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Measurement of the relative longitudinal spin-dependent total cross-section difference in $\vec{n}-\vec{d}$ scattering

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We report relative measurements of the $\vec{n}-\vec{d}$ longitudinal spin-dependent total cross-section difference $(\Delta\sigma_L)_d$, at $E_n(\text{lab}) = 5.0$, 6.88, and 9.0 MeV. The deuteron target was polarized via dynamic nuclear polarization at 250 mK in a 2.5-T external magnetic field. The target polarization was monitored by nuclear magnetic resonance and was calibrated by a $(\Delta\sigma_L)_d$ measurement at $E_n(\text{lab}) = 1.18$ MeV. The polarized neutron beams were produced through the $^3\text{H}(\vec{p},\vec{n})^3\text{He}$ and $^2\text{H}(\vec{d},\vec{n})^3\text{He}$ reactions. The neutron polarizations were determined either by direct measurement or from known or calculated polarization-transfer coefficients. The results for $(\Delta\sigma_L)_d$ show agreement with theoretical calculations based on nucleon-nucleon potential models but are not of sufficient precision to distinguish the presence or absence of three-nucleon force contributions to the cross sections.

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I. INTRODUCTION

When the high-precision nucleon-nucleon (*NN*) potential models AV18 [1], CD-Bonn [2], Nijm I, Nijm II, and Nijm 93 [3] are used to calculate the binding energies of three-nucleon (3N) systems, one finds that they underbind ^{3}H and ^{3}He by about 5%–10% [4]. The missing binding energy can be accounted for by adding a three-nucleon force (3NF) to the nuclear Hamiltonian [5]. Where the pairwise interactions alone fail to reproduce the data, modern 3NFs with parameters fitted to reproduce the 3N binding energies also provide remarkable improvements in the description of 3N observables in the continuum. In the energy regime below about 150 MeV, the classic example is the discrepancy between data and rigorous calculations using only *NN* interactions for the nucleon-deuteron (*Nd*) differential cross section in the angular range of the cross-section minimum [6,7]. Cadman *et al.* [8] also find evidence in 197-MeV *p-d* scattering for contributions of 3NF to polarization observables. Unfortunately, present-day 3NFs do not provide a cure for all *Nd* continuum observables. Striking differences between data and calculations based on pairwise interactions are still seen; the most spectacular cases include the so-called 3N analyzing power puzzle [9,10] in elastic *Nd* scattering and the space-star anomaly in the *Nd* breakup reaction [11,12].

The spin-dependent cross-section difference, $(\Delta\sigma_L)_d$, in the $\vec{n}-\vec{d}$ total cross section has been shown to be sensitive to the same 3NF components that correct the triton binding energy problem [13]. In 1999 we undertook a study of $(\Delta\sigma_L)_d$ to test if the presence of these 3NF components could also be detected in the three-nucleon continuum. No data existed at the time for this observable. Those early experiments [14] indicated large disagreements with *NN* model predictions for 5- to 9-MeV neutrons but were not considered definitive because of concerns about the absolute polarization of the deuteron target. We therefore undertook a remeasurement with improved beam polarization monitoring and a higher polarization for the target and utilizing a transmission measurement to provide a relative calibration of the product of target thickness and polarization. Our new results remove the large disagreement we found earlier and are consistent with the energy dependence shown by calculations based on current *NN* potential models with 3NFs. They are, however, not of sufficient precision to distinguish the presence or absence of 3NF components.

II. EXPERIMENTAL METHOD

The experimental methods and analysis are similar to those described in our earlier work on measurements of $(\Delta\sigma_L)_p$ in *n-p* scattering [15] and are described in more detail in Foster [16]. The longitudinal spin-dependent total cross-section difference is defined as the difference between the total cross section for beam and target spins antiparallel and parallel and with spins aligned along the beam momentum axis: $\Delta\sigma_L = \sigma_a - \sigma_p$. Defining $T^{a,p}$ to be the ratio of transmitted flux to incident flux for the antiparallel and parallel spin geometries, respectively, the polarized-neutron, polarized-target transmission asymmetry $\varepsilon = (T^a - T^p)/(T^a + T^p)$, is given by

$$\varepsilon = P_n \tanh[P_d(\Delta\sigma_L)_d x_d]/2, \qquad (1)$$

where P_n and P_d are the (vector) polarizations of the neutron beam and the deuteron target, respectively, and x_d is the target thickness in atoms per barn. The argument is typically small and can safely be expanded to give $\varepsilon = P_n P_d(\Delta\sigma_L)_d x_d/2$.

