Discrepancies between Global Nucleon-Nucleon Phase Shifts and New Data for *n-p* Scattering at 16.9 MeV

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Data for the analyzing power $A_y(\theta)$ for n-p scattering at 16.9 MeV have been measured for the range from 50 to 145° (c.m.). Eleven values are reported to an accuracy of about ±0.002, the highest overall precision ever obtained in *any* fast-neutron polarization experiment. Predictions based on phase-shift sets obtained from global analyses of nucleon-nucleon scattering disagree significantly with the new data. The data are sufficiently precise to show a dependence on the f-wave spin-orbit phase parameter.

In order to determine the $T = 0$ component of the nucleon-nucleon interaction, one must resort to comparisons between data and predictions for the scattering process $^1H(n,n)^1H$. There now exist several sets of phase shifts[1-3] which have been derived from global analyses of n-p data up to 500 MeV. In the past few years, the assumption has been that the most recent sets give reliable cross-section and polarization predictions for energies below 20 MeV. Figure 1 illustrates the situation that existed when we undertook our measurements. Plotted here are n-p analyzing-power measurements[4-7] and phase-shift predictions for energies near 16 MeV. Clearly, at this time the experiments were able to distinguish between the poorer prediction based on the "Yale IV" set[1] and the more favorable prediction[2] based on the Lawrence Livermore Laboratory group's set LRL X. However, the data as a whole were unable to provide the necessary stringent test to examine critically the LRL X prediction because the uncertainties were in general too large compared to the (very low) magnitude of the analyzing power. Additionally, other information about spin-orbit "phase parameters"[8,9] was lost because the data were not sufficiently accurate to determine details about the shape of the analyzing-power function $A_y(\theta)$. Because we now have the techniques and polarized-neutron fluxes needed to obtain a precision of better than ± 0.002 in determining the analyzing power for n-p scattering in the 10–18-MeV region, we made a series of measurements to test our present understanding of the n-p interaction. We report in this Letter new experimental results for $A_y(\theta)$ at 16.9 MeV and conclusions based on comparisons and fits to the data. To our knowledge, these new data are the most accurate results ever reported for *any* polarization experiment employing fast neutrons.

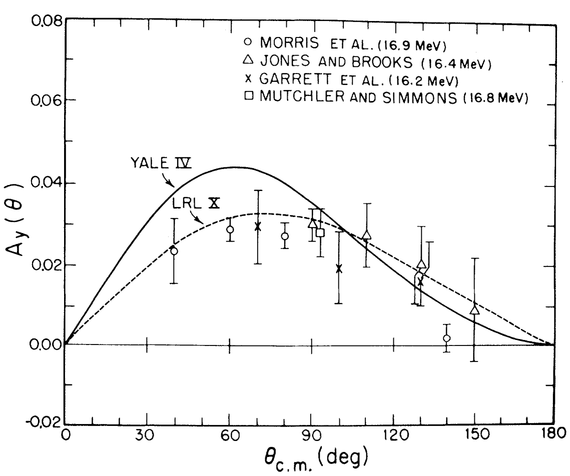

FIG. 1. Neutron-proton analyzing-power data around 16.9 MeV and nucleon-nucleon phase-shift predictions as of a year ago.

As the analyzing power A_y in n-p scattering is only a few percent between 10 and 20 MeV, both an intense and a highly polarized neutron beam is needed to accumulate accurate A_y data with a reasonable amount of accelerator time. Since polarized deuteron beams of sufficient intensity are now available at many laboratories, considerable improvements in the production of polarized fast-neutron beams have become possible via polarization transfer reactions. In the present experiment, the reaction $^2H(d,n)^3He$ with a polarized incident deuteron beam was used to produce polarized neutrons. The technique takes advantage of both the high polarization-transfer capability[10] and the high differential cross section of this reaction for a reaction angle of 0°. The Triangle Universities Nuclear Laboratory Lamb-shift polarized-ion source produced the polarized deuteron beam. After acceleration with the tandem Van

