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A Study of the Alpha-Particles from Po with a Cyclotron-Magnet Alpha-Ray Spectrograph

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A description is given of an alpha-ray spectrograph, consisting of the Princeton cyclotron magnet and a Plexiglas deflection chamber, in which the alpha-particles can be bent into a semi-circle of about 80-cm maximum diameter. Three different methods of detection have been employed according to the different strengths of the radioactive sources. They are the ordinary photographic method, the counting method, and the method of photographic tracks. The behavior of the spectrograph has been investigated with Po alpha-particles by the three methods of detection. The forms of the energy distribution have been determined, respectively, by these three methods and agree fairly well with one another. The half-width of the main line under favorable conditions is less than ½ mm, which is equivalent to about 0.01 Mev. The intensities a few millimeters away from the maximum are less than 0.1 percent of the main line intensity. The track method of detection has been used to study both the low and high energy regions of the main line of the Po alpha-particles. Microscopic examination reveals distinctly a series of weak groups in the low energy region, while in the high energy region no indication of any discrete group has been found. These experiments have been carefully repeated with three different sources and under different experimental conditions. In each case similar results have been obtained. The emission of these different alpha-particle groups from Po may, as in the case of ordinary fine structure, leave the product nucleus, Pb, in different excited states. Then, when the Pb nucleus falls from one of these quantum states to the normal state, a gamma-ray quantum is given off. As far as energy and intensity are concerned, these weak groups of alpha-particles are generally compatible with the gamma-ray lines from Po as measured by Bothe. However, their intensities are not in agreement with the current theory of alpha-decay, as can be seen from the abnormally large spin changes deduced from the theory for the different alpha-transformations, and also from the large deviation of the Geiger-Nuttall curve for these groups from the curve for the members of the Ra family. Possible explanations of these short-range alpha-particles from Po have been suggested and discussed.

I. INTRODUCTION

To determine the energy of a particle coming out from a nucleus is one of the few ways to approach the problem of structure of the nucleus. From the energies of the particle-groups an energy level system can be deduced for the nucleus. It has been shown elsewhere that there are indications of regularities in the energy levels of both light[1] and heavy[2] nuclei. Since the data are rather insufficient at the present time, the conclusions so far drawn are only provisional. However, when the results become more complete and accurate, a more exact relationship between the energy levels and certain properties of the nucleus may be obtained, which will certainly serve as an empirical basis for theoretical investigation. Therefore, it is important to determine accurately the spectra (alpha-, beta-, and gamma-rays) of radioactive nuclei as well as the energy spectra of particles emitted in nuclear reactions.

The best method so far known for measuring accurately the energies of alpha-particles is the semi-circular magnetic focusing method, the momentum of the particle being calculated from the radius of the circular path and the value of the applied magnetic field. In order that the magnetic spectrograph may have a very high resolving power, the radius of the semi-circular path in the uniform magnetic field must be very large. This means that a huge magnet must be designed and installed. Fortunately it has been possible to make use of the Princeton cyclotron magnet for this purpose. We have been able to construct a Lucite deflection chamber in which the diameter of an alpha-particle path can be as large as about 80 cm. Since the gap between the two pole-pieces of a cyclotron magnet is usually greater than 10 cm, the solid angle of detection in the spectrograph so constructed is much larger than usual. In our case about one particle out of every 5000 particles emitted can reach the detection instrument.

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[1] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 303 (1937); W. Y. Chang, Phys. Rev. **A65**, 352 (1944); K. M. Guggenheimer, Proc. Roy. Soc. **A181**, 172 (1942).

[2] Rutherford and Ellis, Proc. Roy. Soc. **A132**, 667 (1931); Rosenblum, Comptes rendus **202**, 943 (1936); Rosenblum and Guillot, Comptes rendus **204**, 975, 1727 (1937).

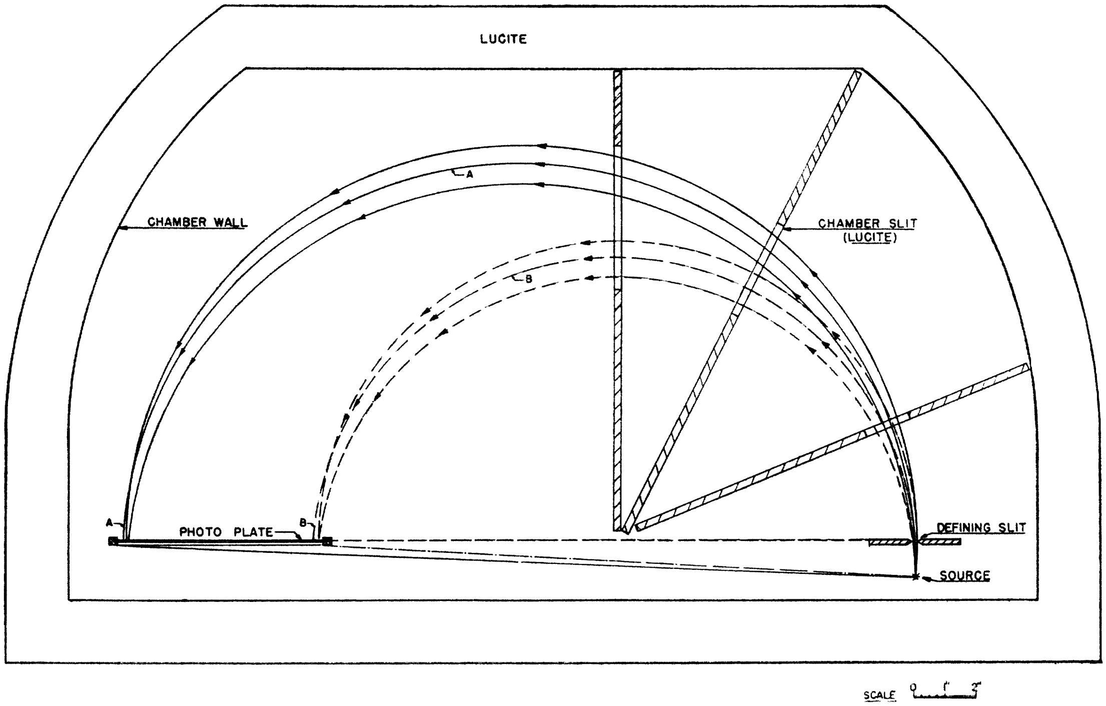

FIG. 1. The schematic diagram of the deflection chamber. It shows the focusing action on two groups of alpha-particles, and the arrangement of the chamber slits.

From some natural radioactive substances, one expects that alpha-particle groups of extremely small intensities may be emitted, for in one or two cases very weak gamma-rays have been observed. If an extremely sensitive method could be devised to measure the energy groups of these alpha-particles, additional information might be obtained about the actual mechanism of the alpha-decay process. During the last few years the photographic track method has been well developed and applied with certain success to the study of scattering, artificial disintegration, and cosmic rays. This method registers every particle, and when it is used in conjunction with an alpha-ray magnetic spectrograph, there is practically no ambiguity in deciding the origin (and nature) of the heavy charged particles. This method and the use of Eastman fine-grain alpha-particle plates, have been shown in our case to be very satisfactory in recording the weak alpha-particle groups, especially in the low energy region with respect to the main group where the background is large. Using this method, we have found 12 very weak alpha-particle groups from Po, the intensities of which do not seem to be compatible with the current theory of alpha-decay. Their energies and intensities are, however, generally compatible with the gamma-ray lines from Po determined by Bothe.

Since 1936 very little work has been done on the alpha-ray spectra. Rosenblum and his co-workers[3] have redetermined the relative intensities of the fine-structure groups of radioactinium and its disintegration products. Several new groups have been found. A 60° magnetic focusing spectrograph has been constructed by Roy Ringo.[4] It may prove useful for the study of particles emitted in artificial disintegration as well as for the investigation of alpha-ray spectra. It has the advantage of portability and low cost because of the use of a much smaller magnet. But for some reason or other, the energy distributions obtained with this instrument do not seem to be satisfactory. Data on the alpha-ray

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[3] Rosenblum, Guillot, and Percy, Comptes rendus **202**, 1274 (1936); **204**, 175 (1937).

[4] Roy Ringo, Phys. Rev. **58**, 942 (1940).

