Experiments on $N-P$ Scattering with 260-Mev Neutrons*

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(Received March 29, 1950)

Neutrons produced by 350-Mev protons impinging on beryllium are scattered by hydrogen. The differential scattering cross section is measured as a function of the scattering angle.

I. INTRODUCTION

WHEN the circulating proton beam of the 184-inch cyclotron is intercepted by a beryllium target at a radius of 81 inches, high energy neutrons are produced in the forward direction with an energy distribution maximum at about 260 Mev. Using this neutron beam with a low energy cut-off at 200 Mev we have performed $n-p$ scattering experiments similar to those previously carried out with neutrons of 40- and 90-Mev mean energies.[1]

The methods and apparatus used will in general be described only where they differ from those of the previous work and the reader is referred to the earlier paper for the missing details and for notation.[2] The principle of the experiment is to measure the number of protons scattered from a hydrogenous target into a fixed solid angle $d\Omega = d\psi d\cos\Phi$ at angle Φ; this number is proportional to the differential cross section $\sigma(\Phi)$. From this we find the differential cross section $\sigma(\theta) = \sigma(\Phi)[d(\cos\Phi)/d(\cos\theta)]$ in the center-of-mass system. The direct measurement of $\sigma(\Phi)$ is not on an absolute scale, but we can normalize it and pass to an absolute scale by requiring that

$$\int \sigma(\Phi)d\Omega = \text{total scattering cross section} = \sigma_t.$$

In practice polyethylene was used for the hydrogenous target and the effect of the carbon was measured (using graphite) and then subtracted.

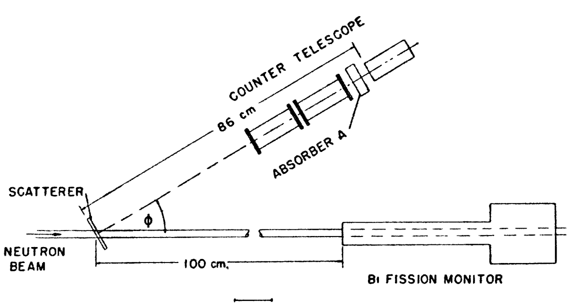

FIG. 1. General arrangement of apparatus.

The main results of the investigation are given in Tables I and II and Fig. 3. These results have been communicated in a preliminary form to Messrs. R. S. Christian and E. W. Hart, who have taken them into account in a theoretical paper endeavoring to interpret all $n-p$ scattering data through a suitable potential. We refer to their paper for the theoretical treatment of the data.[3]

II. APPARATUS

The arrangement of apparatus shown in Fig. 1 was used for all angles Φ. The diameter of the last counter has been increased to 5.1 cm and absorber A has been changed to the appropriate thickness of tungsten to give a primary neutron beam cut-off at an energy of 200 Mev; otherwise this apparatus is the same as apparatus A previously described in reference 1. The equipment was checked by all the performance tests described in Section II.E of reference 1. The approximate angular resolution of the telescope is 3°. The error in the value of $\sigma(\Phi)$ introduced by this lack of resolution is significant only for the value measured at $\Phi=0$; here we estimate that this effect would put the true cross section possibly 10 percent above the observed value (we have not made this correction to the data).

III. EFFECT OF ABSORBER A

The thickness of absorber A required to give a 200-Mev energy cut-off of the primary neutron beam (approximately 12 cm of Al or 4.5 cm of Pb at small angles) causes losses of the coincidence counting rate of the recoil protons and the variation of these losses with Φ is not small. These losses are due primarily to nuclear interaction, both elastic and inelastic, and to multiple small angle Rutherford scattering; estimates of the losses indicated tungsten to be a suitable material for absorber A and accordingly tungsten was used. It is not possible to calculate these losses accurately, due in part to lack of data and in part to the poorly defined geometry of the sensitive region of the counter behind absorber A.

To get an empirical measure of the loss due to absorber A the telescope was placed in the external deflected proton beam, the diameter of which was larger than that of the counters, and the attenuation of the telescope coincidence counting rate was measured for

* This work was performed under the auspices of the AEC.
[1] Hadley, Kelly, Leith, Segrè, Wiegand, and York, Phys. Rev. **75**, 351 (1949).
[2] In formula (5) of reference 1, Θ should be replaced by Φ; in the sixth line, first column of page 361, $d(\cos\Omega)/d(\cos\theta)$ should be replaced by $d(\cos\Phi)/d(\cos\theta)$, and the formula of the second column of page 361 should read $V(r) = (g^2/r)e^{-Kr}(1/2)(1+P)$.
[3] R. S. Christian and E. W. Hart, Phys. Rev. **77**, 441 (1950).

TABLE I. $\sigma(\Phi)$ in 10^{-27} cm^2 per steradian. All runs have been fitted to run 2, and normalized to the value of $\sigma_t = 0.035 \times 10^{-24}$ cm^2.

