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The Angular Distribution of Protons Projected by Fast Neutrons

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[Plate 16]

1—Introduction

The nature of the interaction between neutron and proton has assumed great importance in modern nuclear theory, since it is now generally assumed that these two particles form the fundamental constituents of all nuclei. Little direct evidence exists, however, as to the nature of this interaction.

The stable existence of the deuteron shows that the force between neutron and proton is attractive, and for purposes of calculation a "square hole" potential well has generally been assumed. With this model some success has been obtained* in correlating the magnitudes of a number of experimentally measurable quantities such as (*a*) the binding energy of the deuteron, (*b*) the total cross-section for neutron-proton scattering (Tuve and Hafstad 1936; Amaldi and Fermi 1936*a*), (*c*) the cross-section for photo-electric disintegration of the deuteron (Chadwick and Goldhaber 1935), and (*d*) the cross-section for capture of neutrons by protons (Amaldi and Fermi 1936*b*). The interaction is not completely derivable from the above data, since the values of these quantities depend mainly upon r^2V, where r is the mean radius and V is the depth of the potential hole.

The magnitudes of the binding energies of some of the light nuclei (^3H, ^3He, ^4He) can be explained by assuming that the force between neutron and proton falls off very rapidly when the distance between the two particles increases beyond about 2×10^{-13} cm. (Wigner 1933; Thomas 1935; Feenberg 1935), but the law of variation of force with distance cannot be obtained from the experimental data. The calculations of these binding energies, however, involve assumptions as to the magnitudes of neutron-neutron and proton-proton forces.

* For a full account of the theoretical interpretation of these results see Bethe and Bacher (1936).

A more direct method of obtaining information about this interaction is by the investigation of the angular distribution of protons projected by fast neutrons, since the form of this distribution depends more markedly upon the width of the potential hole. According to Morse, Fisk and Schiff (1937), this angular distribution depends also upon the shape of the potential hole. Thus while Bethe and Bacher (1936) find that for a "square hole" interaction with $V = 0$ for $r > r_0$ the distribution would be isotropic for incident neutrons of energy less than 10^7 e-volts, Morse, Fisk and Schiff state that small but finite values of V for $r > r_0$ should give rise to marked differences from isotropy for much smaller neutron energies.

2—Modes of Representing the Distribution of Scattered Protons

Before considering the results which have been obtained upon the angular distribution of protons recoiling under the impacts of fast neutrons we shall briefly summarize the methods by which this distribution may be represented, since many workers, both theoretical and experimental, have chosen different schemes of representation of their results, rendering intercomparison difficult. Consider first the motion referred to the centre of gravity of the two particles which then approach one another along the line joining them each with velocity v. Let $(180° - \phi)$ be the angle through which each particle is deflected, the particles then receding after the collision, each with velocity v, in opposite directions. Then the required distribution function $f(\phi)$ is equal to the number of protons (or neutrons) scattered per unit solid angle in the direction ϕ, and an isotropic distribution corresponds to $f(\phi)$ = constant. The number of protons scattered between ϕ and $(\phi + d\phi)$ is then proportional to $f(\phi) \sin\phi \, d\phi$.

Consider now a collision specified as above in terms of ϕ, viewed from the co-ordinate frame of the laboratory. In this system, relative to which the proton is initially at rest, the incident neutron has velocity $2v$. It may readily be shown that if in these co-ordinates θ = the angle of projection of the proton relative to the direction of the incident neutron then $\phi = 2\theta$.

The number of protons scattered between θ and $(\theta + d\theta)$ is therefore proportional to $f(2\theta) \sin 2\theta \, d\theta$, which may also be written $f(2\theta)\, d(\cos 2\theta)$. The obvious method of investigation is therefore to count the number of recoil proton tracks occurring within equal intervals of $(\cos 2\theta)$, and the form of the function $f(2\theta)$ is then directly obtained.

For purposes of graphical representation a number of methods may be used:

(*a*) The numbers of observed angles of projection lying within equal intervals of $\cos 2\theta$ are plotted as ordinates and the corresponding values of $\cos 2\theta$ as abscissae. On such a histogram the important case $f(\phi) =$ constant appears as a line $y =$ constant.

(*b*) The same numbers as in (*a*) are taken as ordinates, while the corresponding values of 2θ are taken as abscissae. An isotropic distribution again appears as a line $y =$ constant.

(*c*) The numbers of recoil tracks with angles of projection lying between θ and $(\theta + d\theta)$ are taken as ordinates while the corresponding values of θ are taken as abscissae. (This is the method adopted by Harkins.) The ordinates of such a graph being proportional to $f(2\theta) \sin 2\theta$, an isotropic distribution appears as a $\sin 2\theta$ curve with maximum at 45°.

(*d*) The numbers of particles scattered at angle θ per unit solid angle referred to the laboratory co-ordinates are taken as ordinates and the corresponding θ values as abscissae. The ordinates are obviously proportional to $f(2\theta) \sin 2\theta \, d\theta \div \sin \theta \, d\theta$, i.e. to $f(2\theta) \cos \theta$. Thus an isotropic distribution appears as a cosine curve with maximum at 0° and zero at 90°. (This method is adopted by Kurie 1933).

In view of the importance of easy intercomparison of past results and of the many results which doubtless will appear in the future, it seems desirable that a common practice should be adopted in future work.

Since the fundamental question at issue is the extent to which the distribution departs from isotropy, it would seem that either method (*a*) or (*b*) is to be preferred, since on these methods an isotropic distribution receives the simplest possible representation $y =$ constant.

For purposes of representation of experimental results method (*a*) has the great advantage that the area under the curve between any two values of $\cos 2\theta$ is proportional to the number of particles observed in this angular range, so that so long as the main errors are statistical ones this representation is the most direct and most easily gives a correctly weighted distribution. We have used method (*a*) in the manipulation and representation of our results (figs. 5, 6).

For theoretical purposes the method (*b*) is the logical one and is much to be preferred to (*c*) or (*d*).

This representation is simply obtained from (*a*) and we have used it for comparison of our results with theory (fig. 8).

