of the points is not serious, since the dispersion of the method is so high that the greatest spread corresponds to less than ± 0.01 cm in range. The chief uncertainty is in the value of L used. The results can be said to give an average value of the slope of the range-energy curve in this region of 200 kv per mm range to within 3 percent. This result is independent of the assumption made by Holloway and Livingston (who obtained the range-energy curve in this region by integrating their specific ionization curve) that the ratio between energy loss by ionization and by excitation is constant. Our result, then, is an indication of the validity of this assumption for this region.

The author is greatly indebted to Professor S. K. Allison for his very helpful supervision of this research. He wishes to thank also Dr. L. S. Skaggs and Dr. N. M. Smith, Jr., for their help in performing the experiments.

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The Velocity Spectrum of α-Particles

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A 60° magnetic α-particle spectrograph has been constructed and used on a number of natural α-particle emitters, with photographic plates to detect the particles. The energy of the main group of protoactinium α-particles was found to be 5.053 ± 0.007 Mev. With the thinnest sources of Po, ThC, and ThC′ α-particles, as many as 10 percent of the particles were found to have energies 5 percent or more below the energy of the maximum of any one group.

1. INTRODUCTION

IT is desirable to determine the energy set free in nuclear transformations with the greatest possible precision. This can frequently be done by finding the energies of the charged particles produced in the transformations. The most satisfactory method of measuring the energy of these particles is by their deflection in electric or magnetic fields. The difficulties involved in producing large electric fields make their use less suitable than magnetic fields for the deflection of the heavy particles of mass 1 or more and of energy greater than 2 Mev. Focusing magnetic spectrographs, for measuring the energies of the natural α-particles, have been built by Rosenblum[1] and Rutherford, Wynn-Williams, Bowden and Lewis,[2] using the focusing properties of 180° deflection to increase intensities. Rosenblum, working with the large electromagnet of the Académie des Sciences at Bellvue, detected the α-particles by the blackening they produced on photographic plates. His spectrograph had some disadvantages. The magnet could not be moved, hence it could not be used on reactions produced by artificially accelerated high energy particles. The method also required very strong sources.

Rutherford and his group used an annular electromagnet and detected the particles in an ionization chamber connected to an amplifier and counter. Rays of different velocities were brought into the chamber by varying the magnetic field. The type of magnet used was limited to 180° deflections, this required the source and detector to be in the magnetic field. In addition the sensitivity of the detector was limited by the background counting rate produced by contamination and cosmic rays. These two limitations restricted the usefulness of the instrument mainly to α-particles from strong natural radioactive sources. The energies of all the α-particles from the natural radioactive elements with disintegration rates equal to or greater than that of radium, have been measured by these two instruments.

In this investigation a spectrograph was used which deflected the particles through 60° and which has the source and detector about 40 cm

[1] S. Rosenblum, J. de phys. et rad. [7] **1**, 438 (1930).
[2] Rutherford, Wynn-Williams, Bowden and Lewis, Proc. Roy. Soc. **A139**, 617 (1933).

from the magnetic field. This follows a suggestion of Herzog[3] that the energies of α-particles could be measured conveniently by the use of such deflections. The α-particles are detected in this apparatus by means of a photographic plate in which the tracks made by the individual particles are found by microscopic examination. This method records every particle and has practically no uncertainty due to background. There is also the advantage that exposures of indefinite length can be taken, permitting the use of very weak sources.

2. Description of the Apparatus

The two core pieces of the magnet, on which the coils are wound, are 37 sq. in. in cross-sectional area and 9 in. high. The yoke is a hollow iron rectangle made of four pieces, $2\frac{1}{2}$ in.$\times$10 in. in cross section, providing a return path for the flux on both sides of the core and windings. The core pieces are mounted inside this rectangle one attached to the top piece and the other to the bottom. The pole pieces and the assembly which holds them in alignment, fit between the core pieces and are easily inserted and removed. The iron parts are all made from Armco Ingot forgings, chosen for their high saturation flux density.

