${}^{T}T_{20}$ analyzing powers from ^{12}C(^{7}Li,α)^{15}N

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The transverse analyzing powers ${}^{T}T_{20}$ were obtained from a polarized beam study of the reaction ^{12}C(^{7}Li,α)^{15}N at $E_{\text{lab}}({}^{7}\text{Li}) = 34$ MeV for several well known, strongly populated and isolated states in ^{15}N to determine if they contained a sufficiently distinctive signature to be used to provide a test against which selectively populated and strong, but not well understood states, such as the one at 13.17 MeV could be used to determine their spins and parities. Unfortunately, current finite range distorted wave Born approximation and coupled channels Born approximation calculations were not able to describe the data to the well-known states. The current work presents these experimental analyzing powers with the expectation that they can be used as a test of future detailed reaction model calculations.

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Introduction. A simple ${}^{12}\text{C} + t$ cluster model [1] was proposed early in the study of multiparticle transfer reactions on ^{12}C to explain the highly selective population of states in the ^{15}N energy spectrum in three-nucleon transfer reactions. Unfortunately, the development of a cluster model of ^{15}N has been hindered due to the lack of techniques to determine spin-parity values for the high lying peaks populated by the ^{12}C(^{7}Li,α)^{15}N reaction [2,3] that occur above all particle decay thresholds. Definite spin-parity values often are obtained by the measurement of gamma decay from the states of interest, but these states have such small gamma-decay branching ratios when compared to the much stronger particle-decay branches that their gamma decay cannot be observed, thus requiring other techniques for extracting their properties.

In this Brief Report, we present measured transverse analyzing powers ${}^{T}T_{20}$ for the well known states in ^{15}N. This analyzing power was chosen because the elastic and inelastic analyzing powers ${}^{T}T_{20}$ for the system ${}^{7}\text{Li} + {}^{12}\text{C}$ were well described by assuming they arise from the reorientation of the ^{7}Li ground state. The first rank ${}^{T}T_{10}$ and third rank ${}^{T}T_{30}$ analyzing powers were not described due to their having sizable interfering but poorly quantified contributions from virtual coupling to the excited states of ^{7}Li, a spin-orbit potential and reorientation of the ^{7}Li ground state [4].

It was not possible to describe the transfer reaction analyzing powers in the current work by either finite range distorted wave Born approximation (FRDWBA) or coupled channels Born approximation (CCBA) calculations that included transfer from the ^{7}Li ground state, including its reorientation. It is expected that future improvement in reaction models will allow the analyzing power ${}^{T}T_{20}$ to be used to determine the spin and parity of states like the one at 13.17 MeV that is strongly populated in the ^{12}C(^{7}Li,α)^{15}N reaction and has had numerous proposed spin-parity values since its observation 40 years ago [2].

Experiment. Analyzing powers for the ^{12}C(^{7}Li,α)^{15}N reaction were determined using a polarized 34 MeV ${}^{7}\text{Li}^{3+}$ beam produced at the Florida State University (FSU) Tandem/Linear Accelerator (LINAC). The ^{12}C target was a 100 $\mu\text{g/cm}^2$ self-supporting foil. The α-particle identification was achieved by using two $\Delta E - E$ telescope detectors with $\pm 0.25^\circ$ opening angle. The detectors were placed at 17 angles separated by roughly 2° on both sides of the beam.

The FSU optically pumped polarized Li ion source was used to produce the ^{7}Li polarized beam with typical on-target polarization tensors of $t_{10} = 0.54 \pm 0.02$, $t_{20} = 0.60 \pm 0.03$, and $t_{30} = 0.55 \pm 0.03$, determined by Cathers *et al.* [5]. The average beam on target intensity was about 100 nA. Analyzing power angular distributions were determined for the following ^{15}N states: 6.32 $(3/2^-)$, 7.16 $(5/2^+)$, 7.57 $(7/2^+)$, 8.57 $(3/2^+)$, 9.15 $(5/2^+)$, 10.69 $(9/2^+)$, 13.00 $(11/2^-)$, and 15.37 MeV $(13/2^+)$.