In the present work we have measured ε at four laboratory neutron energies: 1.18, 5.0, 6.88, and 9.0 MeV. The measurement at $E_n(\text{lab}) = 1.18$ MeV, where $(\Delta\sigma_L)_d$ calculations with and without 3NF differ by 5%, was used to calibrate the polarization of the deuteron target relative to an NMR signal. This NMR calibration was then used in the determination of the polarization of the deuteron target for the higher-energy data (see later).

The polarized neutron beam at 1.18 MeV was produced as a secondary beam from the $^3\text{H}(\vec{p},\vec{n})^3\text{He}$ reaction at $E_p = 1.98$ MeV. For this measurement, the transmitted neutron flux was normalized to the proton beam current. The beams at 5.0, 6.88, and 9.0 MeV were produced in the $^2\text{H}(\vec{d},\vec{n})^3\text{He}$ reaction with the neutron-detection threshold set high enough to exclude low-energy neutrons from the deuteron breakup channel. For these measurements the transmitted neutron flux was normalized to a neutron monitor upstream of the polarized target to compensate for flux variations because of the tensor polarization of the incident deuteron beam [15]. The polarized protons and deuterons were obtained from the TUNL Atomic Beam Polarized Ion Source (ABPIS) and were accelerated to the appropriate energy by the TUNL Tandem Van de Graaff accelerator. The relative polarization of the beam over time was monitored at the ion source via the TUNL spin-filter polarimeter. A Wien filter at the output of the ion source rotated the polarization direction to compensate for precession through the analyzing magnets upstream and downstream from the accelerator.

For the $^3\text{H}(\vec{p},\vec{n})^3\text{He}$ reaction, the target was a 0.11 mg/cm^2 tritiated titanium foil. The neutron beam polarization was derived from a measurement of the proton polarization and from knowledge of the longitudinal polarization-transfer coefficient for the reaction:

$$P_n(0^\circ) = P_p K_z^{z'}(0^\circ). \tag{2}$$

The proton beam polarization was determined from an up-down elastic scattering asymmetry measurement using a one-atmosphere ^{4}He gas cell mounted inside a charged-particle scattering chamber containing two proton detectors mounted at laboratory angles of ±75°. For the purposes of the measurement the proton beam polarization axis was rotated into the horizontal transverse direction and accelerated to 2.52 MeV to provide a better signal. Asymmetry measurements were also made with the beam polarized longitudinally to check for a transverse component of the polarization and to verify that the Wien filter settings for longitudinal were correct. The polarization of the neutron beam was of order 25%.

For the $^2\text{H}(\vec{d},\vec{n})^3\text{He}$ reaction, the neutron production target was a 6-cm-long, three-atmosphere deuterium gas cell. In our earlier work we derived the neutron polarization from a measurement of the vector and tensor polarizations of the deuteron beam in an upstream scattering chamber. We chose to measure the neutron polarization directly in the present work, carrying out a left-right neutron scattering asymmetry measurement at 6.88 MeV using a high-pressure ^{4}He gas-cell polarimeter on an adjacent beamline. For this measurement the deuteron polarization axis was rotated vertically in the Wien filter and the scattered neutrons were detected at ±116°. The measurement confirmed that the values of the neutron polarization used in our earlier work were reasonable. The polarization-transfer coefficients and the analyzing powers for the longitudinal and transverse $^2\text{H}(\vec{d},\vec{n})^3\text{He}$ reactions are different, so the measured transverse neutron polarization for $E_n = 6.88$ MeV is used to calculate P_z and P_{zz} for the deuteron beam using the known analyzing power, $A_{zz}(0^\circ)$, and the known transverse polarization-transfer coefficient, $K_y^{y'}(0^\circ)$. The neutron polarization at 5.0 and 9.0 MeV was then determined from the relative measurement of the deuteron polarization determined from the ABPIS spin filter and measured values of the longitudinal polarization-transfer coefficients $K_z^{z'}(0^\circ)$ and the analyzing powers $A_{zz}(0^\circ)$:

$$P_n(0^\circ) = \frac{\frac{3}{2}P_i K_i^{i'}(0^\circ)}{1 + \frac{1}{2}P_{ii}A_{ii}(0^\circ)}. \tag{3}$$

P_z and P_{zz} were taken to be equal, as was expected from the setup parameters of the ABPIS. This procedure is quite accurate at higher energies where the values of $K_z^{z'}(0^\circ)$ and $A_{zz}(0^\circ)$ have been measured to be relatively constant with energy [17]. For incident deuteron energies less than 3.25 MeV the values have not been verified experimentally, and calculations [18] show values of $K_z^{z'}(0^\circ)$ changing significantly with energy. In particular, an extrapolation of the data of Salzman *et al.* [17] produces a significantly different value than that of Hale [18]. We chose to use the value extracted from a fit to the data of Ref. [17], albeit with a larger error reflecting the uncertainty in the extrapolation. This uncertainty is the dominant source of error in the 5-MeV result.

TABLE I. Properties of the polarized deuteron target used in the 1.18-MeV measurement.

Target mass (g)	1.9434 ± 0.0001
Fraction of propanediol	0.965
Mass of propanediol (g)	1.875
Mass of EHBA/CrV (g)	0.0668
x_d (b^{-1})	0.0552 ± 0.0010
x_p (b^{-1})	0.00123 ± 0.00010

Target parameters for the 1.18-MeV measurement are listed in Table I. The deuteron target was polarized via dynamic nuclear polarization at 250 mK in a ^{3}He-^{4}He dilution refrigerator and a 2.5-T high-homogeneity magnetic field. The target itself was composed of 1-mm-diameter frozen beads of fully deuterated 1,2-propanediol (D8) doped with EHBA/CrV complex to 5.1×10^{21} spins/ml. The beads were contained in a Kel-F box immersed in the liquid ^{3}He-^{4}He mixture in the mixing chamber of the refrigerator. The nominal volume of the box was 2.729 ± 0.006 cm^3 and the length in the beam direction measured to be 1.405 ± 0.003 cm. The target thickness was determined by retrieving, melting, and weighing the target material at the conclusion of each experimental run. Neutron radiography was used to check that the target, postcollimator, and detector were aligned with each other and the neutron production target.

The dilution refrigerator followed a PSI design [19] with the substitution of a coiled heat exchanger made of 0.7-mm-inner-diameter × 0.15-mm wall teflon tubing [20]. The refrigerator operation was monitored with RuO resistance thermometers referenced to a calibrated germanium thermometer. The target was surrounded by a four-turn copper coil connected to a series tuned Liverpool NMR circuit. The diode detected signal

TABLE II. Summary of neutron asymmetries and NMR areas for the 1.18-MeV calibration runs. All asymmetries are $\times 10^{-4}$. The neutron polarization was $P_n = 0.24 \pm 0.02$.

E_n	ε^-	ε^+	A^-	A^+	ε^-/A^-	ε^+/A^+
1.18	-0.72 ± 4.8	23.9 ± 5.3	-0.189 ± 0.006	0.788 ± 0.039	3.8 ± 25.4	30.6 ± 6.9
1.18	-27.2 ± 3.8	32.2 ± 8.1	-0.699 ± 0.023	0.811 ± 0.034	40.5 ± 5.8	37.8 ± 9.3

was read into a computer using Labview to provide a continuous relative measurement of the target polarization. The target was continuously irradiated with 69.5-GHz microwaves produced by a klystron. The klystron frequency was manually and electronically retuned to polarize or to reverse the target polarization, which typically took 3 hr.