3—Experimental Results of other Workers

The experimental results of different workers on the form of the scattering distribution are widely contradictory. Thus Kurie (1933), from measurements on expansion chamber photographs of protons projected from a layer of paraffin by neutrons from a source of polonium and beryllium, obtains a distribution which shows wide departures from isotropy. Meitner and Philipp (1934), on the other hand, using a similar neutron source and measuring the angles of projection of 100 recoil protons originating in the gas of the expansion chamber, find a distribution which is isotropic within the large limits of statistical error. Similar results were obtained by Auger and Monod Herzen (1933) by measurements upon eighty-four recoil proton tracks. A more detailed study has been made by Harkins, Kamen, Newson and Gans (1935, 1936), who used neutron sources of beryllium mixed with mesothorium and thorium X and in some cases of beryllium mixed with radiothorium. They photographed 730 tracks of recoil protons originating in various hydrogenous gases in an expansion chamber. Their distribution, plotted according to method (*c*) § 2, shows a maximum at 25° instead of at 45° as would be the case for an isotropic distribution.

In criticism of the above results it must be noted that in all of these experiments the incident neutrons must have been widely inhomogeneous in velocity. Thus for the polonium-beryllium sources the neutrons might be expected to have energies from zero up to 10×10^6 e-volts, whilst the sources used by Harkins probably gave neutrons with energies from zero up to 12×10^6 e-volts with a maximum in the number × energy distribution at about 5×10^6 e-volts. Harkins states that 25 % of the neutrons had energies less than 10^6 e-volts.

The disadvantages of this inhomogeneity are twofold. In the first place it is probable that the required function $f(\phi)$ is different for different values of the energy of the incident neutrons, so that any satisfactory comparison of the results with theory is extremely difficult. But from an experimental standpoint there also exists a serious disadvantage. Consider, for example, the collision of neutrons of energy 10^6 e-volts with protons. The range in air at N.T.P. of a proton projected at angle $\theta = 0°$ with the direction of the incident neutron is 2·5 cm. For $\theta = 45°$, however, the range of the projected proton is 1·0 cm., while for $\theta = 60°$ the range is 4 mm. It is obvious that if for any reason there is a minimum detectable range of the projected protons the distribution obtained will show a deficit of scattered protons for large values of θ as compared with the true distribution. Whilst such effects upon the distribution may be negligible for neutrons of high energy, for which the ranges of the protons projected at large values of θ are still large, the presence of appreciable numbers of neutrons of lower energies may introduce considerable error. For all work with inhomogeneous neutrons it is therefore possible that, owing to this cause, a distribution which represented according

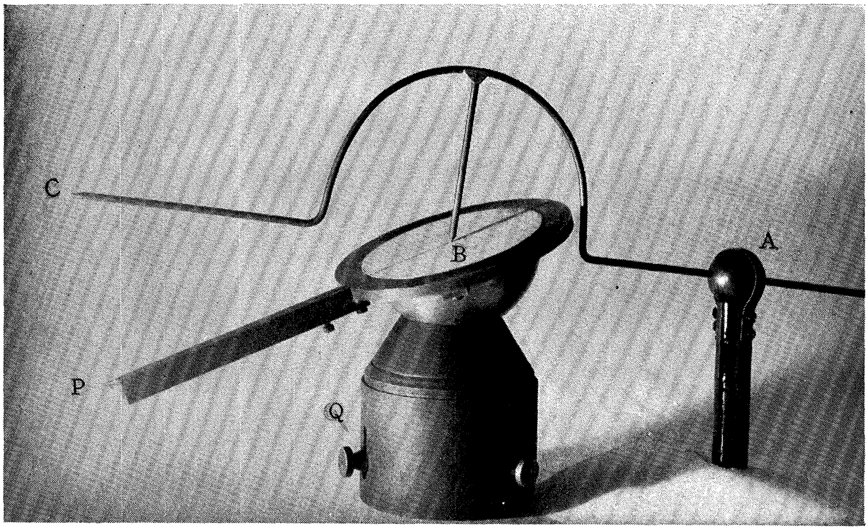

FIG. 1.

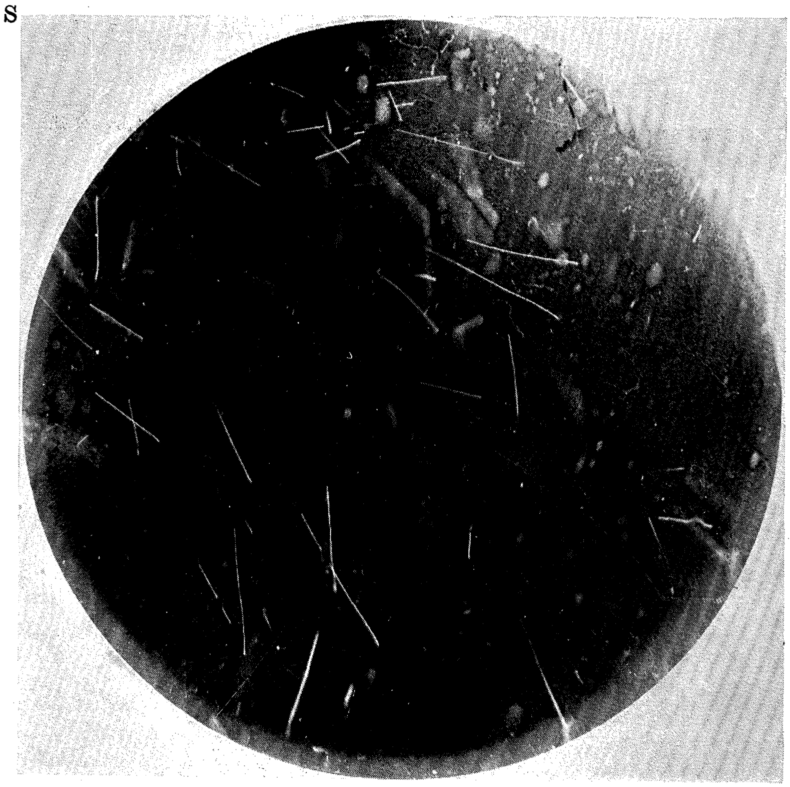

FIG. 2—Tracks of protons recoiling from the impacts of neutrons of $2{\cdot}4 \times 10^6$ e-volts energy. The neutron source was at the point S.

