Isovector $0^+ \to 0^-$ Transition Observed in the Reaction $^{16}O(p,n)^{16}F$

H. Orihara
Cyclotron and Radioisotope Center, Tohoku University, Sendai 980, Japan

and

S. Nishihara, K. Furukawa, and T. Nakagawa
Department of Physics, Faculty of Science, Tohoku University, Sendai 980, Japan

and

K. Maeda
College of General Education, Tohoku University, Sendai 980, Japan

and

K. Miura
Tohoku Institute of Technology, Nagamachi-Koeji, Sendai 982, Japan

and

H. Ohnuma
Department of Physics, Tokyo Institute of Technology, Oh-okayama, Tokyo 152, Japan

(Received 10 September 1982)

The angular distribution for the reaction $^{16}O(p,n)^{16}F(0^-)$ has been measured at $E_p = 35$ MeV between 0° and 140° (lab), or momentum transfer 0.34–2.0 fm^{-1}. This is the first observation of an isovector $0^+ \to 0^-$ transition, corresponding to a pure longitudinal spin response, at large momentum transfers. Distorted-wave Born-approximation calculations with the M3Y interaction give a reasonable account of the observed cross sections except at $1.4 \lesssim q \lesssim 2.0$ fm^{-1}. This discrepancy might be due to the effects of the pion field in nuclei.

PACS numbers: 25.40.Ep, 21.10.Jx, 27.20.+n

An isovector excitation of a particle-hole (p-h) state coupled to $J^\pi = 0^-$ from a 0^+ ground state is of particular interest since it carries the simplest pionlike quantum numbers. Experimental studies of such excitation (or deexcitation) have been limited so far to only low momentum transfers. More specifically, $0^\pm \to 0^\mp$ transitions have been investigated experimentally in three cases[1-3]: $^{16}N(0^-, T=1) \xrightarrow{\beta} {}^{16}O(0^+, T=0)$; $\mu^- + {}^{16}O(0^+, T=0) \to {}^{16}N(0^-, T=1)$; and $^{18}Ne(0^+, T=1) \xrightarrow{\beta} {}^{18}F(0^-, T=0)$. Axial-vector and pseudoscalar currents are responsible for these first-forbidden transitions in nuclear weak processes. The ratio of the muon-capture rate to the β-decay rate is hoped to give the pseudoscalar coupling constant in a way less sensitive to nuclear structure uncertainties.[1,4,5] Recently Kubodera, Delorme, and Rho[6] pointed out the importance of the two-body meson-exchange effects in the timelike component of the axial-vector current. They found that the meson-exchange effects enhance the β-decay rate by a factor of 4. A recent measurement of the ^{16}N β-decay rate agrees with the predicted enhancement.[1]

Many authors have emphasized the importance of nucleon internal excitation in isovector magnetic excitation of p-h states with unnatural parities.[4,7-10] Experimentally observed "quenching" of Gamow-Teller strengths, g factors, magnetic multipole transitions, etc., has been suspected as evidence of such an effect. However, many other explanations remain possible for the quenching. The intermediate nucleon-hole and Δ-isobar-hole excitations[10,11] reveal themselves in the renormalization of spin-isospin operators. The spin-isospin response is transmitted by p-h interactions of a form which contains the longitudinal $(\vec{\sigma}\cdot\vec{q})$ as well as the transverse $(\vec{\sigma}\times\vec{q})$ spin response. The pion field in nuclei, expected to be larger than the free value, is known to affect the longitudinal response significantly.[7-11] Therefore, experiments which are sensitive to the longitudinal spin density are expected to provide crucial tests of the pion field in nuclei. The advantage of $0^+ \to 0^-$ transitions, compared with $0^+ \to 1^+$ transitions and other unnatural parity transitions on which most of previous experimental studies have concentrated, is that the transverse contribution vanishes. On the other hand, this unique feature of $0^+ \to 0^-$ transitions makes it impossible to study them in (e,e') experiments as a result of the transverse character of one-photon exchange. Thus hadron scattering and charge-exchange reaction studies for isovector $0^+ \to 0^-$ excitations are expected to provide unique information, which otherwise would be difficult to extract in a pure form, on pion-exchange currents at large momentum transfers.

