PHYSICAL REVIEW C VOLUME 21, NUMBER 4 APRIL 1980

Neutron-proton scattering. I. Differential cross section at 63.1 MeV

N. S. P. King
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
and Crocker Nuclear Laboratory, Davis, California 94516

J. D. Reber,* J. L. Romero, D. H. Fitzgerald,† J. L. Ullmann, T. S. Subramanian, and F. P. Brady
Crocker Nuclear Laboratory and Department of Physics, University of California, Davis, California 94516

(Received 12 February 1979)

The neutron-proton differential cross section has been measured at 63.1 MeV. The data span an angular range from $\theta_{\text{c.m.}} = 40°$ to 165° with a relative precision of $\lesssim 3.0\%$. A different angular behavior is observed in the present results as compared to that in the data between 55 and 65 MeV currently used in phase parameter analyses.

[NUCLEAR REACTIONS $^1\text{H}(n,p)n$, $E_n = 63.1$ MeV; measured $\sigma(\theta)$ from 39.4 to 165.8 c.m.]

INTRODUCTION

Several years ago, phase shift analyses[1-3] of n-p scattering data near 50 MeV revealed that, although the phase parameters were generally well determined, ambiguous and/or anomalous values were obtained for two important phase parameters. The $^3S_1$-$^3D_1$ mixing parameter $\bar{\epsilon}_1$ was undetermined in the range −10° to 3°, and the $^1P_1$ phase shift disagreed both with values expected from models and with any smooth interpolation of $\bar{\delta}(^1P_1)$ values from adjacent energies.[3] In order to help clarify the situation, the n-p differential cross section, analyzing power, and spin correlation parameter A_{yy} were measured at 50.0 MeV (Refs. 4–6).

A phase shift analysis[7] including these measurements, at 50 MeV, led to a value of $\bar{\delta}(^1P_1)$ near −7° and produced a fit to the p-p and n-p data with a well-defined minimum in χ^2 vs $\bar{\epsilon}_1$ and the value $\bar{\epsilon}_1 = +0.3 \pm 1.6°$. This value for $\bar{\epsilon}_1$ is below that predicted by various models (2°–3°). In addition, the best-fit values for $\bar{\epsilon}_1$ and $\bar{\delta}_1(^1P_1)$ were found to depend strongly on the 60.9 MeV differential cross-section data.[8] Removal of these data from the n-p data set caused $\bar{\epsilon}_1$ to increase by about 2.0°.

Another analysis[9] which used different higher phase parameter constraints due to boson exchange contributions obtained $\bar{\epsilon}_1 = -0.92$ and $\bar{\delta}(^1P_1) = -4.2$.

This unsatisfactory situation prompted us to measure the n-p differential cross section at 63 MeV in order to provide additional data for phase shift analyses in this energy range and to allow comparison with the 60.9 MeV data. In this work, we report differential cross-section measurements at 63.1 MeV for 39° to 166°. A discussion of their effect as well as that from a second measurement of A_{yy} (Ref. 10) on the phase parameters $\bar{\delta}(^1P_1)$ and $\bar{\epsilon}_1$ is given in Ref. 11.

EXPERIMENT

The experimental facility and beam production techniques were similar to those which have been described in earlier publications.[4,12,13] Figure 1 shows the overall arrangement for neutron beam production and collimation, proton detection, and data capture. A neutron beam was obtained from the $^7\text{Li}(p,n)^7\text{Be}$ reaction and collimated at 0° to 24 mm high by 12 mm wide with an intensity of $\simeq 10^6$ n/sec in the full energy peak at 63.1 MeV. The protons were bent by a magnet into a Faraday cup, which provided a secondary monitor of the neutron flux. The neutron beam was incident on a scattering target 3.5 m from the ^{7}Li target. The mean energy of neutrons in the high energy peak was determined to within ±0.2 MeV via time-of-flight (TOF) relative to a beam pickoff just upstream of the ^{7}Li target. The high energy peak had an energy spread of approximately 1.9 MeV full width at half maximum (FWHM) which resulted primarily from energy losses by protons in the ^{7}Li target.