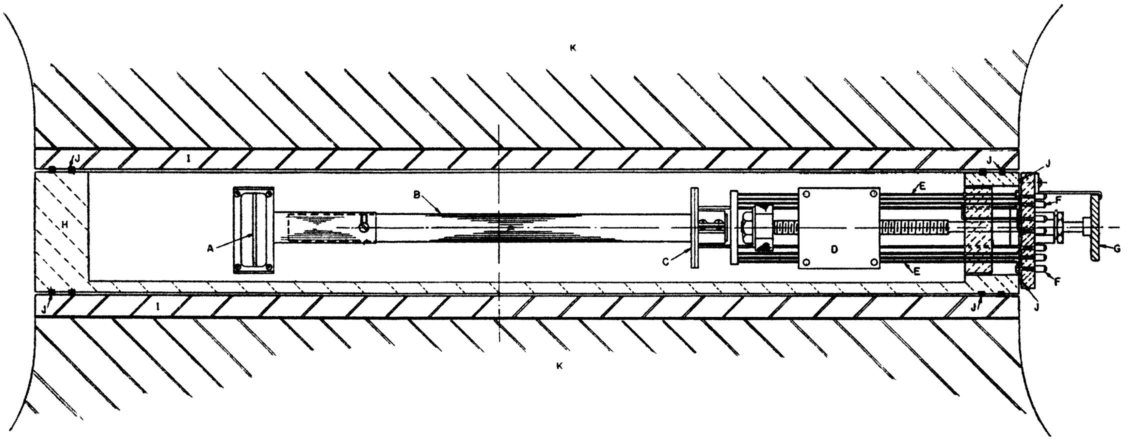

FIG. 2. The vertical section of the deflection chamber between the two pole pieces of the cyclotron magnet. It shows the vacuum seals by neoprene strips and the detailed construction of the system containing the source-box and the support for the counter and camera. *A*—defining slit; *B*—quartz rod; *C*—lead screening plate; *D*—support for camera or counter; *E*—connecting wires (7) for counter (each has a slide contact below the movable support "*D*"); *F*—binding posts (7) for counter; *G*—turning head (one revolution = 50/1000"); *H*—Lucite chamber wall; *I*—iron plates (2); *J*—neoprene strips; *K*—magnet pole pieces.

spectra investigated prior to 1936 can be found in the books of Gamow and Rasetti, respectively, entitled "Structure of Atomic Nuclei and Nuclear Transformations" and "Elements of Nuclear Physics."

II. THE SPECTROGRAPH

The magnetic spectrograph consists of three main parts, namely, the deflection chamber, the magnet, and the detection instruments.

A. The Deflection Chamber

The deflection chamber of the spectrograph is made of transparent Plexiglas in which the alpha-particles can be bent by the magnetic field into a semi-circle of about 80-cm maximum diameter. Figure 1 shows the schematic diagram of the chamber. It has the form of a trapezoid with the legs having the curvature of the pole pieces of the cyclotron magnet. The over-all length (including the thickness of the walls) of the longer side is 89 cm, of the shorter side 60 cm, and the over-all distance between these two sides is 53 cm. The thickness of each of the four walls is 5 cm and the height of the chamber 11 cm (cf. Fig. 2). These four walls were joined together with Lucite cement. A Lucite plate with a small hole at the center (so as to have equal pressures on both sides of the plate) was similarly cemented to the quadrilateral frame as the bottom of the chamber, and aluminum plates were used as the cover on the top. Particles from the source of the same velocity will complete semi-circles of the same radius at a line in the focal plane—the plate. In Fig. 1 the paths of two different groups of alpha-particles are indicated. It is seen from the paths of each group that the semi-circle (*A* or *B*) passing through the center of the defining slit hits the photographic plate, which is at the continuation of the defining slit, at a point farthest from the source, while all the other circles strike the plate at points nearer to the source with the former point as a limit. This gives rise to a sharp edge at the high energy side[5] of a fairly narrow line image. Each of the three chamber slits is also made of a Lucite plate which has a rectangular hole for the slit to allow the alpha-particles to pass through. The shapes of the edges of each hole are such that alpha-particles cannot hit the photographic plate after single scattering from the edges. These slits serve to reduce scattering from the top and the bottom as well as from the walls of the chamber. In fact, the primary advantage of the use of Plexiglas is that the effect of scattering is small. This was shown by the fact that the background of an

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[5] For theoretical analysis, see K. T. Li, Proc. Camb. Phil. Soc. **33**, 164 (1937); J. L. Lawson and A. W. Tyler, Rev. Sci. Inst. **11**, 6 (1939).

alpha-ray line as detected by the track method (cf. C) was very small and was not much increased when the chamber slits were not used. The defining slit and the source slit (not shown) are made of aluminum. Tests have also been made by using brass slits; the background then seemed to be larger.

Figure 2 shows the vertical section through the deflection chamber which has been put between the two pole pieces, *K*, of the cyclotron magnet. Two iron plates, *I*, of about the same area as the pole pieces and about three cm in thickness are placed above and below the chamber, respectively. These plates are used to stand the force caused by the pressure difference produced when the chamber is evacuated. Between each of the iron plates and the wall of the chamber is placed a pair of neoprene loops, *j*, to make the system vacuum tight. The interspace between the two loops of each pair can be evacuated too. The source box and the detection instrument form a single unit which can be easily taken out through a hole in the chamber wall. A source in the form of a long narrow strip (maximum length about 6.5 cm) can be mounted at a distance of 2.85 cm behind the defining slit. If the source is wide, it can be inclined firmly at any angle, so that the projection of its width on the defining slit is still only a few tenths of a millimeter. Thus a better line-shape can be secured. The source box is rigidly connected by means of the quartz rod, *B* (44 cm long and 2.7 cm in diameter), to the support, *D*, for a camera or a system of counters. The distance of the source relative to the detection instrument then will not be changed appreciably when the room temperature varies owing to the small thermal coefficient of expansion of the quartz rod. The seven bronze wires, *E* (one for the common counter voltage), are used to connect six counters (cf. C) in a box set on the support *D* to the seven binding posts, *F*, outside the chamber. Since the support *D* has to be moved when a system of counters is used, each of the seven wires has a slide contact below *D*. The support, *D*, is moved through a distance 50/1000 inch for each complete revolution of the turning head, *G*. The head, *G*, is turned through a Wilson seal[6] so as to prevent leaks into the chamber. This Wilson seal and the binding posts, *F*, are fixed by using rubber seals on a Lucite plate, which covers the hole in the chamber wall tightly by means of the neoprene loop, *j*. To prevent the hole from being collapsed by air pressure, a Lucite block is used which is just big enough to slide freely in and out of the hole. All the above parts form a single rigid system, which is confined to slide only on a pair of tracks parallel to its length, and can then be taken out easily through the hole.

A large hole at the middle of the shorter side wall (cf. Fig. 1) has been provided (having a seal with a brass disk pressed against a neoprene loop) for measuring the magnetic field inside the chamber when necessary. Two small tubes on the opposite sides of this hole are inserted into the chamber wall, so that each tube can be used for pumping the air out of the interspace between the two neoprene loops of each pair. A small hole in the "leg" side wall near the detection instrument is used to let the air into the chamber. This is done by turning a rod through the hole in order to loosen the Wilson seal inside. A system of three shutters over the source box is controlled through a Wilson seal by a turning head outside the deflection chamber. These three shutters are used to stop the beam of alpha-particles from coming out when necessary and are for three different positions of the source box. A large hole provided with a Wilson seal in the "leg" side wall near the shutters is connected to a high capacity oil diffusion pump. A Cenco-Hypervac 20 is used as a fore-pump. The pressure inside the chamber is always maintained lower than 10^{-3} mm of Hg, so that scattering from the residual gas is negligible. Consequently the chance for the capture and loss of electrons[7] by the alpha-particles in their paths is small too.

The dimensions and hence the resolution of the present deflection chamber are larger than the one used by Rosenblum[8] before 1938 and about the same as the annular magnetic spectrograph of Rutherford and his co-workers.[8] However, in the case of the annular magnetic spectrograph, alpha-particles of different ve-

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[6] R. R. Wilson, Rev. Sci. Inst. **12**, 91 (1941).

[7] E. Rutherford, Phil. Mag. **47**, 277 (1924).

[8] Rutherford, Wynn-Williams, Bowden, and Lewis, Proc. Roy. Soc. **A139**, 617 (1933); Rosenblum, Actualités scientifiques et industrielles (Exposés de Physique Théorique, edited by M. L. de Broglie), XXXI (1932).

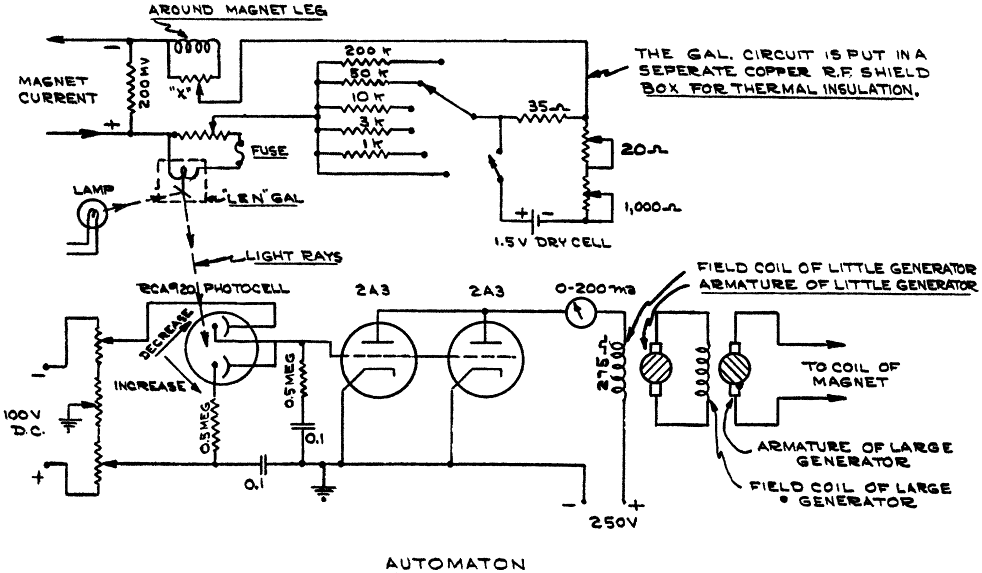

FIG. 3. The automaton for controlling the magnet current. It shows the principle of operation.

locities were brought into the ionization chamber by varying the magnetic field, so that at one field only one velocity could be studied. In our case, however, particles differing in energy by 3 Mev or more can be studied without varying the magnetic field. Moreover, the solid angle of detection in our case is about 1 in 5000,[9] while in the annular case it was only about 1 in 20,000.

