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Neutron-Proton Scattering at 152 MeV*

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The differential cross section for neutron-proton scattering has been measured at 152 ±1 MeV. Protons were detected in the angular range of 5 to 50° relative to the incident beam direction, corresponding to neutron scattering angles of 169 to 78° in the c.m. system. The angular distribution is consistent with earlier data at the smaller proton angles, but significant discrepancies are apparent at angles greater than 25°.

INTRODUCTION

Recently we have performed several experiments using the monokinetic neutron beam of the Harvard University synchrocyclotron.[1] These have included studies of the reactions ^{4}He$(n,p)^4$H (described earlier[2]), $p(n,d)\gamma$, $d(n,d)n$, $d(n,p)2n$, and ^{4}He(n,d)-^{3}H. In order to normalize the differential cross sections for these reactions, elastic n-p scattering was studied with the same equipment, with the intention of normalizing all the cross sections to the values determined by Measday[3] at 150 MeV.

When the comparison was made, however, the present experiment took on added significance because the angular distribution of the n-p cross section disagreed significantly at the larger proton angles from the earlier results.[3]

APPARATUS AND PROCEDURES

The relative cross sections were determined by detecting protons knocked out of a liquid-hydrogen target by monokinetic neutrons. The neutron beam was collimated by a 1.875-in. (high)×0.875-in. rectangular aperture and had an intensity of 4×10^4 neutrons/sec. Details of the beam characteristics have been presented earlier.[1,3] The target was liquid hydrogen contained in a vertical cylinder which had a diameter of 2 in. and a length of 5 in., with walls of 0.002-in. Kapton polyimide film.

Because the apparatus was designed primarily for use in other experiments, runs were made with two different configurations for the telescope which detected the recoil protons. In both cases, a plastic detector[4] was placed in the neutron beam in front of the target as an anticoincidence counter to assure that any stray protons in the beam would not contribute to the scattering process under observation. A diagram of the arrangement is displayed as Fig. 1; telescope parameters are given in Table I. The sodium iodide crystal[5] was used with a DuMont 6363 photomultiplier. All other scintillators were plastic[4] and were viewed by RCA 7850 photomultipliers. A 2-in.×1-in. detector was the defining counter for each telescope, and the angular resolution ranged from ±1.5° (lab) at small angles to ±2.2° at larger angles.

Each telescope included a thick detector ($\frac{1}{2}$ in.) to measure the rate of energy loss (dE/dx) for a particle traversing the telescope. For each particle satisfying the coincidence $\bar{A}BCD$, the pulse heights in the dE/dx and NaI (energy E) detectors were recorded using a PDP-1 computer (Fig. 2). As described later, a comparison of E and dE/dx for a particle made it possible to distinguish protons from deuterons in those reactions in which both particles were produced.

Data were accumulated in two runs, one for each telescope. At the start of each run the beam was located in the target region by placing a 2-in.×1-in. ×$\frac{1}{8}$-in. plastic scintillator in the beam in such a way that the beam struck the 2-in.×$\frac{1}{8}$-in. edge. The counting rate as the detector was moved through the beam in small horizontal and vertical steps provided profiles of the beam in both directions. A theodolite and a plumb bob were used to

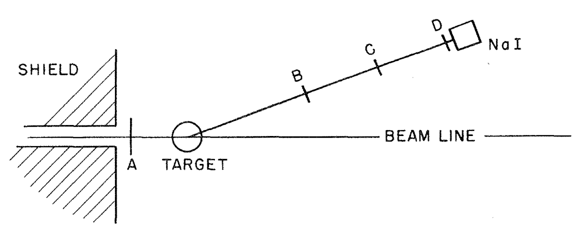

FIG. 1. Experimental arrangement (not to scale). Detector A is an anticoincidence counter.

locate the target in the center of the beam (±0.05 in.) and to place the pivot of the telescope arm beneath the target (±0.05 in). At the target the beam was symmetrical horizontally with a full width at half height (FWHH) of 1.1 in.

