The Collisions of Neutrons with Protons

FRANZ N. D. KURIE,† *Sloane Physics Laboratory, Yale University*
(Received July 17, 1933)

A linear polonium source of about 2 millicuries strength is surrounded by beryllium contained in a brass cylinder coated with a layer of paraffin. This assembly is mounted on the piston in the center of a large automatic Wilson cloud chamber, in which the tracks due to protons projected from the paraffin layer by the neutrons are photographed. The angle between the proton track and its associated radius is measured. Corrections for scattering volume and effective solid angle of the cloud chamber are applied. On plotting the corrected number of proton tracks against the angle of projection a sharp maximum is found at 0°. The bearing of this distribution on the structure of the neutron is discussed.

THE field of the neutron may be studied by examining the interaction of that field with some particle. It is of course desirable that the particle chosen be as simple as possible in order that the results may be easily interpreted. For that reason we have chosen the proton, since the possibility is still open that in close encounters with other more complex nuclei the neutron may penetrate the potential barrier and be scattered by the internal field of the nucleus. Collisions between neutrons and protons may be brought about by bombarding a hydrogen-rich substance such as paraffin with neutrons. Protons will be knocked out of the paraffin by the impacts and will be distributed at angles to the neutron paths in numbers directly dependent upon the form of the neutron's potential field.

Several authors[1] have developed models of the neutron which account for such characteristics as its great penetrating power and its failure to interact with electrons. The models proposed may be summarized as follows: (1) an elastic sphere, (2) a dipole, (3) a proton imbedded in an electron. On classical theory the impact of elastic spheres of equal mass is such that the number projected at an angle θ to the direction of motion of the incident sphere is proportional to cos θ. H. S. W. Massey[1] has calculated the distribution of projected protons for the case of the dipole neutron and has shown that the number tends to infinity as θ tends to 90°. The third case cannot be treated by quantum mechanics in its present condition since the large binding energy necessary calls for relativity methods. In the same paper Massey has made an approximation to the third case, however, by considering a neutron in which the electron is bound very tightly to the proton by a fictitious high nuclear charge Z. To account for the penetrating power of the neutrons Massey is obliged to choose $Z \geq 2500$. The distribution-in-angle of projected protons exhibits a maximum which moves from 65° to 0° as Z increases from 2500 to infinity. In the latter limit the distribution is proportional to cos θ.

It was hoped at the outset of this work that experimental evidence in favor of one or the other of these models might be advanced, and so give insight into the nature of the neutron. It became apparent however that the data would conform to none of the prophecies.[2]

EXPERIMENTAL ARRANGEMENT

For this study a Wilson cloud chamber was used, which together with the camera has been described previously.[3] Since it was not necessary

† Sterling Fellow.

[1] H. S. W. Massey, Proc. Roy. Soc. **A138**, 460 (1932). J. L. Destouches, *État Actuel de la Théorie du Neutron*, Paris, 1932. J. Solomon, J. de Physique **4**, 210 (1933). I. I. Rabi, Phys. Rev. **43**, 838 (1933).

[2] The distribution reported by the author in a Letter to the Editor, Phys. Rev. **43**, 672 (1933), should be corrected by deleting the sentence "The present data seem best to fit the cosine curve which describes the scattering of elastic spheres." This statement arose through a numerical error in computing the solid angle subtended by the cloud chamber. This calculation will be given in the section headed "Corrections."

[3] F. N. D. Kurie, Rev. Sci. Inst. **3**, 655 (1932).

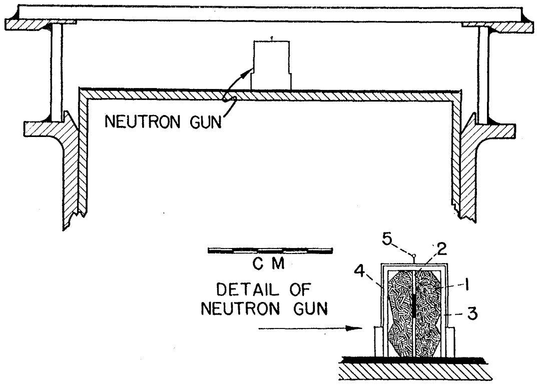

FIG. 1. Arrangement of the neutron source in the cloud chamber. In the inset is shown a cross section of the gun.

