tion is not well known. From the number of slow protons which can be identified as such and with reasonable assumptions as to the proton energy distribution it has been estimated[15] that the total number of protons is of the order of 2 percent of the total penetrating component. As Wilson[3] has shown, a component of this order would not be evident as regards its effect upon the multiple electrical scattering. *However the possibility cannot be excluded that a great fraction or even the total of the anomalous large angle scattering observed is associated with the proton component and not with the mesotron component.* The observed number of tracks scattered in an anomalous way amounts to about 2 percent and is of the same order as the estimates of the proton component. If the cross sections for the proton-proton and proton-neutron scattering at cosmic-ray energies were about 100 times larger ($\sim 10^{-26}$ cm^2) than that calculated here for mesotrons, we could attribute the whole effect to the proton component. A further indication that we might have to seek for an explanation of the anomalous scattering in the proton component rather than in the mesotron component is the abnormally high energy loss of protons in lead reported by Wilson.[16]

The author wishes to express his deepest appreciation to Dr. Thomas H. Johnson whose permanent interest, advice, and inspiring guidance have made this work possible.

Acknowledgment is also made of extensive support given to this work by the Carnegie Institution of Washington.

[15] T. H. Johnson, J. G. Barry, and R. P. Shutt, Phys. Rev. **57**, 1047 (1940).

[16] J. G. Wilson, Proc. Roy. Soc. **A172**, 517 (1939).

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Scattering of Protons by Deuterium

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The scattering of protons by deuterium has been studied in the energy interval between 200 kev and 300 kev and as a function of angle between 20° and 90°. The ratio of observed scattering to that expected on the basis of Rutherford's formula is found to differ appreciably from unity and increase, both with increasing energy and angle.

THE work of Tuve, Heydenburg and Hafstad[1] has shown that at proton energies near 800 kev the scattering of protons from deuterium does not obey Rutherford's formula. They find a slow increase in the ratio of observed to Rutherford scattering between the angles 20° and 75°. Beyond 75° the ratio increases extremely rapidly. Primakoff[2] and Ochiai[3] have investigated proton-deuteron scattering theoretically, making use of calculated neutron-deuteron cross sections but find difficulty in fitting the observed data at large angles. It is useful to determine the energy and angular dependence of the protons scattered from deuterium since it may lead to information about the proton-proton and proton-neutron interactions.

The scattering of protons from deuterium has been observed in the energy interval between 200 kev and 300 kev, from the scattering chamber-proportional counter system described in a previous article.[4] The source of high potential[5] and the differential pumping system[6] have also been previously described. The collision products were detected by three proportional counters,

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[1] M. A. Tuve, N. P. Heydenburg, and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).

[2] H. Primakoff, Phys. Rev. **52**, 1000 (1937).

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[4] G. L. Ragan, W. R. Kanne, and R. F. Taschek, Phys. Rev. **60**, 628 (1941).

[5] L. J. Hayworth, L. D. P. King, G. T. Zahn and N. P. Heydenburg, Rev. Sci. Inst. **8**, 486 (1937).

[6] W. R. Kanne, R. F. Taschek, and G. L. Ragan, Phys. Rev. **58**, 693 (1940).

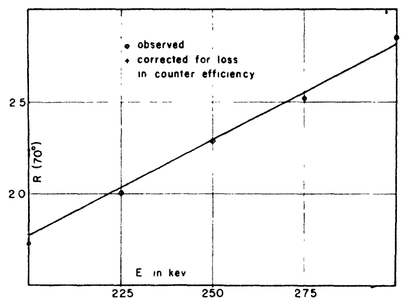

FIG. 1. Energy dependence of $R(70°)$.

one rotatable, and the other two fixed at 15° to each side of the incident beam. The dimensions of the detecting slits of the counters and other quantities which determine the geometry factor are as follows, in the notation of Breit, Thaxton, and Eisenbud:[7]

Rotatable counter	$2b = 0.0868$ cm, $2a = 0.2009$ cm, $h = 4.0$ cm, $R_0 = 7.0$ cm.
15° counters	$2b = 0.0106$ cm and 0.0100 cm, $2a = 0.1028$ cm and 0.1018 cm, $h = 4.0$ cm, $R_0 = 19.0$ cm.

The geometrical factor is $4\pi ba^2/R_0h$ and the ratio of the factor for both 15° counters to the factor for the rotatable counter was 44.4. The counters were kept filled with palladium purified hydrogen to a pressure of about 40 mm of mercury.