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to (*c*) § 2 should show a maximum at 45° will in fact show a maximum at smaller angles.

The results of Harkins and of Kurie plotted according to this scheme show a maximum at 25°, and the possibility of this explanation of the departure from isotropy must be borne in mind. On the other hand, the advance notice of a paper by Kruger, Shoupp and Stallmann (1937) using the homogeneous neutrons from deuterium under deuteron bombardment would seem to be free from this error, and the results of these workers are in substantial agreement with the results of Harkins and of Kurie. Similar results have been found by Lampson, Mueller and Barton (1937) using a similar neutron source but detecting the recoil protons in a photographic emulsion. It is doubtful whether this method can have the same reliability as that of the expansion chamber.

Another feature of such experiments which may give rise to error lies in the fact that the path of the incident neutron does not appear on the photograph. The direction of the neutron has by all workers been assumed to be given by the direction of the line joining the neutron source to the point of origin of the track of the recoil proton. In other words the resulting distribution must include a certain percentage of recoil tracks which were due to neutrons which had not proceeded directly from the source. These effects of scattering of the neutrons by the matter surrounding the gas in the chamber might reasonably be expected to tend to conceal any departures from isotropy which may actually exist in the true distribution and can therefore only be regarded as a possible criticism of the methods which have yielded an isotropic distribution. As will be shown in the next section, we have adopted a method which should minimize both of these two main sources of experimental error. A further difficulty of such measurements lies in the large statistical error which must be present unless a great number of tracks are measured. The only distribution which contains more than 250 particles is that of Harkins, who measured 730 tracks. Our results refer to measurements upon about 2000 recoil proton tracks.

4—Experimental Method

We have seen from the preceding discussion that the important points to be considered in these experiments are (1) the use of homogeneous neutrons and (2) the elimination from the statistics of recoil tracks produced by neutrons which have not proceeded directly from the source.

We have accordingly used as a source in these experiments the homogeneous neutrons of $2{\cdot}4 \times 10^6$ e-volts energy, which are produced by bombarding with deuterons a target containing deuterium. In order to satisfy the second condition the recoil proton tracks were photographed in an expansion chamber containing a mixture of 60 % methane and 40 % argon at a total pressure of about 3·5 atm. Under these conditions the range of a proton projected at $\theta = 0°$ with the direction of the incident neutron was about 3·5 cm. For all other values of θ the ranges were correspondingly less. We have thus been able to measure, for each recoil track, both the angle of projection relative to the line joining its point of origin to the source and also the length of the track. Each recoil track was then represented by a point upon a diagram having range and angle as ordinate and abscissa respectively. With strictly homogeneous neutrons, all proceeding directly from the source, and with negligible errors of measurement, all such points should then lie smoothly upon a theoretical curve relating the ranges and corresponding relative angles of projection of the protons. Conservation of momentum and energy are sufficient conditions for the calculation of this curve.

Allowing for the slight inhomogeneity of the neutrons, due to the effects of the finite bombarding energy of the deuterons, and for some errors of measurement, we might expect that the experimental points would show a concentration about the theoretical line, while recoil tracks due to scattered neutrons would be distributed at random over the diagram. A typical experimental diagram obtained in this way is shown in fig. 3. It is obvious that by the use of this method the tracks due to scattered neutrons can be eliminated from the required statistical distribution.

The above method of elimination of tracks due to scattered neutrons can only be used when the maximum length of the recoil tracks is small compared with the dimensions of the expansion chamber. Previous work upon this distribution has been carried out with expansion chambers operated at about atmospheric pressure. Under such conditions the tracks usually passed right across the chamber, so that this method of elimination of the effects of scattering could not be used.

Our choice of this method of elimination of tracks due to scattered neutrons, instead of the possible alternative method of constructing a chamber with such thin walls that the scattering of neutrons might be reduced to the lowest possible minimum, was partly conditioned by the necessary screening of the chamber from X-rays produced by the high-voltage apparatus. This screening was effected by a lead-lined hut, at the base of the accelerating tube, inside which the chamber was operated. It seemed possible that the number of neutrons scattered from the walls of this hut might not be negligible. The elimination of such scattered neutrons by the method which we have used would not be possible unless the chamber were constructed to work at fairly high pressures, and this condition would seem to preclude the use of such a thin-walled chamber.

The target used in this work was a disk of heavy aluminium hydroxide, 12 mm. in diameter, contained in a wide evacuated tube down which passed the beam of accelerated deuterons. The target lay in the median plane of the chamber, 17 cm. from its centre. The expansion chamber was 25 cm. in diameter and 6 cm. deep, these large dimensions being chosen in order to be able to select for measurement only those tracks which occurred within a certain chosen central region of the chamber. This region was chosen in such a manner that any recoil proton track which originated within it would appear completely whatever its direction of projection. No systematic errors could therefore be introduced into the statistics by the effects of the walls, etc., of the chamber. An expansion chamber of a water-piston type was developed in order to facilitate the use of a large chamber at high pressures. The general experimental method was the same as that described in earlier papers (Dee 1935). Two main series of photographs were taken, in which the voltages applied to the accelerating tube were 300 and 100 kV respectively. A typical photograph is shown in fig. 2, Plate 16.

5—Reprojection and Measurement of the Recoil Tracks

In order to measure the ranges (l) and angles of projection (θ) of the protons relative to the direction of the incident neutrons it was necessary to develop a method which would be rapid in use, in order to deal with the great number of tracks required for a satisfactory statistics.

The two cameras used to photograph the recoil tracks were rigidly fastened together, and after a set of photographs had been taken they were removed as a unit from the expansion chamber support and placed upon two upright pillars fixed to a "reprojection" table. By illuminating the plates from behind, two images of the expansion chamber were produced about 15 cm. above the reprojection table top. This horizontal table top was hinged so that its height could easily be varied.