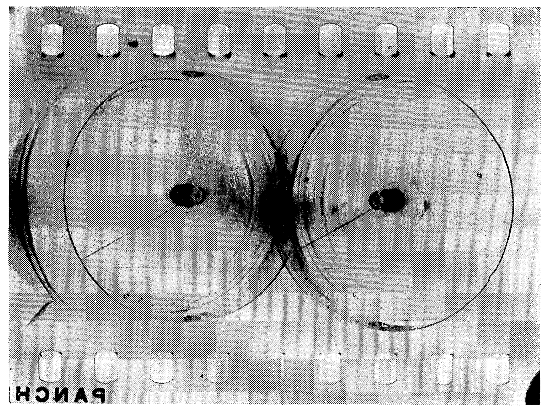

FIG. 2. A simultaneous pair of photographs of a proton track ejected by a neutron from the neutron gun in the center of the chamber.

to know the stopping power of the gas in the chamber to any high degree of precision the chamber was operated with a shorter interval between expansions than is permissible for more exact work. Actually the chamber made three expansions per minute.

The source of neutrons is shown in Fig. 1. Two pieces of beryllium had flat surfaces with a 1 mm step in them cut by a surface grinder. By not quite meshing these steps together a square hole *2* about 1 mm on a side was formed in the composite piece of beryllium *1*. In this hole a 2 millicurie polonium source was deposited by evaporating a polonium solution drop by drop. The source is indicated by the black portion of the hole *2* in the figure. The pieces of beryllium with the polonium were placed in a small brass cylinder *3* and centered by two pins one at either end (not shown in the figure). The box was blackened chemically and then dipped in paraffin saturated with lampblack, forming a thin layer *4* on the surface. The purpose of the blackening was to cut down the reflected light from the brass box which would otherwise spoil the pictures. The cylinder was waxed on the roof of the piston as shown. A small platinum bead *5* on the top of the cylinder served as a fiducial mark in the measurements of the tracks.

The direction of motion of the neutron is thus fairly well known, since it originates in a small volume and proceeds with negligible scattering to the point at which the proton is projected. There are some disadvantages to this arrangement as we shall see later but it has the desirable features that the paraffin subtends a large solid angle at the neutron source and allows the camera good vision of the chamber.

The tracks of the protons were photographed from two directions at right angles by a single lens camera.[3] (See Fig. 2.) The measurement of the tracks was accomplished by reprojecting the photographed images through the same optical system and recombining them on a screen equipped with divided circles so that the complete orientation of the track could be read directly. In Fig. 3 are shown the two angles, φ and δ, measured directly. The vertical distance y between the fiducial bead and the origin of the proton track was also measured.

The neutrons were assumed to move along the X axis, Fig. 3, this being merely a horizontal radius vector. Of the neutrons striking any point on the paraffin layer, the majority will come from that portion of the source which is nearest it so that the most probable direction of motion of the neutrons is in a horizontal plane. Corroborative evidence is furnished by the data shown in Fig. 4 where the number of protons is plotted as a function of y, the distance of their origin below the fiducial bead. This clearly shows a flat topped maximum over the length of the source, and so points to the reasonableness of the assumption that most protons are due to neutrons which arise from the part of the neutron source nearest the origin of the proton track. This assumption is an admitted compromise, since the true direction of the neutron's path cannot be precisely known,

