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np-elastic analyzing power A_{N0} at 485 and 788 MeV

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Measurements are reported for the *np*-elastic analyzing power from 30° to 128° c.m., at 485 and 788 MeV, with a typical precision of 0.005 and absolute accuracy of 2%. Results strengthen the isospin-0 phase-shift analysis, and clarify the absolute normalization of the polarized neutron beam and the isospin-0 inelasticity.

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I. INTRODUCTION

A. Nucleon-nucleon interaction

The nucleon-nucleon (*NN*) interaction is fundamental to nuclear physics. *NN* data serve as tests of the strong interaction, and as input to microscopic models of the nucleus. The data are usually parametrized in terms of a phase-shift analysis (PSA) or partial wave analysis (PWA) such as those published by Arndt *et al.* [1] and by Bugg *et al.* [2,3]. These parametrizations facilitate the calculations of scattering amplitudes, and of any *NN* observable.

The proton-proton (*pp*) interaction has been well studied at intermediate energies [4–13], leading to a complete determination of the isospin-1 phase shifts and scattering amplitudes [1,2]. More recently, measurements of the four spin-correlation parameters [14–17] and the five spin-transfer parameters [18–20] for neutron-proton (*np*) elastic scattering have led to a complete determination of the isospin-0 phase shifts and amplitudes at intermediate energies [1,3]. *NN* scattering has recently been reviewed [21].

Nevertheless there remain two controversial questions, concerning (a) the absolute normalization of the spin dependent data, and (b) the inelasticity. The measurements of the

np-elastic analyzing power, reported here, address both of these.

B. Absolute normalization

The absolute normalization of the polarization of a nucleon beam is difficult [22]. New data are usually normalized relative to a previous measurement, often via a chain of relative measurements deriving from one absolute measurement. The neutron beam polarization at the Los Alamos Meson Physics Facility, LAMPF, has historically been derived from one of two absolute measurements: the measurement of the np analyzing power by Newsom *et al.* [23] using a polarized proton target, and the double-scattering measurement from deuterium by McNaughton *et al.* [24]. These two methods disagree significantly.

By overlapping with previous forward-angle data, the present data provide independent confirmation of the absolute neutron beam polarization. The previous data of Glass *et al.* [25] and of Barlett *et al.* [26] were obtained by scattering the LAMPF polarized proton beam from the quasifree neutron in deuterium, thus normalizing to the well-established proton beam polarization [12,27]. In the present experiment a polarized neutron beam was scattered from the protons in liquid hydrogen, normalizing to the neutron beam polarization. Thus, by comparing the present ^{1}H$(n,p)n$ data with the previous ^{2}H$(p,pn)2p$ data, we compare the neutron and proton beam polarizations.

It should be noted that this comparison is valid subject to two assumptions. First, it is assumed that the scattering from the neutron in deuterium is quasifree, i.e., that the proton in deuterium is a spectator that does not affect the experiment. This assumption is generally accepted, except possibly at low energies ($\ll 100$ MeV) or forward angles ($\ll 10°$ c.m.). Second, it is assumed that charge symmetry holds, i.e., that scattering a polarized proton from a neutron is the same as scattering a polarized neutron from a proton. Charge symmetry has been tested extensively, and found to be correct except for small corrections [28,29].

C. Inelasticity

The second controversial question concerns the inelasticity. Recent measurements of the np inelastic reactions at intermediate energies [30,31] have not resolved the question of which partial waves contain significant inelasticity. Verwest *et al.*, [32] and Bystricky *et al.* [33] parametrized the np inelastic data, and came to very different conclusions concerning the isospin-0 inelasticity. Bystricky *et al.* include two possible solutions, A and B (see p. 1921 and Fig. 32 of Ref. [33]) which differ by 5 mb.

