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Forbidden (p,d) pickup to stretched states of ^{26}Al

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The ^{27}Al$(p,d)^{26}$Al reaction has been studied at $E_p=35$ MeV with high resolution to populate known 5^- and 6^- stretched states of $d_{5/2}$-hole$-f_{7/2}$-particle structure, and to obtain the weak spectroscopic factors. These are compared to results also obtained for the ^{26}Mg$(p,d)^{25}$Mg and ^{26}Mg$(^3$He$,\alpha)^{25}$Mg reactions to known $\frac{7}{2}^-$ states. An analysis of these results in the Nilsson scheme exposes the structure of the 6^- stretched states and offers an understanding of the fragmentation of $M6$ stretched transition strength in ^{26}Mg, as seen by electron scattering. This work is part of a consistent study of many nuclear reactions to stretched states in mass 26, to serve as a test case for these important single-particle modes.

I. INTRODUCTION

Although the stretched states, made by the $1\hbar\omega$ single-particle single-hole promotion of greatest angular momentum, are readily made by stripping reactions on the single-hole target nucleus, they should not be excited by pickup reactions in the simplest picture. Only by admixtures from the higher shell into the target ground state could such a reaction occur. Such occupation from higher shells would be important because of a dual effect upon the stretched inelastic scattering strength. Fewer hole states and fewer unblocked particle promotions would be available, quenching the strength, and more high-spin states may be formed, spreading the strength. In the lead region it has been shown theoretically that correlations cause partial-shell occupancy such that agreement is obtained with the inelastic electron scattering strength to the stretched states.[1]

As part of an extensive study of the spectroscopic features of the $(d_{5/2}{}^{-1}f_{7/2})$ 6^- stretched states for $A=26$, we have measured cross sections for the neutron pickup reaction ^{27}Al$(p,d)^{26}$Al to the 6^- states known from proton stripping[2] and by analogy to states known from inelastic electron scattering on ^{26}Mg (Ref. 3) and neutron stripping to ^{26}Mg.[4] Pickup spectroscopic factors to known and suspected 5^- states in ^{26}Al were also determined, based in some cases on recent spectroscopic results from other reactions.[5–7] Accompanying these results are studies of the (p,d) and $(^3$He$,\alpha)$ pickup reactions on ^{26}Mg leading to known (and suspected) $\frac{7}{2}^-$ and $\frac{5}{2}^+$ states in the mass-25 core nucleus. Splitting of the $d_{5/2}$ strength in the core nucleus is important because it leads directly to splitting of the 6^- strength. Both $T=\frac{1}{2}$ and $T=\frac{3}{2}$ $\frac{5}{2}^+$ states of mass 25 serve as the hole states for generating 6^- stretched states in mass 26. We have measured the spectroscopic factors and searched for splittings of both of these $l=2$ hole states to examine the hole bases of the 6^- stretched excitations.

An important feature of these studies is the consistent usages in the distorted-wave Born approximation (DWBA) reaction calculations. It has been demonstrated that the parameters of the potential binding the transferred nucleons greatly influence the magnitudes of the DWBA calculated cross sections and hence the spectroscopic factors.[2] Previous analyses for 6^- states in $A=26$ by (α,t) (Ref. 2), $(\alpha,{}^3$He$)$ (Ref. 4), and (e,e') (Ref. 8) use the same parameters as the present work. Since a large fraction of the $M6$ single-particle strength is observed in electron scattering on ^{26}Mg,[8] it can be anticipated that the pickup-occupation strengths will be less than those computed for the lead region, which lead in that case to more severe quenching of the single-particle stretched excitations.[1]

We have used beam energies such that the usual DWBA reaction models are known to be reliable and where optical-model distorting potentials are well determined, including a new analysis of proton elastic scattering. Where the same projectiles are used as for the previous studies, the same families of optical-model parameters are used. Our goal will be a consistent analysis of the spectroscopic features of the simple 6^- stretched states for $A=26$, where several such states are known and the quenching of the $M6$ strengths from the single-particle sum is small.[8]

Both (p,d) and $(^3$He$,\alpha)$ pickup reactions are used in order to vary the momentum transfer for pickup from ^{26}Mg. This comparison compliments the study of angular distributions to determine the orbital angular momentum of the pickup to verify the $\frac{7}{2}^-$ assignments, some of which are not certain in the compilations.[9]