The two pole pieces are trapezoids at the back surfaces ($8\frac{3}{8}$ in. and $12\frac{19}{32}$ in.$\times$3 in.) which fit against the core, and taper down to curving pole faces $1\frac{3}{16}$ in. wide, as indicated in Fig. 1. They are $2\frac{1}{8}$ in. high and tapered at an inclination of 45° to the pole face. Four columns set in holes in the pole pieces as shown in Fig. 1 keep them in alignment. The columns are steel below the surface of the pole pieces and brass above. They were pressed into their holes on the sloping sides of these pieces and the whole face side of each piece, including the tops of the columns, was ground off to the same level. The two pole pieces are clamped together by means of brass rods, threaded at both ends, running through the columns and held by steel nuts in holes countersunk in the back surfaces of these pole pieces.

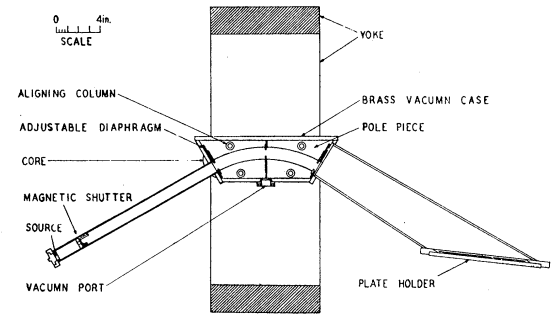

FIG. 1. A horizontal cross section through the spectrograph, taken at the level of the middle of the gap between the poles. The vacuum line and the magnet windings (on the core) are omitted.

[3] R. Herzog, Zeits. f. Physik 89, 447 (1934).

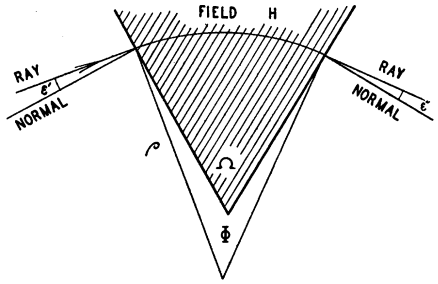

FIG. 2. The path of a charged particle through a magnetic field with the boundaries shown. The direction of the field is perpendicular to the plane of the paper.

The pole pieces are separated from each other by brass washers, $\frac{1}{8}$ in. thick, between their columns. This insures the pole faces being parallel and separated by a constant distance.

The windings consist of 1000 turns of No. 12 wire on each core piece, cooled by copper sheets between every other layer of the windings. This arrangement carries a current of 2 amp. with little heating after an hour's operation. This current was sufficient for the α-particles studied. A current as large as 8 amp. can be safely carried if a desk fan is turned on the coils.

The whole instrument weighs about 1200 pounds and is mounted on a truck so that it may be moved easily.

The magnet current was drawn from a 48-volt battery of lead cells. It was measured by a potentiometer and held constant, to within 1 part in 3000, by varying a rheostat in series with the magnet.

The source and plateholder were designed according to the equations for the focusing of ion beams given by Herzog.[3] The relation between the position of the source and the position of the focus for an ion beam with the central ray incident normally on, and emerging normally from the boundaries of a homogeneous magnetic,

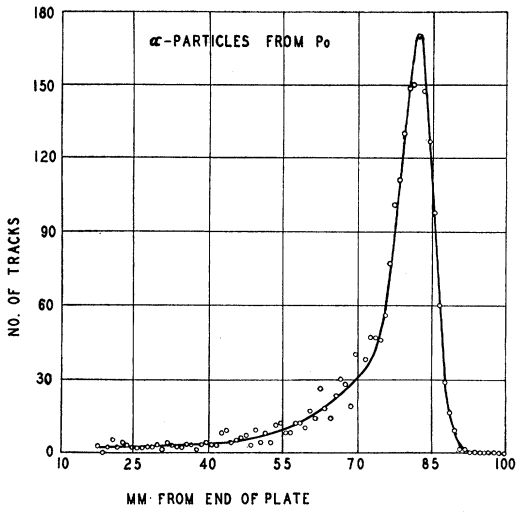

FIG. 3. The number of α-particles from the thicker Po source reaching 0.64 mm² of the plate, plotted against the distance from the low energy end of the plate. In the region of the maximum 1 cm change in position represents 1.5 percent change in energy. The exposure time was 1 hour.

