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Neutron-Proton Scattering at 91 Mev*

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The angular distribution of neutrons scattered by protons has been measured for center-of-mass scattering angles between 60° and 180°. The effective neutron energy was 91 ± 1 Mev. A liquid hydrogen scatterer and plastic scintillation proton counters were used. The experimental results are in good agreement with previous experiments at this energy.

I. INTRODUCTION

THE angular distribution of neutron-proton scattering has been measured in the past at Berkeley[1] and Harvard,[2] using neutron beams with an effective energy of about 90 Mev, and more recently at Harwell using 104-Mev neutrons.[3] Because of the importance of this experiment to the nuclear force problem, it has now been repeated with different equipment.

In this measurement, a liquid hydrogen scatterer was irradiated by neutrons from a beryllium target inserted in the circulating proton beam of the Harvard synchrocyclotron. The relative number of recoil protons at various scattering angles was measured by a movable scintillation telescope. A similar, fixed, telescope facing a CH_2 radiator monitored the neutron flux. Since the effective thickness of the liquid hydrogen target varied from one angle to another, the energy interval of protons accepted by the telescope was varied to keep the effective energy of measurement constant at 91 Mev. The results were also corrected for variation of the telescope efficiency with proton energy. The resultant relative cross sections, transformed to the center-of-mass coordinate system, were normalized to the $n-p$ total cross section.

The notation for the scattering angles follows the practice introduced by Hadley *et al.*[1] Θ and Φ are, respectively, the laboratory system neutron and proton scattering angles, and ϑ and φ the corresponding angles in the center-of-mass system. The kinematic transformation equations are given by Hadley.[1]

II. EXPERIMENTAL EQUIPMENT

A schematic diagram of the equipment used in this experiment is shown on Fig. 1. Neutrons from the $\frac{1}{8}$-in. beryllium target were collimated by a 6-ft long tapered brass collimator inserted in the water shielding tank. This defined a cone of neutrons 4 cm wide and 10 cm high at the hydrogen target about 7 meters from the source. A lead shielding block 24 in. thick, piled against the cyclotron tank, shielded against stray radiation from the cyclotron. Another lead block, 18 in. thick, at the outside of the water tank, shielded against particles scattered by the collimator walls.

Since liquid hydrogen is not normally available at this laboratory, a helium-hydrogen converter has been constructed to liquefy the small amounts of hydrogen actually needed for scattering purposes, and to keep these targets liquid for a period of several days which is required to perform an experiment. This cryostat will be described in detail elsewhere.[4] The target used in the $n-p$ experiment consisted of a 3-cm diameter cylinder of liquid hydrogen in a foil tube of 0.0006-in. thick beryllium copper. A second, evacuated tube was mounted on the same plate, and could be bombarded alternately by rotating the cryostat. In this way background scattering was measured. The copper foils did not contribute very much to the background.

The targets were kept in a large steel scattering chamber.[5] Neutrons entered, and recoil protons left through 0.005-in. aluminum windows. The targets were surrounded by a radiation shield at near liquid nitrogen temperature, having windows of 0.0005-in. aluminum in the beam direction. The counter telescope was placed on one of two I-beams attached to the chamber base. This entire assembly rotated about an axis through the liquid hydrogen target, and could be positioned by remote control to within $\pm\frac{1}{5}°$. It was convenient to use one of the counter positions (on the beam 15° from a line perpendicular to the chamber face) for recoil proton angles $\Phi=0°$ to 30°. To reduce the scattering of the protons by a long air path, a helium balloon about 2 meters long was placed between the vacuum chamber and the counter telescope. Angles from $\Phi=20°$ to 60° were measured with the counter telescope on the 45° arm. Since protons here had lower energy it was necessary to extend the vacuum chamber to the counters. The telescope was closer to the target in this position

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[1] J. Hadley *et al.*, Phys. Rev. **75**, 351 (1949); K. A. Brueckner *et al.*, Phys. Rev. **75**, 555 (1949); R. H. Fox, University of California Radiation Laboratory Report UCRL-867 (unpublished); R. Wallace, Phys. Rev. **81**, 495 (1951); O. Chamberlain and S. W. Easley, Phys. Rev. **94**, 208 (1954); W. M. Powell and Chih (private communication); W. M. Powell, Phys. Rev. **94**, 786 (1954).