Precise monitoring of the neutron beam intensity was obtained from a high stability proton-recoil telescope positioned downstream from the scattering chamber as well as from a ΔE-E charged particle telescope mounted outside the scattering chamber at a fixed angle of 15°.[14] In general, the three monitors used (charged particle telescope, proton-recoil telescope, and Faraday cup) showed very good agreement.

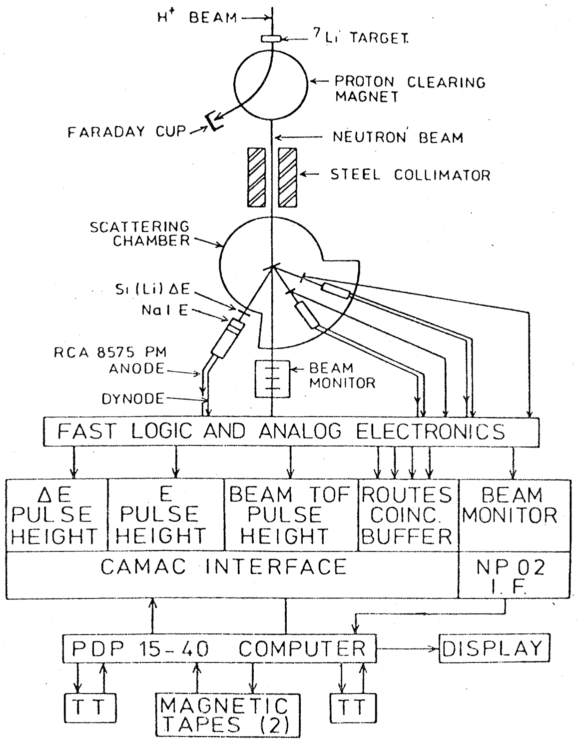

FIG. 1. Overall arrangement for neutron beam generation and data capture system.

Data were taken using three ΔE-E telescopes mounted inside the scattering chamber. Silicon detectors were used for the ΔE elements and NaI(Tl) scintillators coupled to RCA 8575 phototubes for the E elements. Each telescope subtended a lab angle of 5° at the target. Timing signals derived from the E detectors were measured relative to a beam pickoff. Amplitude and fast timing signals for ΔE, E, and TOF parameters were transferred to a PDP 15/40 computer via a CAMAC interface and recorded, event-by-event, on magnetic tape.

The overall recoil proton energy width ranged from about 2.4 MeV at forward recoil proton angles (7° lab) to about 4 MeV at the largest angles (70° lab). Data were taken with solid CH_2 targets 0.144 g/cm^2 in thickness for $25° \leq \theta_{1ab} \leq 60°$, and with a high pressure (typically 130 psi) LN cooled H_2 gas target for $25° \leq \theta_{1ab} \leq 70°$. This provided overlap data for normalization between the two cases. In the case of the gas target a two-collimator system was used with geometry such that the acceptance angle of each counter telescope included very little of the 0.125 mm thick aluminum walls of the 63 mm diameter gas cell (a beer can). At backward angles, the back collimator was 9.9 mm wide and 250 mm from the target center, while the front collimator was 10.2 mm wide, at 65 mm. For the forward angles, the back collimator was 9.9 mm wide at 250 mm, and the front one 3.8 mm wide at 70 mm from the target. The background in the gas target spectra was determined from runs with the gas cell empty. For the CH_2 target data, the yield due to reactions on carbon was estimated from runs using a carbon target.

DATA ANALYSIS AND RESULTS

The usual method of sorting the 3 parameter event-by-event data was to first select the particle type (proton, deuteron, etc.) by making cuts on each two-parameter ΔE vs E spectrum. Then the two-parameter TOF vs E spectrum was displayed for the events corresponding to the particle of interest, and cuts made to remove most of the events associated with low neutron bombarding energies. The result following these restrictions is a histogram containing the recoil proton peak.