The apparatus shown in fig. 1, Plate 16 stood upon this table top. A steel hemisphere could slide smoothly in a concentric spherical cup which forms the upper surface of the support Q. The projected tracks were viewed upon the flat (white) surface of the hemisphere. By suitable adjustment of the position of Q upon the table top, and of the height of the latter, it was simple to arrange that the points of origin of the two projected images of any selected track lay both at the centre B of the hemisphere. By rocking the hemisphere in its cup this adjustment remained unaltered, while the whole lengths of the two images were brought into coincidence. The single track then observed coincides with the position (relative to the cameras) of the track which was photographed. The length (l) of the track was then read off. A thin diametral wire carried by a brass ring which could be rotated relatively to the steel hemisphere was then brought into coincidence with the track image. This ring also carried a pointer P in line with the diametral wire. Thus BP defined the direction of the recoil track in space. The angle θ between this direction and the direction of the incident neutron was measured by using the ⊓ shaped rod which could slide smoothly through the centre A of the ball of a cup and ball joint. The centre of this ball occupied the same position relative to the cameras as had been occupied by the neutron source when the photograph was taken. The tip of the central prong was placed upon the origin of the track at B. The rod was constructed so that A, B and C were collinear, and hence this line defined the direction of the incident neutron. Further, BC was constructed equal in length to BP (16 cm.). Hence the angle θ was readily obtained by measurement of the distance CP ($= 32 \sin \theta/2$ cm.).

For the purpose of eliminating the recoil tracks due to scattered neutrons the value of θ for each recoil track was not calculated, the directly measured value of CP (d) being used on all such diagrams.

This method has proved very rapid in use and is sufficiently accurate for most expansion chamber measurements. (The support Q was actually a "pot" electromagnet, so that the hemisphere could easily be locked in position by passing current through its coil when desired. This feature has proved very useful when detailed measurements need to be made upon, for example, a disintegration fork produced in the gas.)

By this method the tracks of about 2000 recoil protons were measured and plotted upon l, d diagrams. Measurement was confined to tracks occurring within a selected region of the chamber as described in § 4. Every track originating within this region was measured. The measurement was not continued for ranges less than 5 mm. owing to the difficulties of measurement and elimination of the effects of scattering. A typical diagram is shown in fig. 3.

6—Experimental Results

Twelve diagrams, similar to the one reproduced in fig. 3, were obtained by plotting the experimental points obtained in a number of runs under similar conditions. Preliminary experiments had given diagrams which showed much smaller concentration about the theoretical range-angle curve, this being mainly due to bombardment of the target tube down which the beam of accelerated deuterons passed. Conditions were much improved by making this tube wide, so that the beam of deuterons did not fall on any parts of the apparatus other than the actual target.

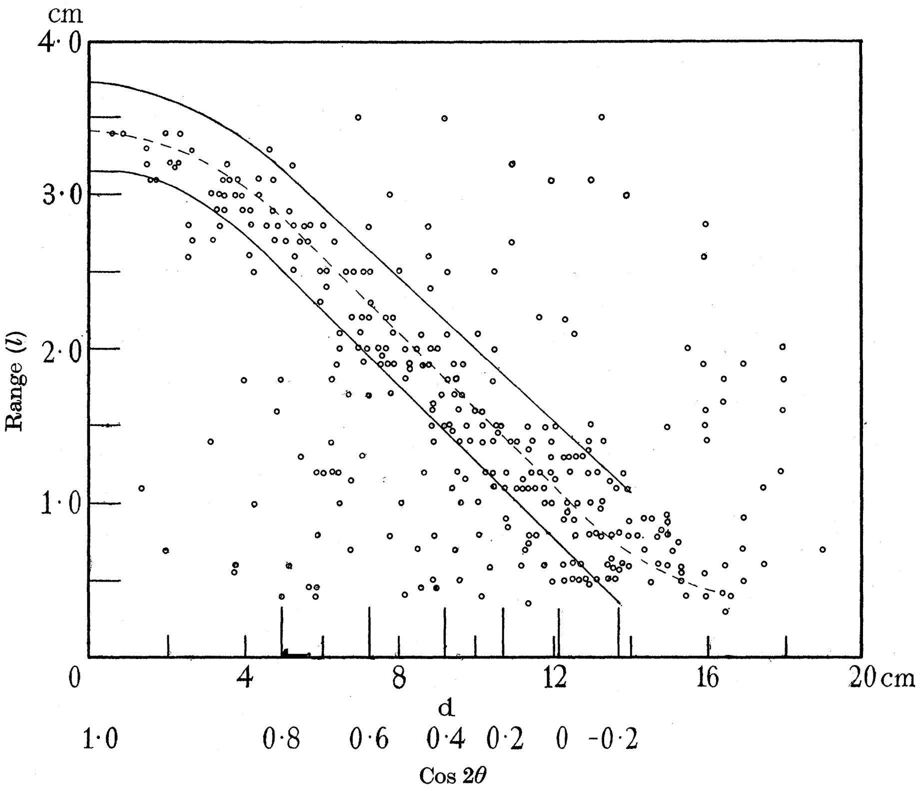
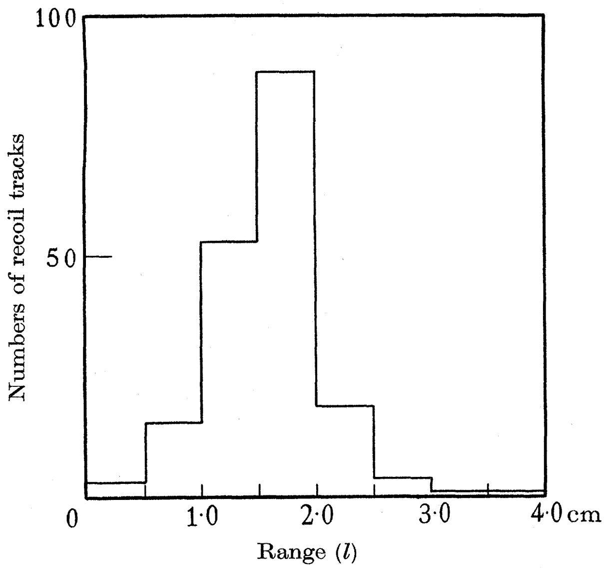


FIG. 3—Each point upon this diagram refers to a recoil proton track, plotted so that the ordinate represents the length of the track (l), and the abscissa the quantity d, which is a measure of the angle of projection of the proton relative to the direction of the incident neutron. The dotted line represents the theoretical relation between l and d for neutrons of energy $2{\cdot}4 \times 10^6$ e-volts.

