Spin Dependence in Low-Energy Neutron-Proton Scattering

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The analyzing power in neutron-proton scattering at 25 MeV neutron energy has been measured to an accuracy of typically ± 0.002 for c.m. scattering angles between 50° and 165°. Contrary to the conclusions reached from earlier precision measurements at 16.9 MeV, the contributions to partial waves with $l \geq 3$ are consistent with predictions based on one-pion exchange. The new data are well described by the Paris potential and by a recent global phase-shift analysis.

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The still incomplete understanding of the nucleon-nucleon (*NN*) interaction at low energies leads to continued interest in this most basic force for nuclear physics. In the present approach the experimental results can be represented either by an effective *NN* potential (e.g., the Paris potential[1]) or by energy-dependent phase shifts where the energy dependence of each phase shift is given an analytical parametrization (e.g., Arndt and coworkers[2,3]). In either case, the choice of parametrization is influenced by theoretical arguments based on the assumption that the *NN* force arises from meson exchange. In particular, there is firm evidence that the long-range part of the interaction, which is reflected mostly in the higher partial waves, arises from one-pion exchange.

It is not unusual, of course, that conflicts with accepted ideas arise as new, more accurate experimental methods are developed. For scattering of neutrons by protons (*np*), new methods to produce fast neutrons of reversible polarization have made possible much improved measurements of the polarization effects. A Letter[4] and a subsequent detailed paper[5] reported new measurements of the analyzing power A_y as a function of scattering angle θ in the *np* system at 16.9 MeV to an accuracy of ± 0.002. These results were in conflict with existing models of the *NN* interaction and led the authors[5] to call for a "reassessment of all nucleon-nucleon models for low-energy *np* scattering." These discrepancies were considered fundamental in nature since the new data required a significant contribution from *F* waves, contrary to the prediction of one-pion exchange.[6] While it would be premature to speculate that these findings indicate the presence of an anomalous long-range force[7] between quark bags (van der Waals force), the discrepancy with one-pion-exchange predictions is serious and warrants further study.

We decided to perform new polarization measurements in the *np* system at 25 MeV. One can expect that at this energy the possible *F*-wave effects should be enhanced. These effects manifest themselves in the 16.9-MeV data mostly at backward scattering angles, in particular by the steep falloff of the analyzing power. Since backward angles are crucial in the comparison between experimental results and current theories,[8] in our measurements special attention was devoted to the large scattering angles.

Polarized neutrons of 25 MeV energy were produced by polarization transfer in the reaction $T(d_{pol},n_{pol})^4He$ at 0°. This reaction has a much larger *Q* value than the $D(d_{pol},n_{pol})^3He$ used in Refs. 4 and 5, so that the outgoing neutrons are very well separated in energy from the continuum of low-energy neutrons due to deuteron breakup. The smaller cross section of the reaction $T(d,n)^4He$ was compensated by use of a more intense (0.5 μA) deuteron beam which was provided by a tandem accelerator equipped with a polarized-ion source.[9] The polarization was reversed every 0.25 sec by switching of rf transitions at the ion source. Both the vector polarization ($p_y \approx 0.61$) and the tensor polarizatoin ($p_{yy} \approx 0.05$) of the incident deuterons were monitored continuously by use of a thin carbon-foil transmission polarimeter located upstream of the tritium gas target. The outgoing neutron polarization was determined by elastic scattering from a ^{4}He gas scintillator.[10] The relative normalization error of the *np* analyzing powers which arises from the uncertainty in the neutron polarization is 3.3%.

A broad angular range in *np* analyzing-power measurements was covered by application of two different experimental techniques. The common feature of both methods is that the neutrons emitted at 0° impinge on a hydrocarbon scintillator, which serves as a target providing protons (center detector), and outgoing particles are detected by scintillation counters (side detectors) placed symmetrically to the left and right of the beam axis. The measurements at laboratory angles $\theta_{lab} = 25° - 75°$ ($\theta_{c.m.} = 50° - 150°$) were performed by detection of the scattered neutrons. This method becomes increasingly difficult at large scattering angles because of the low energy of the scattered neutrons and rapidly decreasing laboratory cross section. In order to obtain more reliable data and to provide an independent cross check at large scattering angles, the angular range $\theta_{c.m.} = 125° - 165°$ was covered by detection of recoil protons in the forward direction. Both experimental techniques use the same strategy to discriminate against accidental background: Coincidences between the center and side detectors are recorded and the time of flight (TOF) of particles between center detector and side detectors is measured. The experimental spectra for both methods are shown in Fig. 1. Since the measurements[4,5] at 16.9 MeV indicate that back-angle data are of special importance,[8] we will first discuss the part of the experiments in which recoil protons were detected.

