I. 2 0\,+\,+\,0\,-\,Transition\,Observed\,in\,the\,Reaction\,16O(p,n)16F

Cyclotron and Radioisotope Center, Tohoku University
Department of Physics, Faculty of Science, Tohoku University*
College of General Education, Tohoku University**
Tohoku Institute of Technology***
Tokyo Institute of Technology****

An isovector 0\,+\,+\,0\,-\,transition is of particular interest because it carries the simplest quantum numbers of bound pions. We present here the observation of a 0\,+\,+\,0\,-\,transition by the reaction 16O(p,n)16F at E_p = 35 MeV, where it has been shown that spin-isospin modes of nuclear excitation are selectively observed.1-4 In the case of nuclear weak processes, the 0\,+\,+\,0\,-\,transitions are unique transitions which are governed by the nuclear axial vector current. Experimentally, the 0\,+\,+\,0\,-\,transitions so far have been investigated for three cases: 16N(0\,-,T=1) + 16O(0\,+,T=0)→0\,-\,5, \nu + 16O(0\,+,T=0) + 16N(0\,-,T=1)→0\,-\,5, and 18Ne(0\,+,T=1) + 18F(0\,-,T=0)→0\,+\,4. Recently, it is noted by Kubodera, Delome and Rho8) that two-body meson-exchange effects in the time-like component of the axial-vector current play an important role.

In hadron scattering, on the otherhand, much less is known about the isovector 0\,+\,+\,0\,-\,transition. Indeed the 0\,-\,T=1 state has not yet been observed by the (p,p') experiment on 16O. The low-lying state of 16F provides one of the rare 0\,+\,+\,0\,-\,transitions which are accessible by a charge exchange reaction. Moss and Comiter9) measured neutron spectra from the 16O(p,n)16F reaction at E_p = 23 MeV, and Nann et al.10) reported a spectrum from the 16O(3He,t)16F reaction at E_t = 35 MeV. Recently, Fazely et al.11) have reported spectroscopy of 16F from the 16O(p,n)16F reaction at 99 and 135 MeV, where low-lying 0\,-\, and 1\,-\,states were not observed, partly because of a resolution of 260 keV. For the first four states in 16F, the relative ordering itself of the J\,,\, is still ambiguous. At E_t = 70 MeV, the transition strengths favor the sequence 0\,-\,, \,1\,-\,, \,2\,-\,, \,3\,-\, for the first four states at 0.0, 0.19, 0.42 and 0.72 MeV, respectively in 16F.12

Thus, it is expected that the (p,n) reaction on 16O at a sufficiently high proton energy to observe the spin-isospin modes of nuclear excitation with high-resolution may presumably provide possible evidence for pion-exchange currents which are included in the axial-vector time component. Furthermore, measurements of angular distributions of the cross section may give more relevant information on the role of tensor interaction, which is caused by the one-pion exchange potential. We report the observation of the 0\,+\,+\,0\,-\,transition in an A=16 nucleus, where the transfer-L is unique in spite of the excitation of unnatural parity state, and a good place may be provided to find the effect of pion exchange.

The experiment was performed with use of a 35-MeV proton beam from the
azimuthally varying field cyclotron and the time-of-flight facilities at the Cyclotron and Radioisotope Center, Tohoku University. We have utilized a beam swinger system, and measured angular distributions of emitted neutrons between 0° and 143° (C.M.) from a target made of 3.5 mg/cm² thick Mylar foil of natural isotope abundance. Overall time resolution for a γ-flash was 0.9 nsec, which corresponds to 60 keV for neutrons in the vicinity of the ground state transition by employing a neutron flight-path of 30 m. The errors in the absolute cross section are estimated to be ±20 %, while the relative error are ±10 %. Further details of the experiment have been given elsewhere. 13)

A representative energy spectrum of neutrons leading to the first four states in ¹⁶F is shown in fig. 1. Energy independent background comes from the ¹³C(p,n)¹⁴N reaction. A peak-fit code gives us the excitation energies of 0.0, 0.19, 0.42 and 0.72 MeV, which are quite consistent with those listed in ref. 12. We estimate the width of the ground state, which is unstable to proton decay, is ~40 keV by quadratically subtracting the contributions of time spread and target thickness from the observed peak width.