[2] Selove, Strauch, and Titus, Phys. Rev. **92**, 724 (1953).

[3] R. Wilson (private communication) and *Proceedings of the Fourth Annual Rochester Conference on High-Energy Physics*, (University of Rochester Press, Rochester, 1954), p. 5.

[4] C. A. Swenson and R. H. Stahl, Rev. Sci. Instr. **25**, 608 (1954).

[5] Built by J. M. Teem and U. E. Kruse.

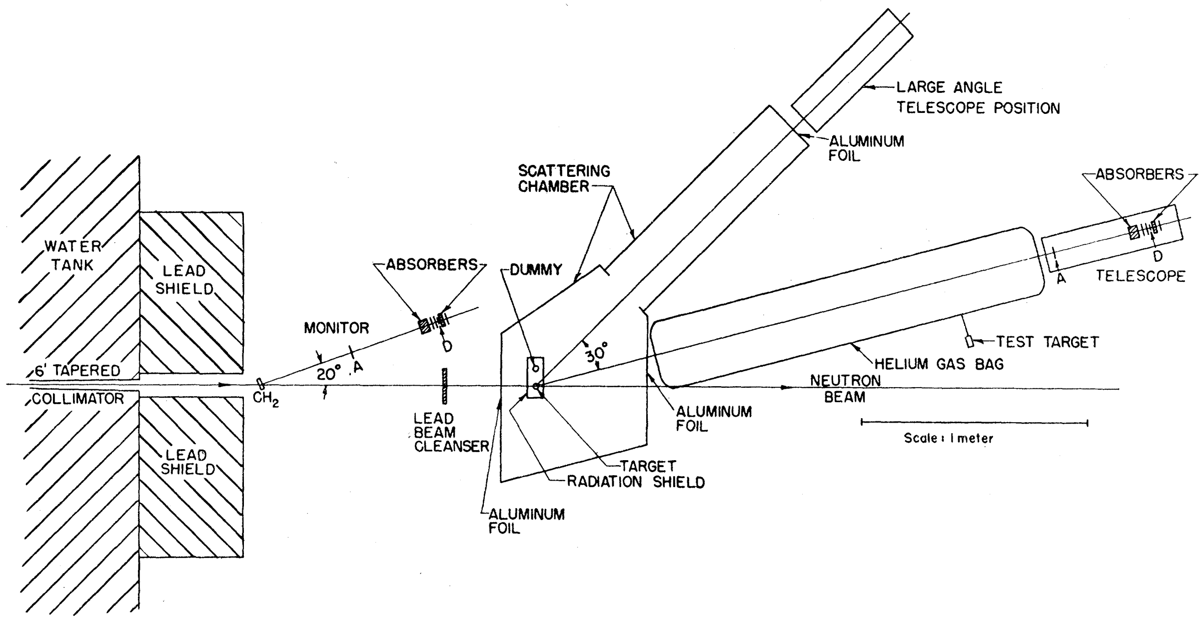

FIG. 1. Schematic diagram of $n-p$ experiment.

to improve counting rates at large proton scattering angles.

The monitor telescope with its CH_2 radiator, and a lead beam cleanser were located between the shielding and the scattering chamber. No charged particle in the neutron beam emerged from the lead with an energy above the telescope threshold.