B. The Magnetic Field

The description of the design and installation of the Princeton cyclotron magnet was published by Henderson and White.[10] Here we only mention a few things which are particularly important in our case.

(*1*) *The Mapping of the Magnetic Field*

The spatial distribution of the magnetic field at a value of about 11 kilogauss was mapped along two perpendicular diameters with a cylindrical search coil and a fluxmeter. The search coil has a height about equal to the length of the gap between the two pole pieces and a diameter of about 5 cm. The variations along the two perpendicular directions are quite similar to one another and are only from 1 to 2.5 gauss, until a region beyond 37 cm from the center of the pole pieces is reached where the field drops rapidly toward the edge. This is consistent with the results of Henderson and White. In our case the radii of the alpha-particle paths are in most experiments smaller than 32 cm. Therefore, for this working region no effort is necessary to correct the variation of the edge field.

(*2*) *The Control of the Magnetic Field*

An automaton, which has a principle very similar to the automaton built by Henderson and White[10] and which was constructed for the former cyclotron work by Mr. R. Kamm, to whom we are thankful, has been used with some modifications to control the magnet current. Figure 3 shows the arrangement. A small voltage (about 200 mv) from a shunt in the field coil is applied to the galvanometer circuit and balanced by the voltage of the dry cell. The photo-cell-2A3 circuit is so arranged that when the magnet current increases relatively to the dry cell voltage, the galvanometer coil is deflected in such a direction that the light beam reflected from its mirror falls more into the upper photo-cell. This makes

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[9] Estimated by counting the number of alpha-particles from a known strength of Po source and also checked by geometrical calculation.

[10] M. C. Henderson and M. G. White, Rev. Sci. Inst. 9, 19 (1938).

the grid bias of the 2A3 more negative and hence the anode current smaller. Since this anode current passes through the field coil of the small generator, which supplies the field current of the large generator, its decrease thus reduces the magnet current. Similarly, when the magnet current decreases, more light falls into the lower photo-cell, and consequently it is increased again. The sensitivity of the twin photo-cell can be varied by the two extreme slide contacts, while the grid bias of the 2A3 can be independently changed by the grounded slide contact. The sensitivities of the galvanometer, of the twin photo-cell, and of the 2A3 have been so adjusted that a field of about 12 kilogauss, which is about the working field in the future, can be maintained constant within 1 in 10^4 for many hours as shown by the indicating coil (see below). Under such circumstances the range of control is only within about 80 gauss. This means that when, because of the variation of the field, a Po alpha-ray beam is fluctuating more than 5 mm[11] in the focal plane of the deflection chamber, the light beam will be thrown out of the twin photo-cell, and the control will be then out of action. When this happens (very rarely), the magnet current increases rapidly to its maximum—about 350 amperes—and never goes back to its normal value again. This latter fact is very useful, however. For, when too large fluctuation of the magnet current occurs, one is perfectly sure that the photographic plate has been ruined and must be discarded. Hence there is no possibility of being misled in analyzing the results of the spectra. A safety relay system[12] has been used across the input voltage of the field coil of the magnet and breaks the field current of the small generator when the magnet current reaches a certain value.

(*3*) *The Measurement and the Indication of the Field*

A magnetic balance which is sensitive to about 1 in 10^4 has been devised to measure the magnetic field and has been described elsewhere.[13] Ordinarily the field strength can be, however, more conveniently found from the values of $H\rho$ and ρ of some known alpha-ray beam.

To indicate a small variation of the magnetic field, a non-linear indicating coil carrying a small constant current has been always used.[13] It has been put in that part of the field which is not occupied by the deflection chamber. A deflection of 1 mm on a scale at 180 cm from the coil indicates a change of the field equal to about 2 gauss at a total field strength of 12 kilogauss. It was intended at first to use this coil, instead of the galvanometer circuit, in conjunction with the photo-cell-2A3 circuit (cf. Fig. 3) to control directly the magnetic field. However, since the slow zero shift of the coil caused much trouble, this plan was not adopted.

C. The Detection Instruments

Three detection methods have been used depending on the different strengths of the sources or different intensities of the alpha-ray lines from a single source:

(*1*) *The Ordinary Photographic Method*

This method is used only when the source is strong, for it needs four or five thousand particles per square millimeter in order to make a line visible. The camera is made of aluminum so that scattering from its parts will be small, and can easily be slid on to the support, *D*. The back plate for holding the photographic plate in position is lined with a 5-mm thick lead sheet so as to absorb any gamma- or x-rays from outside. The emulsion layer of the plate is about in the focal plane and has the dimensions 6.5×19 cm.

The Eastman "fine grain alpha-particle plates" have been used throughout the experiments. They are sensitive to alpha-particles but less sensitive to gamma-rays or light and give a very clear background. After being exposed to the alpha-rays, they are developed in D11 for 6 minutes at 22°C. They are then dipped into 2.8 percent acetic acid for about one minute in order to neutralize the alkaline D11 (or the background will be deep brown) and then fixed until clear

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[11] Since the momentum of a given alpha-particle beam is constant, we have

$$\delta H = -\frac{H\delta\rho}{\rho} \simeq \frac{1.0\times10^4\times0.5}{60} \simeq 80 \text{ gauss.}$$

[12] I am thankful to Mr. Thomas Coor for his help in building this relay system.

[13] W. Y. Chang and S. Rosenblum, Rev. Sci. Inst. **16**, 75 (1945).

(15–20 min.) in a fixing solution (four parts of hypo to one part of acid hardener). The emulsion layers usually break into pieces during exposure in vacuum; this can be cured at least partly by coating the edges with collodion solution.

(*2*) *The Counting Method*

This method is used when the source is weak, that is, when it takes too long a time to make an exposure in order to have a line visible. It is also a very convenient method when one wants to know instantly the homogeneity of an alpha-particle group. The counters used here have been specially developed for the purpose of investigating alpha-ray spectra and have been already described elsewhere.[14] It may consist of several fine wires stretched in front of a common brass plate, each wire then behaving as an alpha-ray counter. Hence in a single run several distribution curves for the same energy group can be obtained.

(*3*) *The Photographic Track Method*[15]

Each counter of any type has a natural background. If the source is so weak that the number of alpha-particles reaching the counter is below the background, the counting method is no longer applicable. In this case the photographic track method has been shown to be very satisfactory. Each alpha-particle produces a track in the emulsion layer of a plate. In order to get tracks of considerable length, the plate must be inclined to the incident beam. Eastman fine grain alpha-particle plates, which have been especially developed for this track method, 2 cm wide and 19 cm long, have been used throughout all the experiments in this method. The width of a plate is inclined at an angle with the incident beam (the latter is actually in the form of a thin sheet, cf. Fig. 2), while its length is perpendicular to the beam, so that the whole plate is still more or less in the focal plane. The plate holder of the camera mentioned in (*1*) is so made that it can hold four plates at the same time side by side. Each of the two is inclined at an angle of 30°, while each of the other two is at 45° to the incident beam. They are developed and fixed in exactly the same manner as in (*1*) except that they are developed in total darkness and for four minutes only in order to get clearer background.

When a plate is examined with a microscope, it is illuminated with green light. The green light provides a good contrast between the tracks and the background and gives considerable comfort to the eyes. An intense beam of green light can be obtained from a mercury arc through an ordinary green glass filter. On the plate a number of equidistant lines (spacing about 0.9 cm) parallel to the main line of alpha-particles are drawn across the plate with a razor blade. These reference lines are used for checking the measurement of the distance from the main line and hence the energy of the alpha-particle groups (cf. III B (*3*) and Fig. 7). If the plate being examined with a microscope is properly moved lengthwise and if the counting of the microscopic views along the plate is correct, then the number of views, in each of which the tracks are counted, must be the same in each interval between two successive lines.

From the disposition of the photographic plate, it is clear that the tracks produced in the emulsion layer caused by the alpha-particles, which have been coming directly from the source, must appear (1) parallel to one another, (2) perpendicular to the length of the plate, and (3) incident into the emulsion layer at about the same angles. It is this directional effect which enables us to discriminate between the alpha-particles coming directly from the source and the diffusely scattered alpha-particles. Certainly, particles scattered in their very early paths or coming from some contaminated parts near the source may also produce tracks approximately satisfying the above three conditions. However, experiments showed that the first effect is extremely small, while the contaminated parts (if any) can easily be cleaned or covered with thick aluminum foils. From our experience the number of irregular tracks, under favorable conditions, is negligibly small in the region near the main line and is only a small percentage of the corresponding regular tracks in the region further away.

Therefore, the track method not only records every particle, but also gives information, respectively, from the orientation and appearance of

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[14] W. Y. Chang and S. Rosenblum, Phys. Rev. **68**, 222 (1945).