The peaks are clean, except for a background which arises from reactions on carbon or aluminum depending on the target configuration. Owing to the rather poor timing characteristics of the proton beam at this energy ($\Delta t \simeq 3$ nsec), the separation of the peak from the tail is not as good as for cyclotron tunes at some other energies. The gas target background was very small due to the previously mentioned collimation system. The estimation of the background contributions to the peak constitutes the main uncertainty in the peak extraction. (The criterion which is most important for the present case is that a consistent method be used from angle to angle.) Several methods were used to determine the number of counts above background in the peak in each spectrum. From the dispersion in the values obtained, it was estimated that the background could be determined at worst to within 3% of the peak yield for a single run.

Data were taken in a number of runs, each of which consisted of angular distribution measurements for a CH_2 and a gas target. Although the relative (run to run) target thickness in the LN cooled gas target could be well monitored, its absolute value is more difficult to establish. The relative normalization between CH_2 and the gas target runs was achieved by minimizing χ^2 for a fourth order Legendre polynomial fit to the c.m. angular distributions as well as by using an average normalization factor only in the overlap regions. The two methods were in agreement within a percent. The former method was used in the final normalization.

Corrections to the data were made for the effects of finite solid angle, effective target thick-

TABLE I. *n-p* differential cross section at 63.1 MeV.

$\theta_{c.m.}$	$\sigma_{c.m.}$ (mb/sr) [a]	$\Delta\sigma$
39.4	11.01	0.68
49.3	9.61	0.26
59.2	8.75	0.17
69.1	8.45	0.18
79.1	7.91	0.16
86.2	8.28	0.14
89.0	8.23	0.15
99.1	7.97	0.16
109.1	8.91	0.16
110.3	8.54	0.28
119.2	9.40	0.14
125.2	9.39	0.34
126.4	9.83	0.16
129.3	10.08	0.23
139.4	10.68	0.33
149.5	11.81	0.27
150.7	11.77	0.44
159.7	12.79	0.31
165.8	13.60	0.46

[a] Data have been normalized to $\sigma_t = 121.6$ mb by fitting a fourth order Legendre polynomial.

ness (for the gas target data), telescope detection efficiency, and nuclear reactions in the NaI(Tl) detectors.[15]

The data were normalized to a total cross section of 121.6 mb as predicted by Binstock's parametrization[16] utilizing the integral of the fourth order Legendre fit to the data. Sensitivity to angles near 0° and 180° is not great due to weighting by $\sin\theta$. The results are given in Table I and shown in Fig. 2 along with the 60.9 MeV data[8] from ORNL (open triangles) and the Harwell data (open squares) at a mean energy of 62.5 MeV.[17]

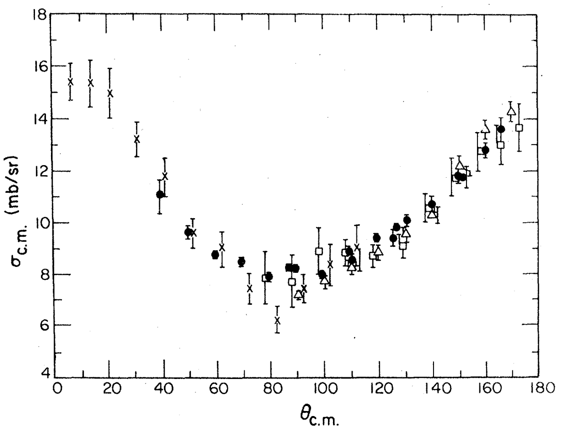

FIG. 2. Comparison of differential cross-section data near 60 MeV. Solid circles are the present measurements at 63.1 MeV. Open triangles are the ORNL data at 60.9 MeV from Ref. 8. *X*'s are forward angle and open squares back angle data from Ref. 17.

The uncertainties given for the differential cross sections are due to counting statistics in the recoil proton peak (≤2%), estimated uncertainties in background determination (≤3%), effective solid angles (≤1%), relative gas target thicknesses (≤1%), nuclear interaction corrections (≤0.5%), and telescope efficiencies (≤0.5%).

