Fragmentation of high-spin particle-hole states in ^{26}Mg

R. E. Segel

Northwestern University, Evanston, IL 60204*

and

Argonne National Laboratory, Argonne, IL 60439-4843Received by C...
NOV 22 1989A. Amusa,[†] D. F. Geesaman, R. D. Lawson and B. ZeidmanArgonne National Laboratory, Argonne, IL 60439-4843

C. Olmer, A. D. Bacher, G. T. Emery, C. W. Glover, H. Nann and W. P. Jones

Indiana University Cyclotron Facility, Bloomington, IN 47405

S. Y. van der Werf

Kernfysisch Versneller Instituut, Groningen, The Netherlands

R. A. Lindgren

University of Virginia, Charlottesville, VA 22901**Abstract**

The inelastic scattering of 134 MeV protons to seven 6^- states in ^{26}Mg has been studied. By combining the results with those of a companion electron scattering study, and utilizing DWIA calculations, it has been possible to extract isoscalar and iso-vector excitation amplitudes. Shell model calculations using $(1d_{5/2})^{10-n-p} (2s_{1/2})^n (1f_{7/2})^p$, with $p = 0$ and 1, model spaces can reproduce the general features of the fragmentation, but not the structure of the yrast 6^- state.

*Permanent address.

[†]Permanent address: Obafemi Awolowo University, Ile-Ife, Nigeria.

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I. INTRODUCTION

Systematic information is now being obtained from inelastic scattering and charge exchange reactions on the excitation of spin-flip degrees of freedom throughout the periodic table. A systematic quenching of the isovector spin-flip strength has been identified,¹ though the quenching mechanism is not understood. Inelastic proton and pion scattering reactions also indicate substantial quenching for isoscalar spin flip excitations, but the systematics of this effect are less well established.^{2,3}

Several theoretical explanations have been offered for this reduction in the spin-flip strength. These explanations include: fragmentation of the single-particle strength,^{4,5} large 2-particle, 2-hole correlations due to the tensor force,⁶ mesonic renormalization of the spin current⁷ and the explicit inclusion of $\Delta(1232)$ isobar-hole states.⁸ The last two mechanisms do not contribute significantly in isoscalar channels. One approach to separate these mechanisms is to study the inelastic transition strengths as a function of single-particle occupation probability and angular momentum. Data for neighboring nuclei exist only in the p shell and the (sd) shell, but in ^{12}C and ^{16}O substantial isospin mixing introduces complications for the high spin (4^-) states. The deformed nuclei in the (sd) shell seem to be excellent candidates for these studies with several high-spin, 6^- , and low spin, 1^+ , states known from previous work.^{2,3,9}

This work presents a study of the 6^- states in ^{26}Mg . Since the ^{26}Mg ground state is $T = 1$, $T_z = 1$, one-particle one-hole excitations can form both $T = 1$ and $T = 2$ states. While the excitation of the $T = 2$ states must be pure isovector, $T = 1$ states will be formed by a combination of isoscalar and isovector excitations. However, as is detailed below, by combining the results of electron and polarized proton scattering measurements, the excitation of a

given state can be decomposed into its separate isospin components. The present work reports the results of the scattering of 134 MeV polarized protons by ^{26}Mg . In the analysis these results are combined with those from a companion electron scattering experiment¹⁰ in order to deduce the isoscalar and isovector contributions to the cross sections. Comparing these results with previously published data on ^{24}Mg and ^{28}Si makes it possible to determine the variation of the quenching as the s-d shell is filled.

II. EXPERIMENTAL RESULTS

Polarized protons from the Indiana University Cyclotron Facility were scattered by an 8.45 mg/cm² ^{26}Mg target, enriched to > 98.8% ^{26}Mg , and analyzed by the QDDM magnetic spectrometer. The magnitude of the beam polarization was about 70%. The polarization was checked every few hours and did not vary significantly throughout the run. The direction of the polarization was reversed once a second.

Data were taken every 5° from 10° to 60° for states in the excitation range from 0 to 20 MeV. Four field settings of the spectrometer were required in order to cover this range. In addition, data were taken at 35° with a Si target where the yields to the ground state (0^+) and the 11.58 MeV and the 14.35 MeV (6^-) states² were used to check the solid angle and energy calibration of the spectrometer. A partial spectrum of inelastically scattered protons at 45° is shown in Fig. 1. Angular distributions and analyzing powers were extracted for all states below 13 MeV excitation. Based on the angular distributions, 6^- states were identified at 9.18 ± 0.03 MeV, 11.98 ± 0.03 MeV, 12.49 ± 0.03 MeV and 12.85 ± 0.03 MeV and 5^- levels were identified at 7.96 ± 0.03 MeV and at 8.62 ± 0.03 MeV. Above 13 MeV, the discrete states appear to lie on top of a significant continuum background. The strong

state at 18.05 ± 0.05 MeV could also be clearly identified as a 6^- level. Otherwise only those states in the 13-20 MeV region whose electron scattering angular distributions indicated a possible 6^- assignment were analyzed, i.e. the peaks corresponding to states at 14.50 ± 0.05 , 15.36 ± 0.05 , 15.46 ± 0.05 and 16.50 ± 0.05 MeV.