[15] T. R. Wilkins, J. App. Phys. **11**, 35 (1940); M. M. Shapiro, Rev. Mod. Phys. **13**, 58 (1941); Chadwick, May, Pickavance, and Powell, Proc. Roy. Soc. **A183**, 1 (1944); Champion and Powell, Proc. Roy. Soc. **A183**, 64 (1944).

the tracks about the origin and nature of the particles. This is why it is very useful for counting particles in the presence of a relatively large general background (cf. the experiments below on the short range Po alpha-particles).

III. EXPERIMENTS WITH Po ALPHA-PARTICLES

A. The Main Group of Po Alpha-Particles

The behavior of the above spectrograph has been investigated with Po alpha-particles by using the three methods of detection. Sources of different forms have been prepared, by spinning, in RaD solution, thin platinum wires, narrow strips of nickel foils, and the edges (about 0.2 mm wide) of nickel foils. All surfaces to be used for coating with the source have been well polished previously. In the latter case the two opposite faces of the edge have been always well covered with two pieces of thin glass plates, so that during preparation Po is deposited only on the edge. Any one source can be covered with the source-slit so that only the central strip portion is used. It has been shown that a thin wire source does not give as sharp and narrow a line image as a narrow strip source or an edge source does. The third method of preparation gives a uniformly strong source and is the most economical one, for all of the Po is deposited only on the useful edge. In any case, the source must be fresh, uniformly thin, and show no traces of tarnish in order to get a sharp-narrow line image.

The forms of the number-energy distribution curves have been determined, respectively, by the above three methods of detection and agree with one another fairly well. The width of the main line at half intensity is under favorable conditions less than $\frac{1}{2}$ mm, i.e., about 0.01 Mev.[16] According to the dimensions of the spectrograph, two lines separated by 0.01 Mev or less can thus be resolved. The intensities at 0.25 Mev or more below the energy of the main group are less than 0.1 percent of the maximum intensity. This is about 100 times smaller than that found by Roy Ringo.[4] The distribution curves determined by the counting system have been published elsewhere.[14]

The microscopic examination of the tracks distribution (as well as the microphotometric examination[17] of an ordinary photographic line or the distribution determined by the counters) does not reveal any fine structure of the main line. If there were fine structure of the main group, the separation should be less than 5 kev, for, as mentioned above, our spectrograph is able to resolve two lines separated by about 5 kev. Inconsistent splitting of the main line into two or three lines (separated by one or two millimeters, that is, equivalent to 0.02 or 0.04 Mev[16]) was happening at first but was soon discovered to be caused by the improper adjustment of the automaton which controls the magnet current (cf. II (B)). In the following experiments, the form of the main line has been generally used, therefore, to obtain information about the behavior of the magnet current during exposure of the plates.

B. The Short Range Po Alpha-Particles

By carefully studying the region of about 2 Mev below the main line of Po, a series of weak groups of alpha-particles from Po have been found. For these experiments the sensitive track method of detection has been used in conjunction with the above large spectrograph. A preliminary report of these results was published recently.[18] In the following we shall describe the experiments in some details:

(*1*) *Experiments with the Different Sources*

(*i*) *The two and one-half months old source.*—A source of about $\frac{1}{3}$ mc was used at first. It was prepared by coating the edge of a nickel foil with Po as described in A. In order to have alpha-particles coming out only from the central strip portion, the source was covered with the source slit. The track method of detection as given in (II C.) was employed in recording the alpha-particles, the time of exposure being four hours. The plate was then examined with a microscope of 430× (710× for more highly populated plates). The number of alpha-particle tracks which satisfied the above three conditions was counted in a strip of 20 successive views across the plate.

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[16] The relation between $H\rho$ and α, the energy of the alpha-particles in Mev, is given by $H\rho = 1.436\times 10^5\alpha^{\frac{1}{2}}$ without relativistic correction. Hence $2\delta\rho = 1.436\times 10^5\delta\alpha/(H\alpha^{\frac{1}{2}})$, ρ being in cm and H in gauss.

[17] I should like to thank Mr. J. R. Winckler for his help in some of these microphotometric measurements.

[18] W. Y. Chang, Phys. Rev. **67**, 267 (1945).

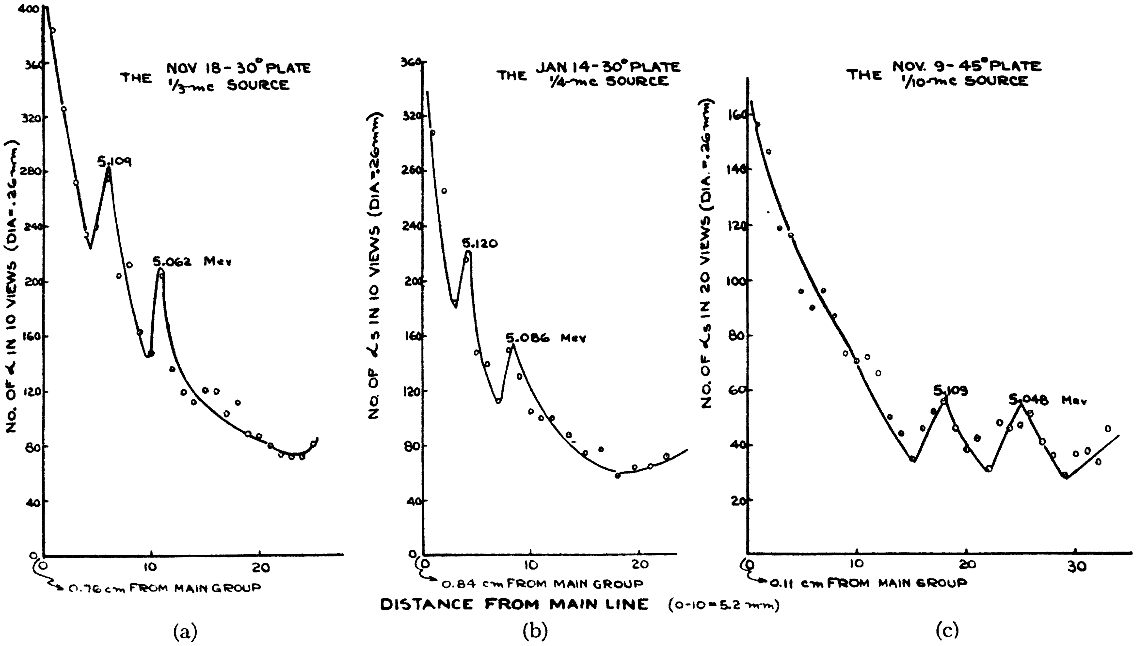

FIG. 4. The distribution of the first two groups of short range Po alpha-particles as obtained from three different sources. The ordinate represents number of alpha-particles in 10 or 20 views across the plate. The abscissa represents distance from the main line in terms of microscope views along the plate, distance of the origin O from the main line being indicated.

Under favorable conditions, the number of irregular tracks is, as mentioned before, negligible in the region near the main line and is only a small percentage of the corresponding regular tracks in the region farther away. To save time, the counting was carried out only for every other strip across the plate (cf. Fig. 7). The number of tracks was then plotted against the distance from the main line. The number-energy distribution curve so obtained reveals distinctly twelve extremely weak groups in the low energy region from about 0.04 to about 2 Mev below the main line. The first two groups stand out more clearly only on the curve obtained with the weakest source (cf. (*3*)), where the background near the main line is smaller. The number of tracks for each point on a curve varies from 50 to 250. The region lower than 2 Mev from the main line has not been examined, for in order to have this region on the plate, the main line, which is used to infer the behavior of the magnetic field, will be out of the plate.

(*ii*) *The condensed source.*—The above source was already about two and one-half months old when it was used for these investigations. But it had been kept in vacuum, and according to Karlick and Rona,[19] Po nuclei diffuse extremely slowly into nickel. However, we were still afraid that some contamination of the surface or non-uniform distribution of Po might falsify the results or at least might be responsible for the comparatively large background. A fresh source was then prepared by vaporization and condensation of several old sources according to a procedure of Rona and Schmidt.[20] Po vapor was condensed onto a well-polished palladium rod having a diameter of 1 mm and a length of 50 mm. The end of the rod further away from the old sources was hard-soldered to a long piece of copper wire, which served to cool the palladium rod so as to increase the efficiency of condensation. The palladium rod and the old sources were placed in a quartz tube which had a diameter of 1.5 mm and a length of about 250 mm. The old sources were carefully heated red hot with a very small oxygen flame when a stream of hydrogen gas was passed through the quartz tube. The rate of flow of the hydrogen gas through the tube was about 1 cc per sec. (higher than that recom-

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[19] B. Karlick and E. Rona, Wien Ber. **143**, 217 (1934); J. Schintlmeister, Wien Ber. **146**, 389 (1937).

[20] E. Rona and Schmidt, Wien Ber. **137**, 103 (1928).

