A RECORDING X-RAY SPECTROMETER, AND THE HIGH FREQUENCY SPECTRUM OF TUNGSTEN.

By Arthur H. Compton.

ALTHOUGH the photographic method of obtaining the spectrum of a beam of X-rays reflected from a crystal has led to most interesting results in the hands of Moseley,[1] de Broglie[2] and others, it has been found possible to examine such a spectrum more thoroughly by ionization methods.[3] The reason for this is that while by the photographic method the intensity of the different spectrum lines can at best be only qualitatively measured, the ionization method is capable of giving quantitatively the relative intensity of the reflected beam of X-rays at different angles. The ionization method as usually applied, however, is open to the objection that a very large number of separate observations are necessary to obtain accurately a complete spectrum. In the present paper an apparatus will be described which gives a continuous record of the intensity of the beam of X-rays at different angles, and a study of the X-ray spectrum of tungsten will be made to illustrate the manipulation of the instrument.

This apparatus differs from the well-known Bragg X-ray spectrometer in two essentials: (1) The ionization current due to the reflected beam of X-rays, instead of charging up an electroscope directly, goes to one pair of quadrants of an electrometer and is shunted to earth through a high resistance. The electrometer thus acts as a highly sensitive galvanometer, a steady ionization current producing a steady proportional deflection. (2) The angle of the crystal and of the ionization chamber are varied continuously in such a manner that the ionization chamber is always in position to receive the reflected beam of X-rays, and the electrometer deflections corresponding to each particular angle of the crystal are recorded on a moving roll of photographic paper. In this manner a record of the complete spectrum can be obtained with a minimum of trouble and of exposure to the X-rays.

The arrangement of the apparatus is shown diagrammatically in Fig. 1. The X-rays pass from the anticathode A, through the slits B and B',

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[1] H. G. J. Moseley, Phil. Mag., 26, 1024 (1913).

[2] M. de Broglie, Compt. Rend., 157, 924 and 1413 (1913).

[3] Cf. W. H. Bragg and W. L. Bragg, X-rays and Crystal Structure, p. 66.

are reflected from the crystal *C* and pass through the slits *D′* and *D* into the ionization chamber *I*. The ionization chamber rests on an arm fastened to the spectrometer table *S*, and the table on which the crystal rests is geared to move with half the angular velocity of the ionization chamber, though its position can also be varied by means of the slow motion screw *F*. The ionization current is carried from the chamber *I* to one pair of quadrants of a highly sensitive electrometer *E*, and is shunted to the ground through a variable xylol-alcohol resistance *R*. The intensity of the primary beam is measured in a similar manner by means of the ionization chamber *I′*, the resistance *R′* and the electrometer *E′*. The mirrors of both electrometers reflect beams of light from the Nernst glower *N*, through a fine horizontal slit *k* onto a roll of bromide paper *P*. A motor-actuated driving clock *MQ* moves, by means of a system of pulleys and worm gears, both the spectrometer table and the roll of bromide paper at a constant, though adjustable, speed. The pointer *H* is so geared to the shaft which drives the spectrometer table that it makes one revolution for each degree through which the table turns, and by means of a mercury contact the lamp *L* is turned on for an instant at each degree or half degree. This illuminates the slit *K* and marks off the angle by a series of lines across the bromide paper, as is shown in the records, Figs. 4 to 11.

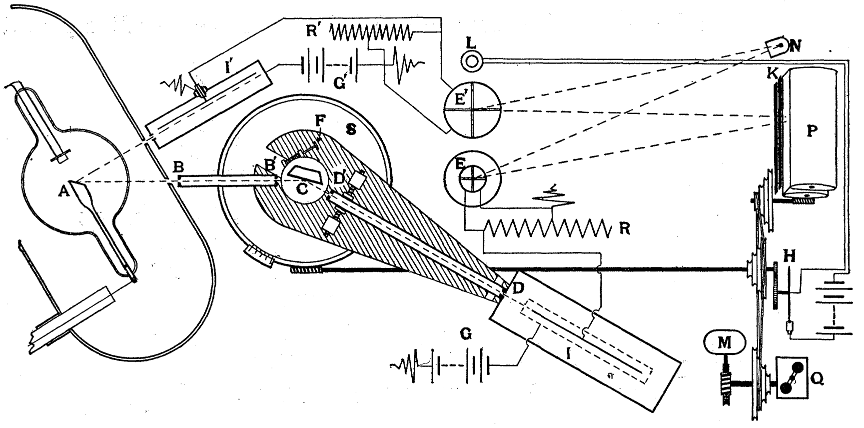

Fig. 1.