Deuterium gas (obtained from the Stuart Oxygen Company and labeled 95+percent pure, dried with liquid air), was continuously passed through palladium tubes and kept the scattering chamber at a pressure of about 1.3 mm of mercury, measured with an oil manometer. The Pd tubes were heated in a vacuum for about thirty minutes before passing deuterium through them. Since there was always a very slow leakage of hydrogen from the counters into the scattering chamber through the thin collodion foils, and since the impurities in the deuterium were probably principally hydrogen, the principal contaminating gas was hydrogen.

The observation of proton-deuteron scattering is complicated by the fact that the energy of a deuteron recoiling at angles less than about 50° from a proton of incident energy greater than 250 kev, should be sufficient to produce a pulse in the counter. The efficiency of the rotating counter decreased rapidly if the energy of a proton incident on it was less than about 100 kev[4] so that for angles greater than 50° only protons scattered from deuterium had sufficient energy to give a countable pulse, but near 90° the energy again became too low for reliable counting. At small angles it was found impossible to distinguish clearly on the oscilloscope between pulses due to scattered protons and pulses from recoil deuterons, for pressures in the counters ranging from 30 mm to 65 mm of mercury.

The data taken consisted of observations of the number of protons scattered into the rotatable counter at some angle in a given time interval and the simultaneous determination of the number of particles entering one or both of the fixed monitor counters at 15°. The mônitor counters received protons scattered from deuterium, from contaminating gases (especially hydrogen) and recoil deuterons. The number of recoil deuterons at 15° is practically negligible compared to the number of scattered protons, since the recoils arise from protons scattered at about 125°.

A calculation was made to find out how large an effect the scattering from contaminating

TABLE I. Energy dependence of $R(70)$. The value of R in parenthesis is corrected for loss in counter efficiency by use of the efficiency curve in reference 4.

Proton energy in kev	θ	No. of protons	$\left[\frac{Y(\theta)}{Y(15)}\right]_{obs}$	$\left[\frac{Y(\theta)}{Y(15)}\right]_{calc}$	R
200	290°	A16 33,568 B4 1,804	0.0539	0.0311	1.730 (1.781)
225	290°	A16 40,672 B4 2,636	0.0624	0.0311	2.01
250	70°	A16 37,104 B4 2,644			
250	290°	A16 30,144 B4 2,148	0.0711	0.0311	2.29
275	70°	A16 23,024 B4 1,804			
	290°	A16 24,816 B4 1,976	0.0785	0.0311	2.52
300	290°	A16 20,000 B4 1,776	0.0889	0.0311	2.858

[7] G. Breit, H. M. Thaxton and L. Eisenbud, Phys. Rev. 55, 1018 (1939).

hydrogen would have. It was found that if the pressure of the hydrogen were as large as 0.15 mm of mercury, i.e., 10 percent or more of the total pressure in the scattering chamber, a constant correction of 8 percent *of* the ratio $[Y(\theta)/Y(15)]_{\text{obs}}$ would have to be added *to* this ratio. This correction is constant only for angles at which no protons scattered from hydrogen are detected by the rotatable counter, i.e., the angles at which most of the data were taken. Whatever contaminating gases were present, remained constant in amount since the data taken from day to day with varying pressures of hydrogen in the counters and of deuterium in the scattering chamber were comparable within limits of error set by other factors. No correction for the amount of contamination present was made.

The experimental values obtained consisted of the ratio of the number of protons scattered into the rotatable counter at an angle θ, to the total number of protons and deuterons entering the 15° monitors during the same time interval. The ratio is expressed as $[Y(\theta)/Y(15)]_{\text{obs}}$; the same ratio was calculated for the known counter geometry on the basis of Rutherford's formula, and the quantity

$$R=[Y(\theta)/Y(15)]_{\text{obs}}/[Y(\theta)/Y(15)]_{\text{calc}}$$

was used to express any observed deviation from classical scattering. The quantity R is the ratio of the observed proton-deuteron cross section to the Rutherford cross section for scattering at an angle θ if the scattering at 15° is Rutherfordian.

Since only a small amount of deuterium was available and that which passed through the differential pumping system was not recovered, a greatly detailed study of proton-deuteron scattering was not possible. The energy dependence of $R(70°)$ is shown in Fig. 1, the data obtained are given in Table I. The letters A and B refer, respectively, to the monitors and to the rotatable counter, while the numbers 4 and 16 refer to the factor of the scaling circuit used in each case. It will be seen that corresponding data on opposite sides of the beam have been obtained in only a few cases, but the chamber was known to be accurately aligned from the detailed work on proton-proton scattering.[4] No corrections have been applied to the data except for counter efficiency at 200 kev.

