Measurements at low energies of the polarization-transfer coefficient $K_{yy}'$ for the reaction $^3\text{H} (\vec{p}, \vec{n}) ^3\text{He}$ at $0^\circ$

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(July 28, 2018)

Abstract

Measurements of the transverse polarization coefficient $K_{yy}'$ for the reaction $^3\text{H} (\vec{p}, \vec{n}) ^3\text{He}$ are reported for outgoing neutron energies of 1.94, 5.21, and 5.81 MeV. This reaction is important both as a source of polarized neutrons for nuclear physics experiments, and as a test of theoretical descriptions of the nuclear four-body system. Comparison is made to previous measurements, confirming the $^3\text{H} (\vec{p}, \vec{n}) ^3\text{He}$ reaction can be used as a polarized neutron source with the polarization known to an accuracy of approximately 5%. Comparison to $R$-matrix theory suggests that the sign of the $^3F_3$ phase-shift parameter is incorrect. Changing the sign of this parameter dramatically improves the agreement between theory and experiment.

I. INTRODUCTION

A polarized neutron beam is an important tool in studying the spin-dependent aspects of the nuclear interaction. Intense beams of polarized neutrons can be produced from reactions involving polarized charged-particle beams, provided the reaction has a non-zero polarization transfer coefficient. One reaction which is often used at few-MeV energies is the $^3\text{H} (\vec{p}, \vec{n}) ^3\text{He}$ polarization-transfer reaction. This reaction was chosen as a polarized neutron source for recent experiments at Triangle Universities Nuclear Laboratory (TUNL). As the transverse polarization transfer coefficient $K_{yy}'$ for protons on tritium was measured...
more than 20 years ago [3], we felt it important to confirm the values at energies of interest. In addition, despite advances in the $R$-matrix treatment of the four-body system, there is no recent comparison with polarization transfer data.

The polarization-transfer measurement is made using a transversely polarized proton beam incident on a tritiated target. Two polarimeters are used, one for the proton beam, and one for the neutron beam. The transverse polarization transfer coefficient $K_{y'y'} = P_n/P_p$ is determined by the ratio of the neutron polarization, $P_n$, to the proton polarization, $P_p$.

The measurements were made at neutron energies of 1.94, 5.21, and 5.81 MeV. The results are in excellent agreement with the previous data, and confirm that the $^3\text{H}(\vec{p},\vec{n})^3\text{He}$ reaction can be used as a polarized neutron source to an accuracy of approximately 5%.

In comparing the data to $R$-matrix predictions, we find a discrepancy which we attribute to the sign of the $^3F_3$ phase shift parameter. Changing the sign of this parameter dramatically improves the agreement with experiment, while having little effect on other observables.

II. EXPERIMENTAL APPARATUS

The polarized proton beam is produced by the TUNL atomic beam polarized ion source (ABPIS) [4] and accelerated by a tandem Van de Graaff. The proton polarization is set by a Wien filter spin precessor to be vertical, along the $y$ direction. The neutron production target is a tritiated-titanium foil ($3 \times 10^{10}$ Bq/cm$^2$) on an isotopically pure $^{58}\text{Ni}$ backing. This backing material is chosen as the 9.44 MeV threshold for the $^{58}\text{Ni}(p,n)^{58}\text{Cu}$ reaction greatly reduces the background neutron level.

Slit feedback steering is used to control the position of the beam after acceleration, keeping the beam centered on the entrance to the proton polarimeter. In addition, a beam-profile monitor is used to determine the beam centroid 2 m from the neutron production target. A computer-controlled feedback system uses this information to center the beam in the beam pipe. This system, in combination with a slit feedback loop, keeps the beam centered on the neutron production foil. The tritiated-titanium foil is isolated from the beam line by a 2.5 µm havar foil. The intervening space is filled with helium gas at a pressure of 0.1 Mpa.