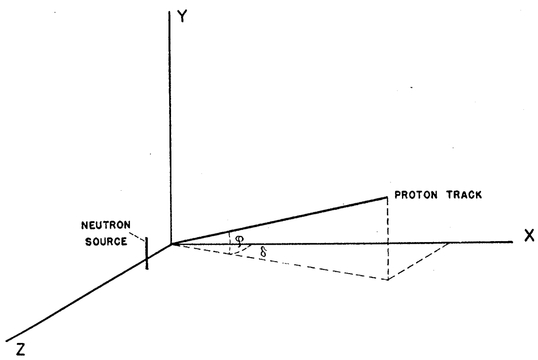

FIG. 3. The two angles φ and δ, which are measured for each proton track shown in their relation to the source of neutrons.

but it is believed to be the best that can be made.

The angle θ between the direction of motion of the neutron and the direction of motion of the proton is then simply $\cos^{-1}(\cos\delta\cos\varphi)$. This angle was computed from the measured angle for 160 tracks and a curve was plotted showing the number of tracks found between $\theta-5°$ and $\theta+5°$. Before this curve has any significance a number of corrections must be applied.

Corrections

In order to avoid the chance of mistaking α-particles due to contamination for protons only those tracks were considered which extended completely to the cylindrical periphery of the chamber. This restriction gives rise to a correction for the volume of paraffin effective in scattering. Referring to Fig. 5, let ON be the direction of motion of the neutron and AP that of the proton. Now let R be the mean range of the proton and R' the least emergent range (roughly 8 cm); then $\rho=R-R'$ is the greatest range in paraffin permissible. The effective scattering volume per unit length of the cylinder is then $\pi(a^2-r^2)$, where $OB=a$ and $OA=r$. Since $\rho\leqq 20$ cm air $=0.009$ cm paraffin ρ^2 may be neglected. We are here using 26 cm as the range of the protons;[4] using the longer ranges that are now being found by others will not affect this point. The effective scattering volume is finally

$$\pi(a^2-r^2)=2\pi a\rho\cos\theta. \qquad (1)$$

The observed distribution must then be multiplied point by point by $1/\cos\theta$.

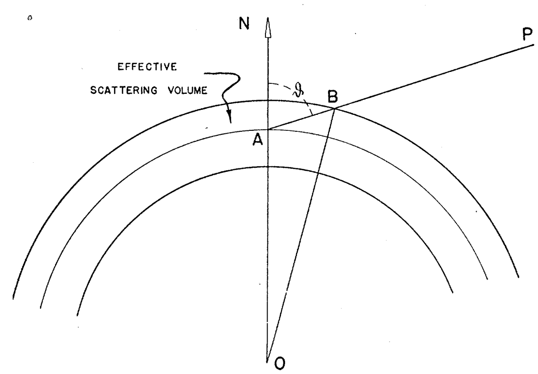

FIG. 5. Diagram indicating the dependence of the effective scattering volume in the paraffin layer on the angle θ.

The solid angle subtended by the chamber varies greatly with θ so that an approximate calculation must be made of this quantity in order that the observed data may be expressed as the number of protons projected per unit solid angle in the direction θ. We may simplify the problem by considering all the protons to start at the center of the neutron source, namely, at a point on the axis of the cloud chamber 7.5 mm from the bottom and 29.5 mm from the top. Taking the origin of a system of spherical polar coordinates

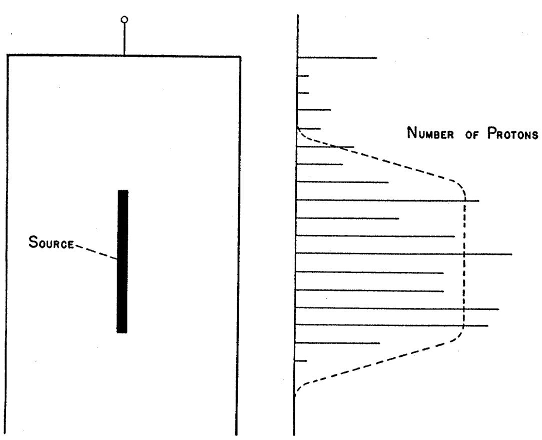

FIG. 4. Vertical distribution of the origins of the proton tracks, indicating that on the average the protons are projected by neutrons which start from the nearest portion of the neutron source.

