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Polarization transfer in the $^{3}\mathrm{H}(\vec{p},\vec{n})^{3}\mathrm{He}$ reaction and the 0^{-} level in $^{4}\mathrm{He}$

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Longitudinal polarization-transfer coefficients for the $^{3}\mathrm{H}(\vec{p},\vec{n})^{3}\mathrm{He}$ reaction have been measured at zero degrees for proton energies of 1.3–2.8 MeV. The results show a striking resonance behavior for energies corresponding to excitation of the 0^{-} level in $^{4}\mathrm{He}$ at 21.0 MeV. In agreement with R-matrix calculations, the value approaches unity at 1.52 MeV, the peak of the resonance. Near this same energy, at 1.62 MeV, the transverse polarization-transfer coefficient was measured to be consistent with zero. [S0556-2813(98)05108-5]

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We present results from measurements of the longitudinal and transverse polarization-transfer coefficients $K_{z}^{z'}(0^{\circ})$ and $K_{y}^{y'}(0^{\circ})$ in the $^{3}\mathrm{H}(\vec{p},\vec{n})^{3}\mathrm{He}$ reaction from 1.3 to 2.8 MeV. Previous data extended no lower than 4 MeV and 3 MeV proton energies, respectively [1,2]. The new measurements were carried out in an energy range which corresponds to excitation of the 21.0 MeV 0^{-} second excited state of $^{4}\mathrm{He}$ [3]. This narrow 0^{-} level lies close to the broad subthreshold 20.2 MeV 0^{+} first excited state, and R-matrix calculations predict a very clear signature for the presence of these levels: values of $K_{z}^{z'}(0^{\circ})$ approaching 100% at the peak of the 0^{-} resonance, with values of $K_{y}^{y'}(0^{\circ})$ essentially zero.

Our results provide striking confirmation of these predictions, and fully confirm the resonance parameters of the 0^{-} level, parameters derived in the past from studies of final-state interactions [4–6] in the $^{7}\mathrm{Li}(p,\alpha)$ reaction and from $^{3}\mathrm{H}(p,n)$ analyzing power measurements [7]. Our results show that the $^{3}\mathrm{H}(\vec{p},\vec{n})^{3}\mathrm{He}$ reaction is an exceptional source of longitudinally polarized neutrons at energies around 700 keV.

The measurements were made possible by the development of a dynamically polarized proton target which could be used as a high-efficiency neutron spin analyzer [8]. Using the polarized target required an order of magnitude less time per energy than conventional double-scattering measurements, and allowed us to map out the energy dependence over the whole energy range in a short amount of time.

Figure 1 shows a schematic of the experimental setup. Longitudinally polarized neutrons were created with the $^{3}\mathrm{H}(\vec{p},\vec{n})^{3}\mathrm{He}$ reaction using longitudinally polarized protons from the TUNL polarized ion source. Typical beam currents were 1 μA at 70% polarization and the target was a 0.8 Ci/cm^{2} tritiated titanium foil. The proton polarization was reversed at 10 Hz in the eight-step sequence $+--+-++-$ to remove possible drifts in time. Periodically, the proton spins were precessed into the vertical $(+x)$ direction at the source in order to measure the polarization via left-right scattering from a $^{4}\mathrm{He}$ gas cell upstream from the neutron production target.

The polarized proton target consisted of 1 mm beads of propanediol doped with EHBA-chromium(V) which were maintained at approximately 65% polarization through the use of a $^{3}\mathrm{He}$ evaporation refrigerator and microwave-induced polarization. The sample was located in a 3 cm^{3} Kel-F container in a 550 mK bath of $^{3}\mathrm{He}$ at the center of a 2.5 T magnet. The product of polarization and thickness for the proton target was approximately 0.04 b^{-1}. The relative polarization was continuously monitored with a NMR circuit and a coil wound around the target container. (The absolute calibration of the polarization times thickness was determined from a separate double-scattering experiment described later.) By changing the microwave frequency, the

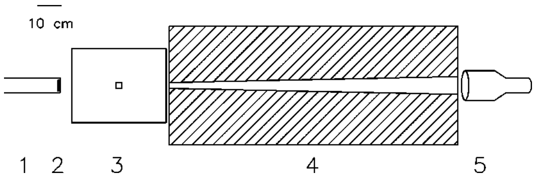

FIG. 1. Experimental layout for neutron-transmission measurements. A longitudinally polarized proton beam (1) was incident on a tritiated titanium target (2) and produced a beam of longitudinally polarized neutrons. The neutrons passed through a dynamically polarized proton target (3) used as a neutron polarization analyzer. Polyethylene collimation (4) defined the acceptance angle of the liquid scintillator detector (5) that was used to count the transmitted neutron flux at zero degrees.

