Neutron-proton differential cross section measurements at 25.8 and 50.0 MeV†

T. C. Montgomery,* B. E. Bonner,‡ F. P. Brady, W. B. Broste, and M. W. McNaughton§
Crocker Nuclear Laboratory and Department of Physics, University of California, Davis, California 95616
(Received 9 March 1977)

The neutron-proton differential cross section has been measured at 25.8 and 50 MeV to a precision of ≈2% for backward hemisphere c.m. angles and ≈3% for forward angles. Relative cross sections are presented for a c.m. angular range from 20° to near 180°. The 25.8 MeV data are in good agreement with previous measurements at 24.0 and 27.2 MeV. The 50 MeV data are not in agreement with previous measurements, and as has been noted before it is believed that these previous data are in error.

[NUCLEAR REACTIONS H$(n,p)n$ 25.8 and 50.0 MeV neutrons; measured $\sigma(\theta)$ from 20° to 175° c.m., normalized to σ(tot).]

In an earlier publication[1] we reported measurements of the n-p elastic differential cross section at 50.0 MeV and showed that this data resolved the anomaly in the value of the phase shift parameter $\delta(^1P_1)$ at this energy.[2] We now present final data at 50.0 MeV together with new data at 25.8 MeV. The 50 MeV data presented here differ from the earlier data[1] only at forward angles (scintillating target technique). This has been revised in the light of new work on the neutron detection efficiency[3,4] which will be discussed further below.

The experimental facility and beam production technique, which were similar for both 25.8 and 50.0 MeV neutron beams, have been described in earlier publications.[1,5,6] Neutron beams of the required energies were obtained from the ^{7}Li(p,n)^{7}Be reaction using protons from the Crocker Nuclear Laboratory CNL cyclotron incident on thin ^{7}Li targets. Neutrons were collimated at 0° to form a beam 24 mm high and 12 mm wide, while protons were swept by a magnetic field into a Faraday cup, which provided a crude monitor of the neutron flux. More precise monitoring was obtained from a high stability recoil-proton telescope.[7] Neutrons in the high energy peak were selected, and their mean energy measured to 0.1 MeV by time of flight (TOF).[8] The high energy peak had an energy spread of approximately 2 MeV resulting primarily from the energy lost by protons in passing through the ^{7}Li target.

Different techniques were used for forward and backward angles so that experimentally no information (other than continuity at the overlap angles) was obtained on the relative normalization of these separate data sets. Backward angle data were obtained by detecting the recoil proton from a CH_2 target in one of three ΔE-E telescopes (subtending a lab angle of 5.1° at the target) two of which were movable, mounted in an evacuated scattering chamber, while the third, fixed at 30° lab, acted as a monitor.[6] Background events from carbon were measured using carbon targets of appropriate thickness, and were subtracted.

At forward angles a wedge shaped scintillating target cut from a 2.54 cm cube of NE102A was used in conjunction with four identical neutron detectors. Figure 1 shows the arrangement of detectors, electronics, and the data acquisition system. As shown the beam strikes the thin edge of the wedge so recoil protons lose all their energy in the scintillator. For each event, recoil proton pulse height in the scintillating target, E_p(ST), incident time of flight (INCTOF) relative to a beam pickoff unit just upstream from the ^{7}Li target, scattered neutron time of flight (NTOF), and neutron pulse height were recorded. See Fig. 1. One neutron detector was retained in a fixed position to act as a monitor. The neutron detectors subtended a lab angle at 3.0° at the target.

In the case of back hemisphere angles where only recoil protons were detected the data were analyzed by first selecting the protons via cuts on the ΔE vs E two parameter spectra. Then proton events due solely to the beam peak were selected by making cuts on the beam TOF vs E two parameter spectra. For the more difficult cases several passes through the data with different cuts and cut sequences were made.

