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An Investigation of the Ranges of the Long Range α-Particles from Thorium C and Radium C, using an Expansion Chamber.

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[Plates 11, 12.]

Introduction.

The existence of the so-called long range α-particles was first pointed out by Rutherford and Wood,* who found, when observing scintillations caused by α-particles from thorium active deposit, that particles were present of ranges estimated as 10·2 and 11·3 cm. in air† at 760 mm. and 15° C. Later work, both by Rutherford‡ and by Wood§ in 1921, showed that these long range particles were α-particles coming from the source, and in view of the possible theoretical importance of these results, Bates and Rogers‖ in 1923–24 made an intensive search for long range particles of all ranges. From thorium C they found in all three groups, one at 11·5 cm. and two of greater range at 15·0 and 18·4 cm. respectively, but their methods were open to serious objection, and later experiments by Yamada¶ yielded certain evidence of one group only, that at 11·5 cm. Up to this point only scintillation methods had been employed, but in 1926 Meitner and Freitag** published an account of some

* 'Phil. Mag.,' vol. 31, p. 379 (1916).
† Air under these conditions is referred to throughout this paper as standard air.
‡ 'Phil. Mag.,' vol. 41, p. 570 (1921).
§ 'Phil. Mag.,' vol. 41, p. 575 (1921).
‖ 'Roy. Soc. Proc.,' A, vol. 105, p. 97 (1924).
¶ 'J. Physique,' vol. 6, p. 380 (1925).
** 'Z. Physik,' vol. 37, p. 481 (1926).

experiments on these long range particles in which an expansion chamber was used. They detected a group of particles at 11·5 cm. in standard air and also another group at 9·5 cm. Philipp,* using the scintillation method, was also able to detect the 9·5 cm. particles and obtained results agreeing closely in all respects with those of Meitner and Freitag.

The long range particles from radium active deposit were first observed by Rutherford† in 1919 and were subsequently studied by Bates and Rogers (*loc. cit.*), who in this case also found three groups of long range particles, with ranges 9·3, 11·2 and 13·3 cm. in air. In 1924, also, Rutherford and Chadwick‡ gave an account of a very thorough investigation of the long range particles from radium active deposit. They showed that the particles arose from radium C or its products and that those of range 9·3 cm. were certainly α-particles. They also found a group of range 11·2 cm. containing approximately one-sixth as many particles as were contained in the 9·3 cm. group.

A little later Yamada (*loc. cit.*) reported the results of his experiments on the long range α-particles from radium C but in this case he detected only particles of 9·3 cm. range.

More recently Philipp§ investigated these particles using an expansion chamber but only twenty-six long range tracks were photographed. Of these four had ranges between 9·5 and 12 cm.

Survey of Methods of Range Measurement as Applied to Long Range Particles.

Though there are some obvious objections to the use of the scintillation method for the above purpose, it is the method which has been most frequently employed in determining the ranges of the long range particles. The method theoretically yields a curve giving number of α-particles with range greater than R against R, but actually before such a curve can be drawn a smoothing process is necessary in order to eliminate irregularities due to probability fluctuations in the emission of the particles; and even after this has been done the curve obtained does not give ranges as accurately as its derivative curve (number of particles with ranges between R and $R + \Delta R$ against R). In addition, counting becomes very difficult when observing the low velocity particles at the end of the range, and so this number distance curve

* 'Z. Physik,' vol. 37, p. 518 (1926).
† 'Phil. Mag.,' vol. 37, p. 571 (1919).
‡ 'Phil. Mag.,' vol. 48, p. 509 (1924).
§ 'Naturwiss.,' vol. 14, p. 1203 (1926).

must be considerably distorted just where it is required to be most accurate. The custom has been to obtain from such a scintillation curve an extrapolated range, but, on examining the justification for this procedure, it is seen that even if the scintillation measurements were reliable, the range obtained would depend upon the straggling coefficient of the medium through which the particles had passed as well as upon the actual mean range of the particles.

On the other hand the expansion chamber can be made to give the actual range of each particle forming a track, and the evidence in connection with any given track is recorded permanently on a photographic plate. (The plate gives only a two-dimensional picture of tracks in three dimensions, but, as long as all the tracks are approximately in the plane on which the camera is focussed, this need involve no error.) Consequently from a series of photographs we can find the relationship between the range R and the number of particles with ranges between R and R + ΔR and from this relationship the range of any group of α-particles. If the range distribution is Gaussian the mean range will be the same as the most probable range, and it is this, rather than any extrapolated range, which has real meaning for a group of α-particles.

In cases where contamination occurs the expansion chamber has a distinct advantage over the scintillation method for in many cases with the expansion chamber tracks due to the presence of contamination can be recognised because they are formed by particles which obviously do not come from the source.

The main objections to the expansion chamber are that in the first place it is recording α-particles for no more than 1/5000th of the total life of the source and so many photographs and long periods of photographing are necessary before an accurate value of the range can be obtained, and in the second place there is a little difficulty in finding accurately the stopping power of the gas in the chamber at the moment of admission of the particles.*

Experimental Arrangement.

Within the last year considerable attention has been given to the ranges of the various groups of α-particles emitted by radioactive substances, for according to Rutherford's† recent theory certain α-particle ranges only are possible. The theory is fairly successful when applied to the ranges of known groups of

* For details of previous range measurements with an expansion chamber see Van der Merwe, 'Phil. Mag.,' vol. 45, p. 379 (1923); Curie, 'Ann. Physique,' vol. 3, p. 299 (1925); Curie and Mercier, 'J. Physique,' vol. 7, p. 289 (1926); Meitner and Freitag, *loc. cit.*; Laurence, 'Phil. Mag.,' vol. 5, p. 1027 (1928).

† 'Phil. Mag.,' vol. 4, p. 580 (1927).

α-particles and so there is some interest in testing it by examining how closely it predicts the ranges of the long range α-particle groups.

The experiments were therefore undertaken with a view to finding accurately the ranges of the α-particle groups which were supposed to exist rather than with the intention of looking for new groups of α-particles, for obviously it is only when dealing with groups which contain comparatively large numbers of α-particles that it is practicable to use the expansion chamber for range measurements.