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target polarization could be reversed relative to the neutron beam direction. This reversal was performed every 2 h and provided a means of canceling false asymmetries not associated with the polarized target.

The neutron-transmission asymmetry was measured using a shielded 12.7 cm diameter and 12.7 cm thick BC-501 organic liquid scintillator located at zero degrees. The solid angle subtended by the detector was 2.5 msr and a tapered 1.3 m polyethylene collimator was used to prevent the neutrons that passed around the target from reaching the scintillator. With a 1 μA proton beam current the neutron count rate was $\sim$700 Hz. Pulse-shape discrimination was used to separate neutron events from γ rays. To determine the neutron energy precisely, a separate measurement of n-^{12}C transmission was performed for energies near the 6.864 MeV resonance in ^{13}C. This calibration determined the energy of the neutron beam to within ± 20 keV.

The neutron-transmission data consisted of groups of measurements representing transmission with beam and target polarizations parallel and antiparallel. The data were collected in 15 min sets of 1024 eight-step sequences and each measurement at a given energy consisted of four sets with target polarization parallel to the beam direction and four sets with target polarization in the antiparallel direction. An asymmetry was formed for each target-spin state according to the equation

$$\epsilon^{p,a}=\frac{N_+^{p,a}-N_-^{p,a}}{N_+^{p,a}+N_-^{p,a}}, \tag{1}$$

where N is the number of neutrons counted in the liquid scintillator, $+$ $(-)$ represents neutron polarization parallel (antiparallel) to the beam direction, and p (a) represents proton target polarization parallel (antiparallel) to the beam direction. An average asymmetry was calculated from

$$\epsilon=\frac{1}{2}(\epsilon^p-\epsilon^a), \tag{2}$$

and the polarization-transfer coefficient was calculated from

$$K_z^{z'}(0°)=\frac{2\epsilon}{P_T x P_p \Delta\sigma_L}. \tag{3}$$

Here, P_T is the target polarization, x is the proton target thickness, P_p is the proton beam polarization, and $\Delta\sigma_L$ is the longitudinal $n-p$ total cross section difference calculated from known $n-p$ phase shifts [9,10]. In practice the absolute value of the product $P_T \times x$ was known only to about 20% (from NMR measurements and target weighing) and so separate double-scattering measurements were performed in order to normalize the relative transmission data.

Figure 2 shows a schematic of the experimental setup used for the double-scattering measurements. The techniques have been described by Wilburn *et al.* [11]. The measurements were carried out in longitudinal and transverse geometries at 1.62 MeV, an energy that corresponded to close to the maximum value of the longitudinal polarization transfer determined from the relative transmission measurements. The transverse double-scattering measurement was made to confirm the nonresonant behavior of $K_y^{y'}(0°)$ as compared to the $K_z^{z'}(0°)$ values found in the transmission measurements.

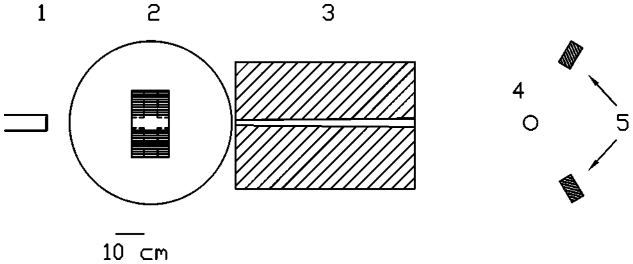

FIG. 2. Experimental layout for neutron double-scattering measurements. A longitudinally polarized 1.62-MeV proton beam (1) was incident on the tritiated titanium target and produced a beam of longitudinally polarized neutrons. The neutrons passed through a superconducting magnet (2) which precessed the spins into the vertical direction. A collimator (3) defined the neutron flux onto a high-pressure ^{4}He gas scintillator (4) and scattered neutrons were detected (5) at $\pm 59°$ in coincidence with recoil signals in the gas scintillator.

