Neutron-Proton Differential Cross Section at 129 and 150 MeV*

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The differential cross section for neutron-proton scattering has been measured from 70° to 180° (center-of-mass system) at energies of 129±1 and 150±1 MeV. A neutron beam was used which has an energy width of 6 MeV. The data have relative errors of from 3 to 4%. They have been normalized to total-cross-section data with the aid of phase-shift analyses; differences between various solutions imply an uncertainty in the absolute value of these cross-section data of as much as 6.5%. The data at 150 MeV are shown to be more reasonable than previous data in this energy region. The data at 129 MeV agree well with earlier work.

INTRODUCTION

THE phenomenological description of the nucleon-nucleon force has become much clearer in the last few years.[1–3] However, the phase-shift analysis of neutron-proton scattering shows that further data are required before completely satisfactory solutions are obtained.

A recent comparison[4] of neutron-proton charge-exchange scattering has shown that the previous results at 156 MeV[5] were inconsistent with other work at 91,[6] 200,[7] and 350 MeV.[8] The experiments described below were undertaken to clarify this situation and thus to provide more accurate data for phase-shift analyses.

The mono-kinetic neutron beam used for these measurements is obtained by bombarding a liquid-deuterium target with the external proton beam of the Harvard synchrocyclotron.[9] The neutron-proton differential cross section was measured by detecting the protons scattered by the neutron beam from a liquid-hydrogen target. The detector was a plastic scintillator telescope in coincidence with a sodium iodide crystal.

APPARATUS AND PROCEDURES

The neutron beam has an intensity of 4×10^4 neutrons/sec and an energy width of about 6 MeV; Fig. 1 shows an energy spectrum of the 150-MeV beam. The spectrum was obtained directly by the equipment used in this experiment. The neutron beam was collimated by a $1\frac{7}{8}$ in.$\times\frac{7}{8}$ in. rectangular aperture. The collimator consists of a 2 in.$\times$1 in. copper waveguide set in a lead matrix; it is 8 ft long and has antiscattering regions towards the experimental area.

A liquid-hydrogen target was used. The liquid was contained in a 1-in.-diam plastic cylinder 5 in. long which was constructed from 0.001-in. Kapton polyimide film (formerly *H* film). This was bonded to itself and to the brass end pieces with an epoxy cement. Epon 828 was used with the hardener V25; it is manufactured by the Shell Chemical Company. The cryostat was of standard design with a liquid-nitrogen heat shield. The liquid hydrogen lasted for at least 5 days.

The protons scattered by the neutron beam were detected by a plastic scintillator telescope and sodium iodide crystal. The plastic scintillator used was Pilot B,[10] and in all the counters it was viewed by RCA 7850 photomultiplier tubes. The 3-in.$\times$3-in. sodium iodide crystal[11] was viewed by a Du Mont 6363 photomultiplier tube. Figure 2 shows the experimental arrangement. The first two counters A and B in the measuring telescope had scintillators measuring 4 in.$\times2\frac{1}{2}$ in.$\times\frac{1}{16}$ in. The defining counter C was 2 in.$\times$1 in.$\times\frac{1}{16}$ in., and was placed immediately in front of the sodium iodide crystal. As the counter and target are both 1 in. wide in the horizontal plane, this means that the angular resolution is about 4° in the laboratory coordinates or 8° in the center-of-mass coordinates.

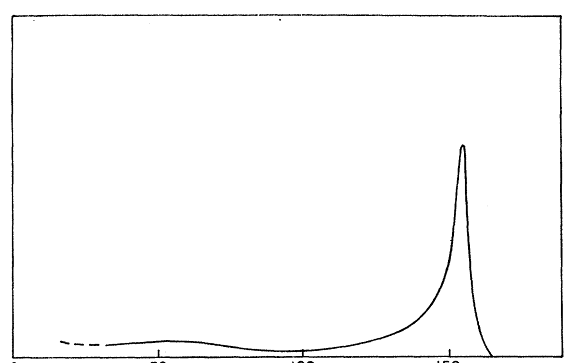

FIG. 1. Energy spectrum of 150-MeV beam.