Based on its strong excitation in (e, e') and systematics, the 18.05 MeV state is believed to be the lowest $T = 2$, 6^- state. All the lower energy states are assigned $T = 1$. Angular distributions of the cross sections for each of these states are shown in Fig. 2 and for the analyzing powers are shown in Fig. 3.

III. EXTRACTION OF ISOSPIN AMPLITUDES

If one describes the ground state of ^{26}Mg in terms of the $(1d, 2s)^{10}$ configuration and the 6^- states as $((1d, 2s)^9 1f_{7/2})$, the (p, p') -scattering cross section for exciting the i^{th} 6^- state can be written as

$$\left(\frac{d\sigma^p}{d\Omega}\right)^i = |z_0^i M_0^p + z_1^i M_1^p|^2 \quad (1)$$

where $M_{0(1)}^p$ are the complex isoscalar (isovector) transition amplitudes for single particle excitation of a $d_{5/2}$ nucleon to the $f_{7/2}$ orbit and $z_{0(1)}^i$ are nuclear structure amplitudes for these isoscalar (isovector) excitations. In a similar way, the electron scattering cross section to the i^{th} 6^- state is

$$\left(\frac{d\sigma^e}{d\Omega}\right)^i = |z_0^i M_0^e + z_1^i M_1^e|^2 \quad (2)$$

where $M_{0(1)}^e$ are the transition amplitudes for $d_{5/2} \rightarrow f_{7/2}$ electron scattering. $M_{0(1)}^e$ are related by the expression

$$M_0^e = \frac{\mu_n + \mu_p}{\mu_n - \mu_p} M_1^e = -0.187 M_1^e \quad (3)$$

where the free particle values of the neutron and proton magnetic moments have been used in the numerical estimate. For these equations $M_{0(1)}^p$ were calculated using the distorted wave impulse approximation (DWIA) while the plane wave Born approximation, with Coulomb distortion accounted for by the effective momentum transfer approximation, was used to calculate $M_{0(1)}^e$. Thus, if both the electron scattering and the proton scattering to the 1^{th} state have been measured, Eqs. (1) and (2) can be used to solve for Z_0 and Z_1 . However, because the equations are quadratic there will be an ambiguity and two solutions may be found. The proton analyzing powers can be expected to resolve this ambiguity. Of course, only the relative sign of Z_0 and Z_1 is of significance and in the present work Z_1 was always taken to be positive.

The inelastic proton scattering amplitudes, $M_{0(1)}^p$, calculated using the code DW81,¹¹ are subject to considerable uncertainty. First, since this is a DWIA calculation the optical model parameters needed to generate the distorted waves must be known. This potential is usually determined from a fit to the elastic proton scattering data. However, in this experiment only a limited amount of elastic scattering data was taken and as a consequence the optical model parameters for ^{28}Si , determined by Olmer et al.,¹² were used in calculating $M_{0(1)}^p$. Second, the spin flip interaction causing the transition to the 6^- states is not unambiguously known. Various effective interactions were studied in the analysis¹² of the excitation of the 6^- states in ^{28}Si . Of those investigated, the Love-Franey interaction,¹³ while not without faults, gave results consistent with other probes in both isoscalar and isovector channels. In the present work the Love-Franey and the more recent Franey-Love-85¹⁴ interactions were used. The calculations did not differ

significantly for the two choices of interaction and all results shown here use the Franey-Love-85 interaction. Since the electromagnetic interaction leading to and the calculation of $M_{0(1)}^e$ is well understood, some of the uncertainty in the calculation of $M_{0(1)}^p$ can be eliminated by forcing the Z_1 coefficient, extracted from the analysis of a purely isovector transition, to be the same for protons and electrons.

There are two sources of confusion in comparing the electron and proton results. The electron scattering results are traditionally analyzed including a center of mass correction in momentum space and a correction for meson exchange currents. The center of mass correction can be included in the coordinate space proton calculation for harmonic oscillator single particle wave functions by: 1) Doing the (p,p') calculation with an oscillator parameter which is reduced by $\sqrt{(A-1)/A}$ from that used in the electron calculations. In Ref. 10, the oscillator parameter $b = 1.77$ fm was used. In the present work this is rescaled to 1.736 fm. 2) The calculated (p,p') DWIA cross sections are increased by $(A/(A-1))^L$ (for 6^- states $L = 5$). The calculated DWIA cross sections in this work include these two center of mass corrections.