III. THE PROTON POLARIMETER

The proton polarimeter consists of a carbon foil and two solid state charged-particle detectors contained within a small scattering chamber as shown in Fig. [4]. The aluminum chamber is made of a cylindrical body with two arms acting as particle flight paths to minimize the internal volume and thus reduce the need for vacuum pumping. The detectors are mounted at the ends of the arms with three sets of tantalum collimators defining the scattered beams with an angular acceptance of $\pm 3.46^\circ$. The carbon foil is 22 mm in diameter and $5 \mu$g/cm$^2$ thick and is mounted on a plunger so that it can be removed from the beam when not in use. Slits in front of the polarimeter define the beam to be $12.7 \times 12.7$ mm. The slit currents are fed back to a steering magnet which keeps the beam centered on the entrance of the polarimeter. The detectors and all but the first set of collimators are electrically isolated to reduce noise pickup. The detectors are silicon charged-particle detectors with
300 mm² active areas and depletion depths of 1000 µm. The angle of the arms is fixed, for simplicity, at ±40°. This angle is chosen to provide a relatively large analyzing power over a range of energies for protons elastically scattered from carbon. At the lowest energy of this experiment (E_p = 3.02 MeV), however, the analyzing power is small. In this case, the proton beam polarization is measured at a higher energy before and after the measurement.

The detector signals are amplified and sent to single-channel analyzers (SCA). The outputs of the SCA’s are counted by scalers and stored in the computer. Three well-separated peaks are observed in the pulse height spectra with negligible background. In order of increasing energy of the detected particle they are elastic scattering from hydrogen H(⃗p, p)H, inelastic scattering from carbon ^{12}C(⃗p, p_1)^{12}C, and elastic scattering from carbon ^{12}C(⃗p, p_0)^{12}C. In the case of elastic scattering from hydrogen, it is the recoiling proton which is detected. The SCA windows are set around the ^{12}C elastic scattering peak.

IV. THE NEUTRON POLARIMETER

The neutron polarimeter consists of a ^{4}He target and neutron detector pairs placed symmetrically about the beam direction as shown in Fig. 2. Since the analyzing power of neutrons scattered elastically from helium can be calculated from the n-^4He phase shifts with an accuracy of approximately ±0.01 in the energy range of interest, the neutron beam polarization can be extracted from the measured left-right asymmetry. The polarimeter is located behind a polyethylene collimator which defines the neutron beam. The distance from the neutron source to the center of the polarimeter target is 1.79 m.

The target consists of helium–xenon gas mixture at a pressure of 10 MPa in a steel cylinder with 1 mm walls [5]. The active volume of the cell has a diameter of 44.6 mm and a height of 158.2 mm. Upstream neutron collimation defines a beam spot at the center of the polarimeter that is 31.5 mm in the horizontal direction by 94.5 mm in the vertical direction. The gas cell, shown in Fig. 3, has windows at both ends to allow scintillation light from the recoiling ^{4}He to be detected in photomultiplier tubes. Approximately 5% xenon, by partial pressure, is added to the helium to increase the light output. This arrangement makes it an active target and allows the measurement of both timing coincidences and ^{4}He recoil energy, thus reducing the background considerably. The inner walls of the gas cell are coated with 0.8 mm of magnesium oxide as a reflector. The windows are opaque to the majority of the scintillation light, whose wavelength is centered in the extreme ultraviolet (XUV) spectral region. Therefore 120 µg/cm² of p-quaterphenyl is evaporated on top of the reflector and acts as a wavelength shifter. The photomultiplier tubes are Hamamatsu type H1161 having a diameter of 51 mm. Care is taken while filling the gas cell to eliminate contaminants such as nitrogen and oxygen, which greatly reduce the performance of the cell by absorbing the light of scintillation.

The neutron detectors are placed symmetrically about 0° at angles where the product of the square of the analyzing power and the cross section is a maximum for ^{4}He(⃗n, n)^{4}He. There are two such angle pairs, one forward and one backward, and two detector pairs are used. At the lowest energy measured, however, one maximum is too low in magnitude to be useful and only one detector pair is used. The detectors are organic liquid scintillators (NE213) coupled to photomultiplier tubes through light guides. The light guides match
the geometry of the $45 \times 158 \times 76$ mm thick rectangular scintillator cells to the 51 mm diameter phototubes. The photomultiplier tubes are Hamamatsu type H1161. The neutron detectors are mounted to a detector ring having $1^\circ$ graduations. The entire apparatus is aligned optically with the neutron beam collimator.

