A NEW MAGNETIC SPECTROGRAPH FOR THE STUDY OF X-RAY PHOTO-ELECTRONS

By

Johannes A. Van den Akker

In partial fulfillment of the
requirements for the degree of
DOCTOR OF PHILOSOPHY

California Institute of Technology
Pasadena, California

1931

ABSTRACT

Qualitative experiments with the new Geiger-Müller ion-counter furnish information on the theory of operation of this instrument. Careful tests have established the limits of validity of a small Geiger-Müller tube of a nature typical of ion-counters which will be used for the measurement of beams of electrons and several precautions to be observed in the use of such a tube are given, together with a simple test of the worth of the anode wire in the tube. The smallness of the length to diameter ratio of the tubes used in this investigation has fortuitously made it possible to develop a corrective theory for the comparison of various rates of counting. This theory can be applied to tubes of greater size.

A means of restricting the active volume in a small tube has been found, and the operation of a tube in the specialized form recommended has proved very satisfactory. In this form, the Geiger-Müller tube has been built into a magnetic spectrograph of new design. Measurements taken with this spectrograph show that it possesses a very high resolving power, and that it will be of value in discovering new "lines" or peaks. Several new lines found are given, some of which could be attributed to mercury which was undoubtedly present in the sputtered gold film which was used. This suggests a means of accurately measuring the M level values in the mercury atom. L_I electrons ejected from gold by Mo $K\alpha_2$ were detected, showing that the new method will be efficacious where relatively slow electrons are measured. An attempt was made to measure the angular distribution of L_{III} electrons ejected from a very thin sputtered film of gold by Mo $K\alpha_1$, and the distribution curve obtained agrees well in its indications with inferences recently drawn from spectra obtained with the photographic method.

INTRODUCTION

The general study of x-ray photo-electrons may be divided into three important fields of investigation. First, an exact measure of the energies of electrons ejected from the atom by incident quanta furnishes us with an exact measure of the various energy levels in the atom and, where refined methods are used, will perhaps yield valuable information on double quantum absorption by an atom with the expulsion of a single electron, or on the expulsion of two electrons by the absorption of a single quantum. Second, a study of electrons which are ejected from atoms as the result of transitions in those atoms leads to a knowledge of how the energy levels in the atom change with various excited states or with chemical combinations and furnishes us with a means of testing the existence of certain forbidden transitions which might occur with the expulsion of an electron, but not of a quantum. Third, a true measure of the spatial distribution of electrons ejected from certain levels in the atom is of great theoretical interest.

Using a magnetic spectrograph, Robinson 1) has accurately evaluated most of the energy levels in a number of the elements and has found evidence for certain "forbidden", radiationless transitions. However, his apparatus was not designed for the study of spectra of electrons ejected at any given angle, although the use of foils so thick that scattering has made the distribution of electrons in his spectrograph practically isotropic has enabled him to infer the relative numbers of electrons which have been ejected from various levels in the atom as a function of the energy of the incident quantum. Watson[2)] has greatly improved the general method by the design of an apparatus which obtains spectra of electrons ejected at any given angle with the x-ray beam. In this apparatus, films of an element so thin that only single scattering can occur have generally been used. The use of a photographic plate for detection of the necessarily weak beams of electrons, however, suffers three handicaps: For a satisfactory spectrum at each angle, a long run of about one hundred hours has been necessary; the photographic method, as in ordinary spectroscopy, does not furnish an accurate measure of intensity; and in the regions of greatest interest, where the energy of the level from which an electron is expelled is comparable with the energy of the incident quantum, the energy of the photo-electrons is too low for satisfactory recording on a photographic plate.

It was the purpose of the work described here to develop a method by which individual photo-electrons of an given energy ejected at any given angle could be detected. The new Geiger-Müller tube was chosen for the detector of the electrons because of its extremely high sensitivity and reliability. Wherever a new instrument is used, however, one must know the extent of its validity and its more important properties. Since the characteristics of the new Geiger tube counter had not been measured, the greatest part of the work described in this thesis was devoted to a critical study of this new detector of individual ions.

INVESTIGATION OF THE VALIDITY OF A GEIGER-MÜLLER ION-COUNTER TUBE

1. General Discussion

For the sake of brevity, let us refer to the Geiger-Müller ion-counter as the G-M tube. As described by Geiger and Müller[3], this tube is a metallic cylinder with a specially prepared wire stretched along its axis. The wire is usually passed through hard rubber plugs at the ends of the cylinder, and the chamber thus formed is filled with dry gas, usually air, to a pressure of about five centimeters of mercury. The cylinder is connected to the negative pole of a source of high potential, while the anode wire is grounded through a high resistance as shown in Fig. 1. The purpose of the condenser C is two-fold. After an impulse the potential of the anode wire must reduce to zero slowly; a capacity effects this and conveys the impulse to a recording mechanism.

According to Geiger and Müller, the anode should be a wire of perfectly uniform diameter coated with a layer of badly conducting material of uniform thickness. In agreement with H. Kniekamp[4], and L. F. Curtiss[5], the writer has found that a bare polished wire gives satisfactory results if the resistance R and the capacity C are given proper values. The writer's best results have been obtained when the anode was a bare highly polished copper wire. How-

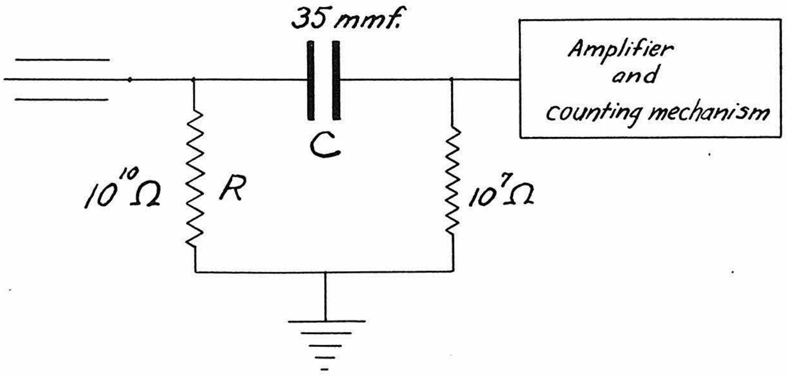

35 mmf.
C
Amplifier and counting mechanism
$10^{10}\Omega$
R
$10^{7}\Omega$

Fig. 1

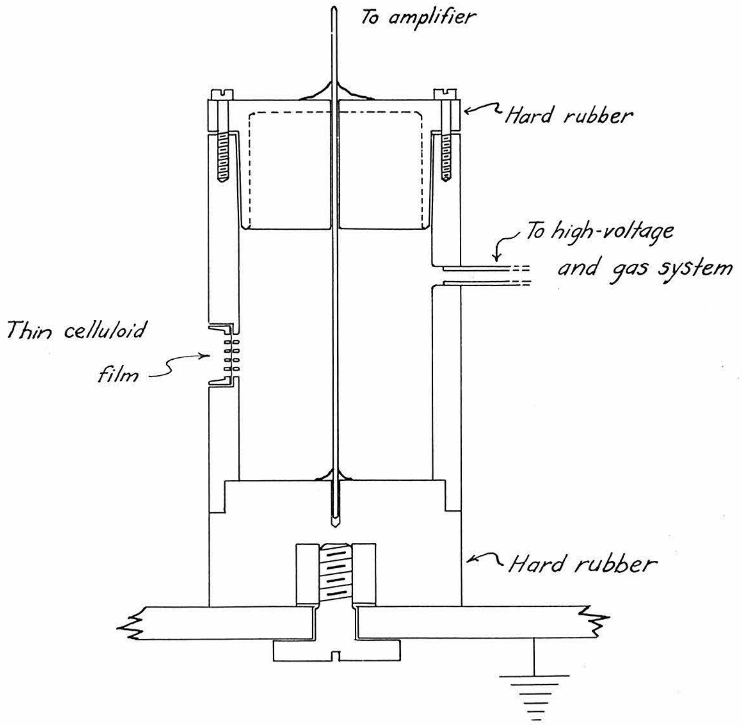

To amplifier
Hard rubber
To high-voltage and gas system
Thin celluloid film
Hard rubber

Fig. 2

ever, there is no significant difference so far as the sensitivity of the G-M tube is concerned between a bare highly polished wire and the same wire with an ideal coating of oxide. The surfaces of all the copper wires which have been used have acquired a visible coating of oxide after a few hours of continuous operation, and careful tests have failed to reveal changes in the characteristics of the G-M tube over the time of operation.

In some cases where the surface of a freshly prepared copper wire has been unsatisfactory, it has been possible to make it good by simply reversing the polarity of the chamber and running the G-M tube over a period of about one hour with the voltage considerably higher than that used in normal operation. This treatment has always failed to rectify a tube in which an unsatisfactory platinum wire was used. This suggests that the bombardment of the surface of a copper wire with positive ions melts or breaks down any microscopic points or feathers which would constitute a source of spurious ionization.