Unfortunately, virtually nothing is known about isovector $0^+ \to 0^-$ transitions in hadron scattering or charge-exchange experiments. The 0^-, $T=1$ state in ^{16}O has not yet been observed in (p,p') work because of its weak excitation and large background. Although the (p,n) and $(^3He,t)$ reactions on ^{16}O have been studied by several authors,[12,13] no angular distribution has been measured at reasonably high incident energies for the 0^- state of ^{16}F. This is because of the small cross section of the $0^+ \to 0^-$ transition and the difficulties in resolving the four low-lying states in ^{16}F. In this work we report the first angular distribution measurement of the isovector $0^+ \to 0^-$ transition $^{16}O(p,n)^{16}F(0^-)$ at an incident energy of 35 MeV, where a number of unnatural parity states have been observed.[14,15] High-resolution time-of-flight facilities enabled us to resolve clearly the low-lying states of ^{16}F. The measurement covers a wide range of angles, between 0° and 143° (c.m.), corresponding to momentum transfers between 0.34 and 2.0 fm^{-1}.

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 140° (lab) from a target made of 3.5-mg/cm²-thick Mylar foil of natural isotope abundance. The overall time resolution for a γ flash was 0.9 nsec, which corresponds to 60 keV for the most energetic neutrons over a flight path of 30 m. The errors in the absolute cross sections are estimated to be ~20%. Further details of the experiment have been given elsewhere.[16]

A sample energy spectrum of neutrons leading to the first four states in ^{16}F is shown in Fig. 1. An energy-independent background comes from the $^{13}C(p,n)^{13}N$ reaction. A peak-fit code gives us excitation energies of 0.0, 0.19, 0.42, and 0.72 MeV for these states, in good agreement with those listed in Ref. 17. Figure 2 shows the angular distributions for the ground state and the first-excited state. The solid curves in Fig. 2 are distorted-wave Born-approximation (DWBA) predictions calculated by the code DWBA-70, which includes knockon exchange contributions.[18] A set of effective interactions of Bertsch *et al.* (M3Y)[19] were used in the calculations. The *LS* interaction does not contribute to the 0^- cross section, and is omitted in the calculations. Optical-potential parameters of Fabrici *et al.*[20] are used for protons. Those for neutrons are self-consistent potential parameters derived by Carlson, Zafiratos, and Lind.[21] Pure $\nu p_{1/2} \to \pi s_{1/2}$ transitions are assumed for the ground state and the first-excited state as suggested by random-phase-approximation calculations.[22,23] The $s_{1/2}$ proton in ^{16}F is unbound. Instead of using an unbound wave function for the $s_{1/2}$ proton, we assumed it to be bound by 0.05 MeV in a Woods-Saxon potential with standard geometry ($r_0 = r_{s.o.} = 1.25$ fm, $a_0 = a_{s.o.} = 0.65$ fm, $V_{s.o.} = 6$ MeV).

The spin sequence of 0^-, 1^-, 2^-, 3^- for the lowest four states of ^{16}F was proposed by DeMeijer, van Royen, and Brussaard[24] on the basis of the Coulomb displacement energies. These assignments have been favored in many experimental works.[13,25] On the other hand, Otsubo *et al.*[26] suggested an inverted order for the 0^- and 1^- states on the basis of the n-p angular correlations in

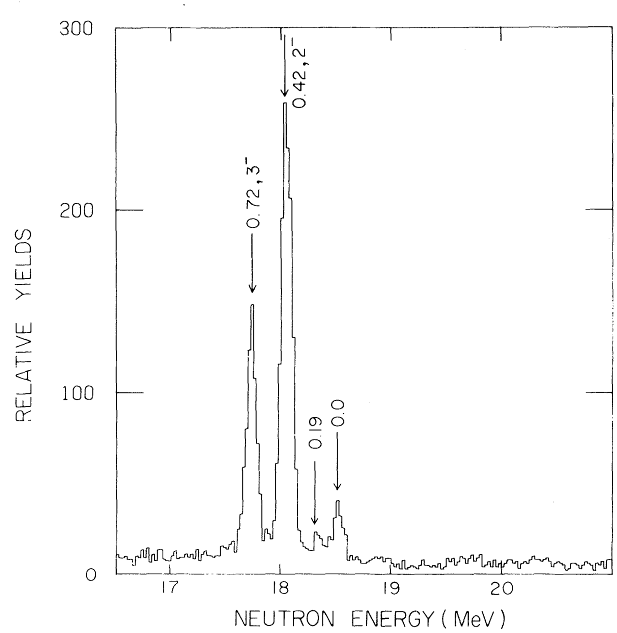

FIG. 1. Neutron energy spectrum for the reaction $^{16}O(p,n)^{16}F$ at $\theta_{lab} = 40°$ measured with 35-MeV protons at a neutron flight path of 30 m. The ordinate is compensated for the variation of the detector efficiency with respect to neutron energy. Energy per bin is 25 keV.