Despite the conclusion of Meitner and Freitag as to the certainty with which α-particles can be distinguished from swift protons by the density of the tracks they produce, it was felt that only such experimental arrangements should be used as did not furnish an appreciable number of protons within the interval of range in which long range particles were expected. It is almost certain that it is impossible to prepare a source which does not emit a small number of "natural" protons. These particles, which are almost certainly secondary in origin and depend upon the method of preparation of the source, are mostly, perhaps entirely, of very long range, and so there is little lost if the experimental arrangement augments the number of protons of range greater than, say, 15 cm. What is required is an arrangement in which the main α-particle groups produce very few protons of apparent range between 7 cm. and 15 cm. for radium C′ and 8·6 cm. and 15 cm. for thorium C′.

Two entirely different arrangements were used, but before describing either of them some mention should be made of expansion chamber apparatus common to both.

The expansion chamber was a standard 16 cm. diameter chamber of the Wilson type in which the glass cylinder had a height of about 4 cm. The lighting was produced by discharging a battery of Leyden jars (0·03 mfd.) through a single quartz mercury lamp similar to that used by Wilson. The lamp was placed at the back of the chamber and by means of a cylindrical lens the light from it was concentrated in the region where tracks were produced by particles from a source in front of the chamber. Vertically above the chamber was a single camera with a lens of aperture f/4·5 and of 15 cm. focal length. The distance between the top of the chamber and the camera lens was about 50 cm. and so the magnification of the camera was approximately 0·4. All photographs were taken on plates and in order to save plates and to increase the speed of working, a plate was placed in the camera and left there until three photographs had been taken on it. This procedure spoils the photographs slightly but otherwise there is no objection to it.

The expansion chamber apparatus was semi-mechanical, a large number of operations being carried out in correct sequence simply by turning a handle. In all cases it was arranged that between each photograph and the next there was a clearing expansion, for without this good photographs were impossible.

With sources having a γ-ray activity equal to that of about 2 mgm. of radium, photographs could be taken at the rate of about 200 per hour, but with stronger sources than this the rate of photography had to be considerably reduced or the photographs became worthless.* For such strong sources the field across the chamber was about 120 volts per cm., but in general with weaker sources a field strength of 50 volts per cm. was quite sufficient to allow of good photography. By calculation from the observed temperature of the room and the pressure in the chamber when the gas had warmed to room temperature some time after an expansion, it was possible to find the density of the air in the chamber at the moment of track formation and hence the stopping power of the air in the chamber at this time. The formula for obtaining the stopping power in this way is derived below.

The same principles were involved in the measurement of the photographs in both arrangements and a formal treatment of the method used is given in what follows.

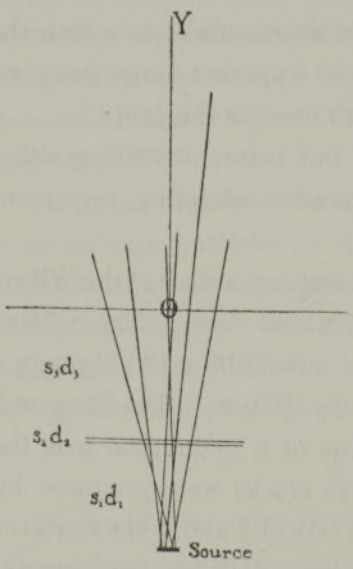


Fig. 1.

Suppose that the magnification of the camera is μ for points lying in the object plane of the lens and consider a hypothetical photograph showing one long range track and a few tracks belonging to a group of α-particles of known mean range. Suppose that the tracks in the chamber are all in one plane. Fig. 1 shows the positions of the source and the absorbing materials relative to the expansion chamber and also shows the tracks which are to be photographed and the co-ordinate system by which their lengths are to be found. The source is in a medium (air, oxygen or carbon dioxide) of stopping power (with respect to standard air) s_1 and is d_1 cm. away from a second medium (mica) of thickness d_2 and stopping power s_2. Suppose that a given track formed by a member of the group of α-particles of known mean range R_0 makes an angle θ with the axis OY and that its end point has ordinate y

* *Cf.* p. 677.

measured parallel to this axis. Suppose also that the distance between the reference point O and the nearer side of the mica is d_3 and that the stopping power of the gas in the chamber is s_3. Then the equivalent range in standard air of the particle considered is $[s_1d_1 + s_2d_2 + s_3d_3 + ys_3]\sec\theta$ cm. of standard air. If there are n such tracks belonging to the group of range R_0 we can find the mean range for these n tracks and this will be very close to R_0 the true mean range.

Therefore

$$nR_0 = \sum_n [s_1d_1 + s_2d_2 + s_3d_3 + ys_3] \sec\theta,$$

or

$$R_0 = [s_1d_1 + s_2d_2 + s_3d_3]\,\overline{\sec\theta} + s_3\,\overline{y\sec\theta}, \qquad (1)$$

where

$$\overline{\sec\theta} \equiv \frac{1}{n}\sum_n \sec\theta \quad \text{and} \quad \overline{y\sec\theta} \equiv \frac{1}{n}\sum_n y\sec\theta.$$

Therefore

$$[s_1d_1 + s_2d_2 + s_3d_3] = (R_0 - s_3\,\overline{y\sec\theta})/\overline{\sec\theta}. \qquad (2)$$

Suppose that the long range track makes an angle θ_1 with the y axis and that its end point has ordinate y_1.

Then, neglecting the very small change of stopping power with velocity of the particle, R, the range of the particle, is

$$[s_1d_1 + s_2d_2 + s_3d_3]\sec\theta_1 + s_3y_1\sec\theta_1$$

i.e.,

$$R = [R_0 - s_3\overline{y\sec\theta} + y_1s_3\,\overline{\sec\theta}]\sec\theta_1/\overline{\sec\theta},$$

y is the actual distance in the chamber, and so if η is the variable on the plate corresponding to y in the chamber, we have $\eta = y\mu$ and consequently in terms of distances on the plate

$$R = [R_0\mu - s_3\overline{\eta\sec\theta} + s_3\,\overline{\sec\theta}\,\eta_1]\sec\theta_1/\mu\,\overline{\sec\theta}.$$

In general, θ was so small that $\sec\theta$ was very insensitive to changes in θ and thus, if measurements of η and θ are made on the plates, and if R_0, s_3 and μ are known, R can be accurately determined. μ is found by photographing a scale in the chamber and s_3 calculated from the readings of a mercury manometer which may be connected to the chamber after the expansion has occurred and the gas in the chamber has attained room temperature again. A consideration of the magnitudes involved shows that any one determination of R should in the experiments described below be accurate to about 0·5 mm.