field is

$$(l'-g')(l''-g'')=f^2, \tag{1}$$

where l' is the distance of the source, or object, from the edge of the field, l'' is the distance of the focus, or image, from the other edge, g' is the distance from the edge of the field to the focal point on the source side (i.e., the point where a parallel bundle of rays, incident normally to the edge of the field on the image side, should focus), and g'' is the corresponding distance on the image side. In this case $g'=g''=14.03$ cm and f is the focal length, the distance from the principal plane to the focal point, which for 60° deflection is $2g'$. For the case $l'=l''$, (1) gives $l'=42.09$ cm.

For a particle going through the field in a path whose radius of curvature ρ differs from that of the particles following the middle of the pole faces, the angular deflection and the focal position are different. For this more general case we have from Herzog's paper

$$g'=\rho\frac{\cos\epsilon'\cos(\Phi-\epsilon'')}{\sin\Omega}, \tag{2}$$

$$g''=\rho\frac{\cos\epsilon''\cos(\Phi-\epsilon')}{\sin\Omega}, \tag{3}$$

$$f=\rho\frac{\cos\epsilon'\cos\epsilon''}{\sin\Omega}. \tag{4}$$

Equation (1) holds also. The symbols have the meanings defined above or shown in Fig. 2.

In the instrument under discussion, with $\epsilon'=0$, the maximum radius of curvature of any path which will pass through the diaphragm at the exit from the field, when it is open 1 in., is 25.8 cm and the minimum is 22.9 cm. From this, and Eqs. (1)–(4), we have $l''=36.0$ cm and 51.9 cm in the two cases. By finding the direction of the ray by geometrical construction on a drawing of the pole face, and laying off l'' along it, one obtains the position of the focus for these extreme rays. The plateholder is designed so that the plate passes through the positions of the foci of the rays of maximum, middle and minimum radii.

The source mounting is 42.1 cm from the entrance to the magnetic field so that l' will equal l'' for the rays entering and leaving the field normally. The plateholder is in the position indicated in Fig. 1. It is set at an angle of 21° from the normal to the edge of the field. At this angle of incidence the α-particles leave tracks, each one of which is observed as a row of developed grains on the developed plate but which has sufficient depth to be distinguished from a surface scratch. Because a vacuum of 10^{-3} mm of mercury is sufficient, it is convenient to break the vacuum every time the plate is changed and no special equipment is used for inserting the plates.

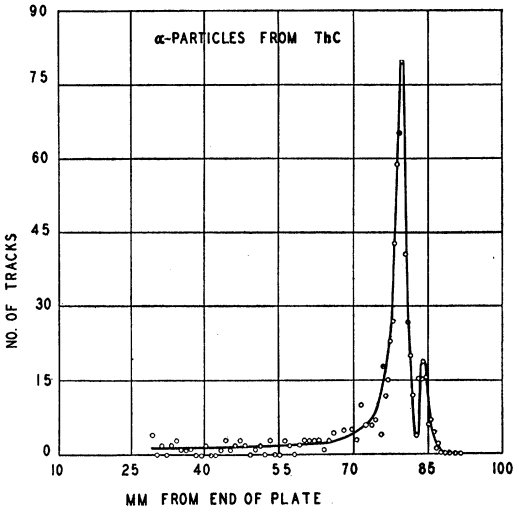

FIG. 4. The number of α-particles from a ThC source on 1 mm² of the plate, plotted against the distance from the low energy end of the plate.

A vacuum good enough to remove the danger of change of charge of the particles during passage through the magnetic field is all that is needed, for scattering is unimportant with such energetic particles. At a pressure of 10^{-3} mm the mean free path for the gain of an electron is 10^5 cm, and for loss of an electron by He^+ particles, which are present in the radiation from even thin natural radioactive sources to the extent of one percent, the mean free path is 10^4 cm.[4] Either process thus is quite unlikely in the 26 cm of path in the field.