Run number Date Φ(deg.)	1 (3-10-49)	2 (3-23-49)	3 (3-31-49)	4 (4-7-49)	5 (4-14-49)	6 (4-21-49)	Weighted average	Transmission of absorber A
0			62±9				62.0±9.0	0.60
5			29±5			42.0±6.0	35.4±3.8	0.60
10	30±5	28.4±2.2	27±4			29.5±2.6	28.7±1.5	0.61
15		20.5±2.1	20±4				20.4±1.9	0.63
20		17.8±2.0				19.4±2.9	18.7±1.3	0.65
25		11.0±1.6					11.0±1.6	0.68
30		6.1±1.0				9.7±1.7	7.0±0.9	0.72
35		7.0±1.1		7.4±2.0	7.7±1.6	6.1±1.3	6.9±0.7	0.76
40		3.4±0.8					3.4±0.8	0.81
45	5.7±0.8	6.1±0.7		5.9±1.5	5.6±1.2	3.8±0.6	5.2±0.4	0.86
50				4.8±1.7			4.8±1.7	0.90
55				7.0±2.0	2.9±1.0		3.7±0.9	0.93
60					2.0±1.2		2.0±1.2	0.95
65				3.0±1.8	6.0±1.2		5.1±1.0	0.96
70				7.9±2.3	3.7±1.0		4.4±0.9	0.97

various thicknesses of tungsten placed in the position of absorber A. This was done as follows. In order to determine the number of incident protons an extra counter tube was placed in front of the telescope and electronically connected in triple coincidence with the first two counter tubes of the regular telescope. This electronic connection did not influence the operation of the regular telescope. In order to verify the voltage plateaus of the two systems of three counters the extra counter tube was de-sensitized by lowering its voltage so as to make it the controlling counter of the monitor coincidence circuit; the voltage on the regular telescope was then varied and in this way we could verify that the regular telescope was operating on a voltage plateau. Next, the sensitivity of the extra counter tube was increased until it was the same as that of the others and this was confirmed by the fact that, with no tungsten absorber, the regular telescope coincidence counting rate was 0.98 of the monitor coincidence counting rate. Finally the attenuation measurements were made.

The attenuation caused by the tungsten was found to be approximately linear with the thickness of the tungsten, ending in a sharp cut-off which gave the range of the proton beam. Data were taken at proton beam energies corresponding to ranges in tungsten of 109, 58, 38, and 24 g cm^{-2}. (The energy of the proton beam was varied by placing Al absorbers between the magnetic deflector and the focusing magnet of the cyclotron beam deflecting system.) On the basis of these data and the energy distribution of the neutron beam given in the next section, the attenuation due to absorber A was computed. Corrections for this have been applied to the differential cross sections given in Tables I and II and Fig. 3; the values of the transmission of absorber A are listed in Table I. We estimate these attenuation values to be good to about 10 percent.

IV. NEUTRON BEAM

The neutron beam was produced by intercepting the circulating beam of 350-Mev protons with a 5.08-cm thickness of beryllium. The beam was collimated in the forward direction by a hole in the 10-foot thick concrete walls of the cyclotron shield and emerged through an aperture whose diameter varied from 1 to 3 cm in the various runs; the neutron beam intensity at the scatterer was about 10^4 to 10^5 neutrons cm^{-2} sec.$^{-1}$. The equipment was accurately centered in the beam by the use of x-ray film preceded by a sheet of polyethylene for an intensifier.

An experimental determination of the energy distribution of the neutron beam was made by the method described in reference 1 of de-sensitizing the last counter of the telescope and varying the amount of tungsten placed in the position of absorber A. Allowing for the dependence of the $n-p$ scattering cross section on angle and energy and for the variation in loss due to different thickness of tungsten at the position of absorber A we obtain the results given in Fig. 2. For the 200 Mev cut-off used this gives a mean neutron energy of about 260 Mev.

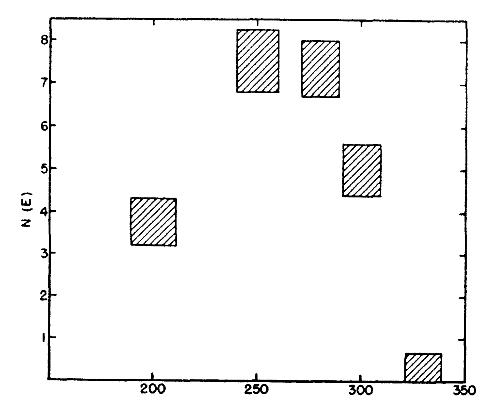

FIG. 2. Energy distribution of the primary neutrons in the beam in the forward direction obtained by 350 Mev protons incident on 5.08 cm thick beryllium. The width of the boxes represents the energy resolution of the detector and the height of the boxes represents the standard deviation due to counting statistics alone.

TABLE II. $\sigma(\theta)$ (center of gravity system) in 10^{-27} cm² per steradian; $\sigma(\theta)$ has been obtained by multiplying $\sigma(\Phi)$ of Table I by the appropriate values of d $(\cos\Phi)$/d $(\cos\theta)$ for neutrons of 260-Mev energy.

