less radial wave functions as encountered in the present experiment. Here theory predicts that mesonic effects prevail. Calculations including ρ exchange, which are precise enough to exploit the accuracy of our measurement for a more detailed comparison, have not yet been performed.

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"Stretched" 6^- $T=1$ State in ^{24}Al Observed in the Reaction ^{24}Mg$(p,n)^{24}$Al

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An isovector $M6$ transition is observed for the first time in a (p,n) reaction. A prominent peak was seen at $E_x = 5.545 \pm 0.025$ MeV in ^{24}Al in the study of the reaction ^{24}Mg$(p,n)^{24}$Al at $E_p = 35$ MeV. This state is interpreted as the "stretched" particle-hole state with $J^\pi = 6^-$, $T=1$, which corresponds to the 15.13-MeV state in ^{24}Mg. Distorted-wave Born approximation analysis gives a result consistent with those for (p,p') and (e,e') reactions, indicating that at least 50% of the isovector $M6$ strength is missing.

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The magnetic excitation of nuclei is an area of high current interest. A π meson carries a unit of $\Delta\sigma$ and $\Delta\tau$, where σ and τ are the nucleonic spin and isospin variables. Hence pioniclike excitations are unnatural-parity excitations having $T=1$. The spin-isospin mode of excitation can be directly related to charge-exchange reactions such as (π^+, π^0), (p,n), $(^3\mathrm{He}, t)$, etc. For example, Gamow-Teller (GT) states in $N>Z$ nuclei have been studied in charge-exchange reactions and it seems established[1-3] that the observed GT strength is usually (30–50)% of the sum-rule limit. Dependencies of quenching effects of nuclear magnetic properties on the mass and spin[4] are expected to advance the study of nuclei as systems of elementary particles. The one-pion exchange also gives rise to a strong tensor interaction in the (τ, τ) channel.[5] The tensor interaction can be studied in (p, n) reactions in which high-spin states are excited. Thus new data on high-spin unnatural-parity states, especially "stretched" particle-hole states, i.e., $(j_p j_n^{-1})_{\max}$, where $j_p = l_p + \frac{1}{2}$, $j_n = l_n + \frac{1}{2}$, and $j_{\max} = j_p + j_n$, present challenging problems in various aspects of physics today. The number of one-particle, one-hole excitations which can contribute to these states is severly restricted, and hence they also provide excellent candidates to test the validity of a model calculation.

Such stretched states have been studied so far in medium-energy electron scattering experiments at backward angles and (p, p') experiments. For example, Zarek *et al.*[6] observed a 6^-, $T=1$ state in the reaction ^{24}Mg(e, e'); the high-spin particle-hole states in ^{28}Si and ^{24}Mg were observed by Adams *et al.*[7] in the scattering of 135-MeV protons and by Hosono *et al.*[8] in the scattering of 65-MeV protons. Stretched states of different configurations, i.e., the $(\pi f_{7/2} \nu f_{7/2}^{-1})_{7^+}$ state in ^{48}Sc ("$0\hbar\omega$" excitation) and the $(\pi d_{5/2}\text{-}\nu p_{3/2}^{-1})_{4^-}$ state in ^{16}F ("$1\hbar\omega$" excitation), have recently been observed in the reactions ^{48}Ca$(p, n)^{48}$Sc,[9] and ^{16}O$(p, n)^{16}$F.[10,11]

In this Letter we report, for the first time, the observation of a stretched particle-hole 6^- state of a $1\hbar\omega$ character populated in a (p, n) charge-exchange reaction. We have studied the reaction ^{24}Mg$(p, n)^{24}$Al at $E_p = 35$ MeV, and observed a prominent narrow peak at $E_x = 5.545$ MeV. A comparison of the cross section with the prediction of distorted-wave Born approximation (DWBA) gives us information on the quenching effect of nuclear magnetic properties.