An experimental run consisted of an approximately 15-min set of data in which the d-NMR signal was recorded and a transmission asymmetry measured. The area, A, of the background-subtracted d-NMR absorption signal is assumed proportional to P_d and was used as a run-to-run monitor of the relative target polarization. The neutron beam polarization was flipped every 0.1 sec in an eight-step sequence ($+ - - + - + + -$), which eliminated any detector drifts linear or quadratic in time. Each 15-min run included 1024 eight-step sequences. The proton beam data are normalized to a beam current monitor. The deuteron beam data are normalized to the upstream transmission neutron flux monitor.

The proton beam at 1 MeV is slightly deflected when the deuteron polarizing magnet is energized. The deflection is compensated by an upstream steering magnet to maintain the beam on the tritium foil. The maximum transverse field 5 mm off axis in the polarized deuteron target is a few gauss and does not cause any significant rotation of the neutron spin direction. Deflection of the beam was negligible for the higher energy deuteron beams.

About 25 runs were taken with the target polarization in one direction. The target was then repolarized in the opposite direction, without changing the direction of the external magnetic field, and without changing the tuning parameters of the ABPIS. Asymmetries ε^+ and ε^- were calculated for the target in the $+$ and $-$ polarization states and then averaged to produce the asymmetry $\bar{\varepsilon}$. This subtracts out any residual asymmetry associated with incomplete compensation by the monitor of the flux asymmetry because of spin state differences in the deuteron beam tensor polarization.

The 1.18-MeV asymmetry data were taken in a 10-day experimental session with a target of thickness $x_d = 0.0552$ atoms/b. The 5.0-, 6.88-, and 9.0-MeV asymmetry data were taken in a separate 10-day run using a target made of the same 1,2-propanediol, but with slightly larger thickness: $x_d = 0.0574$ atoms/b. The NMR calibration constant found in the 1.18-MeV measurement was reduced by 0.96 in analyzing the higher energy data to take into account the difference in thickness of the two targets.

III. ANALYSIS

Because of the presence of polarized protons in the EHBA/CrV dopant ($N_p/N_d \approx 2\%$), a correction must be applied to the calculation of $(\Delta\sigma_L)_d$ from the experimental results. The measured asymmetry therefore consists of two terms:

$$\varepsilon = P_n P_d x_d (\Delta\sigma_L)_d/2 + P_n P_p x_p (\Delta\sigma_L)_p/2, \qquad (4)$$

where x_p and P_p are the thickness and polarization of the polarizable protons in the target, and $(\Delta\sigma_L)_p$ is the longitudinal spin-dependent total cross-section difference for hydrogen. Assuming the proton and deuteron spin systems are at the same spin temperature T_{ss} and experience the same magnetic field B, the proton and deuteron polarizations are related and given by $P_p = \tanh(\mu_p B/kT_{ss})$ and $P_d = 4\tanh(\mu_d B/kT_{ss})/[3 + \tanh^2(\mu_d B/kT_{ss})]$ [21,22]. Once the deuteron polarization is known, the proton polarization can be inferred, and the proton contribution to the measured asymmetries ε calculated using the $(\Delta\sigma_L)_p$ data of Walston [15].

It turns out that the proton contribution to the asymmetries is negligible at the higher energies, typically less than 1%. The contribution is 14% for the 1.18-MeV calibration data however, because of the large value of $(\Delta\sigma_L)_p$ at low energies. Average asymmetries and average d-NMR areas are extracted

TABLE III. Calculation of $(\Delta\sigma_L)_d$. The asymmetries are $\times 10^{-4}$. The target thicknesses for these measurements were $x_d = 0.0574 \pm 0.0010$ (b^{-1}) and $x_p = 0.00128 \pm 0.00010$ (b^{-1}). The correction term $(\Delta\sigma_L)_C = (P_p x_p / P_d x_d)(\Delta\sigma_L)_p$ is the effective contribution of the polarized protons to the $(\Delta\sigma_L)_d$ cross section.

