Possible evidence of tensor interactions in $^{16}$O observed via (p,d) reaction

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(Dated: May 1, 2014)
Abstract

We have measured $^{16}$O(p,d) reaction using 198-, 295- and 392-MeV proton beams to search for a direct evidence on the effect of the tensor interactions in light nucleus. Differential cross sections of the one-neutron transfer reactions populating the ground states and several low-lying excited states in $^{15}$O were measured. Comparing the ratios of the cross sections for each excited state to the one for the ground state over a wide range of momentum transfer, we found a marked enhancement for the positive-parity state(s). The observation indicates large components of high-momentum neutrons in the initial ground-state configurations, due possibly to the tensor interactions.

PACS numbers: 21.30.-x, 24.50.+g, 25.40.Hs

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Tensor interactions are some of the most important nuclear interactions acting between two nucleons. The tensor interactions, originate mainly from the pion-exchange interactions, provide the most significant attraction in nuclear interactions. The necessity to include tensor interactions in theoretical calculations to reproduce the quadrupole moment \[1\] as well as the binding energy \[2\] of the deuteron, which is the simplest and only stable two-nucleon composite system, affords decisive evidences on the importance of the tensor interactions. The tensor interactions provide 70 ∼ 80% of the attractive interactions \[3, 4\] in deuteron and induce nucleons with high momenta \[4\] through the D-wave component.

Besides the deuteron, earlier theoretical studies \[5\] had also pointed out the importance of the tensor interactions to the binding of three- and four-nucleon systems, accounting for almost 50% of the nuclear attraction. Several experiments using polarized deuteron beams had since been performed to measure the tensor analyzing powers for stripping reactions \[6\] and deuteron capture reaction \[7\], providing evidences on the existence of the D-state components in the $^3$H and $^{3,4}$He.

For heavier nuclei, recent ab-initio calculations \[8\] on light nuclei also show essential importance of the tensor interactions for binding nuclei up to mass number $A = 12$. The pion exchange interactions, in which the tensor interactions are the dominant components, constitute 70–80% of the whole two-body potentials. In addition, detailed studies on experimental data \[9\] and the subsequent theoretical studies \[10\] have indicated a possible important role of the tensor interactions in changing the magic numbers and the orders of single-particle orbitals in neutron-rich nuclei, although the strength of the tensor interactions in the shell-model space is not large, and is treated only as a perturbation. More recently, theoretical calculations on $^9$–$^{11}$Li that include explicitly the tensor interactions have pointed out \[11\] the importance of the tensor interactions in understanding the structure of those nuclei, and predicted high momentum components in the ground states. The results offered a possible intriguing explanation to the development of the neutron-halo structure through the Pauli blocking effect in $^{11}$Li.

Experiments using the electron \[12, 13\] or proton-induced \[14\] knockout reaction had been performed to probe the tensor correlations in nuclei from $^{12}$C to $^{208}$Pb. However, since it is difficult to isolate the tensor effects unambiguously in these experiments due to the presence of other correlations such as the short-range repulsion, alternative methods that could provide more direct experimental evidences are called for.
In this paper, we report a possible direct observation of the tensor-force effect in the “doubly-closed-shell” $^{16}$O using the one-neutron transfer (p,d) reaction. The tensor interactions mix large orbital angular momentum states, giving rise to high momentum components through D-wave component in the relative coordinate of two nucleons in finite nuclei. In fact, recent theoretical calculations [16–18] have predicted enhanced momentum distributions at around 2 fm$^{-1}$ due to the tensor interactions. In this work, we measured the cross sections of the one-neutron pickup reaction at momentum transfer around 2 fm$^{-1}$ by observing the ground state as well as excited states in $^{15}$O. We found strong relative enhancements of the cross section to the positive-parity excited state(s) (the $\frac{1}{2}^+$ and/or $\frac{5}{2}^+$ states) at high momentum transfer.