Tables IIa and III list the angular distribution data obtained at 250 kev and 275 kev in the

TABLE IIa. Angular distribution of protons scattered from deuterium at 250 kev. The values of R in parenthesis are corrected for loss in counter efficiency by use of the efficiency curve in reference 4.

θ	No. of protons	$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{obs}}$	$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{calc}}$	R
45°	A16 11,296 B4 3,536	0.3201	0.2293	1.362
50°	A16 9,632 B4 1,936	0.2010	0.1361	1.475
55°	A16 13,296 B4 1,848	0.1388	0.0877	1.581
60°	A16 21,232 B4 2,348	0.1105	0.0595	1.860
65°	A16 18,320 B4 1,616	0.0882	0.0423	2.083
70°	A16 37,104 B4 2,644			
290°	A16 30,144 B4 2,148	0.0711	0.0311	2.29
75°	A16 29,616 B4 1,748	0.0589	0.02333	2.522
80°	A16 32,688 B4 1,628	0.0498	0.01782	2.792
85°	A16 42,256 B4 1,636	0.0387	0.01421	2.718 (2.895)
90°	A16 42,320 B4 1,328	0.0314	0.01143	2.742 (3.078)

TABLE IIb. Small angle values of R at 250 kev, obtained by correcting the observed data for the number of recoil deuterons.

θ	No. of protons	$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{obs}}$	$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{corr}}$	$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{calc}}$	R
20°	A4 1,216 B16 27,360	22.5	22.2	20.65	1.072
25°	A4 2,256 B6 17,760	7.89	7.54	6.88	1.094
30°	A4 1,512 B16 5,632	3.73	3.25	2.84	1.146
35°	A4 2,212 B16 4,704	2.125	1.558	1.361	1.141
40°	A16 684 B4 7,984	0.731	0.477	0.382	1.250
45°	A16 832 B4 7,024	0.528	0.285	0.229	1.241

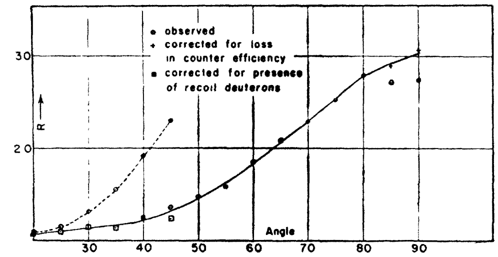

FIG. 2. Angular dependence of R at 250 kev.

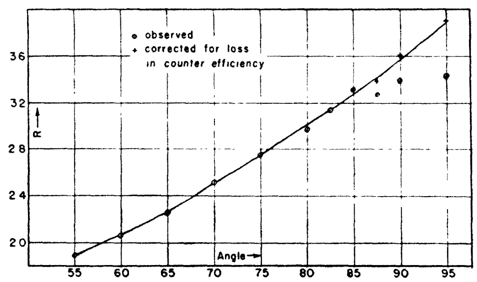

FIG. 3. Angular dependence of R at 275 kev.

angular range where only protons scattered from deuterium were counted. The values of $[Y(\theta)/Y(15)]_{\text{obs}}$ and $[Y(\theta)/Y(15)]_{\text{calc}}$ are given for each angle together with their ratio R.

In the data of Table IIa the counter pulses obtained at angles larger than 45° arise only from deuterium scattered protons. In order to obtain approximate values of R for smaller angles, the scaling circuit bias for the rotatable counter was set to count all particles entering the counter, the particles other than scattered protons being almost entirely recoil deuterons. Since the recoil deuterons arose from protons scattered at large angles the equation

$$\frac{d\Omega(\Theta)}{d\Omega(\theta)}=4\frac{\sin\Theta\cos^2\Theta\cos^2\theta}{\sin\theta\cos^2 3\theta}(1+2\sin^2\theta),$$

relating the solid angle $d\Omega(\Theta)$ into which protons are scattered by the deuterons which recoil into the solid angle $d\Omega(\theta)$ was used to obtain corrected values of R. Θ and θ are, respectively, the angles of a scattered proton and its recoil deuteron. Since the scattering volumes at the angles Θ and θ were also different, the true value of $Y(\theta)/Y(15)$ at angles less than 45° was obtained from

$$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{cor}}=\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{obs}}-\frac{d\Omega(\Theta)}{d\Omega(\theta)}\frac{\sin\Theta}{\sin\theta}\left[\frac{Y\Theta}{Y(15)}\right]_{\text{obs}},$$

where the last term is the contribution to the ratio at the angle θ due to recoil deuterons which arise from protons scattered at Θ, and where $[Y(\Theta)/Y(15)]_{\text{obs}}$ is obtained from the large angle data. Only a small amount of data was obtained between 20° and 45° and these are listed in Table IIb.