Instead of relying on inelastic data, Bugg and Bryan [3] conclude that the total inelasticity should be deduced from the difference between total and elastic cross sections. Furthermore, they argue that the elastic phase shifts contain important clues about which partial waves contain significant isospin-0 inelasticity. The phase-shift analyses show structure in the $I=0$, $^3G_3$ phase shift near 800 MeV, suggesting that this partial wave might provide a dominant mechanism for inelasticity. Since the $^3G_3$ partial wave couples easily to two deltas, a significant part of the $I=0$ inelasticity may be due to coupling to two deltas (note that $I=0$ partial waves cannot couple to a single delta). Since 800 MeV is far below the 1380 MeV mean energy for production of two deltas, this coupling might well be much stronger at higher energies. (See, for example, Fig. 9 of Ref. [34] for the energy dependence.) Furthermore, if the dominant inelasticity is via two delta resonances, this would indicate that $I=0$ inelasticity is small at energies below 800 MeV. This interpretation would be consistent with solution B of Bystricky *et al.* [33] but not solution A.

In an attempt to check Bugg's hypothesis, we searched for a precise measurement that is a sensitive probe of the structure of the $^3G_3$ phase shift. We discovered that the ratio of the forward to backward peaks in the np-elastic analyzing power is especially sensitive to the $^3G_3$ phase. The precise measurement reported here, using a single experimental technique for both forward- and backward-angle peaks, clarifies the $^3G_3$ structure that Bugg interprets as coupling to a pair of deltas.

II. EXPERIMENT

A. Experimental technique

To fix the ratio of the forward to backward peak magnitudes, and to tie down the absolute neutron and proton beam polarizations, it is important to use the same experimental technique to measure the forward peak near 30° c.m. and the backward peak near 110° c.m. For this purpose, we modified the apparatus used previously [18] to allow us to reach 30°. The experimental method used for the present data was almost identical to the previous method [18].

Briefly, polarized protons from the optically pumped polarized ion source (OPPIS) were accelerated in the Los Alamos Meson Physics Facility (LAMPF) to 797 or 497 MeV. These were directed through a pair of proton polarimeters [35], and onto a 25-cm-long liquid deuterium (LD_2) target. Polarized neutrons produced from the ^{2}H(p,n) reaction were collimated at 0°. The neutron energy spectrum [36] consisted of a high energy peak, less than 15 MeV wide (FWHM), and a low energy tail that was excluded by time-of-flight measurements. The polarized neutron beam passed through four magnets to a 39-cm-thick by 24-cm-diam liquid hydrogen (LH_2) target. The magnets served both to precess the neutron spin, and to sweep charged particles from the neutron beam.

Scattered neutrons were detected in a position sensitive neutron detector [37] with an efficiency about 50%. Scattered protons were detected in the Vartola magnetic spectrometer, with a few percent resolution. Scattered neutrons near 15° lab and protons near 70° lab correspond to a scattering angle, θ, of about 34° c.m.

B. Analyzing power

The spin-precession magnets precessed the neutron beam polarization to the "N-spin" direction, i.e., normal to the scattering plane [35]. The analyzing power for an N-spin polarized neutron beam scattered from an unpolarized hydrogen target is usually called A_{N0} and is defined in [18] (Sec. III D) as well as [38,39]. Briefly,

$$A_{N0}=\frac{L-R}{P(L+R)},$$

where L and R are the number of neutrons elastically scattered to the left and right, respectively, divided by the incident beam intensity. P is the polarization of the neutron beam.

The beam spin was periodically flipped 180°, allowing R to be defined as the number of neutrons scattered right when the beam spin was up, and L as the number scattered right when the beam spin was down. The spin was flipped inside the OPPIS source every minute by changing the frequency and circular polarization of the optical-pumping lasers. This in turn flipped the spin of the polarized neutron beam.

The neutron-beam polarization, P, was obtained by measuring all three components (x,y,z) of the proton-beam polarization using the beam line polarimeters [35] and multiplying by the spin-transfer parameter K_{LL} for $^2\mathrm{H}(p,n)$ in the LD_2 target [24]. Typical values of the polarization were 0.65 for the proton beam, and 0.47 for the neutron beam.

C. Good events

A good elastic scattering event was defined by having correct values for the following parameters: incident-neutron-beam time-of-flight, scattered-neutron time-of-flight, scattered-proton time-of-flight, scattered-proton momentum, opening angle, and coplanarity between scattered proton and neutron. In addition, traceback of the scattered-proton trajectory established that the event originated in the liquid hydrogen (LH_2) target. The number of good events was corrected for incident beam, detector live time, detector efficiency, and background. Background was subtracted by extrapolating under the momentum peak. Background corrections were less than 1%, i.e., 0.003 for an analyzing power of 0.3. More details are contained in [18] Sec. III E.

