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著者	石井　慶造
journal or publication title	Physical review. C
volume	41
number	5
page range	2414-2417
year	1990
URL	http://hdl.handle.net/10097/35226

doi: 10.1103/PhysRevC.41.2414

PHYSICAL REVIEW C VOLUME 41, NUMBER 5 MAY 1990

$0\hbar\omega$ stretched states observed in the (p,n) reactions on ^{22}Ne and ^{26}Mg

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(Received 11 December 1989)

Stretched particle-hole states of a $0\hbar\omega$ $(\pi d_{5/2},\nu d_{5/2}^{-1})_{5^+}$ type were observed as low-lying isolated peaks in the high-resolution (p,n) reactions on ^{22}Ne and ^{26}Mg at $E_p=35$ MeV. Angular distributions of the differential cross sections have been successfully interpreted, especially at large angles, or in high-momentum transfer regions ($q\sim 2$ fm^{-1}), by microscopic distorted-wave Born approximation calculations using shell-model wave functions and the M3Y interaction. No quenching of the (p,n) cross sections has been observed for these $0\hbar\omega$ stretched transitions in light nuclei.

The number of one-particle one-hole excitations in an isovector stretched transition is severely restricted, and hence such a transition provides a good place to probe spin-isospin properties of nuclei and to study the isovector part of the tensor interaction at large-momentum transfer in a straightforward manner.

Stretched particle-hole states have been investigated through backward-angle electron scattering, pion, and nucleon inelastic scattering, and charge-exchange reactions. Zarek and his collaborators first observed[1] the stretched particle-hole excitation in backward-angle electron scattering on ^{24}Mg with momentum transfer up to ~ 4 fm^{-1}. They located a $1\hbar\omega$ jump 6^-, $T=1$ state at $E_x=15.130$ MeV in ^{24}Mg, while the same state has been observed by Adams *et al.*[2] through proton inelastic scattering at $E_p=135$ MeV. Following the first observation[3] of the $1\hbar\omega$ stretched excitation through the charge-exchange (p,n) reaction on ^{24}Mg, a systematic investigation of the low-energy (p,n) reactions on ^{12}C, ^{14}C, ^{16}O, and ^{28}Si has been reported.[4] Several $\Delta T=1$, $[\pi d_{5/2}, \nu p_{3/2}]_{4^-}$, and $[\pi f_{7/2},\nu d_{5/2}]_{6^-}$ $1\hbar\omega$ jump stretched transitions have been observed in *p*- and *sd*-shell nuclei, respectively, in Ref. 4. Anderson and his collaborators have reported[5] $1\hbar\omega$ stretched states in the ^{28}Si(p,n) and ^{40}Ca(p,n) reactions at intermediate energies. One of the striking features found in these $1\hbar\omega$ stretched excitations is their considerably large quenching. We need renormalization factors smaller than 0.5 to fit the theoretical cross sections to the data. This seems to be independent of the probe used in the excitation. Petrovich and Lindgren reported[6] from the discussion of (e,e'), (p,p'), and $(\pi^\pm,\pi^{\pm\prime})$ scattering that the extracted S^2 values, which denoted a measure of quenching, for isovector $1\hbar\omega$ jump stretched transitions were typically 38% of simple shell-model predictions.

Anderson *et al.*[7] have reported $0\hbar\omega$ 7^+, 7^+, 9^+, and 13^+ stretched states in the (p,n) reactions on ^{48}Ca, ^{54}Fe, ^{88}Sr, and ^{208}Pb, respectively. Contrary to the case of $1\hbar\omega$ stretched transitions, they obtained larger S^2 values ranging from 0.60 (for ^{48}Ca) to 0.96 (^{208}Pb). Isovector $0\hbar\omega$ stretched state excitations can be studied almost solely through (p,n) reactions. Furthermore, some of such states lie at low-excitation energies where the level density is low, and can be observed as isolated peaks in high-resolution (p,n) experiments. A low-energy (p,n) experiment is more attractive in this regard, although interpretations of intermediate energy data may be more straightforward. This seems especially true in an investigation of the presently discussed $0\hbar\omega$ stretched states appearing at low-excitation energies with level spacings of ~ 100 keV.