Of the 57 states of ^{25}Mg known below the 7.788-MeV

$\frac{5}{2}^+$, $T=\frac{3}{2}$ state,[9] 44 were resolved and analyzed in the ^{26}Mg$(p,d)^{25}$Mg spectra and 25 in the ^{26}Mg$(^3$He$,\alpha)^{25}$Mg spectra. Only 10 spectroscopic factors are listed in the ^{25}Mg compilation,[9] so many more are available from our new data. Since the focus of the present work is on the $l=3$ pickup, the extensive data and analysis for the other peaks will be treated and reported separately. Of the 39 states known below 5 MeV in ^{26}Al,[9] the present work provides resolved angular distributions for 24. Complete data for these, and many other transitions, will also be provided later.

II. EXPERIMENTAL METHODS

The (p,d) reactions were carried out on natural aluminum and on 99.55% enriched ^{26}Mg. The 35.19-MeV proton beam was provided by the INS sector-focussed cyclotron, and the reaction products were analyzed by a magnetic spectrometer,[10] with position determination obtained by a hybrid drift chamber,[11] making possible an overall energy resolution of 18 keV. Particle identification was determined by the energy deposited in a pair of plastic scintillators behind the focal plane detector.[11] Sample spectra are shown in Figs. 1–4. These are formed from several overlapping spectra at different magnetic field settings. The excitation energy scale is based on the prominent contaminant peaks in each spectrum. An uncertainty of 10 keV is obtained for the final states.

For the $(^3$He$,\alpha)$ spectra, using a 55.22-MeV beam, the energy resolution of 41 keV would not permit useful results for the 6^- states in doubly odd ^{26}Al but was used to excite $\frac{7}{2}^-$ states in ^{25}Mg. A sample spectrum is shown as Fig. 5. A single spectrometer field setting was sufficient for this spectrum.

For the ^{27}Al data, elastic proton cross sections determined by knowledge of target thickness and solid angle were in agreement with optical-model calculations to better than 5%. For the ^{26}Mg target, the data were adjusted to agree with the elastic calculations for both proton and ^{3}He beams. This will give good relative results for the (p,d) data on the two targets. The quality of the normalization procedure followed has been shown to give absolute cross sections to an overall accuracy better than 10%.

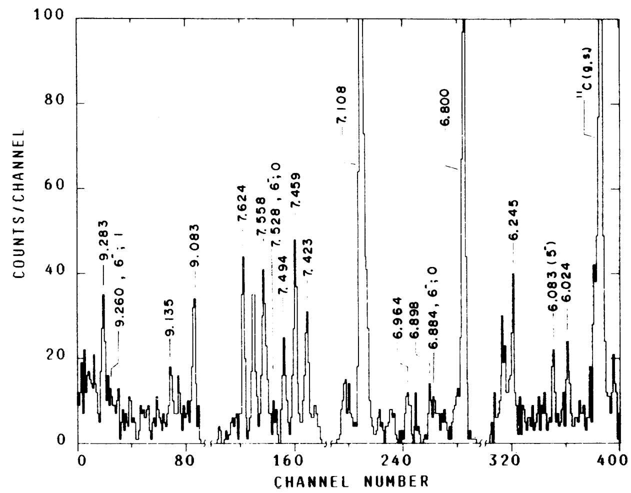

FIG. 2. Enlarged views at 15° or 20° of the spectrum in Fig. 1 showing the weak 5^- and 6^- peaks known from other evidence on ^{26}Al.

The states of interest for the present work are for $f_{7/2}$- and $d_{5/2}$-hole states in ^{25}Mg and the 5^- and 6^- states in ^{26}Al. These are indicated in the spectra, as known for other studies.[2,6,9] The inevitable contaminations of ^{12}C and ^{16}O provided an excellent energy calibration for the final levels.

