Proton induced deuteron knockout reaction as a probe of an isoscalar proton-neutron pair in nuclei

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Background: The isoscalar pn pair is expected to emerge in nuclei having the similar proton and neutron numbers but there is no clear experimental evidence for it.

Purpose: We aim to clarify the correspondence between the pn pairing strength in many-body calculation and the triple differential cross section (TDX) of proton-induced deuteron knockout (p, pd) reaction on 16O.

Methods: The radial wave function of the isoscalar pn pair with respect to the center of 16O is calculated with the energy density functional (EDF) approach and is implemented in the distorted wave impulse approximation (DWIA) framework. The pn pairing strength V0 in the EDF calculation is varied and the corresponding change in the TDX is investigated.

Results: A clear V0 dependence of the TDX is found for the 16O(p, pd)14N(1+) at 101.3 MeV. The nuclear distortion is found to make the V0 dependence stronger.

Conclusions: Because of the clear V0-TDX correspondence, the (p, pd) reaction will be a promising probe for the isoscalar pn pair in nuclei. For quantitative discussion, further modification of the description of the reaction process will be necessary.

I. INTRODUCTION

The nucleon-nucleon (NN) correlation is one of the most important properties to understand atomic nuclei. The pairing correlation of pp and nn, for which the total isospin T = 1 and total spin S = 0, has extensively been studied for many years [1, 2]. Another type of NN correlation is a spatially correlated two neutrons, i.e., dineutron, expected to emerge in a dilute system [3]. After the invention of radioactive beams, properties of dineutron and how to probe it have been discussed theoretically and experimentally [4-8, 21]. Development of the physics of unstable nuclei also provided a new opportunity to investigate N ∼ Z nuclei in medium- and heavy-mass regions; N (Z) is the neutron (proton) number. In such nuclei, because the shell structure around the Fermi levels of p and n are similar to each other, the pn correlation of either or both T = 0 and T = 1 types is expected to play an important role [9]. Recently, it was suggested with an energy density functional (EDF) approach that a T = 0 pn pairing vibrational mode possibly emerges in N = Z nuclei [10-11]. Among conceivable probes for the T = 0 pairing inside N ∼ Z nuclei, we consider the deuteron knockout reaction for the transition.

In this study, we discuss the proton-induced deuteron knockout reaction for 16O, 16O(p, pd)14N*; 14N is in the 1+ state in the final channel. This reaction with 101.3 MeV proton was carried out at Maryland [12] and a triple differential cross section (TDX) of the same order of magnitude as that of 16O(p, 2p)15N.g.s. at 101.3 MeV was obtained. This indicates that quite a large amount of pn pair that is detected as deuteron may exist in 16O. In Ref. [12], a distorted wave impulse approximation (DWIA) calculation was performed with assuming a single-particle model for the bound deuteron and a deuteron spectroscopic factor was deduced. However, a more microscopic treatment of the pn pair inside 16O will be important to clarify its correspondence to the TDX of the 16O(p, pd)14N* reaction.

To achieve this, we adopt the EDF for describing the structure of 16O, i.e., the radial wave function of the pn pair regarding the center of 16O. The DWIA calculation is then performed to evaluate the TDX. Our main purpose is to clarify how the TDX behaves when the pn pairing strength V0 is changed in the EDF calculation. The distortion effect on the TDX-V0 correspondence is discussed as well as the spatial region of 16O that is relevant to the (p, pd) process.

The construction of this paper is as follows. In Sec. II we present the formalism of DWIA and EDF for the calculation of the TDX of 16O(p, pd)14N*. We show numerical results of the structural calculation and the TDX in Sec. III. A summary and perspective are given in Sec. IV.