The details of detectors, scattering chamber, and targets are similar to those reported in Ref. [5]. The detected alpha-particle energy resolution was approximately 100 keV as shown in a typical spectrum depicted in Fig. 1. As was found early on in the study of this reaction [2,6], it is highly selective in the states populated in ^{15}N. The current peak identifications were based on those from Ref. [6]. The equations required to extract analyzing powers from polarized beam experiments were obtained from the work of Cathers *et al.* [5]. The present analyzing power data were collected by cycling between the magnetic substates $m_I = \frac{3}{2}, \frac{1}{2}, -\frac{1}{2}$, and $-\frac{3}{2}$ and polarization off for equal amounts of integrated beam current which was typically every three minutes.

Results and Discussion. Figures 2 and 3 display analyzing power ${}^{T}T_{20}$ data obtained for well-known positive and negative parity states in ^{15}N. Figure 2 presents the ${}^{T}T_{20}$ values corresponding to $3/2^+$, $3/2^-$, and $5/2^+$ states including the strongly excited state at 9.155 MeV for which gamma-ray decay data [7,8] have shown that it is the 9.155 MeV $5/2^+$ state that is populated in the (^{7}Li,α) reaction with almost no strength to the nearby 9.152 MeV $(3/2^-)$ state. Figure 3 contains ${}^{T}T_{20}$ angular distributions corresponding to states with $J^\pi = 7/2^+$, $9/2^+$, $11/2^-$, and $13/2^+$.

The data displayed in Fig. 2(a) clearly distinguish $3/2^+$ from $3/2^-$ states. It is also evident that states having the

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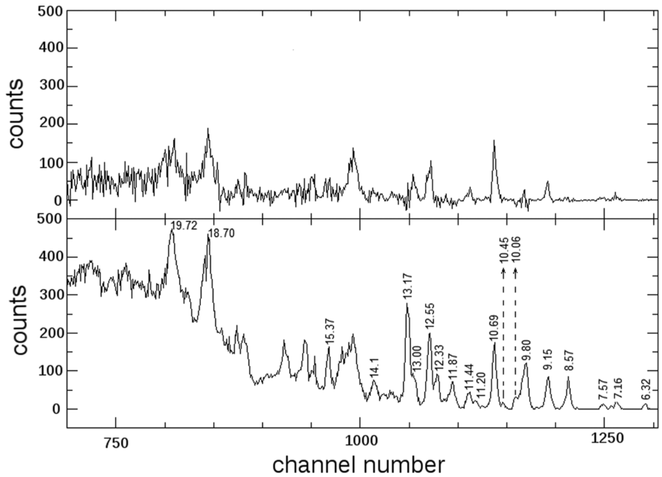

FIG. 1. ^{12}C(^{7}Li,α)^{15}N spectra collected at $\theta_{\rm lab} = 10^{\circ}$, $E_{\rm lab} =$ 34 MeV. The lower panel contains an unpolarized beam spectrum where states in ^{15}N are identified with accepted excitation energies [6]. The upper panel displays the difference between polarized beam spectra corresponding to $m_I = -\frac{3}{2}$ and $\frac{3}{2}$ and demonstrates that selectively populated ^{15}N states have varying analyzing powers.

same parity are well separated: the $3/2^+$ ${}^T T_{20}$ analyzing power displayed in Fig. 2(a) is highly oscillatory and varies between -0.5 and $+0.3$ while for both $5/2^+$ states [Fig. 2(b)], it is less oscillatory, always positive, and changes between $+0.5$ and $+0.2$. The $7/2^+$ ${}^T T_{20}$ analyzing power [Fig. 3(a)] is smaller than the ${}^T T_{20}$ of the $5/2^+$ states [Fig. 2(b)] and varies between $+0.2$ and 0.0. ${}^T T_{20}$ for the $9/2^+$ state [Fig. 3(a)] is about 0.4 to 0.5, has a different angular distribution, and is larger than the ${}^T T_{20}$ of the $7/2^+$ [Fig. 3(a)], $5/2^+$ [Fig. 2(b)], and $3/2^+$ [Fig. 2(a)] states. The negative parity states also have clear signatures: for the 6.32 MeV ($3/2^-$) state [Fig. 2(a)], ${}^T T_{20}$ does not oscillate much and changes between $+0.5$ and 1.0