2. Apparatus

The form of the G-M tube which was used in the experiments described in this section is similar to that of the tube which was later employed in the magnetic spectrograph, and is shown in Fig. 2. The characteristics of this tube should be typical of all small tubes of small length to diameter ratio. The particular data with which we shall deal in this section were obtained when a copper wire 0.064 cm diam served as anode. The inside diameter of the tube was 1.9 cm, and the length of the active part of the chamber was 5 cm. The tube was of brass. The lower hard rubber plug was waxed into the chamber, while the tapered fit of the top plug was rendered air-tight by stopcock grease. The shape of the top plug which was first used in the spectrograph is given by the dotted line; the change from a solid to a hollow plug does not significantly alter the characteristics of the tube. The inner surface of the tube was made very smooth, and the edges of the holes through its wall were well rounded. The wire was waxed, as shown, to the two plugs at their upper surfaces.

The source of high potential was a charged 1 mf condenser (Westinghouse, Type LD) which was fed by a 2200 volt transformer through a UX-281 rectifier tube and a resistance of 10 megohms. The high resistance served to keep the potential of the condenser very steady and almost independent of rapid fluctuations in the line voltage. In later work, a ballast lamp was arranged in the primary circuit of the transformer as shown in Fig. 9, p. 26, so that slow changes in the line voltage would affect the potential by only a small amount. A Shrader6) electrostatic voltmeter used with a scale having a narrow horizontal slit permitted precise measurement of small voltage differences. The beam of light which came to this slit after reflection from the voltmeter mirror had its origin in a lamp placed behind a very fine line scratched on a black photographic plate. The real image of the fine line was seen in the slit of the scale, while the eye was focused on the scale. At the working voltage of the G-M tube, usually about 1600 volts, 1 mm deflection on the scale corresponded to a voltage change of only 2.5 volts.

Using this arrangement, voltage differences of 0.5 volts could be detected, and the working voltage could easily be kept constant to within 0.1 percent of its value. The importance of maintaining the voltage at a very constant value will be evident later.

The best values for the resistance R and the capacity C (hereafter referred to as R and C) were found to be about 10,000 megohms and 30 cm. Various investigators have found the optimum value of the product RC to be of the order of 0.35 ohm-farad, with R never much less than 5,000 megohms. The most satisfactory high resistance was found to be an India-ink line boiled in paraffin. Such a resistance is sensibly constant over a very wide range of voltages, while the resistance of an India-ink line in dry air may change by a very large amount in going from low to high voltages. The condenser was simply two parallel plates mounted on hard rubber supports.

A three stage, resistance-coupled amplifier, shown in Fig. 9, p. 26, amplified the impulses from the G-M tube to a strength sufficient for the operation of an electrical counter placed in the plate circuit of the output tube. The grid of the first tube was connected to the "C" battery through 10 megohms; smaller resistances shortened the duration of the impulses in the amplifier to such an extent that they were not satisfactorily recorded. Larger blocking condensers than 0.06 mf lengthen the duration of an impulse in the amplifier, but where large blocking condensers are used, there is some danger of "motor-boating" in the amplifier.

The last tube was given a bias sufficiently high to reduce the plate current to about 0.2 m.a; when an impulse occurred the current would momentarily rise from this value to several milliamperes. The whole amplifier and the input lead from the G-M tube were carefully electrostatically screened to preclude the possibility of registration on the counting mechanism of electrical disturbances in the immediate neighborhood.

The electrical counting mechanism was in essence an escapement wheel accelerated by two fine jets of air and released by an escapement fork; the escapement fork and armature were one piece arranged like the armature of a polarized relay. The time resolution of this device was about 0.02 sec. and the current necessary for positive operation was about 5 m.a. The asymmetry of the permanent magnetic field in which the fork was placed was so adjusted that when the current through the magnetizing coil was about 0.2 m.a the fork was strongly damped. If this were not done, there was danger of the counter operating spontaneously.

A loud speaker was placed in series with the counting mechanism in order that the qualitative nature of the impulses from the amplifier could be heard.

3. Procedure

The chamber was ordinarily allowed to stand for some time after evacuation before dry air was admitted. A constant pressure device took care of any slow leaks that might have been present, so that it was possible to carry a run over several days with the pressure constant to within an altogether negligible fraction of its value. A satisfactory G-M tube always commenced operating at a quite definite voltage which we shall call the threshold voltage. At this voltage, the impulses from a satisfactory tube would increase in strength from zero to quite audible surges within a range of about one volt. The impulses would become sufficiently strong for recording on a further increase in voltage of one volt, if the rate at which the impulses occurred was less than about one per second. Thus variations in the value of the threshold voltage could be determined within 0.1 percent. In all the work which has been done, voltages have been made relative to the threshold voltage. Where the pressure has been kept perfectly constant and the temperature of the room has not varied more than two or three degrees, the value of the threshold voltage has not usually varied by more than 0.1 percent of its initial value during several hours of operation. The maximum variation of the threshold voltage over the three days when the particular results given here were obtained amounted to 9.0 volts or less than 0.6 percent. During the tube's first eight hours of almost continuous operation, the maximum variation was less than 0.1 percent. At the beginning of operation on the following day, the threshold had increased by 0.5 percent, but remained constant within the limits of observational error over the five hours of continuous running on that day, while on the third day, the threshold had suffered no change from that observed on the second day.

If a tube were not satisfactory, weak surges became audible at voltages considerably less than that at which they became suddenly strong; thus the definiteness of the threshold voltage is a good test for a G-M tube. To obtain a valid count from a tube which has a very sharply defined threshold voltage, R and C must be given the correct values.

4. Results

The rate of counting at various voltages was measured using various kinds and sizes of anode wires, as well as various values for R and C. The set of curves given in Fig. 3 was obtained when R was 10,000 megohms, C was about 30 cm and the pressure was 5 cm of mercury. In this case, the threshold voltage was 1550 volts. About 500 impulses were counted for each of the points which determine the curves A, 750 impulses for each point on curve B and 1500 impulses for each point on curve C.

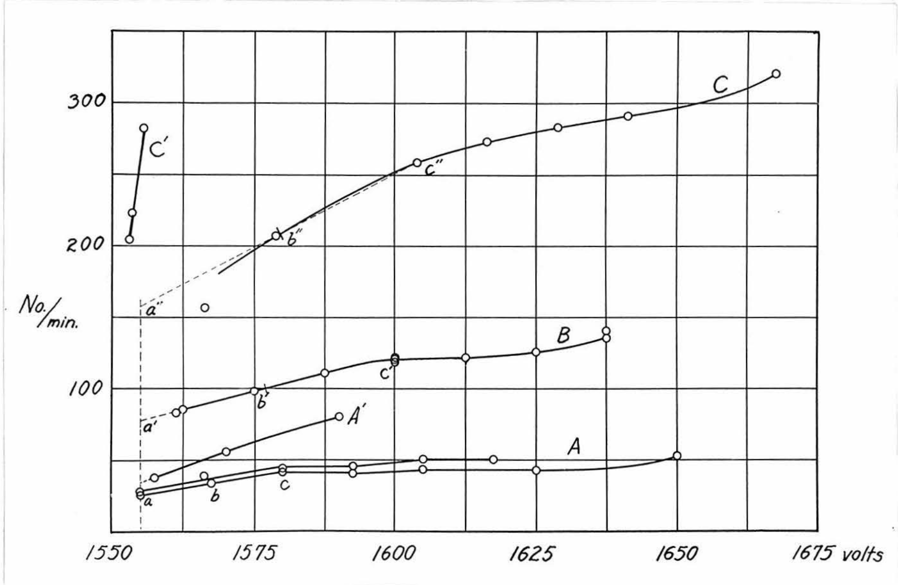


Fig. 3

The lowest curve shown was the residual count. It will be seen that at this rate of counting, which is about the usual cosmic ray count, the number of impulses is sensibly constant for voltages lying between 1580 and 1635 volts. The next curve above was simply the count when a very weak source of Ra D was brought into the neighborhood of the G-M tube. Curve B was obtained when a few milligrams of mesothorium was placed 7.5 meters from the tube, while curve C was obtained when the mesothorium was 4.65 meters from the tube. Curves A' and C' are illustrative of how the count mounts with increasing voltage when R is given a smaller value (350 megohms); this change in R did not change the threshold voltage by an observable amount, but as is indicated by the steepness of these curves, caused the tube to suffer many spurious discharges. To illustrate the constancy of the sensibility of the tube over a fairly long time (and after the copper anode wire had acquired a heavier coating of oxide,) three points on curve B which were taken on the day after the other points had been observed are shown: One is the point nearest a', another is the middle point of the three at c', while the third is the upper point of the two at the extreme right end of the curve. The deviations of these three points are each within the probable error.

5. Explanation of the Curves and Theory.

Before offering an explanation of these curves and a theory or description of the way in which a G-M tube operates, two simple qualitative experiments should be described.