In actual practice we cannot regularly hope to obtain photographs of long range particles on plates containing only a few tracks of range R_0 as has been

assumed when considering the theory of the measurements. Consequently the photographs of the few particles of range R_0 have to be taken at one time and the photographs of the long range particles at another time. As the values of s_1 and s_3 and perhaps d_1 are not the same in the two cases, small corrections have to be made on account of these changes, but these corrections are so small that R can accurately be found provided that d_1 and d_3 are approximately known.

In the first arrangement the radioactive material was deposited on a small platinum plate 2·5 mm. long and 0·8 mm. broad. This source, S, (see fig. 2) was put outside the chamber in air and about 7 mm. in front of a mica window, W, 5·2 mm. in diameter. The mica used, chosen for its uniformity, had a stopping power of just over 2 cm. of standard air and closed a small hole drilled through the glass wall of the expansion chamber. Between the source and the mica window was a lead screen, L, with a hole in it, and arrangements were made so that at the correct time this screen could be driven downwards by means of a strong spring. In general, the screen was stopped again as soon as the hole in it was in such a position that the particles could enter the chamber, and a moment later the screen was allowed to fall further so that the particles were cut off again. Inside the chamber was a lead block, B, with a slot in it through which the α-particles passed, but the beam was limited not by this slot but by a horizontal slit 19 mm. long and 2·2 mm. high in a piece of mica attached to the face of the lead block. Fig. 2 shows a vertical section of the arrangement. A calculation, using the fact that the slit on the lead block was 2·3 cm. from the mica window, shows that even particles of 12 cm. range would never be as much as 6 mm. above or below the object plane of the camera, and while the photograph of such a track will not give a true measure of its length, yet with the actual arrangement used the measured range could not differ by more than 0·25 mm. from the true range. As the error may either be positive or negative it must have a negligible effect on the value of a mean range determined from a number of particles.

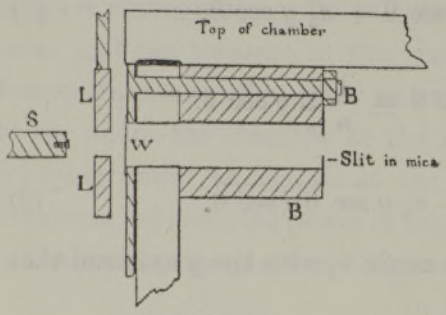


Fig. 2.

In this arrangement swift protons can originate in many ways, for, besides the natural H-particles from the source, secondary H-particles will be produced by disintegration of nitrogen atoms both inside and outside of the

chamber, by disintegration of aluminium atoms in the mica, and by the ejection of protons from the water vapour in the air inside and outside the chamber and from the water of constitution of the mica.

The angular spread of the beam (in the horizontal plane only) was about 40°, and so when considering the possibility of recognising protons produced inside the chamber it is reasonable to assume that most of those ejected at an angle greater than 30° with the direction of the impinging α-particle would be recognised as such. As far as disintegration protons are concerned little is known with certainty except that many of them have very long ranges. On investigating the number of secondary H-particles produced from various places, it appears that in all every 10^6 α-particles of 7 cm. range would produce by elastic collision about 1·5 protons of apparent range between 7 and 15 cm. making an angle of less than 30° with the direction of the incident α-particle, and in addition to these a number of protons from aluminium and nitrogen disintegrations about which little is known.

The arrangement just described was used only with radium C sources. Calibration was effected by waiting until the radium C source had so far decayed in situ that it produced only about 40 tracks per expansion. Four photographs were taken at this stage and these were subsequently measured up to give $\overline{\eta \sec \theta}$ and $\overline{\sec \theta}$.

In general, a spot on the top of the piston was taken as the zero from which to make the measurements, and even though this spot was somewhat out of focus it provided a perfectly reliable zero.

The slit which let in the α-particles had a mechanical oscillograph built into it and it was also possible to connect the piston of the expansion chamber to a second oscillograph mirror on the slit system. By taking oscillograms of an expansion with the timing of the slit the same as that used during a run, it was possible to find the mean position of the piston during the time of entry of the particles.

If p_0 is the pressure in the chamber before expansion, and $p_0 - p_1$ the pressure when the air has attained room temperature again after an expansion (the piston is still down), and if p_w is the pressure of water vapour at room temperature then the expansion ratio v_2/v_1 is $(p_0 - p_w)/(p_0 - p_1 - p_w)$.* If, however, the piston has completed only $1 - \varepsilon$ of its total travel when the particles enter the chamber then the actual expansion ratio used is $\{v_2 - \varepsilon (v_2 - v_1)\}/v_1$ or $(p_0 - p_w - \varepsilon p_1)/(p_0 - p_1 - p_w)$. Suppose that the

* v_1 is initial volume above piston and v_2 volume after expansion. The pressure relationship assumes that the air in the chamber has become saturated before $p_0 - p_1$ is measured.

air in the chamber is initially at a temperature t_0 and that t_{15} and p_{76} are the temperature and pressure of standard air, then the stopping power of the gas in the chamber relative to standard air before an expansion is

$$\frac{t_{15}}{t_0}\left[\frac{p_0 - p_w}{p_{76}} + \frac{p_w S}{p_{76}}\right],$$

where S is the stopping power (with respect to standard air) of water vapour at standard temperature and pressure. If we assume that during the expansion the mass of water vapour in the chamber is not sensibly altered, we obtain for the mean stopping power of the gas during the time of entry of the particles

$$\frac{p_0 - p_1 - p_w}{p_0 - p_w - \varepsilon p_1}[p_0 - p_w + S p_w]\,\frac{t_{15}}{t_0 p_{76}}. \qquad (3)$$

The value of ε was found to depend somewhat on the material on to which the piston fell. With thick rubber it had a value as high as 0·19, with thin rubber it was 0·11, and with leather instead of rubber it was 0·07. For accurate range measurements considerable error results in assuming $\varepsilon = 0$.

The second arrangement was designed to avoid the bulk of the disintegration protons which, as mentioned above, were produced in the first arrangement. For this purpose an entirely new slit system was built in order to make it possible to surround the radioactive source with a gas which did not undergo disintegration. The shutter arrangement was as shown in fig. 3.