The construction of the system for measuring the reflected beam of X-rays is shown in more detail in Fig. 2. The ionization chamber *I* is closed at one end by a thin mica window *m* and at the other by a perforated brass cap covered with a plate of glass *g*. This arrangement allows the crystal to be adjusted optically to the angle of reflection.

The outside of the ionization chamber is grounded, but the wire framework f is raised to a sufficiently high potential to produce a saturation current to the wire w which is connected with the electrometer. The wire w passes through the ebonite plug e_1, is fastened to one terminal of the glass tube R containing a mixture of xylol and alcohol, and goes through the ebonite plugs e_2 and e_3 to the electrometer. The wire can be grounded directly by screwing up the mercury cup O until it touches a contact point, or it can be grounded through the desired high resistance by moving up one of the other mercury cups. If all the cups are down the system is insulated. The electric shielding consists of the rather heavy copper box c and the brass tube b. The electrometer E is placed directly over the axis of the spectrometer, so that the joint in the shield at j permits free motion of the spectrometer arm, while an oil seal renders the shield airtight.

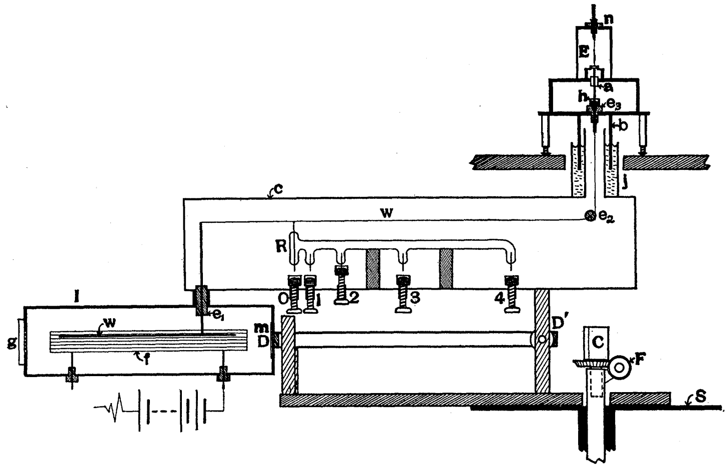

Fig. 2.

The electrometer E deserves particular mention, because it is so admirably adapted to this work. Its chief advantages lie in its flexibility, in its high sensitivity, in its perfect electrostatic shielding and in the use of a single piece of insulation for the sensitive quadrants. The quadrants of the electrometer are only 1.3 cm. in diameter. One pair of quadrants is supported by brass rods which fit into the electrometer case, and is thus permanently grounded; while the other pair is supported on a fine brass rod which passes through the amber insulation a and dips into the mercury cup h. The needle is suspended by a fine quartz fiber, and the whole system is sputtered with platinum. Most of the moment of inertia of the needle is due to the mirror, so this is made just large enough to reflect a sufficiently strong beam of light. The needle is "dead-beat," and comes approximately to rest in a few seconds. With ten volts on the needle the electrostatic control is small, and with the suspension used the sensitivity is about 1,000 divisions per volt. When the potential of the needle is above forty volts, the electrostatic control becomes the determining factor, and the sensitivity can be varied from 1,000 divisions to ∞ by adjusting the position of the quadrants and the height of the needle. The highest sensitivity that it has been found practicable to use is about 25,000 mm. per volt at a distance of a meter. The capacity of the electrometer is about 15 electrostatic units, so that it is capable of measuring a very small charge.

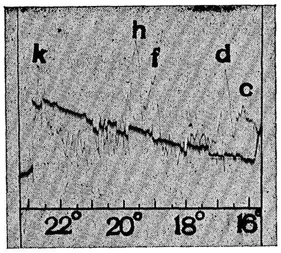

Fig. 3.

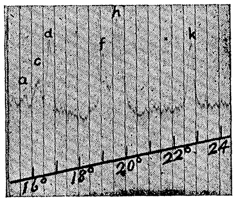

Fig. 4.

The Effect of Slight Radioactivity in the Ionization Chamber.—Fig. 3 shows an early attempt to obtain the X-ray spectrum of tungsten with this apparatus. The dark line represents the primary beam of X-rays and the light one the reflected beam. The electrometer in this case had a sensitivity of about 10,000 divisions per volt, and the shunting resistance was rather high. The electrostatic shielding at this time consisted of steel tubing and galvanized iron. Although the more prominent spectrum lines are easily distinguishable, there are so many spurious deflections of the electrometer which in no way correspond to variations of the primary beam of X-rays that it is impossible to make any accurate measurements. Supposing that these irregular motions were due to stray ionization currents within the electrostatic shield, a copper and brass shield was used instead, thus decreasing the contact potential difference between the shield and the wire. In this manner the relative size of the spurious deflections was much reduced, as is shown in Fig. 4, though these motions were still so large as to interfere seriously with the readings.

