$^{11}B(p,n)^{11}C(0)$ Polarization-Transfer Measurement at 0° and the Effective Two-Nucleon Interaction*

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The transverse polarization transfer coefficient, $K_y^{y'}(0°)$ has been measured for the reaction $^{11}B(p,n)^{11}C(0)$ at $E_p = 16.3$, 21.3, and 26.5 MeV. The results are not in agreement with direct-reaction-theory calculations using an empirical charge-exchange effective interaction which includes both central and tensor forces.

Since the measurement[1] of the quadrupole moment of the deuteron in 1939, it has been known that there is a tensor component in the two-nucleon interaction.[2] Evidence for the existence of tensor forces in nucleon-nucleon scattering was first reported in 1950.[3] Since that time considerable effort has been expended in attempts to determine whether a tensor component is required in the effective two-nucleon interaction used both in nuclear structure and in nucleon-nucleus scattering. The importance of tensor forces in nuclear-structure calculations was demonstrated in 1957 when Visscher and Ferrell[4] showed that the tensor force was essential to an explanation of the anomalously long β-decay lifetime of ^{14}C. The evidence from nucleon-nucleus scattering is not nearly as clear.

The reaction $^{14}C(p,n)^{14}N(0)$ involves the same nuclear states as the ^{14}C β decay and the normally dominant $L = 0$ contribution to this reaction is very nearly proportional to the allowed β-decay matrix element, which is suppressed. This transition thereby became a prime candidate for study in that effects of a tensor force might be observed when the central-force contributions cancel. A detailed study of this reaction[5] has been made for proton energies between 7.2 and 18.3 MeV. It showed that by including a tensor force, a significant improvement is achieved in calculating both the magnitude and shape of the differential cross section. A study of the $^{14}N(p,p')^{14}N$ (2.31 MeV 0^+, $T = 1$) angular distribution at 24.8 MeV[6] showed that inclusion of a tensor force in the effective interaction made some improvement in the agreement between theory and experiment. A similar discrepancy in nonanalog transitions with the $(^3He, t)$ reaction was resolved[7] by including a tensor force in the effective interaction. In contrast, polarization measurements included in the $^{14}C(p,n)^{14}N(0)$ study[5] could not be fitted by theory using any force, either with or without a tensor component. Since the tensor force is a spin-flip interaction, this failure is significant. Wong *et al.*[5] argued that the chief difficulty in applying direct-reaction theory to their data resulted from optical-model-parameter uncertainties.

In 1974 Madsen, Anderson, and Brown[8] calculated the transverse-polarization transfer coefficient $K_y^{y'}(0°)$ for charge-exchange reactions using the distorted-wave Born approximation (DWBA) with central and tensor spin-dependent forces. For (p,n) reactions at 0° the polarization transfer coefficient $K_y^{y'}(0°)$ is just the outgoing neutron polarization divided by the incident proton polarization. The calculations were made for the $^{11}B(p,n)$ analog reaction using the Watson optical potentials[9] and the Cohen-Kurath p-shell wave functions.[10] The energy dependence of $K_y^{y'}(0°)$ was found to be sensitive to the relative strengths of the spin-independent, central spin-spin, and tensor forces. These calculations gave rise to the hope that measurements of $K_y^{y'}(0°)$ in charge-exchange reactions would provide a significant test of the importance of the tensor force in nucleon-nucleus scattering.

The neutron facility[11] at the Texas A & M University cyclotron is fully instrumented for making measurements of $K_y^{y'}(0°)$ with (p,n) reactions. The beam from an atomic-beam polarized-ion source was injected axially into the cyclotron, accelerated, and transported to the neutron-production target. The beam polarization is vertical and can be reversed at the source in alternate runs so as to eliminate false asymmetries. It was monitored continuously by measuring the asymmetry in p-^4He elastic scattering in a gas polarimeter located upstream of the target area. The average polarization of the beam, as determined from analyzing powers given by p-^4He phase shifts of Bacher *et al.*,[12] was 76% at 16.3 MeV, 66% at 21.3 MeV, and 77% at 26.5 MeV. After passing through the target the beam was magnetically deflected into a heavily shielded

Faraday cup. The intensity of the polarized beam on target varied from about 30 to 60 nA. Self-supporting 25 mg/cm^2 targets enriched to 97% ^{11}B were used.