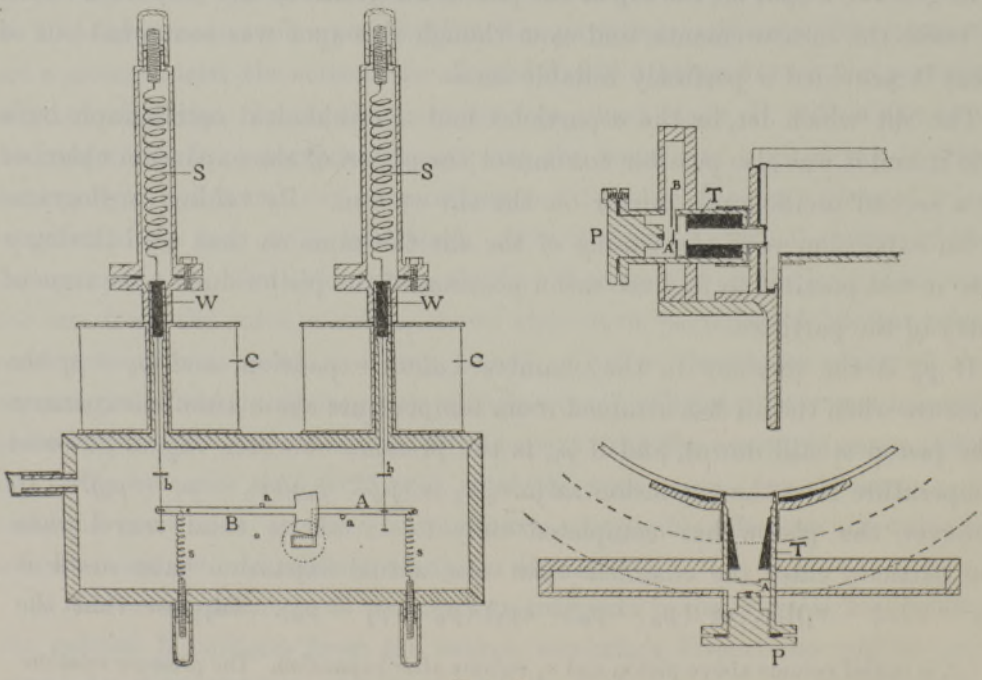


Fig. 3.

When the current flowed through the coils C the iron weights W were pulled downwards and the small springs *s* pulled the levers A and B against the stops *a*. When the currents in the coils were broken, the weights W were pulled upwards by the springs S. After these weights had moved 5 mm., the acceleration being about 10 g., stops on the wires *b* came in contact with the levers and the lever A was turned clockwise and the screen on the left-hand end of it uncovered a slit in a piece of brass, and the lever B was similarly turned clockwise and the screen on the right-hand end of it covered the slit again. The currents in the two coils were broken separately by a high speed switch and it was possible to alter the time between the opening of the two circuits, and so the time for which the slit was uncovered.

As the levers were made extremely light the slit was very quickly opened and closed. The radioactive source was placed immediately behind the screens (to the left in the vertical section of fig. 3) and as mentioned above immediately in front of them was the slit, made double in the form of a box. The end of the tube T (see fig. 3) was closed by a mica window and this whole tube was waxed into the front of the expansion chamber. The mica used was uniform in thickness and had a stopping power between 1 and 1·5 cm. of air. After an expansion the pressure in the box was much higher than that in the chamber, and, as it was necessary to exhaust the box in the process of filling it, the mica was supported between two metal grids to which it was waxed. The effective area of the mica window was 16 × 4 mm., the double grid containing sixteen holes 2 mm. square. Provided the mica was well waxed in, it easily stood a difference of pressure of half an atmosphere in either direction, and doubtless it would have stood more.

This box was at first filled with carbon dioxide at fairly high pressure but it was found that, with such high absorptions in the box, the tracks formed were not as good as those obtained when, say, oxygen at atmospheric pressure was used in the box. It appears that the tracks must be formed at a considerable distance from a strong source or else the strong γ-ray ionisation prevents good track formation.

The source used was a platinum button 2·4 mm. in diameter, which was screwed tightly into the brass plug P closing the back of the tube T. This button was then about 3·6 cm. from the mica window. With the exception of the two short runs when carbon dioxide was used, the box was filled with oxygen at a pressure of about 81 cm. of mercury.

Under these conditions a 12 cm. particle at the end of its track might be as far as 10 mm. from the object plane of the camera lens, but the arrangements

were such that particles of this range ended very near to the centre of the chamber and as the axis of the camera lens passed through this point the position of the end of the track on the plate was little influenced by the amount the track was above or below the object plane of the camera.

Two brass pins were fixed at opposite sides of the chamber so as to lie in the mean plane of the entering α-particles and so that the line joining their ends was perpendicular to the direction of the central ray of the α-particle beam. These pins appeared on all the photographs and provided a suitable base line from which to make the measurement of the plates.

In this arrangement the calibration was carried out with a weak source of thorium C, the measurements being made on the 8·6 cm. α-particles. Calibrations were necessary only as often as the mica was changed, for conditions were sufficiently similar from day to day to make only small corrections necessary for changes of density in the chamber and in the box containing oxygen.

The value of the correcting factor ε was assumed the same in this series of experiments as in that for which it was directly measured. The stopping power of the gas in the chamber obtained in this way using equation (3) and measured values of p_0, etc., was then compared with a value found directly from experiment. This value was obtained by taking two sets of photographs with the same source, the box being filled with air, first at atmospheric pressure π_0, and then at some smaller pressure π_1. Then, by equation (1), for the first series,

$$R_0 = (s_1d_1 + s_2d_2 + s_3d_3)\,\overline{\sec\theta_0} + s_3\overline{y_0\sec\theta_0} \qquad (4)$$

and, for the second series,

$$R_0 = \left(s_1d_1\frac{\pi_1}{\pi_0} + s_2d_2 + s_3d_3\right)\overline{\sec\theta_1} + s_3\overline{y_1\sec\theta_1}. \qquad (5)$$

Therefore

$$[s_1d_1 + s_2d_2 + s_3d_3]\,\overline{\sec\theta_0} + s_3\overline{y_0\sec\theta_0} = \left[s_1d_1\frac{\pi_1}{\pi_0} + s_2d_2 + s_3d_3\right]\overline{\sec\theta_1} + s_3\overline{y_1\sec\theta_1},$$

or

$$s_3[\overline{y_0\sec\theta_0} - \overline{y_1\sec\theta_1}] = s_1d_1\left[\frac{\pi_1}{\pi_0}\overline{\sec\theta_1} - \overline{\sec\theta_0}\right] + [s_2d_2 + s_3d_3][\overline{\sec\theta_1} - \overline{\sec\theta_0}]. \qquad (6)$$

In general, $\overline{\sec\theta_1}$ is very nearly equal to $\overline{\sec\theta_0}$ and hence only a very approximate value of $s_2d_2 + s_3d_3$ is required; and knowing s_1d_1 which was capable

of accurate measurement, such a value can be obtained from equation (4) if R_0 is known. Hence, from equation (6) above, we can find s_3 the actual mean density at the time of entry of the particles. The value obtained using thorium C′ α-particles agreed well with the value calculated from equation (3).