All counters used in this experiment were plastic scintillators[6] attached to 1P21 photomultipliers tubes. Usually five scintillator telescopes were used; the fourth (D) was the defining crystal, and had the same size as the active portion of the hydrogen target -3 cm$\times$10 cm. The rest were larger, 4.4 cm$\times$11.5 cm. CH_2 absorbers were placed in front of the B crystal and behind the D crystal. The protons of interest were those which penetrated into D but not E. Different absorbers were used at each angle, calculated as described below in Sec. III, using the range energy curves of Aron, Hoffman, and Williams.[7] Polyethylene was selected as absorber material in order to keep the range telescope, of which the absorber forms a variable part, relatively homogeneous. At large recoil angles, at which the recoil proton energy is low, first C and then also B scintillators were removed from the telescope. Overlapping portions of the $n-p$ curve were taken using all states of the recoil telescope.

The amplifiers and coincidence circuits used in this experiment have been described by Strauch.[8] The only change has been the addition of a one-stage limiting preamplifier immediately following the phototubes, built around a Phillips EFP 60 secondary emission tube. The high transconductance of this tube makes it possible to build a conventional amplifying circuit with a rise time of about 10^{-8} second. Use of this amplifier improved the plateaus of the counters, while the resolution of the circuits became slightly poorer. Tests were made for accidental coincidences by displacing one counter laterally until no true coincidences could occur. It was found that at the counting rates of this experiment the accidental rate was negligible.

Individual counter efficiency was checked by inserting defining scintillators in front and back of the telescope, and requiring agreement of TT, $TABCDET$ counting rates. Efficiencies exceeded 99 percent, and were rechecked at least daily in the course of the cyclotron runs. No great variation of efficiency over the area of these rather large scintillators was noted.

The efficiency with which the telescope counted protons was checked experimentally, using cyclotron external proton beams with energies between 20 Mev and 90 Mev. A two scintillator monitor was used (the second crystal of defining size) and the telescope was set up in the external proton beam, about $1\frac{1}{2}$ meters from the monitor. The strength of the beam was reduced to eliminate chance coincidences. The variation of the monitor—D coincidence counting rate was then observed as a function of absorber thickness. The results of the calibration are shown on Fig. 2. It is seen that the efficiency is quite uniform above 35 Mev. Below that, the outscattering by the A scintillator increasingly exceeds the in-scattering. The A crystal had been placed about 16 in. in front of the D crystal in order to reduce background counting rates at large Φ.

When the telescope is set up at an angle Φ, it is of

[6] Pilot Chemicals Inc., Waltham, Massachusetts; Larco Nuclear Instruments Company, Palisades Park, New Jersey.
[7] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU 663, 1949 (unpublished).
[8] K. Strauch, Rev. Sci. Instr. 24, 283 (1953).

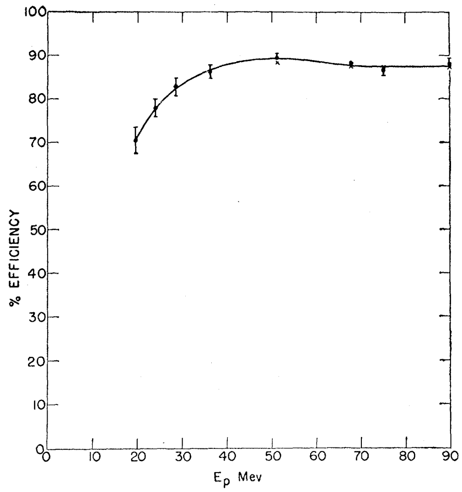

FIG. 2. Efficiency of recoil counter telescope. ×—computed from initial slope of integral range curves; ○—directly from integral range curves.