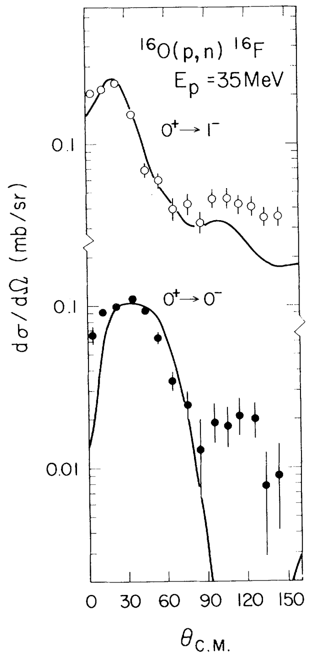

FIG. 2. Differential cross sections for the peaks corresponding to the ground state and the 0.19-MeV state in ^{16}F. The curves are DWBA predictions calculated with the M3Y interaction. The error bars stand for statistical uncertainty and that of background subtraction. The curves are normalized to the data at $\theta_{c.m.} \simeq 22°$.

the reaction $^{14}N(^3He,n)^{16}F(p)^{15}O$, with A_2 measured to be -0.514 ± 0.059 for the ground state of ^{16}F. However, this large A_2 value is unlikely since (1) the decay mainly involves $s_{1/2}$ proton emission, and (2) the ground states of ^{14}N, ^{3}He, and n have spins 1, $\frac{1}{2}$, and $\frac{1}{2}$, respectively. As one can see in Fig. 2, there is a slight difference in the (p,n) angular distributions for the ground state and the first-excited state, the first maximum of the latter being shifted forward by ~10° relative to the former. This difference has been reproduced by the present DWBA calculations with the spin sequence of DeMeijer, van Royen, and Brussaard. We should add that the angular distribution for the first-excited state is more similar to the $^{13}C(p,n)^{13}N(2.37\ \mathrm{MeV}, \frac{1}{2}^+)$ angular distribution obtained at the same incident energy. This is what is expected for the 1^- state, since both the $0^+ \to 1^-$ and $\frac{1}{2}^- \to \frac{1}{2}^+$ transitions are almost pure $p_{1/2} \to s_{1/2}$ transitions induced primarily by the central part of the interaction.

The calculated cross sections are too large by a factor of 3 for 1^-, and by a factor of 2 for 0^-. The larger discrepancy for 1^- in the cross-section magnitudes may be attributed to the presence of the $E1$ giant resonance. The use of a weakly bound wave function for the $s_{1/2}$ proton, instead of an unbound wave function, may be responsible for the overestimation of the calculated cross sections for both 0^- and 1^-. Furthermore, pure $\nu p_{1/2} \to \pi s_{1/2}$ transitions were assumed in the present analysis. The other configurations ignored here possibly introduce suppression of the cross sections. In particular, Bertsch has pointed out[27] that the 0^- cross section can be sensitive to a small configuration admixture. In Ref. 5 it is shown that the transition strength for the operators $\sigma \cdot r$ and $\sigma \cdot p$ can vary by as much as a factor of 4 depending on the interactions used to calculate the configuration admixture. The 0^- cross section at the first maximum is expected to scale as the transition strength of the $\sigma \cdot r$ operator.[27] Therefore there can be a strong suppression of the cross section within current models. In addition, contributions from higher-order reaction processes as seen for the 4^- state[15] are also possible, although they are expected to be small for 0^-.

In spite of various ambiguities in the structure and reaction models it is clear that the overall angular distribution shape for the 1^- state is reasonably reproduced by the calculation, whereas the present analysis fails to reproduce the second maximum in the 0^- angular distribution. Results calculated with different effective interactions[28-30] could not reproduce this second maximum either. The tensor interaction gives negligible contribution to the 1^- cross section, while it is almost as important as the central interaction for 0^-. It is suggested that the effects of the pion field in nuclei as discussed earlier show up in this momentum transfer region of the pure longitudinal transition, although various ambiguities in the DWBA analysis make it difficult to draw a positive conclusion at this moment.

In conclusion, we measured the (p,n) angular distribution of the $0^+ \to 0^-$ transition in a momentum transfer range 0.34–2.0 fm^{-1}. This is the first measurement of a pure longitudinal isovector transition at large momentum transfers. Such a measurement is hoped to give unique information on the pion field in nuclei. The DWBA calculation with the effective interaction of Bertsch *et al.* seems to give a reasonable account of the measured cross sections except at large momentum transfers. It is possible that the discrepancy observed in the large-momentum-transfer region is due to the effects of the pion field in nuclei, although more definite conclusion awaits further detailed analyses of the present data.

The authors are indebted to Dr. G. T. Garvey, Dr. R. Madey, Dr. M. Hynes, Dr. G. Bertsch, and Dr. H. Toki for their helpful discussions.