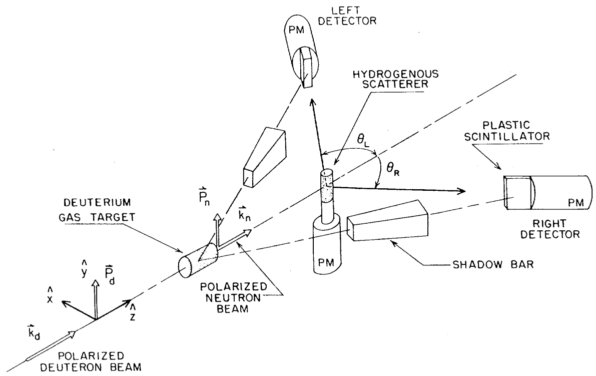

FIG. 2. Schematic diagram of the experimental arrangement.

de Graaff, a 14.4-MeV deuteron beam entered a 300-keV-thick deuterium gas target to produce polarized neutrons with a mean energy of 16.9 MeV at 0°. The deuteron beam polarization was monitored in short time intervals by the quench-ratio method[11] and typically had a magnitude of $p_y = p_{yy} = 0.73$. This polarization gave rise to polarized neutrons with a (transverse) polarization[10] of 0.62. The neutrons were incident on an organic scintillator, 2.5 cm in diameter and 3.8 cm high, which served as the hydrogen target. The arrangement is shown schematically in Fig. 2. The distance between the gas cell and the scatterer was 25 cm. The neutrons scattered to the left or to the right side were detected by a pair of symmetrically located liquid organic scintillators which permitted pulse-shape discrimination between neutrons and background γ rays. These detectors subtended only 5° (full width at half-maximum) in the horizontal plane, and were shielded against the direct neutron flux coming from the target by copper shadow bars designed to provide good shielding with minimal material. In order to reduce instrumental asymmetries, a series of successive measurements were performed with the deuteron spin-quantization axis oriented to produce neutron beams with the spin direction alternately up or down.

The pulse height produced by the proton recoils within the center scatterer and the time-of-flight information between the scatterer and the side detectors were written in an event-by-event mode on magnetic tape in order to generate two-dimensional arrays, i.e., proton recoil energy versus neutron time of flight to the left and to the right detector, respectively.

One common feature of all n-p analyzing power experiments below 20 MeV, the presence of carbon in the organic scintillator scatterer, was investigated carefully. In an experiment[12] with the carbon enhanced, it was found that for our small scatterer the additional carbon did not affect the measured asymmetry within the experimental uncertainties. To provide additional information, such multiple-scattering processes were evaluated in a Monte Carlo simulation. The effects for all types of multiple scattering totaled less than 0.0005 for all angles except 25° and 30° (lab), where it was about 0.0011. Corrections were applied to the measured data accordingly.

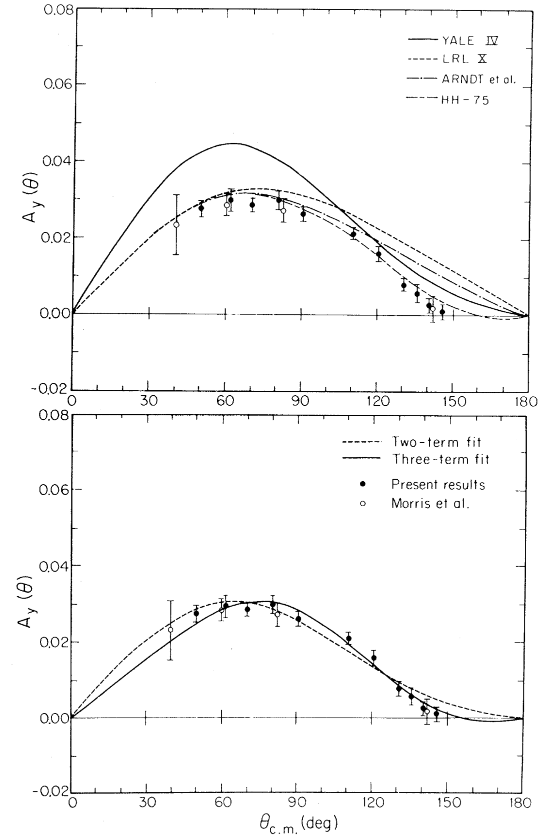

FIG. 3. (a) Present analyzing-power data compared with data from Morris *et al.* and phase-shift predictions. (b) Fits to the present data.