The forward angle data were analyzed in similar fashion with the addition of a cut being made first on the neutron detector pulse height, which was calibrated during each run using several γ-ray energies in the range 0.511 to 4.43 MeV. Successively finer cuts in a variety of sequences were then made on the various two parameter spectra, E_p(ST) vs NTOF, INCTOF vs E_p(ST), etc. This

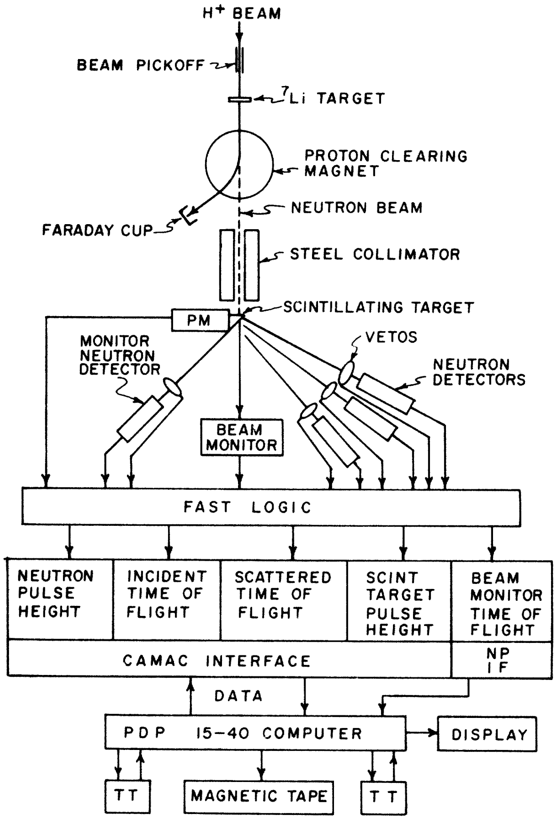

FIG. 1. The experimental layout for the n-p measurements at forward angles where scattered neutrons and recoil protons in the scintillating target are detected.

TABLE I. Differential cross section for n-p scattering at 25.8 MeV. (See text for information on absolute normalization.)

c.m. angle (deg)	Cross section (mb/sr)	Error (mb/sr)
	Forward angle data	
20.15	29.97	0.90
30.22	29.29	0.88
40.28	27.81	0.83
50.34	27.37	0.82
60.38	27.21	0.82
70.42	27.02	0.81
80.45	27.94	0.84
90.47	28.42	0.85
	Backward angle data	
89.54	28.42	0.93
99.54	28.97	0.91
119.58	29.09	0.54
129.06	30.06	0.33
135.60	29.99	0.61
139.60	30.57	0.38
159.56	33.16	0.47
178.00	32.71	1.31

allowed good peak selection and good background estimation.

The forward angle data depend critically on a knowledge of the neutron detection efficiency as a function of neutron energy and the cross section uncertainties there are dominated by uncertainties in the detection efficiencies. For our previously published data at 50 MeV [1] we assumed that the efficiencies were those predicted by Stanton,[9] with an estimated uncertainty of ±5%. These predictions were not in good agreement, however, with the measurements made on one of these detectors to ±3% accuracy at this laboratory.[3] Investigations have shown that this discrepancy resulted primarily from the treatment of the ^{12}C(n,p) reaction. A modified version[4] of Stanton's code incorporating measurements of the ^{12}C(n,p) [or ^{12}C(n,np)] reaction is now in very good agreement with our measurements, especially for the threshold (4.2 MeV electron energy) used in these n-p measurements.

The neutron detection efficiency is a slowly varying function of neutron energy, so that errors in the efficiency will affect only slightly the relative magnitudes of adjacent points, but may make a large contribution to the shape of the curve over a wider angular range. Consequently we have in-

TABLE II. Differential cross section for n-p scattering at 50.0 MeV. (See text for information on absolute normalization.)

c.m. angle (deg)	Cross section (mb/sr)	Error (mb/sr)
	Forward angle data	
20.27	16.17	0.52
30.40	15.41	0.44
40.52	14.17	0.36
50.62	13.02	0.34
60.70	12.06	0.33
70.77	11.89	0.32
80.81	12.17	0.40
90.83	11.39	0.37
	Backward angle data	
69.24	12.28	0.45
79.20	11.59	0.29
89.16	11.57	0.26
99.20	11.64	0.20
109.21	11.95	0.19
119.24	12.86	0.16
129.30	13.40	0.22
139.36	14.34	0.20
149.42	15.79	0.18
159.42	17.23	0.19
169.18	18.10	0.23
173.34	19.16	0.44