Investigation showed that the remaining irregular motions of the electrometer needle were due, in large measure at least, to real ionization currents in the ionization chamber, which were independent of the X-rays, as is shown in Fig. 5 in which the X-ray tube was not running. The magnitude of this current was found to be of the same order as the natural ionization current usually observed in brass vessels. It was also noticed that the deflections always occurred suddenly in the direction of the normal ionization current, and then died out gradually, which suggested ionization due to alpha particles.

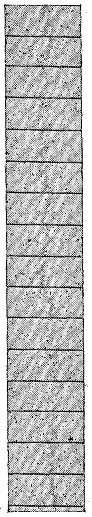

Fig. 5.

As will be shown later (equation 4 below), if the shunt resistance and the sensitivity of the electrometer are known, the total ionization corresponding to each hump on a record can be calculated from the area under the hump. When such a calculation is made on the record shown in Fig. 5, it is found that on the average each hump corresponds to the production of about 8×10^4 ions. Not all of the alpha particles will escape from the walls of the ionization chamber with their full velocity, since most of them will start at some distance from the surface of the metal. If we assume that the alpha particles have a definite range in the metal, a simple calculation shows that the average range of the emitted particles will be half the maximum range. Since, however, the ionization is somewhat greater per centimeter path for the more slowly moving particles, the average ionization will be somewhat more than half, about 0.6 of that produced by a particle which starts from the surface (assuming the emitted particles to be completely absorbed by the gas in the ionization chamber). A particle starting from the surface therefore produces about $8 \times 10^4/0.6 = 1.3 \times 10^5$ ions. An alpha particle from radium would produce 1.5×10^5 ions, which agrees well enough with the observed value to show that these spurious deflections are doubtless due to alpha particles given off either by the walls of the ionization chamber or by the gas within it.[1]

[1] An effect exactly similar to that here described has been observed by Rutherford and Geiger (Proc. Roy. Soc., *A*, 81, 141 (1908)) while counting the alpha particles from radium by an ionization method. They attributed the effect to the natural radioactivity of the metal of which the ionization chamber is composed. Recently Shrader (Phys. Rev., 6, 292 (1915)) has found that if the electrode within the ionization chamber has a sharp point, and if the chamber is at high enough potential to produce ionization by collision, the "natural disturbances" depend only on the nature of the point, and can be practically eliminated if the point is properly treated. It is to be noticed, however, that the only disturbances which would affect his electroscope would be the ones which would ionize the air near the needle point of his electrode, where any ionization was greatly magnified by collision. It would seem that his apparatus was not sufficiently sensitive to be affected by the occasional production of alpha particles in other parts of the ionization chamber. His work cannot, therefore, be taken to indicate that the walls of his ionization chamber were not slightly radioactive, so that his results are not inconsistent with the writer's and those of Rutherford and Geiger.

A thorough cleaning of the ionization chamber with nitric acid seemed to reduce the amount of radioactivity but little. Its relative effect could be greatly diminished, however, by filling the ionization chamber with a dense gas, and thus increasing the ionization due to the X-rays. The spectrum shown in Fig. 6 was obtained in this manner, using a simple ionization chamber such as I', Fig. 1, filled with dry hydrogen iodide. The effect of the alpha particles was still fruther reduced by changing the ionization chamber to the type shown in Fig. 2. The ionization due to the X-rays is produced chiefly within the wire network f, which is kept at a sufficiently high potential to produce a saturation current to the wire w. The outer casing of the ionization chamber is grounded, and enough air-space is left between the casing and the network to absorb all the alpha particles which leave the walls. Thus the particles from the walls of the vessel do not affect the current flowing to the wire w; this is affected only by the radioactivity of the wire netting and of the gas within it. By this means the number of spurious deflections of the electrometer was reduced to about 1/4 of the number when the simpler ionization was used, while the ionization due to the X-rays remained about the same. All of the spectra after Fig. 6 were obtained with this new ionization chamber.

A Study of the High Frequency Spectrum of Tungsten.—As a source of X-rays for the examination of the spectrum of tungsten, a Coolidge X-ray tube with a tungsten anticathode was used. In order that the tube should remain steady over long runs it was found best to heat the thermionic filament by means of batteries of rather large capacity, 175 ampere hours. The source of high potential was a Snook-Roentgen machine. This consists of a 10-kilowatt step-up transformer with a commutating device in the secondary circuit, which makes it possible to obtain a direct though intermittent high potential current. This apparatus was easily capable of running the Coolidge tube at its maximum capacity, and was found to be very satisfactory. In most of the runs a current of about 30 milliamperes was sent through the tube, with an alternate spark gap between sharp points of about 10 cm.