DISCUSSION AND CONCLUSIONS

The present differential cross-section data, regardless of normalization, exhibit a different angular behavior than existing data at 60.9 (Ref. 8) or 62.5 MeV.[17] This can be seen in Fig. 2. The ORNL data (open triangles) at 60.9 MeV have a more rapid increase with angle for $\theta_{c.m.} \gtrsim 90°$. Since the ORNL data have only appeared in preliminary form[2,8] with no experimental details, it is difficult to determine the origin of the present disagreement.

The forward angle Harwell data taken with neutron detectors are shown as *X*'s in Fig. 2 and the backward angle recoil proton data as open squares. The back angle Harwell data obtained by detecting recoil protons agree with the present experiment; however, the contribution to determining phase parameters is slight due to the greater uncertainties quoted in that experiment. At angles forward of 80° cm the Harwell data obtained by detecting neutrons are not in agreement with the present experiment. Although the Harwell data set encompasses a greater angular range than the present experiment, its overall shape as given by a least square fit disagrees in that a deeper minimum near 90° is apparent. The Harwell neutron measurements were based on an absolute efficiency calibration and the back angle data renormalized to give agreement with a total cross-section measurement. This resulted in a change in angular shape near 90° cm. The present experiment did not utilize neutron detectors and did not require significant energy (angle) dependent corrections. Allowing for the energy dependence, the shape and magnitude of the present data are consistent with the angular distribution at 50 MeV of Ref. 4 which spans $20° \leq \sigma_{c.m.} \leq 173°$. This leads one to conclude that some systematic errors exist in the forward angle Harwell data.

Figure 3 contains the present data as solid circles and recently published forward angle data of Bersbach, Mischke, and Devlin.[18] The Bersbach *et al.*[18] data have been averaged into two energy bins, open circles 54.6 to 63.1 MeV and open triangles 63.1 to 72.1 MeV. The solid line is the result of a recent phase parameter fit which includes the present data (see Ref. 11) and can be

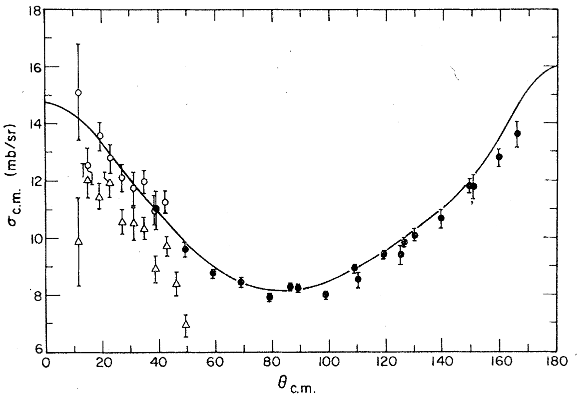

FIG. 3. Comparison of differential cross-section measurements from the present work (solid circles) and forward angle measurements at averaged energies over 54.6 to 63.1 MeV (open circles) and 63.1 to 72.1 MeV (open triangles) from Ref. 18.

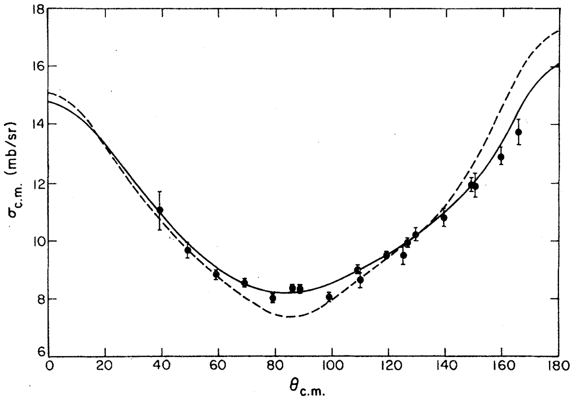

FIG. 4. Present measurements with the differential cross-section parametrization of Ref. 8 (dashed line) and a phase parameter fit of Ref. 11 (solid line).

used to represent the anticipated forward angle behavior of the n-p differential cross section. Although the present measurements and the Bersbach *et al.*[18] data appear to have different absolute normalizations, the relative differential cross sections appear to be consistent, particularly the lower energy bin centered at 58.8 MeV (54.6 to 63.1 MeV).