Figure 2 shows the angular distributions for the ground- and first-excited states measured at E_p = 35 MeV. Solid curves in fig. 2 are DWBA predictions calculated by the code DWBA-74, which includes knock-on exchange contributions. 14) The effective interaction for the reaction has been taken to be the phenomenological nucleon-nucleon force 15) with a 1.0 fm Yukawa (1FY) radial dependence and V_0 = -27 MeV, V_0 = V_0 = 12 MeV, and V_0 = 18 MeV. This interaction has been successfully used 1, 16) in the analyses of many (p,n) analog transitions between E_p = 25 and 45 MeV. In order to examine the role of the tensor force, we add a tensor term, which has been obtained from matching the low momentum transfer components of Hamada-Jonston tensor force and has a radial form of V^{TN}_{12} = (V_{0}^{TN} + V_{1}^{TN}ho_{1,2}^{-2}) i_{12}^2 exp(-iμ_{12}/μ_{0}^2) with V_{0}^{TN} = -0.03 MeV fm^{-2}, V_{0}^{TN} = 7.07 MeV fm^{-2} and μ = 0.857. 17)

It should be noted that inclusion of the tensor force of the one-pion exchange potential improves the DWBA fitting considerably. Optical-potential parameters of Fabrici et al. 18) are used for protons. Those for neutrons are self-consistent potential parameters derived by Carlson, Zahiratos, and Lind. 19) Pure (np_{1/2}, vp_{1/2}) configuration is assumed for the ground state of ¹⁶O. The DWBA curves for the ground and the first excited states are calculated by the pure (np_{1/2}, vp_{1/2})^{0^{-},1^{-}} configuration, as predicted by Gillet and Mau 20) for T=1, 0^{-} and 1^{-} states in ¹⁶O which are analog states of the ground and the first excited states in ¹⁶F.

The spin sequence of a 0^{-}, 1^{-}, 2^{-}, 3^{-} order was proposed by DeMeijer et al. 21) based on calculations on Coulomb displacement energies, and the same results were claimed by Bohne et al. with the ¹⁴N(³He,n)¹⁶F reaction 22) and by Nann et al. 10) with the ¹⁶O(³He,t)¹⁶F reaction, while Otsubo et al. 23) concluded an inverted order for 0^{-} and 1^{-} states. Recent measurements of angular distributions by Fazely et al. have confirmed the 2^{-} (0.4 MeV) and 3^{-} (0.7 MeV) states. As one can see in fig. 2, the angular dependence of the cross sections for neutrons
leading to the ground state show different pattern from that to the first excited state, though transfer momentum in these two transitions is similar (L=1). This well-fitted J-dependence of the (p,n) angular distribution is noticeable, and it seems independent of the inclusion of the tensor force as demonstrated in fig. 2, where predictions by only central force and with the tensor force, which has been derived by Petrovich et al.\textsuperscript{17}, are shown for comparison.

In order to facilitate the discussion we refer to the cross section magnitude of the $0^+ \rightarrow 0^-$ and $0^+ \rightarrow 1^-$ transitions. Fazely et al. have reported a large fraction (typically 20-50%) of the distorted wave impulse approximation for the transitions observed in the $^{16}O(p,n)^{16}F$ reaction. Indeed, in the present $0^+ \rightarrow 1^-$ transition, the fraction is 50% of the DWBA prediction with the 1FY interaction. Meanwhile, nearly entire amounts of the predicted intensities are observed in the $0^+ \rightarrow 0^-$ transitions when we assume the 1FY plus tensor phenomenological interactions, which have been used successfully to explain the cross section of the low-energy (p,n) reactions in the low-L transitions.\textsuperscript{1,15} It should be worthwhile that Moffa and Walker\textsuperscript{24} have predicted the cross section to the $0^-$ state is much less comparing to that of the $2^-$ state. Consequently, the $0^+ \rightarrow 0^-$ (p,n) transition at $E_p = 35$ MeV is believed to be predominantly a one-step process which excites the one-particle, one-hole component of nuclear states.

In conclusion, we measured angular distribution of the (p,n) cross sections of the $0^+ \rightarrow 0^-$ transition in a transfer momentum ranging 0.4-2.2 fm\textsuperscript{-1} by means of high-resolution time-of-flight technique. Spin-sequence of $0^-, 1^-$ for the ground state and the first-excited state in $^{16}F$ was confirmed. The cross section of the $0^+ \rightarrow 0^-$ transition was measured to nearly entire amounts of the predicted strength, and it is strongly supported that the reaction proceeds via the one-step direct process. Further studies are awaited to obtain the relations between hadron scattering data and expressions for the nuclear matrix element of the charge current in terms of appropriate form factors.

Acknowledgement

The authors are thankful to Dr. Garvey for his helpful discussions.

References

3) Orihara H. in Proceedings of Spin Excitation in Nuclei (Telluride, March 1982) to be published.

Fig. 1. Neutron energy spectrum for the reaction $^{16}_0(n,p)^{16}_F$ at $\theta_{lab} = 40^\circ$ measured with 35-MeV protons at a neutron flight path of 30 m. The ordinate is compensated for the variation of the detector efficiency with respect to neutron energy. Energy per bin is 25 keV.
Fig. 2. Differential cross sections for the peaks corresponding to the ground state and the 0.19-MeV state in $^{16}\text{F}$. The curves are DWBA predictions calculated with 1.0-fm-range Yukawa force with and without the tensor force described in the text by solid and dotted lines, respectively. An error bar stands for statistical uncertainty and that of background subtraction. The curves for $0^+ \rightarrow 1^+$ transition are normalized to the data at $\theta_{\text{c.m.}} = 32^\circ$. 