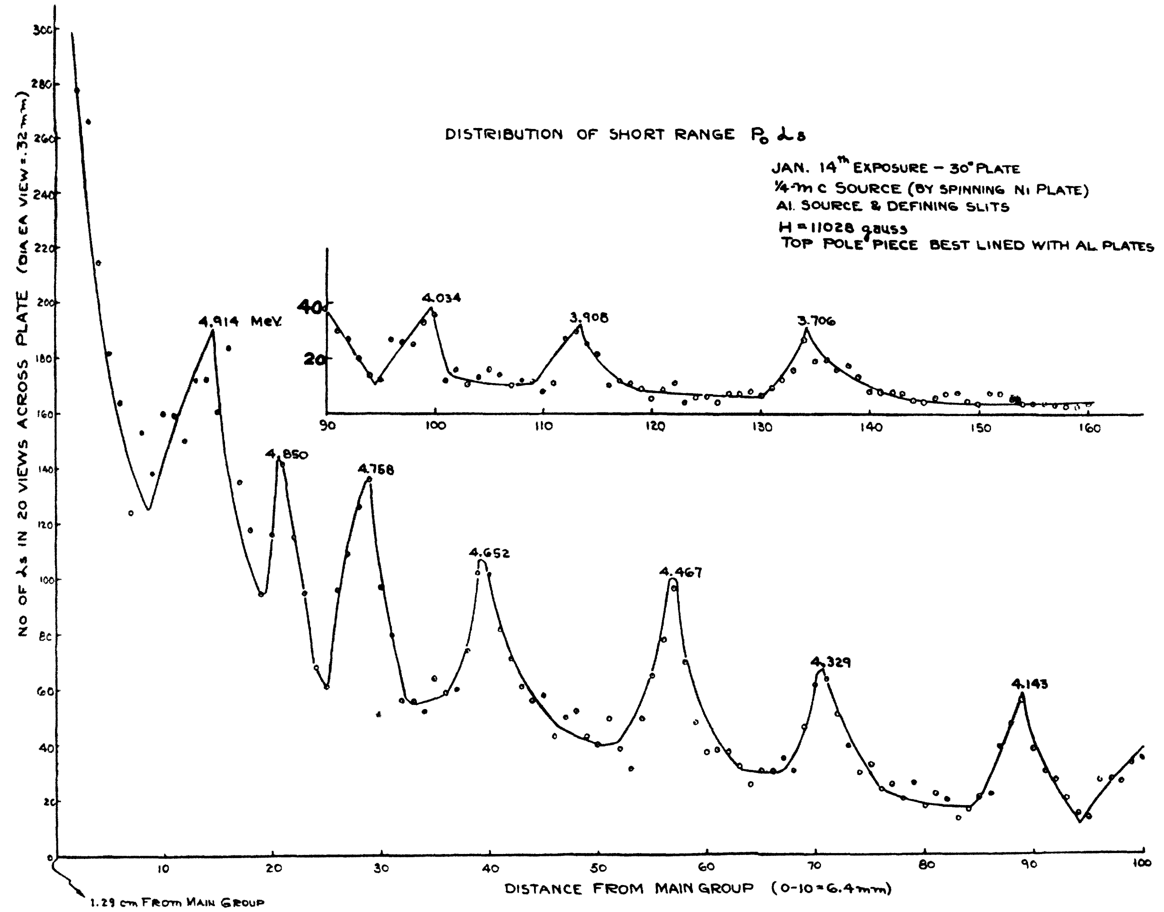

FIG. 5. The distribution of the third to twelfth group of the short range Po alpha-particles. These were examined by a 430× microscope, while those in Fig. 4 by a 710× microscope. The curve in Fig. 5 is one of five such distribution curves, which were obtained with different sources, different fields, and different arrangement of the chamber slits, etc.

mended by Rona and Schmidt) in order to get a uniform distribution of Po along the long rod. The source prepared in this way had a strength of about $\frac{1}{10}$ mc and looked shining and smooth. An exposure was made with this source also for a period of four hours. The energy distribution curve thus obtained is very similar to that obtained from the first one, except that the background is smaller.

(*iii*) *The fresh source.*—A stronger source of about $\frac{1}{4}$ mc was freshly prepared by spinning the polished edge of a nickel foil in RaD solution. The distribution curve from this source is again similar to those above, and the background is smaller than that from the old source but larger than that from the condensed source. All the strengths given above are strengths actually used for exposures.

(*2*) *The General Results*

With these three sources, altogether five different exposures were made under different magnetic fields. Three of them were done without the Lucite chamber slits and the other two with the chamber slits. In the former case three thin lead blocks lined with aluminum and having a height of 9 cm and a length of 18 cm were put into the chamber, so that they diverged out from the center of the line joining the defining slit and the nearer end of the photographic plate. After the first two exposures the material for making the defining and source slits was also changed from brass to aluminum; this resulted in a smaller background. The distribution curves obtained under these different experimental conditions are very similar to one another (except

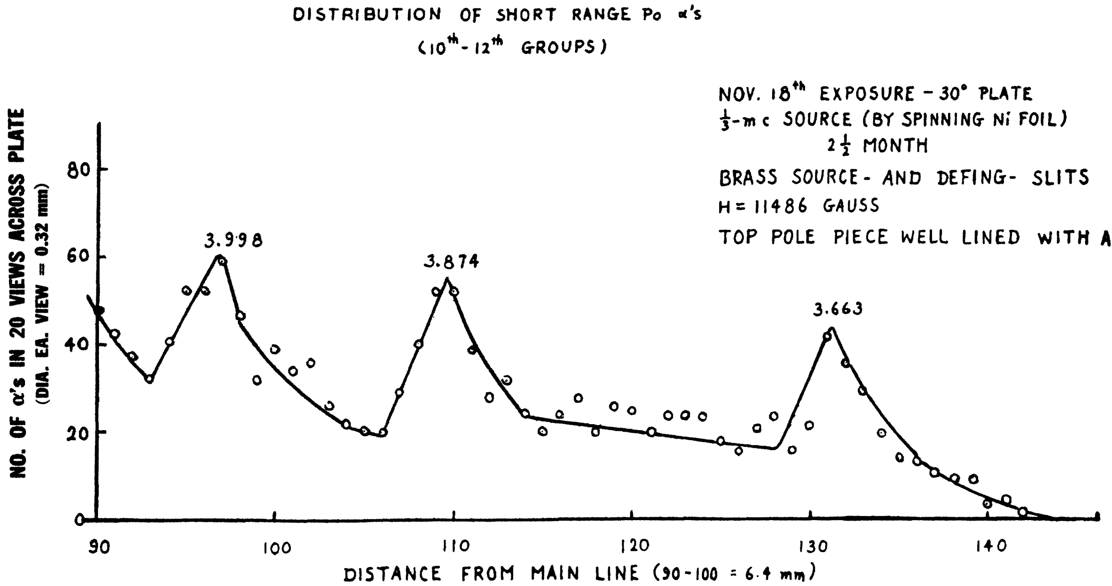

FIG. 6. The last three groups of a curve like Fig. 5, obtained with the $\frac{1}{3}$-mc source. Inclination of the plate and its time of exposure are the same as in Fig. 5, but magnetic field is about 500 gauss more and other experimental conditions are different. After subtracting the general background, the integral intensities of these groups to that of the corresponding groups in Fig. 5 are about in the same ratio as the strengths of the two sources.

the first curve, which was obtained by screening the photographic plate from stray light with one-cm air equivalent aluminum foil at a distance of about one centimeter away from the plate, so that the lines are broader). Plates inclined upward and downward with the incident beam gave the same results. The energy positions of the corresponding groups with respect to the main line in the different curves agree with one another to within about 0.04 Mev. The corresponding separations between these small groups themselves, in the different curves, however, agree with one another to within about 0.02 Mev only. This was chiefly caused by some errors in the measurement of the distance between the reference line and the main line so that in some curves the groups have been all shifted by the same amount from the main line (cf. Figs. 5 and 6; also cf. (*3*) for discussion). The intensities of any one group in the different curves are, as will be also seen in the following, about in the same ratio as the relative strengths of the three sources (reduced to that actually used for exposure). The widths of these groups also increase with the width of the main line.

Figure 4 shows the distribution of the first two groups. (a) was obtained with the $\frac{1}{3}$-mc source having the plate inclined at 30° to the beam, (b) with the $\frac{1}{4}$-mc source (plate inclined at 30°), and (c) with the $\frac{1}{10}$-mc source (plate inclined at 45°). They were examined with the 710× microscope. It is seen that these two groups stand out more clearly in the curve from the $\frac{1}{10}$-mc source, where the background near the main line is smaller. Figure 5 is one of the five curves mentioned above showing the distribution of the groups from the third to twelfth. It was taken with the $\frac{1}{4}$-mc source having the photographic plate inclined at an angle 30° to the incident beam. In Fig. 6 are the last three groups of the *a* distribution curve, like Fig. 5, which was obtained with the $\frac{1}{3}$-mc source, the inclination of the plate and the time of exposure being the same as those in Fig. 5. It is seen that the separations between these groups are practically the same as those between the last three corresponding groups of Fig. 5, although they are all shifted toward the main line by a constant amount (cf. (*3*) for discussion). It is also interesting to note that, after the general background is subtracted, the ratios of the integral intensities of these groups to those of the corresponding groups in Fig. 5 are, respectively, $183:141 \simeq 182:133 \simeq 205:149 \simeq \frac{1}{3}:\frac{1}{4}$, which is about the ratio of the strengths of the two sources. Similar relations have also been found for the other groups from these two sources and from the $\frac{1}{10}$-mc source. This seems to indicate that these weak groups are related with the main group of the Po alpha-particles.