In the longitudinal geometry, the neutrons were produced with longitudinally polarized protons and the neutron spins were precessed transverse to the beam direction using a 0.73 T superconducting magnet. In the transverse geometry no precession was necessary and the neutrons were produced with the needed transverse polarization using a transversely polarized proton beam. In both cases, the neutrons were subsequently scattered in a high-pressure ^{4}He scintillator, with the scattered neutrons detected in a left-right pair of liquid scintillators. The ^{4}He scintillator was placed 175 cm downstream from the production target at zero degrees and consisted of a 5 cm diameter cylinder filled to 1500 psi with a mixture of ^{4}He and 5% Xe. Attached to the top and bottom of the 15 cm high cylinder were two photomultiplier tubes for detection of recoiling ^{4}He nuclei within the scintillator. The left-right detectors, located symmetrically at 59°, were two organic liquid scintillators, 4.8 cm wide, 12.4 cm tall, and 6.9 cm deep, to count scattered neutrons. With 1 μA of 1.7 MeV protons incident on the production cell, double-coincidence count rates were 0.7 Hz for $K_z^{z'}(0°)$ and 0.2 Hz for $K_y^{y'}(0°)$. The energy of the scattered neutron beam was determined by the measured time of flight over the known path length.

The effective analyzing power was calculated from the ^{4}He phase shifts of Stammbach and Walter [12], using a Monte Carlo code to calculate finite-geometry and double-scattering effects, which were of order $\sim$5%. The neutron polarization was then calculated from the measured left-right asymmetry and the effective analyzing power.

Results are summarized in Table I and plotted in Fig. 3. The table shows the proton energy, the neutron energy, and the polarization-transfer coefficients derived from normalizing the transmission results to the absolute double-scattering results. Statistical and systematic errors are shown, the systematic errors being derived from the uncertainty in the beam energy leading to uncertainty in $\Delta\sigma_L$, the uncertainty in the ^{4}He$(\vec{p},p)^4$He analyzing powers leading to uncertainty in

TABLE I. Experimental results for $K_z^{z'}(0°)$ and $K_y^{y'}(0°)$ for the $^3\mathrm{H}(\vec{p},\vec{n})^3\mathrm{He}$ reaction. Mean proton energies E_p and the resulting neutron energies E_n are shown together with the energy spreads associated with stopping in the tritiated titanium foil. The value of $K_z^{z'}(0°)$ at 1.62 MeV is obtained from the double-scattering measurement that was used to normalize the transmission values. Both statistical and systematic uncertainties are shown.

$E_p \pm \Delta E_p$ (MeV)	$E_n \pm \Delta E_n$ (MeV)	Transmission $K_z^{z'}(0°) \pm$ stat $\pm$ syst.	Double scattering $K_y^{y'}(0°) \pm$ stat $\pm$ syst.
1.29 ± 0.03	0.46 ± 0.15	0.400 ± 0.005 ± 0.028	
1.41 ± 0.03	0.58 ± 0.14	0.756 ± 0.005 ± 0.048	
1.52 ± 0.03	0.71 ± 0.13	0.957 ± 0.006 ± 0.058	
1.62 ± 0.03	0.82 ± 0.13	0.927 ± 0.022 ± 0.032	0.086 ± 0.111 ± 0.003
1.72 ± 0.03	0.92 ± 0.12	0.780 ± 0.008 ± 0.044	
1.97 ± 0.02	1.17 ± 0.11	0.502 ± 0.004 ± 0.028	
2.17 ± 0.02	1.37 ± 0.10	0.332 ± 0.003 ± 0.018	
2.75 ± 0.02	1.96 ± 0.08	0.200 ± 0.004 ± 0.010	

P_p, and the uncertainty in the $^4\mathrm{He}(\vec{n},n)^4\mathrm{He}$ analyzing powers and finite-geometry corrections leading to uncertainty in the calculation of $P_T x$.