Isovector electron scattering also contains contributions from pair and meson exchange currents.¹⁵ Calculations indicate that these increase the calculated form factor for the 18.05 MeV, $T=2$ state by 17% at the peak of the form factor.¹⁶ This correction decreases the Z_1^2 needed to fit the experimental cross section by the same factor. A similar fractional increase would be expected for transitions to the $T = 1$ states, assuming the electron results for strong states are dominated by isovector interactions. To be consistent, this now implies that:

$$M_0^e = (\mu_n + \mu_p) / (\sqrt{1.17} (\mu_n - \mu_p)) M_1^e$$

Meson exchange corrections for proton scattering are less well understood. Arguably, they might be similar in relative magnitude for isovector transitions as in the electron case and negligible for isoscalar transitions. However, given this lack of understanding, the effects of meson exchange currents have been ignored in analyzing the proton data in the present work.

The excitation of $T = 2$ states in ^{26}Mg is pure isovector and, therefore, Z_1^2 can be determined directly by comparing the measured angular distribution with that calculated. The angular distribution calculated for a pure isovector excitation is shown in Fig. 4, along with the data for the 18.05 MeV, $T = 2$, state. Except at the lowest angle ($\theta_{\text{cm}} = 26^\circ$) where there may have been contamination from lower spin states, a satisfactory fit to the data is obtained with $Z_1^2 = .094$, and this is to be compared with the value of .122 found in the electron scattering study.¹⁰ Although the agreement is not as close as obtained in ^{28}Si and ^{24}Mg , we have, in all subsequent calculations, rescaled $|M_1^p|^2$ by the factor 0.77 to force Z_1 for this state to be equal to the value determined from electron scattering ($Z_1 = 0.35$). If one assumes that the ratio of the isoscalar to isovector interaction strengths causing 6^- excitation is given correctly by the Franey-Love-85 potential and that these $T = 0$ and $T = 1$ interactions have the same radial localization, a similar rescaling for $|M_0^p|^2$ is called for and we have assumed the same factor, 0.77, for the rescaling of $|M_0^p|^2$. For $T = 0$ transitions, the correctness of the nuclear structure amplitudes, Z_0 and Z_1 , deduced in this work depend on the validity of these two assumptions. (If this correction had not been applied to $|M_0^p|^2$, all of the Z_0^2 would be 30% lower.) The calculated phase angle between the isoscalar and isovector amplitudes varies between 120° and 140° in the 30° to 60° scattering angle range.

In Fig. 4 the angular distribution for a pure isoscalar excitation is compared to that for a pure isovector. Although the data for excitation of the 18.05 MeV $T = 2$ state, also shown in the figure, are somewhat better fitted by the isovector curve, there is little difference in the predicted isoscalar and isovector angular distributions. While the calculated angular distributions depend somewhat on the isospin nature of the excitation, the sensitivity is small and not significant in view of the changes in the calculated distributions that can be brought about by varying the parameters in the DWIA calculation. Thus, it is felt that the angular distribution data cannot be used in determining the isospin composition of the excitation. More definitive are the analyzing powers which are shown in Fig. 5 for this state together with those calculated for pure isoscalar and isovector excitations. The agreement is good for $\Delta T = 1$, but unsatisfactory for $\Delta T = 0$ excitation. This characteristic angular distribution and analyzing power pattern form the basis for the spin assignments to the 9.18, 11.98, 12.49 and 12.85 MeV states. Analyzing powers for natural parity states tend to be greater in magnitude and vary more strongly with angle, reaching large negative values at the greater angles.

Of the eleven 6^- states identified in electron scattering, seven were observed in the present work. The 6^- state seen at 11.98 MeV in the proton scattering is not listed in the electron work. For each of the seven $T = 1$ states observed in both proton and electron scattering the data were used to extract values for Z_0 and Z_1 at each angle where the state was observed. The Z 's thus obtained, in the region of the maximum, were quite consistent for the 9.18, 12.49, 12.85 and 14.50 MeV states. For the 9.18, 12.49 and 12.85 MeV states, the analyzing power data seemed to clearly resolve the ambiguity in solutions, although the maximum and the minimum in the calculated analyzing

power were always at smaller angles than observed. The data and results of the DWIA calculations for the 12.49 MeV state are shown in Figs. 6 and 7. For the 14.50 MeV state, the analyzing power did seem to favor one of the solutions, though the choice was not clear cut.

The fit to the angular distribution for the 15.36 MeV state is not nearly as good as for the above mentioned states, as can be seen in Fig. 8. In fact, it looks like a lower spin might be more appropriate. The analyzing power is compared to the calculation in Fig. 9 and, for a 6^- state, the solution with $Z_0 = Z_1 = 0.2$ appears to be favored. The 15.46 MeV state is reported as strong in the electron scattering work but is fairly weak in proton scattering. In fact, at most angles no solutions could be found which fit both the (e,e') and the (p,p') data. Furthermore, the (p,p') angular distribution appears to favor a lower spin assignment, while the large negative analyzing power at large angles is characteristic of a natural parity state. It is, therefore, concluded that there is little 6^- strength in any state at or very near 15.46 MeV.