Fig. 6 shows a complete spectrum of the X-radiation from tungsten as analyzed by a crystal of zinc-blende. As in the other figures the heavy line indicates the strength of the primary beam, and the light one of the reflected beam of X-rays, though of course the two curves are on greatly different scales. Each vertical line corresponds to one degree on the spectrometer table, or 1/2 degree of rotation of the crystal. The angles marked on all of the spectra indicate the glancing angle θ of the beam of X-rays which strikes the crystal. The broken base line represents the zero point for the electrometer measuring the reflected beam, and the solid line that of the one measuring the direct beam of X-rays. At the angle $\theta = 30.5°$ a zero reading was taken, by putting a lead screen between the slit B' and the crystal, to make sure that the zero point of the sensitive electrometer had not shifted. In obtaining this spectrum wide slits were used, the slit at D being about 1.0 cm. The shunting resistance was about 3.5×10^{11} ohms, and the sensitivity 1,050 mm. per volt. With this low resistance and wide slits it was possible to go over the complete spectrum in an hour and a half.

Owing to the comparatively great wave-length of the characteristic L-radiation from tungsten and to the closeness of the layers of atoms in the cleavage planes of zinc-blende, it is impossible to obtain a complete third order spectrum in this case, but the first and second orders stand out very clearly. The line marked k is the single line observed in the spectrum of tungsten by Moseley,[1] and the prominent lines c, d, f, h and k correspond to the five lines observed by Moseley and Darwin[2] in the spectrum of platinum. Recently Barnes[3] has detected also the lines g and i in the tungsten spectrum by a photographic method. Lines at a and l can also be seen plainly in this photograph, l being visible only in the second order spectrum because of its proximity to the prominent line k. An indication is also given of possible lines at e and j. These are confirmed by other records, though the line j is rather doubtful. A series of four records, such as Fig. 7, which is a part of the first order spectrum from rock-salt using a slit at D only 0.4 mm. wide, indicates that the line c is really a very close double. A line also appears con-

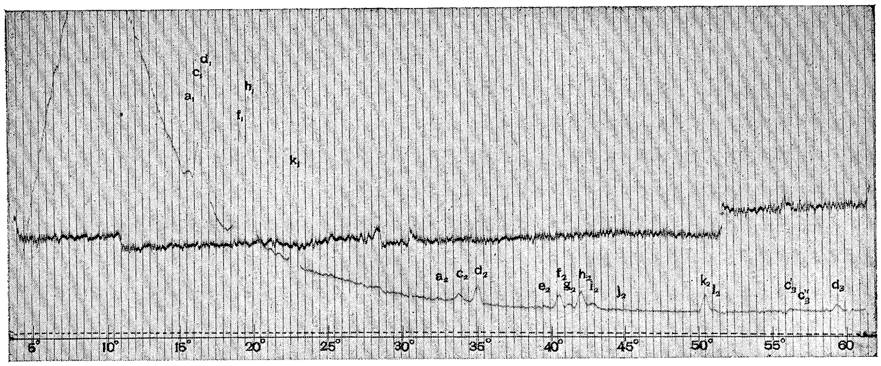

Fig. 6.

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[1] H. G. J. Moseley, Phil. Mag., 27, 703 (1914).

[2] H. G. J. Moseley and C. G. Darwin, Phil. Mag., 26, 211 (1913).

[3] J. Barnes, Phil. Mag., 30, 368 (1915).

sistently on a number of records between *a* and *c*. All of these lines are shown more or less distinctly in Fig. 8.

In order to make an accurate determination of the wave-length of the different lines, a crystal of calcite was used, as recommended by Professor Bragg, because of the extremely perfect faces obtainable. The X-ray tube was swung around until the rays which fell on the crystal left the target almost tangent to its face, the slits *B* and *D* were about 2 mm., and the slits *B'* and *D'* were made wide. The slit at *D* and the target of the X-ray tube were set as nearly as possible at equal distances, about 52 cm., from the crystal. With this arrangement it was found possible to measure the angles of reflection with considerable precision.

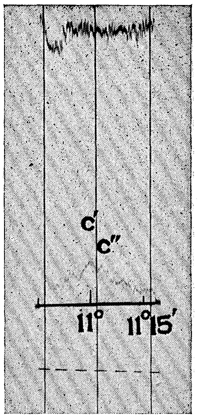

Fig. 7.