Monte Carlo techniques are used to calculate the effective analyzing power of the neutron polarimeter. These calculations make corrections for the finite geometry of the target cell and neutron detectors, and for double-scattering events. Double scattering which includes neutrons scattering from materials in the target cell other than helium must be considered. The double-scattering events which are considered are He–He, He–Xe, Xe–He, He–Fe, and Fe–He. Since only events which include the detection of $^4$He recoil are recorded, single scattering events from elements other than helium need not be considered. Cross sections and analyzing powers are obtained from phase-shift data sets. The phase shifts for $n$-$^4$He come from experimental data as do the phase shifts for $n$-Xe and $n$-Fe at the higher energies. At the lowest energy measured, 1.94 MeV, experimental cross section data for xenon are used with analyzing powers assumed to be zero.

For an event to be considered valid, three criteria must be satisfied. First, there must be a coincidence between the top and bottom photomultiplier tubes of the target cell, reducing the noise from the tubes. Second, the signal from the neutron detector must meet pulse-shape discrimination requirements, eliminating signals from gammas. Third, there must be a coincidence between the target cell signal and one of the neutron detector signals, in order to reject neutron background events. The anode signals from the target cell photomultiplier tubes are used to form the coincidences, while the dynode signals provide the $^4$He recoil energy information. Summing the dynode signals improves the energy resolution of the detector as only part of the light of scintillation is deposited in each photomultiplier tube. The gains of the two tubes are matched using a $^{137}$Cs source. Since the $^4$He recoil energy is quite different for the forward and backward angles, the summed dynode signal is split into two signals which are amplified and delayed by different amounts before being recombined. This process creates two pulses for each $^4$He recoil, one large in amplitude and one small. The large amplitude pulse is gated through to the data acquisition system only when an event occurs in one of the backward angle detectors. Conversely, the small amplitude pulse is gated through only when an event occurs in one of the forward angle detectors. This arrangement allows a single ADC to digitize the $^4$He recoil energy for both detector pairs. Neutron time-of-flight from the target cell to the neutron detectors is determined using Ortec 467 time-to-amplitude converters (TAC). The start signal for each TAC comes from the timing signal of the corresponding neutron detector after the coincidence with the target cell anode coincidence signal. The coincidences are formed such that the timing signal from the neutron detector determines the timing of the TAC start signal. The stop signal comes from a delayed version of the target cell anode signal. This delay is adjusted to give a suitable range for the neutron time-of-flight signals (typically 100–200 ns). Because of the coincidence requirements, the count rates are low, typically a few per second.
V. DATA ACQUISITION

Data from the measurements are collected by CAMAC modules controlled by a MBD-11 Multiple Branch Driver [8]. The MBD is connected to a Digital Electronics Corporation VAXStation 3200 which supervises the data acquisition, stores the data, and performs online analysis. In addition, this computer performs part of the feedback steering of the proton beam. The data acquisition software runs under the TUNL XSYS data acquisition and analysis system [9].

For the polarization measurements it is necessary to measure count-rate asymmetries to an accuracy of order $1 \times 10^{-3}$. Instrumental asymmetries due to the data acquisition system must therefore be of order $1 \times 10^{-4}$ or less. To achieve this level of stability, fast spin-reversal is employed. The spin of the neutron beam is reversed at a rate of 10 Hz to reduce the effects of detector gain drifts and other instrumental shifts. Precision timing is used to insure that the same amount of time is spent counting in each spin state.

The fast spin-reversal is controlled by a NIM Spin State Control (SSC) module. The module produces an eight-step spin sequence: $+ - - + + - - + -$ which cancels the effects of detector drifts to second order in time [10]. All scaler data and ADC gates pass through a Phillips 706 sixteen-channel discriminator. Gate and delay generators are used to create a veto signal which blocks the data during a spin reversal, allowing time for the polarization of the beam from the source to stabilize. The SSC determines the spin state of the ion source by sending TTL level signals to the ABPIS through fiber optic cables. The signals modulate the RF supplies of the two transition units. The SSC provides duplicates of these signals for routing information. At the end of each eight-step sequence, the CAMAC preset is decremented. A run is comprised of 1023 such spin sequences. At the end of a run, signaled by the CAMAC preset scaler reaching zero, the data are written to disk.