It is clear that the points are mainly concentrated in a band of width 3 cm. on the abscissa scale of d, which is a measure of the angle of projection of the recoil protons.

Four factors might be expected to contribute to the width of this band, namely, (1) effects of bombarding energy of the deuterons, giving rise to slight inhomogeneity of the incident neutrons, (2) the finite target area, (3) errors of measurement of the ranges and angles of the tracks and (4) small angle scattering of the neutrons in passing through the walls of the expansion chamber.

The energy of the neutrons would be $2\cdot4 \times 10^6$ e-volts for zero bombarding energy of the deuterons. For deuterons of energy E striking a thin target, the energy of the neutrons emitted at right angles to the direction of the bombarding beam would be greater than the above value by an amount $E/4$. Since disintegrations in the thick target used might have been effected by deuterons of all energies up to the maximum value of 300 kV, we conclude that the incident neutrons might have had energies varying between about $2\cdot4$ and $2\cdot5 \times 10^6$ e-volts. Calculation shows that the spread of d due to this cause should be about 2 mm. The effect of target area might be expected to give rise to a spread of d of about 14 mm. By reprojecting and measuring a few plates several times in succession the third effect was shown to account for a spread of d of about 7 mm. Calculation from the known cross-section for scattering showed that the fourth effect should be unimportant. We can therefore readily account for a total spread of 23 mm. and the agreement with the observed spread is considered sufficiently close.



Cross-section of band $\cos 2\theta = 0\cdot4$ to $\cos 2\theta = 0\cdot2$

FIG. 4

In order to obtain the required distribution function and to eliminate the effects of scattered neutrons, graphs were plotted of the type shown in fig. 4, in each of which the numbers of points occurring within intervals of l

were plotted against l for a fixed interval of d. Upon such graphs the width of the main peak was approximately constant independently of the particular value of d for which this cross-section was made. The two full lines shown in fig. 3 were therefore drawn in such a manner as to include these main peaks. Using the diagrams such as fig. 3, counts were then made of the number of points included between these two lines for different intervals of d, chosen in such a manner that they corresponded to equal intervals of $\cos 2\theta$. Fig. 5 shows the results of this statistics, in which the ordinate scale represents this number of points (in all = 1534), and the abscissa scale the corresponding value of $\cos 2\theta$. The shaded area corresponds to the runs made with smaller bombarding energy, in which the experimental conditions were rather more satisfactory.

It should be noted that owing to the predominant character of the peaks, as illustrated by fig. 4, no very radical difference in this distribution can be introduced by small variations in the choice of the "allowed" breadth of the band of fig. 3, providing that the main peaks of the diagrams such as fig. 4 are included. To check this, and to make a correction for the background due to scattered neutrons, similar counts were made using a width of band twice that previously employed, with very similar results. As a correction for background the differences between the ordinates of these two distributions for each interval of $\cos 2\theta$ were then subtracted from the distribution shown in fig. 5. This in effect means that the background of fig. 5 is being taken as given by the density of points on fig. 3 in the neighbourhood of the main band. The result of this correction is shown in fig. 6, which includes data for 1111 recoil proton tracks.

A straight dotted line has been drawn to represent the probable shape of the distribution indicated by these experiments. The equation of this line is $N = N_0\{1-\lambda(1-\cos 2\theta)\}$, where $\lambda = 0{\cdot}14 \pm 0{\cdot}1$. The distribution obtained in this way shows therefore a small deficit of recoil tracks projected at large angles as compared with an isotropic distribution. It must be noted, however, that the method employed in making the correction for background might tend to introduce such a deficit into the distribution. Thus the effects of small deflexions of the tracks, errors of measurement, etc., would be more important for the protons projected with large values of θ, since the tracks are then relatively short. Hence it is possible that some of the tracks which have been taken as background should actually be included in the counts of the numbers lying within the allowed error limits, and that this error would be relatively more important for the higher values of θ.

Alternative methods of analysing the results have been used. The final result of such calculations shows that if the distribution be represented by a straight line, as described, the most probable value of λ is $0{\cdot}1 \pm 0{\cdot}1$.

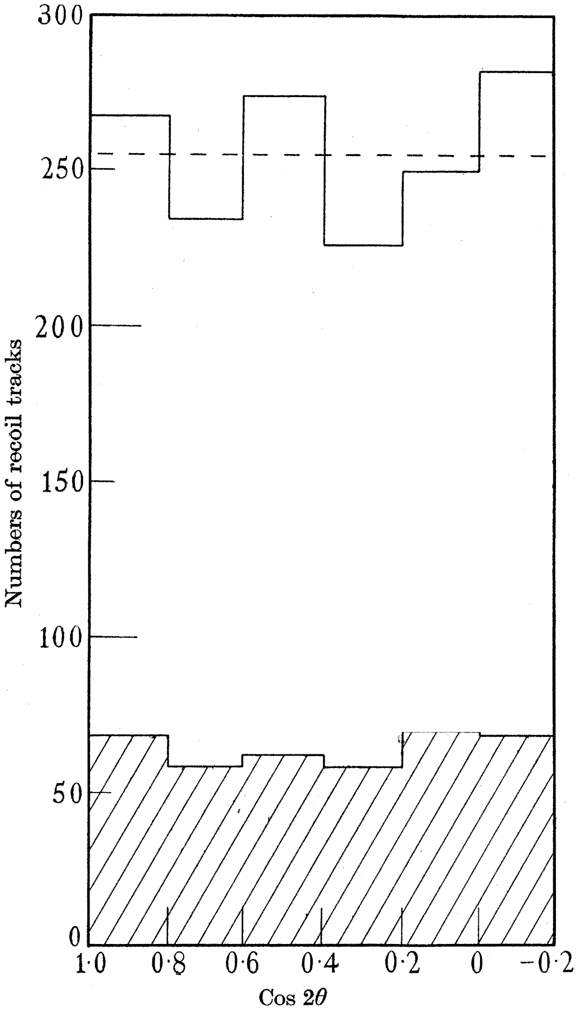


Fig. 5

Figs. 5 and 6—Numbers of recoil tracks {lying within the allowed band (see fig. 3)} with angles of projection corresponding to fixed intervals of cos 2θ. Fig. 5 without correction for scattered neutrons; fig. 6 (opposite) with correction for scattered neutrons. Shaded area = results of experiments with low bombarding energy of the deuterons.