It was necessary first to determine the zero point accurately. This was done by taking a series of four records, two on either side of the zero point, one with the spectrometer moving toward and the other from zero. Fig. 8 is one of this series, taken with the spectrometer moving toward the zero point. The mean angle as measured from the three most prominent lines in the four records was taken as the true zero, and this could be determined with a probable error of less than ± 0.2'. The angle of the spectrum lines was then determined from a series of six records of the first order spectrum and two records showing the third order *k* and the fourth order *c*, *d*, *f* and *h* lines. Fig. 9 shows a part of one of these

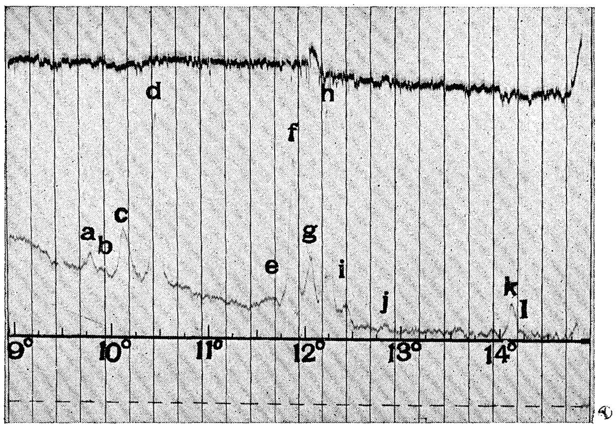

Fig. 8.

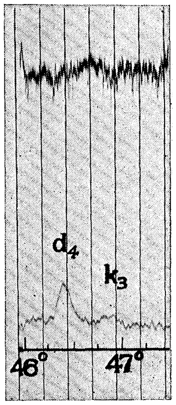

Fig. 9.

records, including the fourth order *d* and the third order *k* lines. The angles found for the higher order spectra did not correspond exactly with those calculated from the first order according to the formula

$$n\lambda = 2d \sin \theta.$$

The reason for the difference was traced to a combination of two causes: first, the front edge of the crystal projected about 0.5 mm. in front of the axis of the crystal table, and second, the slight penetration of the X-rays into the crystal made the observed angle slightly less than the true angle of diffraction. The latter effect is very small, being only about 0.2′ for tungsten rays diffracted by calcite. For X-radiation of short wave-length, however, and a crystal such as diamond, this error becomes of considerable magnitude, as has been noticed in the case of rhodium rays.[1] The correction due to the inaccurate adjustment of the crystal could be calculated accurately from a comparison of the position of the different orders of the same line. The sum of the two corrections was 3.15′ ± 0.10′, being practically equal for the different lines. The corrected angles of the lines of the first order spectrum are given in column 2 of Table I. The error in the angle here given for the more intense lines is probably less than ± 0.5′, though for some of the fainter lines the probable error is as much as ± 1.0′.

TABLE I.

Line.	θ	$\lambda \times 10^8$ Cm.	Barnes's Values.	Remarks.
a	9° 44.5′	1.0387		
b	9° 53.1′	1.0539		Line somewhat doubtful.
c′	10° 3.7′	1.0725	1.082	Very close double.
c″	10° 7.7′	1.0796		
d	10° 25.7′	1.1107	1.113	
e	11° 36.3′	1.2349		
f	11° 49.9′	1.2587	1.258	
g	12° 0.4′	1.2771	1.277	
h	12° 11.4′	1.2962	1.296	
i	12° 22.7′	1.3160	1.312	
j	12° 44.7′	1.3543		Line uncertain.
k	14° 4.7′	1.4933	1.477	Moseley gives 1.486.
l	14° 11.1′	1.5044		

The distance between the successive atomic layers in the cleavage planes of calcite may be calculated according to the formula[2]

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[1] W. H. Bragg, Phil. Mag. 27, 898 (1914).

[2] W. H. Bragg, Proc. Roy. Soc., *A*, 89, 468 (1914). "X-rays and Crystal Structure," p. 112. Professor Bragg uses the value $\phi(\beta) = 1.08$, which makes his value of *d* for calcite differ appreciably from that here obtained.