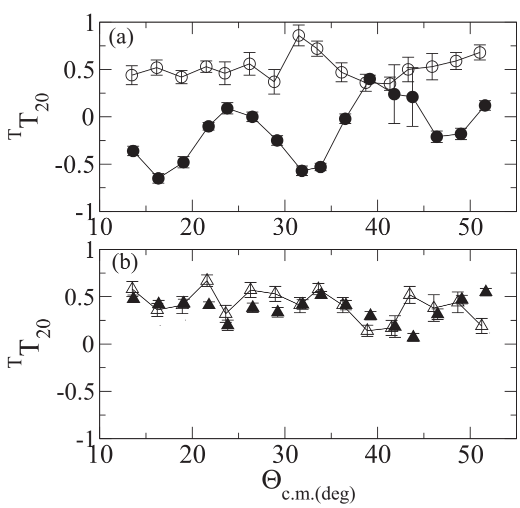

FIG. 2. Experimental ${}^T T_{20}$ angular distributions obtained from a study of the beam polarized ^{12}C(^{7}Li,α)^{15}N reaction at $E_{\rm lab}$(^{7}Li) = 34 MeV. The data correspond to the states in (a) 8.57 MeV, $3/2^+$ (solid circles) and 6.32 MeV, $3/2^-$ (open circles). In (b) 9.155 MeV, $5/2^+$ (solid triangles up), 7.16 MeV, $5/2^+$ (open triangles up).

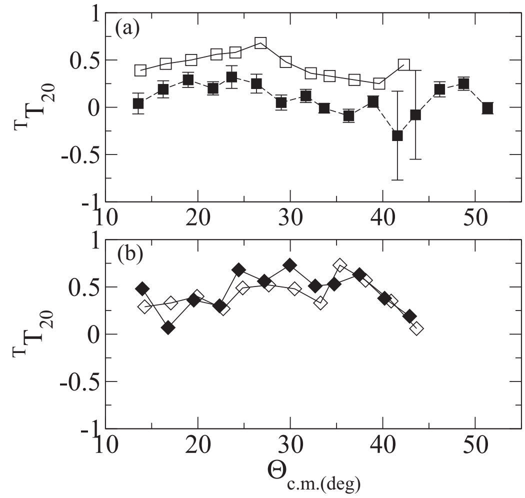

FIG. 3. Experimental ${}^T T_{20}$ angular distributions obtained from a study of the beam polarized ^{12}C(^{7}Li,α)^{15}N reaction at $E_{\rm lab}$(^{7}Li) = 34 MeV. The data correspond to the states (a) 7.57 MeV, $7/2^+$ (solid squares) and 10.69 MeV, $9/2^+$ (open squares); (b) 13.00 MeV, $11/2^-$ (solid diamonds) and 15.37 MeV, $13/2^+$ (open diamonds). Error bars are not displayed when their sizes are comparable to or smaller than the corresponding symbol size.

while for the 13.00 MeV ($11/2^-$) state, ${}^T T_{20}$ oscillates more and has values between 0.0 and $+0.5$ [Fig. 3(b)].

The ${}^T T_{20}$ values associated with the 9.155 ($5/2^+$) and 7.16 MeV ($5/2^+$) states have the same size and similar behavior as a function of the scattering angle as expected since these states have the same spin parity. However, these states have different underlying structures: the 7.16 MeV state has been shown to be strong in single-nucleon transfer reactions such as the ^{14}N(d,p)^{15}N reaction [9] while the 9.155 MeV state is prominent in three-nucleon transfer reactions such as the one studied in the current work. This may indicate the structure independence of ${}^T T_{20}$ and consequently, its possible usefulness to help make J^{π} assignments.

