Dominance of Tensor Correlations in High-Momentum Nucleon Pairs Studied by (p,pd) Reaction

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The isospin character of p-n pairs at large relative momentum has been observed for the first time in the ^{16}O ground state. A strong population of the $J, T = 1, 0$ state and a very weak population of the $J, T = 0, 1$ state were observed in the neutron pickup domain of ^{16}O(p, pd) at 392 MeV. This strong isospin dependence at large momentum transfer is not reproduced by the distorted-wave impulse approximation calculations with known spectroscopic amplitudes. The results indicate the presence of high-momentum protons and neutrons induced by the tensor interactions in the ground state of ^{16}O.

High-momentum components in atomic nuclei are important for understanding the roles of noncentral nuclear interactions, such as the tensor interactions, beyond the single particle motion characterized by the Fermi momentum. The importance of the tensor interactions, which act mainly between a proton and a neutron in a nucleus, have been recognized from the binding energies of light particles such as the deuteron and alpha particle, and the presence of large D-wave mixing in the deuteron [1], although changes in single-particle orbitals in heavier nuclei have been attributed to the tensor interactions [2]. Therefore, it is extremely important to study the effect of tensor interactions on nuclear structure on a more direct basis such as their induction. Recent theoretical developments, particularly in *ab initio*–type calculations, enable treatment of high-momentum components directly including tensor interactions. An important feature in theoretical calculations [3,4] is a strong spin-isospin character of a pair of nucleons at large relative momentum in light nuclei.

Extensive experimental studies via proton- and electron-induced reactions have been made at large momentum transfer [5–11]. These measurements show a dominance of p-n over p-p pairs at large relative momenta, which

indicates the existence of short-range tensor correlations. Tensor correlations at large relative momenta could be extracted clearly by a spin-isospin correlated pair. Hence, identifying the spin isospin of a pair is a key for distinguishing tensor and central interactions. The difference in cross sections between different spin-isospin states, denoted $S, T = 0, 1$ and $S, T = 1, 0$ in p-n pairs, provides unique information on tensor correlations. The $S, T = 1, 0$ channel exhibits the strongest effect due to the tensor interaction, which may play a dominant role at higher momentum, especially around 2 fm^{-1}. In contrast, the $S, T = 0, 1$ channel has a negligible contribution from tensor interactions, with the main contribution coming from the central forces.

Recently, the (p, d) reaction at intermediate energies has been found to exhibit an effect of tensor interactions from the energy dependence of the cross sections populating specific excited states in ^{15}O [12]. An unexpected relative enhancement of the neutron pickup cross section feeding a positive parity state at large momentum transfers was detected, implying possible sensitivity of the (p, d) reaction to high-momentum components with tensor interactions in nuclei. A coincidence measurement (p, nd) of
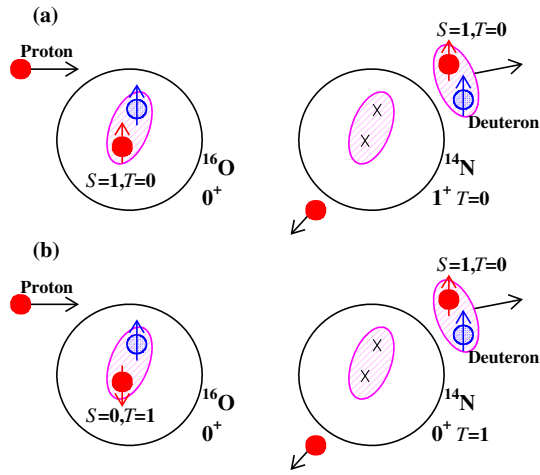
FIG. 1. Schematic view of neutron pickup reaction with coincidence with a proton assuming (a) a $S, T = 1, 0$ correlated pair and (b) a $S, T = 0, 1$ correlated pair at the initial states in the (p, pd) reaction.

a nucleon N (p or n) associated with a deuteron emitted at a small angle has strong sensitivity to correlated pairs of nucleons whose relative momentum is large. In the (p, Nd) reaction, we can distinguish the spin isospin of the nucleon pairs p-n, and n-n by measuring the specific final state of the residue with good energy resolution. Figure 1 shows a schematic view of the expected processes in the (p, pd) reaction. The pickup mechanism of a neutron dominates when a scattered deuteron is observed at small angles. If a reaction occurs with an $S, T = 1, 0$ pair, as shown in Fig. 1(a), both nucleons are removed and thus the final state of the residual should have $T = 0$. If instead the p-n pair has $S, T = 0, 1$, the final state should be $T = 1$, as shown in Fig. 1(b).