The electron scattering work reports a group of unresolved states in the region of 16.5 MeV which contain a good bit of the 6^- strength, about 14% of the total predicted for $T = 1$ states by the extreme single particle model. In proton scattering, a weak state seen at 16.5 MeV has a 6^- angular distribution. No combination of $T = 0$ and $T = 1$ amplitudes fits both the proton and the electron scattering data. The weakness of the state in (p,p') requires $|Z_0| < .1$ and $|Z_1| < .15$.

The situation with regard to the 11.98 MeV state is very puzzling. A weak state with a 4^- angular distribution was seen at 11.92 MeV in (e,e') . If this state were 6^- it would be much weaker than the other 6^- states that are discussed here. On the other hand, the angular distribution

for the 11.98 MeV state that is observed in (p,p') fits a 6^- assignment very well. The combination of the (p,p') differential cross sections and the failure to observe the state in (e,e') yields $Z_0 = .21$, $Z_1 = .04$. The fit to the analyzing powers is poor with these isospin amplitudes. Nevertheless, it is the above amplitudes that have been used in the tabulations of total strengths. Values of Z_0 and Z_1 which are consistent with the observed analyzing power predict that the state should be strong in (e,e'). It should be noted that the 11.98 MeV state is seen with considerable strength in the $^{25}\text{Mg}(\alpha, ^3\text{He})$ reaction¹⁷ as is its analogue in the $^{25}\text{Mg}(\alpha, t)$ reaction.¹⁸ A transition to a 6^- state at 12.0 MeV has been observed¹⁹ in the $^{26}\text{Mg}(p, n)^{26}\text{Al}$ reaction. Since the (p,n) reaction is pure isovector an isovector amplitude, $Z_1 = 0.17$, can be extracted for the analogous transition in ^{26}Mg if, indeed, the ^{26}Al state is $T = 1$. The (p,p') data would then require $Z_0 = 0.24$ for the 11.98 MeV state.

A weak state at 7.54 MeV was seen in electron scattering but was not observed in the proton scattering. Fairly weak states reported at 13.00 MeV and 13.97 MeV in (e,e') were not apparent in the (p,p') spectra.

Table I lists the isospin amplitudes for the states that have been observed in the present work. For comparison, the electron scattering results are also presented in Table I. The tabulated quantity for each state is: $\tilde{Z} = Z(18.05) * \sqrt{F_T(1)/F_T(18.05)}$. In the limit that electron scattering was pure isovector, this would give Z_1 . In fact, for the majority of the states, the relative sign of Z_0 and Z_1 is positive, corresponding to destructive interference between isoscalar and isovector contributions in electron scattering. The Z_1 obtained from the combined analysis is therefore generally slightly larger than $\tilde{Z}$.

IV. COMPARISON WITH OTHER PROBES

The inelastic scattering results can be compared to other studies of 6^- states in ^{26}Mg . The most direct comparison is the study of $^{26}\text{Mg}(p,n)^{26}\text{Al}$ by Anderson et al.¹⁹ at 134 MeV. The (p,n) reaction directly measures the isovector amplitude, Z_1 , for states which are the isobaric analogs of the $T_z = 1$ states studied here. In addition, (p,n) reactions are quite selective for spin-flip transitions, since the strong isoscalar central interaction cannot contribute to the cross section. The (p,n) study does have the additional complexity that it can populate $T = 0$, 6^- states in ^{26}Al which might be expected in the same region of excitation. In Table I, the value of Z_1 for each state in (p,n) was obtained by assuming that all states except the 18.2 MeV state were $T = 1$. Anderson et al.¹⁹ tabulated the fraction of the extreme single particle sum rule (FESPM) decomposed by isospin, which corresponds to $Z_1^2 / (\sum Z_1^2)$ ESPM (see eq. 5 below, i.e., for $T = 1$ states $Z_1^2 = \text{FESPM}/2$). In Table 1, all values of Z_1 have again been renormalized to force $Z_1(18.05) = 0.35$. This increases the Z_1 for the (p,n) by $\sqrt{1.39}$ compared to Ref. 19. The analysis of Anderson et al.¹⁹ was performed with the same optical potential and residual interaction as in the present work, but with a slightly different harmonic oscillator parameter, $b = 1.70$. It is possible to directly compare the measured cross sections for the $T = 2$ states which would be expected to show $\sigma(p,n)/\sigma(p,p') = 2/3$. The extrapolated peak cross sections (at $\theta_{\text{cm}} \sim 38^\circ$) are in this ratio, although for $\theta_{\text{cm}} > 40^\circ$, where the data can be directly compared, the angle averaged ratio is about 0.8. Again since, only relative numbers are tabulated in Table I, the analysis is not sensitive to this difference.