7—Discussion of Results

The experimental result given by fig. 6, which as shown in § 2 (*a*) represents the number of protons projected per unit solid angle (in the coordinate system relative to which the centre of gravity of the two particles is at rest) plotted against the corresponding values of the cosine of the

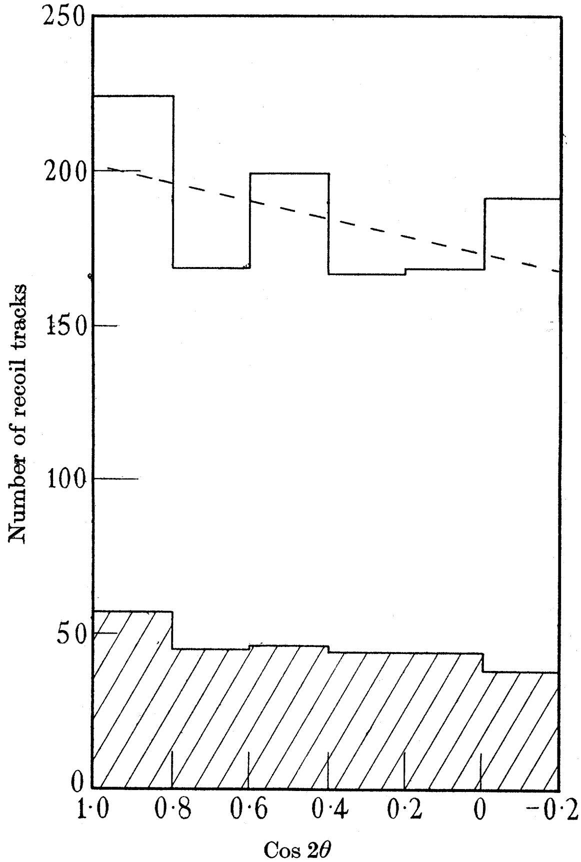


Fig. 6

common angle of deflexion, is reproduced in fig. 7, together with the results of Harkins. For the purpose of this comparison we have transformed his experimental representation from the mode of § 2 (*c*) to the mode (*a*). The areas under the two histograms are proportional to the numbers of tracks included in each statistical distribution. The two results are therefore widely contradictory. It will be seen that our result conforms much more closely to an isotropic distribution.

The marked disagreement between the two results seems much too great to be accounted for by the difference in the energies of the neutrons used in the two experiments. The disagreement with the results of Kruger, Shoupp and Stallmann, who agree with Harkins in finding a peak in the distribution (§ 2 (*c*)) at 25°, could certainly not be explained in such a manner since the neutron source used by these workers was the same as that used in our experiments.

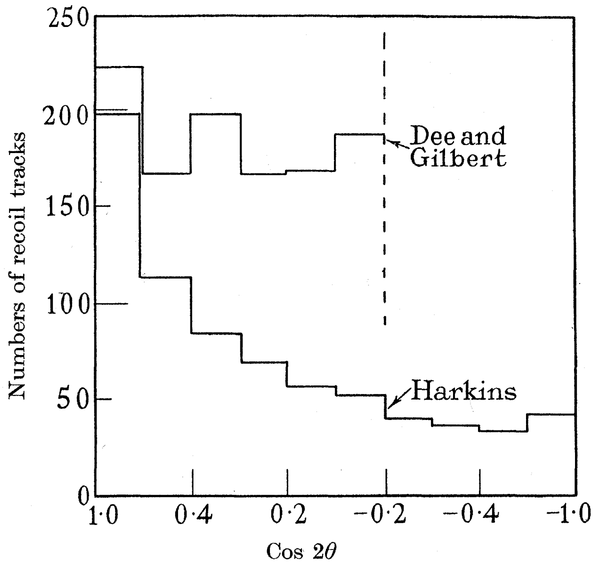


FIG. 7—*Angular distribution of recoil protons.* Numbers of recoil tracks within angular intervals which correspond to equal intervals of cos 2θ. Upper curve—result of these experiments, lower curve—result of Harkins.

It has been stated by Harkins that the large departure from isotropy indicated by his results could not be reconciled with the requirement of modern theory that no such anisotropy should be evident for the neutron energies used in his experiments (Bethe and Peierls 1935; Bethe and Bacher 1936). Our own experiments do not support this suggested inadequacy of the theory since the observed departure from isotropy is not much greater than the statistical errors involved.

On the other hand, Morse, Fisk and Schiff (1937) regard the results of Harkins as support for their assumption of an exchange interaction with a particular shape of potential hole, and claim that his results are in much better agreement with the results of their calculations than with the square hole potential previously assumed by Bethe and Bacher.

For this comparison with theory we have transformed the dotted line representing our averaged distribution (fig. 6) to the mode of representation of § 2 (*b*); see fig. 8, curve *A*. We show also upon this diagram Harkins's result (*B*) directly transformed from his smoothed curve and also the theoretical curves (*C*, *D*, *E*) of Morse, Fisk and Schiff, for different values of the energy (in the laboratory co-ordinates) of the bombarding neutrons.