Changes from the previous experimental apparatus [18] were as follows. First, the LH_2 target was moved 1.5 m downstream to allow the proton spectrometer to clear the shielding wall. Second, the neutron-beam collimation was reduced to a radius of 5 cm to keep the neutron beam well within the 12-cm radius of the LH_2 target. Third, one of the three planes of scintillators was removed from the proton spectrometer, and fourth, the carbon was removed from the Janus [40] detector array, in order to detect low momentum protons near 70° lab. The agreement between the present data using a smaller collimator and the previous data [18] near 110° c.m. using a larger collimator confirmed that collimator size does not significantly affect the data. The removal of the carbon from Janus meant that every proton passed through a total of nine multiwire chambers, allowing the detector efficiency to be measured several ways [4]. All of these were in good agreement.

D. Low energy protons

Most of the possible systematic errors associated with this experimental setup have been carefully investigated and found to be extremely small [41]. The detection of low energy protons near 70° lab raised the possibility of some additional sources of error, which are discussed in this section.

At the limits of this experiment, some of the lowest energy protons stopped in the LH_2 target or in the spectrometer. Any movement of the beam would affect the thickness of hydrogen traversed by the scattered protons, and therefore the number of protons detected. If the movement was correlated to the beam spin direction, this would lead to an error. Because the beam spin was flipped by changing only the OPPIS lasers, no beam movement is expected. This was measured [41] and found to be generally less than 0.01 mm at the LH_2 target. This implies an error in the asymmetry which is less than 0.01 mm divided by the effective neutron beam size of 0.1 m, which is negligible.

Coulomb multiple scattering of low energy protons barely emerging from the LH_2 target can bias the measurement of the scattering angle. In some cases, those protons that scatter toward a smaller angle can pass through less liquid hydrogen and so are detected with a higher probability. This was modeled with a Monte Carlo program. Corrections to the scattering angle for the 485 MeV data were as follows: 43.43° point: measured angle =43.34°, correction =+0.09°; 40.43° point: measured angle =39.71°, correction =+0.73°.

The 35.68° point was obtained from hydrogen gas, so the multiple scattering was small. At 788 MeV, the angular corrections do not affect the analyzing power, since the slope is almost zero at the extreme angles near 30° c.m.

An uncertainty equivalent to the size of the correction was included for each data point.

To check the effects of the LH_2 target on low energy protons, data were taken with a cold hydrogen gas target. Results were generally consistent with the liquid hydrogen data, within the quoted uncertainties, at the two angles, 40.43° and 43.43°, where both data sets were taken. The data points at the most forward c.m. angle (most backward proton angle) at each beam energy were obtained from hydrogen gas only, since for these extreme angles, the protons stopped within the liquid target.

E. Absolute angle

The absolute angle at which the analyzing power is zero is important. A common test of charge symmetry compares the zero-crossing angle for polarized protons on neutrons with that for polarized neutrons on protons [28,29,42]. Near the zero-crossing angle, an error in the absolute angle would affect the fit. The slope is about 0.03 per degree, so that an uncertainty of 0.1° is equivalent to an uncertainty of 0.003 in the analyzing power. This error is likely to be correlated for all points.

The absolute scattering angle was measured by two independent methods. First, the absolute angle was surveyed directly using standard survey equipment. Second, as an independent check, the maximum deuteron angle was measured for the reaction $np \rightarrow d\pi$, using a method similar to the method described in [43] (p. 628) and [4] (p. 668), detecting the deuteron in the proton spectrometer and the associated pion in the neutron detector. The measured deuteron angle was then compared with kinematic calculations. Agreement between these two methods was good.

The scattering angle is determined by the multiwire proportional chambers (MWPC's) closest to the target, but these were difficult to access with survey equipment. We estimate the uncertainty in the direct surveys to be approximately 0.1° lab.

The method using the maximum deuteron angle in $pp \to d\pi$ was investigated by Gülmez [43], resulting in an estimated uncertainty of 0.04°. In the present experiment, however, the resolution was poorer, mostly because of multiple scattering from the thick target and increased background, so we estimate the uncertainty of this method to be 0.1° lab.