(p, pd) reactions with forward deuteron detection have been reported for ⁶Li and ¹²C with 670-MeV incident protons [13,14]. However, the energy resolutions were insufficient to resolve the final states of the residual nuclei. Several studies on ¹²C and ¹⁶O with low-energy protons have been reported [15–17]. Although the studies had sufficient resolution to resolve the individual states, the limited statistics and low incident energy for the quasifree scattering makes it difficult to discuss the spin-isospin dependence in the (p, pd) reactions at large momentum transfer.

In this Letter, experimental results are presented for high-momentum components observed in the (p, pd) reaction at high energy and at small deuteron scattering angle. The spin-isospin of the final states have been identified with high statistics and moderate energy resolution. The dominance of the $S, T = 1, 0$ channel in the cross section is observed for the first time in low-energy excited states of nuclei. Another channel in (p, nd) was measured at the same time but the results will be described elsewhere.

The experiment was performed at the West-South (WS) course of the Research Center for Nuclear Physics (RCNP)

cyclotron facility using the newly constructed GRAF (Grand-RAiden Forward mode) beam line [18]. Protons were accelerated to 392 MeV by the ring cyclotron and achromatically transported to the target in a scattering chamber. The beam spot was less than 1 mm in diameter. We used a windowless and self-supporting ice-sheet target [19] of thickness 56.2(4) mg/cm². Scattered deuterons were momentum analyzed by the high-resolution spectrometer Grand Raiden [20] equipped with two drift chambers and a pair of plastic scintillators on the focal plane. A typical intensity of incident beam was around a 20 nA. An excitation energy resolution of 260 keV full width at half maximum (FWHM) in the (p, d) reaction was achieved, in which the limiting factors were stochastic energy loss in the target and the energy spread of the incident beam. The energy of the deuterons was calibrated over the whole acceptance range of the spectrometer using several transitions to discrete states in ¹⁵O. The coincidence detector array for protons consists of two 3-mm-thick (ΔE) plastic scintillators and four horizontally segmented 60-mm-thick (E) and 240×60-mm² plastic scintillator blocks. The array covered a wide angular range corresponding to 240 and 90 mrad on the horizontal and vertical axes, respectively. The array was placed outside the scattering chamber through a thin window at backward angles to cover the zero recoil momenta of ¹⁴N in the ¹⁶O(p, pd)¹⁴N reaction. The excitation energies were determined from the momentum vectors of the detected deuterons and protons, where a coplanar geometry between deuterons and protons was assumed. A typical excitation energy spectrum of ¹⁴N is presented in Fig. 2. The achieved energy resolution in the (p, pd) reaction, about 1.6 MeV

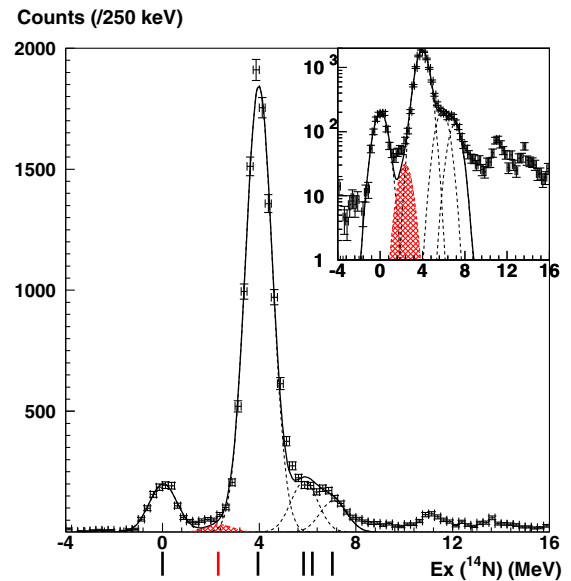FIG. 2. The excitation energy spectrum of ¹⁶O(p, pd) for $\theta_d = 8.6°/\theta_p = 138.4°$ with the total and individual fitting results shown by the solid and dashed lines, respectively.

FWHM was dominated by the energy resolution of scintillators for protons.