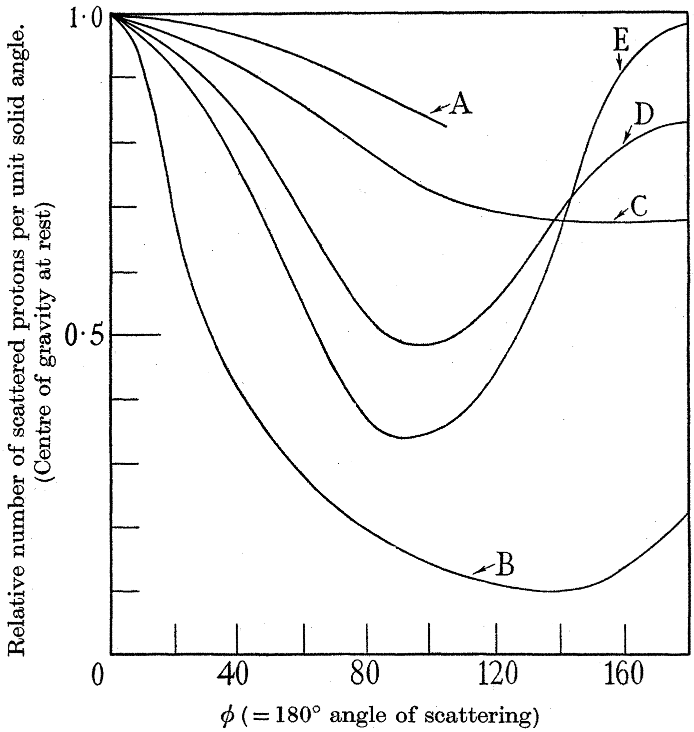


FIG. 8—*Angular distribution of scattered protons.* Curve *A*, experiments of Dee and Gilbert. Curve *B*, experiments of Harkins. Curve *C*, *D* and *E*, theoretical curves of Morse, Fisk and Schiff for neutrons of energies (in the laboratory co-ordinates) 5, 15, and 25×10^6 e-volts respectively.

Since the neutron energies used by Harkins had an upper limit of 12×10^6 e-volts and probably had a mean value of about 5×10^6 e-volts it is difficult to see how support for their view can be derived from these curves.

It might be thought that our own results are in better agreement with the predictions of Morse, Fisk and Schiff, but it should be emphasized that the departure from isotropy which we observe is not sufficiently great to enable any precise conclusions to be drawn as to the shape of the potential hole. According to recent calculations* by Massey and Buckingham (1937) our results could be fitted with a "square" hole of radius about $3\cdot0\times10^{-13}$ cm. and ordinary forces, whereas with an exponential, or inverse fifth power field, and ordinary forces, agreement could be obtained with a range of interaction of about $2\cdot5\times10^{-13}$ cm. The assumption of exchange forces is also shown by Massey and Buckingham to lead to departures from isotropy which would correspond to a preferential projection of the protons at large angles as compared with an isotropic distribution. These departures from isotropy, however, are small so that assumptions of "ordinary" or "exchange" forces are both compatible with our experimental results providing that the range of the interaction is less than $3\cdot0\times10^{-13}$ cm.

We wish finally to express our appreciation of Lord Rutherford's constant interest and encouragement. We are indebted to Drs. H. S. W. Massey and R. Peierls for many helpful discussions, and to Mr. J. C. Bower for some technical assistance.

Summary

Expansion chamber photographs have been obtained of about 2000 tracks of protons recoiling from the impacts of neutrons of $2\cdot4\times10^{6}$ e-volts energy.

By measurement of the ranges and angles of projection of the protons relative to the direction of the incident neutrons the angular distribution function for the collision has been determined.

The function obtained is $N = N_0\{1-\lambda(1-\cos 2\theta)\}$ where N = the number of protons projected per unit solid angle in a direction making an angle θ with the direction of the incident neutrons. The value of λ obtained is $0\cdot1\pm0\cdot1$ and the distribution of scattered protons is therefore almost isotropic about the centre of gravity of the colliding particles. This result is at variance with that obtained by a number of experimenters who have observed angular distributions showing wide departures from isotropy. The result obtained lends support to the view that the force of interaction between neutron and proton is very small when the relative separation of the particles exceeds 3×10^{-13} cm.

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The Nature of the Interaction between Neutron and Proton from Scattering Experiments

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Although our knowledge of atomic nuclei has expanded greatly in the last few years we are still in the lamentable position of having no certain information concerning the nature of the interaction between neutron and proton. Heisenberg's suggestion (1932), in the form as modified by Majorana (1933), that this interaction is of an exchange nature has been much used for the discussion of the binding energies of the heavy nuclei. It has the great advantage of providing a simple explanation of the proportionality of nuclear binding energies to the number of nuclear particles, but there is no direct experimental evidence that it is correct. The simplest way in which one can hope to test any assumed form of interaction is from observation of the collisions between neutrons and protons. Unfortunately the relative velocities of the colliding particles which would give the most decisive test