The radiator of the protons consisted of a $3\times5\text{-cm}^2$ plastic scintillator of 3-mm thickness, located 30 cm from the neutron production target. Recoil protons were detected by scintillation counters placed 50 cm from the radiator. The side detectors were 6 mm thick and had an angular rms spread of 3° in the laboratory system. For each coincident event between the radiator and either side detector, the pulse height in each detector was recorded, as well as the time of flight of the protons. Possible sources of systematic effects were studied. For example, events induced by neutrons scattered in the radiator and detected in the side detector are indistinguishable from those caused by recoil protons. Such undesired events are rare because of the small efficiency for neutron detection (thin side scintillators) and they amount to less than 2×10^{-4} of the events of interest. Provision was made to diminish the effect of a possible background from the reaction $^{14}\text{N}(n,p)^{14}\text{C}$ in the air surrounding the detectors by the placing of a ^{4}He balloon between the neutron source and the center detector. Iron shielding was used to protect the side detectors from the direct neutron flux from the tritium cell, reducing accidental coincidences by an order of magnitude.

True and accidental coincidences were determined by the imposing of cuts in the peak and flat part of the TOF spectra. Accidental background contributed only ≈ 0.0001 of the true np events. Dead-time corrections to the np analyzing powers amount to less than 0.001. Corrections were made for the finite geometry of the experimental arrangement. These corrections have two predominant effects: The nominal angle of the detectors is changed (e.g., by 1.9° at $\theta_{\text{lab}}=15°$), and effective polarization of the incoming neutrons is reduced (e.g., by 5% at $\theta_{\text{lab}}=15°$). The results of the recoil measurement are shown in Fig. 2 as solid squares.

The measurements based on the detection of the scattered neutrons were performed with a geometry similar to that for the recoil-proton experiment. The primary difference is that the target consisted of a 2.5-cm diameter by 5-cm-high liquid scintillator. Two pairs of side detectors (liquid scintillators) were used. Pulse-shape discrimination (PSD) was used in all five detectors to reject pulses caused by γ rays. The proton recoil pulse height in the target, the PSD signals for the target and side detectors, and time of flight of the neutrons were recorded. In the analysis, target-recoil pulses were gated by windows placed around pronounced peaks defining good events in the PSD and TOF spectra. The background from accidental coincidences increased from 0.003 at forward angles to 0.045 at backward angles. Corrections for multiple scattering of the neutrons were studied with use of a computer code with random sampling integration. The largest corrections increased the value of A_y by 0.0020. The results of this part of the experiment, analyzed as described above, were presented at a conference.[12]

Only later, two additional subtle instrumental effects, which were not taken into account in the earlier analysis, were discovered. These effects are caused by the variation of neutron flux across the scattering sample which results from the vector analyzing power of the reaction

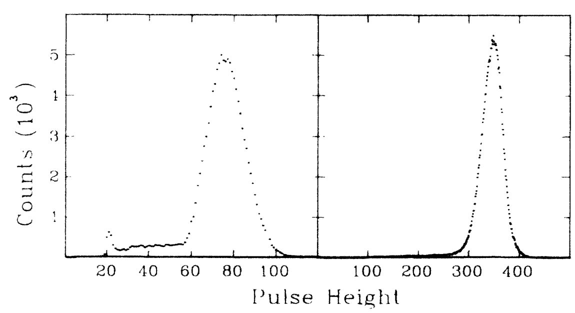

FIG. 1. Pulse-height spectra for np scattering. The graph on the left shows the pulse-height spectrum of recoil protons in the center detector, in coincidence with scattered neutrons detected in the side detector at $\theta_{\text{lab}}=45°$. The plateau of pulses on the left of the peak is caused by recoil protons which deposit only part of their energy in the center detector (edge effect). The graph on the right shows the spectrum of pulse heights in the proton-recoil experiment: The spectrum displayed is the sum of pulse heights in the center detector and in the side detector positioned at $\theta_{\text{lab}}=15°$. The background from accidental coincidences is in both cases too small to be shown.