In this arrangement the number of swift protons produced is much smaller than before, and as the width of the beam was only 30° we need consider only the number produced within 20° of the direction of the incident α-particle. Oxygen in the box was equivalent in stopping power to nearly 4 cm. of standard air and so α-particles from radium C′ entering the mica window had a range of 3 cm. only. Thus very few, if any, disintegration protons would be produced from the mica, and consequently, besides natural H-particles from the source, we have only to consider those ejected from the water of constitution of the mica and from the water vapour in the chamber.

On the same basis of calculation as before we find that 10^6 α-particles produce somewhat fewer than 0·25 proton in passing through the piece of mica (1·5 cm. is assumed as its equivalent thickness) and in the chamber an additional 0·25 proton. The number of protons produced in the chamber does not include those ejected in the last 2 mm. (in standard air) of the path of the particle, because, although very many protons must arise here, their ranges are so short that they do not really affect the measurements. Thus the total number of non-disintegration protons likely to cause confusion has been decreased to about one-third of the number in the previous case and the number of disintegration protons must have been enormously reduced. Calculation shows that considerably more protons are produced when thorium C replaces radium C, but even here the number is only about 1 per 10^6 8·6 cm. α-particles and the 4·8 cm. α-particles produce no protons that are seen beyond the 8·6 cm. main beam. In addition, there are so many long range particles emitted from thorium C that the protons produced here are much less serious than in the case of radium C first considered.

In taking a run on radium C a source of radium B + C of about 10 mg. γ-ray activity was obtained by exposing the platinum button to radon. The source was washed in alcohol and then heated to 450° C. in an exhausted silica tube. Eighteen minutes after taking the source off it was placed in position in the box which was then exhausted to a pressure of about 5 mm. Oxygen was blown into the box, it was again exhausted and it was then filled with oxygen to the desired pressure and was left in communication with a bulb of oxygen of about 2 litres capacity. Throughout the run a careful watch was kept on the pressure in this box, on the temperature of the room and on the pressure

of the air in the chamber after an expansion. With a radium C source photography was continued for from 2 to $2\frac{1}{2}$ hours.

For measurements on the long range particles from thorium C, sources of thorium B + C were available and so, on account of the long period of thorium B, photography could be continued for 3 hours or more and in all ways runs on thorium B + C could be carried out with much less haste than was imperative in the case of radium B + C. Sources up to 4·3 mg. γ-ray activity were used in the case of thorium C. Separate platinum buttons and plugs were kept for the two types of source.

Results.

Thorium C.—Only the second arrangement was used and most of the data were obtained as the result of two runs using oxygen in the box. Previously, in runs in which carbon dioxide was used in the box, about 70 tracks were photographed and their ranges are included in the results. In all, about 1200 photographs were taken and on these were obtained the tracks of 563 long range particles. Thirteen of these particles passed outside the chamber and nine had ranges between 12·5 and 17 cm. Fig. 4 shows the ranges of all particles lying between 9·0 and 15·0 cm.

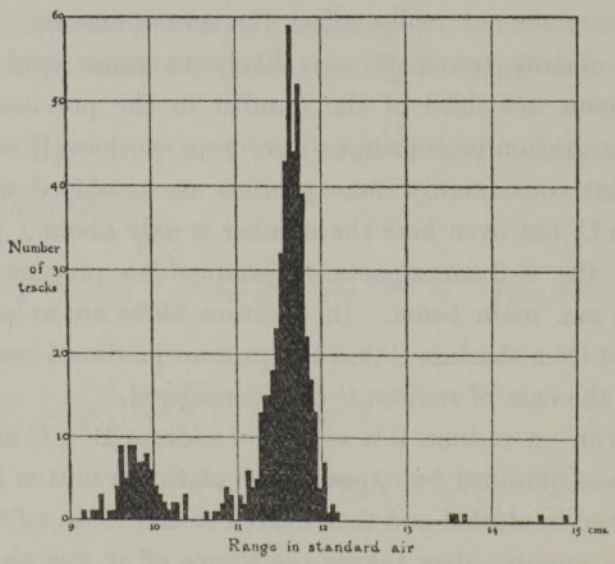


Fig. 4.

It will be seen that these tracks fall into two groups, and if the mean ranges are calculated for these groups they are found to be 9·82 and 11·62 cm. in standard air. As has already been pointed out the method of measurement yields the range of a given α-particle as so much in excess of the mean range

of a group of α-particles, and in giving the above values for the mean ranges of these groups from thorium C it is assumed that the mean range of the thorium C′ α-particles is 8·54 cm. The exact value of the mean range is doubtful, but as the difference between extrapolated ionisation ranges is not likely to be very different from that between mean ranges for corresponding groups the extrapolated ionisation ranges of these groups can be taken as 9·90 cm. and 11·70 cm.

The curves in fig. 5 show the distribution* of range of the 11·7 cm. particles photographed and also that of 161 particles of range 8·62 cm. used in the

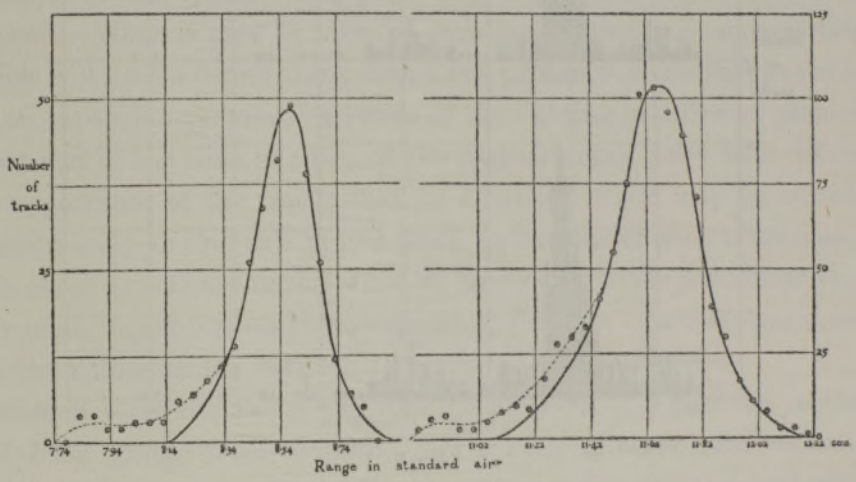


FIG. 5.