II. FORMALISM

A. DWIA framework

We consider the 16O(p, pd)14N* reaction in normal kinematics; in the final channel 14N is assumed to be in the second 1+ excited state. The incoming proton is labeled as particle 0, and the outgoing proton and deuteron are labeled as particles 1 and 2, respectively. We denote the target (residual) nucleus 16O (14N*) by A (B) and its mass number by A (B). In what follows, hK, Ei, and Ti represent the momentum, the total energy, and the kinetic energy of particle i (= 0, 1, 2, A, or B), respectively. The solid angle of the outgoing particle j (= 1 or 2) is denoted by Ωj. The quantities with
and without the superscript \( L \) represent that we evaluate these in the laboratory (L) and \( p-A \) center-of-mass (c.m.) frames, respectively.

![Diagram](image)

**FIG. 1:** Coordinates of the \( A(p, pd)B \) reaction system.

In the distorted wave impulse approximation (DWIA) framework, the transition amplitude of the \( A(p, pd)B \) reaction is given by

\[
T = \left\langle \chi_{1,\kappa_1}(R_1)\phi_d(r)\chi_{2,\kappa_2}(R_2) \right| t_{pd}(s) \left| \chi_{0,\kappa_0}(R_0)\phi_d(r)\varphi_{pn}(R_2) \right\rangle, \tag{1}
\]

where \( \chi_{i,\kappa} \) with \( i = 0, 1, \) and \( 2 \) are the distorted waves of the \( p-A, p-B, \) and \( d-B \) systems, respectively. The coordinate between the incoming (outgoing) proton and \( A (B) \) is denoted by \( R_0 (R_1) \) and that between the outgoing deuteron and \( B \) by \( R_2. \) As seen from Fig. 1, \( R_2 \) also means the coordinate of the c.m. of the isoscalar \( (T = 0) \) spin-triplet \((S = 1)\) \( pn \) pair relative to \( B \) inside \( A. \) The scattering waves with the superscripts \((+)(-)\) satisfy the outgoing and incoming boundary conditions, respectively. \( \phi_d \) is the \( pn \) relative wave function in the ground state of deuteron and \( t_{pd} \) is the effective interaction between \( p \) and \( d. \) The coordinate relevant to \( \phi_d \) and \( t_{pd} \) are denoted by \( r \) and \( s, \) respectively. \( \varphi_{pn} \) defined by

\[
\varphi_{pn}(R_2) = \langle \Psi_B | \Psi_A \rangle \xi_B \tag{2}
\]

is the wave function between the c.m. of the \( pn \) pair and \( B \) inside \( A; \) \( \Psi_C \) \((C = A \) or \( B)) \) is the many-body wave function of \( C. \) In Eq. (3), it is understood that the integration is taken over all the intrinsic coordinates \( \xi_B \) of \( B. \) A detailed description of \( \varphi_{pn} \) is given in Sec. 11B.

We apply the asymptotic momentum approximation \([13]\) to the distorted waves in Eq. (1) and obtain

\[
T \approx \tilde{t}_{pd}(\kappa', \kappa) \int dR \ F(R) \varphi_{pn}(R). \tag{3}
\]

Here, \( \kappa \) \((\kappa') \) indicates the relative momentum between \( p \) and \( d \) in the initial (final) state, and we define \( \tilde{t}_{pd} \) and \( F \) as follows:

\[
\tilde{t}_{pd}(\kappa', \kappa) = \left\langle \phi_d(r) e^{i\kappa' \cdot s} \right| t_{pd}(s) \left| \phi_d(r) e^{i\kappa \cdot s} \right\rangle, \tag{4}
\]

\[
F(R) \equiv \chi_{1,\kappa_1}(R) \chi_{2,\kappa_2}(R) \chi_{0,\kappa_0}(R) e^{-2iK_0 \cdot R/A}. \tag{5}
\]

Using the final-state on-the-energy-shell prescription, i.e.,

\[
\kappa \approx \kappa' \kappa, \tag{6}
\]

in the evaluation of \( \tilde{t}_{pd}, \) we find

\[
\frac{\mu^2_{pd}}{(2\pi\hbar^2)^2} \frac{1}{6} \left| \tilde{t}_{pd}(\kappa', \kappa) \right|^2 \approx \frac{d\sigma_{pd}}{d\Omega_{pd}}(\theta_{pd}, E_{pd}), \tag{7}
\]

where \( d\sigma_{pd}/d\Omega_{pd} \) is the \( p-d \) elastic differential cross section in free space with \( \theta_{pd} \) and \( E_{pd} \) being the c.m. scattering angle and the scattering energy, respectively. \( \mu_{pd} \) is the reduced mass of the \( p-d \) system.