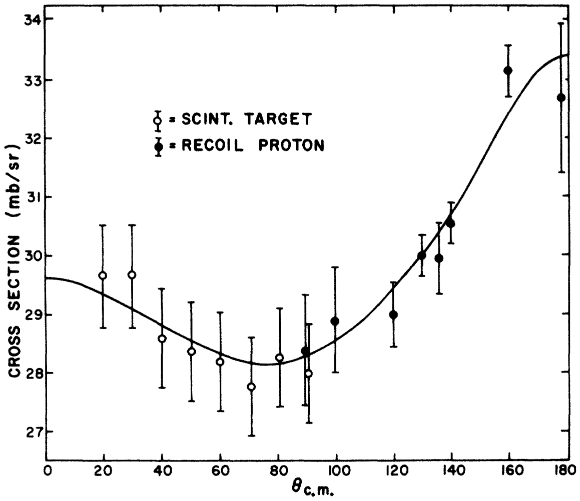

FIG. 2. Differential cross section for n-p scattering at 25.8 MeV shown in comparison to phase shift predictions (Ref. 11). In order to optimize the fit, the forward angle data of Table I have been multiplied by the function $F(\theta)$ (see text) and renormalized with $N_f=1.037$ and $N_b=0.999$ for forward and backward angle data, respectively.

corporated the contribution of the efficiency to the final error in a single function of angle. Our experience of various predictions of efficiency indicates that the uncertainty in neutron detection efficiency over the ranges involved here can be roughly characterized by a broad curve whose sharpness varies from one prediction to the next.

For mathematical convenience we have chosen to characterize these curves by the parabola $F(\theta) = N[a(\theta-55°)^2+1]$ where N is a normalization factor and θ is the c.m. angle (degrees). If the forward angle data at both 25.8 and 50.0 MeV is multiplied by the function F then $N=1$ and $a=0$ reproduce the data tables while $|a|=5\times10^{-5}$ (degrees^{-2}) represents one standard deviation (S.D.) of error in efficiency.

The absolute normalization of the data in Tables I and II was obtained by a preliminary fit[10] integrated to total cross section data from this laboratory.[7] Relative normalization between the forward and backward angle data was based only on the overlap points near 90° c.m. A recent phase shift analysis[11] incorporating the present results indicates that the fit to our data can be improved by renormalizing the forward and backward data by small factors as well as incorporating the detector efficiency uncertainty function for the forward angle data. Thus the data plotted in Figs. 2 and 3 have been multiplied by this function with $a=-3.8\times10^{-5}$ (25.8 MeV) and $a=-0.76\times10^{-5}$ (50 MeV), both cases corresponding to less than 1 S. D. of the uncertainty in the efficiency. The renormalization factors are given in the figure captions.

The uncertainties quoted in the tables include those due to counting statistics which vary from 0.4 to 1%, and uncertainties in beam and peak energy cuts both in the movable arms and the fixed (monitor) arm. The latter vary up to a maximum of ≃ 1% for the smallest recoil proton energies in the ΔE-E detectors or in the scintillating target

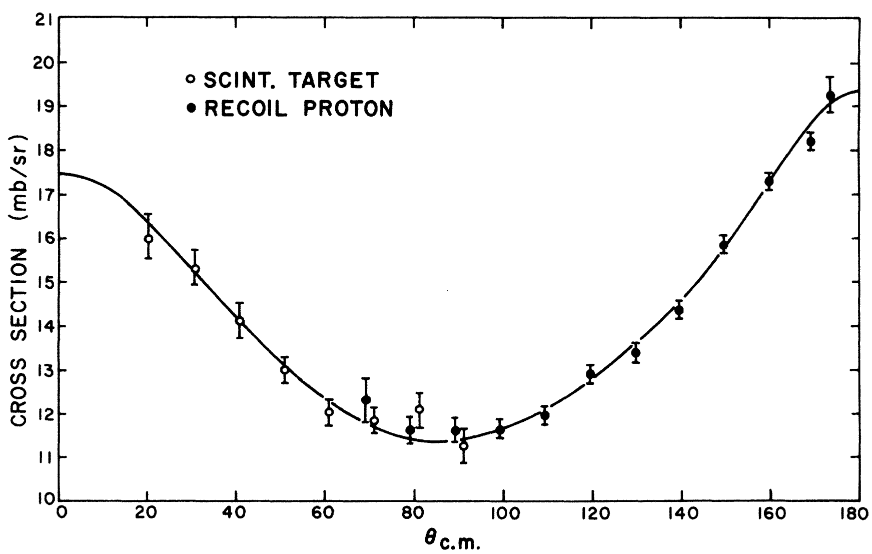

FIG. 3. Differential cross section for n-p scattering at 50.0 MeV shown in comparison to phase shift predictions (Ref. 11). In order to optimize the fit, the forward angle data at Table II have been multiplied by the function $F(\theta)$ (see text) and renormalized with $N_f=1.001$ and $N_b=1.005$ for forward and backward angle data, respectively.

