-coated targets, obtained lines which they ascribed to oxygen. The strong maxima at 13·8 volts for calcium oxide and 13·2 volts for strontium oxide are fairly close to the ionisation potential 13·56 volts for atomic oxygen, but the corresponding maximum in the case of barium oxide is too far removed to make this interpretation appear likely to be correct.

Maxima in the distribution curves, which result from the excitation of free atoms, should be expected to be very sharp. The greater width of the maxima found, as compared with the width of the peak due to reflected electrons, could be accounted for by the fact that the regions for which energy changes take place in solids are often quite broad. Small changes in energy, suffered by the scattered electron along its short path in the target, would produce the same result. In the case of ionizing collisions the energy lost should vary from a lower limit upwards, depending on the amount of kinetic energy with which the liberated electron escapes; hence the maximum may appear shifted to a higher voltage value than the actual ionizing potential. An accurate knowledge of the energy distribution for the slow-moving secondary electrons formed, and particularly of the position of its maximum, would make it possible to correct for this shift. With this object, I have spent much time trying to measure the low-velocity end of the distribution curves for different targets. The influence of the magnetic field due to the heating current, which prevented measurements in this region in the earlier work, was satisfactorily removed by the construction of the new target holder, but owing to the effect of space charge, necessarily present for bombarding currents of this magnitude, the behaviour of the tube was sometimes erratic. When conditions were steady, curves very similar to those for cold targets were obtained. The position of the maximum in these curves—plotted against energy after recalculation—often exhibited changes for the same substance much greater than those in the curves for the scattered electrons. Apart from the deformation of the curve probably produced by the space charge, the distribution of the electrons escaping from the surface could scarcely be expected to be identical with the

* 'Leeds. Phil. Lit. Soc. Proc.', vol. 1, p. 162 (1927).

Energy Losses of Electrons.

139

initial one for the secondary electrons at the moment they leave the parent atom, since subsequent collisions on their way out is likely to change this. In view of this uncertainty, no attempt has been made to apply a correction of the kind mentioned to the data in Table X.

Recently E. Rupp* has published some interesting results on the absorption and reflection suffered by comparatively slow-moving electrons in thin films of a number of different elements. Characteristic maxima were found in the curves, which were very similar for the two kinds of phenomena under investigation. They are regarded as indications of characteristic absorption frequencies for the electron waves analogous to the characteristic frequencies in the corresponding case of optical dispersion. The general shape of these maxima is often similar to that for the peaks found in the present research, but for the few elements which have been tested in both respects, the positions of the maxima are different. In spite of this, it would seem likely that there is a relation between the two effects.

It would be a matter of great interest if a characteristic spectrum of radiation, related to the energy losses found, could be obtained by subjecting solid targets to electron bombardment. Such a spectrum should occur in the region from the visible down to the far ultra-violet. In the case of metals, a survey of existing experimental data by different investigators has recently led me to conclude, that there is no appreciable amount of such radiation emitted for bombarding voltages of the magnitude here considered, and that the return of the atoms to the normal state must therefore involve some kind of a radiationless process.† For the oxides things may possibly be different. Whilst thus the prospects do not look entirely hopeful for a fresh attempt to find characteristic radiations to correlate with the maxima here found, it is possible that previous shortcomings could be due to a failure to hit some essential condition, such as, perhaps, heating the target, in the experiments hitherto performed. It appears to me a matter of some importance to re-investigate this point, and I am hoping to be able to try some experiments of this kind presently.

Summary.

An apparatus is described by means of which the velocity distribution of an initially homogeneous beam of electrons can be obtained after scattering from the surface of targets of different substances, kept at incandescence.

* 'Z. Physik,' vol. 58, p. 145 (1929).

† *Loc. cit.*

The distribution with respect to energy among the scattered electrons has a sharp peak, corresponding to truly reflected electrons, and several small maxima for slightly lower values of the energy, which form the principal object of the present investigation. These maxima are characteristic of the substance forming the target, and their position with respect to the reflected peak remains constant for the wide range of bombarding voltages tested. Using a modified form of the same apparatus in which the target and electron gun can be rotated, it has been proved that these maxima are also independent of the angle of scattering.

Tables are given containing the positions of such maxima measured for different targets.

In discussing these results it is pointed out that the maxima show the characteristics which they should possess, if they result from inelastic collisions with the target atoms involving definite energy changes, such as excitation and ionization of the latter ones. No definite conclusion concerning their classification has, however, so far been arrived at, from a comparison of the values obtained with existing spectroscopic data for the gaseous state. In this connexion the demand for investigations on the radiation from heated solids, bombarded by electrons, is emphasized.