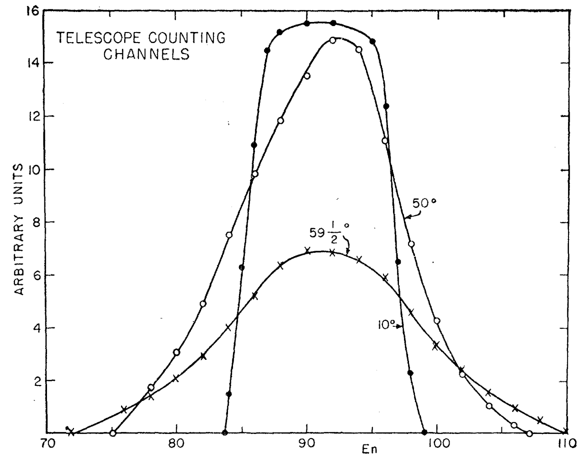

FIG. 4. Effective flux counted at various angles—typical BF curves.

course sensitive to a range of angles about Φ. The angular resolution of the equipment is conveniently defined as the full width at half height of the angular sensitivity function. It depends on a number of factors: (1) the divergence of the incident neutron beam, (2) the size and separation of the counter-scatterer system, and (3) scattering of protons in the hydrogen, the surrounding foils, and in the telescope. Assuming each of these to yield a roughly Gaussian distribution, the angular resolution may be computed and has been shown in Fig. 3. The rise at large θ, i.e., at the smallest recoil proton angles, is caused by the long vertical shape of the counters and the active target.

The neutron monitor consisted of a telescope of the same size as the main telescope, operating as a permanent $\Phi=20°$ channel. It faced a CH_2 radiator of the same thickness to protons as the liquid hydrogen target at 20 (0.408 g/cm^2). The angular resolution was poorer. The

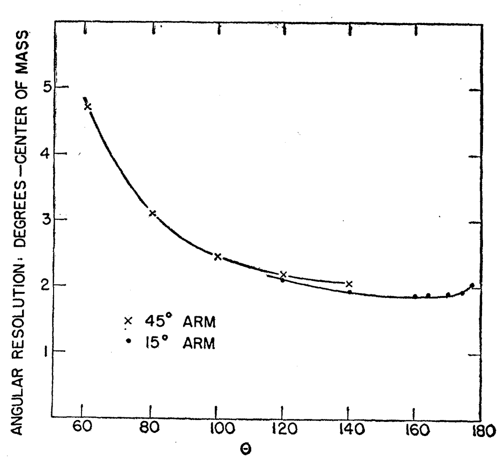

FIG. 3. Approximate angular resolution of equipment at various angles.

scattering by carbon in the CH_2 amounted to (7.2 ± 0.5) percent, and the background was 0.5 percent of the hydrogen rate. These corrections of the monitor counting rate were not normally made.

III. COUNTING CHANNEL CALCULATIONS

In all $n-p$ experiments, the incident neutron beam contains a considerable spread of energies, only a protion of which is used. The interpretation of the experimental data therefore depends on a precise knowledge of the effective flux. The energy of the recoil protons decreases rapidly with angle $(E_p(\Phi)\simeq E_n\cos^2\Phi)$ while the scatterer dE/dx increases. However, in experiments using CH_2-C targets, it is customary to use at each angle scatterers designed to have the same stopping power on a neutron energy scale. On such a scale, therefore, the energetics of the experiment are then kept constant for all angles. In this experiment the same 3-cm diameter liquid hydrogen scatterer was used throughout since it was not feasible to replace the liquid hydrogen target frequently. The target thickness as seen by a proton recoiling at the center of the cylinder from a neutron of a certain energy increased rapidly with Φ. If the energy interval of protons accepted by the telescope (on the neutron energy scale) had remained constant for all Φ, then at larger Φ recoils from higher-energy neutrons would have been counted preferentially. The telescope counting channel was therefore varied to keep the energy of measurement constant.