The deuteron angle was measured five times under different conditions, resulting in an average that was $0.1 \pm 0.1°$ less than the kinematically expected angle. We conclude that the two methods agree to within the expected uncertainties.

In summary, we estimate the uncertainty in the absolute scattering angle θ to be 0.1° lab. This has been included as an uncertainty in the analyzing power A of up to 0.003.

The location of the multiwire chambers relative to the spectrometer frame was not changed between the present and previous measurements [18], so that the agreement with the $np \to d\pi$ data is also a check of the previous measurement of the angles.

III. CONCLUSIONS

A. Results

Results for the np elastic analyzing power at 485 and 788 MeV are listed in Tables I and II. The overall normalization uncertainty of 2% at 485 MeV and 2.4% at 788 MeV comes from the measurement of the spin-transfer parameter K_{LL} for the ^{2}H(p,n) reaction [24] and is common to the previous data [18]. The results are shown in Figs. 1, 2, and 3, and are compared with recent phase-shift solutions of Arndt [1] and Bugg [3], and with previous measurements. Some previous data with larger relative uncertainties [23,28,44,45] are not included in Figs. 1, 2, and 3. The fits attributed to Arndt and Bugg are new fits which include the present data.

The agreement with Bugg's fit is good, with a χ^2 per degree of freedom that is less than 1, because the uncertainties include systematic errors that are correlated for many data points, e.g., uncertainties in angle, and background subtraction.

Agreement is also good between the present data and the previous experiment using similar apparatus at LAMPF [18].

The absolute zero-crossing angle agrees well with the data from the TRIUMF charge-symmetry experiment [28, 29], but is greater than the zero-crossing angle reported by Glass *et al.* [25] (see Fig. 1), and less than that reported by Clough *et al.* [46] (see Fig. 2).

The data of Clough *et al.* [46] were obtained as part of the experiment at the TRIUMF accelerator to measure the spin-transfer parameters. These were first reported by Axen *et al.* [47], and are sometimes associated with this reference. Since the angle is less important for the spin-transfer parameters, the absolute angle was not measured precisely. Much of the difference between the present data and the TRIUMF data can be explained by Bugg's suggestion that the TRIUMF angles are incorrect [2].

B. Absolute normalization

Previous forward angle data [25, 26, 48-50] were obtained using a polarized proton beam scattered from the quasifree neutrons in an unpolarized liquid deuterium target. Assuming charge symmetry and quasifree scattering, these previous data should agree with the present data which used a polarized neutron beam. The good agreement is important because it ties together the absolute normalization of the neutron and proton beams.

TABLE I. np-elastic analyzing power A_{N0} at 788 MeV. Overall normalization uncertainty is 2.4%.

$\theta_{\mathrm{c.m.}}$	A_{N0}
128.02	-0.226 ± 0.004
123.86	-0.236 ± 0.004
118.20	-0.259 ± 0.004
116.38	-0.268 ± 0.004
112.33	-0.268 ± 0.004
106.89	-0.276 ± 0.004
105.40	-0.278 ± 0.004
101.01	-0.263 ± 0.004
96.09	-0.243 ± 0.004
94.88	-0.236 ± 0.004
89.68	-0.185 ± 0.004
84.65	-0.127 ± 0.004
80.24	-0.058 ± 0.005
79.12	-0.047 ± 0.004
75.97	-0.004 ± 0.004
74.80	0.015 ± 0.004
70.62	0.073 ± 0.004
66.29	0.126 ± 0.005
64.86	0.134 ± 0.004
60.99	0.179 ± 0.004
57.14	0.215 ± 0.004
55.77	0.218 ± 0.005
52.12	0.248 ± 0.005
48.33	0.268 ± 0.005
46.73	0.279 ± 0.004
43.74	0.287 ± 0.004
40.32	0.305 ± 0.004
38.53	0.317 ± 0.004
36.01	0.321 ± 0.004
32.60	0.327 ± 0.004
29.67	0.327 ± 0.005

We have used Bugg's phase-shift analysis code QUAPS to obtain new fits. This analysis renormalizes the present data by dividing by 1.005, and the data of Glass *et al.* by dividing by 1.015. If we select only the data in the overlapping angular region, as shown in Fig. 3. the agreement is even better, with a renormalization factor of 1.004 for Glass *et al.* This agreement is well within the normalization uncertainties: 2.4% for the present data at 788 MeV, and 3% for Glass *et al.* (The estimate of 3% for the normalization uncertainty of the Glass *et al.* data was chosen conservatively because the quench ratio method [12] was new at that time; subsequent experience [27,35] suggests that a normalization uncertainty of 2% would be more appropriate.)