Two ADC’s are used for the neutron polarimeter. The first records the $^4$He recoil energy signal from the center detector. Gates for this ADC can come from coincidences with any of the four neutron detectors. Next, coincidences are formed between gates from the forward detectors and their corresponding PSD signals. The PSD coincidences for the backward detectors are generated at an earlier stage. Routing information is created by the ADC interface according to the neutron detector and the spin state. Delays are applied to the linear signal and the gates to allow a proper time relation to be established. The second ADC records the neutron time-of-flight signals from the four neutron detectors. The linear signals are fanned together using sum and invert amplifiers. The gate for this ADC comes from the interface for the first ADC so that the ADC’s are triggered together and both $^4$He energy and neutron time-of-flight are recorded for each event. The events are stored in two-dimensional spectra with neutron time-of-flight as the $x$-axis and $^4$He recoil energy as the $y$-axis (Fig. [3]). There are two spectra for each of the four neutron detectors, corresponding to the two spin states.

VI. DATA ANALYSIS

The proton beam polarization is determined by observing the asymmetry between the number of counts from each detector, $\varepsilon_p$, for the $^{12}$C elastic peak and averaging over both
spin states:

\[ \varepsilon_p = \frac{1}{2} \left( \frac{N_{L+} - N_{R+}}{N_{L+} + N_{R+}} - \frac{N_{L-} - N_{R-}}{N_{L-} + N_{R-}} \right). \] (1)

Here, \( N_L \) and \( N_R \) refer to the number of counts in the left and right detectors and the subscripts “+” and “−” refer to the spin-state of the beam. The average proton beam polarization, \( P_p \), is then given by

\[ P_p = \frac{\varepsilon_p}{A_y^p}, \] (2)

where \( A_y^p \) is the analyzing power at 40° for \(^{12}\text{C}(\vec{p}, p_0)^{12}\text{C}\). The analyzing powers are obtained by fitting published analyzing power data as a function of angle \([11,12]\). The proton polarimeter asymmetries and analyzing powers as well as the beam polarization are listed for each energy in Table I.

The neutron polarimeter asymmetry is calculated for each pair of detectors by forming the following asymmetry for the two detectors:

\[ \varepsilon_n = \frac{\sqrt{N_{L+}N_{R-} - N_{L-}N_{R+}} - 1}{\sqrt{N_{L+}N_{R-} - N_{L-}N_{R+}} + 1}. \] (3)

\[ \Delta \varepsilon_n = \sqrt{\frac{N_{L+}N_{R-}(N_{L-} + N_{R+}) + N_{L-}N_{R+}(N_{L+} + N_{R-})}{(\sqrt{N_{L+}N_{R-}} + \sqrt{N_{L-}N_{R+}})^2}}. \] (4)

\( N_L \) and \( N_R \) refer to the number of counts in the left and right detectors respectively. This method of averaging reduces the sensitivity of the asymmetry to beam misalignments and detector efficiency differences. In addition, since two detectors are used, it is not necessary to know the incident neutron flux. The average neutron polarizations can be calculated from the average asymmetries using

\[ P_n = \frac{\varepsilon_n}{A_y^n}, \] (5)

where \( A_y^n \) is the \(^4\text{He}(\bar{n}, n)^4\text{He}\) effective analyzing power. The uncertainties in the analyzing powers are treated as systematic uncertainties. The results for each angle pair at each energy as well as the weighted averages over both angles are listed in Table II.