If $C(\Phi)$ is the counting rate at an angle Φ, then

$$C(\Phi)=NVg\int\sigma(\Phi,E_n)F(E_n)B(E_n,\Phi)dE_n,$$

where N is the proton density in the scatterer, V the scatterer volume, g the solid angle intercepted by the telescope, $\sigma(\Phi,E_n)$ the $n-p$ differential cross section, $F(E_n)$ the incident neutron flux, and $B(E_n,\Phi)$ the probability of counting a proton recoiling anywhere in the scatterer at an angle Φ from a neutron with energy E_n. It is useful to expand the cross section about E_0.

$$\sigma(\Phi,E)=\sigma(\Phi,E_0)\times\left\{1+\alpha_\Phi\left(\frac{E-E_0}{E_0}\right)+\beta_\Phi\left(\frac{E-E_0}{E_0}\right)^2+\cdots\right\}.$$

If we define E_0' such that

$$\int B(E_n\Phi)F(E_n)\left(\frac{E-E_0'}{E_0'}\right)dE_n=0,$$

then E_0', the center of gravity of the BF curve, is the energy of measurement.

$$C(\Phi)=NVg\sigma(\Phi,E_0')\times\left\{\int BFdE+\beta_\Phi\int BF\left(\frac{E-E_0'}{E_0'}\right)^2dE\right\}.$$

The calculation of $B(E_n,\Phi)$ falls into two parts:

$$B(E_n,\Phi)=\bar{\eta}(\Phi)B'(E_n,\Phi).$$

Here $\bar{\eta}(\Phi)$ is the average telescope efficiency for proton energies encountered at an angle Φ. It has been measured experimentally as described in the previous section. The theoretical counting efficiency $B'(E_n,\Phi)$ was computed for each angle, and the telescope limits fixed to keep the center of gravity of the $B'F$ curve at 91 Mev. Corrections were made for the circular cross section of the scatterer. $\int BFdE$ was then measured graphically. A number of these curves are shown on Fig. 4.

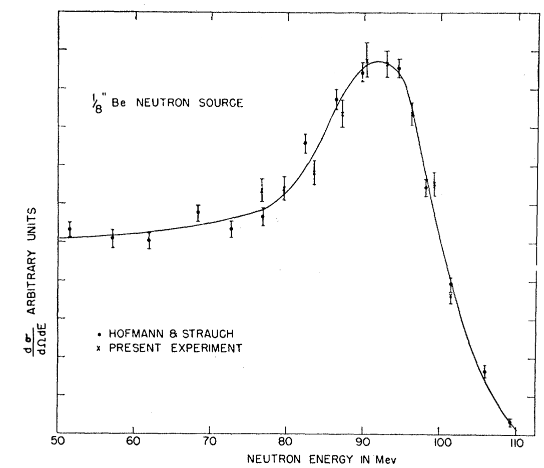

FIG. 5. Energy distribution of the $\frac{1}{8}$-inch Be neutron beam.

The neutron energy spectrum used in these calculations is shown on Fig. 5. It has been measured in the past by Hofmann and Strauch,[9] and again as part of this experiment. Small variations of the neutron energy distribution could be detected by the change in the fraction AE/AD in the monitor. No changes corresponding to a shift of the neutron spectrum leading edge by more than $\frac{3}{4}$ Mev were noticed when cyclotron operation was steady.

The reliability of this correction has been investigated

TABLE I. Differential $n-p$ scattering cross section in the center-of-mass system. Neutron energy=91 Mev (lab).