The (p, d) reaction at small angles is dominated by the pickup of high-momentum neutrons of correlated p-n pairs. The correlated protons are emitted with a high momentum at a backward angle, just like protons emitted in a backward angle in $p + d$ elastic scattering. The importance of the pickup process increases with increasing scattering angle which is represented by the rise of the cross section [21–23]. The 2.31-MeV state in ^{14}N is $J, T = 0, 1$ and the 3.95-MeV state is $J, T = 1, 0$, and thus they are suitable for the present study. It should be noted that $J^\pi = 1^+$ in the residue allows both $L = 0$ and $L = 2$ transitions, and the dominant transitions to the ground state and the second excited state at 3.95 MeV are considered to be $L = 2$ and $L = 0$, respectively, based on a theoretical study by Cohen and Kurath [24]. Thus, the ground state 1^+ with $L = 2$ does not satisfy the criteria used for the later analysis. Therefore, we focus only on the first and second excited states in this Letter.

Both states that can be described by a transferred angular momentum $L = 0$ in the ^{16}O(p, pd) reaction were observed with similar amplitudes in experiments with 75-MeV protons [16]. In the present experiment the yield of the first excited state of 2.31 MeV is much lower than that of the 3.95-MeV state. The solid curves in Fig. 2 represent the spectra fittings assuming Gaussian line shapes with the same width. Here $E_x = 0.00, 2.31, 3.95, 5.83, 6.20,$ and 7.03 MeV below the proton separation energy 7.30 MeV in ^{14}N, indicated by the vertical lines at the bottom of Fig. 2, were assumed. The peak at 2.31 MeV is shown by the red hatched area, the contribution from the other states are shown by the dashed lines. The fitted curve including all the states is shown by the solid curve. The observed reduction of the $S, T = 0, 1$ state at 2.31 MeV is qualitatively consistent with the expected momentum dependence between $S, T = 1, 0$ and $S, T = 0, 1$, when the tensor interactions play an important role. We study this ratio in a more quantitative way by the distorted-wave impulse approximations (DWIA) in the following.

The experimental results were interpreted in terms of factorized amplitude DWIA using the code THREEDEE [25]. The three-body triple differential cross section for ^{16}O(p, pd) is given as

$$\frac{d^3\sigma}{d\Omega_p d\Omega_d dT_d} = S_d F_k \frac{d\sigma}{d\Omega}_{p+d} \sum_{\Lambda L} |T_L^\Lambda|^2 \quad (1)$$

for the particular case of $L = 0$ [16,25], where F_k is a kinematic factor, and S_d is the spectroscopic factor for deuteron in ^{16}O. $\sum_{\Lambda L} |T_L^\Lambda|^2$ is the transition matrix, which is given by the overlapped function. The matrix contains the information of each quantum number of the deuteron, the relative angular momentum L and its projection Λ. The off-shell cross section of $p + d$ was approximated by the

on-shell cross section with three conventional prescriptions called the initial energy, final energy, and momentum transfer-final energy prescriptions in the DWIA. We prepared the phenomenological optical potential of $p + d$ elastic scattering by introducing an l-dependent Majorana exchange term [26,27], and fitting the data from the measurement with 392-MeV protons [22]. Distorted waves of protons were calculated using the Schrödinger equivalent reduction of the global potential from the Dirac phenomenology with the Darwin term [28]. The optical potential deduced from the deuteron elastic scattering of ^{16}O at 400 MeV [29] was used for the distorted waves of deuterons. The deuteron bound-state wave function generated using the Woods–Saxon potential had radius and diffuseness parameters of $r_0 = 1.25$ and $a_0 = 0.65$ fm, respectively. The well depth was adjusted to reproduce the separation energy. The Perey factor for a nonlocality correction [30] was applied at 0.54 fm for the deuteron scattering wave function and the bound state wave function.