The experiment was performed with use of a 35-MeV proton beam from the azimuthally varying field cyclotron and the time-of-flight facilities[12] 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°. The target was prepared by rolling metallic magnesium enriched to 99% in ^{24}Mg. Its thickness was 3.4 mg/cm^2. Overall time resolution was 1.3 ns. The errors in the absolute cross section are estimated to be ~20%, while the relative errors are ~7%. Further details of the experiment are given in our previous papers.[2,12]

A representative neutron energy spectrum is shown in Fig. 1. A peak at $E_x = 5.545 \pm 0.025$ MeV is conspicuous at large momentum transfer. The 5.545-MeV state in ^{24}Al should correspond to a $T=1$ ^{24}Mg state at 15.06 MeV or a little higher con-

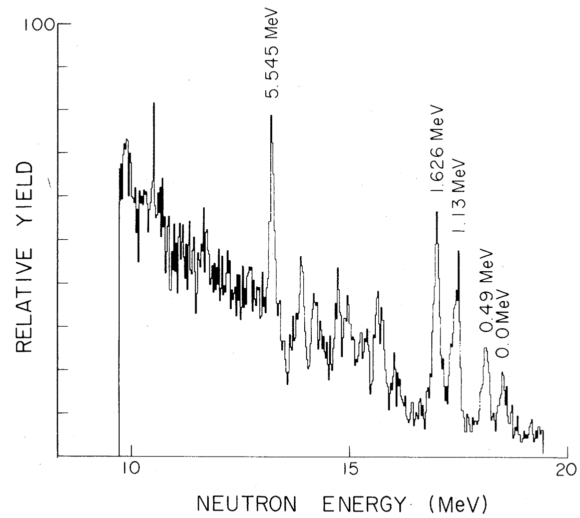

FIG. 1. Neutron energy spectrum for the reaction ^{24}Mg$(p, n)^{24}$Al at $\theta_{\rm lab} = 80°$ measured with 35-MeV protons at a neutron flight path of 24.6 m. The ordinate is compensated for the variation of the detector efficiency with respect to neutron energy. Energy per bin is 25 keV.

sidering the Thomas-Ehrman shift[13] for the unbound ^{24}Al state. This energy is in good agreement with the excitation energy of the 6^-, $T=1$ state in ^{24}Mg reported by Zarek *et al.*[6] (15.130 ±0.040 MeV) and by Adams *et al.*[7] (15.137 ±0.022 MeV). We estimate the width of the 5.545-MeV state to be $\lesssim 110$ keV by quadratically subtracting the contributions of time spread and target thickness from the observed peak width. Another strongly populated level at $E_x = 1.626 \pm 0.025$ MeV is also noticeable. A comparison with backward-angle electron scattering data suggests that this state is the analog of the 4^-, $T=1$ state at $E_x = 10.95$ MeV in ^{24}Mg.[14]

Figure 2 shows the angular distributions for the 5.545- and 1.626-MeV states at $E_p = 35$ MeV. Solid curves in Fig. 2 are DWBA predictions calculated by the code DWBA-70, which includes knock-on exchange contributions.[15] For the p-n interaction, a set of effective interactions (M3Y), which has been derived by Bertsch *et al.*[16] by fitting a superposition of Yukawa potentials with different ranges to the G matrix generated from the nucleon-nucleon potential, is employed. Optical-potential parameters of Fabrici *et al.*[17] are used for protons. Those for neutrons are self-consistent potential parameters derived by Carlson, Zafiratos, and Lind.[18] Pure $(\pi d_{5/2}{}^4 \nu d_{5/2}{}^4)$ configuration is assumed for the ground state of ^{24}Mg. The DWBA curve for the 5.545-MeV state

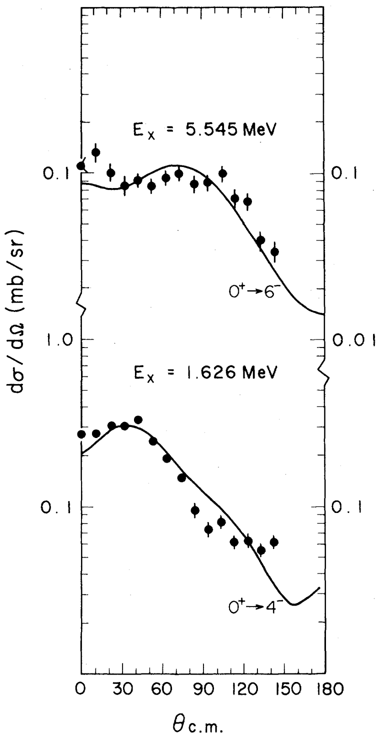

FIG. 2. Differential cross sections for the peaks corresponding to the 5.545- and 1.626-MeV states in ^{24}Al. The curves are DWBA predictions calculated with the M3Y interaction. The curves are normalized to the data at $\theta_{c.m.} \approx 32°$.