A similar comparison is possible with the other data shown in Figs. 1, 2, and 3 but the precision is less good, either because there are fewer points, the error bars are larger, or the absolute normalization is less precise. The data of Marshall *et al.* [48] and Barlett *et al.* [26] were both ob-

TABLE II. np-elastic analyzing power A_{N0} at 485 MeV. Overall normalization uncertainty is 2.0%.

$\theta_{c.m.}$	A_{N0}
108.96	-0.298± 0.004
104.41	-0.301± 0.005
99.67	-0.299± 0.004
78.29	-0.106± 0.006
73.87	-0.053± 0.005
69.81	0.003± 0.005
68.76	0.015± 0.006
65.47	0.055± 0.008
64.88	0.057± 0.006
60.76	0.112± 0.006
59.90	0.126± 0.006
56.73	0.168± 0.005
52.68	0.204± 0.005
50.45	0.236± 0.007
47.85	0.254± 0.008
43.43	0.304± 0.009
40.43	0.335± 0.009
35.68	0.353± 0.013

tained using the LAMPF polarized proton beam scattering from deuterium. Bystricky *et al.* [49] at Saclay, and Cheng [50] at Berkeley also used quasifree scattering from deuterium. The agreement with these data is generally good, except for Cheng's most forward angle point near 40°.

The earlier publication of Korolev *et al.* [51] and the later publication of Silverman *et al.* [52] report the same set of data, obtained with polarized neutrons at Saclay. These agree with the present data at the overlap angle near 30°, although the Saclay data are below the fits at smaller angles.

The data of Clough *et al.* [46], obtained with the polarized neutron beam at the TRIUMF accelerator were discussed at the end of Sec. III A.

C. Inelasticity

As discussed in the Introduction, Sec. I C, the ratio of the forward- to backward-peak magnitudes in the np analyzing power is sensitive to the precise value of the $^3G_3$ phase shift. A hypothetical change of 10% in the relative peak magnitudes causes a change of 2° in the $^3G_3$ phase shift, which is sufficient to bring the value into agreement with the one-pion-exchange (OPE) calculation. The phase-shift analyses of Arndt [1] and of Bugg [2,3] include absolute normalization factors for each data set, so in previous analyses, this adjustment was possible with a small χ^2 penalty. For example, Arndt renormalizes the data of Korolev *et al.* and Silverman *et al.* [51,52] by 10%, or 3 standard deviations, with a χ^2 penalty of 9. With the present data, which extend over both forward and backward peaks with a single normalization factor, a 10% adjustment would result in a χ^2 penalty of almost a thousand.

We have used Bugg's phase-shift analyses code QUAPS to obtain a new value for the 800 MeV $^3G_3$ phase shift of $-6.51°$. This is almost identical to the value of $-6.53°$ obtained previously [3]. This supports the suggestion [3] that the $^3G_3$ phase shift may be influenced by impending inelas-

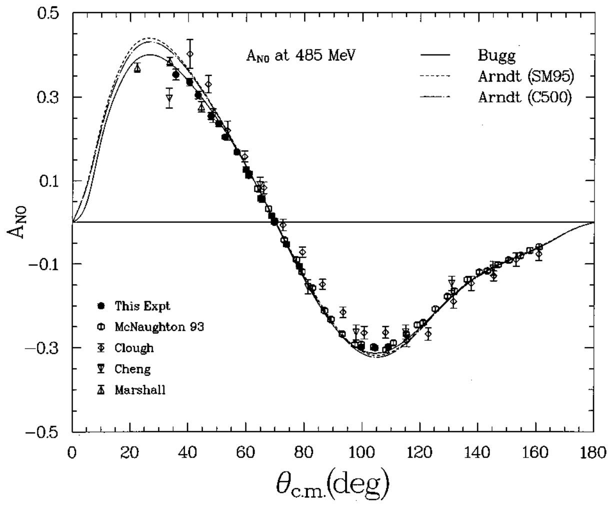

FIG. 2. A_{N0} at 485 MeV in comparison with the phase-shift fits of Arndt and Bugg, and previous data.