The photographic detection of the particles follows a technique recommended by Wilkins.[5] The plates used were Eastman α-particle plates 1 in.$\times$8 in., which were developed 4 min. 30 sec. at 18°C in Eastman x-ray developer. The plates were then cut into three pieces after the separation of fiducial marks on each piece was measured, and examined in a microscope using 450$\times$magnification and bright field illumination. The distribution of α-particles over the plate is found by counting the number of α-particle tracks in a definite vertical range as the plate is moved along horizontally.

3. Preliminary Observations

The behavior of the spectrograph was first studied with α-particles from polonium and thorium C. The distribution of α-particle tracks after an exposure of one hour to a polonium source, is shown in Fig. 3. The source was a silver wire, 0.3 mm in diameter, which had been dipped in a radium D solution in which polonium was growing. This source emitted 6.7×10^5 α-particles per sec. in all directions. The graph shows the horizontal position on the plate as abscissa and the number of tracks observed in a strip 2 mm high and 0.32 mm wide, at that position as ordinate. Figure 4 shows the number on a strip 3 mm high from a thorium C source emitting approximately 7×10^4 particles per sec. in all directions. The exposure time was two hours. The ThC source was prepared by collecting the active deposit of thoron produced by some radiothorium, on a charged platinum wire 0.2 mm in diameter.

In Fig. 4, the two lines photographed by Rosenblum[1] and referred to as α_0 and α_1, are seen to be separated. The two very faint lines recorded in his photographs, α_2 and α_3, do not show up, probably because of insufficient exposure. Many tracks of particles with velocities less than those of the two main groups appear. Similar tracks of low velocity particles from Po are seen in Fig. 3. These would not have been expected from the clear backgrounds shown in Rosenblum's photographs and their origin will be discussed in Section 6.

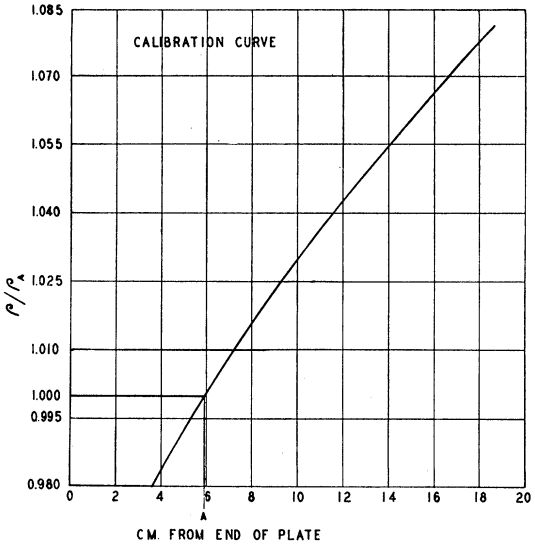

FIG. 5. The ratio of the radius of curvature in the magnetic field, corresponding to a point s on the plate, to the radius of curvature of the particles arriving at A, plotted against the distance from the low energy end of the plate, s. This ratio is equal to the ratio of the momenta of the particles arriving at s to those arriving at A. A is arbitrarily chosen as the point at which the Po α-particles happened to fall on a plate used in drawing the curve.

4. Calibration of the Spectrograph

The strength of the magnetic field was measured by a method of Ellis and Skinner,[6] which was modified slightly. The charge produced by removing a small search coil from the field was balanced against that produced in a search coil in a long solenoid when the current in the solenoid is interrupted. A ballistic galvanometer was used for the balance. The results obtained by this method were checked by measurements of the $H\rho$ of α-particles of known energy. The results from these two methods of the measure-

[4] E. Rutherford, Phil. Mag. **47**, 277 (1924).
[5] T. R. Wilkins, J. App. Phys. **11**, 35 (1940).
[6] C. D. Ellis and H. W. B. Skinner, Proc. Roy. Soc. **A105**, 60 (1924).

ments of H agree within the probable error, which was about two percent, because of stray fields, lack of precision in measuring the angle of deflection and variation in the magnetic field corresponding to one setting of the magnet current. It was found that a current of 1.5 amp. produced a field of 11,900 oersteds between the pole faces, 3 amp. a field of 21,600 oersteds, and 6 amp. one of 25,000 oersteds, at which current the iron was nearly saturated. With a field of 25,000 oersteds, α-particles of energy as large as 19.5 Mev could be brought on the plate.