is calculated for the pure $(\pi f_{7/2} d_{5/2}{}^4 \nu d_{5/2}{}^3)_{6^-}$ configuration. The curve for the 1.626-MeV state is calculated for the 4^- state with the same configuration. Other configurations are likely to be involved in the 4^- state, as indicated by the 200-keV shift in Coulomb energy, and so the DWBA curve is displayed in Fig. 2 for the purpose of comparison only. The calculated angular distribution shapes for these states are in reasonable agreement with the measurements, supporting the 6^- and 4^- assignments for the 5.545- and 1.626-MeV states, respectively.

The cross-section magnitude calculated for the 6^- state with the pure configuration is much larger than the experimental value: σ_{exp}/σ_{th} is found to be 0.25. Lindgren *et al.*[19] compared the (e,e') cross sections with the (p,p') cross sections for the stretched states to check the high-momentum components of the tensor part of the nucleon-nucleon force. Assuming pure particle-hole configuration, they obtained $\sigma_{exp}/\sigma_{th} = 0.27$ for the (e,e') transition, and $\sigma_{exp}/\sigma_{th} = 0.30$ for the (p,p') transition at $E_p = 135$ MeV, to the 15.13-MeV (6^-, $T=1$) state in ^{24}Mg. The present result is consistent with those of Lindgren *et al.*, in spite of the fact that the momentum transfer involved in the present work, 0.49–2.15 fm^{-1}, is smaller than in the (e,e') and (p,p') experiments. Such an agreement corroborates the 6^-, $T=1$ assignment for the 5.545-MeV state in ^{24}Al. It also implies that the 15.1-MeV state in ^{24}Mg is a good $T=1$ state. The ratio σ_{exp}/σ_{th} for the 1.626-MeV state is 0.38, suggesting again mixtures of other components in the 4^- state. In particular, a small mixture of the $(\pi f_{7/2} \nu s_{1/2}{}^{-1})$ and $(\pi p_{3/2}\text{-}\nu d_{5/2}{}^{-1})$ particle-hole excitations, which are not included in the present DWBA calculation, would enhance the cross section considerably.

It has been shown that the tensor force plays the most important role in the analyses of the 135-MeV (p,p') data.[19-21] In the present case about a half of the calculated cross section is due to the tensor force. The consistency of the present result with the previous (p,p') analyses indicates therefore that the missing $M6$ strength cannot be attributed to the choice of the effective interactions.

Because of large deviations in the ratio σ_{exp}/σ_{th}, Petrovich and Love[20] have suggested that there are significant differences in the structure of the stretched 6^- $T=0$ and 6^- $T=1$ states in ^{24}Mg and ^{28}Si, probably more complicated structure in the 6^- $T=0$ wave functions than in the 6^- $T=1$ wave functions. Zarek *et al.* found that the ratio $\sigma_{exp}/\sigma_{th} = 0.48 \pm 0.2$ for the (e,e') transition for the 15.13-MeV state in ^{24}Mg when the open-shell random-phase–approximation wave functions were used.[6] The analysis of the 135-MeV (p,p') data by Amos *et al.*[22] using projected Hartree-Fock wave functions was consistent with the (e,e') result in that they had to reduce the effective interaction strength to 70%. The ratio σ_{exp}/σ_{th} for the (p,n) reaction is expected to increase also to about 0.5 by the use of such sophisticated wave functions, since the present analysis using the pure wave functions for the (p,n) reaction leading to the 6^- $T=1$, $T_z = -1$ state gives a consistent result with those for the (e,e') and (p,p') reactions leading to the 6^- $T=1$, $T_z = 0$ state. Therefore it seems that about 50% of the isovector $M6$ strength is missing at present even if complicated wave functions are used.

In conclusion, we observed a state at an excitation energy of 5.545-MeV in the reaction ^{24}Mg$(p,n)^{24}$Al. Its width is less than 110 keV. An assignment of 6^- $T=1$ has been given to this state, on the basis of the excitation energy, angular distribution, and strength. This is the first time that the isovector $M6$ transition has been observed in a (p, n) reaction. At least 50% of the isovector $M6$ strength remains unexplained and awaits further studies of the magnetic properties of nuclei.

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