Once the neutron and proton beam polarizations are known, the polarization-transfer coefficient is simply the ratio of the two,

\[ K_{y'y} = \frac{P_n}{P_p}. \] (6)

The resulting values of \( K_{y'y} \) for the three measurements are listed in Table III. The proton energies listed in the table give the average energy and energy width after losses are calculated. The data are plotted in Fig. 6. The figure also includes the Los Alamos data [3] and the recent Wisconsin measurement [13]. As can be seen in the figure, the data sets are in agreement.
VII. COMPARISON TO THEORY

The $^3$H($p, n$)$^3$He reaction has a spin structure consisting of two spin-$\frac{1}{2}$ particles in both the entrance and exit channels. In this regard it is similar to nucleon-nucleon ($NN$) scattering, and the formalism developed for that problem can be used to describe the $^3$H($p, n$)$^3$He reaction with few modifications. A complete description of the formalism for polarization transfer in the $^3$H($p, n$)$^3$He reaction can be found in ref. [14].

The transverse polarization transfer coefficient $K_y'$($\theta$) is analogous to the Wolfenstein $D$ parameter for $NN$ scattering except that the incoming and outgoing particles are different. The lower index on $K_y'$($\theta$) indicates the component of the polarization vector for the incoming proton beam, while the upper index refers to the component for the outgoing neutron. In both instances the momentum vector of the incoming (outgoing) beam defines the $z$ ($z'$) axis, and the +$y$ axis is defined by $\vec{k}_\text{in} \times \vec{k}_\text{out}$. At $0^\circ$ the $y$ axis is undefined, and is taken to be in the vertical direction for this experiment.

The $M$-matrix formalism, described in detail by La France and Winternitz [13], is well suited for the description of polarization observables in scattering and reaction processes. The $M$-matrix for the $^3$H($p, n$)$^3$He reaction is a $4 \times 4$ matrix whose elements can be written as

$$M_{s's'm'}^{s'm'} = \frac{i\sqrt{\pi}}{k} \left[ \sum_{Jlm} \sqrt{2l + 1} \langle slm|Jm\rangle \langle s'l'm'(m - m')|Jm\rangle U_{s's'lm'}^J Y_{lm'}(\theta, 0) \right],$$

(7)

where $l$ ($l'$) is the orbital angular momentum of the incoming (outgoing) system, $s$ ($s'$) is the incoming (outgoing) channel spin, and $k$ is the wave number in the incoming channel. The angular momenta are coupled according to

$$J = (I_a + I_A) + l = s + l,$$

(8)

where $I_a$ is the spin of the proton (neutron) and $I_A$ is the spin of the $^3$H ($^3$He) nucleus. The collision matrix $U_{s's'ts}^J$ can be written in terms of the scattering matrix as

$$U_{s's'ts}^J = -e^{i(\omega_l + \omega_{l'})} S_{s's'ts}^J,$$

(9)

where $\omega_l$ and $\omega_{l'}$ are the modified Coulomb phase shifts for the incoming and outgoing waves,

$$\omega_0 = 0$$

(10)

$$\omega_l = \sum_{j=1}^{l} \arctan \left( \frac{\eta}{j} \right),$$

(11)

with the Coulomb penetration factor $\eta$ given as

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar \nu},$$

(12)

$\nu$ being the proton velocity.
In terms of the \( M \) matrix, \( K_y'(\theta) \) is given as

\[
K_y'(\theta) = \frac{\text{Tr}(M\sigma_y^1M^1\sigma_y^2)}{\text{Tr}(MM^1)}
\]

(13)

where \( \sigma_y^1 \) and \( \sigma_y^2 \) are spin matrices for the incoming proton and outgoing neutrons, respectively. At \( 0^\circ \) all non-diagonal \( M \)-matrix elements vanish, and \( K_y'(0^\circ) \) reduces to

\[
K_y'(0^\circ) = \frac{2\text{Re}[M_{11}^{11}(M_{00}^{11} + M_{00}^{00})]}{2|M_{11}^{11}|^2 + |M_{00}^{11}|^2 + |M_{00}^{00}|^2}.
\]

(14)

Since \( K_y'(0^\circ) \) is sensitive to relatively few matrix elements, its behavior can be analyzed in terms of the excited states of the \(^4\text{He} \) compound nucleus. In Fig. 5 we compare the present and previous results for the \( 0^\circ \) transfer coefficient to predictions based on a charge-independent \( R \)-matrix analysis of \( A = 4 \) scattering and reaction data \([16]\). Neither the present nor previous results were included in the \( R \)-matrix analysis.