Vertical and horizontal beam profiles were measured in a similar way at the defining-counter distance from the target; the beam was symmetrical in both directions, with FWHH of 3 and 1.75 in., respectively. These profiles were used to determine the appropriate height for the defining counter and the location of the horizontal beam centroid (±0.05 in.), which represented a scattering angle of 0°. The telescope arm (beam on which the detectors were mounted) was set at various scattering angles by means of a sine bar[6] which located the defining counter within a lateral accuracy of 0.005 in. Spirit levels on the arm were used to maintain its levelness at all angles.

The neutron beam was monitored by an ionization chamber[7] which measured the intensity of the proton beam incident on the deuterium target used in the production of the neutron beam. Earlier measurements[3] indicated that the variations in the monitor response never exceeded ±1%.

In each run scattering data were taken in three steps. Background measurements were taken at all angles with an evacuated target. The target was filled with liquid hydrogen, and foreground measurements were made with several observations at each angle. Then background scattering was observed again at most angles. The beam position was rechecked at least once during the run; no significant deviations were observed.

The beam-energy determination depended ultimately on a range-energy measurement. The range in copper of protons in the external cyclotron beam was measured, and a beam energy of 161.0 MeV was found using range-energy tables of Janni.[8] (Range measurements in aluminum yielded an energy of 159.3 MeV from the same tables.) These beam protons lose on the average 2.4 MeV in the deuterium target before reacting to produce neutrons, and an additional 3.5 MeV is consumed

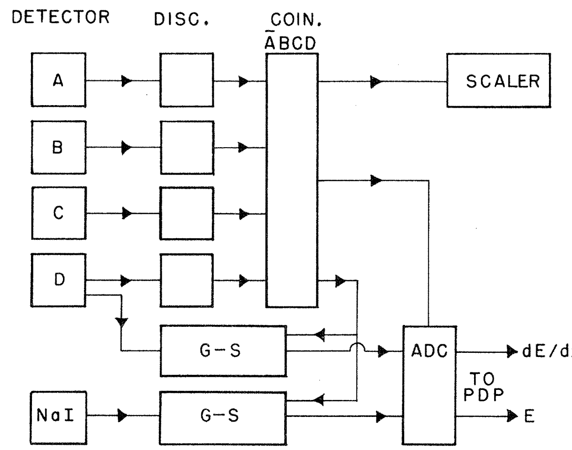

FIG. 2. Simplified block diagram of electronic system. The coincidence circuit is triggered by the combination $\bar{A}BCD$. The unit *G-S* refers to a gate and pulse stretcher circuit. ADC is the analog-to-digital converter which digitized signals for the computer inputs.

in the $d(p,n)2p$ reaction,[3,9] resulting in an energy of 155.1 MeV at the peak of the neutron beam spectrum. This method of calculating the neutron beam energy has been checked[10] within 0.3 MeV by comparing the result with that found from the energy of small-angle protons from elastic n-p scattering.

CALCULATIONS AND RESULTS

The data for each of the observations at each angle were stored on magnetic tape as a 256×256 array, corresponding to dE/dx versus E. For all proton (lab) angles greater than 10°, there was in this array a single "band" of cells which contained significant numbers of counts. These cells corresponded to those events for which dE/dx and E were appropriately related for protons traversing the telescope. At the smallest angles a second band was evident, with larger dE/dx for a given E, corresponding to deuterons detected as a result

TABLE I. Telescope characteristics.

	Telescope I		Telescope II	
Detector [a]	Size (in.)	Position [b] (in.)	Size (in.)	Position [b] (in.)
A	6×7×0.125	···	4×2.5×0.063	···
B	3×2×0.031	13	3×2×0.031	15
C	4×2.5×0.063	21	2×1×0.063	27
D	2×1×0.50	29	3×3×0.50	31
NaI	3×3 (diam)	$30\frac{1}{2}$	3×3 (diam)	$32\frac{1}{2}$

[a] As indicated in Fig. 1.