The first experiment is convincing only when a very good tube is used. A satisfactory tube which had not been used for several hours was evacuated and freshly filled with dry air to the usual pressure of 5 cm. On increasing the voltage slowly and continuously from zero, a discharge of the sort that occurs in ordinary operation would usually be heard at quite a low voltage, which was of the order of one-third the threshold voltage. No subsequent discharges were ever heard at this voltage or voltages considerably higher over a reasonably long period of time. A second discharge would not usually occur until the voltage was increased to the threshold value; if a second discharge occurred at a voltage lower than the threshold, it was always relatively weak and took place at a voltage not very much less than the threshold voltage.

An attempt to repeat the observation of this isolated discharge by reducing the voltage to zero and again slowly raising it to the threshold value always failed. If, however, the voltage was reduced to zero and increased in the other direction (chamber positive), an isolated discharge at low voltage could again be heard. On returning to the normal threshold voltage by reducing the voltage to zero and then increasing it in the normal direction (chamber negative), the isolated discharge could be heard again, as above, at about 500 volts. This method of hearing the one strong isolated discharge at low voltage by changing the potential on the chamber from one threshold through zero to the threshold in the other direction could be carried on indefinitely.

This simple experiment proves the existence of ion and electron layers on the surfaces of the tube and the wire, and shows that these potential walls are of such sign and magnitude as to make the actual potential gradient at any point in the tube several times smaller than that which might be calculated from the observed voltage, when it is assumed that potential walls are absent. Making this assumption and applying the relation $E/p \cong 60$ for breakdown in dry air (where E is the potential gradient in volts per centimeter and p is the pressure in millimeters), we find that, in the absence of ion and electron layers, discharges would occur at about 330 volts.

The second experiment was performed in the following manner: The voltage on a tube which had been in normal operation was slowly reduced to zero, and the chamber was then grounded. The pressure of the air in the chamber was then slowly reduced to zero from the normal value of 5 cm. During the time of evacuation, several strong discharges could be heard, the first at about 3 cm pressure, the second at about 0.5 cm, while the remaining discharges of diminishing intensity would follow at low pressures, separated by small differences in pressure. In one case, fifteen definite discharges were counted, twelve of which were of intensities comparable to that of a discharge in normal operation. This behavior, though less marked, could be observed after the chamber had been grounded for several minutes.

The explanation of this curious behavior is simple if we assume that the probability of ionization by collision increases extremely rapidly at some critical potential gradient (which is a function, of course, of the nature of the gas, the pressure and the temperature). The fact that the threshold voltage is so sharply defined gives further weight to this assumption. Now the ion layers give rise to a certain gradient at the surface of the wire; as the pressure is slowly reduced, a value is reached where this gradient is sufficiently great for ionization by collision to occur. An ion formed in the chamber then gives rise to many ions, which travel to the surfaces of the chamber and wire. In view of the first experiment, which indicates that a large portion of the stable ion layers present in normal operation are formed in one strong discharge, and sometimes a second very weak discharge, and in view of the fact that in the second experiment the second discharge occurs at a very low pressure, where the breakdown field is very small, it seems reasonable to assume that the ion clouds which travel to the chamber and the wire rob the surface charges of about the amount necessary to neutralize themselves. The potential walls which remain give rise to a gradient sufficient for a discharge at some lower pressure.

The conclusion can then be drawn that in the normal operation of a G-M tube, a discharge breaks off abruptly when the potential gradient between the chamber and the anode wire is greater than that corresponding to the threshold voltage by a very small amount. The fact that in normal operation, occasional pairs of impulses of very small time separation have been heard where the second impulses of these pairs have been very audible but not sufficiently strong for recording, lends still further weight to this conclusion when it is recalled that at the threshold voltage impulses gain in intensity from zero to a value sufficient for recording within a voltage range of approximately 2 volts. This is illustrated in the voltage scale given in Fig. 4. V_0 is the

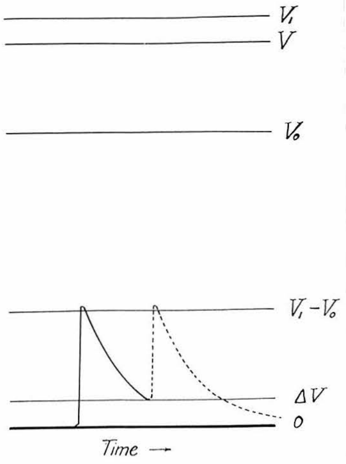


Fig. 4

threshold voltage, While V_1 is the observed working voltage. According to the above assertion, a surge in the tube suddenly lifts the potential of the anode wire from zero to a voltage slightly higher than (V_1-V_0), at which point the discharge breaks off and the condenser C leaks exponentially. Now if a very slow count is recorded, V corresponds to a certain potential gradient at the surface of the wire. If the count is fairly rapid, however, one surge (given by the solid curve) will be followed by another (the dotted curve) in an interval of time not sufficiently great for the condenser C to leak off to an essentially zero potential. Hence at higher rates of counting, the potential of the chamber must be Made $(V+\Delta V)$, if the gradient at the surface of the wire is to be the same as that corresponding to V when the rate of counting is very slow. Thus, at higher rates of counting and at voltages somewhat above the threshold voltage, although most of the impulses might be sufficiently strong for recording, some of the pairs of impulses occur with such small time separations as to make the second impulses of the pairs too weak for registration on the counting mechanism.

The only point given in Fig. 3 at which an appreciable number of impulses were not sufficiently strong for registration is the isolated point near a"; the voltage at the point b" was sufficiently great for all of the impulses to be recorded. The linear rise in the first part of the curves A and B has been observed in similar sets of curves and is attributed to the fact that, in the particular tube which was used, the length to diameter ratio was small; at the threshold voltage only a central part of the tube was effective, while at some higher voltage (for instance, 1600 volts for curve B), the whole volume of the tube had become effective. An ideal curve should be horizontal for voltages higher than this; thus the curves A and B are ideal for voltages up to about 1600 and 1615 volts, respectively, while for the curve C, there is no ideal portion unless it is in the neighborhood of the point b", where only a fraction of the volume of the tube is effective. An examination of the curves shows that the number of spurious discharges is not a function of the voltage alone, but of both the voltage and the rate of counting. This has always been observed and the way in which the spurious discharges enter at higher voltages is always the same: Some of the impulses occur in pairs or triplets with improbably small time intervals, judging by the frequency with which these groups occur. L. M. Mott-Smith, who is at present working with large G-M tubes, informs the writer that he has observed that the spurious discharges which enter at higher voltages occur in groups of this sort; moreover, the anode wires which he used were of steel, oxidized by dipping into dilute nitric acid. Strays of this sort can be reduced in number by making R sufficiently great; but, of course, this renders the counter worthless where the rate of counting is high. The best that one can do, apparently, is to find the optimum values of R and

and C by the method of trial and error and then proceed to test and analyze the curves obtained by some method such as that given below.

6. Analysis of the Count-Voltage Curves

The curves A doubtlessly give a valid measure of the intensity of the total gamma and cosmic radiation which the chamber received over a range of about 50 volts. However, a true measure of the number of ions formed per unit volume can be obtained only from the first horizontal portion of the curve A. (Hereafter we shall refer only to the lower of the two curves).

Now although the apparent voltage at which the whole chamber became effective for the curve B, at c', was greater than that for the curve A, at c, nevertheless, we know that the actual voltages for these two points must have been the same. The explanation is implied above. At a higher rate of counting, the lowest potential of the anode wire is not zero, but, on an average, ΔV. The point on the curve C which corresponds to c and c' is designated by c", where the curve suffers the sharpest bend. The points a' and a" must correspond closely to the point a, because the voltage for these points is only 5 volts above the threshold. The point b is midway between a and c. The points b' and b" have been located midway between a' and c', and a" and c", respectively. The effective volumes corresponding respectively to the points a, a', a" and c, c', c" should be the same. Since the first portion of all valid curves which have been obtained is linear, we may tentatively assume with some legitimacy that the points b and b" correspond to the point b. If this is so, then the effective volumes corresponding to the points b, b', and b" should be the same.