In the independent single particle model (shell model), the ground state of $^{16}$O consists of eight protons and eight neutrons filling up the 1s$\frac{1}{2}$, 1p$\frac{3}{2}$ and 1p$\frac{1}{2}$ orbitals. Hence, the positive-parity states in $^{15}$O can be reached through direct neutron-pickup reaction only if the $^{16}$O ground state has an admixture of 1d$\frac{5}{2}$ or 2s$\frac{1}{2}$ state, in the absence of multi-step processes. Such admixture is possible if the tensor interactions play a dominant role, since the tensor interactions induce changes in the total orbital and spin angular momenta by $|\Delta L|=2$ and $|\Delta S|=2$, giving rise to two-particle two-hole (2p2h) configurations which include $(1p_{3/2})^{-2}(1d_{5/2})^2$ and $(1p_{1/2})^{-2}(2s_{1/2})^2$ in the ground state of $^{16}$O [19].

The (p,d) reaction has been applied extensively to study the single particle nature of nuclei. In this reaction, a neutron is picked up from the target nuclei to form a deuteron. The advantage of this reaction lies in the selectivity of the momentum of the picked-up neutron. Under the single-step pickup reaction using a deuteron target, the momentum of the picked-up neutron in the target deuteron is equivalent to the momentum transfer, namely the difference between the momenta of the outgoing deuteron and the incident proton $\vec{P}_d-\vec{P}_p$. Neutron pickup reactions with a nuclear target, when a deuteron is observed at small scattering angles, are expected to occur under the same reaction mechanism and thus can be used to extract spectroscopic information on the neutron residing in the target nucleus.

The experiment was performed at the WS beamline of the RCNP cyclotron facility. Proton beams at $E_p = 198$, 295 and 392 MeV were provided by the RCNP ring cyclotron and transported in the achromatic mode to a target placed in a scattering chamber. The typical beam spot size at the target was 1 mm in diameter.

We used a windowless and self-supporting thin ice sheet [20] as the target. The thin ice
sheet, which was made of pure water, was cooled by liquid nitrogen and kept below 140 K throughout the experiment. A new ice target was prepared before each measurement with different proton beam energy to reduce $^{12}$C contaminants from vacuum pump oil. The thicknesses of the targets were determined to be $32 \pm 2$, $30 \pm 3$ and $62 \pm 5$ mg/cm$^2$ for the measurements with $E_p = 198$, 295 and 392 MeV respectively, through measurement of the elastic scattering off the hydrogen.

The deuterons produced in the one-neutron pickup reactions were momentum analyzed by the Grand Raiden spectrometer [21] and detected by two multi-wire drift chambers and two 10-mm thick plastic scintillation detectors placed at the exit focal plane about 20 m from the target. The acceptance of the scattered deuterons was limited to 40 mrad horizontally and 60 mrad vertically using a collimator slit. The deuterons were identified using the time-of-flight information and the pulse-height information from the two plastic scintillators. The momenta were determined based on the horizontal position information obtained with the drift chambers and the strength of the magnetic field.

To cover momentum transfer at around 2 fm$^{-1}$, we have performed measurements at several finite angles ($\theta_{\text{lab}}$) from 5° to 25°. The proton beam exiting the target was stopped in a Faraday cup. The beam current was monitored throughout the experiment using a current integrator connected directly to the Faraday cup.

The excitation energy spectra of the $^{16}$O(p,d)$^{15}$O reaction were reconstructed using the information of the proton beam energy as well as the scattering angle and the measured momenta of the deuterons. Figure 1(a) and (b) show the excitation energy spectra for the reactions obtained with proton beams at 392 and 198 MeV, where the deuterons were detected at 10° with respect to the incident beam. The measurement time was about an hour and the beam intensity was about 2 nA for each measurement. Several peaks corresponding to the ground state as well as the excited states of the residual nuclei $^{15}$O were clearly observed. For reference, the level scheme is shown at the top of the figure. The 5.183-MeV, $\frac{1}{2}^+$ and the 5.240-MeV, $\frac{5}{2}^+$ states in $^{15}$O were not resolved in the present experiment. Nonetheless, this should not alter our conclusion. For comparison, the energy spectrum for $E_p = 45.34$ MeV at 20.1° replicated from the figure in ref. [22] is also shown (Fig. 1(c)).