Run number Date θ(deg.)	1 (3-10-49)	2 (3-23-49)	3 (3-31-49)	4 (4-7-49)	5 (4-14-49)	6 (4-21-49)	Weighted average
180			13.7±2.1				13.7 ±2.1
169.3			6.4±1.2			9.2±1.2	7.8 ±0.8
158.7	6.8±1.1	6.4±0.5	6.1±0.9			6.6±0.6	6.4 ±0.3
148.1		4.8±0.5	4.6±0.9				4.7 ±0.4
137.6		4.3±0.5				4.7±0.7	4.5 ±0.3
127.1		2.8±0.4					2.8 ±0.4
116.7		1.7±0.3				2.6±0.5	1.90±0.24
106.5		2.0±0.3		2.2±0.6	2.3±0.5	1.8±0.4	2.02±0.21
96.3		1.1±0.3					1.09±0.26
86.3	2.0±0.3	2.2±0.3		2.1±0.5	2.0±0.4	1.4±0.2	1.85±0.14
76.4				1.9±0.7			1.9 ±0.7
66.6				3.2±0.9	1.3±0.5		1.7 ±0.4
56.8					1.1±0.6		1.1 ±0.6
47.2				1.9±1.2	3.9±0.8		3.3 ±0.6
37.7				6.4±1.9	3.0±0.8		3.6 ±0.7

V. CONCLUSION

The normalized values of $\sigma(\Phi)$ for all the runs are given in Table I. The normalization is carried out as explained earlier by requiring that

$$\int \sigma(\Phi)d\Omega = \sigma_t = 0.035\times 10^{-24}\ \text{cm}^2.$$

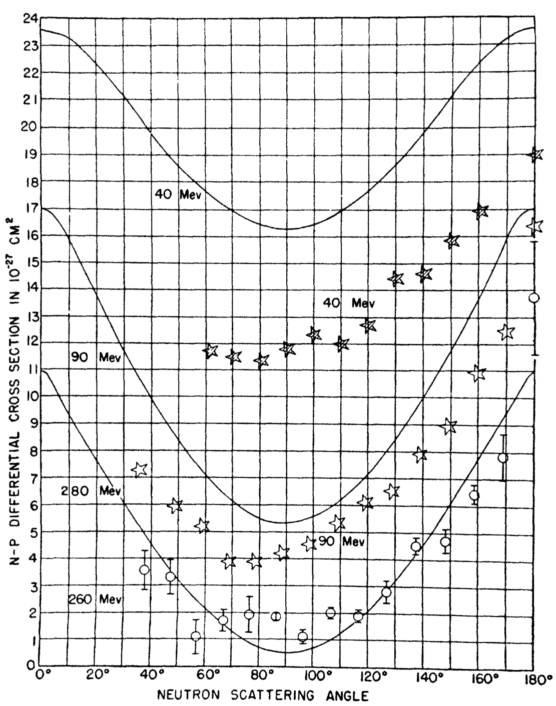

FIG. 3. Differential neutron proton cross section in the center-of-mass system in 10^{-27} cm² per steradian. The stars represent data published earlier but are included here for reference. The lowest curve represents the data taken with 260 Mev neutrons; the errors given are standard deviations due to counting statistics alone. The solid curves are the theoretical predictions for a Yukawa tensor force model and have been copied from Fig. 17 of reference 3. (The predicted cross section for 280 Mev $n-p$ scattering is 0.037×10^{-24} cm², the value quoted in reference 3 being incorrect.)

Since $\sigma(\Phi)$ is not known for the entire range of Φ we have arbitrarily extrapolated $\sigma(\Phi)$; using units of 10^{-27} cm² we have put $\sigma(\Phi)$ equal to 3.6 at 75°, 3.0 at 80°, 2.0 at 85° and 0 at 90°. The contribution of the extrapolated part of the curve to σ_t is 15 percent of the total. The value of σ_t has been measured in this laboratory,[4,5] using two types of detectors; the value of $\sigma_t = 0.035\times 10^{-24}$ cm² has been taken as approximate average of these data. As was explained in Section III of reference 1 this value of σ_t is subject to considerable uncertainty (25 percent) because of the neutron energy distribution and the change of sensitivity with energy for the particular detectors used.

To find $\sigma(\theta)$, the center-of-mass differential cross section, the value of $\sigma(\Phi)$ must be multiplied by d $\cos\Phi$/d $\cos\theta$ and the result paired with the value of θ corresponding to the Φ considered. This has been done using the appropriate values of d $\cos\Phi$/d $\cos\theta$ for neutrons of 260 Mev energy and the results for all runs are given in Table II; the weighted averages of these data are shown in Fig. 3. For comparison we have included in Fig. 3 the previous measurements at 40 and 90 Mev which are shown as stars. The errors given in the tables are the standard deviations calculated from counting statistics only.

The weakest points of these experiments are the broadness of the primary neutron spectrum, the uncertainty in the total neutron cross section, and the fact that the form of the primary neutron spectrum is not well known. If a better neutron source (e.g., protons on deuterons) should be found, it would be worthwhile to repeat the whole experiment, possibly with considerable changes in technique, for example, with scintillation counters. In the meantime we have decided to publish the present results even though they are probably less reliable than those given in reference 1.

[4] R. Fox, C. Leith, K. McKenzie, and L. Wouters (to be published).

[5] J. DeJuren (to be published).