$$d = \left(\frac{1}{2}\frac{M}{\rho N\phi(\beta)}\right)^{\frac{1}{3}},$$

where M is the molecular weight of $CaCO_3$, ρ is the density of the crystal, N is the number of molecules per gram-molecule, and $\phi(\beta)$ is the volume of a rhombohedron the distance between whose opposite faces is unity and the angle between whose edges is β. This function may be shown to be

$$\varphi(\beta) = \frac{(1 + \cos\beta)^2}{\sin\beta(1 + 2\cos\beta)}.$$

For calcite, β is 101° 54′, which makes $\phi(\beta) = 1.0960$[1]. The density of the crystal used was carefully determined, and was found to be $\rho = 2.7116 \pm 0.0004$ g. cm^{-3}. (at 18°). Taking $M = 100.09$ and $N = 6.062 \times 10^{23}$ (Millikan), we find $d = 3.0279 \times 10^{-8}$ cm. From this value of d the wave-lengths can be immediately calculated according to the expression

$$\lambda = 2d \sin\theta.$$

Using the values of θ given in the second column of Table I., we obtain the wave-lengths given in the third column. For convenience in comparison the wave-lengths found by Barnes[1] are given in the fourth column.[2]

The Intensity of the Different Orders of Spectra.—It is difficult to obtain an accurate estimate of the relative intensity of the various lines in the same order of the spectrum, on account of the difference in the absorption of the corresponding wave-lengths. It is possible, however, to make a comparatively accurate determination of the relative intensity of the different order reflections of the same line. In order to do this, the slit at B' was made narrow, about 0.9 mm., slit D' was removed, and slit D was made 12 mm. wide, which was more than broad enough to take in all the rays reflected from the crystal. When the crystal and ionization chamber are moved at uniform speed past a spectrum line, the area under the curve representing the line on the resulting record is proportional to the integral of the ionization current produced by the line, and hence to the intensity of the line itself. Thus by comparing

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[1] J. Barnes, loc. cit.

[2] Note added May 12, 1916: In a preliminary report on this work, made at the meeting of the American Physical Society on February 26, the wave-lengths of the spectrum lines were calculated using as the grating space for calcite 3.0695×10^{-8} cm. instead of the value here found. The results thus obtained agreed acceptably with Barnes's measurements. W. S. Gorton has since shown (Phys. Rev., Feb., 1916), by comparison with rock-salt, that d for calcite is rather about 3.028×10^{-8} cm., which called my attention to an error in my previous calculation of the grating space. The wave-lengths here obtained are in much better agreement with those found by Gorton than with those due to Barnes.

the areas under the humps on the record, the intensities of the different order lines may be compared.

Since the period of the needle and the time required for the electrometer to charge up to its maximum potential might also be expected to affect the area of the hump, it may be worth while to investigate the question in detail. The equation of motion of the spot of light reflected by the electrometer needle onto the photographic paper is

$$I\frac{d^2y}{dt^2} + D\frac{dy}{dt} + My = \frac{M}{a}V, \tag{1}$$

where y is the deflection of the spot of light, I is the inertia term, D the damping term, M represents the restoring force, $1/a$ is the sensitivity of the electrometer, and V is the potential difference between the two pairs of quadrants. On integrating this expression between the times t_0 and t_1 we obtain,

$$\frac{Ia}{M}\left[\frac{dy}{dt}\right]_{t_0}^{t_1} + \frac{Da}{M}\left[y\right]_{t_0}^{t_1} + a\int_{t_0}^{t_1} ydt = \int_{t_0}^{t_1} Vdt. \tag{2}$$

The potential of the system at any time is given by the expression

$$V = Ri - RCdV/dt,$$

where R is the resistance of the shunt to ground, i is the ionization current, and C is the electrostatic capacity of the system. Integrating as before,

$$\int_{t_0}^{t_1} Vdt = R\int_{t_0}^{t_1} idt - RC\left[V\right]_{t_0}^{t_1}.$$

Combining with equation (1) and substituting in (2) we get

$$\begin{aligned}\int_{t_0}^{t_1} idt = \frac{a}{R}\int_{t_0}^{t_1} ydt + \left(\frac{aD}{RM} + aC\right)\left[y\right]_{t_0}^{t_1} \\ + \left(\frac{aI}{RM} + \frac{aCD}{M}\right)\left[\frac{dy}{dt}\right]_{t_0}^{t_1} + \frac{aCI}{M}\left[\frac{d^2y}{dt^2}\right]_{t_0}^{t_1}.\end{aligned} \tag{3}$$

Since the intensity of a line is proportional to the total ionization produced in the ionization chamber as it moves past the line, expression (3) is evidently a measure of the intensity if the times t_0 and t_1 are taken just before and just after the line is traversed. If the displacement, velocity and acceleration of the spot of light are the same at the times t_0 and t_1, equation (3) reduces to

$$\begin{aligned}\int_{t_0}^{t_1} idt = \frac{a}{R}\int_{t_0}^{t_1} ydt = \frac{a}{R}\frac{dt}{dx}\int_{x_0}^{x_1} ydx \\ = \frac{a}{R}\frac{dt}{dx}A,\end{aligned} \tag{4}$$

where dx/dt is the velocity with which the roll of paper moves, and A is the area under the hump on the record. In practice it is easily possible to satisfy these conditions with sufficient accuracy, so that the intensity may be taken to be proportional to the area under the curve.