The dispersion, defined as the separation of particles differing one percent in momentum, was obtained by measuring the distribution of particles from several natural radioactive elements, Po, ThC, ThC′, and RaC′. A wire coated with Po and one coated with the thorium-active deposit were mounted together in the source position and the separation of the α-particle groups measured. The ThC α-particles ($E=6.086$ Mev, $H\rho=3.532\times10^5$) were 103.5 mm from the Po particles ($E=5.303$ Mev,[2] $H\rho=3.302\times10^5$). Hence the average dispersion is 15.3 mm for a one-percent change in momentum.

To each point on the plate, distant S from one end, corresponds a definite radius of curvature (ρ) in the magnetic field. Thus if we plot a curve of the position, S, of tracks of several groups of α-particles of known energy, for some one value, H, of the field, against $K\rho$ for these particles, where K is an arbitrary constant, we may read off the curve, for any two points on the plate, the ratio of the ρ's corresponding to the α-particles that caused the tracks appearing at those two points. Since the momentum of a particle is proportional to ρ, this ratio is also the ratio of the momentum of the two α-particle groups. Such a curve is given in Fig. 5. The ordinate is the ratio $\rho/\rho_A=K\rho$ and the abscissa, the distance S along the plate, A is arbitrarily chosen as the point at which the Po α-particles happened to fall on one exposure.

Two points on the curve in Fig. 5 are given by the results with ThC and Po mentioned above, and the slopes at various points, which are inversely proportional to the dispersions at these points, are given by the separation of the two main groups of the ThC α-particles. The slope is found to be 1.5 times as large at the position of

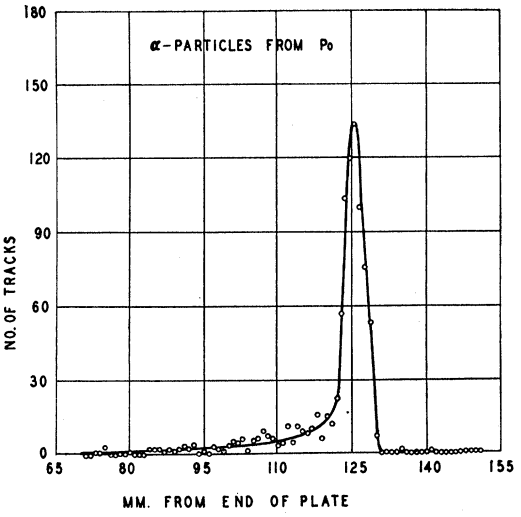

FIG. 6. The number of α-particle tracks from the thinner Po source on 0.64 mm² of the plate, plotted against the distance from the low energy end of the plate. Exposure time was 4 hours.

the Po α-particle tracks as at the position of the most intense ThC α-particle group on the plate on which both are recorded. From these data, the calibration curve which is not far from a straight line, can be drawn as shown in Fig. 5.

In Herzog's theory,[3] the dispersion, D, is given by

$$D=\frac{\rho}{100}\left(1+\frac{f}{l'-g'}\right)$$

($=2\rho/100$ in our case). However this is dispersion in a direction perpendicular to the beam; to get the dispersion along the plate, it is necessary to divide by the sine of the angle between the plate and the beam, 21°. This gives $D=13.6$ mm for one percent change in momentum at the position on the plate where the beam leaving the field normally strikes, that is 8 cm from the left-hand, or low energy end of the plate. This is very near the measured value of 13.7 mm.