Our analyzing-power results are given in Fig. 3 along with the previously most accurate data set, i.e., the data obtained by Morris *et al.*[4] Our error bars include a conservative estimate of the uncertainties associated with background subtraction and with the incident neutron beam polarization. The present data are consistent with nearly all of the previous data (which are shown in Fig. 1). In Fig. 3(a) predictions from the global nucleon-nucleon phase-shift analyses have been plotted

TABLE I. Spin-orbit phase parameters (in degrees) at 16.9 MeV.

	Yale IV	LRL X	Two-term fit	Three-term fit
$\Delta_{LS}{}^P$	0.616	0.538	0.455 ± 0.012	0.451 ± 0.012
$\Delta_{LS}{}^D$	0.097	0.033	0.072 ± 0.005	0.058 ± 0.005
$\Delta_{LS}{}^F$	0.0004	0.0003	...	-0.015 ± 0.003

along with a curve (HH-75) taken from the recent paper[13] reporting an analysis of n-p data between 10 and 23 MeV. The disagreement between the present data and the predictions from the global analyses is very clear.

Another significant comparison follows from the approach outlined by Mutchler and Simmons.[7] These authors have derived the analyzing power for n-p scattering in our energy range in terms of spin-orbit phase parameters. Their relation is

$$\sigma(\theta)A_y(\theta) = \frac{\sin^2\delta_{01}}{4k^2}\sin\theta(12\Delta_{LS}{}^P + 60\Delta_{LS}{}^D\cos\theta). \quad (1)$$

To arrive at this form, one must assume that the maximum orbital angular momentum L_{max} is 2, that the p- and d-wave phase shifts are small, and that the mixing parameters are approximately zero. Here θ is the c.m. scattering angle, $\sigma(\theta)$ the differential cross section, k the c.m. wave number of either particle, and δ_{01} the triplet s-wave phase shift. The phase parameters $\Delta_{LS}{}^P$ and $\Delta_{LS}{}^D$ are expectation values of the spin-orbit interaction in the nucleon-nucleon P and D states in the Born approximation as given by Gammel and Thaler[8] and by Perring[9]:

$$\Delta_{LS}{}^P = \tfrac{1}{12}(-2\delta_{10} - 3\delta_{11} + 5\delta_{12}), \quad (2)$$

$$\Delta_{LS}{}^D = \tfrac{1}{60}(-9\delta_{21} - 5\delta_{22} + 14\delta_{23}). \quad (3)$$

Here the nucleon-nucleon phase shifts are denoted by δ_{LJ} with L and J being th orbital and total angular momentum, respectively.

In order to fit the present data according to Eq. (1), the triplet s-wave phase shift δ_{01} was calculated from the effective-range formula using parameters given by Houk[14] and Loman and Wilson,[15] and the n-p differential cross section $\sigma(\theta)$ was computed from Gammel's formula,[16] which is based on measured total cross sections for the n-p interaction. The fit obtained is plotted in Fig. 3(b) as a dashed curve. The results for the phase-shift parameters $\Delta_{LS}{}^P$ and $\Delta_{LS}{}^D$ derived from this fit are given in Table I along with values calculated from the global nucleon-nucleon phase-shift analyses LRL X and Yale IV.

