Neutron-Proton Differential-Cross-Section Measurements at 50 MeV*

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The neutron-proton differential cross section at 50.0 MeV has been measured to a precision of ≃ 2% for backward-hemisphere c.m. angles and ≃ 3% for forward angles, both relative. The present data are not in good agreement with the previous *n-p* measurements near this energy. A preliminary phase-shift analysis using the present data produces more satisfactory results, particularly for the $^1P_1$ phase shift.

Considerable information exists on the $T=1$ states of the nucleon-nucleon system exhibited in proton-proton scattering, at least for energies below 400 MeV. However, similar information on the $T=0$ states is lacking at the kinds of energies encountered in nuclear systems.[1] Neutron-proton experiments are necessary to obtain these $T=0$ phase shifts, and at the present time experimental data are inadequate to produce an accurate or even a unique phase-shift analysis at almost any energy. Furthermore, the *n-p* data in a given energy range often come from a single source or single laboratory and have never been verified by experiments in different laboratories or using different techniques. The situation at $E \leq 50$ MeV is particularly in need of attention according to MacGregor.[2]

In this work we report a new measurement of the *n-p* differential cross section at 50 MeV, which appears to resolve the conflict between energy-independent analyses on the one hand and predictions of energy-dependent analyses and boson-exchange models on the other. The data also indicate that those potential models, such as the widely used Reid potential,[3] which are based on the older data should be modified to fit the new data and the resultant new value of the $^1P_1$ phase shift. This value is in agreement with that given by boson-exchange models of the nucleon-nucleon interaction.

Two recent energy-independent phase-shift analyses[4,5] of the nucleon-nucleon data near 50 MeV give anomalous values for the $\delta(^1P_1)$ phase parameter, in disagreement both with energy-dependent analyses[1,6] and with the predictions of boson-exchange models.[5] MacGregor, Arndt, and Wright[4] obtained $\delta(^1P_1) = -1.34° \pm 1.71°$ in an energy-independent analysis at 50 MeV, which is less negative than the value obtained either at 25 MeV ($-4.00° \pm 0.69°$) or at 95 MeV ($-10.83° \pm 2.88°$). This value is also in conflict with their 50-MeV constrained energy-dependent result, $-7.19° \pm 0.24°$, and with the value $-7.01° \pm 0.49°$ found in an energy-dependent analysis carried out by a group at Yale.[6]

A second energy-independent analysis around 50 MeV has been performed at Texas A & M by Arndt, Binstock, and Bryan.[5] Using *p-p* and *n-p* elastic scattering data in the energy region 47.5 to 60.9 MeV, they found $\delta(^1P_1)$ to be $-3.52° \pm 1.04°$ which differs from the predictions of meson models ($-8.5°$ to $-10.5°$) by 5 or more standard deviations; it was the conclusion of these authors, as discussed previously by Signell,[7] that the *n-p* differential–cross-section data[8] were responsible for the anomalous value of the $^1P_1$ phase shift.

Replacing these previous *n-p* differential–cross-section data[8] with new data presented in this paper gives a value of $\delta(^1P_1) = -7.03° \pm 1.81°$ in a constrained energy-independent calculation.[9] This result is in considerably better agreement with results from other energies and with boson-exchange models.

The experimental facility and details concerning the beam have been given[10] previously. In brief, a 5–10-μA proton beam from the isochronous cyclotron of Crocker Nuclear Laboratory strikes a metallic ^{7}Li target, and neutrons from ^{7}Li$(p,n)^7$Be are collimated at 0° by a 1.55-m-long steel collimator. A well-defined beam of size 12 mm wide × 24 mm high and of intensity 4×10^5/cm^2 sec is formed. Roughly 60% of the neutrons produced in the reaction ^{7}Li$(p,n)^7$Be fall within a well-defined high-energy peak about 2 MeV wide, corresponding to transitions principally to the ground state of ^{7}Be. The remaining neutrons are spread over a broad, lower-energy tail. The mean energy of the beam peak was determined to within ±100 keV by a time-of-flight technique.[11] The beam intensity is monitored by a high-stability recoil-proton telescope which has been described elsewhere.[12]

Measurements of forward- and backward-angle relative cross sections were made separately, employing different techniques. In each, several movable detector arms were used simultaneously, in addition to an arm at a fixed angle ($\simeq 20°$) to monitor the product of beam intensity and the number of scattering centers. All arms shared the same analog electronics for digitizing pulse-height and time-of-flight parameters. Analog data, in addition to a detector identification signal, were transferred to an on-line PDP 15/40 computer via a CAMAC interface, and recorded event by event on standard magnetic tape. The data were subsequently analyzed using a suite of interactive programs written for the PDP 15.