There have been several analyses published to determine if (^{7}Li,α) angular distributions can be described by FRDWBA calculations. Mordechai and Fortune [10] as well as Farra [11] showed that the forward angle angular distribution data of strong positive parity states produced in the unpolarized beam ^{16}O(^{7}Li,α)^{19}F reaction at $E_{\rm lab}$(^{7}Li) = 20 MeV can be described by FRDWBA calculations while the backward angle data seem to contain cluster exchange and compound nucleus contributions. Lee *et al.* [12] carried out FRDWBA angular distribution calculations for several states in ^{15}N populated by the unpolarized beam ^{12}C(^{7}Li,α) reaction at $E_{\rm lab}$(^{7}Li) = 52.5 MeV assuming a direct triton-transfer reaction mechanism. However, when these calculations are repeated and analyzing powers are produced, they fail completely to describe them, and even after extensive adjustments of various input parameters were made, it was not possible to describe any of the measured analyzing powers. CCBA calculations that included a contribution arising from reorientation of the ^{7}Li ground state quadrupole moment did not improve the theoretical description of the data.

A spin-parity value of $11/2^-$ proposed earlier [13] for the state in ^{15}N at 13.00 MeV was confirmed by analyzing powers from the ^{12}C(^{6}Li,^{3}He)^{15}N reaction at $E_{\rm lab}(^6{\rm Li}) = 50$ MeV [14]. A reanalysis of just the unpolarized angular distribution data [12] confirmed that the spin-parity of this state could not be obtained from these data alone, which nicely showed the importance of analyzing powers for extracting final state J^π values.

Since gamma decay from strongly populated peaks in ^{15}N above the proton, neutron, and alpha-particle decay energy threshold, 11 MeV, is very weak and not observable as compared to the much stronger particle decays and, in view of the reasonable J^π separation observed in the current work between experimental $^TT_{20}$ values associated with different states in ^{15}N (Figs. 2 and 3), one way to restrict the spins and parities of unknown states to a set of possible values may be to compare their experimental $^TT_{20}$ angular distributions to those of well-known states. It is important to mention that an ultimate J^π determination should be achieved by comparing the data and theoretical calculations. This is especially necessary in cases such as the one depicted in Fig. 3(b) where the closeness between the $^TT_{20}$ values of the well-known states at 13.00 ($11/2^-$) and 15.37 MeV ($13/2^+$) means it is not possible to distinguish $11/2^-$ from $13/2^+$ solely from the $^TT_{20}$ data.

Kemper *et al.* [14] proposed $J^\pi = 7/2^+$ or $5/2^-$ for a 13.17 MeV state based on an analysis of the polarized beam ^{12}C(^{6}Li,^{3}He)^{15}N reaction at $E(^6{\rm Li}) = 50$ MeV. A more recent study of the same reaction by Lee *et al.* [12] suggested a J^π value of $5/2^-$ based on the analysis of unpolarized and polarized data. Ajzenberg-Selove [13] compiled a state at 13.17 MeV with an uncertain $J = 9/2$. From an analysis of the ^{16}O(^{7}Li,α)^{19}F reaction, Tserruya *et al.* [15] assigned either $J^\pi = 3/2^-$ or $7/2^-$ to a strong state in ^{19}F observed at an excitation energy of 6.89 MeV. Correspondence between ^{19}F and ^{15}N $3p$-$4h$ states has been established previously [16] based on a comparison of data obtained from an analysis of the ^{12}C(α,p)^{15}N and ^{16}O(α,p)^{19}F reactions. Based on Refs. [15] and [16], if the 13.17 MeV state had a $(sd)^2f$ configuration, it could have a negative parity and it would not be observed in reactions such as ^{13}C(^{6}Li,α)^{15}N and ^{13}C(α,d)^{15}N, as has been reported in Refs. [17] and [18], respectively. The results depicted in Fig. 5(a) seem to rule out the $7/2^+$ [14] and $9/2^+$ [13] values suggested in the literature. As shown in Figs. 4 and 5, the $^TT_{20}$ angular distribution of the 13.17 MeV state does not resemble any of the distributions corresponding to the well-known states presented in this work. It was not possible to test the proposed $5/2^-$ assignment for this state because no well-isolated and strongly populated state with this spin-parity value is observed in this reaction.