Figure 3 shows the triple differential cross sections of ^{16}O$(p, pd)^{14}$N as a function of deuteron energy for the region between 2 and 6 MeV in excitation energy. Panels (a)–(d) show the cross sections obtained from four blocks of proton detectors covering different scattering angles, as indicated in the figure. The curves
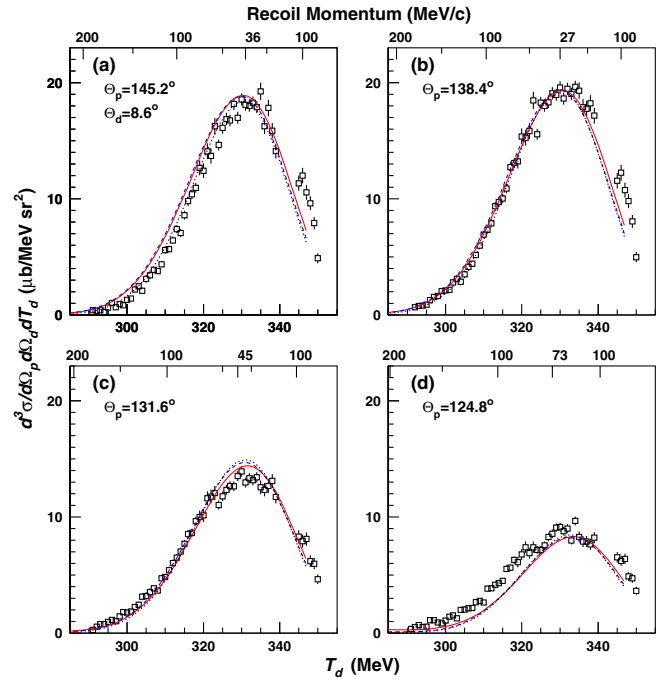

FIG. 3. Energy sharing spectra of deuterons around 4 MeV in the ^{16}O(p, pd) reaction at four different proton angles (a),(b), (c), and (d). The upper abscissas provide scales for the averaged recoil momentum. The curves represent the DWIA calculations with the three different prescriptions, final energy (red-solid), initial energy (blue-dashed), and momentum-final energy (black-dotted).

in Figs. 3(a)–3(d) are the results of the DWIA calculations for the 3.95-MeV state with $L = 0$ transition. The upper abscissas in the figure provide scales for the averaged recoil momentum with angular acceptances of the detectors. One of the detectors whose data were shown in panel (b) covered the zero recoil part of the kinematics. The three different prescriptions, as described above, are presented by the three curves. The spectroscopic amplitude was adjusted by the one block at the peak nearest to the zero-recoil condition to reproduce the cross section They give almost the same results for all cases except for the absolute scales of the cross sections. As seen in Fig. 3, the DWIA calculations describe the cross section very well, which confirms that the transition is dominantly $L = 0$, and the mixing of $L = 2$ is negligibly small, consistent with previous findings. This agreement also indicates that the background from a sequential decay with the two-body (p, d) transfer reaction was negligibly small in the present kinematical domain.

The state at 2.31 MeV in $T = 1$ was also expected to be of $L = 0$ transition. We therefore apply the quasifree $^{16}O(p, pd)^{14}N$ reaction calculations with a similar procedure but replacing the off-shell cross sections from the $p + d$ elastic scattering with the more appropriate cross sections in the present DWIA. In this case a correlated p-n pair (denoted as d^*) has $S, T = 0, 1$, and the cross section of $d^*(p, p)d$ was deduced from the detailed balance of the inverse reaction for the break-up $d(p, pn)p$ reaction using the relevant kinematics. Unfortunately, no experimental data for the break-up reaction are available at energies higher than 26 MeV [31]. Therefore, we deduced the cross section of a related reaction with the Faddeev calculation [32] using the CD-Bonn interaction [33] at 392 MeV. We followed the treatment in Refs. [34,35] and integrated the cross section with respect to the relative energy of p-n, which is a singlet state of deuteron d^*, up to 1 MeV. Similar calculations were performed for data at 75 MeV [16] as references. The differences in the energy dependence for the angular distribution of the elastic scattering $p + d$ and the $d^*(p, p)d$ reaction introduce an energy dependence for the ratio between the two states. The ratio of the cross sections for the two reactions from around 37.5° at 75 MeV to that at 392 MeV was estimated to be roughly a factor of 3 in the present analysis.