The background of the curves must be chiefly caused by the straggling of the different groups of alpha-particles through the finite thickness of the source. By changing slightly the air pressure in the chamber or by performing experiments with and without the chamber slits (provided the top pole-piece was properly lined with aluminum), the background was not affected very much. This shows that the effect of scattering from the residual gas as well as from the chamber was small. Moreover, the background due to radioactive contamination of the chamber as shown from blank experiments was found to be very small, about 2 percent of the third group intensity in the first part of the energy region mentioned above, and nearly zero in the latter half of the region. Certainly, the background (and also the number of irregular tracks which were not actually counted) became smaller, when the source- and the defining-slits were made of aluminum instead of brass, but the decrease was still too small to account for the total background. One experiment was also performed with a source in the chamber but covered with the shutter in order to test the proper operation of the shutter. The plate after being exposed for one hour in the chamber also showed a very small background.

TABLE I. Energy of groups of Po alpha-particles.

Group	Group energy in Mev	$E_n = \alpha_0 - \alpha_n$ in Mev	Relative integral intensity
α_0	5.303	0	10^6
α_1	5.113±0.02	0.190	(96)
α_2	5.065±0.02	0.238	(126)
α_3	4.901±0.01	0.402	84
α_4	4.838±0.01	0.465	49
α_5	4.749±0.01	0.554	64
α_6	4.640±0.01	0.663	70
α_7	4.449±0.01	0.854	79
α_8	4.303±0.01	1.000	43
α_9	4.111±0.01	1.192	48
α_{10}	4.016±0.01	1.287	19
α_{11}	3.890±0.01	1.413	18
α_{12}	3.685±0.01	1.618	21

(*3*) *The Energy and the Intensity. Possible Error*

The energies of these groups have been calculated by comparison with that of the main group, the latter being taken as 5.303 Mev. The value of ρ_n, the radius of curvature of the nth group, was obtained by measuring (*1*) the distance, l_0, between the main group and the defining slit and (*2*) the separation, s_n of this small nth group from the main line. s_n was obtained from the distribution curve by calibrating the field of view of the microscope. The distance, k, of the source from the defining slit is 2.85 cm. These quantities are indicated in Fig. 7. The relativistic correction has been neglected. The energy, α_n, of the nth group is thus related to the energy, α_0, of the main group by the following expression:

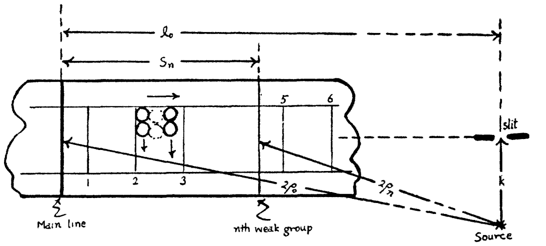

FIG. 7. The scanning of a photographic plate by a microscope and the location of a small group relative to the source. The full circles represent the microscopic views in which the tracks are counted. Tracks in dotted circles are not counted. They are very much exaggerated. The lines 1, 2, ⋯ across the plate are the reference lines for the microscopic counting, etc.

$$\frac{\alpha_n}{\alpha_0}=\left(\frac{2\rho_n}{2\rho_0}\right)^2=\frac{(l_0-s_n)^2+k^2}{l_0{}^2+k^2}. \tag{1}$$

The counting of the tracks on the plate was usually started from some reference line near to the main line of alpha-particles (cf. II C(*3*)). Therefore, s_n equals the separation between the peak of the nth group and this reference line (from the distribution curve) plus the distance of this reference line from the main group. The latter quantity was measured up to the sharp edge at the high energy side of the main line. However, in the case where the main line is broad, this edge is not well defined, and this makes the measurement a little difficult. An error in the measurement of this quantity will cause a constant shift of all the groups in the distribution curve from the main line (cf. (*2*)). The energies so obtained are summarized in Table I. The energy value of each group in the table represents the average of three corresponding values from three different curves, which were obtained with the three Po sources.

It may be useful to find how the errors in the measurements of l_0 and s_n affect α_n, the energy of the nth group. This can be seen by differentiating α_n with respect to l_0 and s_n. Hence, letting $\rho_0 \sim l_0$ and neglecting a term containing $1/\rho_0^3$, we have,

$$\frac{\delta\alpha_n}{\alpha_0} \simeq \left(\frac{s_n}{2\rho_0^2} - \frac{1}{2\rho_0}\right)\delta s_n - \frac{s_n \delta l_0}{4\rho_0^2} \simeq \frac{\delta s_n}{2\rho_0}, \tag{2}$$

as the other two terms at most introduce errors, respectively, equal to $0.02\delta s_n$ percent and $0.01\delta l_0$ percent ($\rho_0 \sim 60$ cm, $s_n \sim 15$ cm maximum). Hence, the uncertainty of α_n is chiefly determined by the uncertainty in s_n. The error, δs_n, consists of (1) the error in measuring the distance of the reference line from the main line, (2) the error in locating the peak of the nth group due to different possible tracings of the distribution curve, and (3) the error in counting the number of the microscopic views along the plate (cf. Fig. 7 and II C. (*3*)). The first and the second errors are each about ±0.5 mm. The number of views counted in each interval between two adjacent reference lines can fluctuate on the average by about ±2 views (in about 30 views), i.e., about ±0.6 mm. Hence,

$$\delta\alpha_n \simeq \pm\left[\frac{1.6}{2\times 600}\times 5.303\right] \simeq \pm 0.008 \text{ Mev.}$$

In the last column of Table I are the relative integral intensities with respect to that of the main line. The area of each group in a distribution curve was measured and then compared first with that of the third group (i.e., latter taken as unity), after the general background was subtracted according to its natural trend. Three series of such ratios were obtained from three of the distribution curves, each belonging to a different Po source. A series of average values was thus found. However, since the subtraction of the background is somewhat arbitrary and since the curves can be drawn differently, these integral intensities can be off by a factor of magnitude ranging from about 0.75 to 1.5, especially in the earlier region where the arbitrariness in determining the background is larger. It is to be noted that the integral intensities as well as the peak positions of the first two groups can hardly be accurately determined, because the background here is very large compared with the peak intensities of these two groups. The integral intensity of the main line cannot be determined from the same plate as the weak groups, because the population of tracks in this line is too high to permit counting. It was obtained under the same geometrical conditions by exposing a separate plate to the alpha-particles for a much shorter time (1 to 2 min.). The third group intensity was then compared to it. The intensity distribution of the main line was, as a check, also determined by an alpha-ray counter of the type mentioned above and by using $\frac{1}{4}$ of the $\frac{1}{3}$-mc source (the other $\frac{3}{4}$ was covered with a metal foil). The ratio of the corresponding third group intensity to this main intensity was found to be about two times larger than the above ratio for which the track method was also employed for the main line. This is to be expected, because the number of alpha-particles counted by a counter must be smaller than that obtained by the track method, for this latter method, as mentioned above, registers every particle. Each value in the table represents the average of three corresponding values obtained from the three Po sources. The relative intensities reported before[18] were relative peak values.

(*4*) *Comparison with Gamma-Ray Lines*

In 1935 Bothe[21] found five gamma-ray lines, namely, 0.202, (0.355), (0.433), 0.798, and 1.068 Mev, the lines in the brackets being less certain. The emission of these weak groups of alpha-particles may lead to the formation of the Pb nucleus in different excited states as in the case of the ordinary fine-structure lines. If the effect of the recoil energy on the excitation energy is neglected, the differences between the main group energy and the individual group energies thus give the corresponding energy levels of the Pb^{206} nucleus. These are shown in the

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[21] Bothe, Zeits. f. Physik **96**, 607 (1935).

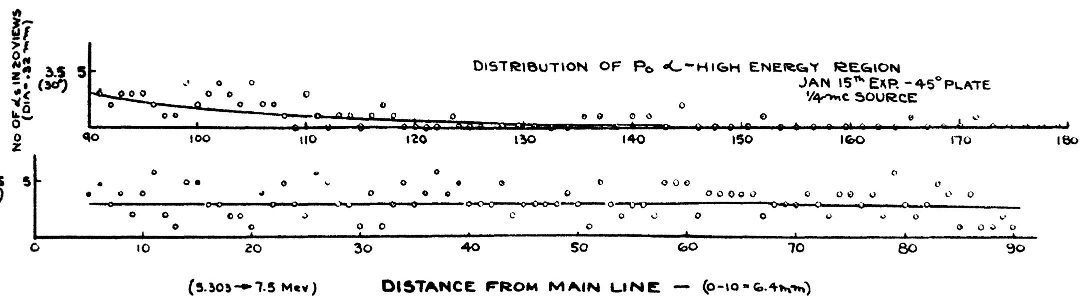

FIG. 8. The distribution of Po alpha-particles in high energy region. The ordinate represents number of alphas in 20 views across the plate; the figure 3.5 (opposite to 5) is the corresponding number of alphas when the plate is inclined at 30 degrees to the beam instead of 45. The abscissa represents distance from the main line in terms of microscope views along the plate; main line is about at the origin *O* and the curve extends to about 7.5 Mev.

third column of Table I. When the Pb nucleus falls from an excited level to the ground level, a gamma-ray quantum is emitted. If this interpretation is correct, an exact correspondence is expected between the above gamma-ray lines and these alpha-particle groups. It is possible to find transitions in our level system which agree approximately with Bothe's gamma-ray lines. But this comparison is rather arbitrary, as there are 78 possible transitions between the 13 levels, and so more than one possible transition can be found to give the same gamma-ray line. A decision may possibly be made to find one (out of the two or more transitions) which actually corresponds to the gamma-ray line, if one knows the spins of the various levels and the selection rules for gamma-transitions (cf. Discussion below). The average number of quanta, as reported by Bothe, is about 7 in 10^6 of the alpha-particles. This ratio seems to be too small in comparison with the relative intensities of our alpha-particle groups. However, a smaller gamma-ray intensity relative to the main group intensity of alpha-particles is expected, as the method of detection he used for gamma-rays has an efficiency, which is neither high nor definitely known. In general we may say that, as far as energy and intensity are concerned, these gamma-ray lines are compatible with the alpha-particle groups.

