PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

Pion scattering to 6^- stretched states in ^{24}Mg and ^{26}Mg

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(Received 20 August 1991)

Inelastic $\pi^{\pm}$ cross-section measurements at pion incident energies of 150 and 180 MeV were made on 6^- states in ^{24,26}Mg. In particular, we have determined the $(f_{7/2}d_{5/2}^{-1})_{6^-}$ isoscalar $Z_0=0.21\pm0.02$ strength for the strongest $T=0$, $J^{\pi}=6^-$ state located at 12.11 ± 0.05 MeV in ^{24}Mg, and the isoscalar $Z_0=0.17\pm0.04$ and isovector $Z_1=0.21\pm0.02$ strength for the strongest $T=1$, $J^{\pi}=6^-$ state located at 9.18 MeV in ^{26}Mg. The distorted-wave impulse-approximation pion cross-section calculations required a multiplicative normalization factor of 1.2 ± 0.1 in order to reproduce the pure isovector strength deduced from electron scattering for the well-known $T=1$, $J^{\pi}=6^-$ state at 15.15 MeV in ^{24}Mg and the $T=2$, $J^{\pi}=6^-$ state at 18.05 MeV in ^{26}Mg.

I. INTRODUCTION

The literature has a minimal amount of experimental information on isoscalar transition strengths to unnatural parity states. Measurements on isoscalar magnetic transitions are very important because they help constrain the poorly known strengths of the isoscalar tensor and spin-orbit forces in the nucleus, which are required for a better understanding of nuclear structure and of inelastic proton-nucleus scattering at intermediate energies [1]. One of the chief difficulties in obtaining isoscalar magnetic transition strengths is the lack of any one probe to selectively excite them with a well-understood reaction mechanism. The well-known electromagnetic interaction strongly favors isovector magnetic transitions over isoscalar magnetic transitions. Even in the few cases where transitions to known $T=0, J^{\pi}=1^+$ and 4^- states in ^{12}C and ^{16}O have been observed [2,3], the extraction of the isoscalar part is complicated by strong $T=1$ isospin admixtures.

In contrast, pion scattering at energies near the delta (3,3) resonance excites pure isoscalar magnetic transitions about a factor of 4 times more strongly than pure isovector transitions. For a few cases [4–6], pion scattering data near resonance, when combined with electron scattering data, has been very effective in determining the isoscalar and isovector "stretched" transition strength for pure and mixed isospin transitions. A comparison of these measurements for $M6$ transitions in ^{28}Si with recent large basis nuclear structure shell model (LBSM) calculations[7] shows that, although the experimental *isovector* $M6$ strength to the yrast $T=1, J^{\pi}=6^-$ state at $E_x=14.356$ MeV is reproduced within 15%, the experimental *isoscalar* $M6$ strength to the yrast $T=0, J^{\pi}=6^-$ state at $E_x=11.579$ MeV $[(Z_0^2)_{\text{exp}}=0.14\pm0.04]$ is 43% smaller than theory $[(Z_0^2)_{\text{th}}=0.20]$.

We do not feel that the ^{28}Si nucleus is an isolated example of the failure of such calculations, but is a symptom of a systematic failure in several nuclei. For example, in ^{24}Mg, similar calculations [8] predict a similar distribution of isoscalar and isovector $M6$ strength (see Table I). However, previous proton scattering measure-

TABLE I. The Z coefficients for the pure isoscalar and pure isovector 6^- states in ^{24}Mg, ^{26}Mg, and ^{28}Si observed by pion and electron scattering [7,19]. The theoretical Z coefficients are from the sum rules of Ref. [6] for the extreme-single-particle model (ESPM) and from the large basis shell model (LBSM) calculations of Carr [7,8]. The ratio between experiment and theory is defined as $S_\tau^2=(Z_\tau^2)_{\rm exp}/(Z_\tau^2)_{\rm th}$.