[b] Distance from center of target.

of the radiative pickup reaction $p(n,d)\gamma$. This behavior of the detection system is illustrated in Fig. 3, which represents an E versus dE/dx density plot produced from (n,p) and (n,d) reactions with a helium target.

Computerized calculations were used to select events from the "proton band" and produce an energy spectrum of detected protons at each angle. Channel-by-channel combination of foreground and background data at each angle produced a raw spectrum to which various corrections had to be applied. The background-to-foreground ratio was about 10% at 5° and less than 6% at other angles.

The spectra were distributed into 256 cells or channels, representing equal increments in the pulse height produced in the NaI scintillator. Relativistic kinematics and range-energy relations[8] were used to determine the energy the recoil protons were expected to have at each angle as a result of the elastic scattering of 155.1-MeV neutrons. Comparison with the actual spectra showed that the NaI crystal was slightly nonlinear. A cubic relationship between NaI energy and channel was found and used to determine the energy represented by each channel. The spectra were then redistributed into new channels corresponding to equal energy intervals ($\frac{1}{2}$ MeV) in NaI energy.

A correction has to be made to the proton spectra because of reactions in the NaI detector. Observations have been made[11] of the spectra produced by monoenergetic protons incident on each of the telescopes used in this experiment. Not only is the fraction of protons removed from the expected peak known as a function of peak energy, but also the shape of the resulting tail of the spectrum. Therefore each spectrum was corrected by starting at the highest channel, increasing the number of counts in it by the appropriate factor, and subtracting the added counts from the appropriate lower channels. The procedure was repeated for successively lower channels until the entire spectrum had been corrected. This telescope-dependent correction to the number of counts in the peak of a spectrum varied from 2% at 50° to 23% at 5°.

Corrections also had to be applied for scattering of protons in the target and the telescope. Known elastic and inelastic total cross sections for neutrons[10,12] and protons[13] were used to calculate the fraction of protons scattered at the appropriate energies in the target, counters B and C, and in the air along the path of the telescope. The loss in counter D was determined experimentally by comparing the number of BCD coincidences with the number of counts recorded in the NaI detector in a calibration run in which monoenergetic protons were incident on the telescope.[11] The total correction for telescope losses ranged from $2\frac{1}{2}$% at 5° to 8% at 50°.

The relative differential cross sections were calculated by summing the corrected counts in each spectrum from the channel corresponding to elastic scattering of 120.1-MeV neutrons to the highest channel with counts in it. In the run with

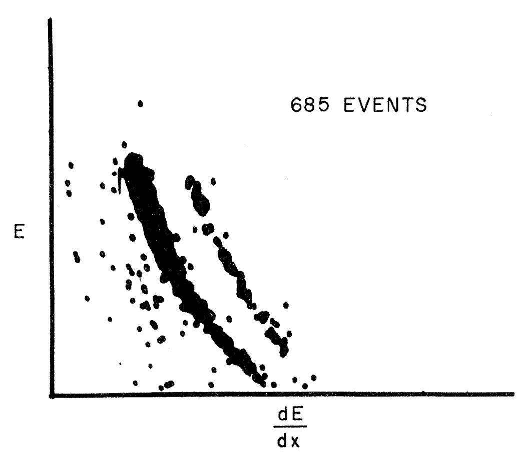

FIG. 3. Oscilloscope scatter plot of E vs dE/dx, with E plotted as the ordinate. The left band represents protons, the other represents deuterons, produced by neutrons incident on a helium target.