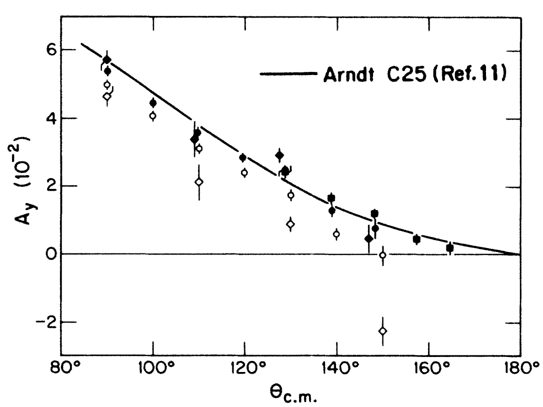

FIG. 2. Backward-angle analyzing powers obtained by different experimental techniques. Detection of recoil protons, squares; detection of scattered neutrons, circles (small center detector), diamonds (large center detector). Open symbols, raw data; filled symbols, all corrections included. The solid line shows phase-shift analysis in the energy range 15–35 MeV (Ref. 11), which does not include the present data.

$T(d_{pol},n_{pol})^4He$: Depending on whether the spin of the incident deuterons (and thus the spin of the outgoing 0° neutrons) is up or down, the left or the right side of the scattering sample is more strongly illuminated. This flux asymmetry causes a false left-right asymmetry in the neutron detectors, and thus a false analyzing power. The effect arises primarily from the attenuation of the scattered neutrons in the scattering sample, which shifts the effective scattering center toward the side detectors. The effect increases with neutron scattering angle, because lower-energy neutrons are more strongly attenuated. An additional correction of the same nature is caused by edge effects of the recoil protons in the scattering sample. Since we reject events where the recoil proton left the scattering sample, the effective center is once more displaced from the geometric center.

In order to correct for the false asymmetries, the vector analyzing power of the reaction $T(d_{pol},n_{pol})^4He$ near 0° was measured in a separate experiment. After application of appropriate corrections for these effects, excellent agreement between recoil and scattered neutron experiment was achieved (Fig. 2). The corrections were tested experimentally by repetition of measurements with a center detector of twice the normal diameter. Although in this case the raw analyzing powers were incompatible with the recoil data by more than 7 times the error bars, very good agreement between all corrected results was obtained (Fig. 2). Table I presents the final *np* analyzing powers from the present experiments.

We note that the earlier precision measurements[4,5] did not include corrections for the effects described above. For the reaction $D(d_{pol},n_{pol})^3He$ used in these experiments the vector analyzing power near 0° is not known precisely, but data at larger angles[13] suggest that the corrections will be significantly smaller than in the present case.

The new data at 25 MeV completely rule out a zero crossing of the analyzing power near $\theta_{c.m.} \approx 150°$, in contrast to the results reported at 16.9 MeV. Figure 3 shows all relevant *np* analyzing-power data at 25 MeV. There is fair agreement with the less precise results published recently by Wilczynski *et al.*[14] The accuracy of the present measurements allows the establishment of significant constraints upon existing theoretical models of the *NN* interaction at low energies. The predictions of the Paris potential[15] and the phase-shift analyses of Arndt[11] are also shown in Fig. 3. It is worth noting that no adjustable parameters are involved in this comparison between the theory and experiment. Very good agreement with the Paris[15] potential is observed. Furthermore, very good description of the data is obtained from the most recent global phase-shift analysis (SP86, Ref. 11). Previous energy-dependent phase-shift analyses[3,11] do not fit the data.[16]

In conclusion, high-precision measurements of the polarization in neutron-proton scattering reported here resolve discrepancies between experiment and current theories. In contrast to the earlier 16.9-MeV data,[4,5] these new results do not indicate the need for large contributions from *F* waves in low-energy *np* scattering. While the previous precision measurements of *np* analyzing powers indicated a significant disagreement with meson-exchange theory of the *NN* force, the present measurements support the view that no unexpected phenomena have to be invoked to explain the low-energy *np* interaction.

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TABLE I. Analyzing power in neutron-proton scattering at 25.0 MeV.

c.m. angle (deg)	Analyzing power (10^{-2})	Error[a] (10^{-2})
	Scattered-neutron experiment	
50.7	5.73	0.39
60.9	6.36	0.16
70.7	6.31	0.18
80.5	6.15	0.15
90.3	5.37	0.15
100.0	4.45	0.15
109.7	3.57	0.17
119.5	2.85	0.15
128.8	2.45	0.17
139.0	1.27	0.18
148.4	0.76	0.31
	Recoil-proton experiment	
128.7	2.44	0.20
138.7	1.66	0.18
148.1	1.20	0.15
157.3	0.46	0.15
164.6	0.20	0.21

[a]Uncertainty in scale factor of 1 ± 0.033 is not included.