E_x (MeV) exp	th	τ	$(Z_\tau^2)_{\rm exp}$	$(Z_\tau^2)_{\rm th}$ ESPM	$(Z_\tau^2)_{\rm th}$ LBSM	S_τ^2 ESPM	S_τ^2 LBSM
^{24}Mg							
12.11	14.4	0	0.04±0.01	$\frac{2}{3}$	0.20	0.07	0.22
15.15	16.9	1	0.19±0.01	$\frac{2}{3}$	0.30	0.29	0.65
^{26}Mg							
18.05	18.8	1	0.15±0.02	$\frac{1}{3}$	0.20	0.44	0.73
^{28}Si							
11.58	11.7	0	0.14±0.04	1	0.20	0.14	0.69
14.36	14.4	1	0.33±0.04	1	0.37	0.33	0.88

ments [9], which identified the $T=0$ and $T=1, J^\pi=6^-$ states in ^{28}Si and the $T=1, J^\pi=6^-$ state in ^{24}Mg, were unable to identify any $T=0, J^\pi=6^-$ state in ^{24}Mg. Consequently, the concentration of the yrast isoscalar $M6$ strength must be much weaker than current shell model predictions and weaker than the sensitivity of previous proton scattering measurements in ^{28}Si.

In this paper, we report on new results from pion measurements on ^{24}Mg that, when combined with electron scattering, identify the missing $T=0$ "stretched" $(f_{7/2}d_{5/2})_{6^-}$ strength at $E_x=12.11$ MeV in ^{24}Mg, which is indeed significantly weaker than any theoretical predictions. In addition, we report on possible (isoscalar and isovector) $M6$ strength for the "stretched" $(f_{7/2}d_{5/2})_{6^-}$ transition to the yrast $T=1, J^\pi=6^-$ state at 9.18 MeV in ^{26}Mg, which is in strong disagreement with that from analysis of recent proton scattering measurements [10]. We also discuss the pure isovector $M6$ strengths for transitions to 6^- states at 15.15 MeV ($T=1$) in ^{24}Mg and 18.05 MeV ($T=2$) in ^{26}Mg.

II. EXPERIMENT

The work described here is part of a larger study reporting angular distributions for pion scattering to approximately 40 excited states in ^{24}Mg and ^{26}Mg [11]. Inelastic π^+ and π^- cross sections were measured at the Clinton P. Anderson Meson Physics Facility (LAMPF) of the Los Alamos National Laboratory using the Energetic Pion Channel and spectrometer (EPICS) facility described elsewhere [12]. This experiment used π^+ and π^- beams incident on ^{26}Mg at 116, 180, and 292 MeV during one data-acquisition period and on a split target of ^{24}Mg and ^{26}Mg at 150 and 180 MeV during another period. The targets consisted of 97-mg/cm^2 ^{24}Mg foils and 200-mg/cm^2 ^{26}Mg foils enriched to greater than 99%. Pion scattering on hydrogen was used for absolute normalization.

Examples of π^+ and π^- spectra in the excitation energy range $8 \le E_x \le 16$ MeV at $\theta=90°$, normalized and corrected for the spectrometer acceptance, are shown for ^{24}Mg in Fig. 1. The prominent peaks at 9.97, 11.08, 12.89, and 13.96 MeV are characteristic of, or are known to have, isospin $T=0$ and spin-parity assignments $J^\pi=5^-$, 3^-, 0^+, and 3^-, respectively. The peaks at 15.15 and 15.5 MeV are identified with the known $T=1, J^\pi=6^-$ and 4^- states, respectively. The prominent peak at 12.11 MeV is identified in this work as the $T=0, J^\pi=6^-$ state. The extracted cross sections for the states of interest at $E_x=12.11$ and 15.15 MeV in ^{24}Mg and at $E_x=9.18$ and 18.05 MeV in ^{26}Mg are plotted together with distorted-wave impulse-approximation (DWIA) calculations in Figs. 2 and 3.