It is clear, then, that if the residual count curve A is given by a function f(V), another curve is not simply kf(V), as it would be for an ideal instrument, but would be kf(V'), where the voltage scale V' is the V-scale expanded. Referring to Fig. 4 again, V_o and V_1 are respectively the measured threshold and operating voltages. It can be easily shown by an approximate treatment that the potential difference between chamber and wire (not between the surfaces because of the presence of potential walls) is

$$V_1 - \Delta V = \frac{V_1\left(e^{\frac{1}{NRC}} - 1\right) + V_o}{e^{\frac{1}{NRC}}}, \qquad (1)$$

where N is the number of impulses per second. Putting in the values $R = 10^{10}$ ohms, $C = 3.5\times10^{-11}$ farad, $N = 0.67$/sec. (the rate for curve A), we find that ΔV is negligibly small. Then for curve A, we may say that the measured voltage is the actual potential difference between chamber and wire. If the measured voltage of a point on curve A is V, the corresponding point on a curve such as B, where the rate of counting is higher, is located where the voltage <u>measured</u> is

$$V_1 = \frac{V\, e^{\frac{1}{NRC}} - V_o}{e^{\frac{1}{NRC}} - 1} \qquad (2)$$

Since voltages are made relative to the threshold voltage, a more convenient form is

$$V_1 - V_o = \frac{e^{\frac{1}{NRC}}}{e^{\frac{1}{NRC}}-1}(V-V_o) \qquad (3)$$

To get a better approximation, we consider the s^{th} impulse, which is separated from the preceding impulse by τ_s. Then

$$\Delta V_s = (V_1 - V_0)\,e^{-\tau_s/RC} = (V_1-V_0)\,e^{(1/N-\tau_s)/RC - 1/NRC}$$

$$= (V_1-V_0)\,e^{-1/NRC}\,e^{\Delta\tau_s/RC}$$

$$= (V_1-V_0)\,e^{-1/NRC}\left(1 + \frac{\Delta\tau_s}{RC} + \frac{(\Delta\tau_s)^2}{2(RC)^2} + \cdots\right)$$

$$\overline{\Delta V} = (V_1-V_0)\,e^{-1/NRC}\,\frac{\sum_{s=1}^{s=n}\left(1 + \Delta\tau_s/RC + (\Delta\tau_s)^2/2(RC)^2 + \cdots\right)}{n}$$

$$= (V_1-V_0)\,e^{-1/NRC}\left(1 + \frac{\overline{(\Delta\tau)^2}}{2(RC)^2} + \frac{\overline{(\Delta\tau)^3}}{6(RC)^3} + \cdots\right)$$

Since $\Delta\tau$ is small where this theory is applicable, we can neglect terms of higher order than the second. Then

$$V_1 = V + \overline{\Delta V}$$

and

$$V_1 - V_0 = V - V_0 + (V_1-V_0)\,e^{-1/NRC}\left(1 + \frac{\overline{(\Delta\tau)^2}}{2(RC)^2}\right)$$

or

$$V_1 - V_0 = \frac{e^{1/NRC}}{e^{1/NRC} - \left(1 + \frac{\overline{(\Delta\tau)^2}}{2(RC)^2}\right)}\cdot(V-V_0) \qquad (4)$$

In general, Eq. (4) should be used; it is suggested that one draw the V=const. curves from this equation. Then when a count is recorded at a measured voltage V_1, this count should be made relative to a count on another curve where the same V=const. curve intersects. In doing this, the assumption is made that if strays enter, their number is proportional to the count recorded if V is constant, <u>not when the measured voltage V_1 is constant</u>. In general, where strays enter, this is perhaps the best procedure to follow. Unfortunately, we cannot apply this method with Eq. (4) to the curves given in Fig. 3, for the time fluctuations were not measured when the data for these curves were obtained.

Applying the more approximate Eq. (3) to our problem, we find the following values for V_1 at a', a'', b', etc.,

At a', $V_1 = 1555$ volts

a, $V_1 = V = 1555$ volts

a'', $V_1 = 1557$

b', $V_1 = 1572$

b, $V_1 = V = 1568$

b'', $V_1 = 1581$

c', $V_1 = 1593$

c, $V_1 = V = 1580$

c'', $V_1 = 1614$

Since the values of R and C were obtained rather inaccurately, the agreement is only rough, but sufficiently good to show that considerations similar to these must be made where a G-M tube is used.

The nine points a, a', a", b, etc. were fixed experimentally. The following table gives the ratios of appropriate ordinates of the curves, where, for simplicity, the letters stand for the values of the ordinates at the points which they designate. The last column should give the ratio of the intensities of the gamma rays received by the tube when the curves C and B were taken.

	$a'/a=2.98$	$a''/a= 6.17$	$(a''-a)/(a'-a) = 2.61$
	$b'/b=2.98$	$b''/b= 6.23$	$(b''-b)/(b'-b) = 2.64$
	$c'/c=2.95$	$c''/c= 6.30$	$(c''-c)/(c'-c) = 2.72$
means	2.97	6.23	2.66

If the inverse square law is applicable, the ratio given in the last column should be 2.60. The fact that this increases with increasing voltages is attributed to the spurious counts which enter at the higher rate of counting for curve C, in view of the increase in the ratio given in the second column. For the apparently valid curves A and B, the ratios of appropriate ordinates (first column) hold together very well.

This investigation shows that the Geiger-Müller tube is quantitative only where the rate of counting is moderate, and that it is particularly accurate where the rate of counting is very low. The spurious discharges which enter at higher rates of counting and at higher voltages seem to be part of the intrinsic nature of the instrument in its present form. It is quite likely that where air is used, many of the extra discharges are due to the presence of a very small amount of ozone. The breakdown of the ozone molecule to the formation of an oxygen molecule and an ion would, of course, constitute a source of ionization which would increase with both the voltage and rate at which ions are formed in the chamber. In the work which is described later, nitrogen passed over hot copper and through a U-tube immersed in liquid air was used; the improvement in the action of the counter was marked. There was definitely less grouping of the discharges.

A STUDY OF PART OF THE MAGNETIC SPECTRUM OF ELECTRONS EJECTED FROM A THIN SPUTTERED FILM OF GOLD BY X-RAYS FROM A MOLYBDENUM TARGET

1. Apparatus

The general method of De Broglie7), Robinson8), Whiddington9), and Watson10) for the focussing of electron beams in a uniform magnetic field takes advantage of the fact that a system of equal circles whose centers lie on a straight line osculate over an appreciable distance along the two common tangent lines. The extent of the circles of equal size has usually been restricted by a slit and a limited area on the surface from which the photo-electrons are ejected. However, when a detector of electrons can be employed, we may restrict both the extent and size of the circular paths of the electrons by two slits and a limited area on the surface of the electron source. This has been done in designing the apparatus described here. Fig. 5 shows a horizontal section of the magnetic spectrograph and the system of focussing of the electron beams. The principal dimensions are given in Fig. 6.

The sputtered celluloid film is fastened to the spectrograph so that it turns with it. Hence the electrons studied always leave the film normally to the surface of the film. Since the beam of x-rays at the axis of rotation is approximately 4 mm wide or twice the width of the film, electrons are ejected from a constant area of the film for all angles.

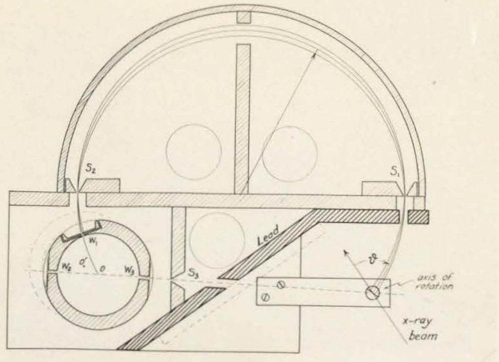
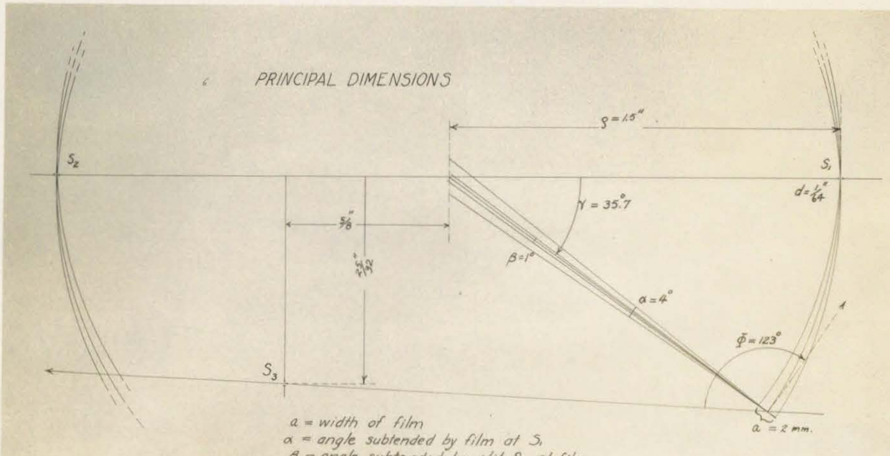


Fig. 5



a = width of film
α = angle subtended by film at S_1
β = angle subtended by slit S_1 at film
Φ = angle between x-ray beam
when through S_3 and mean direction of electrons

Fig. 6

The spectrograph is supported, as shown in Fig. 7, to a large brass taper, in order that rotation may be effected from the outside. A pointer moving over a scale graduated in degrees allows one to read directly the angle θ between the x-ray beam and the initial direction of the electrons which pass through the slit S_1 and ultimately through the windows W_1 of the G-M tube.