For the $T = 1$ states, the Z_1 values obtained in (p,n) agree well with the present work for the 12.49, 12.85 and 14.50 MeV states. The

significant disagreement for the 9.18 MeV state and the corresponding disagreement between (p,n) and (e,e') may indicate the population of a 6^- $T = 0$ state in ^{26}Al near this excitation energy. The resolution of the (p,n) work is significantly poorer than that of the present work. A $T = 0$ state in ^{26}Al may also be responsible for the apparent discrepancy between the (p,n) and (e,e') results at 12.0 MeV excitation.

Stretched configuration states can be expected to be strongly excited in single nucleon transfer reactions. The 9.18, 11.98, 12.49, 12.85, and 14.50 MeV states have been found to be populated in the $^{25}\text{Mg}(\alpha, ^3\text{He})^{26}\text{Mg}$ reaction¹⁷ and their spectroscopic factors are given in Table I. In addition, three other 6^- states are seen very weakly. The total $l = 3$ strength seen below 16.5 MeV accounts for a surprisingly small portion (27.1%) of the sum rule for stripping into the empty $f_{7/2}$ shell. In the $^{25}\text{Mg}(\alpha, t)^{26}\text{Al}$ reaction¹⁸ the analogs of the four lowest 6^- $T = 1$ states have been seen. Again the sum of the spectroscopic factors is a rather small, 40% of the sum rule limit.

With the sign convention used in the present work, when $Z_0 = -Z_1$ the excitation is pure proton, while $Z_0 = Z_1$ signifies a pure neutron excitation. A proton excitation leaves behind $[(\pi d5/2)^3 (\nu d5/2)^6]$ which must be $T = 3/2$ and, therefore, several MeV higher than the $T = 1/2$ component of the $[(\pi d5/2)^4 (\nu d5/2)^5]$ remaining after a neutron is elevated. Thus, low-lying $T = 1$, 6^- states can be expected to be primarily neutron excitations as is, indeed, indicated by the data. The inelastic cross section to 6^- states can be written as

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \alpha \left| \langle F | a_{7/2}^+ a_{5/2} | I \rangle \right|^2 \\ &= \alpha \left| \sum_N \langle F | a_{7/2}^+ | N \rangle \langle N | a_{5/2} | I \rangle \right|^2 \end{aligned} \quad (4)$$

where $I(F)$ are the initial (final) states involved in the reaction, N is a complete set of intermediate states, and $a_j^+(a_j)$ are creation (destruction) operators for nucleons in the single particle state j . If only neutron excitation is important $a_j^+(a_j)$ involves only a neutron. Furthermore, if neutron pickup on ^{26}Mg populates only the ^{25}Mg ground state, then only a single term, $|N\rangle = ^{25}\text{Mg}$ ground state, occurs in the sum in Eq. (4). In this case the (p,p') cross section should be proportional to the probability that in the 6^- state an $f_{7/2}$ neutron couples to the ground state of ^{25}Mg , namely the spectroscopic factor for populating the 6^- state in the $^{25}\text{Mg}(\alpha, ^3\text{He})^{26}\text{Mg}$ reaction. The constant of proportionality is smoothly varying and hence with these assumptions the (p,p') cross section to the first three $6^- T = 1$ states should be in the ratios of the pickup spectroscopic factors, i.e., 1.0:0.22:0.43. Experimentally the (p,p') cross sections are all about the same. Thus, as is already known from pickup studies,²⁰ more than one state of ^{25}Mg is populated in neutron pickup so that there is no simple relationship between the inelastic and stripping cross sections.

V. DISCUSSION AND CONCLUSIONS

In the $(d_{5/2}, f_{7/2})$ model for the 0^+ and 6^- states the ground state of ^{26}Mg is $(d_{5/2})^{-2}$ and the excited 6^- states are $[(d_{5/2})^{-3} \times f_{7/2}]6^-$. With this description of the levels there is a sum rule for the nuclear structure amplitudes Z_0 and Z_1 , namely:

$$\sum_i (Z_0^i)^2 = \frac{n+n_p}{(4j+2)} = \frac{10}{12}$$

$$\sum_i (Z_1^i)^2 = \frac{n}{(4j+2)} = \frac{6}{12} \quad (5a)$$

for the $T = 1$ states,

$$\sum_i (z_1^i)^2 = \frac{n_p}{(4j+2)} = \frac{4}{12} \quad (5b)$$

for excitation of the 6^- $T = 2$ levels and

$$\sum_i [(z_0^i)^2 + (z_1^i)^2] = \frac{n_p + n_n}{2j + 1} = \frac{10}{6} \quad (5c)$$

for excitation of all 6^- levels. $n_p(n_n)$ is the number of protons (neutrons) in the last occupied orbital ($d_{5/2}$).