For the case of forward c.m. angles a scintillating target of NE102A was used. The design of the target, in the form of a triangular prism of NE102A epoxied to the face of an RCA 8575 phototube, allowed it to remain fixed while a large angular range of scattered neutron angles was covered by movable detectors, without incurring loss in the recoil pulse height due to the effect of target edges. Scattered neutrons were detected in NE102A plastic scintillators, 7.1 cm diam, 15.2 cm long, at a distance of 137.5 cm from the target. A charged-particle veto detector was mounted directly in front of each neutron detector. Four neutron detectors were used simultaneously, one of which remained fixed as a monitor.

Each event was characterized by four parameters: the scintillating-target (ST) pulse height, the neutron-detector pulse height, the incident time of flight, and the scattered-neutron time of flight. The third of these was the time between a signal from the beam pickoff, located just ahead of the ^{7}Li target, and one from the ST. The fourth parameter measured the time between an ST signal and that of a neutral particle registering in one of the neutron detectors. Zero-crossing timing was used on the beam pickoff, ST, and neutron detectors to minimize time walk. The neutron pulse height was calibrated from the Compton edge of 4.4-MeV γ rays from a Pu-Be source.

During analysis, events falling in the high-energy incident time-of-flight peak were selected and displayed as a two-parameter histogram of ST pulse height versus scattered time of flight. A clear single peak was observed and summed, subtracting accidental ST-n coincidences by sampling a region of the scattered time-of-flight spectrum where no physical process could lead to a true coincidence.

The major contribution to the error in the forward-angle data is the uncertainty in the neutron-detector efficiency, which has been calculated (as a function of energy) using the computer program written by Stanton.[13] Measurements of the neutron-detector efficiencies for the detectors used were made at this laboratory for neutron energies less than 34 MeV[14] and indicate that the $\pm 5\%$ estimated by Stanton as the absolute accuracy of his program is in general realistic. We estimate a relative uncertainty in the detector efficiency as a function of energy of $\pm 1.5\%$ between adjacent data points (10° apart), accumulating to the estimated uncertainty of $\lesssim 5\%$ over the full angular range (20° to 90°). The energy variation of the corrections for multiple scattering and attenuation of scattered neutrons ($\simeq 6\%$) is estimated to have a relative uncertainty of $\simeq 1.5\%$.

For back hemisphere c.m. angles recoil protons were detected from n-p scattering in polyethylene $(CH_2)_n$. Preliminary results[15] were reported earlier. The detector system consisted of three DE-E telescopes, two of which were mounted 20° lab apart on a movable arm inside an evacuated scattering chamber, with the third being mounted at a fixed angle (30° lab) outside the scattering chamber, where it viewed the $(CH_2)_n$ target through a thin Mylar window. This third arm served to monitor the product of beam intensity and number of scattering centers. Each arm consisted of a thin (200 or 400 μm) surface-barrier silicon transmission DE detector backed by a sodium-iodide crystal coupled to an RCA 8575 phototube serving as an E detector. A 2.0-cm-diam, 0.63-cm-thick brass collimator was mounted in front of each silicon DE detector.

The most serious backgrounds were due to C(n,p) reactions. A C target containing nearly the same number of C nuclei was used to measure this background. The background was normalized to foreground through the use of the beam monitor. Background protons beneath the ^{1}H$(n,p)n$ peak ranged from less than 1% at forward lab angles to less than 8% at backward lab angles (corresponding to a range of $\simeq 180°$ to 80° c.m.). The largest corrections here were to account for peak losses due to nuclear interactions in the NaI. These losses ranged from $\simeq 1\%$ at 25 MeV to $\simeq 4.5\%$ at 50 MeV.[16]

Results are quoted in Table I with the relative normalization of forward-to-backward angle data determined by the three overlap angles. In Fig. 1 the relative and absolute normalization of the two sets of relative cross-section measurements