* This work was suported by the U. S. Office of Naval Research.
[1] G. Breit, M. H. Hull, K. E. Lassila, and K. D. Pyatt, Phys. Rev. **120**, 2227 (1960).
[2] M. H. Hull, K. E. Lassila, H. M. Ruppel, F. A. McDonald, and G. Breit, Phys. Rev. **122**, 1606 (1961).
[3] M. H. McGregor and R. A. Arndt, Phys. Rev. **139**, B362 (1965).
[4] Richard Wilson, Ann. Phys. (N.Y.) **32**, 193 (1965).
[5] T. C. Randle, A. E. Taylor, and E. Wood, Proc. Phys. Soc. (London) **A213**, 392 (1952).
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[7] Yu M. Kazarinov and Yu N. Simonov, Zh. Eksperim. i Teor. Fiz. **43**, 35 (1962) [English transl.: Soviet Phys.—JETP **16**, 24 (1963)].
[8] A. Ashmore, W. H. Range, R. T. Taylor, B. M. Townes, and R. F. Peierls, Nucl. Phys. **36**, 258 (1962).
[9] D. F. Measday, Nucl. Instr. Methods (to be published).
[10] Manufactured by Pilot Chemicals, Inc., Watertown, Massachusetts.
[11] Manufactured by Harshaw Chemical Company, Cleveland, Ohio.

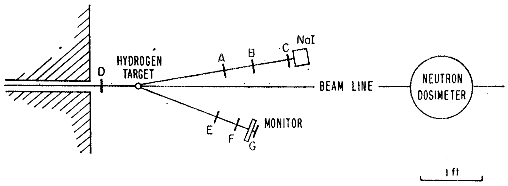

FIG. 2. Experimental layout.

For the larger center-of-mass angles the telescope intercepts the neutron beam. Protons of the same energy as the neutron beam can be formed by conversion in the air and in the collimator material; these contaminate the neutron beam. When measuring these larger center-of-mass angles it was therefore necessary to add a fourth plastic scintillator D before the hydrogen target. This is placed in anticoincidence with the other detectors and therefore requires that an uncharged particle entered the hydrogen target. The counter measured $7\frac{1}{2}$ in.$\times$6 in.$\times\frac{1}{32}$ in. Because of its large area and small thickness, the resolution of this detector was not very good and the anticoincidence efficiency was only 99%. However, this was adequate.

The alignment of the target and scattering arm were accomplished from a direct measurement of the neutron beam position. A 2-in.$\times$1-in.$\times\frac{1}{8}$-in. plastic scintillator was placed with the $\frac{1}{8}$-in. dimension across the axis of the beam. The neutrons scatter off the hydrogen in the plastic and the high-energy protons can be detected. Because of the large background of low-energy neutrons in the experimental area a discriminator curve was run and a setting was chosen at which less than $\frac{1}{2}$% of the counts were from the room background. Figure 3 shows a typical beam profile obtained in this manner. This is the profile at the back of the scattering table; this is used to determine the beam direction. A similar profile is taken at the target position. The beam center can be located to $\pm$0.03 in. at both the pivot point and the extremity of the scattering arm. There is a further uncertainty of $\pm$0.03 in. in the positioning of the hydrogen target cup with respect to the pivot point. These uncertainties add a small error to the cross section at a few angles. It is always less than $\frac{1}{2}$%. The scattering arm is positioned with a sine bar; this locates the end of the arm to within 0.005 in. of the desired position and so contributes no significant error. Spirit levels were permanently fixed to the arm to check that it was always level.

The neutrons were monitored continuously by three methods. The prime monitor was a second telescope placed at $18\frac{1}{2}°$ (laboratory coordinates) to the beam, and on the other side of the measuring telescope. It detected protons scattered from the one hydrogen target. The counter dimensions in the monitor telescope were: E, 3 in.$\times$2 in.$\times\frac{1}{32}$ in.: F, 4 in.$\times2\frac{1}{2}$ in.$\times\frac{1}{8}$ in.; G, 5 in.$\times$3 in.$\times\frac{1}{8}$ in. Between counters F and G was placed 11.32 g/cm^2 thickness of copper. This means that it requires a proton of energy at least 100 MeV to penetrate the final counter, and be detected. The monitor telescope subtended an angle which was ten times larger than that of the measuring telescope; the count rate of the monitor telescope was therefore always greater than the measuring telescope, but the statistics of both are included in the quoted errors.