The records shown in Figs. 10 and 11 are examples of this method of comparing intensities. Fig. 10 shows the first and second order f and h lines as reflected from a cleavage plane of rock-salt, and in Fig. 11 the second and third orders of these lines are compared. In Fig. 10 the lighter line has been inked, in order to make a better reproduction. The areas under the humps were measured with a planimeter. The largest part of the error probably occurred in selecting the base line from which

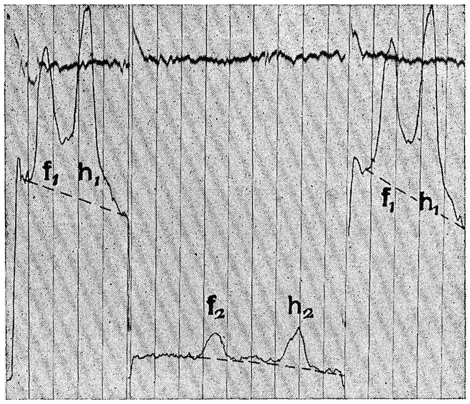

Fig. 10.

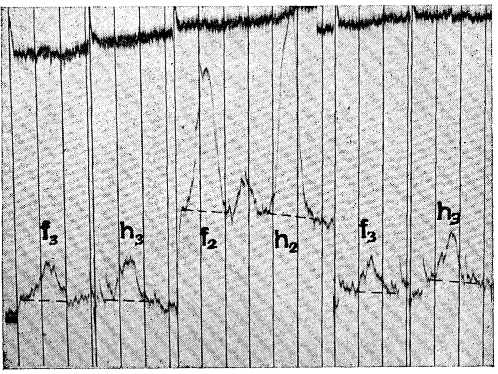

Fig. 11.

to measure the area. These records give the ratio of the intensities of the three orders as 100 : 18.9 : 3.9.

Bragg[1] has studied the relative intensities of the first three orders of reflection from rock-salt, using the rhodium line of wave-length 0.614 × 10^{-8} cm. He found that he could express his results within the probable error of his experiments by the formula

$$J_\theta = \frac{A(1 + \cos^2 2\theta)\, e^{-\beta \frac{\sin^2\theta}{\lambda^2}}}{\sin^2\theta},$$

where J_θ is the intensity of a given spectrum line when reflected at the angle θ, and A and B are constants. The factor $(1 + \cos^2 2\theta)$ was deduced theoretically by J. J. Thomson, and indicates a polarization of the reflected beam. Since in Bragg's measurements θ never became greater than about 20°, he was unable to decide experimentally whether this factor should really appear. In the writer's experiments the angle θ for the third order was 43°, so that the polarization should have been nearly complete. In the following table the first calculated values do not include the factor $(1 + \cos^2 2\theta)$, but this factor is included in the second calculation. The fact that the observed values agree much more closely with the values calculated when this factor is considered shows that the crystal grating does polarize the reflected beam and that this polarization is approximately complete when the angle of reflection is 45°.

TABLE II.

Order.	Mean Angle.	Intensities.		
		Calc.$_1$	Obs.	Calc.$_2$
1	13° 5′	100.0	100.0	100.0
2	26° 55′	21.6	18.9	16.2
3	42° 59′	7.5	3.9	4.2

Summary.—A recording X-ray spectrometer has been described by means of which a continuous record can be obtained of the ionization produced by a beam of X-rays reflected from a crystal as the angle of the crystal is varied.

A spurious and irregular current in the ionization chamber has been observed, which has been found to be due to a slight radioactivity within the ionization chamber. Methods are described whereby the effect of this radioactivity may be considerably reduced.

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[1] W. H. Bragg, Phil. Mag., 27, 893 (1914). also "X-rays and Crystal Structures," p. 198.

The X-ray spectrum of tungsten has been examined in some detail. In addition to the seven lines already known, an indication has been found of six others, two of which are, however, somewhat uncertain. The wave-lengths of the different lines have been carefully determined.

The relative intensities of the different order reflections of the same line have been shown to be proportional to the areas under the humps produced in the record by the spectrum line; and the relative intensities of the first three orders in the spectrum from rock-salt have been determined by measuring these areas.

The observed intensities of the different orders indicate that polarization occurs when a beam of X-rays is reflected by a crystal.

In conclusion I wish to thank Professor H. L. Cooke for many valuable suggestions in the design of the apparatus and for helpful advice in all parts of the work.