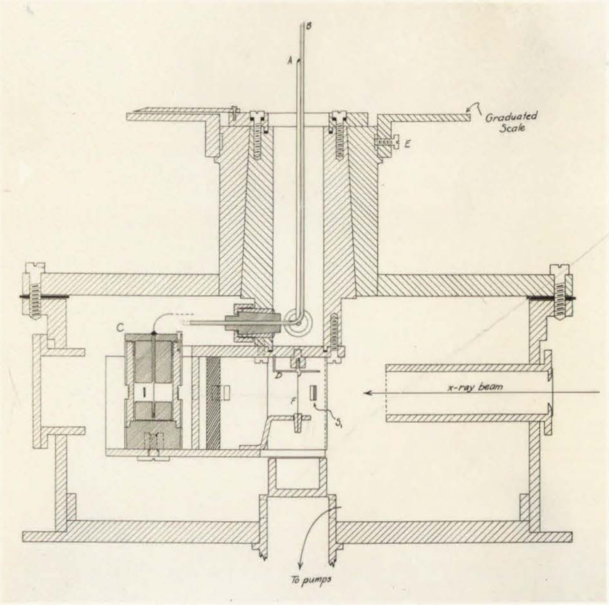


Fig. 7

The windows W_2 and W_3 and the slit S_3 are for calibrating the angular scale at the top of the apparatus. The spectrograph is rotated until the x-ray beam passes through S_3, W_3, W_2 and finally through a plate glass window in the large external chamber, and in this position the scale is set where the pointer indicates 123° (see Fig. 6). When the x-ray beam passes through these openings, it is detected as a small spot on a fluorescent screen held in front of the plate glass window. For this purpose of calibration the axis of the G-M tube was at O. However, in normal operation, the axis was moved over into the position O' so that the windows W_1 were immediately behind the slit S_2 and the hole through the lead screen was covered by an accessory lead plate, indicated by the dotted line.

The chamber of the G-M tube was connected to an external gas system by way of a very small brass pipe B which passed through a hard rubber plug. The gas system consisted of a large bottle to which an oil manometer was connected. The lead-in to the anode wire of the G-M tube was also passed through a hard rubber plug, which is shown in Fig. 8.

2. The Windows W_1

In order that slow x-ray photo-electrons might be studied, the windows W_1 must be exceedingly thin and composed of a material of small density. Since the pressure outside the G-M tube is as low as possible and the pressure inside of the order of 5 cm, these windows must be sufficiently thick to withstand the latter pressure. Both of these restrictions were satisfied by the use of thin films of celluloid of the sort that are used in work with very soft x-rays. These films were prepared by the standard method of dissolving celluloid in amyl acetate and touching a small

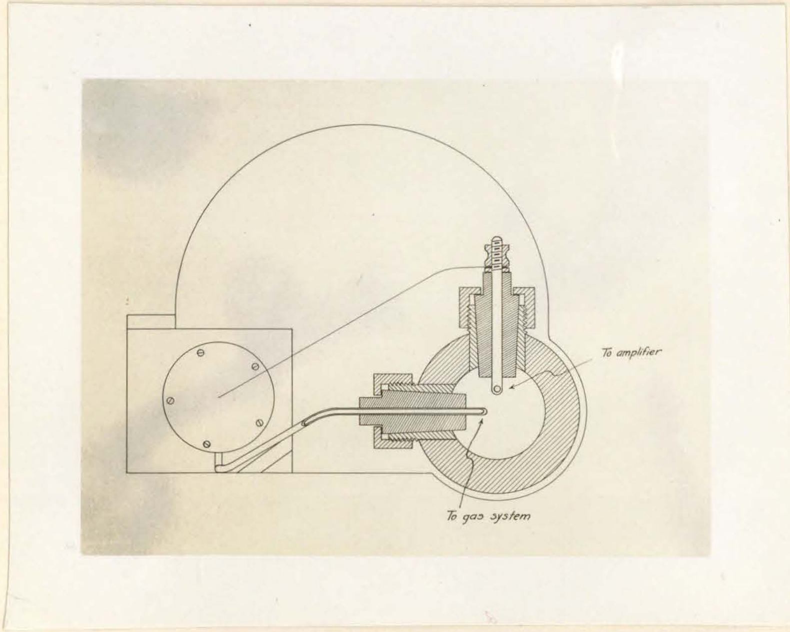


Fig. 8

drop of the solution to the surface of water. The size of the films made was fixed by the area of the water surface; the end of a small brass cylinder of about 1 cm diameter was allowed to project up through the surface of water in a beaker. The film of celluloid formed in this small circular area would not touch the inside surface of the brass cylinder for it would not spread up the slope formed by capillary attraction. After the film had formed, the general level of the water in the beaker was raised until the surface was above the end of the cylinder, when the small disc of film would float clear of the cylinder and could be picked up by a frame.

The windows were five small holes in a vertical line and drilled so close to each other as nearly to touch. Each hole was approximately 0.8 mm in diameter. The G-M chamber was placed in a lathe and a flat-faced disc was cut into its wall until the thickness of the wall where the five holes were subsequently to be drilled was about 0.3 mm. A very thin disc also having five small holes could be placed over this flat surface in the wall of the G-M tube. Fig. 5 shows a cross-section through this disc and the wall of the G-M tube. A suitable film of celluloid was lifted from the surface of the water by the disc and after the film had dried, the disc was placed over the flat surface in the side of the G-M tube, its holes being made to fall immediately over the holes in the wall of the G-M tube.

All of the films which were used were too thin to reflect colors and the light reflected by them had a deep blue-black tinge. This meant that the thickness was less than

1.1×10^{-5} cm, at which thickness a faint straw-yellow color is reflected. Moreover, as we shall see later, these films passed an appreciable fraction of electrons whose $H\rho$ value was as low as 188 gauss-cm or $\beta = 0.106$ (L_1 electrons ejected by Mo $K\alpha$). According to Lenard[11)], the fraction of electrons which pass through a sheet of thickness x and density d is $n/n_0 = e^{-axd}$. Now the measured intensity of the beams of "background" electrons at 250 gauss-cm was found to be approximately twice that for electrons at 188 gauss-cm. If we assume that the initial intensity of these background electrons is sensibly the same in these two regions of the spectrum (the region between $H\rho = 188$ and $H\rho = 250$ is about one-sixth the whole spectrum), then if a_1 and a_2 are the values of the mass-absorption coefficient for electrons of 188 gauss-cm and 250 gauss-cm respectively, and f_1 and f_2 are respectively the fractions of electrons that get through the film,

$$e^{(a_1-a_2)xd} = f_2/f_1 = 2.$$

Putting in the values $a_1 = 7.2 \times 10^5$, $a_2 = 2.3 \times 10^5$ and $d=1$, we find that the thickness x was about 10^{-6} cm. Thus the optimum thickness of the films used was of the order of 5×10^{-6} cm. If the thickness of the films used was 10^{-6} cm, for example, the fraction of electrons which passed at the low end of the spectrum was 0.5, while at the high end ($H\rho = 470$), more than 99 percent should have passed.

3. The Arrangement of the Geiger-Müller Tube.

It was of course impossible to put the chamber of the G-M tube at a high negative potential for the electrons would be retarded to speeds too low for passage through the windows of the tube. The anode wire was therefore connected to the source of high potential through the resistance R, as shown in Fig. 9;

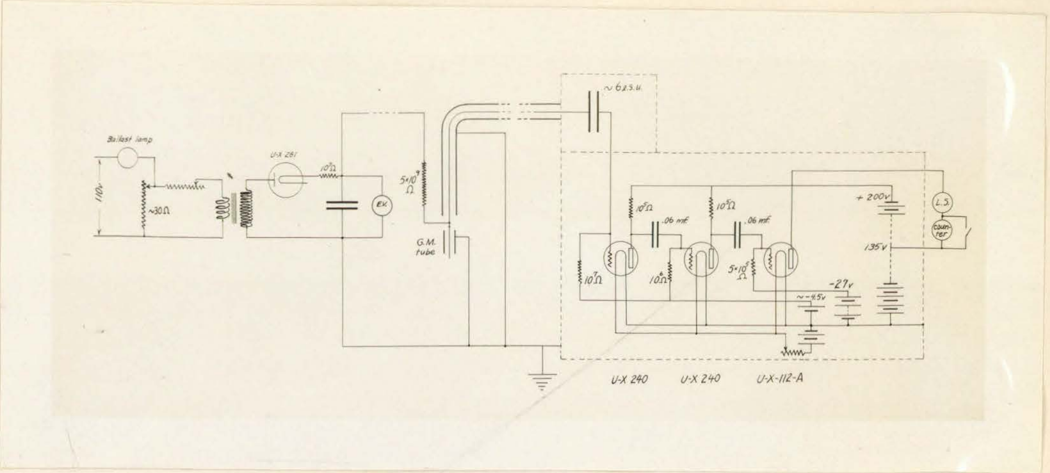


Fig. 9

the total resistance to ground between the anode wire and the lead to the amplifier was so high that this method of connecting the tube to the amplifier was equivalent to the usual wiring scheme.

The lead to the amplifier was approximately eight feet long, and since it was very near the x-ray tube and the high potential lines from the x-ray transformer, it had to be very well shielded. For this purpose, the wire was put through a one-inch lead pipe and insulated from the pipe by two concentric rubber tubes. The total capacity to ground, including the capacity of the condenser C, should not have been greater than about 35 mmf; to cut the capacity of the necessarily long lead to the amplifier to a minimum, number 40 gauge wire was strung through the pipe. The capacity between the wire and pipe was found to be approximately 35 mmf which left very little for a capacity connection to the amplifier. However, 6 mmf was found to be large enough to convey the impulses from the G-M tube to the amplifier with sufficient strength for satisfactory recording. The total capacity was therefore a bit greater than the optimum value, but the operation of the G-M tube was nevertheless found to be sufficiently good.