The influence of the recent measurements of the n-p observables including the present data in reducing the ambiguities and uncertainties in the isoscalar phase shift parameters near 50 MeV, particularly $\overline{\delta}(^1P_1)$ and the $^3S_1$-$^3D_1$ mixing parameter $\overline{\epsilon}_1$, are presented in Ref. 11. There is found a marked dependence of $\overline{\epsilon}_1$ on the differential cross-section measurements included in the overall data set. In Fig. 4 the present measurements are shown with a parametrization by Binstock[16] (dashed line) and a phase parameter fit (solid line) obtained in Ref. 11. The absolute normalization was allowed to vary in the phase parameter search. The normalization factor obtained was 1.0117, and the data shown in Fig. 4 have been renormalized by this factor. The parametrization by Binstock agrees well with the ORNL 60.9 MeV data. The difference therefore between the phase parameter fit and the parametrization further serves to illustrate the disagreement in angular behavior between the present results and the earlier measurements.

ACKNOWLEDGMENT

The authors would like to thank Professor P. Signell for valuable discussions and contributions concerning phase parameter analyses near 50 MeV. This work was supported in part by the National Science Foundation under Grants Nos. PHY 71-03499 and PHY 77-05301.

---

*Permanent address: Department of Physics, SUNY, Geneseo, N. Y. 14454.

†Present address: Los Alamos Scientific Laboratory, Los Alamos, N. M. 87545.

[1] J. K. Perring, Rev. Mod. Phys. 39, 550 (1967).

[2] R. A. Arndt, J. Binstock, and R. Bryan, Phys. Rev. D 8, 1397 (1973).

[3] J. Binstock and R. Bryan, Phys. Rev. D 9, 2528 (1974).

[4] T. C. Montgomery, F. P. Brady, B. E. Bonner, W. B. Broste, and M. W. McNaughton, Phys. Rev. Lett. 31, 640 (1973); T. C. Montgomery, B. E. Bonner, F. P. Brady, W. B. Broste, and M. W. McNaughton, Phys. Rev. C 16, 499 (1977).

[5] S. W. Johnsen, F. P. Brady, N. S. P. King, and M. W. McNaughton, Phys. Rev. Lett. 38, 1123 (1977) and references mentioned therein.

[6] J. L. Romero, M. W. McNaughton, F. P. Brady, N. S. P. King, T. S. Subramanian, and J. L. Ullmann, Phys. Rev. C 17, 468 (1978).

[7] P. Signell (private communication).

[8] M. J. Saltmarsh, C. R. Bingham, M. L. Halbert, C. A. Lindemann, and A. van der Woude, Oak Ridge National Laboratory (unpublished). See Ref. 2 for table of this data.

[9] R. A. Arndt, R. H. Hackman, and L. D. Roper, Phys. Rev. C 15, 1921 (1977).

[10] D. H. Fitzgerald *et al.*, following paper, Phys. Rev. C 21, 1190 (1980). This article contains a more complete discussion of the influence of A_{yy} measurements on ϵ_1.

[11] D. H. Fitzgerald, N. S. P. King, F. P. Brady, and P. Signell (unpublished).

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

[13] F. P. Brady, N. S. P. King, M. W. McNaughton, J. F.

Harrison, and B. E. Bonner, NBS SP425 1, 103 (1975), edited by R. A. Schrack and C. D. Bowman.

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

[15] D. F. Measday and C. Richard-Serre, Nucl. Instrum. Methods 76, 45 (1969); C. A. Goulding and J. G. Rogers, TRIUMPF Report No. TRL-753, 1975 (unpublished).

[16] J. Binstock, Phys. Rev. C 10, 19 (1974).

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

[18] A. J. Bersbach, R. E. Mischke, and T. J. Devlin, Phys. Rev. D 13, 535 (1976).