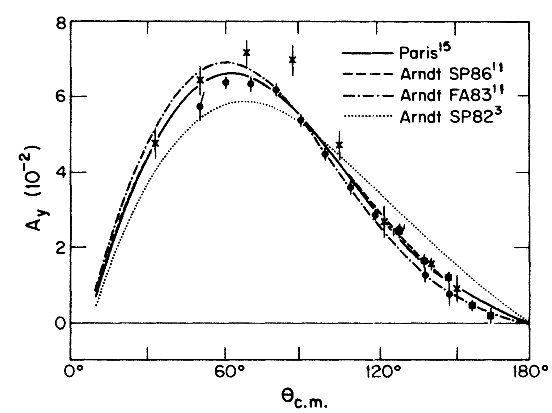

FIG. 3. Neutron-proton analyzing powers at 25 MeV laboratory energy (circles and squares, present work; crosses, Ref. 14) and current theoretical predictions from the potential model of *NN* interaction (Ref. 14) and energy-dependent phase-shift analyses (Refs. 3 and 11).

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[1]M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Côtè, P. Pirès, and R. de Tourreil, Phys. Rev. C **21**, 861 (1980).

[2]R. A. Arndt, R. H. Hackman, and L. D. Roper, Phys. Rev. C **15**, 1002 (1977).

[3]R. A. Arndt, L. D. Roper, R. A. Bryan, R. B. Clark, B. J. VerWest, and P. Signell, Phys. Rev. D **28**, 97 (1983).

[4]W. Tornow, P. W. Lisowski, R. C. Byrd, and R. L. Walter, Phys. Rev. Lett. **39**, 915 (1977).

[5]W. Tornow, P. W. Lisowski, R. C. Byrd, and R. L. Walter, Nucl. Phys. **A340**, 34 (1980).

[6]E.g., spin-orbit combination of the triplet phase shifts Δ_{LS} required by the experiment amounts to $-0.015° \pm 0.003°$ (Refs. 4 and 5) while the theories predict less than 0.001° [J. Côtè, M. Lacombe, B. Loiseau, P. Pirès, R. de Tourreil, and R. Vinh Mau, in *Polarization Phenomena in Nuclear Physics —1980,* edited by G. G. Ohlson, R. E. Brown, N. Jarmie, W. McNaughton, and G. M. Hale, AIP Conference Proceedings No. 69 (American Institute of Physics, New York, 1981), Pt. I, p. 114].

[7]L. Bracci, G. Fiorentini, and R. Tripiccione, Nucl. Phys. **B217**, 215 (1983).

[8]Côtè, Lecombe, Loiseau, Pirès, de Tourreil, and Vinh Mau, Ref. 6.

[9]W. Haeberli, M. D. Barker, C. A. Gossett, D. G. Mavis, P. A. Quin, J. Sowinski, T. Wise, and H. F. Glavish, Nucl. Instrum. Methods Phys. Res. **196**, 319 (1982).

[10]D. Holslin, J. Sromicki, and W. Haeberli, J. Phys. Soc. Jpn. Suppl. **55**, 904 (1986).

[11]R. A. Arndt, interactive computer code SAID, private communication, 1986.

[12]M. D. Barker, D. Holslin, P. A. Quin, and W. Haeberli, in *Proceedings of the Tenth International IUPAP Conference on Few Body Problems in Physics, Karlsruhe, 1983,* edited by B. Zeitnitz (North-Holland, Amsterdam, 1984), Vol. II, p. 31.

[13]P. P. Guss, K. Murphy, R. C. Byrd, C. E. Floyd, S. A. Wender, R. L. Walter, T. B. Clegg, and W. Wylie, Nucl. Phys. **A395**, 1 (1983).

[14]J. Wilczynski, J. Hansmeyer, F. P. Brady, P. Doll, W. Heeringa, J. C. Hiebert, H. O. Klages, and P. Plischke, Nucl. Phys. **A425**, 458 (1984).

[15]M. Lacombe, B. Loiseau, and R. Vinh Mau, private communication; parameters updated to May 1985 were used.

[16]The following values of χ^2/(degree of freedom) were obtained: Paris, 1.08; SP86, 1.13; FA83, 2.98; SP82, 11.50. This corresponds to the confidence levels of: 37%, 32%, 0.0%, and 0.0%, respectively. In this comparison between present results and theoretical predictions the overall normalization of the data was adjusted well within its experimental error.