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

H. J. Ong[1,a], I. Tanihata[1,2], A. Tamii[1], T. Myo[1,3], K. Ogata[1], M. Fukuda[4], K. Hirota[1], K. Ikeda[5], D. Ishikawa[1], T. Kawabata[6], H. Matsubara[1], K. Matsuta[4], M. Mihara[4], T. Naito[1], D. Nishimura[4], Y. Ogawa[1], H. Okamura[1], A. Ozawa[7], D. Y. Pang[2], H. Sakaguchi[1], K. Sekiguchi[5], T. Suzuki[1], M. Taniguchi[8], M. Takashina[1], H. Toki[1], Y. Yasuda[1], M. Yosoi[1], and J. Zenihiro[1]

[1] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*

[2] *School of Physics and Nuclear Energy Engineering, Beihang University, Beijing, 100191, China*

[3] *General Education, Faculty of Engineering, Osaka Institute of Technology, Osaka 535-8585, Japan*

[4] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*

[5] *RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*

[6] *Department of Physics, Kyoto University, Kitashirakawa, Kyoto 606-8502, Japan*

[7] *Institute of Physics, Tsukuba University, Tsukuba, Ibaraki 305-8571, Japan*

[8] *Department of Physics, Nara Women's University, Nara 630-8506, Japan*

Abstract. We measured the differential cross sections of the ^{16}O(p,d) reaction populating the ground state and several low-lying excited states in ^{15}O using 198-, 295- and 392-MeV proton beams at the Research Center for Nuclear Physics (RCNP), Osaka University, to study the effect of the tensor interactions in ^{16}O. Dividing the cross sections for each excited state by the one for the ground state and comparing the ratios over a wide range of momentum transfer, we found a marked enhancement of the ratio for the positive-parity state(s). The observation is consistent with large components of high-momentum neutrons in the ground-state configurations of ^{16}O due possibly to the tensor interactions.

1 Introduction

Tensor interactions play important roles in atomic nuclei. The tensor interactions are essential to explain the observed quadrupole moment [1] as well as the binding [2] of the deuteron. Besides the deuteron, earlier theoretical [3] studies had also pointed out the importance of the tensor interactions to the binding of ^{3}H and ^{3,4}He; these predictions were later confirmed by experiments [4] which showed the existence of D-wave components. For nuclei heavier than ^{4}He, no direct experimental evidence of the tensor interactions has been reported thus far, although ab-initio calculations [5] have predicted essential importance of the tensor interactions for binding nuclei up to mass number $A = 12$.

Here, we present a brief report of a direct search of the tensor-force effect in ^{16}O using the one-neutron transfer (p,d) reaction, which has been reported [6] very recently. The tensor interactions mix large orbital angular momentum states, giving rise to high momentum components [7] through D-wave mixing in the relative coordinate of two nucleons in finite nuclei. In fact, theoretical calculations [8] 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

---

[a] e-mail: onghjin@rcnp.osaka-u.ac.jp

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 that could be made by D-wave mixing, at high momentum transfer.

2 Experiment

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 bombarded a self-supporting windowless thin ice target [9] placed in a scattering chamber. The deuterons produced in the one-neutron pickup reactions were momentum analyzed by the Grand Raiden spectrometer [10] and detected by two multi-wire drift chambers and two 10-mm thick plastic scintillation detectors placed at the exit focal plane. To cover momentum transfer at around 2 fm^{-1}, we measured the outgoing deuterons at several finite angles from 5° to 25°. For details of the experiment, see Ref. [6].