(5) *The High Energy Region of the Main Line*

An exposure of four hours to the alpha-particles from the strongest source was made with a higher magnetic field, so that the main line was near to the low energy end of the plate. Microscopic examination has been extended over the region from 0.01 to about 2.2 Mev above the main line. It shows a very small continuous background decreasing slowly to zero after about $\frac{3}{5}$ of the region mentioned above. Figure 8 shows such a distribution curve. It is seen that the distribution of the tracks varies only within the statistical fluctuation, and that it is only about 1.5 percent of the third group intensity before it comes to zero. Therefore, if there is any group in this high energy region of the main line, its intensity must be smaller than 2 in 10^6 of the main group intensity. This small background was found to be partly because of contamination of and partly because of scattering from the chamber.

IV. DISCUSSION ON THE SHORT-RANGE Po ALPHA-PARTICLES

A. The Spin Changes from the Alpha-Decay Theory

It has been mentioned above that to fit Bothe's five gamma-ray lines into the level system of Pb^{206} deduced from the alpha-particle groups is rather arbitrary, for there can be more than one possible transition to give the same gamma-ray line. However, if the spin changes, corresponding to the different alpha-transformations, could be estimated, the comparison might be much less ambiguous. The spin values of the various energy levels of the Pb nucleus may be deduced from the above spin changes. Hence one may then apply certain selection rules in conjunction with consideration of the intensities of the gamma-ray lines and the alpha-particle groups. A correct transition corresponding to each of the five lines may thus be chosen.

We have estimated[22] the spin changes by using the current alpha-decay theory of Gamow[23] and others: This theory is based on two main assumptions, namely (1) the existence of the alpha-particles as subunits in a nucleus and (2) a simple rectangular hole for the auxiliary potential. The probability of penetration through the potential barrier is then calculated as a function of kinetic energy of the alpha-particle. The decay constant, λ_k, corresponding to the α_k transformation is connected with the velocity, v_k, of the α_k group by the following equation:

$$\log_{10} \lambda_k = A - \frac{B}{v_k} + C[(r_{\text{eff}})_k]^{\frac{1}{2}}, \tag{3}$$

where A, B, and C are constants for a given nucleus, and λ_k is given by

$$\lambda_k = \lambda(N_k / \textstyle\sum_i N_i). \tag{4}$$

λ is the total decay constant, and $N_k/\sum_i N_i$ is the intensity of the α_k group relative to the total intensity, and is given in the last column of Table I. r_{eff} is defined as the effective radius of the residual nucleus and is given by

$$(r_{\text{eff}})_k = r_0[1 - 0.002 j_k(j_k + 1)], \tag{5}$$

where j_k is the spin change in the α_k transformation, and r_0 is the true radius of the residual nucleus. r_{eff} is equal to r_0 when the change of nuclear angular momentum is zero.

TABLE II. Spin changes in different Po alpha-transformations.

Type of alpha-transformation	$\lambda_k \times 10^{11}$ sec.$^{-1}$	$v_k\left(1+\frac{4}{206}\right)$ $\times 10^{-9}$ cm/sec.	$r_{\text{eff}} \times 10^{12}$ cm	j_k
α_0	5886	1.629	0.71	13
α_1	0.5652	1.600	0.58	15
α_2	0.7419	1.593	0.59	15
α_3	0.4943	1.566	0.63	14
α_4	0.2887	1.557	0.64	14
α_5	0.3769	1.542	0.67	13
α_6	0.4120	1.524	0.70	13
α_7	0.4651	1.492	0.77	11
α_8	0.2531	1.467	0.81	11
α_9	0.2826	1.435	0.89	10
α_{10}	0.1119	1.418	0.91	9
α_{11}	0.1059	1.395	0.97	7
α_{12}	0.1236	1.358	1.08	0

Since A, B, and C are known and λ_k is obtained from (4), r_{eff} is thus calculated from (3) using Table I. From (5) j_k can be then deduced. The various spin changes corresponding to the different alpha-transformations have been so estimated and are given in Table II. In order to obtain the value of r_0, the value of j_{12} corresponding to the maximum value of r_{eff} (cf. Eq. (5)) has been arbitrarily set equal to zero.

It is seen from the table that the alpha-transformations from the normal state of the ${}_{84}\text{Po}^{210}$ nucleus to the excited states, lower than the seventh one, of the ${}_{82}\text{Pb}^{206}$ nucleus would require the spin changes of as high as 14 or 15 units, while those to the states from the seventh to the eleventh result in changes of 11 to 7 units. These abnormally large spin changes are rather amazing, for in any transformation (particle or radiative) no such large spin changes have ever been observed. Moreover, since both the mass number and the charge number of either Po or Pb are even, the angular momenta of both nuclei in their normal states are expected to have zero values; accordingly the spin change in the α_0 transformation between the two normal states of the two nuclei should be also expected to be equal to zero. The value, 13, as calculated from the theory, for the α_0 transformation is far from the value, 0, expected. Certainly, we may assume that, since Po is an unstable nucleus, its normal state may have a spin as high as 13. But this assumption would also lead to the corresponding high spin values for the excited states of the Pb nucleus, which would then completely exclude the possibility of radiative transitions from high levels to low levels. This is in contradiction with Bothe's observation of the gamma-rays from Po. Evidently, there are two possible alternative ways to account for this discrepancy; that is, either these discrete energy groups of the alpha-particles do not originate at the Po nucleus, or the alpha-decay theory needs some modification. However, considering the different experimental conditions described above, it is more probable that these discrete energy groups of the alpha-particles are from within the Po atoms than that they are caused by some external effects. Besides, as far as energy and intensity are concerned, these weak groups of the alpha-particles are

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[22] W. Y. Chang and Thomas Coor, unpublished.

[23] G. Gamow, *Constitution of Atomic Nuclei and Nuclear Transformations* (Oxford University Press, 1937), second edition.

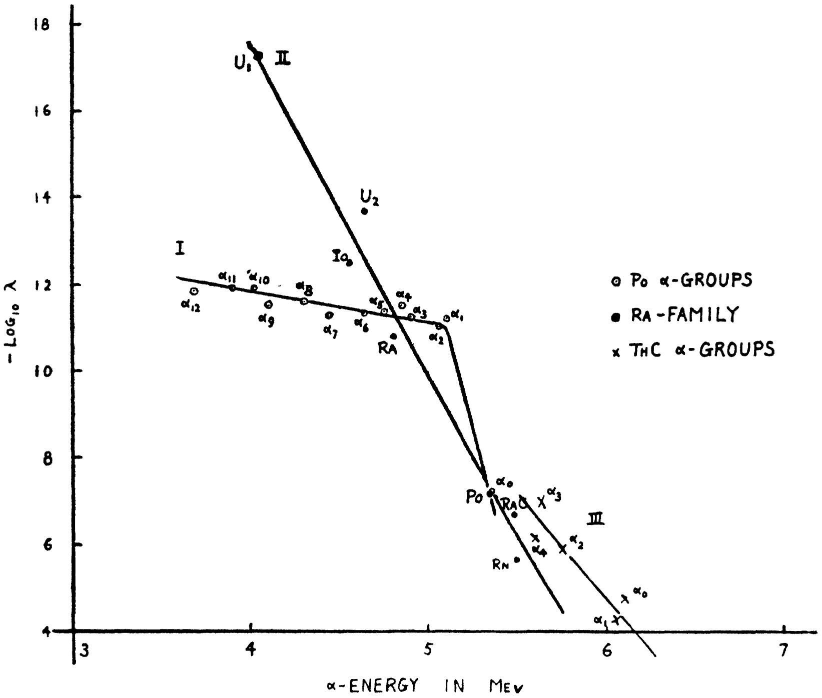

FIG. 9. The Geiger-Nuttall curves showing the deviation of the curve for the Po alpha-groups from that for the Ra family.

generally compatible with the gamma-ray lines from Po as determined by Bothe.