The triple differential cross section (TDX) for the \( A(p, pd)B \) reaction is then given by

\[
\frac{d^3\sigma}{dE_1^2d\Omega_1^2d\Omega_2} = F_{kin}C_0 \frac{d\sigma_{pd}}{d\Omega_{pd}}(\theta_{pd}, E_{pd}) \left| \tilde{T} \right|^2, \tag{8}
\]

where

\[
F_{kin} = J_L \frac{K_1 K_2 E_1 E_2}{(hc)^2} \left[ 1 + \frac{E_2}{E_B} + \frac{E_2}{E_B} \frac{K_1 \cdot K_2}{K_0} \right]^{-1}, \tag{9}
\]

\[
C_0 = \frac{E_0}{(hc)^2} \frac{\hbar^4}{K_0^2(2\pi \hbar\mu_{pd})^3}, \tag{10}
\]

\[
\tilde{T} \equiv \int dR \ F(R) \varphi_{pn}(R). \tag{11}
\]

In Eq. (5), \( J_L \) is the Jacobian from the \( p-A \) c.m. frame to the L frame.

Once all the distorting potentials are switched off, i.e., the plane wave impulse approximation (PWIA) is adopted, \( \tilde{T} \) turns out to be the Fourier transform of \( \varphi_{pn}(R):\)

\[
\tilde{T} \approx \int dR \ e^{-iK_{pn} \cdot R} \varphi_{pn}(R), \tag{12}
\]

where \( K_{pn} \) is given by

\[
K_{pn} = K_1 + K_2 - \left(1 - \frac{2}{A}\right)K_0. \tag{13}
\]

By assuming the residual nucleus \( B \) is a spectator, one can interpret \( K_{pn} \) as the momentum of the c.m. of the \( pn \) pair.

In the recoilless (RL) condition, which is characterized by \( K_{pn} = 0, \) one finds

\[
\tilde{T} \approx \int dR \varphi_{pn}(R) \equiv A_{pn}. \tag{14}
\]

This clearly shows that the TDX in the RL condition reflects the total amplitude \( A_{pn} \) of the \( pn \) pair.
B. Microscopic calculation of the pn pair wave function

We apply the nuclear energy-density functional (EDF) method to describing microscopically the wave function of the \( pn \) pair. In a framework of the nuclear EDF, the \( pn \)-pair-removed excited states in \(^{14}\text{N} \) are described in the proton-neutron hole-hole Random-Phase Approximation (pn-hhRPA) \(^{13}\) considering the ground-state of \(^{16}\text{O} \) as an RPA vacuum; \( |\Psi_{\text{B}}\rangle = \Gamma^\dagger |\Psi_{\text{A}}\rangle \), where \( \Gamma^\dagger \) represents the RPA phonon operator:

\[
\hat{\Gamma}^\dagger = \sum_{i,i'} X_{i,i'} \hat{b}_{i,n,i}^\dagger \hat{b}_{i,n,i'}^\dagger - \sum_{m,m'} Y_{m,m'} \hat{b}_{m,m'}^\dagger \hat{b}_{m,m'}^\dagger , \tag{15}
\]

The \( S = 1 \) \( pn \)-pair-removal transition density that we need for the transition amplitude is given as

\[
\delta \tilde{\rho}_\mu (r_n, r_p) = \frac{1}{2} \sum_{\sigma \sigma'} (-2\sigma') \langle \sigma'|\sigma_\mu|\sigma \rangle \langle \Psi_{\text{B}}|\hat{\psi}_n(r_n - \sigma')\hat{\psi}_p(r_p\sigma) - \hat{\psi}_p(r_p\sigma')\hat{\psi}_n(r_n\sigma)|\Psi_{\text{A}}\rangle , \tag{16}
\]

where \( \sigma = (\sigma_1, \sigma_0, \sigma_{+1}) \) denotes the spherical components of the Pauli spin matrices, and \( \hat{\psi}_\sigma (r \sigma) \) the nucleon annihilation operator at the position \( r \) with the spin direction \( \sigma = \pm 1/2 \) expanded in the single-particle basis with \( q = n \) or \( p \). Since the transition density is spherical in spin space, we have only to consider one of the components for \( \mu \). Here, we take the \( \mu = 0 \) component of the wave function.