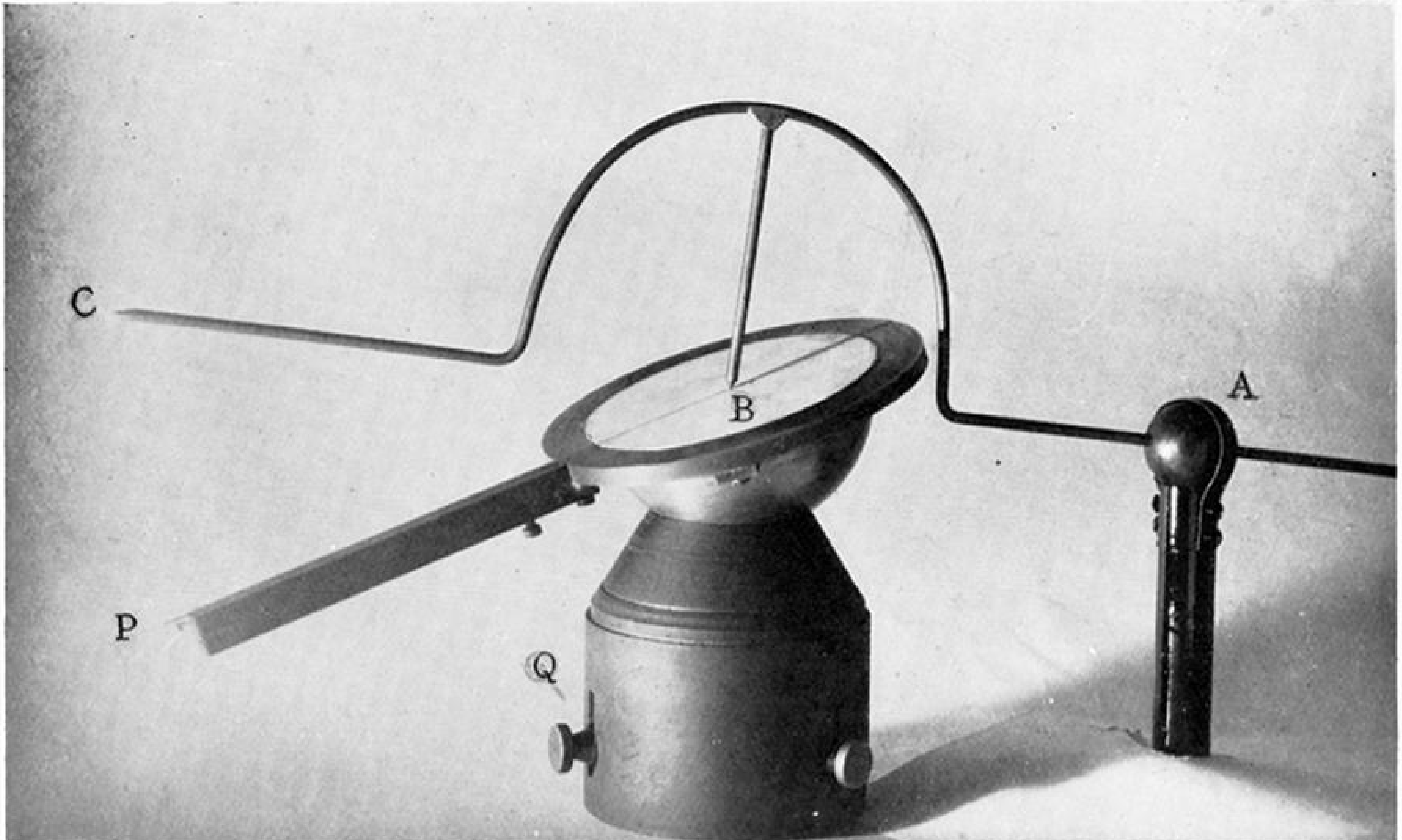

Fig. 1.

S

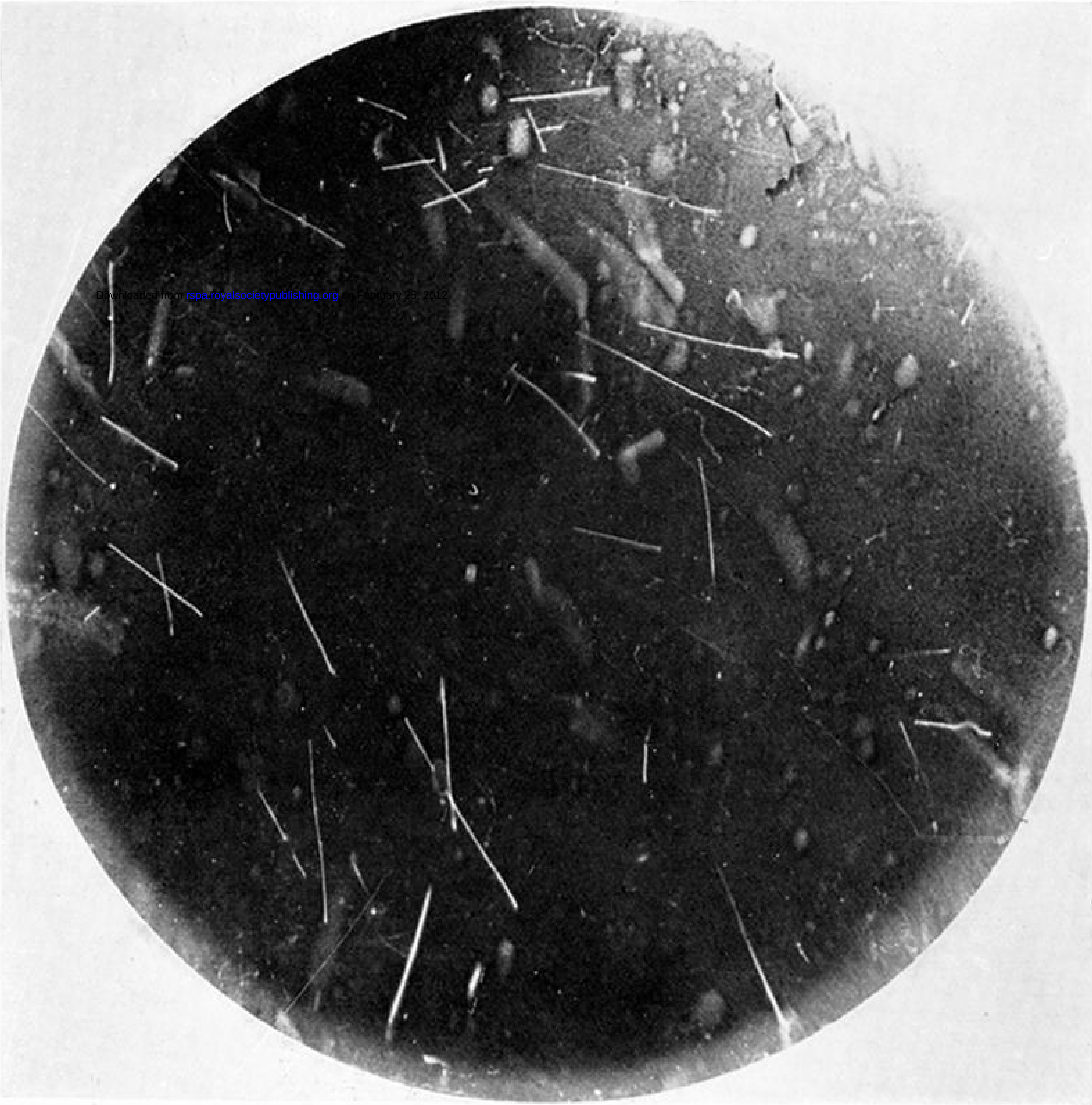

FIG. 2—Tracks of protons recoiling from the impacts of neutrons of $2{\cdot}4 \times 10^6$ e-volts energy. The neutron source was at the point S.