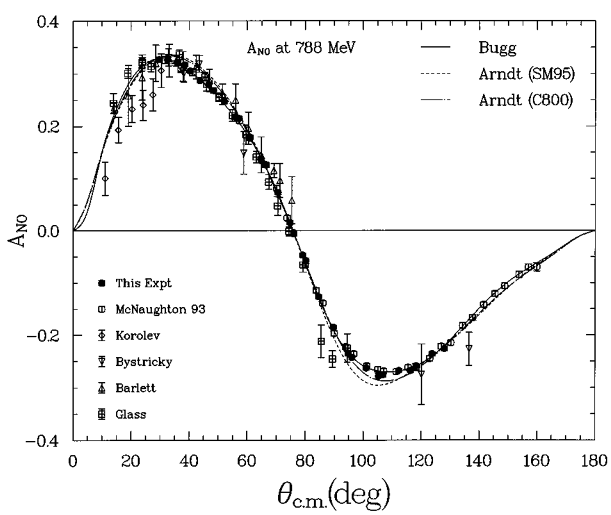

FIG. 1. A_{N0} at 788 MeV in comparison with the phase-shift fits of Arndt and Bugg, and previous data.

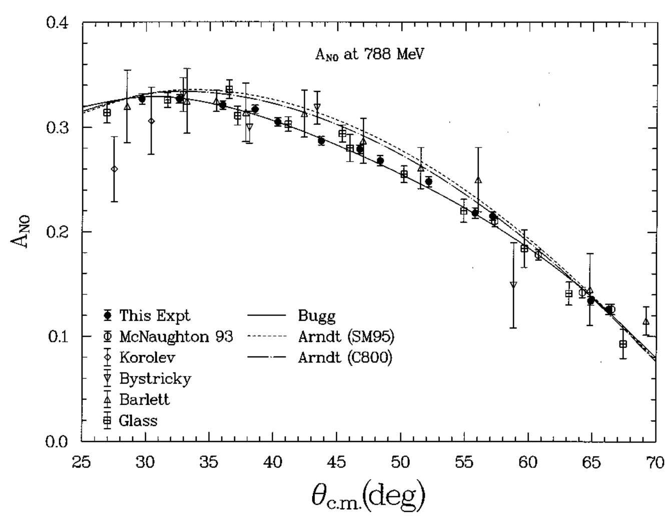

FIG. 3. A_{N0} at 788 MeV in comparison with the phase-shift fits of Arndt and Bugg, and previous data; enlargement of part of Fig. 1.

ticity. Although the $^3G_3$ phase decreases steadily from 0 to 500 MeV, faithfully following the trend of the one-pion-exchange (OPE) prediction, it begins to increase near 800 MeV. Both Arndt's and Bugg's analysis give values of the $^3G_3$ phase shift that are below OPE, with a negative slope, at 500 MeV, and above OPE, with a positive slope, at 800 MeV. Thus, our data, which strengthen the previous phase-shift analyses showing structure in the $^3G_3$ phase shift near 800 MeV, add credence to the explanation that at low energies the dominant mechanism in NN inelasticity is coupling to two deltas, and for this reason, $I=0$ inelasticity is small below 1 GeV.

D. Summary

In summary, the ratio of forward to backward peaks obtained from the present np-elastic analyzing power data, and the excellent agreement with Bugg's analysis [3] strengthen the conclusion that the $^3G_3$ phase shift is increasing with energy near 800 MeV. Since $^3G_3$ couples to a pair of deltas, this may signal impending inelasticity in isospin-0.

Furthermore, the agreement of the present data with Glass *et al.* [25] supports the value of K_{LL} in ^{2}H(n,p) obtained from the double-scattering experiment [24], and also the conclusion that the np analyzing power data of Newsom *et al.* [23] are incorrect. This implies that the older values of K_{LL} [53, 54] obtained by normalizing to Newsom *et al.* [23] are incorrect.

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