III. DWIA CALCULATIONS

The DWIA calculations were performed with the code ALLWRLD [13] in order to generate pion form factors for

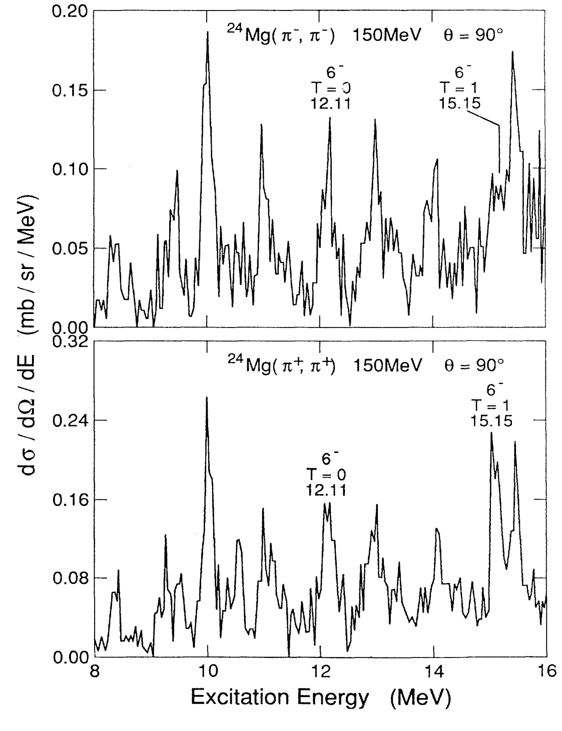

FIG. 1. Spectra of 150 MeV π^- and $\pi^+ \theta=90°$ inelastic scattering from ^{24}Mg. The 12.11 MeV $T=0$ and 15.15 MeV $T=1, J^\pi=6^-$ states are evident.

input to the pion distorted-wave code MSUDWPI [14], using the same spin-orbit force and optical potential parameters as previously reported [6], and a charge radius of 3.06 fm for ^{24,26}Mg from electron scattering [15]. The ground-state density distribution parameters used in these two codes were assumed to have a Woods-Saxon (WS) form $\rho(r)\propto(1+e^{(r-c)/a})^{-1}$ with radius $c=2.88$ fm and diffuseness $a=0.52$ fm taken from previous pion scattering analysis [11]. Two sets of transition densities were used as input to ALLWRLD: a set using simple harmonic-oscillator (HO) wave functions, as well as a set using Woods-Saxon (WS) wave functions which are especially important for unbound states. All of the following results use HO wave functions unless specifically noted. The differential scattering cross section for pion scattering to stretched magnetic transitions between states of isospin T and $T+1$ can schematically be written as

$$d\sigma^{\pm}/d\Omega=N(M_1^{\mp})^2[(M_0^{\mp}/M_1^{\mp})Z_0+Z_1]^2\ , \tag{1}$$

where N is an empirical normalization of the pion calculated cross sections to known electron scattering strengths, $M_\tau^{\mp}$ are matrix elements calculated in DWIA, and Z_τ are spectroscopic coefficients for a pure isoscalar ($\tau=0$) or isovector ($\tau=1$) single-particle-hole $(f_{7/2}d_{5/2}^{-1})_{6^-}$ transition. The simplifying characteristics of stretched excitations which justify the form of Eq. (1), as well as the procedure for center-of-mass corrections, have been discussed elsewhere [1,6]. For incident pion energies near the delta (3,3) resonance $M_0^{\pm}/M_1^{\pm}\approx\mp 2$, for $\pi^{\pm}$ scattering. The normalization factor N is assumed to have the same value in π^+ as in π^- scattering and is determined empirically.