In this report we discuss 5^+ excitations of the $0\hbar\omega$ character in the (p,n) reactions on ^{22}Ne and ^{26}Mg. The lowest 5^+ states in ^{22}Na and ^{26}Al, which should have a dominant $(\pi d_{5/2},\nu d_{5/2}{}^{-1})_{5^+}$ configuration, were observed as background free isolated peaks. Their absolute cross sections were reproduced successfully by the distorted-wave Born-approximation (DWBA) theory. The isovector tensor part of the effective N-N interaction employed in the analysis was found to describe these (p,n) transitions reasonably well over a wide range of momentum transfer (≤ 2.3 fm^{-1}).

The experiment was performed with a 35-MeV proton beam from the AVF cyclotron and the time-of-flight facilities[8] of the Cyclotron and Radioisotope Center at Tohoku University. Two types of gas cell with metallic calcium foil windows filled with enriched (to 99.8%) ^{22}Ne gas were used as targets in the ^{22}Ne experiment. The target for small-angle measurements ($\theta_{\rm lab} \le 40°$) was a disk type having a longitudinal length of 2 cm. The target for large-angle measurements ($\theta_{\rm lab} \ge 30°$) was a cylindrical type having a length of 20 cm and thus making it possible to shield the neutron detectors against neutrons emitted from calcium foils. The effective target thickness was of the order of 1 mg/cm^2 in both cases. A self-supporting ^{26}Mg foil of 2.6-mg/cm^2 thick and enriched to 99.9% was used as a target for the ^{26}Mg experiment.

In Figs. 1(a) and 1(b) are shown sample neutron spectra taken at large angles. Neutron peaks leading to the 5^+ stretched states at $E_x = 1.528$ (in ^{22}Na) and 0.0 MeV (the ground state of ^{26}Al) are clearly resolved from nearby states, although the latter was less conspicuous especially at small angles where the energy resolution was slightly worse due to the kinematical condition. Also seen in the figures are higher-lying weakly populated 5^+ states[9] at 4.71 MeV in ^{22}Na and at 3.40 MeV in ^{26}Al. Angular distributions for neutrons leading to the low-lying 5^+ states in ^{22}Na and ^{26}Al are illustrated in Figs. 2(a) and 2(b) along with DWBA predictions. It should be stressed that no scaling of the calculated curves has been made in these figures to optimize comparison.

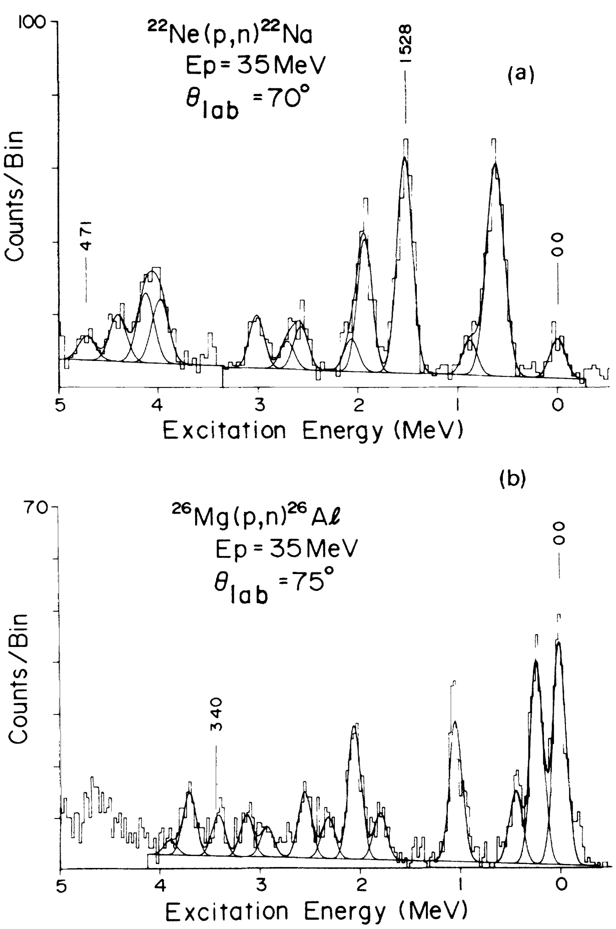

FIG. 1. Sample large-angle neutron energy spectra taken for the (p,n) reactions on ^{22}Ne (a) and on ^{26}Mg (b). Energy per bin is 25 keV.