Neutrons from the target passed through a collimator channel at 0° and were analyzed with a liquid-helium polarimeter[13] located 4.5 m from the ^{11}B target. Neutrons scattered by the helium were detected in one of four NE102 scintillators located at angles near ±80° and ±115° relative to the 0° beam line. Data were obtained with incident proton polarization both up and down. The neutron polarization was determined by making spin-up and spin-down measurements in each of the four side detectors and then calculating the polarization using the measured n-^{4}He analyzing powers of Broste *et al.*[14] at $E_n = 23.7$ MeV and analyzing powers calculated from the phase shifts of Stammbach and Walter[15] at the lower energies.

Since the reaction of interest involves the ^{11}C ground state, it is necessary to have good neutron time-of-flight resolution to separate the ground-state neutrons from those leaving ^{11}C in its first excited state. The proton beams were "time tuned" such that the time width of the beam micropulses ranged from 1.6 nsec [full width at half-maximum (FWHM)] at $E_p = 27$ MeV to 1.9 nsec FWHM at $E_p = 16.3$ MeV. The ground-state group was well separated from the excited-state groups and the asymmetries in the neutron yield for the analog transition could be determined with very little contamination from other transitions. Multiple-scattering and finite-geometry corrections have been applied to the measured asymmetries in determining the neutron polarization. The Monte Carlo computer program developed by Miller, Gibson, and Morrison[16] has been used to calculate the corrections which ranged from 8% for the 80° detectors at $E_n = 23.7$ MeV to 25% for the 115° detectors at $E_n = 13.6$ MeV. The measured values of $K_y^{y'}(0°)$ with their statistical errors are listed in Table I and are shown in Fig. 1. We note that our data represent a reasonable extrapolation of measurements of $K_y^{y'}(0°)$ between $E_p = 10.5$ MeV and $E_p = 15$ MeV.[17]

TABLE I. ^{11}B$(p,n)^{11}$C(0) polarization transfer.

Proton energy (MeV)	$K_y^{y}(0°)$
16.3	0.59 ± 0.05
21.3	0.60 ± 0.04
26.5	0.66 ± 0.08

Also shown in Fig. 1 are the theoretical predictions of $K_y^{y'}(0°)$ by Madsen, Anderson, and Brown.[8] The charge-exchange part of the effective interaction used in the calculations is

$$V_{\text{eff}} = \vec{\tau}_0 \cdot \vec{\tau}_i [f_c(r_{0i})(V_\tau + V_{\sigma\tau}\vec{\sigma}_0 \cdot \vec{\sigma}_i) + V_T S_{12} f_T(\alpha', \beta, r_{0i})], \qquad (1)$$

where a Yukawa form factor was used for f_c and the tensor operator S_{12} was used with its form factor taken to be a "regularized" spherical Hankel function. Curve A in Fig. 1 represents the restricted case in which only $L = 0$ orbital angular momentum transfer is allowed in the calculation. This restricts the reaction to two contributing terms; $S, I = 0, 0$ and $1, 1$ where S is the spin transfer and I is the total angular momentum transfer. Madsen, Anderson, and Brown[8] show that this results in

$$K_y^{y'}(0°) = (\sigma_{S=0} - \tfrac{1}{3}\sigma_{S=1})/(\sigma_{S=0} + \sigma_{S=1}), \qquad (2)$$

which is energy independent as long as V_τ and $V_{\sigma\tau}$ have a common form factor.