E_n(MeV)	$\bar{\varepsilon}$	P_n	P_d	P_p	$(\Delta\sigma_L)_p$(mb)	$(\Delta\sigma_L)_C$(mb)	$(\Delta\sigma_L)_d$(mb)
5.00	-20.7 ± 0.57	0.40 ± 0.14	0.32 ± 0.03	0.93	94.0 ± 10.8	6.3 ± 0.9	-563 ± 197
6.88	-13.0 ± 0.33	0.46 ± 0.03	0.27 ± 0.03	0.87	-2.0 ± 1.8	-0.14 ± 0.12	-359 ± 45
6.88	-9.2 ± 0.36	0.46 ± 0.03	0.23 ± 0.02	0.82	-2.0 ± 1.8	-0.14 ± 0.12	-301 ± 39
9.00	-6.9 ± 0.4	0.52 ± 0.02	0.31 ± 0.03	0.92	-27.6 ± 3.1	-1.9 ± 0.3	-148 ± 19

TABLE IV. Comparison of the present results for $(\Delta\sigma_L)_d$ (in mb) with the theoretical predictions of Witala *et al.* [13] for *NN* and (*NN*+3NF) potentials. The 6.88-MeV value is the weighted average of the values in Table III.

E_n(MeV)	$(\Delta\sigma_L)_d$(exp't)	$(\Delta\sigma_L)_d(NN)$	$(\Delta\sigma_L)_d(NN\text{+3NF})$
5.00	-563 ± 197	-709	-770
6.88	-327 ± 29	-372	-413
9.00	-148 ± 19	-157	-185

for four calibration runs, two with target spin + and two with target spin −. The first run had anomalously low target polarization and neutron asymmetry, but because of the large fractional error, in practice did not affect the final calculation of the calibration constant. The data are shown in Table II.

The calibration procedure is as follows. Setting $P_d = KA$, Eq. (4) can be rewritten as

$$\varepsilon/A = P_n[x_d(\Delta\sigma_L)_d + (P_p/P_d)x_p(\Delta\sigma_L)_p]K/2, \qquad (5)$$

which can be solved iteratively for each value of ε/A to give the unknown calibration constant K and the (initially) unknown ratio P_p/P_d. The 1.18-MeV normalization cross sections used were $(\Delta\sigma_L)_p = 3082 \pm 31$ mb and $(\Delta\sigma_L)_d = -2211 \pm 55$ mb. The $(\Delta\sigma_L)_d$ value is from Table I of Witala *et al.* [13] and is an average of interpolated AV18, CDBonn, NijmI, and NijmII values calculated with and without 3NF; it is assigned an uncertainty of 2.5% to account for both possibilities: *NN* or (*NN*+3NF). A weighted average of the four values yields $K = 0.268 \pm 0.028$ for the 1.18-MeV target and, correspondingly, $K = 0.258 \pm 0.027$ for the target used at higher energies. The error includes the weighted uncertainty from the measured values of ε/A added in quadrature to the 2.5% uncertainty in $(\Delta\sigma_L)_d$.

IV. RESULTS

Table III summarizes the asymmetries, polarizations, and results for $(\Delta\sigma_L)_d$ obtained in the present work. The correction term $(\Delta\sigma_L)_C = (P_p x_p/P_d x_d)(\Delta\sigma_L)_p$ is the effective contribution of the polarized protons in the target and can be seen to be a less than 1% effect at all energies. Two separate runs were carried out at 6.88 MeV, and the results are reported separately for each run. The dominant sources of error are associated with the uncertainties in the NMR calibration constant and the neutron polarization; these are added in quadrature to derive the final errors in $(\Delta\sigma_L)_d$.

Table IV compares the 5.0-, averaged 6.88-, and 9.0-MeV results to the Witala *et al.* calculations made with either *NN* potentials alone or with *NN* potentials, including 3NF contributions. The theoretical values are in each case the average of the AV19, CDBonn, NijmI, and NijmII values. The experimental results follow the trend of the theoretical predictions. The cross sections are smaller in magnitude than both *NN* and (*NN*+3NF) predictions and suggestive of better agreement with the *NN* calculations. However, the measurements are not sufficiently precise to allow a firm conclusion to be drawn regarding the absence of a 3NF contribution to the *n*-*d* continuum reaction mechanism.

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