In using the calibration curve it is assumed that the dispersion is independent of the absolute value of the field. This is true if the stray field does not change too much in proportion to the field proper as the latter is changed. In this spectrograph with a gap of $\frac{1}{8}$ in. between the pole faces and operating well below the point of saturation of the iron, the change in dispersion due to stray field is negligible. This was checked by the results obtained with ThC′ and RaC′

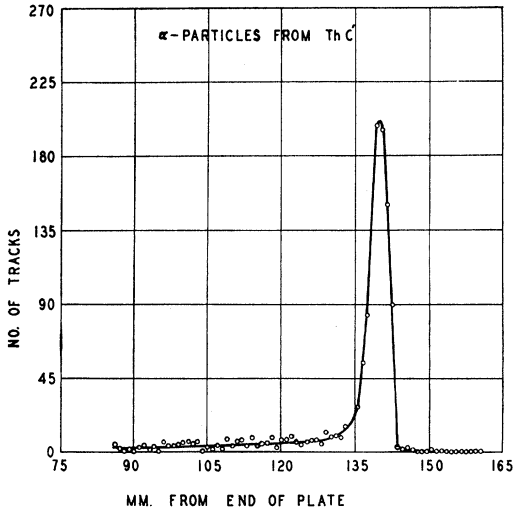

FIG. 7. The number of α-particle tracks from a ThC' source on 0.64 mm² of the plate plotted against the distance from the low energy end of the plate. Exposure time was 4 hours.

α-particle sources together in the spectrograph. The ThC' α-particles ($E=8.778$ Mev²) reached the plate 15.05 cm from the low energy end and the RaC' α-particles ($E=7.683$ Mev²) 4.96 cm from that end. These values fit the calibration curve.

The resolution obtained so far, is at best barely equal to that theoretically expected with the width of sources used. The width of the lines is in theory[7] equal to $\rho\beta^2 \sin \frac{1}{2}\Phi$ where β is the angle between the normal from the source to the boundary of the field and the path deviating the most from that, which still passes through the diaphragms in the field. The width comes out to be 0.2 mm. This width could not be attained because of the width of the sources, which, being over 0.3 mm, gives images over 1 mm wide. Some lines were obtained whose width at $\frac{1}{2}$ of their maximum was 1 mm. These give a resolution (equal to the dispersion×100/line width) of 1300, but most lines were much broader, probably because of absorption of energy in the source for some particles, and unsteadiness of the magnetic field, which, on the long exposures taken with the thinnest sources, varied by more than 1 part in 1000. For the immediate purpose of calibration and for many measurements this broadening of the lines is not a serious disadvantage however.

[7] W. E. Stephens, Phys. Rev. **45**, 513 (1934).

The fraction of the total of emitted α-particles which gets through this spectrograph at the maximum usable field width of 2 cm, is 1 out of 70,000. This compares with 1 out of 20,000 detected in Rutherford's magnet[2] with a diaphragm 3 cm×1 cm. The theoretical and attained resolutions of Rutherford's magnet were slightly larger than those of this magnet.

5. Energy of the Protoactinium α-Particles

Because of the method of detection employed, this instrument can be used to measure the α-particles from quite weak sources. One such source whose α-particles were measured was a preparation of protoactinium, kindly lent by Dr. A. V. Grosse. It contained seven percent Pa_2O_5 mixed with zirconium and hafnium oxides. A source which emitted 1200 particles per sec. was prepared by depositing this material on a platinum strip 1 mm×5 mm in area. The value for the high energy limit of the α-particles from Pa obtained by comparison with the α-particles from Po, put in the spectrograph at the same time, was 5.053 ± 0.007 Mev. This is to be compared with a value 5.063 Mev, found by using the Pa α-particle range, 3.673 cm, and the Po α-particle range, 3.925 cm, in air at 15 C and 760 mm pressure, given by Geiger,[8] the slope of the Cornell University range-energy curve[9] in this region, and the value 5.303 Mev for the energy of the Po α-particles[2] used with the data from the spectrograph.

The thickness of material necessary to obtain a source of the strength used, caused such a broadening of the line by retardation of the particles in the source that nothing could be told of any possible fine structure. This illustrates an inherent limitation of the apparatus when used on weak or impure radioactive materials.

6. Low Energy α-Particles

In addition to the widening of the peak of the α-particle lines observed, and ascribed in part to loss of energy in escaping from the source, many α-particles of much lower energies are observed (cf. Fig. 4). These have been observed before by

[8] H. Geiger, Zeits. f. Physik **8**, 45 (1921).
[9] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).