From Eqs. \(^{14},^{2},\) and \(^{16}\), we can regard the transition density \( \delta \tilde{\rho}_0 \) as

\[
\delta \tilde{\rho}_0 (\hat{R}, r) \approx \varphi_{pn}(\hat{R})\phi_d(r) , \tag{17}
\]

where

\[
\varphi_{pn}(\hat{R}) = \frac{\delta \tilde{\rho}_0 (\hat{R}, 0)}{\phi_d(0)} = \tilde{\varphi}_{pn}(\hat{R})Y_{00}(\Omega_{\hat{R}}). \tag{18}
\]

Thus, in evaluating \( \varphi_{pn} \), we consider the \( pn \) pair as \( S \)-wave and a point particle, namely \( r = \hat{R} \). The use of Eqs. \(^{17}\) and \(^{18}\) means that the component of the \(^{16}\text{O} \) wave function that contains a deuteron is selected out. This treatment is consistent with the DWIA framework described in Sec. II A.

With this, the \( pn \)-pair-removal transition strength is given by

\[
3 \left[ 4\pi \int_0^\infty dR R^2 \varphi_{pn}(R)\phi_d(0) \right]^2 , \tag{19}
\]

where the factor three comes from the sum of \( \mu = -1, 0, \) and \( 1 \) components.

III. RESULTS AND DISCUSSION

A. Numerical inputs

To obtain the single-particle basis used in the pn-hhRPA calculation, the SHF equation is solved in cylindrical coor-

dinates \( r = (r, z, \phi) \) with a mesh size of \( \Delta r = \Delta z = 0.6 \text{ fm} \) and with a box boundary condition at \( r_{\text{max}} = z_{\text{max}} = (14.7, 14.4) \text{ fm} \). The axial and reflection symmetries are assumed in the ground state, and the ground-state of \(^{16}\text{O} \) is calculated to be spherical. More details of the calculation scheme are given in Ref. \(^{14}\). The SGII interaction \(^{15}\) is used for the particle-hole (ph) channel, and the density-dependent contact interaction defined by

\[
\nu_{\text{pp}}(\sigma \tau, \sigma' \tau') = V_0 \frac{1 + P_\sigma}{2} \frac{1 - \rho(r)}{\rho_0} \delta(r - r'), \tag{20}
\]

is employed for the particle-particle (pp) channel. Here, \( \rho_0 = 0.16 \text{ fm}^{-3} \) and \( \rho(r) = \rho_p(r) + \rho_n(r) \). We adopt three values \(-100, -490, \) and \(-600 \text{ MeV} \text{ fm}^3 \) for the pairing strength \( V_0 \).

For the distorting potentials of proton, the EDAD1 parameter set of the Dirac phenomenology \(^{16},^{17}\) is used, whereas we employ the global optical potential by An and Cai \(^{18}\) for deuteron. We construct the Coulomb potential in each distorting potential by assuming a uniformly charged sphere with the radii of \( r_0C^{1/3} \) (\( C = A \) or \( B \)) with \( r_0 \) being \( 1.41 \text{ fm} \). Nonlocality corrections to the distorted waves of deuteron and proton are made by multiplying the wave functions by the Perey factor \(^{19}\) with the 0.54 fm of the range of nonlocality and the Darwin factor \(^{16},^{20}\), respectively. For the \( p-d \) elastic cross section in Eq. \(^{18}\), we take the experimental data from Refs. \(^{23},^{24}\) with the Lagrange interpolation with respect to the scattering angle and energy. The kinematics of all the particles are treated relativistically. The Möller factor \(^{21},^{22}\) is taken into account to describe the transformation of the \( p-d \) transition matrix from the \( p-d \) c.m. frame to the \( p-A \) c.m. frame.
B. Structure of the low-lying $1^+$ states in $^{14}$N

![Graph showing radial component of $\varphi_{pn}(R)$](image)

**FIG. 3**: Radial component of $\varphi_{pn}(R)$. The solid, dashed, and dotted-dashed lines correspond to the cases of $V_0 = -100$, $-490$, and $-600$ MeV fm$^3$, respectively. Note that each line is multiplied by $R^2$.