Conclusion. Transverse frame analyzing powers have been determined for the polarized beam ^{12}C(^{7}Li,α)^{15}N reaction at $E_{\rm lab}(^7{\rm Li}) = 34$ MeV and laboratory angles between 10° and 38.5°. The experimental $^TT_{20}$ angular distributions of the states in ^{15}N with well established J^π : 6.32 ($3/2^-$), 7.16 ($5/2^+$), 7.57 ($7/2^+$), 8.57 ($3/2^+$), 9.155 ($5/2^+$), 10.69 ($9/2^+$), 13.00 ($11/2^-$), and 15.37 MeV ($13/2^+$) have been shown to have magnitudes and shapes, which if described by future reaction calculations might serve as future guides for assigning the spin and parity to the strongly populated 13.17 MeV peak and thus solve long-standing uncertainties for this and other high lying states. Theoretical models for determining the properties of these states need to be pursued if further progress is to be made in bringing together the various nuclear structure models currently used for describing the mass 15 nuclei.

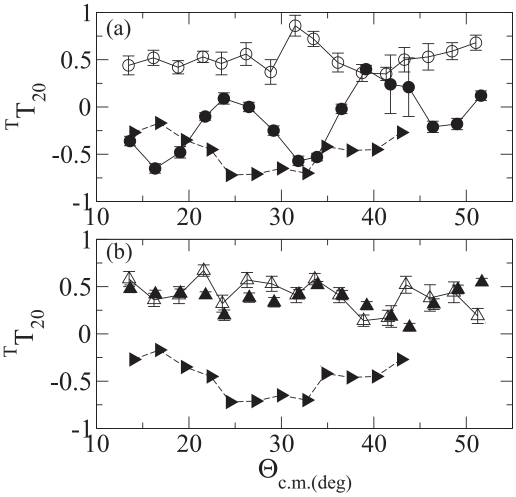

FIG. 4. Experimental $^TT_{20}$ angular distribution obtained for a state in ^{15}N detected at 13.17 MeV (solid triangles right) compared to the angular distributions of the states in (a) at 8.57 MeV, $3/2^+$ (solid circles) and 6.32 MeV, $3/2^-$ (open circles); in (b) at 9.155 MeV, $5/2^+$ (solid triangles up), 7.16 MeV, $5/2^+$ (open triangles up). Error bars are not displayed when their sizes are comparable to or smaller than the corresponding symbol size.

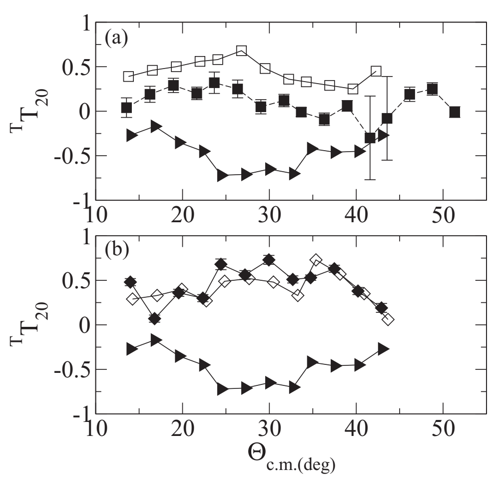

FIG. 5. Experimental $^TT_{20}$ angular distribution obtained for a state in ^{15}N detected at 13.17 MeV (solid triangles right) compared to the angular distributions of the states in (a) at 7.57 MeV, $7/2^+$ (solid squares) and 10.69 MeV, $9/2^+$ (open squares); in (b) at 13.00 MeV, $11/2^-$ (solid diamonds) and 15.37 MeV, $13/2^+$ (open diamonds). Error bars are not displayed when their sizes are comparable to or smaller than the corresponding symbol size.

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