[4] I. Curie and F. Joliot, Comptes Rendus **194**, 273 (1932).

at this center we require the area on a sphere of radius equal to that of the chamber and with center at the origin between the cones $\theta=\theta_1$ and $\theta=\theta_2$ and the planes $x=h_1$ and $x=h_2$ where $h_1=7.5$ mm and $h_2=29.5$ mm. The area A on the sphere of radius r, between the cones $\theta=\theta_1, \theta_2$ and the planes $x=0$, h is given by

$$\frac{A}{r^2}=\int_{\theta_1}^{\theta_2}\sin\theta\, d\theta \int_{\pi/2}^{\cos^{-1}(h/r\sin\theta)} d\varphi$$

$$=\frac{\pi}{2}(\cos\theta_1-\cos\theta_2)-\int_{\theta_1}^{\theta_2}\sin\theta\cos^{-1}\frac{h}{r\sin\theta}d\theta.$$

The last integral may be evaluated by expanding the arc cosine in a power series and integrating term by term. We find finally that only the first two terms of the series are of any consequence so that the area is given by

$$\frac{A}{r^2}=\frac{h}{r}(\theta_2-\theta_1)-B(\cot\theta_2-\cot\theta_1),$$

where B is a power series in h/r which converges very rapidly. The formula just developed is only valid for values of θ given by $h^2/(r^2\sin^2\theta)>1$. The area can be computed by simple geometrical means for values of θ below those for which the formula is applicable. Column 3 of Table I gives the results of the calculation for this case (chamber diameter 16 cm) and column 4 the factor by which the observed scattering must be multiplied to correct for both scattering volume in the paraffin and the solid angle of the chamber.

TABLE I. *Number of protons N_p observed in each angular group and calculated scattering per unit relative solid angle, n_p. Ω is the relative solid angle and f is the correction factor.*

Angular range	N_p	Ω	f	n_p
0°–10°	27.5*	1.00	1.000	27.5
10°–20°	41.5	2.24	0.459	19.0
20°–30°	34	2.37	.464	15.8
30°–40°	19.5	2.18	.560	10.9
40°–50°	20.5	2.14	.658	13.5
50°–60°	14	2.12	.821	11.5
60°–70°	2	2.11	1.113	2.2
70°–80°	1	2.10	1.833	1.8

* When a proton occurs exactly on the dividing line of two groups it counts half in each of the two adjacent groups.

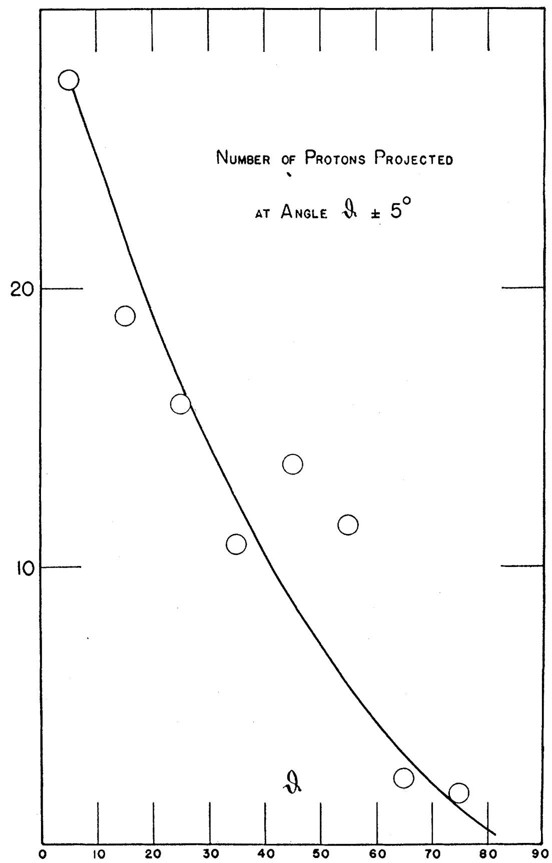

FIG. 6. Distribution-in-angle of protons projected by neutrons, fully corrected for effective scattering volume and for the solid angle subtended by the cloud chamber.