Two secondary monitors were used. The neutron beam was detected directly by a special neutron dosimeter.[12] It is based on a design by Bramblett, Ewing, and Bonner.[13] It consists of a lithium iodide crystal embedded in a 12-in.-diam sphere of polyethylene. A discriminator was set on the pulses from the crystal. A pulse-height setting was chosen which was above the thermal peak so that the detected neutrons had an energy of at least 1 MeV. The count rate of this monitor when it was placed out of the neutron beam was only 0.3% of the count rate when it was in the beam. If a lower discriminator setting had been used, the number of thermal neutrons from the room background detected would have been greater than those from the beam.

In addition to this neutron detector, a continuous check was kept on the proton beam striking the deuterium target. An ionization chamber was used. It was placed immediately before the deuterium target. The plates were made from 0.00025-in.-thick sheets of aluminum. During the runs all the monitors were recorded; a comparison of all three shows that at no time was there a variation outside of statistics. The statistical accuracy was always better than 1% and often as good as 0.2%.

Because the prime monitor was viewing the same target as the measuring telescope, background measurements had to rely on the other two monitors. There was insufficient space to include a second target for the monitor telescope. As the backgrounds were usually

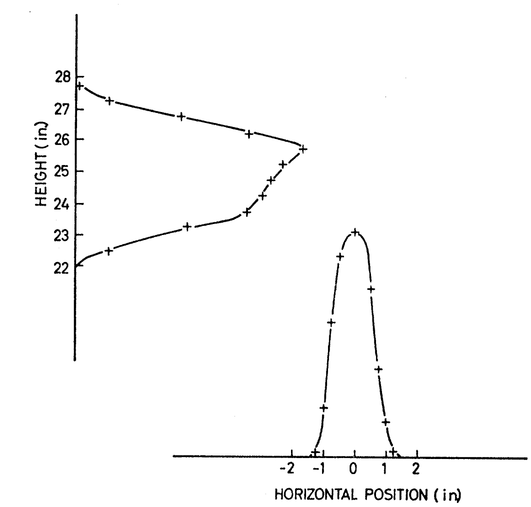

FIG. 3. Beam profile at back of scattering table.

[12] Manufactured by Texas Nuclear Corporation, Austin, Texas.

[13] R. L. Bramblett, R. I. Ewing, and T. W. Bonner, Nucl. Instr. Methods 9, 1 (1960).

only about 10% of the foreground, a small change in the monitor calibration would have caused no loss in accuracy in the cross-section determination. There is an increase in counting rate for the spherical neutron dosimeter during background measurements of 0.2% because of the reduction in absorption from the beam, but this can be neglected since it is a correction of only 0.02% to the cross section. In the background measurements, for small angles (center of mass) the neutron dosimeter was used as a monitor, but for the largest angles the proton telescope and sodium iodide crystal come between the dosimeter and the beam, and so the ionization chamber was used as the monitor.

The energy of the beam is determined ultimately from range-energy measurements. Aluminum and copper were used for the absorbers. The published tables of Sternheimer[14] give inconsistent results. However, his modified values for copper, which are very similar to the earlier tables of Rich and Madey,[15] give results identical to those from aluminum. The modified values predict more accurately than the original ones the experimental range in copper at 658 MeV [16] and so are to be preferred anyway. The tables of Williamson and Boujot[17] were rejected because they also gave inconsistent results; in addition they end rather frustratingly at 150 MeV. The tables of Rich and Madey were used to determine the energy loss in the plastic scintillators.

Two methods were used to measure the peak energy of the neutron beam. First, one can deduce it from the energy of the primary proton beam; this is determined from a range-energy measurement using plastic scintillator counters. Two adjustments have to be made to obtain the neutron energy. The proton loses, on the average, 2.5 MeV in passing through the deuterium target before it interacts. When the reaction occurs, energy is lost in the Q value and some energy is also given to the recoiling diproton. The energy spectrum of the neutrons produced at 0° peaks at a value of 3.5 MeV less than the incident proton energy.[18] Adding these effects together, we estimate that a 157.5-MeV proton beam produces a neutron beam with a peak energy of 151.5 MeV.