B. The Geiger-Nuttall Relation

The deviation of the experimental results from the theory can be more clearly revealed by a plot of the Geiger-Nuttall relation, i.e., $\log_{10}\lambda$ *vs.* α_n, α_n being the energy of the alpha-particle in Mev. This is shown in Fig. 9. Curve I is the plot for these small groups of Po including the main group. Curve II is the one for the members of the radium family, while curve III is for the fine structure groups of ThC. It is supposed that curves II and III can be generally described by the above theory of alpha-decay. It is seen from curve I that $\log_{10}\lambda$ drops very rapidly at first and then decreases very slowly with decreasing energy, α_n, of the alpha-particles. After this drop there is a large systematic departure from the curve for the Ra family. To be in line with the curve of the Ra family, α_1 to α_3 on the one hand have too small intensities, while α_7 to α_{12} on the other hand have too large intensities. However, it may be interesting to mention again that, as reported in his papers, Bothe has not observed either any intense gamma-rays with intensities which could be compatible with this high energy portion of the Ra family curve.

Now let us consider the low energy portion of the curve. Take the eighth group, α_8, as an example. This group may correspond to Bothe's 1.068 Mev gamma-ray line. The observed partial decay constant of this group is about 3000 times larger than the value it should have if it would lie on the Ra family curve. In other words, if there should be any group of this energy, its intensity must be about 14 in 10^9 of the main group intensity of Po alpha-particles in order to be in line with the Geiger-Nuttall curve for the Ra family. Bothe's gamma-ray intensity is about 7 in 10^6 of the main intensity of Po alpha-particles. This is about 500 times larger than the above ratio required to fit in the Ra family curve. Therefore, comparing these experimental results with the Geiger-Nuttall curve for the Ra family, we are led to draw the following alternative conclusions: (1) Bothe, for some reason in his measurement, estimated the gamma-ray intensity 500 times too large (which seems rather unlikely, especially because the measured gamma-ray intensity is almost always smaller than its true value), and the discrete energy groups of the alpha-particles do not originate in the nucleus of Po. (2) Both his gamma-ray lines and our discrete energy groups of alpha-particles do not have their nuclear origins in Pb and Po, respectively. Or (3) some modification is needed either in the development of the theory or in the application of the theory (cf. Professor Gamow's suggestion in the next section). Since the intensities of the gamma-ray lines and these alpha-particle groups are of similar order of magnitude and since the gamma-ray energies are generally compatible with that of these alpha-particle groups, it is very likely that they are related with each other in the usual way.

C. Some Possible Explanations

A close examination of Eq. (3) immediately shows that the theoretical decay constant decreases much more rapidly with decreasing velocity of the escaping alpha-particle than the observed decay constant. It seems, therefore, that there might be some other mechanism which would help the escape of the alpha-particle through the potential barrier, thus giving rise to an additional probability of decay to the probability of penetration through the statical potential barrier. It may be reasonable to assume that, during the alpha-disintegration, the nucleus might be vibrating, and this nuclear vibration might in some way or other affect the probability of penetration through the barrier. This was also generally suggested by Dr. J. M. Jauch[24] and seems to be fairly plausible. The idea of Goldhaber[24] that the Po nucleus may be in a state of pre-fission may be considered to be somehow connected to the idea of nuclear oscillation just mentioned. It will be interesting to determine if those easily fissionable nuclei have alpha-ray spectra similar to that of Po nucleus just discussed above.

To fit the theory with the experiment, the term containing v_k in Eq. (3) should be compensated somehow so that it would not change so rapidly with v_k; otherwise, if it is left as it is, the value of r_{eff} and hence that of j_k have too large a variation as already shown above. We have tried to accomplish this by adding a term of the form $D(\alpha_0-\alpha_n)^N$ to the right-hand side of Eq. (3). D is a constant of about 3 if the alpha-energies α_0, α_n are expressed in Mev, and a value of $N\sim 2$ would suit the purpose roughly. For those groups which are near to the main line (e.g., the ordinary fine structure of alpha-particles), this term is negligibly small, and hence the original form of the theory is still applicable. For those groups farther away from the main group, it becomes more important. Physically, since $(\alpha_0-\alpha_n)$ represents the energy of excitation of the product nucleus, the above term so proposed must represent the contribution to the decay constant, λ, of some mechanism which plays a much more important role when the nucleus is being highly excited. If the "nuclear oscillation" during alpha-disintegration would at all contribute an additional probability of decay to that of penetration through the potential barrier, one might expect this additional probability to be larger as the nucleus is being more highly excited. Therefore, it may be feasible that the above-proposed term may be connected in some way or other with the "nuclear oscillation." However, the actual theoretical ground is completely lacking at present.

An alternative explanation as suggested by Dr. G. Gamow[24] is that each of the small observed groups might have "hyperfine structure." Therefore, if one could determine the intensities of these "hyperfine lines" in each observed group and apply the above formula to these "hyperfine lines" separately, the result might come out in agreement with the alpha-decay theory. It is interesting to note, as pointed out by Gamow, that when the formula of Hardy and Ramanujan[25] for the number of partitions of any integer n:

$$p(n)=\frac{1}{4\sqrt{3}n}\exp\left[\pi(2n/3)^{\frac{1}{2}}\right] \tag{6}$$

is applied to our case (we assume basic levels of 0.2 Mev so that $n\simeq 1.618/0.2\simeq 8$ cf. Table II), the calculated statistical weights, $p(n)$, of higher levels (corresponding to the higher values of n up to 8) increase more or less in the same manner as the effective radii in Table II. This seems to suggest that the effective radii so calculated in Table II may perhaps correspond to the superposition of the "sub-partial" decay constants of the "hyperfine structure lines" in each observed

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[24] Jauch, Goldhaber, and Gamow, private communications. I am grateful to them for their interest and discussion about these difficulties.

[25] G. H. Hardy and S. Ramanujan, Proc. Lond. Math. Soc. (2) **42**, 75 (1918).

group. The criterion in applying this equation to nuclear energy levels is that each energy of excitation may be regarded as to represent combinations of a number of superimposed neutron- and proton-levels in the nucleus. It has been used by Bohr and Kalckar[26] to calculate the density of nuclear energy levels for high excitation and has been shown to be satisfactory in explaining the experimental results of slow neutron capture. This formula is, of course, an asymptotic one, which holds better only for larger values of n. A much smaller basic level should be taken, in order to satisfy the above condition and hence to increase the calculated statistical weights so as to be more compatible with the observed intensities. However, the assumption of such a small basic level is subject to experimental verification. Unfortunately, it is not possible at present to measure the intensities of these "hyperfine lines" of alpha-rays even if they would exist, for the straggling of the alpha-particles through the finite thickness of the radioactive source can easily cause an energy spread of as much as 0.05 Mev or even more. It would not be surprising if one or more cases similar to that of Po could be established in the near future.

Another possible explanation of these short-range alpha-particles, as also suggested by Dr. M. Goldhaber,[24] is the possible alpha-branching of RaD or RaE which may be present in the Po sources as impurities. However, the following experiment does not seem to support this explanation:

The relative beta-activities of two different Po sources, which were also used for the work on the short-range alpha-particles, have been determined. These beta-activities are presumably due to the impurities of RaD and RaE. After subtracting the background (about 15 per minute $\sim$5 percent of the total counts) obtained when the sources were covered by a copper plate 2 mm thick, we have obtained the ratio:

$$(I_1/I_2)_{\mathrm{beta}} = 1.4 \text{ approx.} \tag{7}$$

The ratio of the main alpha-activities of the two sources (after being reduced to that actually used for the exposures) is about

$$(I_1/I_2)_{\mathrm{alpha}} = 0.75. \tag{8}$$

Since the intensities of any one of the weak groups obtained from the two Po sources are about in the same ratio as the main alpha-activities of the two sources, i.e., about 0.75, it does not seem that these weak groups of the alpha-particles are related with the beta-particles, or more specifically, with the amounts of RaD and RaE present in the Po sources. If they were caused by alpha-branching of RaD or RaE, the intensities of any one group from the two sources should be expected to have the ratio of the beta-activities, 1.4. One would come to the same conclusion with the following consideration: Counting all these weak groups together, their total intensity is about 1 in 1000 of the main Po alpha-particles. Now even if we assume RaD and RaE impurities in the Po sources as much as 10 percent (in terms of radioactivity) of the Po alpha-activity, we can only lower the branching ratio to 1 percent. Such a high branching ratio should have been detected before. Besides, since the lifetime of RaD (RaE in equilibrium) is about 40 times longer than that of Po, 10 percent "activity-impurity" would mean that the actual amount of RaD present by weight in the Po source should be about 4 times that of Po. This is very unlikely. In fact from the beta- and alpha-activities it has been roughly estimated that the "beta-activity impurity" in the Po source cannot be greater than 1 percent.

The idea of constructing an alpha-ray spectrograph by using the cyclotron magnet was initiated by Dr. S. Rosenblum, who worked in this Laboratory for some months before I joined him and who left here in the spring of 1944 for war work. Therefore, I am much indebted to him for the design of the Lucite chamber and for valuable information. I am also very grateful to Professor R. Ladenburg for his continued interest and support throughout the progress of the work. I also wish to express my thanks to the former cyclotron group of Princeton for putting some of their apparatus at my disposal, to Dr. M. Blau for preparing some of the sources, to Mr. T. Coor for helping in some of the experiments, to my wife, C. S. Wang Chang, for her discussion and help in presenting this paper, and to Dr. E. C. Campbell for reading the manuscript. Thanks are also due Mr. C. L. Brecht for the machine work in construction of the deflection chamber.

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[26] N. Bohr and Kalckar, Kgl. Danske Acad. Bind **14** (1936–1937).