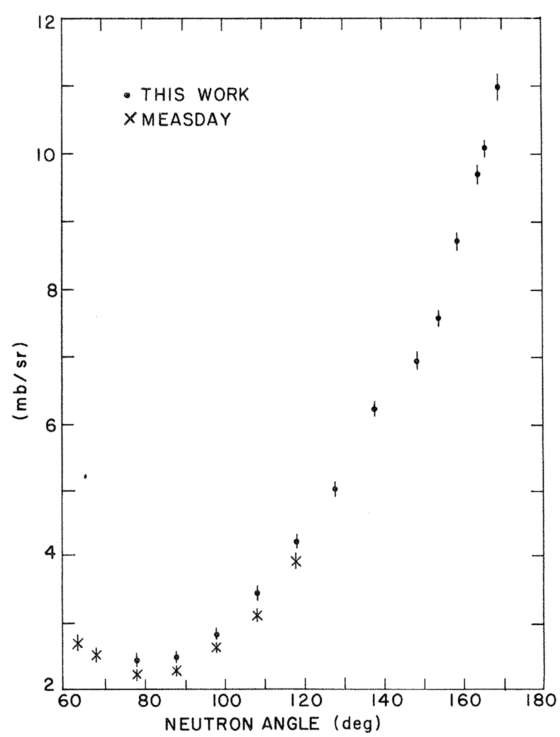

FIG. 4. The neutron–proton differential cross section near 150 MeV. Between 125 and 170° the Measday results agree with the present results and are not displayed.

telescope II the electronic circuits were misadjusted in such a way that some counts were lost at the top of the spectra at small angles; corrections were made, decreasing from $4\pm1\%$ at 5° to $\frac{1}{2}\%$ at 12.5°. At the widest proton angle (50°) only, it was necessary to add a correction of approximately $6\pm2\%$ because of the low-energy cutoff of the telescope.

Because of the inclusion of counts from below the peak in the determination of the cross sections, the average energy of reacting neutrons was less than the energy of the peak in the beam by about 3 MeV. Therefore the effective energy for this experiment is 152.0 ± 1.0 MeV. (The error in this parameter arises from the variations in range measurements and in the steps described earlier for determining the neutron energy from the proton energy. Had the range measurements in aluminum been used, the effective neutron energy would be lower by about 1.7 MeV.)

For each of the two runs the cross sections were normalized by comparing the results at proton angles of $7\frac{1}{2}$ to 25° with the 150-MeV results of Measday,[3] which in turn had been normalized to values from phase-shift set YLAN4MP of Breit *et al.*[14] The results, averaged for the two runs, are presented in Table II and Fig. 4. The experimental uncertainties of the present results include statistical errors and contributions (added quadratically) of $\frac{1}{2}\%$ each due to alignment, monitoring, and telescope-NaI corrections. At the smaller proton angles, the effective angle of scattering is larger than the telescope angle because of the finite heights of the defining counter and the beam. The deviations from the nominal angles (5, $6\frac{1}{2}$, $7\frac{1}{2}$, 10, $12\frac{1}{2}$°) were calculated by numerical integration.

TABLE II. The differential cross section at 152 ± 1 MeV.

Telescope angle (deg)	Neutron scattering angle (c.m., deg)	Current results (mb/sr)	Measday results (mb/sr)
5.15	169.3	10.98 ± 0.22	11.04 ± 0.47
6.61	166.3	10.06 ± 0.10	
7.60	164.2	9.67 ± 0.14	9.78 ± 0.19
10.07	159.1	8.70 ± 0.12	8.54 ± 0.13
12.56	154.1	7.57 ± 0.11	7.61 ± 0.17
15.0	148.9	6.93 ± 0.11	6.99 ± 0.22
20.0	138.5	6.18 ± 0.09	6.14 ± 0.18
25.0	128.2	5.01 ± 0.08	5.05 ± 0.15
30.0	118.0	4.20 ± 0.07	3.91 ± 0.12
35.0	107.8	3.43 ± 0.08	3.12 ± 0.07
40.0	97.8	2.82 ± 0.07	2.63 ± 0.06
45.0	87.7	2.47 ± 0.05	2.29 ± 0.07
50.0	77.8	2.45 ± 0.07	2.23 ± 0.08

DISCUSSION

It is apparent that there is a significant discrepancy between the results of Measday[3] and the present work at proton angles greater than 25°. In both runs of the present experiment the wide-angle cross sections are substantially larger than in the earlier work.