Proton angle (lab) Φ(deg)	Neutron angle (c.m.) θ(deg)	Run No. 2 mb/sterad	±%	Run 4a mb/sterad	±%	Run 4b mb/sterad	±%	Run 4c mb/sterad	±%	Run 5 mb/sterad	±%	Weighted average mb/sterad	±%
$1\frac{1}{2}$	176.6	13.07	3.0					13.06	4.6	13.01	3.7	13.08	3.1
2	175.6	12.90	3.2					13.01	3.6	13.45	3.7	13.09	2.9
3	173.7	13.20	4.5	13.41	3.4			13.09	3.6	13.38	2.6	13.30	2.5
4	171.7	13.36	3.0					13.32	3.1	13.08	2.7	13.24	2.6
5	169.7	13.09	3.0					12.26	2.7	13.14	2.7	12.61	2.5
$6\frac{1}{4}$	167.3	11.94	3.0	11.62	3.4			11.66	3.5	12.01	2.9	11.84	2.5
$7\frac{1}{2}$	164.5	11.82	2.7	12.10	3.4			11.50	4.4	11.74	2.9	11.82	2.6
$8\frac{3}{4}$	162.0	11.02	3.3	10.24	6.2			10.93	3.5	10.72	4.3	10.85	2.8
10	159.4	10.09	3.2	10.60	2.5			10.33	3.9	10.60	3.7	10.42	2.5
−10	159.4							10.84	3.6			10.84	4.0
12	154.9	10.26	3.1	9.47	3.8					10.05	3.7	9.97	3.0
15	149.3			8.53	3.0			8.61	3.6	9.72	2.3	9.13	2.6
20	139.1	7.48	2.6	7.72	3.8	7.86	2.2			7.82	2.6	7.74	2.5
20A	139.1					8.28	3.1			7.94	2.6	8.08	3.5
25	129.0	6.16	2.2	6.40	3.9					6.98	2.4	6.51	2.6
30	118.8	5.92	2.0			6.10	3.0			6.05	2.2	5.99	2.5
35	108.7	4.90	2.9							4.98	3.5	4.93	3.3
40	98.7	4.60	2.3			4.52	3.4			4.33	4.4	4.53	3.0
45	88.7	4.17	2.7							4.40	3.0	4.19	3.5
$47\frac{1}{2}$	82.7					3.79	4.5			4.06	3.4	3.96	3.3
50	78.7	4.08	3.8			4.20	3.1			4.22	2.9	4.17	3.7
52	74.7									4.08	3.5	4.08	4.7
$54\frac{1}{2}$	69.7	3.82	5.6			4.06	4.1			4.50	3.0	4.26	4.3
57	64.8									4.89	4.6	4.88	5.9
$59\frac{1}{2}$	59.8									5.61	3.8	5.61	5.9

[9] J. A. Hofmann and K. Strauch, Phys. Rev. **90**, 449 (1953).