3 Results and Discussion
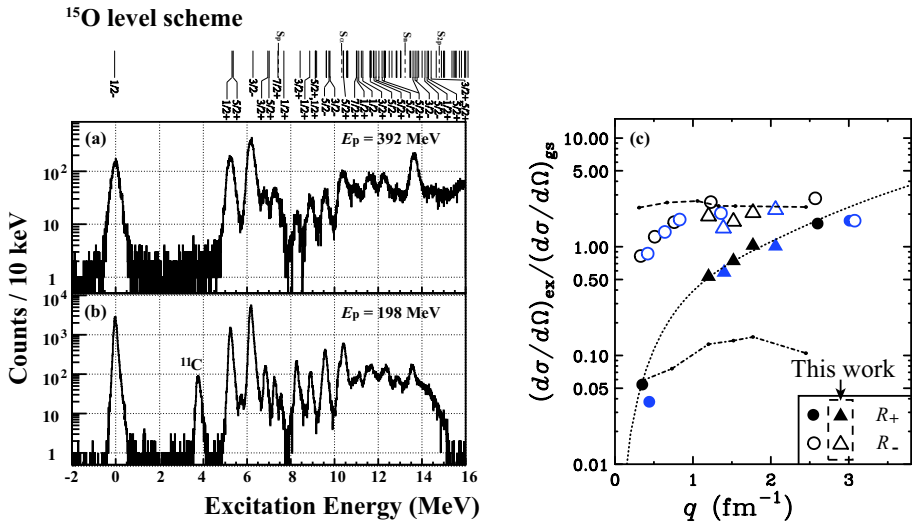
Figure 1. Typical excitation energy spectra for the $^{16}O(p,d)^{15}O$ reactions at 10° deuteron scattering angle, with proton beams at (a) 392 MeV and (b) 198 MeV. (c) Ratios of the intensities of the $\frac{3}{2}^-$ (open symbols) and the positive-parity ($\frac{5}{2}^+$ and/or $\frac{1}{2}^+$) (filled symbols) excited states to that of the ground $\frac{1}{2}^-$ state as functions of momentum transfer. The black (blue) symbols represent the data taken at 10 (15) deg scattering angle. The dashed (dash-dotted) curve represents the calculated ratios, for 10-deg scattering angle, of the $1p_{3/2}$ ($1d_{5/2}$) and $1p_{1/2}$, obtained by zero-range CDCC-BA with finite-range correction using the Dirac phenomenological potentials. The dotted curve is the ratio of squared momentum wave functions for D- and P-wave components, constructed mainly from Gaussian basis functions with small length parameters that yield large tensor-interaction matrix elements.

Figure 1(a) and (b) show the excitation energy spectra for the reactions at 10° deuteron scattering angle, with proton beams at 392 and 198 MeV. Several peaks corresponding to the ground state and 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. We note that although 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, this should not alter our conclusion. 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 ($\frac{5}{2}^+$ or $\frac{1}{2}^+$) states are also strongly populated in the ^{16}O(p,d)^{15}O reaction at high energies, which may indicate contributions from the sd-shell.

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. 1(c). The black (blue) symbols represent the data for 10° (15°) scattering angle. 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, with statistical errors ($< 3\%$), are the data obtained in the present work. The contributions from the ^{12}C contaminant ($< 2\%$) were estimated and subtracted. Other data were taken from the previous measurements with proton energies between 45 and 800 MeV [11, 12]. Notice that the ratios for the positive-parity states increase drastically by a factor of over 30 from q transfer 0.3 fm^{-1} to 3.0 fm^{-1}, whereas the ones for the negative-parity states only triple.

We performed theoretical calculations to determine R_- and R_+ at 10° to understand the relative strengths. The dashed (dash-dotted) curve in Fig. 1(c) show the calculated R_- (R_+), obtained with the Continuum-Discretized Coupled-Channel method with Born Approximation to the transition operator $\hat{V}_{\rm tr}$, i.e. CDCC-BA [13] calculation. We made zero-range approximation with finite-range correction to $\hat{V}_{\rm tr}$, and used nucleon-nucleus distorting potentials based on the Dirac phenomenology [14]. In obtaining the calculated R_-, we have adopted the shell-model spectroscopic factors of 1.68 and 3.7 [15] for the $p_{1/2}$ and $p_{3/2}$ states respectively. The calculations are qualitatively consistent with the experimental data at $q \geq 0.8$ 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.

The calculations using the shell model that include two-particle two-hole (2p-2h) configuration reproduced the experimental data at proton energy below 45.34 MeV. The reported sum spectroscopic factors were as small as 0.15 and 0.02 for the $1d_{5/2}$ and the $2s_{1/2}$ states respectively [11]. Assuming only the $1d_{5/2}$ orbital and the spectroscopic factor of 0.15, we calculated R_+ as shown in Fig. 1(c). The calculated ratio remains constant from $q = 1.0$ fm^{-1} onwards, and underestimate the experimental data at large momentum transfer by an order of magnitude. This result is expected since it is well known [16] that the conventional shell model does not supply enough high-momentum components. To estimate possible contributions from multi-step processes, we performed a two-step CDCC-BA calculation for the reaction at 200-MeV proton energy populating the $5/2^+$ state, taking into account the inelastic channel via the 3^- state in ^{16}O. The contribution from this process was found to be only 0.5% of the one-step cross section, which is insufficient to explain the discrepancy.