Curves B, D, and E result from purely central forces, that is, $V_T = 0$ for these cases. Curve B represents an empirical interaction taken from Anderson *et al.*[18] Curve D results from adjusting the empirical interaction to give the same polarization and total cross section as the central-plus-tensor interaction at 16 MeV. Curve E is the same as D except that the Yukawa range pa-

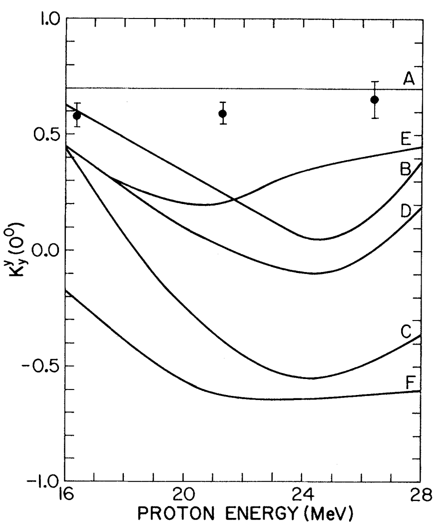

FIG. 1. The measured polarization-transfer coefficients for ^{11}B$(\vec{p},\vec{n})^{11}$C(0) compared to the direct-reaction-theory predictions of Madsen, Anderson, and Brown, Ref. 8. See text for an explanation of curves A–F.

rameter, α, has been increased from 0.714 to 1.0 fm^{-1} and strengths have been adjusted to agree at 16 MeV with curves C and D. The empirical central-plus-tensor interaction[18] produces curve C whereas an increased relative tensor strength produces curve F. Thus, as the complexity of the calculation increases from $L=0$ transfer (A) to central $L=0, 2$ (B, D, E) to central-plus-tensor (C, F), the trend is for the predicted $K_y^{y'}(0°)$ to become more negative and to deviate further from the measured values.

Since the experimental values for $K_y^{y'}(0°)$ are in best agreement with the simple $L=0$ central-force prediction we must look for possible deficiencies in the calculations. *First*, the DWBA calculation omits contributions to this specific reaction channel from the compound nucleus. This may be a difficulty below about 18 MeV[17] but the slow variation of $K_y^{y'}(0°)$ in the range $E_p = 16-27$ MeV seems to rule out any significant compound-nucleus contributions. *Second*, knock-out exchange processes are not included in the analysis. We note that an analysis[19] of the $^{14}N(p, p')^{14}N$ (2.311 MeV, 0^+, $T=1$) angular distribution at $E_p = 29.8$ MeV was significantly improved when exchange processes were included in the central-plus-tensor calculation. Tensor knock-out amplitudes have also been found to be important in the $^{14}N(p,n)^{14}O(0)$ transition.[20] *Third*, the optical-model parameters for such a light nucleus are uncertain. Madsen, Anderson, and Brown[8] emphasized the importance of reliable optical-model parameters in interpreting polarization-transfer experiments. In fact, their analysis based on 0° $^{11}B(p,n)$ analog cross-section measurements indicated that the effective interaction producing curve F in Fig. 1 is preferred to that of curve C. We have measured this cross section near $E_p = 20$ and 30 MeV and get results 1.5 to 3 times larger than the values quoted in Ref. 7. Clearly, further work—both experimental and theoretical—is required to establish reliable optical-model potentials for the reaction $^{11}B(p,n)$.

Thus, the initial measurement of $K_y^{y'}(0°)$ has not borne out the prediction that tensor forces are required to reproduce the energy dependence of $K_y^{y'}(0°)$. The conclusion based on the calculations of Madsen, Anderson, and Brown[8] is that the measured values are in best agreement with the simple $L=0$ transfer which also dominates the total analog cross section. However, inclusion of exchange processes in the DWBA calculations plus further work on the optical-model potentials for this reaction may still allow one to distinguish between the contributions of the effective central and tensor forces. Further measurements of $K_y^{y'}(0°)$ on low-A and medium-A nuclei are planned in order to provide additional tests for the theory.

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