DWBA calculations were made with the code DWBA-74.[10] Optical-potential parameters for protons and neutrons were taken from Ref. 11. Use of different optical-potential parameters may introduce variations of $\sim 20\%$ in predicted absolute cross sections, but not in relative cross sections as discussed in detail in Ref. 12. In order to test the reliability of the present analysis, we analyzed the $0^+(T=1) \to 0^+(T=1)$ analog transition in the ^{26}Mg$(p,n)^{26}$Al ($E_x = 0.228$ MeV) with the same parameters, and found that the calculated result reproduced the experimental absolute cross sections as it did in the case[13] of ^{34}S$(p,n)^{34}$Cl reaction. A set of effective N-N interactions of Bertsch *et al.* (Ref. 14) has been used for the present microscopic DWBA analysis. More specifically, we used a combination of those based on the Reid soft-core central and spin-orbit (LS)-odd forces and the Elliot LS-even tensor force. Calculations were performed also with other sets of effective interactions such as those by Anantaramann, Toki, and Bertsch,[15] and those by Hosaka, Kubo, and Toki,[16] but no significant differences were found among the results. Single-particle radial wave functions were generated in a Woods-Saxon type bound-state potential with $r_0 = 1.25$ fm, $a = 0.65$ fm, and $V_{LS} = 6$ MeV in the present DWBA calculations.

Transition amplitudes have been obtained from recently calculated shell-model wave functions.[17] Stringent tests of these wave functions were made by the present authors in the analyses of various kinds of (p,n) transitions in *sd*-shell nuclei.[13,18] The shell-model calculations predict that almost 90% of the $0^+ \to 5^+$ strengths are in the lowest 5^+ states in both ^{22}Na and ^{26}Al and about 10% in high-lying states. Lebo and his collaborators observed[19] a 5^+ state at $E_x = 3.4$ MeV in ^{26}Al in the (p,n) reaction on ^{26}Mg in addition to the 5^+ ground state and the stretched $1\hbar\omega$ 6^- states. We also observed (see Fig. 1) the neutron peaks corresponding to the 3.40 MeV (in ^{26}Al) and 4.71 MeV (in ^{22}Na) 5^+ states with reasonable intensities as mentioned earlier. However, we concentrate our present discussions on the lowest 5^+ states in ^{22}Na and ^{26}Al, since these are well-established isolated states with purer configurations, and there are much less ambiguities in the analysis.

We have shown before[20] the appropriateness of the strengths of the isovector tensor part of the effective N-N interaction by analyzing the $\Delta J^\pi = 0^-$ transitions observed in the (p,n) reactions on ^{13}C, ^{14}N, and ^{15}N. These transitions are of particular interest because of their high sensitivity to the tensor force in low-multipole, medium-momentum transfer ($q \le 1.3$ fm^{-1}) regions. Isovector stretched transitions, on the other hand, provide information on the tensor force in high-multipole, large-momentum transfer regions. As seen in Fig. 2, the DWBA calculations reproduce the backward-angle (p,n) cross sections including their absolute values reasonably well. This leads to a conclusion that the presently applied effective N-N interaction, especially its tensor parts,