Recently, theoretical calculations using the Tensor-Optimized Shell Model incorporating the Unitary Correlation Operator Method (TOSCOM) have been performed for ^{4}He [17] and ^{9,10,11}Li [18]. In those calculations, the authors included 2p-2h configurations, which contain high-momentum components generated by tensor interactions, in the ground state. Hence, to examine possible contributions from the tensor interactions in the ground-state configurations of ^{16}O, we consider the Gaussian basis wave functions in Ref. [17]. We calculated the squared momentum wave functions for the D-wave and P-wave components. The dotted curve in Fig. 1(c) was obtained with the amplitudes of squared momentum wave functions relevant for He and Li isotopes [17, 18]. The corresponding ratio of the momentum amplitudes for the two P waves (with similar wave functions) is obviously momentum independent and thus is consistent with the observation as well as the CDCC-BA calculation. This marked difference between the D and the P waves indicates that the ratio of momentum amplitudes is the essential ingredient for the observed momentum transfer dependence. Hence, the strong enhancement of the relative cross section for the positive-parity state transition is qualitatively understood by

the inclusion of high-momentum wave functions expected with tensor interactions. Although other correlations such as the pairing correlations of like nucleons are expected to be smaller than the tensor correlations at around 2 fm^{-1} [8], they cannot be ruled out by the present experiment. To confirm whether or not the observed enhancement of the positive-parity states is due solely to the effect of the tensor interactions, reaction analysis using the wave functions of ^{16}O obtained with TOSCOM as well as experiments that can discriminate tensor correlations from the other correlations are anticipated.

4 Summary

In summary, we have measured the differential cross sections of the ^{16}O(p,d) reaction populating the ground states as well as several low-lying excited states in ^{15}O at RCNP, Osaka University using the proton beams at 198 MeV, 295 MeV and 392 MeV to search for a direct evidence on the effect of the tensor interactions. 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 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 is consistent with the enhancement of the high momentum component expected by a model that includes tensor interactions explicitly.

Acknowledgment

References

[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] E. Gerjuoy and J. Schwinger, Phys. Rev. **61**, 138 (1942).

[4] L. D. Knutson *et al.*, Phys. Rev. Lett. **35**, 1570 (1975); B. C. Karp *et al.*, *ibid* **53**, 1619 (1984); H. R. Weller *et al.*, *ibid* **53**, 1325 (1984).

[5] S. C. Pieper and R. B. Wiringa, Annu. Rev. Nucl. Part. Sci. **51**, 53 (2001).

[6] H. J. Ong *et al.*, Phys. Lett. **B725**, 277 (2013).

[7] K. Ikeda *et al.*, *Lecture Note in Physics* (Springer) **818**, 165 (2010).

[8] T. Neff and H. Feldmeier, Nucl. Phys. A **713**, 311 (2003); W. Horiuchi, Y. Suzuki, Phys. Rev. C **76**, 024311 (2007); R. Schiavilla *et al.*, Phys. Rev. Lett. **98**, 132501 (2007).

[9] T. Kawabata *et al.*, Nucl. Instr. Meth. **A459**, 171 (2001).

[10] M. Fujiwara *et al.*, Nucl. Instr. Meth. **A422**, 484 (1999).

[11] J. L. Snelgrove *et al.*, Phys. Rev. **187**, 1246 (1969).

[12] P. G. Roos *et al.*, Nucl. Phys. **A255**, 187 (1975); J. K. P. Lee *et al.*, *ibid* **A106**, 357 (1968); R. Abegg *et al.*, Phys. Rev. C **39**, 65 (1989); G. R. Smith *et al.*, *ibid* **30**, 593 (1984).

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

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

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

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

[17] T. Myo *et al.*, Prog. Theo. Phys. **117**, 257 (2007).

[18] T. Myo *et al.*, Phys. Rev. C **76**, 024305 (2007).