From Table I it appears that experimentally the sum of the excitations to $T = 1$ levels $\sum_i (z_0^i)^2 = 0.32$ and $\sum_i (z_1^i)^2 = 0.20$, whereas for the $T = 2$ state $(z_1)^2 = 0.12$. Thus, for the $T = 1$ states only 37% of the expected isoscalar strength has been seen and 40% of the isovector. For the single $T = 2$ level seen in this experiment 37% of the simple sum rule strength has been observed.

Consideration of the nuclear structure in terms of $(d_{5/2})_{0+}^{-2}$ and $[(d_{5/2})_{6-}^{-3} f_{7/2}]_{6-}$ is clearly naive. Generally two classes of nuclear structure effects have been considered for quenching of spin-flip transitions. Several calculations have indicated the importance of $n > 2$ $\hbar\omega$ excitations, particularly due to the tensor force.⁶ Certainly the full (sd) shell is necessary to describe the positive parity levels and the variation of structure through the middle of the (sd) shell. Calculations for ^{28}Si in which the ground state is described by the configuration $(d_{5/2}s_{1/2})_{0+}^{12}$ and the 6^- levels by $[(d_{5/2}s_{1/2})_{6-}^{11} f_{7/2}]_{6-}$ have been carried out.⁴ Calculations on the same basis, $(d_{5/2}s_{1/2})_{0+}^{10}$ and $[(d_{5/2}s_{1/2})_{6-}^9 f_{7/2}]_{6-}$, were done here for ^{26}Mg . Using this configuration space, there are 12 possible 0^+ , $T = 1$ states. The

shell model Hamiltonian was diagonalized assuming the $(d_{5/2}, s_{1/2})$ interaction of Wildenthal et al.²¹ For the 6^- states the model in which one $d_{5/2}$ or $s_{1/2}$ nucleon is excited to the $f_{7/2}$ level gives rise to 341 $T = 1$ and 149 $T = 2$ states. To diagonalize the shell model Hamiltonian one must know the $(d_{5/2}, f_{7/2})$ and $(s_{1/2}, f_{7/2})$ interaction matrix elements and these were evaluated using the best fit central spin-dependent potential of Schiffer and True²² with $r_1 = 1.415$ fm and $r_2 = 2.0$ fm. Oscillator functions with $\nu = 0.293$ fm⁻² [$\psi \sim \exp - 1/2 \nu r^2$] were used in the calculation of these matrix elements.

From Eq. (4) it is clear that if one sums over all the final states, F , the sum of the cross sections will be proportional to the expectation value of the $d_{5/2}$ number operator, $\sum a_{5/2,m}^+ a_{5/2,m}$, evaluated in the ^{26}Mg ground state. In the $(d_{5/2})^{10}$ model there are always 10 particles in the $d_{5/2}$ level. However, in the $(d_{5/2}, s_{1/2})^{10}$ description with the Wildenthal et al. interaction²¹ the expectation value of the $d_{5/2}$ number operator is 8.75. Thus, the sum rule given by Eq. (5) for the Z^2 's decreases from 10/6 to 8.75/6, compared to the experimental value 0.63.

The single particle level spacing between the $d_{5/2}$ and $f_{7/2}$ states is a parameter in the shell model calculation. If this is chosen so that the yrast 6^- , $T=1$ state in the $(d_{5/2}, s_{1/2})^9 f_{7/2}$ calculation is at the observed excitation energy, the yrast $T=2$, 6^- state is predicted at an excitation energy of 18.07 MeV in excellent agreement with the experimental value of 18.05 MeV. The predicted value of Z_1^2 for this state is 0.205 which, although only 61.5% of the $(d_{5/2}, f_{7/2})$ sum rule limit, is 1.7 times that seen experimentally. A second 6^- , $T=2$ state is predicted at about 19.6 MeV and, according to these calculations, have a cross section about a factor of five smaller than that of the 18.05 MeV state. This level was not seen in either the (p, p') or the (e, e') studies.

For the $T = 1$ states, the yrast 6^- state is predicted to have the spectroscopic strength of $Z_0^2 = 0.088$ and $Z_1^2 = 0.153$ when the $s_{1/2}$ level is included. These numbers are 1.41 and 2.89 times their experimental counterparts. Except for the 9.18 MeV level no states are seen or predicted below 11 MeV. Forty $T=1$, 6^- levels are predicted between 11 and 18.05 MeV. Since small changes in the residual two-body interaction can change the individual values of Z_0 and Z_1 for almost degenerate states, it was felt that the best way to compare theory and experiment was to "bin" the values of Z_0^2 and Z_1^2 in 1 MeV intervals. The results of this binning are shown in Fig. 10.