The triangular symbols in Fig. 4 show the ratio $(R_{2.31/3.95})$ of the cross sections between the 2.31 and 3.95-MeV states determined by the present experiment. The three data points are for different spectrometer settings and cover different proton momenta (P_p), where zero recoil momentum is indicated by the arrow. The ratio $R_{2.31/3.95}$ from the previous data at 75 MeV is denoted by the cross symbol. The results of DWIA calculations are shown by the blue hatched area. The ratio of the spectroscopic amplitudes between 2.31 and 3.95 MeV was adjusted to reproduce the observed cross sections at 75 MeV. The broadening of the blue hatched area is due to the
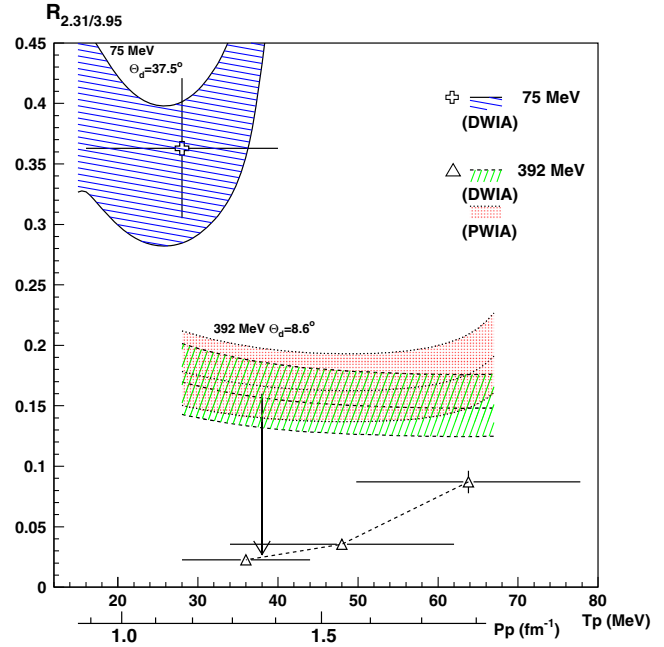

FIG. 4.   Ratio of cross section for 2.31 to 3.95 MeV in the sharing energy spectra of protons in the $^{16}O(p, pd)$ reaction with different magnetic rigidity settings of the spectrometer. The vertical and horizontal bars of the data show the statistical error and detector coverage for each setting, respectively. See the text for details.

uncertainties of the data at 75 MeV [16]. The results of the DWIA calculations at 392 MeV, applying the determined spectroscopic amplitude ratio are shown by the green hatched area. To see the sensitivity of the distorted waves in the calculation, the results of the plane-wave impulse approximation (PWIA) are also shown in the figure by the red dotted area. The ratio is not significantly different from that for DWIA, showing that the effect of distortion is small for the ratio $R_{2.31/3.95}$. The energies and angles of the emitted proton and deuteron are almost the same between the reactions to the first and second excited states, and therefore, the distortions essentially cancel out in the calculation of $R_{2.31/3.95}$. Because of the insensitivity to the distortion of the wave, we expect that the ratio $R_{2.31/3.95}$ closely reflects the ratio of the spectroscopic amplitude between the $S, T = 0, 1$ and $S, T = 1, 0$ states. The results of DWIA calculations indicate that the ratio $R_{2.31/3.95}$ is much smaller than that at 75 MeV due to the effect of tensor interactions. In other words, the apparent spectroscopic amplitude of $S, T = 0, 1$ is much smaller than that of $S, T = 1, 0$. It should be noted that the DWIA calculations include all nucleon–nucleon two-body interactions including tensor interactions. The present experimental values show the expected reduction of the ratio $R_{2.31/3.95}$ qualitatively but the ratio is as much as 5 times smaller than the DWIA prediction. The difference may also reflect a change in the tensor correlations in heavier nuclei. To understand this discrepancy, additional data on the $S, T = 1, 0$ and

$S, T = 0, 1$ amplitudes as a function of the transferred momentum and nuclear mass are necessary. Further theoretical studies that include more realistic structure information and reaction treatments are also anticipated.

In summary, the cross sections of the $^{16}\text{O}(p, pd)^{14}\text{N}$ reactions were measured for 392-MeV incident protons with the coincidences between protons at backward angles and deuterons at forward angles, where the neutron pickup reaction mechanism is dominant. The first and second excited states in the residual ^{14}N with $L = 0$ transitions were compared with the DWIA calculations. A strong relative reduction of the first excited state cross section compared to that of the second excited state was observed, which is expected to be due to the tensor correlations. The DWIA calculations using the two-body interactions including tensor interactions qualitatively explained the reduction of the $S, T = 0, 1$ to $S, T = 1, 0$ ratio of the cross sections. However, The ratio of the experimental cross sections were overestimated by the calculations by as much as a factor of 5. Further experimental and theoretical studies are required to clarify the difference.

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