We briefly mention the structure of the calculated low-lying $1^+$ states in $^{14}$N in the present framework before discussing the TDX. Figure 2 shows the $S = 1$ $pn$-pair-removal transition-strength distributions. The excitation energy is defined with respect to the excitation energy of the simplest configuration of $(p_{1/2})^{-2}$ coupled to $T = 0, S = 1$ in $^{16}$O. The lowest state and the second lowest state for each pairing strength correspond to the ground $1^+$ state and the $1^+_2$ state that we are interested in, respectively. They are constructed by mainly the $(\nu p_{1/2})^{-1}(\pi p_{1/2})^{-1}$ configuration, and the superposition of the $(\nu p_{3/2})^{-1}(\pi p_{3/2})^{-1}$ and $(\nu p_{1/2})^{-1}(\pi p_{1/2})^{-1}$ configurations, respectively. With an increase of the pairing strength, the energies become lower and the strengths get enhanced for both states. For the case of $V_0 = -600$ MeV fm$^3$, the $(p_{3/2})^{-2}$ configuration is not negligible for enhancing the transition strength to the $1^+_2$ state. Therefore, the collectivity of the $1^+_2$ state becomes stronger with an increased pairing strength.

The question arisen here is how much of the pairing strength we should employ. We are going to look at the energy difference of the $1^+$ states; $\Delta E = E_{1^+_2} - E_{1^+_1}$. For the case of $V_0 = -100$, $-490$, and $-600$ MeV fm$^3$, the calculated $\Delta E$ is $5.41$, $4.12$, and $3.48$ MeV, respectively, while $\Delta E = 3.95$ MeV experimentally. We can thus say that the pairing strengths $V_0 = -490$ and $-600$ MeV fm$^3$ are a reasonable choice in the present study.

Next, we check the behavior of $\varphi_{pn}(R)$. The radial components of $\varphi_{pn}(R)$ with $V_0 = -100$ MeV fm$^3$ (solid line), $-490$ MeV fm$^3$ (dashed line), and $-600$ MeV fm$^3$ (dotted-dashed line), respectively, are shown in Fig. 3. It should be noted that each line is multiplied by $R^2$. One can clearly find that the stronger the pair interaction is, the larger the amplitude of $R^2 \varphi_{pn}(R)$ is, i.e., the stronger collectivity the $pn$ pair has. Note that in the $V_0 \to 0$ limit, the independent-particle picture of $^{16}$O is realized. Then, the peak of the $R^2 \varphi_{pn}(R)$ will almost disappear.

C. Triple differential cross section for $^{16}$O$(p,pd)^{14}$N$^*$ reaction at 101.3 MeV

![Graph showing triple differential cross section](image)

**FIG. 4**: Triple differential cross section (TDX) for the $^{16}$O$(p,pd)^{14}$N$^*$ reaction at 101.3 MeV. The solid, dashed, and dotted-dashed lines correspond to the results with $\varphi_{pn}$ of $V_0 = -100$, $-490$, and $-600$ MeV fm$^3$, respectively.