I. Curie[10] and J. Schintlmeister,[11] and are noticeable on curves published by Rutherford.[2] The results in earlier work were all obtained with sources 100 or more times as thick as the comparable sources used in this work and were generally ascribed to absorption in the sources. The results obtained with this spectrograph are shown in Figs. 3, 6 and 7. The density of deposit on the source producing the spectrum shown in Fig. 3, was 9.93×10^{-8} g per cm^2, equivalent in stopping power to 5.3×10^{-4} mm of air. Figure 6 shows the distribution of α-particles from a Po α-particle source of density 5.29×10^{-9} g per cm^2 or 2.8×10^{-5} mm air equivalent, deposited on a flat strip of silver 1 mm$\times$5 mm$\times$0.1 mm. Figure 7 shows the distribution of particles from a ThC′ α-particle source of 0.5×10^{-11} g per cm^2, deposited on a similar platinum strip.

The Po sources were prepared by precipitation on silver from a RaD solution whose only contamination was believed to be inactive lead. The ThC′ was prepared as was the ThC source described previously (Section 3). The sources all appeared clean when first prepared and used but darkened later, presumably because of oxidation resulting from ionization by radiations from the radioactive materials.

In the case of the thinner Po α-particle source 2.6 percent of the particles were retarded by an amount equivalent to 200 to 300 kev, for the other Po α-particle source, 4.3 percent, and for the ThC′ α-particles, 4.0 percent. To retard the particles by an amount equivalent to 250 kev a path in air approximately 1.8 mm long is required. This means a layer of air 5×10^5 atoms deep or $\frac{1}{10}$ as many atoms of the radio-elements if the ordinary free paths for the α-particles are assumed. Assuming a very favorable case for the absorption in the radioactive material, that it is all concentrated in a small area and forms a cone with base diameter equal to the altitude, we find that such a cone, high enough to account for the retardation observed, would contain 3 times as much material as there is Po on the stronger Po source, 50 times the amount on the other Po source and 5000 times the amount of thorium-active deposit present on the ThC′ α-particle source.

[10] I. Curie, Ann. de physique **3**, 299 (1925).
[11] J. Schintlmeister, Sitz. d. Akad. Wien, Abt. 2a **146**, 389 (1937).

The possibility that the active material might have deposited in clumps, was tested as follows. For a short time, the sources were placed in contact with a photographic plate which was protected from infection by the radioactive material by a thin sheet of collodion. The plate was then developed and examined under a microscope. The α-particle tracks were found to be quite uniformly distributed in the case of the Po; no centers were observed. In the case of the ThC many distinct clusters were seen while more than $\frac{3}{4}$ of the area touched showed very few tracks. However the total amount present here is so small that these clusters, by the argument of the preceding paragraph, cannot account for the retardation observed.

Because the retardation does not depend much on the average density of deposit, an increase of 20 times in the density of Po increased the fraction retarded only 60 percent, and because there are hardly enough atoms present in the most favorable case to account for the retardation observed, it is believed that absorption in the source cannot be held responsible for these low energy particles.

Scattering, on the pole faces, or in air, is excluded as a source of these particles, as it should also cause an appreciable number to appear on the high energy side of the peak, by the alteration in direction it causes, and this region is remarkably free of tracks. However, as a precaution against scattering the pole faces had been coated with Aquadag, and diaphragms inserted, which collimated the beam vertically as well as horizontally, so that the number of particles reaching the pole faces was reduced.

If absorption in the source is also excluded as an explanation of these low energy particles, these experiments then show that there is present among the α-particles of homogeneous velocity, a considerable number, leaving the radioactive atoms, or at most small groups of such atoms, with a continuous distribution of energies going down as low as ten percent below the energy of the high energy limit, or lower. This number may include ten percent of the total number of particles in energy ranges five percent below the maximum.

In conclusion the author wishes to express his gratitude for the advice and guidance of Dr. A. J. Dempster, who suggested this problem.