[1]C. A. Gagliardi, G. T. Garvey, J. R. Wrobel, and S. J. Freedman, Phys. Rev. Lett. 48, 914 (1982).
[2]P. Guichon, B. Bihoreau, M. Giffon, A. Gonçalves, J. Julien, L. Roussel, and C. Samour, Phys. Rev. C 19, 987 (1979).
[3]E. G. Adelberger *et al.*, Phys. Rev. Lett. 46, 695 (1981).
[4]J. Speth, V. Klemt, J. Wambach, and G. E. Brown, Nucl. Phys. A343, 382 (1980).
[5]I. S. Towner and F. C. Khanna, Nucl. Phys. A372, 331 (1981).
[6]K. Kubodera, J. Delorme, and M. Rho, Phys. Rev. Lett. 40, 755 (1978).
[7]M. Ericson and J. Delorme, Phys. Lett. 76B, 182 (1978).
[8]H. Toki and W. Weise, Phys. Rev. Lett. 42, 1034 (1979).
[9]J. Meyer-Ter-Vehn, Phys. Rep. 74C, 323 (1981).
[10]E. Oset, H. Toki, and W. Weise, Phys. Rep. 83C, 281 (1982).
[11]G. E. Brown and M. Rho, Nucl. Phys. A372, 397 (1981).
[12]C. E. Moss and A. B. Comiter, Nucl. Phys. A178, 241 (1971).
[13]H. Nann, W. Benenson, E. Kashy, H. P. Morsch, and D. Mueller, Phys. Rev. C 16, 1684 (1977).
[14]H. Orihara, in Proceedings of the Conference on Spin Excitations in Nuclei, Telluride, March 1982 (to be published), and references therein.
[15]H. Ohnuma *et al.*, Phys. Lett. 112B, 206 (1982).
[16]H. Orihara and T. Murakami, Nucl. Instrum. Methods 188, 15 (1981).
[17]F. Ajzenberg-Selove, Nucl. Phys. A375, 1 (1982).
[18]R. Schaeffer and J. Raynal, Saclay Report No. CEA-R 4000, 1970 (unpublished).
[19]G. Bertsch, J. Borysowicz, H. McManus, and W. G. Love, Nucl. Phys. A284, 399 (1977).
[20]E. Fabrici *et al.*, Phys. Rev. C 21, 844 (1980).
[21]J. D. Carlson, C. D. Zafiratos, and D. A. Lind, Nucl. Phys. A249, 29 (1975).
[22]V. Gillet and N. V. Mau, Nucl. Phys. 54, 321 (1964).
[23]T. W. Donnelly and G. E. Walker, Ann. Phys. (N.Y.) 60, 209 (1970).
[24]R. J. DeMeijer, H. F. van Royen, and P. J. Brussaard, Nucl. Phys. A164, 11 (1971).
[25]W. Bohne *et al.*, Phys. Lett. 47B, 342 (1973).
[26]T. Otsubo *et al.*, Nucl. Phys. A259, 452 (1976).
[27]G. Bertsch, private communication.
[28]F. Petrovich *et al.*, Phys. Lett. 46B, 141 (1973).
[29]S. M. Austin, in *The (p,n) Reaction and the Nucleon-Nucleon Force*, edited by C. D. Goodman *et al.* (Plenum, New York, 1980), p. 203.
[30]H. Ohnuma and H. Orihara, Prog. Theor. Phys. 67, 353 (1982).

Nuclear Fragment Mass Yields from High-Energy Proton-Nucleus Interactions

J. E. Finn, S. Agarwal, A. Bujak, J. Chuang,[a] L. J. Gutay, A. S. Hirsch, R. W. Minich,[b] N. T. Porile, R. P. Scharenberg, and B. C. Stringfellow
Departments of Physics and Chemistry, Purdue University, West Lafayette, Indiana 47907

and

F. Turkot
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(Received 11 January 1982)

Isotopically resolved nuclear fragments (A_f, Z_f), $3 \leq Z_f \leq 14$, produced by protons in the energy range $80 \leq E_{inc} \leq 350$ GeV incident on krypton and xenon targets have been studied at the Internal Target Laboratory of the Fermi National Accelerator. A power-law dependence, isobaric yield $\propto A_f^{-\tau}$, was found to describe the data over a broad range of yields. The particular value of τ is a signature for the fragment formation mechanism.

PACS numbers: 25.40.Rb, 13.85.-t, 21.60.Ev

It is well known[1,2] that nuclear fragment production is associated with collisions yielding high-multiplicity final states. The existence of a limiting fragmentation region for energies greater than approximately 10 GeV incident energy establishes fragment production as a distinct high-energy phenomenon.[3] A central question concerns the nuclear state which emits the multiply charged heavy fragments. Previous workers using electronic techniques have focused attention on the