In Fig. 4 we show the TDX for the $^{16}$O$(p,pd)^{14}$N$^*$ reaction at 101.3 MeV as a function of $T_1^*$. The emission angle of particle 1 is fixed at $(\theta_1^*, \phi_1^*) = (40.1^\circ, 0^\circ)$ and that for particle 2...
at \((\theta_1^2, \phi_2^2) = (40.0^\circ, 180^\circ)\); we follow the Madison convention. At \(T_1^2 \sim 52\) MeV, the RL condition is almost satisfied. This kinematical condition corresponds to \(E_{pd} \sim 56\) MeV and \(\theta_{pd} \sim 68^\circ\) for the \(p-d\) scattering. The results using \(\varphi_{\alpha pn}\) calculated with \(V_0 = -100, -490\), and \(-600\) MeV fm\(^3\) are shown by the solid, dashed, and dot-dashed lines, respectively. One sees a clear correspondence between \(V_0\) and the TDX. In other words, the height of the TDX reflects the collectivity of the \(pn\) pair that forms deuteron in \(^{16}\text{O}\). Unfortunately, however, it is difficult to make a quantitative comparison of the current results with experimental data. This is mainly because of the approximate treatment of \(\varphi_{pn}\) in Eq. (18). Besides, there may exist other reaction mechanisms that are not considered in this study; we come to this point in Sec. IV. Nevertheless, the \(V_0\) dependence of the TDX can safely be investigated, which is our primary objective of this study.

The solid lines denote the real part of the TMD, which can be interpreted as a radial distribution of the TDX as discussed in Refs. [38, 39]. To make this interpretation plausible, however, the real part of the TMD should not have a large negative value. Another condition is that the imaginary part of the TMD is nearly equal to 0 for all \(R\). As one sees from Fig. 6, neither of the two conditions is satisfied well. This indicates that the interference between amplitudes at different \(R\) is strong. Furthermore, the TMD is finite even at small \(R\), which means the nuclear absorption is not enough to mask the interior region in the evaluation of the transition matrix. These features are completely different from for \((p, p\alpha)\) reactions discussed in Refs. [38, 39]. In other words, the distortion effect in the \((p, pd)\) reaction investigated in this study is found to be rather complicated and the mechanism for the increase in the relative TDX height due to the distortion is still unclear.

### IV. SUMMARY AND PERSPECTIVE

We have investigated the \(^{16}\text{O}(p, pd)^{14}\text{N}^*\) reaction at 101.3 MeV to the \(1^+_2\) state of \(^{14}\text{N}\) with the DWIA framework combined with a bound state wave function by EDF. As a remarkable feature of the current approach, both the shape and height of the radial wave function of the \(pn\) pair in \(^{16}\text{O}\) are evaluated microscopically. A clear correspondence between...
the pairing strength \( V_0 \) and the TDX was clarified, indicating that the \((p, p\ell)\) reaction is a promising probe for the \( T = 0 \) \( pn \) pair in \( N \sim Z \) nuclei.

It is found that the distortion effect enhances the \( V_0 \) dependence of the TDX. Because the selection of the probed region is not clear in the \((p, p\ell)\) process, however, the mechanism of the enhancement is not clear at this stage. This is a feature of \((p, p\ell)\) that is quite different from \(\alpha\) knockout process, \((p, p\alpha)\), in which only the nuclear surface is selectively probed.

For a quantitative discussion regarding the experimental data, it will be necessary to take into account the deuteron breakup effect in the final channel. Another important future work will be the modification of the elementary process of the \((p, p\ell)\) reaction. In the current DWIA framework, as in all the preceding DWIA studies, an elastic \(p-d\) scattering is considered as an elementary process. This compels one to assume that a deuteron exists in the target nucleus before the knockout process. This may be insufficient to describe the actual \((p, p\ell)\) process, in which a \(pn\) pair that is different from deuteron can be knocked out by the incoming proton. The pair may form deuteron in the scattering process in the final channel by a coupled-channel effect and then is detected. In such a manner, the \((p(pn, dp)\)) process can be another elementary process for the \((p, p\ell)\) reaction. Implementation of both \(p(d, dp)\) and \(p(pn, dp)\) processes to the coupled-channel DWIA framework will reveal the nature of the \(pn\) pair in a nucleus more clearly, and also will be important for applying DWIA to the study of high-momentum \(pn\) pair using the backward \((p, p\ell)\) scattering \(40\). Studies along these lines are ongoing and will be reported elsewhere.

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