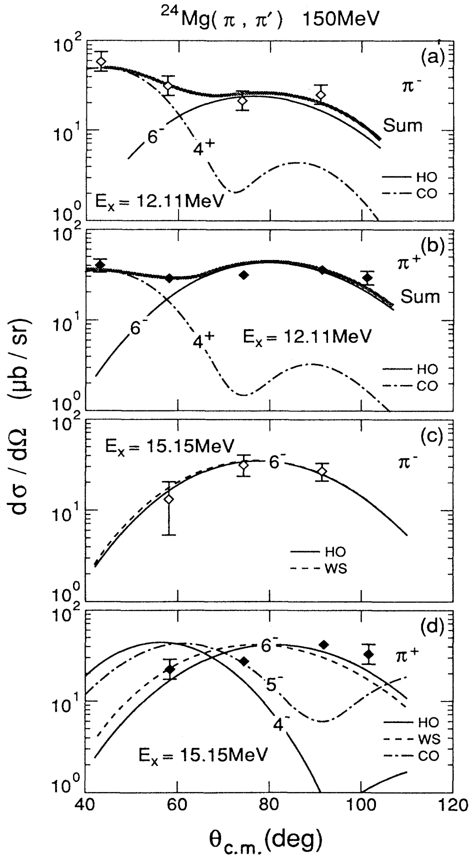

FIG. 2. Data from π^+ (solid diamonds) and π^- (open diamonds) scattering for the identified 6^- states in ^{24}Mg obtained at an incident pion energy of 150 MeV. The data compared to DWIA calculations, which use wave functions based on the harmonic-oscillator (HO) model, the Woods-Saxon (WS) model, and the collective (CO) model. Theoretical calculations for $J^\pi=4^-$ and 5^- multipoles are included for comparison to the known $T=1,J^\pi=6^-$ state at $E_x=15.15$ MeV in ^{24}Mg.

A. ^{24}Mg results

The angular distributions of π^+ and π^- data to the well-known $T=1,J^\pi=6^-$ state at $E_x=15.15$ MeV in ^{24}Mg are shown in Figs. 2(c) and 2(d). For this pure isovector transition, $Z_0=0$ in Eq. (1) and electron scattering results [16] have yielded $Z_1=0.44\pm0.01$. The factor N is varied in the DWIA calculation of the cross section until the lowest χ^2 is obtained in fitting both the π^+ and π^- data at 150 and 180 MeV. An average value of $N=1.23\pm0.11$ was obtained from the fits to the $E_x=15.15$ MeV state shown in Figs. 2(c) and 2(d). In addition, the ratio of π^+ to π^- cross sections, which is independent of N, was fitted by permitting Z_0 to vary freely. As expected, a very small value of Z_0 was found ($Z_0=-0.02\pm0.01$) and Z_1 was in agreement with electron scattering results, $Z_1=0.44\pm0.01$.

The π^+ and π^- cross-section data for a state at 12.11 ± 0.05 MeV are shown in Figs. 2(a) and 2(b) and compared to 4^+ and 6^- angular distributions, with the best fit being given by sum of the $(f_{7/2}d_{5/2}^{-1})_{6^-}$ one-body transition density using $N=1.23$ and the 4^+ angular distribution. The high data point at $\theta_{\text{c.m.}}=42°$ in Figs. 2(a) and (2b) indicates that known levels, such as the $E_x=12.05(4^+)$, $12.1(4^+)$, and $12.157(4^+)$ [17], dominate at low q for our experimental resolution, and therefore both a 4^+ and a 6^- were included in the fit. The Z_0 and Z_1 were varied until the best fit to both the π^+ and π^- data was obtained, resulting in average values of $Z_0=-0.21\pm0.02$ and $Z_1=0.07\pm0.04$. Based on the angular distribution and the extracted Z coefficients, we identify this ^{24}Mg state as a $T=0,J^\pi=6^-$ state, and take $Z_1=0$ (assuming negligible isospin mixing). Previous electron scattering measurements [16] at the peak of the $T=1$, $M6$ momentum transfer at back angles show very weak unresolved structure at about 12.11 MeV excitation that is consistent with the deduced isoscalar strength. In a previous 135 MeV 35° proton scattering spectrum [9], a peak at 12.140 ± 0.007 MeV was observed with a height about half that of the $T=1,J^\pi=6^-$ 15.15 MeV peak, but no angular distribution was reported. The relative height of the 12.140 MeV peak is consistent with proton distorted wave calculations for a $T=0,J^\pi=6^-$ state when using our extracted Z coefficients. Other unknown small peaks in the energy range $10\leq E_x\leq 15$ MeV, such as those at 10.4, 11.3, 13.3, and 14.4 MeV, are each less than 10% of the peak cross section of the 12.11 MeV state shown in Fig. 1, and are too weak to identify the multipolarity.