In the first experiments with the spectrograph, the G-M tube as shown in Fig. 2, p.2, was used. Since the wire was at high potential and the screw in the base of the tube was at ground, the strongest field was located at the lower end of the wire. This meant that the potential of the wire had to be made considerably higher than the threshold voltage before the volume in the central part of the chamber where the electrons enter would become effective. For this reason, many strays entered and the preliminary intensity measurements could not be taken as valid. It should be pointed out, however, that the tube used in this way proved efficacious for exploration in the spectrum because, it will be remembered, the number of stray discharges increases with the rate of counting. This meant that the height of peaks was exaggerated, and, consequently, it was simpler to fix the position of "lines" accurately.

Another serious shortcoming of the tube used in this fashion was that the residual count (the rate of counting when the magnetic field was put equal to zero) was nearly as great as the count due to the electrons at a position of maximum intensity. To over come both of these difficulties as much as possible, the tube was filled with hard rubber except for the volume into which the electrons entered. A solid cylindrical hard rubber plug having a hole of 1 mm diameter along its axis was snugly fitted into the hollow top plug of the Geiger-Müller tube. As shown in Fig. 7, p.22, this plug extended down almost as far as the windows of the tube; a shorter plug with a hole drilled only part way through extended up to within a short distance from the windows. The anode wire ended in this shorter plug and the end of the wire was coated with resin and beeswax. This arrangement functioned remarkably well; the residual count was much lower than before, the reduction having been about three-fold and electrons could be detected at the threshold voltage. Probably very few strays entered because the operating voltage of the tube could be made very little higher than the threshold. Moreover, several tests showed that count vs. voltage curves were horizontal over a range of more than 50 volts and were free of the first rise experienced by the curves in Fig. 3, p.8. Wherever electron beams of extremely weak intensity is measured, this arrangement is strongly recommended.

4. Experimental Procedure

After assembling the apparatus, the large chamber and the gas system connected to the Geiger-Müller tube were pumped down simultaneously. The pressure in the large chamber could not be greater than about 10^{-3} mm, for at pressures higher than this, there was danger of slight scattering or dispersion of the electron beams and danger of the lead-in wire through the evacuated space to the anode wire of the of the G-M tube causing periodic discharges.

In the first work which was done, dry air was used in the G-M tube. When it was feared that ozone might have been present in the tube where air was used, purified nitrogen was used instead. When nitrogen was used, the grouping of discharges into pairs or triplets seemed to be reduced.

Before making a set of measurements, the x-ray tube was usually allowed to run over a period of at least an hour, after which time the temperature of the x-ray transformer would come to equilibrium and the space current in the x-ray tube and primary voltage could easily be held constant. This current and voltage could be held constant to variations not much greater than one percent and hence the source of x-rays averaged over a period of several minutes could be considered constant to within one percent at the ouside. Most of the "runs" were made at night when the line voltage fluctuated very little.

The solenoid current and G-M tube were generally switched on a quarter of an hour before measurements were taken. The threshold voltage of the G-M tube as used in the spectrograph would change by a few volts over the first few minutes of operation, probably due to the fact that surface charges on the dielectric in the tube had to come to equilibrium. During several subsequent hours of operation, the threshold would remain very constant if the pressure in the gas system connected to the tube remained constant.

The current in the solenoid was measured and kept constant by a Leeds and Northrup "Type K" potentiometer.

This current was measured to better than 0.001 amp. and variations were kept within this figure; in the regions where most of the measurements were taken, a variation in the solenoid current of 0.001 amp. would shift the position of a peak at the second slit by approximately one-tenth the width of that slit. To facilitate the adjustment of the current, a high resistance slide wire rheostat was shunted across a low resistance rheostat through which most of the solenoid current passed.

In covering a small region of the spectrum (usually 0.1 amp. where the current was about 2.5 amp.), it was generally the practice to take measures of the count at intervals of 0.01 amp. until the region had been covered and then to return to various parts of the region, taking measurements of the count at smaller intervals and at places where the count had been taken before. In practically all cases, a count was obtained from ten minutes counting, and the minute by minute count was recorded. Before making a ten minute count, the threshold voltage was always measured and the operating voltage was then made a definite quantity greater than the threshold. Thus if the threshold voltage was found to be 31.1 cm scale deflection on the electrostatic voltmeter, the operating voltage would be made 32.4 cm. If, for example, the threshold before a ten minute's count a few hours later was found to be 31.8 cm, the operating voltage was then made at 33.1 cm. This difference of 1.3 cm corresponded to a voltage difference of about 33 volts, where the total voltage was about 1575 volts. The difference of 1.3 cm was quite arbitrary, for as mentioned before, the count was constant over a fairly wide range of voltages; 1.3 cm was chosen because at that difference, the impulses were all strong and recording was positive. Two samples of ten minute runs are given below. The good agreement between the two rates of counting was, of course, accidental, for the probable error was $0.7(250)^{1/2}/10$ or 1.1.

Sol. Current	Voltmeter	Time	Number	No./min.	Av.No./Min.
	Threshold 31.00 cm	0			
		1 min	33	33	
		2	51	18	
		3	79	28	
		4	100	21	
2.528 amp.	33.00	5	130	30	25.1
		6	151	21	
	(50 v. above threshold)	7	181	30	
		8	203	22	
		9	229	26	
		10	251	22	
	Threshold 31.00 cm	0			
		1 min	22	22	
		2	45	23	
		3	68	17	
		4	100	32	
2.528	32.40	5	123	23	25.3
		6	152	29	
	(35 v.above threshold)	7	181	29	
		8	205	24	
		9	228	23	
		10	253	25	

Four other readings taken at this position at voltages 25, 25, 33 and 33 volts above the threshold respectively, were 25.3, 25.3, 24.3 and 26.2/min. The third measurement was taken after an hour and a half of continuous operation, while the last figure was obtained after ten hours. It should be pointed out that the two first figures were the result of the first measurements made with a fresh anode wire.

Ten minutes of counting was found to be optimum where a region of about 0.1 amp. was to be explored; a rather thorough exploration of such a region usually required about twelve hours of continuous observation. However, where many points for a curve were obtained, the probable error was of course considerably less than that of an individual measurement.

The method of correcting a G-M tube given in the preceding section was not applied, because the rate of counting never exceeded 30/min.

A residual count was usually taken after a set of observations.

5. Results

Exploratory runs with the G-M tube used with a large active volume served to locate the exact positions of the L_I, L_{II} and L_{III} electrons. The curves which were obtained are not shown here for they reveal nothing not shown in the curves which follow. The position of the peak due to L_{III} electrons ejected by Mo $K\alpha_1$ was taken as standard for calibration of the spectrograph.

Fig. 10 gives the results of the first runs in the region of the L_{III} electrons, when a satisfactory tube of the improved type (restricted active volume) was found. It will first be seen that the height of the peak is fairly great in comparison with the residual count. Where in the past, a photographic plate has been used, a week of continuous running was necessary for a good impression due to these electrons.