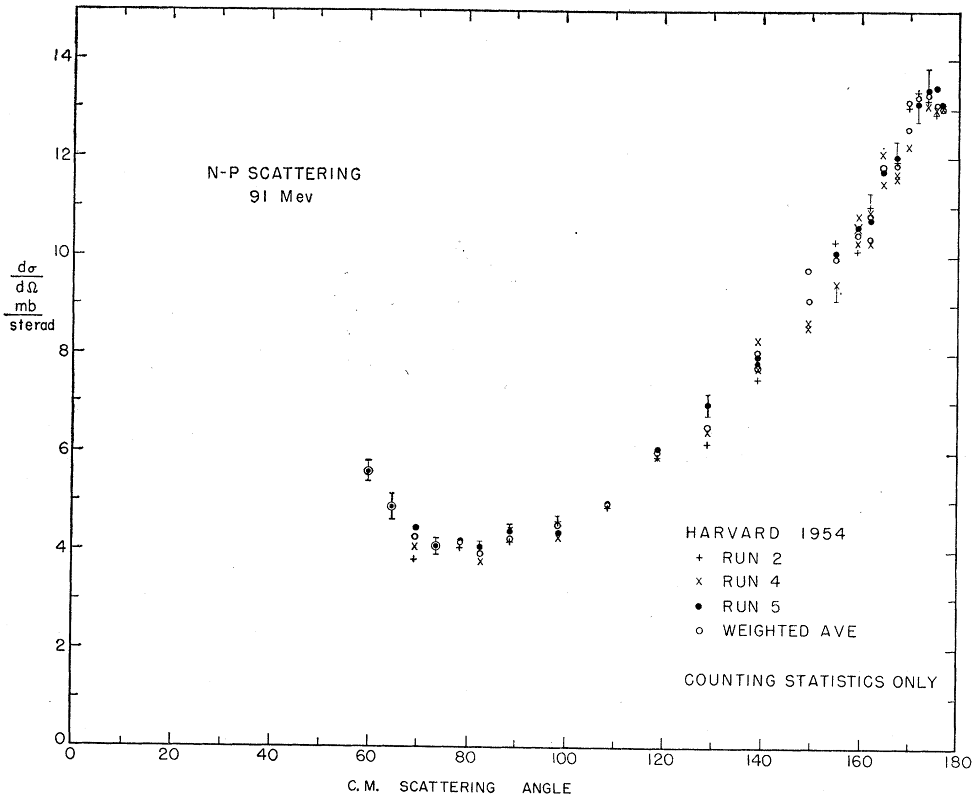

FIG. 6. Results of the individual runs of this experiment, and weighted averages. Errors shown are counting statistical mean deviations.

by varying some of the parameters. Both E_0' and $\int BFdE$ were found quite insensitive to the small variations in the target diameter which occurred when leaky foils were replaced. The integral, but not its center of gravity, was affected by variations in the neutron energy flux, especially at the largest Φ. Raising the leading edge by $2\frac{1}{2}$ Mev changed the ratio of areas at 10° and 59.5° by 5.6 percent. The uncertainty of the neutron flux is thus the chief uncertainty of this correction. As an additional check, two channels were designed for $\Phi=20°$, one using a much larger portion of the neutron spectrum. Cross sections taken in this manner have agreed within counting statistics.

The second order correction was small, a maximum of 1.3 percent at $\Phi=59\frac{1}{2}°$. The factor β was estimated using $n-p$ data at 40 Mev[10] and at 156 Mev,[11] and the integral computed from the BF curve. The error introduced by the uncertainty in this correction should be less than $\pm\frac{1}{2}$ percent for all angles.

IV. NORMALIZATION

The procedure outlined above gave relative differential cross sections in the laboratory system. These were transferred to the center-of-mass system by multiplying by $d\cos\Phi/d\cos\theta$. The total neutron cross section of hydrogen (78.5±3 mb)[12] was then used to place an absolute value on the cross sections. For the region $\Phi=0-60°$, not covered in this experiment, other $n-p$ experiments[1,3] were consulted. This normalization is believed accurate to ±5 percent.

V. RESULTS

The results of the various individual runs, as well as the weighted averages, are given on Table I and on Fig. 6. Errors for the individual runs are counting statistics only, while those of the weighted average are total errors compounded from the following sources:

(1) Counting statistics.

(2) Fitting errors. The counter-monitor ratios, which are the experimental numbers of this experiment, will have the same absolute values only if the equipment is set up precisely the same way each time. This was not done for runs No. 2 and No. 4b, and so an error is introduced fitting these curves to the others. This was taken to be about half the counting statistics.

(3) Error in the correction for telescope efficiency. See Fig. 2. This varies from 1 percent at 180° to 3 percent at 60°.

[10] J. Hadley *et al.*, reference 1.

[11] Randle, Taylor, and Wood, Proc. Roy. Soc. (London) **A213**, 392 (1952).

[12] A. E. Taylor and E. Wood, Phil. Mag. **44**, 95 (1953); J. de Juren and N. Knable, Phys. Rev. **77**, 606 (1950); L. J. Cook *et al.*, Phys. Rev. **75**, 7 (1949).