This includes the 11.293 MeV peak, reported to be a possible 6^- state from 35 MeV proton scattering [18].

Compared to ^{28}Si where the $T=0, J^\pi=6^-$ state represents 14% ($Z_0^2=0.14$) of the total $(f_{7/2}d_{5/2}^{-1})$ strength [7], the $T=0, J^\pi=6^-$ state in ^{24}Mg represents only 4.4% ($Z_0^2=0.044$) of the total $(f_{7/2}d_{5/2}^{-5})$ strength (see Table I). Recent large basis shell model calculations predict that the $T=0, J^\pi=6^-$ strength concentrated in the yrast state should be $Z_0^2=0.20$ for both nuclei [8]. Thus these shell model calculations are about 50% larger than the experimentally determined isoscalar strength in ^{28}Si, but are a factor of about 4 too high for the isoscalar strength in ^{24}Mg. This is in contrast to the much better predictions shown in Table I for the isovector strength for these two nuclei.

B. ^{26}Mg results

The π^+ and π^- data for the known $T=2, J^\pi=6^-$ state at 18.05 MeV in ^{26}Mg are shown in Figs. 3(c) and 3(d). In fitting both the π^+ and π^- angular distribution at 150 and 180 MeV, an average normalization factor of $N=1.25\pm0.14$ was found, which is comparable to the average value obtained for the 15.15 MeV state in ^{24}Mg. For this pure isovector transition, electron scattering results [19] have yielded $Z_1=0.38\pm0.03$.

The π^+ and π^- data for the known $T=1, J^\pi=6^-$ state at 9.18 MeV in ^{26}Mg are shown in Figs. 3(a) and 3(b). The rise in cross section at $\theta_{\rm c.m.}=50°$ compared to the $L=6$ DWIA calculated curve indicates that other levels of lower multipolarity, such as the known 9.261 MeV (4^+) state [20], lie within our experimental energy resolution. Assuming that the observed peak is dominantly the 6^- state observed in (e,e') at 9.18 MeV, Z coefficients extracted from pion and electron data are shown in Table II. The tabulated numbers are weighted averages of four independent pairs of Z_0 and Z_1 from the π^+ and π^- data at 150 and 180 MeV. Since Eq. (1) is quadratic in Z, there are two solutions for each independent data set, but the alternative solution could always be rejected because it led to unphysical values of N and Z.

In Figs. 3(a) and 3(b) the 9.18 MeV cross sections are seen to be about three times larger for π^- than for π^+ near the peak of the $L=6$ part of the total calculated angular distribution. This observation, as reflected by the Z_0 and Z_1 values shown in Table II yielding $Z_n=(Z_0+Z_1)/\sqrt{2}=0.27$ and $Z_p=(Z_0-Z_1)/\sqrt{2}=-0.03$, suggests that this state has a much larger neutron particle-hole component than proton. A peak in this region was also strongly excited in the $(\alpha, ^3\text{He})$ neutron transfer reaction [21], and the Z coefficients from a combined (p,n) and (p,p') analysis [10,22] favor values consistent with a neutron excitation, although the resulting fit to the proton data is poor. In agreement with this experimental data, shell model calculations predict that the lowest 6^- state should be predominantly a neutron