The angular dependence of R at 250 kev and 275 kev is shown in Figs. 2 and 3. In Fig. 2 for angles smaller than 45°, the dashed curve represents the observed value of R before application of the above correction for recoil deuterons. It is seen that the corrected values join fairly smoothly

TABLE III. Angular distribution of protons scattered from deuterium at 275 kev. The values of R in parenthesis are corrected for loss in counter efficiency by use of the efficiency curve in reference 4.

θ	No. of protons	$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{obs}}$	$\left[\frac{Y(\theta)}{Y(15)}\right]_{\text{calc}}$	R
55°	A16 13,216 B4 2,204	0.1658	0.0877	1.89
60°	A16 6,672 B4 832	0.1228	0.0595	2.065
65°	A16 20,000 B4 1,940	0.0959	0.0423	2.265
70°	A16 23,024 B4 1,804			
290°	A16 24,816 B4 1,976	0.0785	0.0311	2.521
75°	A16 26,544 B4 1,720			
285°	A16 8,032 B4 524	0.0643	0.02333	2.758
80°	A16 54,992 B4 2,968			
280°	A16 7,840 B4 404	0.0531	0.01782	2.976
82.5°	A16 82,432 B4 4,184	0.0505	0.01608	3.139
85°	A16 89,216 B4 4,256	0.0473	0.01421	3.325
87.5°	A16 84,112 B4 3,548	0.0418	0.01275	3.275 (3.39)
90°	A16 58,912 B4 2,208	0.0389	0.01143	3.397 (3.605)
95°	A16 38,080 B4 1,256	0.0325	0.00946	3.439 (3.915)

on to the data for angles greater than 45° where no recoil deuterons were present, and approach unity for the smallest angles. The low angle portion of the curve, due to the small amount of data taken and the method of applying the correction, is to be taken merely as indicative of the trend of R. More accurate data would have allowed an evaluation of the amount of contamination present if it is correct to assume that R should be unity at the smallest angles.

The curves show that the deviation from Rutherford scattering increases both with energy and angle, as might be expected. The angular dependence is in qualitative agreement with calculations based on Primakoff's formula with the "one body" theory combined with a theoretical cross section for neutron-deuteron scattering given by Ochiai, but is smaller by almost a factor of two in magnitude. At the largest angles considerable corrections for reduced counter efficiency must be made so these values of R cannot be expected to be very good.

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Magnetic Scattering of Neutrons

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The problem of magnetic scattering of neutrons has been reconsidered. The possible sources of error in the previous estimate are discussed. The form factor of the 3*d* shell of iron has been recalculated, with Hartree functions for Fe. This results in removal of the discrepancy between theory and experiment. Some predicted results of measurements with monoenergetic neutrons are given.

A RECENT theoretical evaluation[1] of neutron polarization experiments has indicated a marked discrepancy between theory and experiment. The calculated values are consistently too low by more than a factor two.

There appear to be three possible causes for this disagreement:

1. Since experimentally only the gyromagnetic ratio is measured, the possibility of neutron spin $=\frac{3}{2}$ might be considered. This suggestion, which would result in an increase in the theoretical estimate, has been made by Halpern and Johnson.[2] However, it is well known to be irreconcilable with our present understanding of the structure of light nuclei.[3]

2. The velocity distribution of the neutrons is not very accurately known. H. H. J. (reference 1) used the data of Dunning, etc.[4] obtained by use of a mechanical velocity selector. Though these results may contain considerable error, the theoretical estimate is not very sensitive to change in the distribution.

3. The calculated values of polarization effect are extremely sensitive to changes in the form-factor of the magnetically active 3*d* shell. H. H. J.

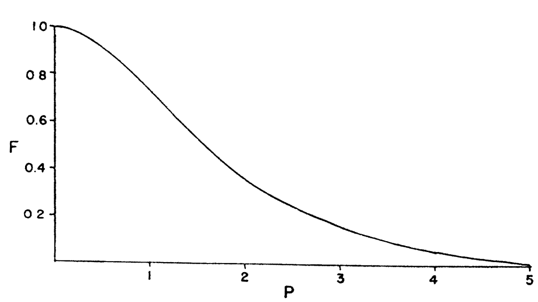

FIG. 1. Form factor for the 3*d* shell as a function of P.

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[3] See also J. Schwinger, Phys. Rev. **52**, 1250 (1937).
[4] Dunning, Pegram, Fink, Mitchell, and Segrè, Phys. Rev. **48**, 704 (1935).