The neutron-beam energy has also been obtained more directly using the scattering telescope and sodium iodide crystal. The crystal was calibrated in the proton beam and then moved to the neutron-beam experimental area and used to detect protons scattered from the hydrogen target by the neutron beam. The photomultiplier tube is well shielded from magnetic fields. However there is a field of 10 G in the experimental area, from the synchrocyclotron; and so the gain stability was checked. Using a source, it was determined that any change in gain due to the moving of the crystal from one area to the other is less than 0.2%. To obtain the neutron-beam energy from the scattered proton spectrum, small corrections have to be made for the scattering angle, target thickness, and energy loss in the scintillator telescope. Using this method, the full-energy neutron beam was shown to have a peak energy of 150.8 ± 1.0 MeV. At the lower energy the values obtained were 131.5 ± 1.0 MeV, deduced from the proton-beam energy, and 131.6 ± 1.0 MeV from a direct measurement.

When the differential-cross-section data were analyzed, all the counts were included which were above a level of 20 MeV below the peak value. This means that the weighted average energy of the neutrons used in the scattering experiment was slightly below the peak value. The difference was 1.1 MeV for the full-energy beam and 2.5 MeV for the lower energy beam. We therefore conclude that this experiment measures the differential cross section at energies of 150.0 ± 1.0 and 129.0 ± 1.0 MeV.

DATA ANALYSIS

Both the monitor telescope and the measuring telescope used coincidence circuits with a time resolution of 20 nsec. The measuring telescope generated a 2.5-μsec pulse which was used to gate a RIDL pulse-height analyzer, model 34-12B. The sodium iodide pulse coincident with this gating signal was then analyzed. All the results were obtained from the proton-energy spectrum. For the 150-MeV data, counts were included if they were from protons which had been scattered by neutrons of energy from 130 to 160 MeV. For the 129-MeV data, a window of 110 to 140 MeV was set. The energy of the proton produced by such neutrons was calculated taking into account the scattering angle and the proton-energy loss in the hydrogen target and scintillator telescope. For the lower center-of-mass scattering angle, where the proton energy is getting small, the width of the peak increases, and so a larger acceptance window was taken and a small correction was added. For the 150-MeV data, the correction was 5.7 ± 1.0% for angles less than and including 87.8° in the center-of-mass system. For the 129-MeV data the correction was 11.0 ± 2.0% for angles less than and including 98.1° in the center-of-mass system.

As mentioned above, the larger center-of-mass angles were more difficult because the proton contamination in the neutron beam was detected. To minimize this, the anticoincidence counter was placed in the neutron beam for these angles. As the telescopes picked up protons scattered from the hydrogen content of the scintillator material, it meant that the larger angles had to be normalized to the rest of the data. For the150-MeV cross section the normalization was 1.073 ± 0.020

[14] R. M. Sternheimer, Phys. Rev. **115**, 137 (1959) and private communication.
[15] M. Rich and R. Madey, University of California Radiation Laboratory Report No. UCRL-2301 (unpublished).
[16] V. P. Zrelov and G. D. Stoletov, Zh. Eksperim. i Teor. Fiz. **36**, 658 (1959) [English transl.: Soviet Phys.—JETP **9**, 461 (1959)].
[17] C. Williamson and J. P. Boujot, Commissariat à l'Energie Atomique, Report No. CEA 2189, 1962 (unpublished).
[18] C. J. Batty, R. S. Gilmore, and G. H. Stafford, Phys. Letters **16**, 137 (1965).

TABLE I. Correction for finite geometry of the counters.

Counter angle (deg)	Average proton-scattering angle (deg)
0	1.58
2.5	2.87
5	5.20
7.5	7.64
10	10.08
12.5	12.54

for angles 169.2° (c.m.) and greater. The two groups were normalized at the angles 159.1° and 164.0°. For the 129-MeV data the normalization was 1.081±0.020 for angles 154.1° and for angles 164.2° and greater. The two groups were normalized at the angles 149.0° and 159.0°.

As the differential cross section at each energy took about a week to run, it was decided to check the 10° (laboratory) proton angle several times. The checks for the 129-MeV run were in excellent agreement but in the 151-MeV data there seemed to be a small change of monitor counts and so the run was split into two sections and a correction of 1.7±1.0% was applied to one group to bring it in line with the other. This affects only four angles, 118.0° through 148.9°.