Wilson has suggested[15] that the charge-exchange differential cross sections at various energies should behave similarly when considered as functions of the four-momentum transfer, $-t$. This behavior is shown in Fig. 5, in which are displayed the data of Ashmore *et al.*[16] at 350 MeV, Measday[3] at 150 MeV, and the present work. The excellent data ($\pm1\frac{1}{2}\%$) at the highest energy are represented by a smooth curve through 15 points. Normalized 199-MeV results[17] (not displayed) agree very well with the 350-MeV data. For $-t$ less than 0.06 $(\text{BeV}/c)^2$ the various sets of data are consistent. For larger values of $-t$, the Measday results deviate significantly below the others. The 129-MeV data (not displayed) of Measday[3] deviate similarly. The present results are more consistent with those at the higher energies.

Although it is difficult to identify reasons for the discrepancies between the results of two experi-

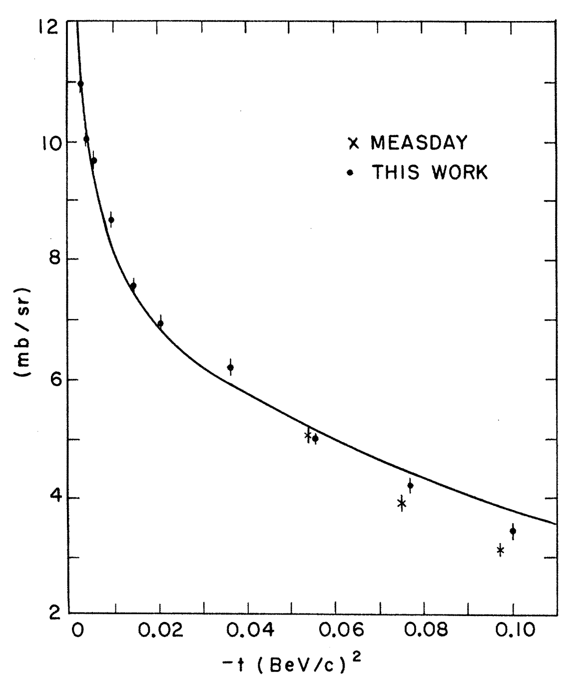

FIG. 5. Comparison of charge-exchange-scattering results. The solid line represents the data at 350 MeV (Ref. 16), multiplied by a factor of 1.171 to provide appropriate normalization. Between 125 and 170° the Measday results agree with the present results and are not displayed.

ments, there are several points worth noting. In the Measday experiment, the relative cross sections were determined from the number of detected protons which had sufficient energy to have resulted from elastic scattering by beam neutrons of at least 130 MeV. Because of the broader peak in the proton spectra at the wider proton angles, it was necessary to "correct" the cross sections at these angles by 5.7%. In order to obviate this correction, the neutron cutoff energy was taken as 120 MeV in the current experiment; calculations based on cutoff energies of 115 and 110 MeV produced variations in the relative cross sections which were much less than the experimental errors. The earlier experiment also had a separate normalization factor at the smallest proton angles because of the effect of the presence of the anticoincidence detector on beam monitoring. Finally, the corrections in the earlier experiment for protons scattered out of the peak in the NaI spectrum were based on measurements[18] for an idealized system; recent observations[11] have shown that this type of correction is quite sensitive to actual telescope parameters.

In order to investigate the internal consistency of the present results, an attempt was made to determine the beam neutron spectrum from the observed proton spectrum at each angle. "Known" n-p differential cross sections were determined from the results of Measday[3] at 129 and 150 MeV and of Scanlon *et al.*[19] at lower energies. The determination of the tail in the neutron spectrum depended mainly on the Scanlon data, and excellent agreement was observed among the data at various angles. The peak of the neutron spectrum depended on the 150-MeV results, and naturally the same wide-angle discrepancies occurred as indicated earlier.

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