Since the ground $\frac{1}{2}^-$ and the 6.176-MeV excited $\frac{3}{2}^-$ states in $^{15}$O can be assumed to be neutron $p_{1/2}$ and $p_{3/2}$ hole states, one expects such states to be relatively strongly populated through direct pickup of a neutron. It is, however, surprising that the positive-parity states
FIG. 1: Typical excitation energy spectra for the $^{16}\text{O}(p,d)^{15}\text{O}$ reactions obtained at proton energies (a) 392 MeV and (b) 198 MeV. The deuterons were detected at 10° with respect to the incident beam. The level scheme for $^{15}\text{O}$ is shown at the top for reference. For clarity, only the well-established spin-parities are shown. (c) A spectrum for $E_p = 45.34$ MeV replicated from the figure in ref. [22] is shown for comparison.

are also strongly populated in the $^{16}\text{O}(p,d)^{15}\text{O}$ reaction. In particular, the population of the $\frac{5}{2}^+$ or $\frac{1}{2}^+$ state indicates possible contribution from the sd-shell. At low energy, as shown in Fig. (c), the cross section to the positive-parity state is smaller than those to the negative-parity states.

In general, the cross sections of all states diminish with increased proton beam energy, i.e. increased momentum transfer, due to momentum mismatching. This trend is particularly pronounced for the ground state, which is an evidence of diminishing high-momentum neutrons in the initial ground-state configurations. Notice that the relative intensity of the positive-parity states around 5.2 MeV in $^{15}\text{O}$ increases at very large momentum transfer,
which apparently indicates slower decrease or relative increase compared with the negative-parity states.

FIG. 2: Ratios of the intensities of the $\frac{3}{2}^−$ (open symbols) and the positive-parity ($\frac{5}{2}^+ \text{ and/or } \frac{1}{2}^+$) (filled symbols) excited states to that of the ground $\frac{1}{2}^−$ state as functions of momentum transfer. The present data are represented by the filled and open triangles. Other data are taken from previous works with 45-, 65-, 100-, 200- and 800-MeV proton energies. The dashed (dotted) curve represents the ratios of the 1p$_{3/2}$ (1d$_{5/2}$) and 1p$_{1/2}$, obtained by zero-range CDCC-BA calculations with finite-range correction using the Dirac phenomenological potentials.

To examine the relative strength of the excited states, we divided the cross sections for the excited states by that of the ground state. The ratios thus obtained were plotted against the averaged momentum transfer as shown in Fig. 2. In order to avoid possible complications due to reaction mechanism, we have confined ourselves to the data at 10$^\circ$. The filled symbols represent the ratios (denoted by $R_+$) for the positive-parity ($\frac{5}{2}^+$ and/or $\frac{1}{2}^+$) states, while the open symbols represent the ratios (denoted by $R_-$) for the negative-parity, $\frac{3}{2}^−$ state. The filled and open triangles are the data obtained in the present work. The error bars, which mainly consist of the statistical errors ($< 3\%$), are smaller than the symbols. Note that the contributions from the $^{12}$C contaminant have been estimated and subtracted. The acceptance and detection efficiency of the deuterons corresponding to the ground and excited states were almost constant. Other data were taken from the previous measurements at proton energies of 45.34 MeV $^{[22]}$, 65 MeV $^{[23]}$, 100 MeV $^{[24]}$, 200 MeV $^{[25]}$ and 800 MeV $^{[26]}$. As evidence from the figure, the ratios for the positive-parity states increase drastically by a factor of 30 from $q$ transfer 0.3 fm$^{-1}$ to 2.6 fm$^{-1}$, whereas the ones for the
negative-parity states only triple over the same momentum-transfer range.

The energy dependence of the differential cross sections at the first \( l=1 \) maxima, which lie between 10° and 20° in the center-of-mass frame close to 10° at the laboratory frame, has been reported for proton energies from 18.5 MeV to 100 MeV [22]. The present data, together with the data at \( E_p=800 \) MeV, indicate that \( R_{-} \) remains almost constant (\( \sim 3.7/1.68 \), see below) above \( q=1 \) fm\(^{-1}\).