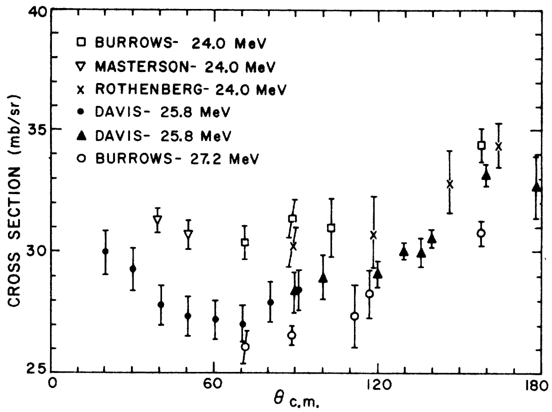

FIG. 4. The 25.8 MeV data of Table I shown in comparison with data from Wisconsin (Refs. 14–16) at 24.0 and 27.2 MeV.

case. Corrections for neutron attenuation were $\leq 5\%$ and their uncertainties $\leq 1\%$. Uncertainties in the corrections for peak losses from nuclear interaction[12] in the target and detectors are $< 0.5\%$. Dead time and finite angle size corrections were also made. The uncertainties in neutron detection efficiency (see above) and in normalization have not been included in the tables.

As has been noted before[1,2] our present data are not in agreement with previous data at 50 MeV.[13] Our 25.8 MeV data lie between, and are consistent with, the Wisconsin measurements at 24.0 and 27.2 MeV.[14–16] (See Fig. 4.)

ACKNOWLEDGMENTS

The mechanical skill of Ralph Rothrock and his staff in constructing the scattering table and accessories, the electronic assistance from Bill Cline and his staff, the electrical help from Harvey Thibeau and his staff, and the beams from Gene Russell and his crew are gratefully acknowledged. Assistance from Stan Johnsen and Joe Wang during parts of the data taking is also gratefully acknowledged.

†Work supported by the National Science Foundation under grant MPS 71-08400 and by the National Cancer Institute under grant PHS CA 16261.

*Associated Western Universities Fellow.

‡Present address: P-DOR, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545.

§Present address: LAMPF MS No. 831, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 85545.

[1]T. C. Montgomery, F. P. Brady, B. E. Bonner, W. B. Broste, and M. W. McNaughton, Phys. Rev. Lett. 31, 640 (1973).

[2]R. Bryant and J. Binstock, Phys. Rev. D 10, 72 (1974).

[3]M. W. McNaughton, F. P. Brady, W. B. Broste, A. L. Sagle, and S. W. Johnsen, Nucl. Instrum. Methods 116, 25 (1974).

[4]M. W. McNaughton, N. S. P. King, F. P. Brady, and J. L. Ullmann, Nucl. Instrum. Methods 129, 241 (1975).

[5]J. A. Jungerman and F. P. Brady, Nucl. Instrum. Methods 89, 167 (1970).

[6]F. P. Brady, N. S. P. King, M. W. McNaughton, J. F. Harrison, and B. E. Bonner, Nat. Bur. Stand. (U.S.) Spec. Publ. 1, 103 (1975).

[7]F. P. Brady, W. J. Knox, J. A. Jungerman, M. R. McGie, and R. L. Walraven, Phys. Rev. Lett. 25, 1682 (1970).

[8]F. P. Brady, W. J. Knox, and S. W. Johnsen, Nucl. Instrum. Methods 89, 309 (1970).

[9]N. R. Stanton, Ohio State Univ. Report No. COO-1545-92, 1971 (unpublished).

[10]J. Binstock (private communication).

[11]P. Signell (private communication).

[12]D. F. Measday and C. Richard-Serre, Nucl. Instrum. Methods 76, 45 (1969).

[13]J. P. Scanlon, G. H. Stafford, J. J. Thresher, P. H. Bowen, and A. Langsford, Nucl. Phys. 41, 401 (1963).

[14]L. N. Rothenberg, Phys. Rev. C 1, 690 (1972).

[15]T. G. Masterson, Phys. Rev. C 6, 690 (1972).

[16]T. W. Burrows, Phys. Rev. C 7, 1306 (1973).