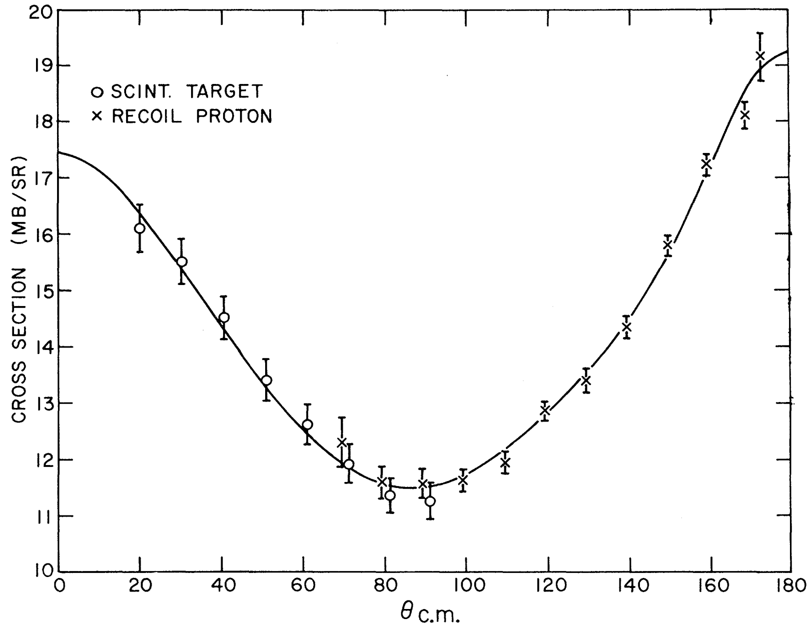

FIG. 1. Differential cross section for n-p scattering at 50.0 MeV, shown in relation to a (constrained) phase-shift calculation (Ref. 9). The forward-angle data of Table I have been multiplied by a factor of 0.975 to optimize the fit. (Note the suppressed zero.)

TABLE I. Differential cross section for n-p scattering at 50.0 MeV.

c. m. angle (deg)	cross section (mb/sr)	error (mb/sr)
Forward angle (ST-neutron detector) data		
20.27	16.51	0.53
30.40	15.91	0.45
40.52	14.90	0.38
50.62	13.74	0.36
60.70	12.93	0.35
70.77	12.22	0.33
80.81	11.67	0.38
90.83	11.56	0.38
Backward angle (recoil proton) data		
c. m. angle (deg)	cross section (mb/sr)	error (mb/sr)
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

have been allowed to vary to give the best fit to a constrained phase-shift calculation.[9] The errors quoted in the table for forward angles include only the point-to-point uncertainty in detector efficiency of $\pm 1.5\%$ (discussed above) and not the estimated cumulative uncertainty of $\lesssim 5\%$ applicable to the full forward-angle range. In obtaining the fit[9] an uncertainty of 5% was assigned to all forward-angle data points to include this cumulative uncertainty. The result of this energy-independent search is a value of $-7.03° \pm 1.81°$ for the $^1P_1$ phase shift.

The overall uncertainties include those due to counting statistics, estimated uncertainties in making beam and energy peak cuts, an estimated $\pm 1.5\%$ uncertainty in relative neutron-detector efficiency, and estimated 1.5% uncertainty in neutron attenuation. The uncertainties in normalizing forward- to backward-angle data and normalizing to a total–cross-section value have not been included. The latter is $\simeq 1\%$ as determined by the precision of total–cross-section data contained in the analysis including measurements at this laboratory with the same beam.[12]

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Fusion and Fission of Light Nuclei with Angular Momenta near the Calculated Liquid-Drop Limit*

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Elemental yields have been measured for the nuclei produced in the reactions of 100- and 180-MeV ^{12}C on ^{27}Al. Fusion cross sections, including those followed by fission, are derived using charge conservation. At 180 MeV the apparent limiting angular momentum for fusion is $40\hbar$, in excellent agreement with a liquid-drop calculation. Fission does not account for more than 18% of the fusion cross section at 180 MeV, unless that fission is of an extremely asymmetric nature indistinguishable from the evaporation of small particles.

In several recent studies, the cross section for fusion of a heavy-ion projectile with a target nucleus has been determined by detection of the recoiling product nuclei.[1-3] At the high projectile energies employed in those experiments (~10 to 15 MeV/amu) the fusion cross sections are found to be well below the corresponding total reaction cross sections. Complementary experiments[4] indicate an increase in the probability of direct reactions in the same region where the fusion cross section is decreasing. However, since only a few of the possible direct-reaction products were observed, a substantial portion of the total reaction cross section remained unaccounted for.

It has recently been suggested[5] that there may be an appreciable cross section for fission of even the light elements when an excited nucleus is formed with very high angular momentum. In such a case the fission component might not be included in the fusion cross-section measurements as they are typically performed. The measured cross section would then be interpreted as the cross section for the formation of a nonfissioning fused nucleus.

This expectation of high probability of fission is based upon liquid-drop-model calculations[6] which indicate that the fission barrier decreases with increasing angular momentum. The angular momentum at which the fission barrier disappears is viewed as the maximum possible angular momentum at which fusion could occur. In view of the fact that the fission barrier is low for angular momenta near the limiting value, fission is predicted to be an important competing mode