calibration for this series of photographs. One naturally expects that the straggling for the 11·7 cm. particles will be greater than that of the 8·6 cm. particles, both from the theory of straggling and also because of increased artificial straggling produced by the expansion chamber. The fact, however, that the curves are of the same shape and of not very different widths indicates that these 11·7 cm. particles are α-particles ejected from the source with almost constant velocity. The distribution of the 9·9 cm. particles is similar to those of the 8·6 and 11·7 cm. particles, but too few tracks are available to allow a straggling curve to be drawn.

Radium C.—Here both arrangements were used. The first arrangement yielded 188 long range tracks and of these 41 passed outside the chamber, the second yielded 273 long range tracks of which 15 only passed outside the chamber. The distribution of length of tracks in these two series is shown in

* In this case in order to smooth the curve a moving average was taken using each track twice.

fig. 6 (*a*) and (*b*) where once more the distances represent mean ranges in standard air on the assumption that the mean range for radium C′ α-particles

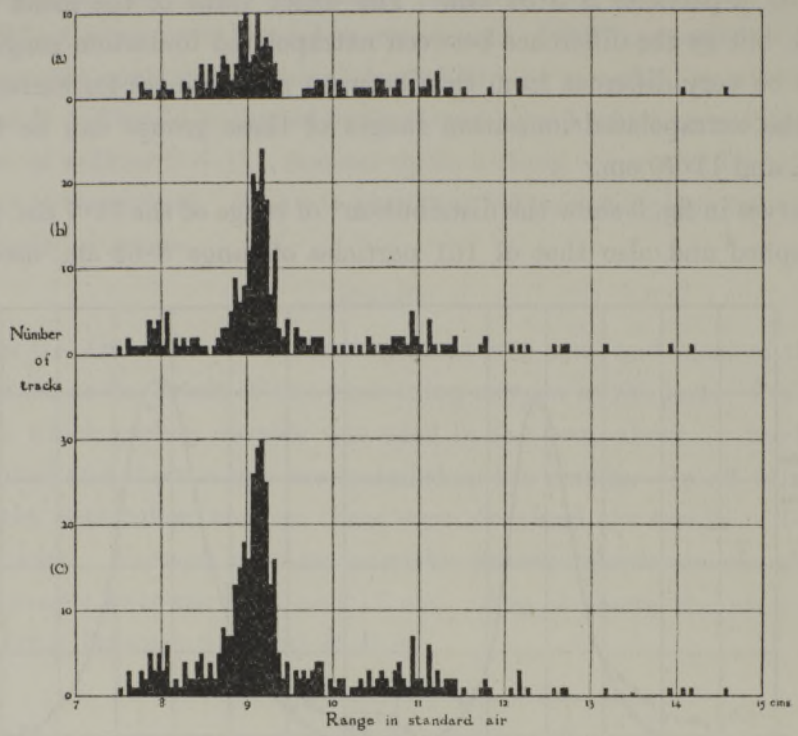


FIG. 6.

is 6·90 cm. (fig. 6 (*a*)) and that the mean range for thorium C′ α-particles is 8·54 cm. (fig. 6 (*b*)). A comparison of the two sets of results indicates that except for the difference in the numbers of long range tracks going right across the chamber* there is nothing essentially different between them and so they were combined to give fig. 6 (*c*).

From this figure one thing can be deduced with certainty and that is that there is a group of α-particles with a mean range just greater than 9 cm. If one calculates as a first approximation the mean range of all tracks between 8·1 and 10·0 cm. the value obtained is 9·08 cm., and if one then calculates the mean range of those tracks (241) having ranges between 8·6 and 9·5 cm. the value 9·08 cm. is again obtained, and, as the second calculation is likely to include all the tracks in this group, 9·08 may be taken as the mean range of the group and 9·16 cm. as the extrapolated ionisation range. Further consideration of fig. 6 (*c*) is reserved for the discussion which follows. A series of

* In the second arrangement these had been reduced to numbers comparable with those to be expected from the results of Rutherford and Chadwick (*loc. cit.*).

photographs is reproduced and a description of them is included as an appendix to the paper.

Discussion.

There can be little doubt that almost all the tracks photographed are α-particle tracks and not those caused by fast protons. This question has been discussed already and the conclusion reached is supported by the fact that the straggling coefficients of the main groups are of the order to be expected for α-particles emitted by the source with uniform velocity. If, however, one examines the tracks which go to make up these groups, one finds that some of them are very thin and in all respects similar to those formed by protons of high speed. While it may be taken as certain that under given conditions an α-particle will form a denser track than a fast proton, it seems that in the actual use of an expansion chamber variation of the lighting in different parts of the chamber and of the time of entry of the particles may cause such differences in the appearance of the tracks that an α-particle track may be actually or photographically as thin as a proton track formed under good conditions. As a result of our experience in this work we have come to the conclusion that the density of the track formed in an expansion chamber is not always a reliable means for distinguishing between fast protons and α-particles.

A point of some interest is the relative numbers of α-particles in the 9·9 and 11·7 cm. groups from thorium C. The ratio of these numbers has been measured by Meitner and Freitag* using an expansion chamber and again by Philipp† using the scintillation method. The results obtained in both these experiments agree in fixing the ratio at 1 : 2·8. For the same ratio the value obtained here is 1 : 5·1. While the present work has shown that the expansion chamber is not a reliable instrument for counting α-particles, it is surprising that the difference between the results of Meitner and Freitag and those obtained here is so large. It is perhaps worthy of note that Philipp found swift protons to the extent of 18 per cent. of the number of long range α-particles observed, while in the arrangement of Meitner and Feitag they were present to the extent of 11 per cent. of the long range α-particles. In the experiments described here the very long range tracks going across the chamber were less in number than 3 per cent. of the long range α-particle tracks.