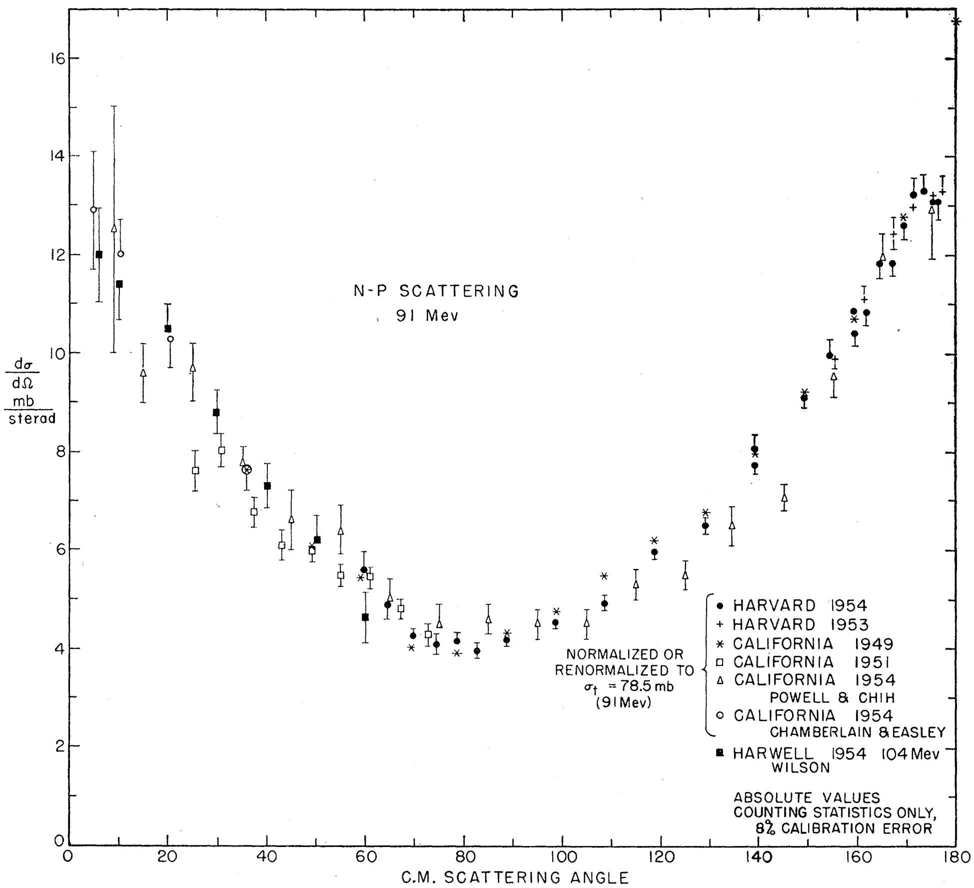

FIG. 7. Summary of $n-p$ scattering results in the neutron energy range 85–105 Mev. The California data of 1949 have been renormalized to a total cross section of 78.5 mb, and the 1951 California and 1953 Harvard experiments have been refitted to the n curve. Errors shown are those listed by each experiment (see Sec. V).

(4) Error in the counting channel computation, caused primarily by uncertainty in the neutron energy distribution. This was taken to be either $1\frac{1}{2}$ percent or the error arising from a 1 Mev shift of the neutron spectrum leading edge, whichever was larger. It rose to 3 percent at 60°.

VI. CONCLUSIONS

A summary of the results of various $n-p$ experiments[1–3] in the energy region 85–105 Mev is given on Fig. 7. For this graph, the results of Hadley *et al.*[1] (California, 1949) have been renormalized to a more recent value of the $n-p$ total cross section. The results of Selove, Strauch, and Titus[2] (Harvard, 1953) and of Wallace[1] (California, 1951) have been renormalized to give a closer fit to the more complete $n-p$ angular distribution curve which is now available. The errors shown for the present experiment are the total errors discussed in the previous section.

These results are seen from Fig. 7 to be in good agreement. The $n-p$ curve is at this energy only slightly asymmetric about 90°. It becomes flat for scattering angles greater than 170°, and may dip again at the largest scattering angles measured, although the uncertainties of the experiment do not permit a definite conclusion on this subject. The ratio of cross sections at $\theta=\pi$ and $\theta=\pi/2$ is 3.15±0.10.

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