Because the two-term fit above was not in close agreement with the data, particularly for the angles near 145° c.m. where effects of higher partial waves would be exhibited, we investigated the effect of including f waves in Eq. (1) using the same approximations as before. One obtains the product

$$\sigma(\theta)A_y(\theta) = \frac{\sin^2\delta_{01}}{4k^2}\sin\theta(12\Delta_{LS}{}^P - 42\Delta_{LS}{}^F + 60\Delta_{LS}{}^D\cos\theta + 210\Delta_{LS}{}^F\cos^2\theta). \quad (4)$$

Here, $\Delta_{LS}{}^F$ is the expectation value of the spin-orbit interaction in the nucleon-nucleon F states in the Born approximation as given by Gammel and Thaler:

$$\Delta_{LS}{}^F = -\tfrac{5}{42}\delta_{32} - \tfrac{1}{24}\delta_{33} + \tfrac{9}{56}\delta_{34}. \quad (5)$$

A fit to the data using Eq. (4) is shown in Fig. 3(b) by the solid curve. Considerably better agreement was achieved for the large scattering angles as compared to the two-term fit, χ^2 per degree of freedom having been reduced from 2.4 to 1.1. The phase parameters $\Delta_{LS}{}^P$, $\Delta_{LS}{}^D$, and $\Delta_{LS}{}^F$ derived from the three-term fit are given along with predictions from LRL X and Yale IV in Table I.

In summary, our new, precise analyzing-power data for n-p scattering disagree significantly with predictions based on the global phase-shift sets for nucleon-nucleon scattering. This finding will require a reassessment of all of the current nucleon-nucleon models which are supposedly valid in the 10–20-MeV range. The new data have been used in the manner of Mutchler and Simmons to derive values of the spin-orbit phase parameters to give determinations suitable for testing p-, d-, and f-wave contributions to the

n-p interaction at 16.9 MeV.

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Structure in the Energy Spectra from Inelastic Heavy-Ion Reactions

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Broad structures have been observed in the incompletely relaxed part of the energy spectra of fragments emitted in the symmetrical reactions $^{40}Ca + ^{40}Ca$ at 284 MeV and $^{63}Cu + ^{63}Cu$ at 450 MeV. Excitation energies of these structures, angular distributions, and (Z,N) distributions leading to multiplicities for nucleon emission have been measured. They can be interpreted as being due to a predominantly direct reaction process, possibly proceeding through the excitation of highly collective high-energy modes in the region of giant resonances.

The mechanisms of heavy-ion–induced transfer reactions have usually been described under the assumption that two different processes are taking place: the quasielastic and the so-called "deep inelastic" transfers.[1,2] A detailed study of the reaction $^{40}Ca + ^{40}Ca$ at 256 MeV has shown[3] that the deep inelastic component could in fact be described by the coexistence of (a) a "slow" process, completely damped in energy, characterized by a $1/\sin\theta$ angular distribution and a broad Z distribution, and (b) a "fast" process, characterized by an incompletely relaxed kinetic energy, an exponentially decreasing angular distribution, and a very narrow, angle-independent Z distribution.

In this Letter, we present more complete data on symmetrical systems, namely, $^{40}Ca + ^{40}Ca$ and $^{63}Cu + ^{63}Cu$, showing the existence of some structure unresolved up to now in the incompletely relaxed component. Complete (A, Z) identification was used, so that the choice of symmetrical systems in the entrance channel gave direct information on the multiplicity for emitted particles in the exit channel, as far as binary processes are considered. The 284-MeV ^{40}Ca and 450-MeV ^{63}Cu beams were accelerated at the Orsay ALICE facility. ^{40}Ca and ^{63}Cu targets were 1 mg/cm^2 thick and self-supporting. Possible contamination of the targets by ^{16}O or ^{12}C was carefully checked by comparison of the results with those obtained by bombarding ^{12}C and B_2O_3 targets. A complete identification of the reaction products in A and Z was performed[4] at 7°, 10°, and 14° (grazing angle) for the reaction $^{40}Ca + ^{40}Ca$ and at 10° for the reaction $^{63}Cu + ^{63}Cu$ by means of a E-ΔE telescope in the focal plane of a magnetic spectrometer. The addition of a time-of-flight measurement be-