In the case of thorium C besides 541 tracks between 8·6 and 12·2 cm. range, 9 tracks were found which did not cross the chamber and which had ranges greater than 12·5 cm. It seems unlikely that many of these tracks can be due to

* *Loc. cit.*

† *Loc. cit.*

fast protons, and the view taken at present is that these tracks were formed by α-particles ejected by the source. It is quite impossible that they were caused by radioactive contamination.

In the case of radium C also the view taken is that the tracks observed with ranges other than 9·2 cm. were formed by α-particles coming from the source. It is impossible to explain the results as being due in part to radioactive contamination, for, though evidence of contamination was sought, it was not found. The results make it quite clear that radium C does not emit only two groups of long range α-particles of 9·3 and 11·3 cm. range as has been supposed for some time on the evidence of scintillation experiments, though the distribution curve shows those particles which in such experiments would produce an effect like an α-particle group of 11·3 cm. range.

When discussing a distribution curve such as fig. 6 (*c*), it is reasonable to postulate that the α-particles forming the tracks observed are emitted in groups of definite velocity, even though it might be possible to explain the distribution by supposing it to be caused, partly or wholly, by a continuous spectrum of α-particles. In the case of the results obtained for radium C the possibility of a continuous spectrum of particles cannot be entirely neglected, but as the chief features of the observed distribution can be explained by assuming groups with ranges of 8·1 and 11·0 cm., with possibly another group at about 10 cm., this explanation is preferable to any which requires a continuous α-ray spectrum. Thus there is strong evidence for additional groups at 8·1 and 11·0 cm. with a doubtful group at about 10 cm. and these groups and the one at 9·2 cm. are considered to include most of the long-range α-particles emitted from radium C, though in addition there are a few particles, most of which must be α-particles from the source, with ranges greater than 12 cm.

It is possible to make a comparison between the results obtained with thorium C and radium C in two slightly different ways. Attention may be directed to the distributions obtained with the same numbers of long range α-particles, or else to the numbers and distributions of the long range particles accompanying the same numbers of primary α-particles (8·6 cm. or 7·0 cm. particles). While the total numbers of the long range tracks recorded here are in the ratio of 5 : 4, they must be associated with about 2×10^6 8·6 cm. α-particles in the case of thorium C and 14×10^6 7·0 cm. α-particles in the case of radium C. The second method of comparison is useful when secondary effects are known to be present, but, as these effects are absent in the results described here, the first method of comparison is used.

It is seen that in each case the most abundant group is accompanied by a group of particles of lower velocity containing about one-fifth as many particles as in the larger group. Furthermore, the energies of the 7, 8·1 and 9·2 cm. particles from radium C are in the ratios 1 : 1·09 : 1·18 and closely similar ratios 1 : 1·09 : 1·20 hold for the energies of the particles in the groups of 8·6, 9·9 and 11·7 cm. range from thorium C, a fact which suggests that the 11·7 and 9·9 cm. groups of thorium C may correspond to the 9·2 and 8·1 cm. groups from radium C. This comparison can, however, be carried no further, for there is no group in the particles from thorium C which corresponds to the 11 cm. group from radium C.

The agreement between the extrapolated ranges found and those given on Rutherford's* theory is not very satisfactory, for in two† cases out of three the experimental ranges lie midway between two ranges predicted as possible. That these long range particles come from thorium C and radium C or their products has already been shown, but the position in the radioactive series of the substance producing them is uncertain. They have generally been assumed to come from the C′ bodies,‡ but if such long range particles are associated, according to the normal relation, with very short decay periods, they can only occupy this position in the sequence by originating in an isotope of the C′ body, the isotope being formed by an extra β-branch at the parent C body. The long range particles might be emitted by substances formed by branchings at other points, and if this were the case the experimental values would not be expected to agree with those given for the C′ bodies on the basis of Rutherford's theory.

There is also the possibility that these α-particles do not exist in the nucleus with abnormally high energies. They may be α-particles of the ordinary groups which, just prior to ejection, are in some way supplied with extra energy. If one overlooks the difficulty of finding a source of energy to supply about 2×10^6 electron volts to a thorium C′ α-particle, this explanation of their presence has much to commend it, for it does not require extra branches and yet it explains the high energy of these particles and their comparatively rare occurrence. If this supply of energy were available only for particles ejected in a very short time after the previous (β) disintegration, then the

* *Loc. cit.*

† The ranges of both groups from thorium C.

‡ The only evidence on this point is that long range α-particles from actinium active deposit have not yet been definitely observed. Here the C′ body is present in very small quantity and the particles of range 6·5 cm. are the normal α-particles from this body.

association of long range particles with thorium C′ and radium C′ and their relative abundance with these elements might possibly find explanation. In any case it would appear significant that these particles are found only with thorium C′ and radium C′, the two substances of most rapid disintegration. If the particles do indeed obtain their high energy as has been suggested their energy would not necessarily correspond to that of a definite orbit in the nucleus.

Summary.

The paper describes in detail experiments which have been made to determine the ranges of the long range α-particles from thorium C and radium C. For this purpose an expansion chamber was employed and descriptions are given of the arrangements used and the precautions taken so that the ranges o the particles might be obtained accurately from photographs of the tracks formed.

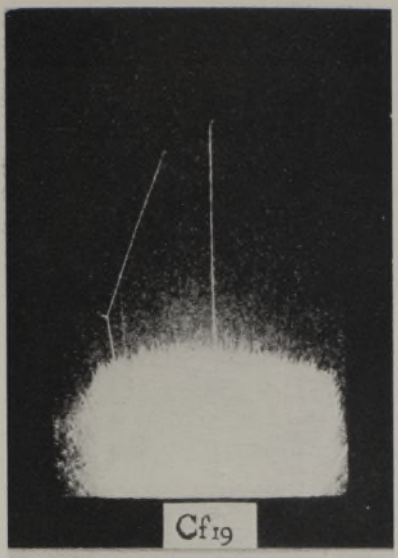
It is concluded that thorium C gives out two groups of α-particles having extrapolated ionisation ranges of 11·70 and 9·90 cm. respectively. A few tracks were found of which the range was greater than 12·5 cm. and these are also thought to be due to α-particles emitted by the source.