Results and Discussion

In Table I is given the number of tracks in each of the angular groups and also these numbers multiplied by the proper correction factor. A graph of the corrected numbers is shown in Fig. 6. The curve clearly presents no maximum and is quite unlike any of the distributions predicted theoretically.

It is unfortunate that the neutrons emitted from beryllium are very inhomogeneous in velocity because this factor undoubtedly influences the character of the distribution-in-angle of the projected protons. This fact must be clearly borne in mind in making any deductions from these data. It is also important to recall that the neutrons in this experiment do not proceed from a point source and that the distribution curve is probably slightly exaggerated in the small angles for this reason.

Recently Auger and Monod-Herzen[5] have published measurements similar to those described in the present paper. They observed the number of proton tracks in the same angular domains as here considered, the tracks being excited in a hydrogen-filled cloud chamber by a source of neutrons placed outside the chamber. Dividing the tracks into "long" and "short" tracks they find the 84 long tracks to fit the distribution curve expected for elastic spheres. It is hard to judge the significance of the distribution curve for the long tracks (which are the only ones which may be compared with the present data) since the solid angle subtended by the chamber, an extremely important factor, is difficult to take into account when the tracks are distributed at random through the chamber.

Neither the distribution of Auger and Monod-Herzen nor the one presented in this paper can be considered as being entirely free from criticism. The author believes that in the curve shown in Fig. 6 the fact that it is concave upwards is real, but whether it is a property of the neutron-proton interaction, or of the distribution-in-velocity of the neutrons, or to some other cause cannot be said at this time.

However since the present distribution presents an appearance quite different from that demanded by the theories of a composite neutron built up of an electron and a proton the urge has been strong to suggest that this is an argument in favor of the neutron being an elementary particle. In view of the absence of a relativity quantum mechanics a close combination of electron and proton has not been properly examined. Until that is done such an argument would be of no value.

The view that a neutron is an elementary particle has however been gaining favor in some quarters. The most cogent evidence at present is perhaps the recent demonstration by Parker[6] that the spin of beryllium is one-half. This of course would make the spin of the neutron one-half and point directly to its being an elementary particle.

I wish to thank Professor Alois F. Kovarik for many valuable discussions of this work. To both Professor Kovarik and Professor John Zeleny I am grateful for generous gifts of radon tubes.

[5] P. Auger and G. Monod-Herzen, Comptes Rendus **196**, 1102 (1933).

[6] A. E. Parker, Phys. Rev. **43**, 1035 (1933).

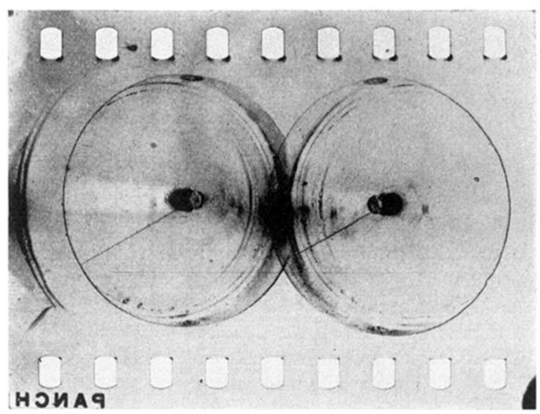

FIG. 2. A simultaneous pair of photographs of a proton track ejected by a neutron from the neutron gun in the center of the chamber.