To investigate the relative strengths, we performed theoretical calculations to obtain the ratios for the \( \frac{3}{2}^- \) and \( \frac{1}{2}^- \) states at 10°. The dashed curve in Fig. 2 shows the calculated ratios for proton energies from 45 to 800 MeV, obtained with the Continuum-Discretized Coupled-Channel method with Born Approximation to the transition operator \( \hat{V}_{tr} \) for the transfer, i.e. CDCC-BA calculation. We made zero-range approximation with finite-range correction to \( \hat{V}_{tr} \), and used nucleon-nucleus distorting potentials based on the Dirac phenomenology [29]. In obtaining the calculated ratios, we have adopted the shell-model spectroscopic factors of 1.68 and 3.7 [30] for the \( p_{1/2} \) and \( p_{3/2} \) states, respectively. The calculations are qualitatively consistent with the experimental data above \( E_p=100 \) MeV (or \( q \gtrsim 0.8 \) fm\(^{-1}\)), indicating that the ratios of the \( 1p_{3/2} \) and \( 1p_{1/2} \) states can be understood within the present shell-model framework. Although not shown in Fig. 2, calculations using the Adiabatic Distorted-Wave Born Approximation [27] with relativistic correction for the reaction with 200-MeV incident protons also give a ratio consistent with the experimental data.

For the positive-parity states, calculations using the shell model which include two-particle two-hole (\( 2p2h \)) configuration were reported to reproduce the experimental data at proton energy below 45.34 MeV. The sum spectroscopic factors were found to be as small as 0.15 and 0.02 for the \( 1d_{5/2} \) and the \( 2s_{1/2} \) states respectively [22]. Assuming only the \( 1d_{5/2} \) orbital and the spectroscopic factor of 0.15, we performed calculations for the positive-parity state. The ratios, which are represented by the dotted curve in Fig. 2, are almost constant from \( q = 1.0 \) fm\(^{-1}\) onwards. It is obvious that the calculations underestimate the experimental data at large momentum transfer by about an order of magnitude. This result is expected since it is well known \( [31] \) that the conventional shell model does not supply enough high-momentum components. Although the analysis of the \( ^{16}\text{O}(e,e'p) \) reaction data has indicated a 15% contribution from the multi-step processes \( [13] \) to the spectroscopic factor of the \( 1d_{5/2} \) state, it is not sufficient to account for the observed enhancement at large
momentum transfer.

Recently, theoretical calculations using the Tensor-Optimized Shell Model incorporating the Unitary Correlation Operator Method (TOSCOM) that include $2p2h$ configurations generated by tensor interactions in the ground state have been performed for $^4$He \[^{15}\] and $^9,^{10,11}$Li \[^{11}\]. The tensor interactions mix the high-momentum components through $|\Delta L| = 2, |\Delta S| = 2$ admixture. To confirm whether or not the observed enhancement of the positive-parity states is due to the effect of the tensor interactions, reaction analysis using the wave functions of $^{16}$O obtained with TOSCOM as well as more experimental data using one-nucleon transfer reactions on other nuclei are anticipated.

We shall note that the scattering angle of deuteron was set to $\geq 10^\circ$ to obtain momentum transfer $\sim 2 \text{ fm}^{-1}$, due to the limitation of the proton-beam energy at RCNP. It would be more desirable to use higher energy proton beam and measure the cross section near $0^\circ$ to minimize possible complications due to reaction mechanisms.

In summary, we have performed an experiment at RCNP, Osaka University using the $^{16}$O(p,d) reactions with proton beams at 198 MeV, 295 MeV and 392 MeV to search for a direct evidence on the effect of the tensor interactions in light nuclei. Differential cross sections of the one-neutron transfer reactions populating the ground states as well as several low-lying excited states in $^{15}$O were measured. By considering the ratio of the cross section for each excited state and the one for the ground state over a wide range of momentum transfer, we have observed a marked enhancement in the ratio for the $\frac{1}{2}^+$ and/or $\frac{5}{2}^+$ state(s) in $^{15}$O. The result indicates relative increase of high-momentum neutrons in the initial ground-state configuration with neutron(s) in $1s_{1/2}$ and/or $1d_{5/2}$ orbital, and thus may be a direct signature of the effect of the tensor interactions in $^{16}$O. The present work shows that one-nucleon transfer reactions, e.g. the (p,d) reaction, afford useful means to probe the effect of the tensor interactions in nuclei.