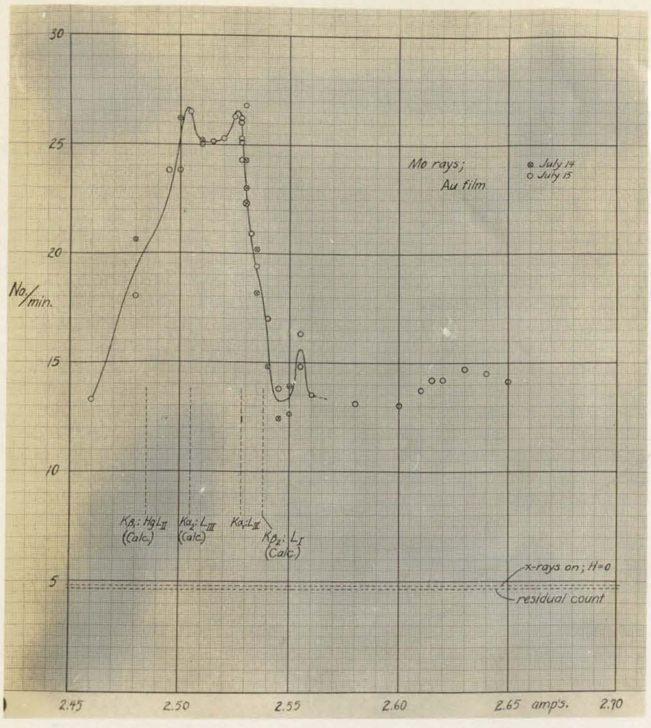


Fig. 10

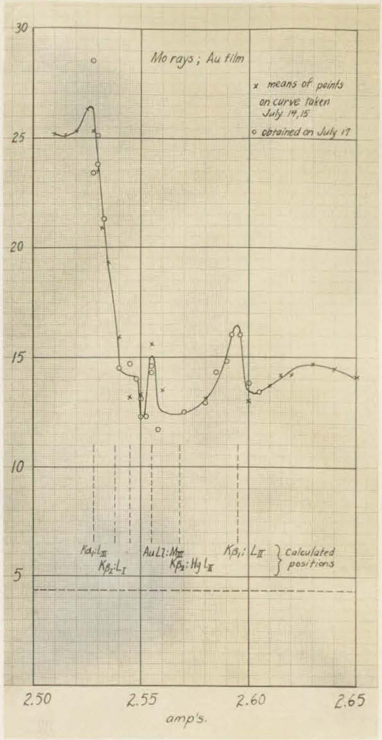


Fig. 10a

The two peaks due to Mo $K\alpha_1$ and Mo $K\alpha_2$ are resolved and the separation is precisely what was calculated. The agreement between the points found on one day and those found on the following day is good; moreover, on the first day of measurements, the voltage on the anode wire of the G-M tube was not kept a definite amount higher than the threshold, as it was in all subsequent work, but was allowed to vary slowly between about 25 and 80 volts above the threshold. Two days later, the points shown in Fig. 10a were obtained. As shown in Fig. 10, the peak due to L_{II} electrons ejected by Mo $K\beta_1$ was missed; the main purpose of the measurements given in Fig. 10a was to locate this peak and to check the existence of other peaks to be discussed later. It will be seen from these curves that the resolution of the spectrograph is very high. The sharp peak at 2.555 amp. appears in the two independent set of measurements shown in Figs. 10 and in two other sets of measurements not given here and can therefore be said to be real. There appears to be a hump at 2.545 amp., another at 2.538 amp., and still another at 2.480 amp. The first two humps appear in the other two sets of measurements not shown here.

Fig. 11 gives the results of four days of exploration in the region from $K\alpha_2:L_I$ to $K\alpha_1:L_{II}$. About eighty-five points, some of which were the result of fifteen minute intervals of counting, were obtained. Air was used in the G-M tube for these measurements (and gas and anode wire in the tube were not changed in going from the measurements given in Figs. 10 to those given in Fig. 11), and consequently, the wire became so badly oxidized toward the end of the runs in Fig. 11 as to render the action of the counter erratic. For this reason and another mentioned before, nitrogen was used in the chamber.

5. Interpretation of the Above Results

We may speak of an electron as having an equivalent ν/R value. For the x-ray photo-electrons, this value by Einstein's photo-electric equation, is the difference between ν/R value of the incident quanta and the ν/R value of the energy level from which the electron is ejected. Now applying the relativity correction and using the following values for the fundamental constants (these are the values which Robinson[12)] chose and are used here for the sake of comparison of this work with his),

$$e = 4.774 \times 10^{-10}$$
$$c = 3 \times 10^{10}$$
$$e/m = 1.7686 \times 10^{7}$$
$$h = 6.545 \times 10^{-27}$$
$$R = 109737$$

we find for the formula for calculating the $H\rho$ value of electrons,

$$H\rho = \left[2.038 \times 10^{-3}(\nu/R)^2 + 153.15\ (\nu/R)\right]^{1/2}.$$

Also for the sake of comparison, the ν/R values for the levels in the gold atom, the molybdenum rays and the emission lines from an excited gold atom were taken from Robinson's paper.

Using the measured constants of the solenoid and the spectrograph and neglecting the earth's field, the position of the $K\alpha_1:L_{III}$ peak was calculated to be 2.57 amp. The effect of the earth's field was to make this position occur at a slightly higher current. However, the apparatus along with the magnetic field of the earth was calibrated, using, as said before, the above peak as standard. It should be mentioned here that the effect of the earth's field in going from the region of the standard peak to the region of the L_{II} peak was to shift the apparent position of the latter peak in the direction of increasing current by approximately 0.003 amp. Consequently, where the apparatus is used for the evaluation of the exact position of peaks, the vertical component of the earth's field should be nullified. However, over a small region, the presence of the earth's field produces no appreciable shift.

Many combinations between the incident quanta and energy levels, and emission lines and the energy levels slightly modified (because of the excited state of the atom from which "fluorescent electrons" are ejected) were tried in an endeavor to fit the various peaks shown in Figs. 10 and 11.

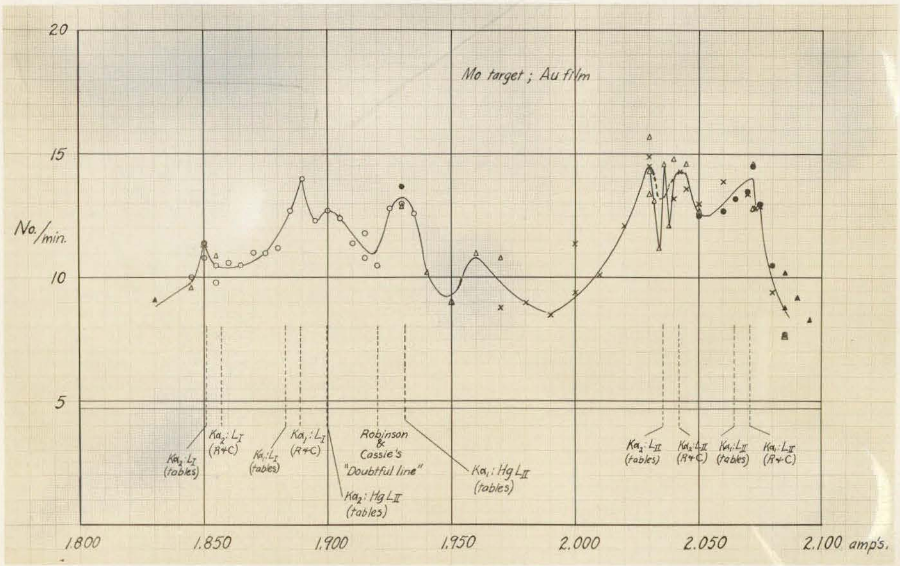


Fig. 11

The simplest combinations are shown and, in most cases, the agreement is very good. In Fig. 11, the letters "R andC" mean that the precision measurements made by Robinson and Cassie have been applied.

The peaks at 1.900 and 1.930 amp. could not be attributed to electrons ejected from the gold aton, but when it was noticed that the separation was almost precisely the separation due to the Kα doublet of molybdenum, it was suspected that mercury might have been present in the gold film. This supposition was justified by the fact that at one time the film was exposed to mercury vapor at room temperature over a long period of time. As shown in the figure, the calculated positions of the peaks due to $K\alpha_{1,2}$:Hg L_{II} fall where these peaks were found. The hump on the left side of the L_{III} peaks might have been due to $K\beta_1$: Hg L_{II}. Electrons ejected from the mercury atom by $K\beta_2$ should have been detected at 2.568 amp., but $K\beta_2$ is so weak that the detection of these electrons could have been accomplished only with great difficulty.

The level values which were used in calculating the positions of the L_I and L_{II} peaks designated by "tables" were obtained from the Handbuch für Physik.

The peaks suggested at 1.960 and 2.030 amp. could not be accounted for by any simple standard combinations and could not be attributed to the simple interaction of a fluorescent line with a perturbed or unperturbed level in the gold atom. Electrons which occurred at 2.545 amp. could not be accounted for, while the sharp peak at 2.555 amp. could have been due to electrons ejected from the perturbed M_{III} level by F:L1 of gold. While the M_{III} level in the normal atom has the value, $\nu/R = 202.8$, the value of this level in an atom in which the transition ($M_I \rightarrow L_{III}$) may occur is, from the position of this peak, 207.6.

6. An Attempt to Measure the Spatial Distribution of the L_{III} Electrons.

Using a different anode wire, new windows and a slightly different strip of sputtered film, the L_{III} peaks were measured at various angles and the results are shown in Fig. 12.

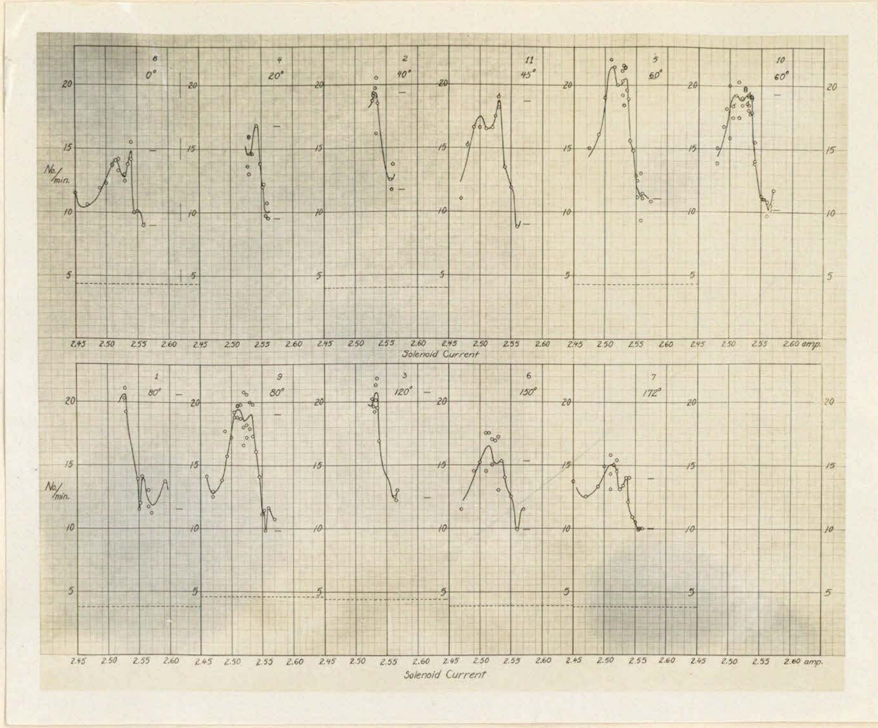


Fig. 12

About 210 points were obtained, a few of which were determined by fifteen minute intervals of counting; these points are differentiated from the ten minute points by primes. The small numbers at the tops of each rectangle give the order of the runs. The probable error for the individual points is given by the vertical lines in the graph at 0°. The dotted lines give the residual counts.