CORRECTIONS

At most of the angles the finite angular resolution of the counters did not matter. However, at the small laboratory angles (large center-of-mass angles) a small correction had to be made because the average proton-scattering angle was greater than the angle of the scattering arm.

TABLE II. Percentage errors for the 150-MeV data.

Angle (c.m.) (deg)	Statistics	Monitor uncertainty	Small angles	Large angles	NaI correction	Alignment	Total
63.2	2.5		1.0		0.5	0.5	4.5
67.9	2.1		1.0		0.5	0.5	4.1
77.8	2.0		1.0		0.5	0.4	3.9
87.8	1.7		1.0		0.5	0.2	3.4
97.8	1.7				0.5	0.2	2.4
107.9	1.9				0.5		2.4
118.0	1.7	1.0			0.5		3.2
128.2	1.7	1.0			0.5		3.2
138.5	1.6	1.0			0.5		3.1
148.9	1.8	1.0			0.5		3.3
154.0	1.9				0.5		2.4
159.1	1.1				0.5		1.6
164.0	1.6				0.5		2.1
169.2	2.0			2.0	0.5		4.5
175.0	4.0			2.0	0.5		6.5
176.8	4.0			2.0	0.5		6.5

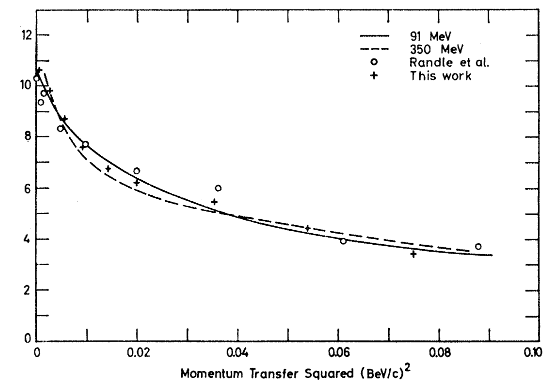

FIG. 4. Comparison of charge-exchange-scattering experiments at 91, 150, 156, and 350 MeV.

The limiting apertures in the proton optics were the 2-in.×1-in. plastic scintillation detector and the source which is the 1-in.-diam hydrogen cup of which about $2\frac{1}{2}$ in. of the cylinder is in the beam. The counter is 30 in. away from the target. A geometrical solution was sought to the problem of what is the average scattering angle. If one considers the source and the detector as divided into 8 equal areas, one can then calculate the scattering angle of a proton passing from a section of the source to a section of the detector. The average angle can then be found. To use this straightforward averaging one has to assume that the cross section varies linearly with angle. This is sufficiently true for all but the counter angles of 0° and $2\frac{1}{2}$°. Here however it is not clear what variation or the differential cross section to fold in, and so as the errors on these points are quite large anyway, the simple average was retained. Table I gives the angle of the scattering arm and the calculated average proton-scattering angle.

To determine the cross section one has to make two corrections to the counts obtained at each angle. First there is the conversion of laboratory solid angle to center-of-mass coordinates. The standard relativistic equations were used. Secondly, a correction has to be made for the fact that some protons which enter the sodium iodide crystal make a nuclear interaction as they slow down. This usually reduces the amount of light produced by the crystal and so some counts are lost from the peak. Values for this correction have already been published.[19] It is the same correction as the "absorber correction" of experiments which use counter telescopes as the detector.

RESULTS

The cross sections we present here are the results from one run at each energy. However, an earlier experiment was performed at 150 MeV using a 2-in.-diam hydrogen target and the results from that run are in excellent agreement with the later run using a 1-in.-diam target.

[19] D. F. Measday, Nucl. Instr. Methods 34, 353 (1965).

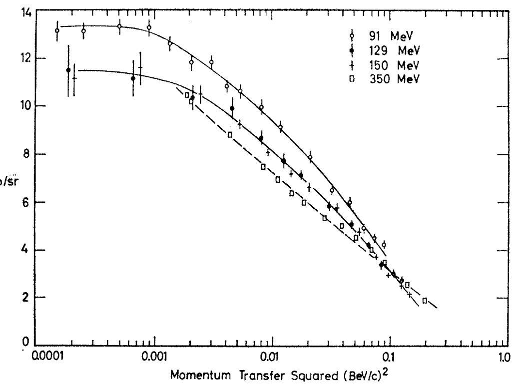

Fig. 5. Charge-exchange-scattering experiments at 91, 129, 150, and 350 MeV.