As indicated by Eq. 14, \( K_y'(0^\circ) \) results from the spin-triplet matrix element \( M_{11}^{11} \) interfering with either \( M_{00}^{11} \) or \( M_{00}^{00} \). For proton energies below about 2 MeV, the \(^3\text{H}(p, n)^3\text{He} \) reaction is dominated by a pair of isospin-0 resonances in the \(^4\text{He} \) compound nucleus. The spins and parities of these resonances are \( 0^+ \) and \( 0^- \). Their resonance energies, according to the \( R \)-matrix analysis, are 20.21 and 21.01 MeV above the \(^4\text{He} \) ground state, respectively. Neither of these resonances contributes to the \( M_{11}^{11} \) matrix element, and \( K_y' \) falls rapidly below 2 MeV.

Above 2 MeV the \( M_{11}^{11} \) matrix element rises rapidly and has a broad peak at \( E_p = 3.7 \) MeV. The \( M_{00}^{11} \) matrix element displays similar behavior, which is due to the emergence of a \( 2^- \) isodoublet at 21.84 and 23.33 MeV. The \( 2^- \) resonances contribute to both \( M_{11}^{11} \) and \( M_{00}^{11} \), and it is the interference of these resonances with one other that is responsible for the sharp increase in \( K_y' \) above 2 MeV.

In addition to the low-energy \( 0^- \) and the \( 2^- \) states, there are four additional \( P \)-wave resonances that are primarily \( p^-\text{H} \) (and \( n^-\text{He} \)) in character. A second \( 0^- \) state, with isospin \( T = 1 \), exists at 25.28 MeV and produces negative values of \( K_y' \). Removing this state from the analysis results in a systematic increase in \( K_y' \) at all energies. A \( 1^- \) isodoublet, \( T = 1 \) at 23.65 and \( T = 0 \) at 24.25 MeV, has little effect on \( K_y' \). Both resonances are essentially pure spin-triplet states, and the \( 3P_1 \) partial wave cannot contribute to the \( M_{00}^{11} \) matrix element. While this partial wave does contribute to \( M_{11}^{11} \), particularly around \( E_p = 4 \) MeV, \( M_{11}^{11} \) is dominated by the \( 3P_2 \) partial wave from the \( 2^- \) resonances. A third \( 1^- \), state \( (T = 0) \) exists at 25.95 MeV, and is primarily spin-singlet. This state has a profound effect on \( K_y' \) values above 2 MeV. Upon removal of the \( 1P_1 \) partial wave, \( K_y' \) still exhibits a sharp rise due to the \( 2^- \) states, but falls to nearly zero at 4 MeV. The interference of the \( 1^- \) state at 25.95 MeV with the \( 2^- \) states at 21.84 and 23.33 MeV generates large values of \( K_y' \) above 4 MeV.

While the \( R \)-matrix analysis is able to describe the qualitative trend of the experimental behavior, it predicts values that are substantially lower at energies above 5 MeV. We find that changing the sign of the \( R \)-matrix \( 3F_3 \) phase shift from negative to positive, improves the agreement. This has comparatively minor effects on other \(^3\text{H}(p, n)^3\text{He} \) observables, notably the analyzing power \( A_y \). It is likely that minor changes can be made to the other phases to compensate for the \( 3F_3 \) phase shift.
VIII. SUMMARY

We have made measurements of the polarization-transfer coefficient $K_y^y$ at 0° for the reaction $^3\text{H}(\vec{p}, n)^3\text{He}$ at three neutron energies in the range 1.94 to 5.81 MeV. This reaction is used at TUNL and other facilities for producing polarized neutron beams at few-MeV energies. Our measurements confirm earlier results from Los Alamos National Laboratory and extend to lower energies. Comparing $R$-matrix predictions to the experimental data reveals a discrepancy which we attribute to the sign of the $^3F_3$ phase-shift parameter. Changing the sign of this parameter from negative to positive dramatically improves the agreement between theory and experiment, while having little effect on other observables.