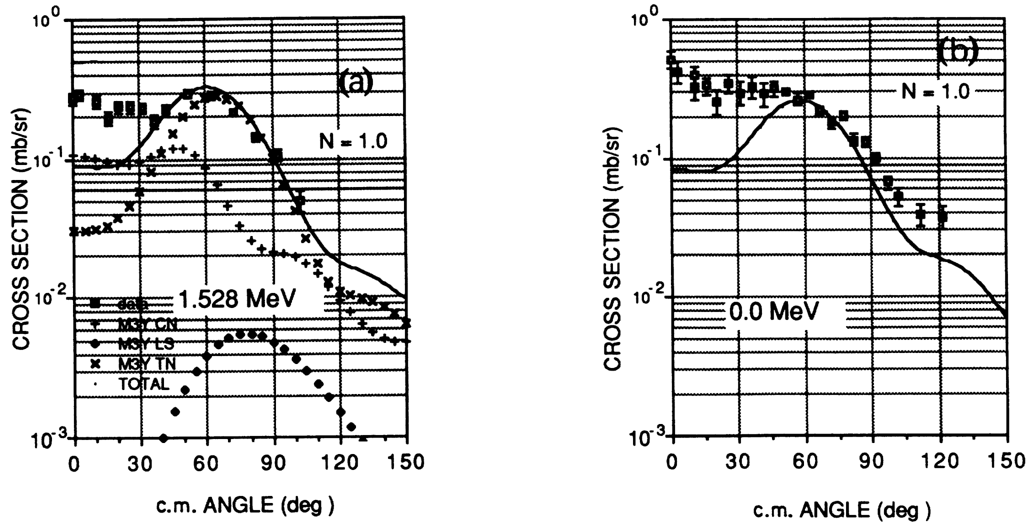

FIG. 2. Angular distributions of neutrons leading to the lowest 5^+ states in ^{22}Na (a) and in ^{26}Al (b). Curves are DWBA predictions without any scaling. The contribution from each part of the effective interaction is shown separately for the ^{22}Ne$(p,n)^{22}$Na reaction.

are as good even in the large-momentum transfer region of $q \sim 1.0$ through 2.0 fm^{-1} as in the medium-q region (~ 0.5 fm^{-1}) confirmed previously from the analysis of $\Delta J^{\pi}=0^-$ transitions.

Also illustrated separately in Fig. 2 are the contributions of central (CN), spin orbit, and tensor (TN) parts of the effective interaction to the $0^+ \rightarrow 5^+ (p,n)$ cross section for the ^{22}Ne$(p,n)^{22}$Na reaction. The differential cross sections due to the direct term of the isovector tensor interaction dominate at least after 30°. Relative importance of the contribution from the central force is one of the features of low-energy (p,n) reactions, while the LS interaction plays only a minor role in an isovector unnatural transition regardless of incident proton energy.

The present DWBA analysis fails to reproduce the (p,n) cross sections at small angles. This situation seems to be common even in the stretched or high-spin state excitations by proton inelastic scattering at higher proton energies as reported by Emery and his collaborators.[21] They observed $\Delta T=0$, 1, and $\Delta S=0$, 1 high-spin states systematically at incident energies ranging from 80 to 180 MeV. Their analysis has shown that the small-angle cross sections are difficult to explain at lower incident energies. As seen in Fig. 2, forward-angle cross sections arise mainly from the central force. Thus, the present result leads to a speculation that high-multipole components of central effective interactions employed in current analyses are unsatisfactory.

In summary, we have observed $0\hbar\omega$ $0^+ \rightarrow 5^+$ stretched particle-hole excitations in the charge-exchange (p,n) reactions on *sd*-shell nuclei. DWBA calculations with effective N-N interactions reproduced the experimental absolute differential cross sections except those at small angles, indicating the applicability of the isovector tensor interaction used in the present analysis in high-multipole large-q regions. Combining this with the previous results for the $\Delta J^{\pi}=0^-$ transitions, where low-multipole medium-q regions of the isovector tensor interaction have been tested against the data, we may conclude that the isovector tensor part of the currently used effective interaction based on the G-matrix theory is quite reasonable over a wide range of momentum transfer ($q \leq 2.3$ fm^{-1}). The differential cross sections at small angles remain unexplained, but the present analysis suggests this may be due to unsatisfactory high-multipole low-q components of the central part of the effective N-N interactions.

This work was partially supported by the Ministry of Education, Science, and Culture of Japan by a Grant-in-Aid for Scientific Research, Grant No. 59540147.

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