With the thicker target the angular range is more limited and so we will not present that data.

Tables II and III show the errors for the 150- and 129-MeV data, respectively. Table IV gives the results for the cross section at 150 MeV and Table V the 129-MeV results.

Wilson has shown[4] that a simple comparison can be made between neutron-proton charge-exchange experiments at different energies if one uses momentum transfer squared as a parameter, rather than the scattering angle in the center-of-mass system. This analysis illustrated the similarity of the data at 200 MeV[7] and 350 MeV.[8] The 91-MeV[6] data were shown to be slightly different. However, the previous work at 156 MeV[5] was quite incompatible. These data are also difficult to fit with energy-dependent phase shifts.[2] In Table VI we list our 150-MeV data using the momentum transfer squared as a parameter. In Fig. 4 we have plotted our data and the 156-MeV data in addition to the work at 91 and 350 MeV which has been represented by lines for simplicity. The lower the energy, the larger the cross section becomes. To simplify the comparison between different energies, we have normalized the various data so that they cross each other. We have multiplied the cross sections by the following factors: Randle *et al.* (156 MeV), 0.96: our 150-MeV data (σ_{YLAN4M}), 0.97: Stahl *et al.* (91 MeV), 0.81. It can be seen quite clearly that the present results at 150 MeV are intermediate between the data at 91 and 350 MeV while the results of Randle *et al.* give a peak which is even broader than the 91-MeV scattering. We conclude therefore that the present results are more reasonable. In Table VII we list our 129-MeV data using momentum transfer parametrization and in Fig. 5 we present all our data on a semilogarithmic plot with other data for comparison.

Table III. Percentage errors for the 129-MeV data.

Angle (c.m.) (deg)	Statistics	Small angles	Large angles	NaI correction	Alignment	Total
73.2	2.7	2.0		0.5	0.4	5.6
78.1	2.5	2.0		0.5	0.4	5.4
88.1	2.4	2.0		0.5	0.2	5.1
98.1	2.1	2.0		0.5	0.2	4.8
108.2	2.2			0.5		2.7
118.3	2.3			0.5		2.8
128.5	2.3			0.5		2.8
138.7	2.0			0.5		2.5
149.0	2.0		0.5	0.5		3.0
154.1	2.2		2.0	0.5		4.7
159.2	2.0		0.5	0.5		3.0
164.2	2.5		2.0	0.5		5.0
169.3	2.8		2.0	0.5		5.3
174.1	4.7		2.0	0.5		7.2
176.8	4.7		2.0	0.5		7.2

Table IV. The differential-cross-section results at 150.0±1.0 MeV.

Telescope angle (deg)	Scattering angle (c.m.) (deg)	σ(mb/sr) (YLAN4MP)	σ(mb/sr) (YLAN4M)	Error (mb/sr)	Error (%)
57.5	63.2	2.70	2.56	0.12	4.5
55.0	67.9	2.52	2.39	0.10	4.1
50.0	77.8	2.23	2.11	0.08	3.9
45.0	87.8	2.29	2.16	0.07	3.4
40.0	97.8	2.63	2.49	0.06	2.4
35.0	107.9	3.12	2.96	0.07	2.4
30.0	118.0	3.91	3.70	0.12	3.2
25.0	128.2	5.05	4.78	0.15	3.2
20.0	138.5	6.14	5.82	0.18	3.1
15.0	148.9	6.99	6.62	0.22	3.3
12.5	154.0	7.61	7.20	0.17	2.4
10.0	159.1	8.54	8.08	0.13	1.6
7.5	164.0	9.78	9.27	0.19	2.1
5.0	169.2	11.04	10.46	0.47	4.5
2.5	174.0	12.23	11.59	0.75	6.5
0	176.8	11.78	11.16	0.73	6.5