All that was necessary for the determination of the angular distribution was a measure of the right hand side of the double peak, but it was thought that a study of the back of this double peak at various angles would be of interest. Comparing the graph at 0°, with that at 172°, we see that there are relatively more scattered electrons in the backward direction than in the forward. While the peak due to $K\alpha_1$ at 0° is relatively greater than that due to $K\alpha_2$, at 172° the peak due to $K\alpha_1$ is definitely much lower. Although $K\alpha_1$ is twice as intense as $K\alpha_2$, these two peaks should appear to have the same height, since the second is added onto the back of the former.

During the eleventh run, the small windows in the G-M tube gave way and the set of measurements could not be completed. However, enough angles were studied to furnish us with at least a qualitative shape of the angular distribution curve. A measure of the number of L_{III} electrons was obtained by subtracting from the ordinate of the peak the ordinate of the first valley (at 2.551 amp. in Fig. 10a). The short horizontal dashes give these ordinates.

The derived distribution curve is shown in Fig. 13, where θ is expressed in degrees. The shape of this curve agrees well with the shape that could be inferred from photographs obtained by Watson13), except that it indicates a maximum considerably farther forward than 80°. The maximum indicated by this curve is in the neighborhhod of 60°; the curve taken at 0° reveals relatively small scattering, which can be taken as evidence for the maximum being fairly well forward from 90°. Perhaps the greatest errors are to be expected at 40° and 45°. At the former angle, we could bring the valley down, making the ordinate of the derived curve *higher*, but since the valley is higher than the average, we cannot very well lift it still higher. This would tend to make the point at 40° fit the curve better, while at 45°

the valley is abnormally low and any change that we could make there would tend to make the point at 45° fit better. In other words, we cannot very well lower the curve in the vicinity of these to angles by enough to shift the maximum of the curve much to the right of 60°. Of course, before much can be definitely said, further work of a more precise nature must be done.

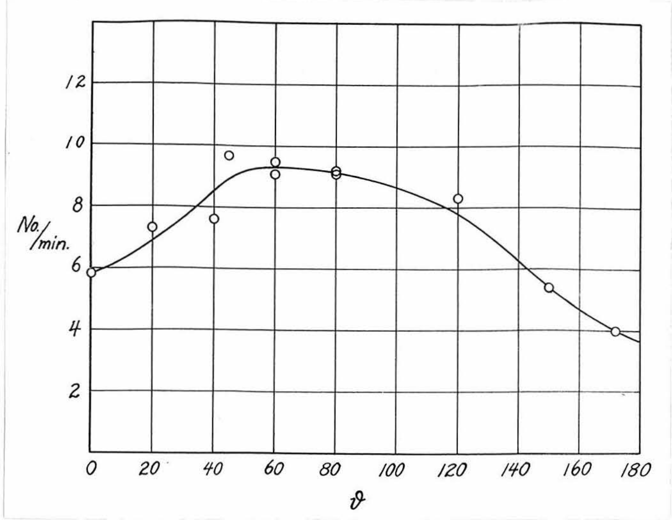


Fig. 13

The small peak (Fig. 10) which apparently flanks the $K\alpha_1$:L_{III} peak probably does not affect the height of the latter peak since it must fall away to a negligible value in 0.01 amp.

Both the theories of Auger and Perrin 14) and Wentzel 15) give a maximum in the neighborhood of 78°.5 for electrons ejected by Mo $K\alpha_1$ from a K level having the same energy as AuL_{III}. Hence the indications of the distribution curve in Fig. 13 are in agreement with what has recently been found by Watson 16), viz. that the distribution curves for electrons from levels of increasing azimuthal quantum numbers have maximums at decreasing angles.

7. Discussion of Errors

The outstanding sources of error are to be found in:

(a) The Geiger-Müller tube,
(b) Fluctuations in the vertical component of the earth's field,
(c) The source of x-rays,
(d) Insufficiently low vacuum in the spectrograph,
(e) Variations in local radioactivity,
(f) Errors due to small numbers.

The ways in which errors arise in the use of a Geiger-Müller tube have already been discussed. If a horizontal count vs. voltage curve is obtainable, then one can feel reasonably certain that strays do not enter in appreciable numbers.

Unfortunately, many of the measurements made in this work were taken during magnetic storms, when at times, the earth's field changed by several percent. A change of four percent in the vertical component would shift the position of a peak by approximately 0.001 amp; on the high velocity side of a peak, this would mean a variation in the rate of counting of about 1/min. For future work, an earth inductor is set up on the neighborhood of the apparatus.

When the x-ray transformer had come to equilibrium, it was not difficult to keep the current in the tube and the voltage constant if the line voltage was reasonably constant. As mentioned before, the error introduced by fluctuations in the source of x-rays could not have been greater than one percent.

If the pressure in the large chamber was not lower than 10^{-3} mm, there was a possibility of slight scattering of the electrons from their circular paths; this would of course result in the broadening of peaks, an effect which has not been observed.

Since the Geiger-Müller tube detects individual ions, it is extremely sensitive to very weak radioactive compounds or stronger gamma ray sources at a great distance. As a test of the G-M tube's sensitivity, a residual count over a period of 50 minutes was taken during which time a few milligrams of mesothorium was taken from the third gallery in the Norman Bridge laboratory and placed in the stockroom which was a distance of more than half the length of the building from the apparatus but on the same floor. The tube was inside the large brass chamber, as in normal use, and this chamber was inside the heavy copper solenoid. The mesothorium was moved after 24 min. of readings and at the end of about 39 min. the mesothorium was returned to the third gallery. Readings of the count recorded were taken every few minutes, so that after the complete run a graph could be drawn, which was found to be three straight lines which intersected at points very close to the times at which the mesothorium was moved. The slope of the first line was 4.1/min, that of the second 5.0/min. and that of the third 3.5/min. Thus the effect of this change in position of a strong radioactive compound at a considerable distance in the laboratory was approximately one ion per minute, or 25 percent of the residual count. A similar test was made with Dr. C. C. Lauritsen's million-volt x-ray tube. A small effect, of the order of 0.8 ions/min, was indicated. Hence care was taken to see that errors of this class could not enter.

Due to the very low rate of counting not sufficient time could generally be spent in any one position for the counting of a large enough number of impulses for the probable error to be as low as, say, 2 percent. Generally the probable error was about 5 percent where the rate of counting was 20/min and about 7 percent where the rate of counting was 10/min. However, where many points were obtained, the probable error of the curve drawn through the "center of gravity of the points" was considerably less than the above figures.

In conclusion, the writer expresses his gratitude to Professor R. A. Millikan for his interest in the work described here and to Professor E. C. Watson for his many helpful suggestions and the use of apparatus which is indispensable in his own research.

REFERENCES

1) H. R. Robinson and C. L. Young, Proc. Roy. Soc., 128, 92 (1930).

2) E. C. Watson, Phys. Rev., 30, 479 (1927).

3) H. Geiger and W. Müller, Phys. Zs., 29, 839 (1928),
" " 30, 489 (1929).

4) H. Kniekamp, Phys. Zs., 30, 237 (1929).

5) L. F. Curtiss, B. S. Jour. Research, 4, 601 (1930).

6) J. E. Shrader, J. Op. Soc. Am., 6, 273 (1922).

7) M. DeBroglie, Jour. de Phys. et rad., 2, 265 (1921).

8) H. R. Robinson, Proc. Roy. Soc., 104, 455 (1923).

9) R. Whiddington, Phil. Mag., 43 , 1116 (1922).

10) loc. cit.

11) P. Lenard, Hand. f. Phys., 24, p.34.

12) H. R. Robinson and Cassier, Proc. Roy. Soc., 113, 282 (1926).

13) E. C. Watson and J. A. Van den Akker, Nat. Acad. Sci., 13, 659 (1927).

14) R. Auger and F. Perrin, Jour. Phys. et rad., 8, 93 (1927).

15) G. Wentzel, (Communicated in Lecture Series of Norman Bridge laboratory).

16) E. C. Watson and J. A. Van den Akker, Proc. Roy. soc., 126, 138 (1929).