Palmer Physical Laboratory,
Princeton University,
February 16, 1916.

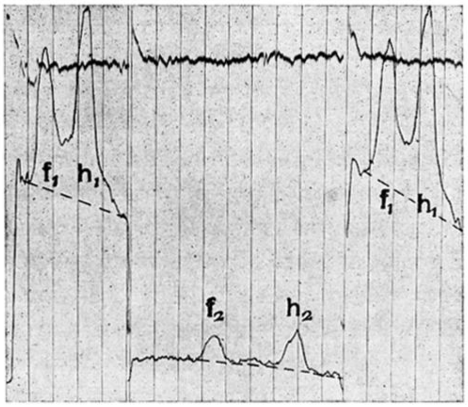


Fig. 10.

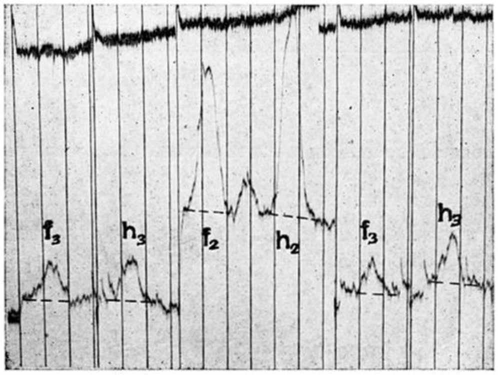
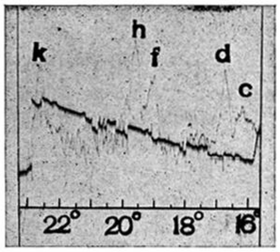


Fig. 11.



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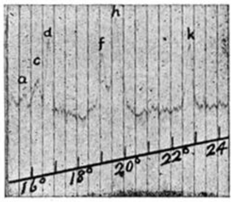
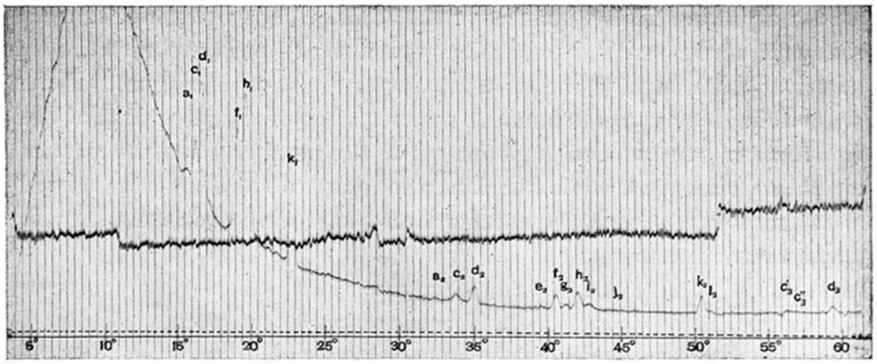


Fig. 4.

Fig. 5.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f_1
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c_2
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h_2
i_2
j_2
k_2
l_2
c'_3
c''_3
d_3
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10°
15°
20°
25°
30°
35°
40°
45°
50°
55°
60

Fig. 6.

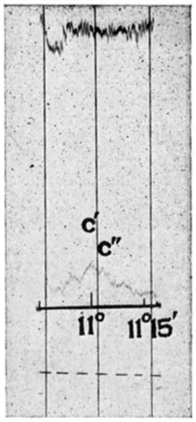
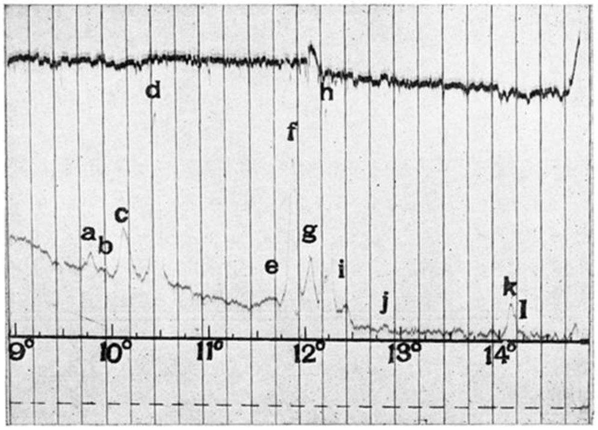


Fig. 7.



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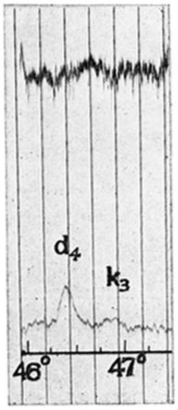

Fig. 9.