IX. ACKNOWLEDGMENTS

This research was supported in part by the U.S. Department of Energy, Office of High Energy and Nuclear Physics, under Grants No. DEFG05-91-ER40619 and DEFG05-88-ER40441.
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| $E_n$ (MeV) | $E_p$ (MeV) | $\varepsilon_p$ | $A_y^p$ | $P_p$ |
|------------|------------|-----------------|---------|-------|
| 1.94       | 3.02       | 0.401           | $-0.851\pm0.009$ | $-0.471\pm0.05$ |
| 5.21       | 6.18       | 0.395           | $-0.851\pm0.009$ | $-0.464\pm0.005$ |
| 5.81       | 6.77       | $-0.316$        | $-0.520\pm0.009$ | 0.608±0.011 |

**TABLE I.** Proton polarimeter data. Left-right scattering asymmetry, analyzing power, and proton polarization with systematic uncertainties are listed for each energy. The statistical uncertainties in the asymmetries are negligible.

| $E_n$ (MeV) | $\theta$ | $\varepsilon_n$ | $A_y^n$ | $P_n$ |
|------------|----------|-----------------|---------|-------|
| 1.94       | 107°     | $-0.2362\pm0.0122$ | $0.764\pm0.010$ | $-0.309\pm0.016\pm0.004$ |
| 5.21       | 50°      | 0.2405±0.0166    | $-0.629\pm0.010$ | $-0.382\pm0.026\pm0.006$ |
|            | 121°     | $-0.3163\pm0.0277$ | 0.919±0.015      | $-0.344\pm0.030\pm0.006$ |
| Average    |          |                 |             | $-0.366\pm0.020\pm0.006$ |
| 5.81       | 51°      | $-0.3045\pm0.0300$ | $-0.632\pm0.010$ | 0.482±0.048±0.008 |
|            | 121°     | 0.4594±0.0560    | 0.916±0.015     | 0.502±0.061±0.008 |
| Average    |          |                 |             | 0.490±0.038±0.008 |

**TABLE II.** Neutron polarimeter data. Left-right scattering asymmetry, analyzing power, and neutron polarization with statistical and systematic uncertainties are listed for each energy and detector pair. The uncertainties in the analyzing powers are treated as systematic. The measured polarization averaged over both detector pairs is also given.

| $E_n$ (MeV) | $E_p$ (MeV) | $K_y^p$ |
|------------|------------|---------|
| 1.94       | 3.02±0.11  | 0.656±0.034±0.011 |
| 5.21       | 6.18±0.08  | 0.780±0.043±0.015 |
| 5.81       | 6.77±0.07  | 0.806±0.063±0.020 |

**TABLE III.** The measured values of $K_y^p$ with statistical and systematic uncertainties. The uncertainty in $E_p$ reflects the energy width of the proton beam due to losses.
FIGURES

FIG. 1. The proton polarimeter showing the carbon foil and the two silicon detectors. Also shown are the tantalum collimators.

FIG. 2. The neutron polarimeter showing the $^4$He gas cell and the forward and backward pairs of neutron detectors.

FIG. 3. The high-pressure $^4$He gas cell.

FIG. 4. The gas filling system for the $^4$He cell.

FIG. 5. A representative two-dimensional spectrum from the neutron polarimeter. The $x$-axis is neutron time-of-flight with time increasing to the left, while the $y$-axis is $^4$He recoil pulse height. The number of counts is shown in the $z$ direction.

FIG. 6. The experimentally determined values of $K_y^{y'}$ from the present work (triangles), the Wisconsin measurement [13], and the previous Los Alamos data (circles) [3]. The error bars indicate the total uncertainty obtained by adding the statistical and systematic uncertainties in quadrature. The lines show the $R$-matrix predictions with (solid) and without (dashed) modification of the $^3F_3$ phase-shift parameter, as explained in the text.
He

Xe

Trap

Rupture Disc

Condensation Chamber

Pressure Gauge

Back Ing Pump

Turbo Molecular Pump

Target Cell