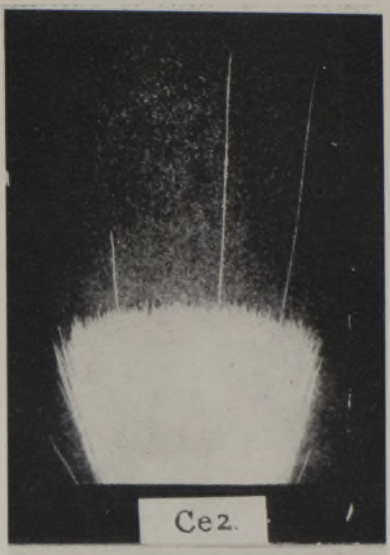
In the case of radium C the conclusions are less definite. There is certainly a group of α-particles having an extrapolated ionisation range of 9·16 cm. in standard air, but besides these particles there are other particles with ranges between 7·5 and 12·5 cm. The number of long range tracks available does not allow any absolute decision to be made as to whether these particles are emitted in groups of constant velocity, but there are very strong indications of groups of ranges 8·1 and 11·0 cm. The experiments show without question that radium C does not emit only two groups of α-particles of ranges 9·3 and 11·3 cm. The actual position is much more complex.

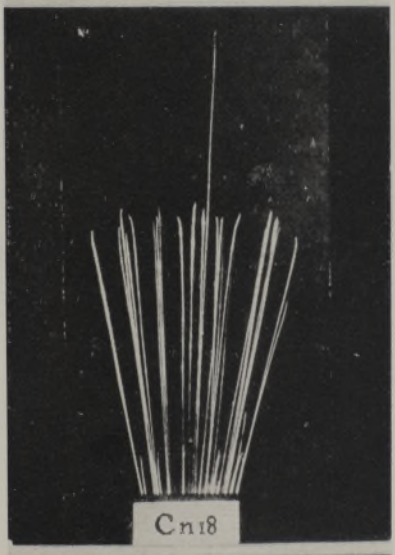
We wish to record our thanks to Prof. Sir Ernest Rutherford for the interest that he has taken in these experiments, and for the encouragement which he has given us in what has proved to be a long and trying investigation. Thanks are also due to Dr. Chadwick for much advice and many helpful discussions, and to Dr. Chadwick and Mr. G. R. Crowe for preparing the radioactive sources.

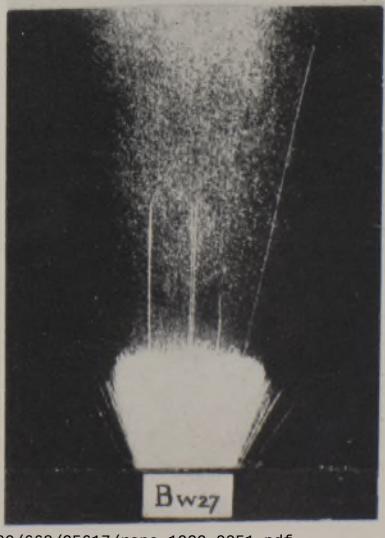
Description of Photographs.

It was the regular practice throughout the work to number all plates before exposure. The serial numbers so assigned have been used for the purpose of the present description. The values of the magnification quoted below are the values of the ratio $\frac{\text{length on photograph}}{\text{length in standard air}}$. The ranges given are ranges in

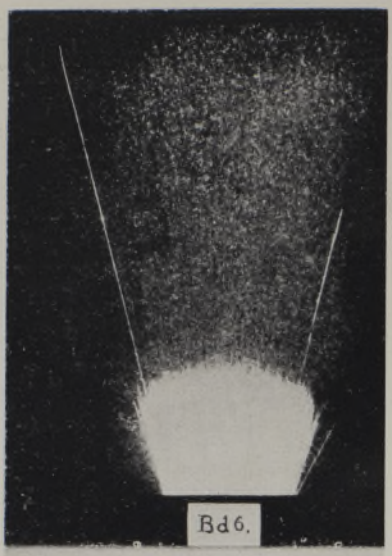


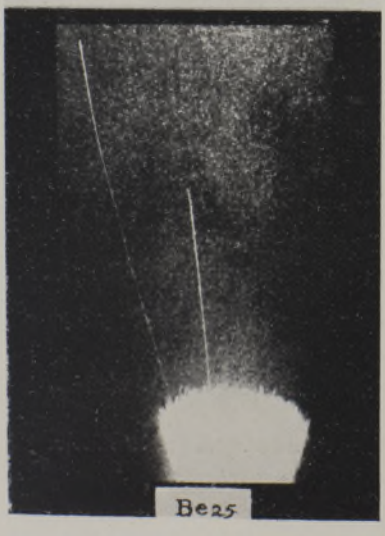






(*Facing p.* 686.)





standard air, and, unless otherwise stated, tracks are taken in order from left to right.

PLATE 11. Long range particles from thorium C.

Cf 19. Magnification 1·03. The right-hand track has range 11·47 cm. Had right-angle photography been employed the left-hand track would have provided very conclusive evidence regarding the nature of the long range particle. With a single photograph no finality is possible, but, owing to the fact that the plane of collision and the object plane of the camera lens cannot be greatly inclined in this case, consideration of the angles on the photograph makes it very unlikely that the collision was other than an α-particle-nitrogen nucleus collision. The very faint track is probably due to a swift proton.

Ce 2. Magnification 1·10. Ranges of long range tracks 9·60, 11·55, 11·52 cm.

Cn 18. Magnification 0·74. Range of long range track 11·40 cm. This photograph and the next were obtained during many test exposures made from time to time with a small source. On plates taken in this way about 3000 8·6 cm. α-particles were registered. On this plate the ends of the 4·8 cm. tracks are also visible.

Ob 2. Magnification 0·91. Range of long range track 11·49 cm.

Ca 27. Magnification 1·15. Ranges of long range tracks 11·59, 11·77, 11·71 cm. This plate was exposed once only.

Bw 27. Magnification 0·65. Ranges of long range tracks 11·64, 11·61, 11·61, 9·92, 14·89 cm.

PLATE 12. Long range particles from radium C.

In this series of photographs special attention is paid to tracks which do not belong to the most abundant group, viz., that at 9·08 cm. mean range. Only one track of that group is included.

Bd 6. Magnification 1·10. Ranges of long range tracks 11·04, 8·93 cm.

Bn 23. Magnification 1·05. Range of long range track 10·91 cm.

Bg 4. Magnification 1·34. Range of long range track 8·42 cm.

Cv 28. Magnification 1·33. Range of long range track 8·36 cm.

Be 25. Magnification 0·94. Ranges of long range tracks 12·17, 9·80 cm.

Df 19. Magnification 1·34. Ranges of long range tracks 10·00, 7·68, 10·42 cm.