The theoretical values of Z_0^2 follow experiment fairly closely up to about 14 MeV. In fact, the predicted sum of Z_0^2 between 9 and 14 MeV is 0.276 whereas experiment gives 0.24. Above 14 MeV the calculated Z_0^2 is larger than seen experimentally. However, very little strength is concentrated in any one state so that even though the sum of the strengths is large, it would be difficult to observe. For example, the strength in the 16-17 MeV range is slightly larger than the value predicted for the yrast level alone, but the strongest state has a value of Z_0^2 only 1/8 that of the 9.18 MeV level. On the other hand, a detailed study of the large predicted strength in the 14-15 MeV range leads one to the conclusion that more than one 6^- level should have been seen in this region. However, since the $d_{3/2}$ single particle orbit lies approximately 5 MeV above the $d_{5/2}$, it is precisely in this region that the simple $[(d_{5/2}, s_{1/2})^9 f_{7/2}]$ model should begin to break down. If the calculation using the $[(d_{5/2}, d_{3/2}, s_{1/2})^9 f_{7/2}]$ configuration was performed, then instead of 341 $T=1$, 6^- levels there would be 29,840. Up to 14 MeV the present calculation predicts the sum of Z_1^2 to be 0.32 while, experimentally, only 0.14 is found. The discrepancy is almost entirely due to the yrast level where the prediction is almost a factor of three too large.

Considering spectroscopic factors for single nucleon transfer, the $[(d_{5/2}, s_{1/2})f_{7/2}]$ model gives $S = 0.536$ for the yrast 6^- state. This value is a factor of more than 4 larger than deduced from the $(\alpha, {}^3\text{He})$ work¹⁷ and about 2-1/2 times that for¹⁸ (α, t) . If the spectroscopic strengths are binned, the model predicts $S = 0.116, 0.157, 0.046$ and 0.020 for the strengths in the 11-12, 12-13, 13-14 and 14-15 MeV regions, respectively. Thus, theory says that 87.5% of the sum rule strength should be seen below 15 MeV whereas only 24% is seen in $(\alpha, {}^3\text{He})$ and 40.3% in the (α, t) reaction.

The theory predicts much larger spectroscopic factors than are seen in the $(\alpha, {}^3\text{He})$ and (α, t) reactions^{17,18} to the 6^- states. However, the ${}^{24}\text{Mg}(\alpha, {}^3\text{He}){}^{25}\text{Mg}$ results, quoted in Ref. 17, for population of the $7/2^-$ level, lead to a value of S which is a factor of two to three smaller than seen in the (d, p) reaction²³ and in an earlier $(\alpha, {}^3\text{He})$ experiment.²⁴ The predicted ratio

$$\frac{Z_N^2}{S_N} = \left(\frac{Z_0 + Z_1}{\sqrt{2}}\right)^2 \times \frac{1}{S_N} \quad (6)$$

of the neutron inelastic scattering strength to the neutron stripping spectroscopic factor varies by a factor of 2 from state to state for the strong states, as do the experimental ratios. Such behavior is indicative of the existence of significant interference between the various terms in the sum of Eq. (4). A major problem with the ${}^{28}\text{Si}$ calculation⁴ was that the predicted $\frac{Z_N^2}{S_N}$ ratio was similar for the various ${}^{28}\text{Si}$ 6^- states, in disagreement with experiment. For ${}^{26}\text{Mg}$, theory and experiment agree quite well for inelastic scattering except for the value of Z_1 predicted for excitation of the yrast 6^- $T = 1$ state. To bring theory and experiment into agreement for this quantity will require some changes in the residual shell model interaction.

Theoretical values of Z_0 for the yrast $T = 1$ and Z_1 for the yrast $T = 2$ levels are within 25% of their experimental counterparts. Particularly for Z_0^2 , a large amount of strength is predicted above 14 MeV excitation, ($\int Z_0^2 = 0.363$ from 14 to 18 MeV) whereas $\int Z_0^2 = 0.066$ for the two observed states. However, not only is the theoretical strength spread over many levels in the $[(d_{5/2}, s_{1/2})f_{7/2}]$ model thereby making observation difficult, but this is exactly where contributions from the $d_{3/2}$ orbit are likely to become important and cause additional dilution of the strength. Consequently, it is not surprising that a large amount of the Z_0 strength has been missed.

In summary, the present work has demonstrated that a combination of electron and proton scattering can be used to extract isospin amplitudes for the excitation of high spin stretched configuration states. These amplitudes are well determined for the 9.18, 12.49 and 12.85 MeV states (and trivially for the 18.05 MeV state). The results for the 11.98, 14.50 and 15.36 MeV states are subject to more uncertainty. In addition, this analysis is based upon a particular choice of effective interaction, and the isoscalar spin-flip interaction is not well constrained by experiment.

The summed isovector strength observed in ^{26}Mg is similar to that observed in neighboring nuclei. Substantially more isoscalar strength, however, is identified in ^{26}Mg than in ^{28}Si or ^{24}Mg . This rapid variation is not understood. Perhaps this is related to the rapid variation of deformation through the s-d shell. The importance of deformation in the quenching of high-spin stretched transitions has been discussed by Liu and Zamick.²⁸ It should be noted that for each state for which there was some question, a solution with a large isoscalar strength was chosen. The shell model calculations are more successful in reproducing the ^{26}Mg results than in ^{28}Si . Only the isovector amplitude for exciting the yrast 6^- state appears to be a problem in ^{26}Mg .