The most notable features of the data are the sharp resonancelike behavior of $K_z^{z'}(0°)$ around 1.52 MeV and the fact that $K_y^{y'}(0°)$ is essentially zero at this same energy. Following the M-matrix formalism of La France and Winternitz [13], the polarization-transfer coefficients are given by

$$\sigma_0 K_z^{z'}(0°) = 2|M_{11}^{11}|^2 + 2\,\mathrm{Re}\{M_{00}^{11*} M_{00}^{00}\} \tag{4}$$

and

$$\sigma_0 K_y^{y'}(0°) = 2\,\mathrm{Re}\{M_{11}^{11*}(M_{00}^{11} + M_{00}^{00})\}, \tag{5}$$

with the unpolarized differential cross section

$$\sigma_0 = 2|M_{11}^{11}|^2 + |M_{00}^{11}|^2 + |M_{00}^{00}|^2. \tag{6}$$

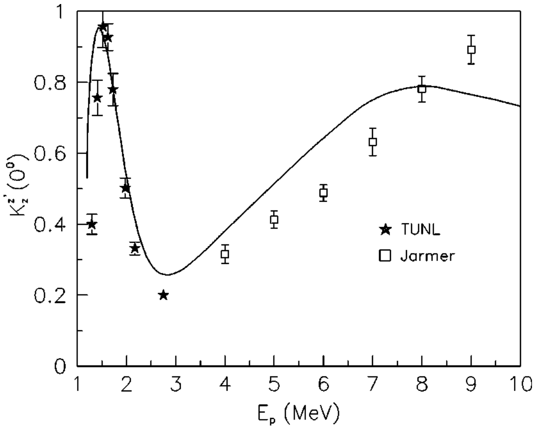

FIG. 3. Comparison of TUNL experimental data for $K_z^{z'}(0°)$ with previous data of Jarmer *et al.* [1] and with an R-matrix calculation based on the phase-shift parameters of Hale [14]. The error bars are the sum in quadrature of the statistical and systematic uncertainties.

Here $M_{\nu',\nu}^{s',s}$ is the M-matrix element for channel spin s (s') and channel spin projection $\nu(\nu')$ for the incoming (outgoing) channels. The solid curve in Fig. 3 is a calculation of $K_z^{z'}(0°)$ based on phase-shift parameters derived from a full R-matrix analysis of the $A=4$ system by Tilley *et al.* [3]. The agreement with the resonance structure at 1.7 MeV is excellent and fully confirms the 0^- assignment to the second excited state of ^{4}He at 21.0 MeV. The value of $K_y^{y'}(0°)$ is also predicted to be small, again agreeing well with the measurement.

The results imply that the reaction at low energies is dominated by just two interfering amplitudes, the 21.0 MeV 0^- level and the broad subthreshold 20.2 MeV 0^+ level. Only M_{00}^{00} is nonzero for a 0^+ resonance and only M_{00}^{11} is nonzero for a 0^- resonance. As a result,

$$K_z^{z'}(0°) \approx \frac{2\,\mathrm{Re}(M_{00}^{11*} M_{00}^{00})}{|M_{00}^{11}|^2 + |M_{00}^{00}|^2} \quad \text{and} \quad K_y^{y'}(0°) \approx 0. \tag{7}$$

If the relative 0^+ and 0^- strengths are equal, $K_z^{z'}(0°)$ approaches unity as $K_y^{y'}(0°)$ remains small. This is effectively what is seen in the polarization-transfer data.

In conclusion, we have measured zero degree longitudinal and transverse polarization-transfer coefficients for the $^3\mathrm{H}(\vec{p},\vec{n})^3\mathrm{He}$ reaction at low energies. The measurements confirm the R-matrix analysis of Ref. [3] and provide perhaps the most direct evidence yet for the presence of the 0^- level in ^{4}He. The $^3\mathrm{H}(\vec{p},\vec{n})^3\mathrm{He}$ reaction is an excellent source of longitudinally polarized neutrons at ~700 keV.

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