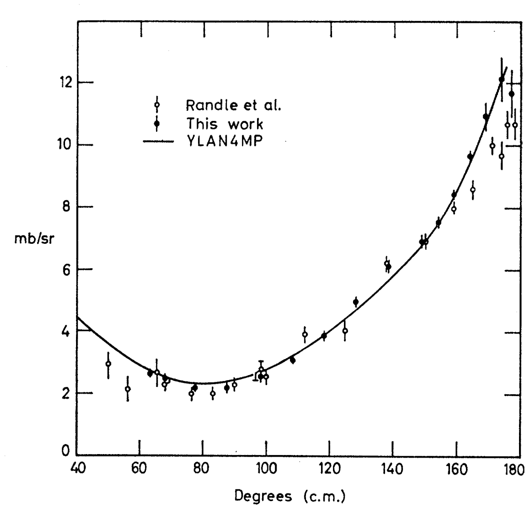

Fig. 6. The 150-MeV data normalized to YLAN4MP.

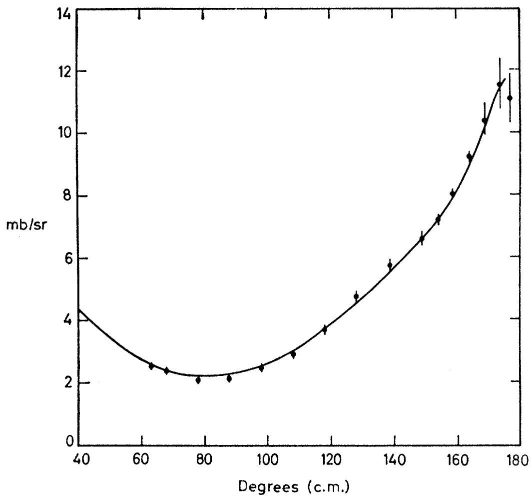

FIG. 7. The 150-MeV data normalized to YLAN4M.

PHASE-SHIFT ANALYSIS

In Fig. 6 we present our data normalized to a preliminary version of the Yale phase-shift analysis YLAN4MP[20]; in addition we have plotted the previous data of Randle *et al.* at 156 MeV. In Fig. 7 our data are presented normalized to the most recent version of YLAN4M. The solution YLAN4MP predicts a larger total cross section than YLAN4M so that there is a 4.8% difference between the normalizations. When our results are normalized to the older solution YLAN3M, the cross sections are 1.7% lower than when normalized to YLAN4M. There is therefore a 6.5% uncertainty in the absolute value of the cross sections we present. YLAN4M is a slightly better fit than YLAN4MP but both are an improvement over YLAN3M.

In Fig. 8 we present our data at 129 MeV normalized to YLAN4M; we also include the previous data of Hobbie and Miller[21] at 128±1 MeV. The agreement between the experiments is excellent. In Fig. 9 our data are plotted normalized to YLAN4MP. The difference between the normalization to YLAN4M and YLAN4MP is 6.2%. The normalization to YLAN3M is 1.3% different from that for YLAN4M and falls between YLAN4M and YLAN4MP. At this energy the prediction of YLAN4MP gives a slightly better fit than YLAN4M but, again, both are a considerable improvement over YLAN3M. The total cross sections predicted by YLAN4M are 56.6 mb at 129.0 MeV and 50.3 mb at 150.0 MeV; those predicted by YLAN4MP are 59.5 mb at 129 MeV and 52.6 mb at 150 MeV.

TABLE V. The differential-cross-section results at 129.0±1.0 MeV.

Telescope angle (deg)	Scattering angle (c.m.) (deg)	σ (mb/sr) (YLAN4MP)	σ (mb/sr) (YLAN4M)	Error (mb/sr)	Error (%)
52.5	73.2	2.97	2.79	0.16	5.6
50.0	78.1	2.70	2.54	0.14	5.4
45.0	88.1	2.90	2.73	0.14	5.1
40.0	98.1	3.19	3.00	0.14	4.8
35.0	108.2	3.57	3.36	0.09	2.7
30.0	118.3	4.49	4.22	0.12	2.8
25.0	128.5	5.39	5.07	0.14	2.8
20.0	138.7	6.22	5.85	0.15	2.5
15.0	149.0	7.62	7.17	0.22	3.0
12.5	154.1	8.25	7.76	0.36	4.7
10.0	159.2	9.21	8.66	0.26	3.0
7.5	164.2	10.52	9.89	0.49	5.0
5.0	169.3	11.00	10.34	0.55	5.3
2.5	174.1	11.86	11.15	0.80	7.2
0	176.8	12.28	11.55	1.12	7.2

TABLE VI. The 150-MeV data analyzed using, as a parameter, the momentum transfer squared of the charge-exchange scattering.