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TABLE I. Isoscalar and isovector amplitudes for M6 excitations in ^{26}Mg . Also shown are spectroscopic factor for single particle reactions to the same, or to analog states.

E_x (MeV)	T	Z_0	Z_1	$\tilde{Z}^d$ (e,e')	E_x (p,n)	Z_1^c (p,n)	S^a [$^{25}\text{Mg}(\alpha, ^3\text{He})$]	S^b [$^{25}\text{Mg}(\alpha, t)^{26}\text{Al}$]
9.18	1	.25 $\pm$.03	.23 $\pm$.03	.18	9.3	.30	.13	.20
11.0					11.0	.21		
11.98	1	.21 $\pm$.03 .24 $\pm$.03	.04 $\pm$.03 † .18 *		12.0	.18	.029	.08
12.49	1	.26 $\pm$.04	.24 $\pm$.03	.21	12.5	.24	.056	.065
12.83	1	.28 $\pm$.02	.17 $\pm$.02	.14	13.1	.25	.013	.058
13.00	1			.11				
13.97	1			.13	14.0	.20		
14.50	1	.16 $\pm$.02(-.06 $\pm$.03)	.17 $\pm$.02(.13 $\pm$.02)	.15	14.6	.21	.012	
15.0					15.0	.24		
15.36	1	.20 $\pm$.03	.18 $\pm$.02	.16				
15.46				.21	15.5	.21		
16.5				.25	16.5	.18		
18.05	2		.35 $\pm$.02 ††	.35	18.2	.35 ††		
		[$Z_0^2 = .31$	[$Z_1^2 = .32$					

^aReference 15.

^bReference 16.

^cReference 19, normalized to $Z_1 = 0.35$ for 18.05 MeV, see text.

^dReference 10, $\tilde{Z}$ would be Z_1 if (e,e') were pure isovector.

† Using (p,p') angular distribution and absence in (e,e').

* From (p,n). Reference 19.

†† Forced to be equal to (e,e') value.

TABLE II. Ratio of total observed inelastic scattering strength to that predicted by the minimum configuration model for "stretched" excited states (Eq. (5)). T_0 is the isospin of the ground state.

Nucleus	J^π_{ex}	$\Delta T=0$	$T=T_0$ $\Delta T=1$	$T=T_0+1$ $\Delta T=1$	All $\Delta T=1$	Ref.
^{14}N	5^-	0.35	-	0.60	.60	25
^{16}O	4^-	0.23	-	0.40	.40	26
^{24}Mg	6^-	<.11	-	0.27	.40	2
^{26}Mg	6^-	0.37	0.40	0.37	.38	present work
^{28}Si	6^-	0.14	-	0.37	.37	3
^{54}Fe	8^-	0.11	0.29	0.52	.38	27

FIGURE CAPTIONS

- Fig. 1 Spectra at 45° of spin-up protons inelastically scattered by ^{26}Mg . Energies are given for the peaks corresponding to states believed to be 6^- .
- Fig. 2 Angular distributions for the candidate 6^- states identified in this work or in Ref. 10.
- Fig. 3 Analyzing powers for the candidate 6^- states identified in this work or in Ref. 10.
- Fig. 4 Calculated angular distributions for pure isovector and isoscalar excitations, along with the measured angular distribution to the 18.05 MeV state. The distributions are drawn with intensities which best fit the data which are $Z_1^2 = .094$, and $Z_0^2 = .044$, respectively. The Z's are those obtained before the calculations were renormalized, as described in the text, in order that the Z_1 obtained for this state agrees with that extracted from the electron scattering data.
- Fig. 5 Calculated and measured analyzing powers for excitation of the 18.05 MeV state.
- Fig. 6 Angular distribution calculated for the 12.49 MeV state for $Z_0 = .263$, $Z_1 = .236$ (————) and $Z_0 = -.138$, $Z_1 = .172$ (-----) along with the experimental data. For this and subsequent figures the DWIA has been rescaled by a factor of 0.77.
- Fig. 7 Measured analyzing powers for the 12.49 MeV state along with those calculated for the two combinations of isospin amplitudes which best fit the angular distribution data (Fig. 6).
- Fig. 8 Calculated and measured angular distribution for the 15.36 MeV state.
- Fig. 9 Calculated and measured analyzing powers for the 15.36 MeV state.
- Fig. 10 Comparison of the observed distribution of excitation strength with that calculated in the $(d_{5/2}s_{1/2}f_{7/2})$ model. a) Isoscalar; b) Isovector. The strengths have been binned in 1 MeV intervals.

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10