**Acknowledgment**

We thank the RCNP Ring Cyclotron staff for the stable proton beams throughout the experiment. H. J. O and I. T. would like to acknowledge the support of Prof. Akihiro Tohsaki (Suzuki) and his spouse which helped to kick-start this project. This work was supported in part by Grant-in-Aid for Scientific Research No. 20244030, 20740163 and 23224008 from
Monbukagakusho, Japan.

[1] J. Schwinger, Phys. Rev. 55, 235 (1939); J. M. B. Kellog et al., *ibid* 56, 728 (1939).
[2] H. A. Bethe, Phys. Rev. 57, 390 (1940); V. Rarita and J. Schwinger, *ibid* 59, 436 (1941).
[3] T. E. O. Ericson and M. Rosa-Clot, Ann. Rev. Nucl. Part. Sci. 35, 271 (1985).
[4] K. Ikeda et al., *Lecture Note in Physics* (Springer) 818, 165 (2010).
[5] Edward Gerjuoy and Julian Schwinger, Phys. Rev. 61, 138 (1942).
[6] L. D. Knutson et al., Phys. Rev. Lett. 35, 1570 (1975); B. C. Karp et al., *ibid* 53, 1619 (1984);
    S. Roman et al., Nucl. Phys. A289, 269 (1977).
[7] H. R. Weller et al., Phys. Rev. Lett. 53, 1325 (1984);
[8] S. C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci. 51, 53 (2001).
[9] A. Ozawa et al., Phys. Rev. Lett. 84, 5493 (2000).
[10] T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005).
[11] T. Myo et al., Phys. Rev. C 76, 024305 (2007).
[12] I. Bobeldijk et al., Phys. Rev. Lett. 73, 2684 (1994); E. Piasetzky et al., *ibid* 97, 162504 (2006); R. Subedi et al., Science 320, 1476 (2008);
[13] M. Leuschner et al., Phys. Rev. C 49, 955 (1994).
[14] Y. Yasuda et al., Phys. Rev. C 81, 044315 (2010);
[15] T. Myo et al., Prog. Theo. Phys. 117, 257 (2007).
[16] T. Neff and H. Feldmeier, Nucl. Phys. A 713, 311 (2003).
[17] W. Horiuchi, Y. Suzuki, Phys. Rev. C 76, 024311 (2007).
[18] R. Schiavilla et al., Phys. Rev. Lett. 98, 132501 (2007).
[19] T. Myo, private communication; Y. Ogawa and H. Toki, Nucl. Phys. A860, 22 (2011).
[20] T. Kawabata et al., Nucl. Instr. Meth. A459, 171 (2001).
[21] M. Fujiwara et al., Nucl. Instr. Meth. A422, 484 (1999).
[22] J. L. Snelgrove et al., Phys. Rev. 187, 1246 (1969).
[23] P. G. Roos et al., Nucl. Phys. A255, 187 (1975).
[24] J. K. P. Lee et al., Nucl. Phys. A106, 357 (1968).
[25] R. Abegg et al., Phys. Rev. C 39, 65 (1989).
[26] G. R. Smith et al., Phys. Rev. C 30, 593 (1984).
[27] R. C. Johnson, P. J. R. Soper, Phys. Rev. C 1, 976 (1970).

[28] M. Yahiro et al., arXiv:1203.5392v1 [nucl-th].

[29] S. Hama et al., Phys. Rev. C 41, 2737 (1990); E. D. Cooper et al., ibid 47, 297 (1993).

[30] B. A. Brown, Lecture Notes in Nuclear Structure Physics (NSCL, Michigan State University, 2005), pg. 250, unpublished.

[31] N. S. Wall and P. R. Roos, Phys. Rev. 150, 811 (1966).