Scattering angle (c.m.) (deg)	Momentum transfer squared $(\mathrm{BeV}/c)^2$	σ (mb/sr) (YLAN4M)
176.8	0.0002	11.16
174.0	0.0008	11.59
169.2	0.0054	9.27
159.1	0.0093	8.08
154.0	0.0143	7.20
148.9	0.0203	6.62
138.5	0.0353	5.82
128.2	0.0539	4.78
118.0	0.0748	3.70
107.9	0.0976	2.96
97.8	0.122	2.49
87.8	0.146	2.16

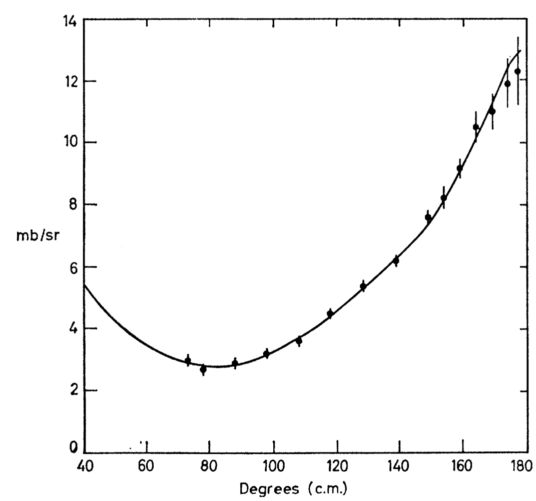

FIG. 8. The 129-MeV data normalized to YLAN4MP.

[20] G. Breit, A. N. Christakis, M. H. Hull, H. M. Ruppel, and R. E. Seamon, Bull. Am. Phys. Soc. **9**, 378 (1964).

[21] R. K. Hobbie and D. Miller, Phys. Rev. **120**, 2201 (1960).

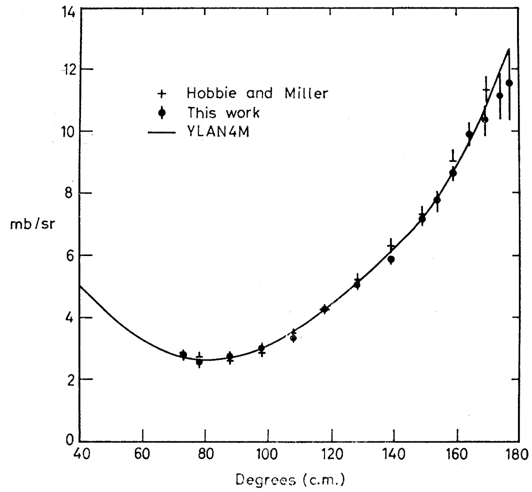

FIG. 9. The 129-MeV data normalized to YLAN4M.

TABLE VII. The 129-MeV data analyzed, using as a parameter, the momentum transfer squared of the charge-exchange scattering.

Scattering angle (c.m.) (deg)	Momentum transfer squared $(\text{BeV}/c)^2$	σ (mb/sr) (YLAN4M)
176.8	0.0002	11.55
174.1	0.0007	11.15
169.3	0.0021	10.34
164.2	0.0046	9.89
159.2	0.0080	8.66
154.1	0.0123	7.76
149.0	0.0175	7.17
138.7	0.0302	5.85
128.5	0.0460	5.07
118.3	0.0642	4.22
108.2	0.0837	3.36
98.1	0.105	3.00
88.1	0.126	2.73

CONCLUSION

The data obtained with the Harvard mono-kinetic neutron beam are more reliable than previous data because it is considerably easier to analyze results when the neutron-energy spectrum has a narrow peak. The limit on the accuracy can be directly or indirectly attributed to the beam intensity. The new cyclotrons now being built will have a much greater external beam intensity than the Harvard synchrocyclotron and so the accuracy of this type of experiment could be improved.

The agreement between our results and the more recent Yale phase-shift analyses is very satisfying. It indicates that the various neutron-proton experiments are consistent and that there will soon be sufficient experimental information for a more complete solution of the nucleon-nucleon elastic-scattering problem.

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