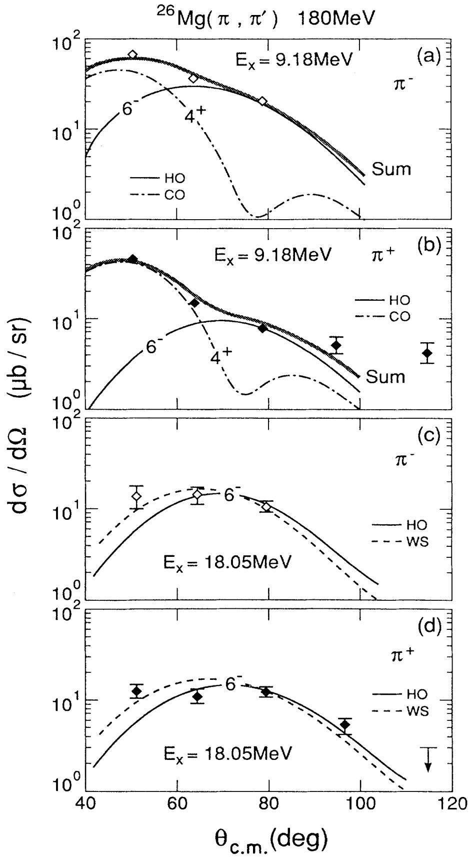

FIG. 3. Data from π^+ (solid diamonds) and π^- (open diamonds) scattering for the identified 6^- states in ^{26}Mg obtained at an incident pion energy of 180 MeV. The data are compared to DWIA calculations, which use wave functions based on the harmonic-oscillator (HO) model, the Woods-Saxon (WS) model, and the collective (CO) model.

TABLE II. The Z coefficients for the 9.18 MeV $T=1, J^\pi=6^-$ state in ^{26}Mg.

	Z_0	Z_1	Ref.
Experiment			
$(\pi,\pi'),(e,e')$	0.17±0.04	0.21±0.02	
$(p,p'),(e,e')$	0.23	0.21	[10]
$(p,p'),(e,e')$	−0.14±0.03	0.15±0.03	[10]
$(p,p'),(p,n)$	0.20±0.03	0.30±0.03	[10]
Theory (shell model)			
$(d_{5/2})^9f_{7/2}$	0.83	0.5	[10]
$(d_{5/2}s_{1/2})^9f_{7/2}$	0.30	0.39	[10]
$(d_{5/2}s_{1/2})^{9-n}d_{3/2}^nf_{7/2}$, $n\le4$	0.26	0.31	[8]

particle-hole excitation [8,10]. In a recent analysis of inelastic proton scattering on ^{26}Mg that was combined with electron scattering data [10], the two sets of Z coefficients shown in Table II were calculated. Values of $Z_0=0.23$ and $Z_1=0.21$, which are consistent with the pion data, yield disturbing fits to the proton data, particularly on the low-q side of the peak. The alternative set of fitting coefficients, $Z_0=-0.14$ and $Z_1=0.15$ are reported to give the best fit to the proton angular distribution of the cross section and analyzing power, but are in strong disagreement with our result from fitting the pion data. This disagreement with the proton data is disturbing and has not yet been resolved. Assuming that proton, pion, and electron scattering are exciting the same state, one interesting possibility is that the Franey-Love interaction [23] of the DWIA calculation may use phases between the isoscalar and isovector reaction amplitudes for mixed isospin transitions that are questionable.

IV. DISCUSSION AND CONCLUSIONS

Including isovector meson exchange current contributions to the electron scattering cross sections will increase the theoretical cross sections by 12% to 17%, thus reducing the value of the isovector Z_1 coefficient. The use of a smaller Z_1 coefficient in the analysis of the pion scattering would decrease the extracted Z_0 coefficient by a similar amount due to the increased value of N. The use of WS wave functions [19] leaves the Z coefficients virtually unchanged for the bound 12.11 MeV ^{24}Mg and 9.18 MeV ^{26}Mg transitions whereas the Z_1 coefficients are increased for the unbound pure isovector transitions—13% for the 15.15 MeV ^{24}Mg state and 23% for the 18.05 MeV ^{26}Mg state.

In conclusion, we find that the extracted isoscalar $M6$ strength in ^{24}Mg is severely quenched, with only 4.4% of the expected total being observed. The percentage is about $\frac{1}{4}$ that predicted by large basis shell model calculations which do reasonably well at predicting the isoscalar $M6$ strength in ^{28}Si. In addition, we find the $T=1, J^{\pi}=6^-$ yrast state in ^{26}Mg to be dominantly a neutron excitation in contrast to a proton excitation as reported from proton scattering. This disagreement suggests that the phases between the isoscalar and isovector scattering amplitudes used in the DWIA calculation are questionable.

The research reported here was supported in part by the U.S. National Science Foundation, the U.S. Department of Energy, and the Robert A. Welch Foundation.

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