Figure 2 shows an expanded (p,d) spectrum near the 6.884-MeV 6^- state in ^{26}Al. States marked by an asterisk were used to establish the energy scale, with these states known from Ref. 7. This 6^- state is the lowest stretched state in ^{26}Al, and its $T=0$ character[7] has been confirmed by the ^{24}Mg$(\alpha,d)^{26}$Al reaction.[12]

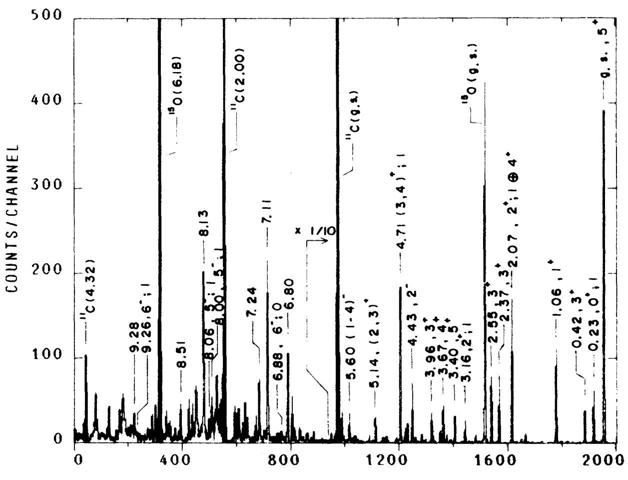

FIG. 1. A momentum spectrum from the ^{27}Al$(p,d)^{26}$Al reaction at 15° and a 35-MeV beam energy. Impurity peaks are noted.

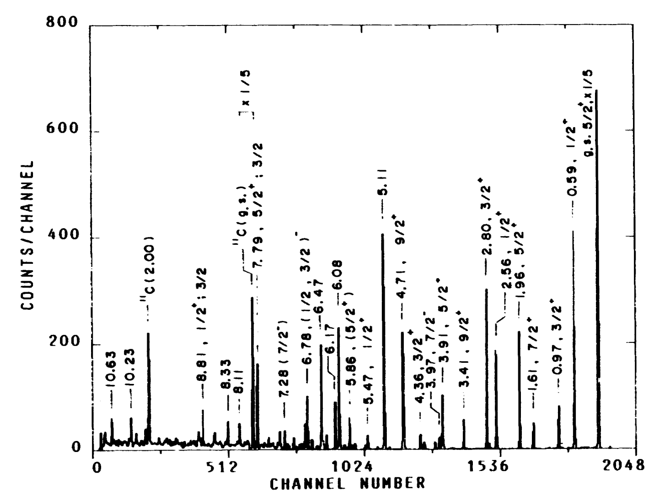

FIG. 3. A momentum spectrum from the ^{26}Mg$(p,d)^{25}$Mg reaction at 20°.

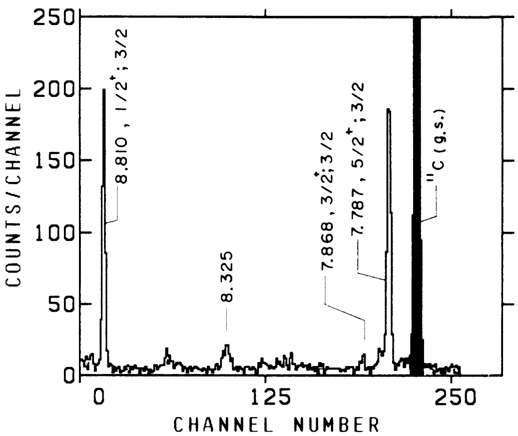

FIG. 4. An enlarged view of the 10° spectrum as in Fig. 3, showing how weak are any candidates for $T=\frac{3}{2}$ $d_{5/2}$ peaks other than the first at 7.787 MeV.

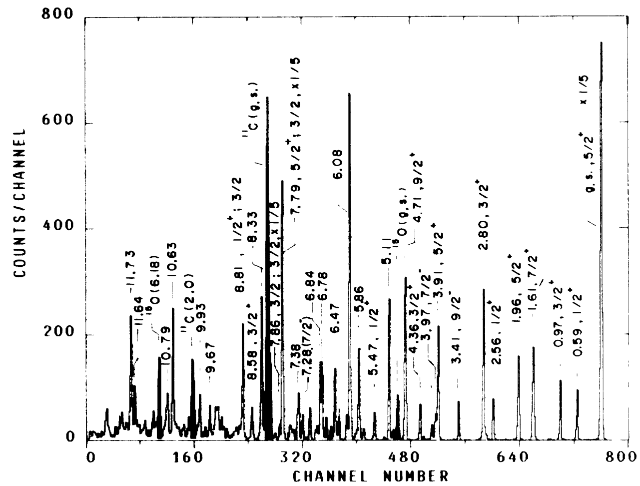

FIG. 5. A spectrum from the ^{26}Mg(^{3}He,α)^{25}Mg reaction at 10°.

III. REACTION CALCULATIONS

All measured cross sections were compared to DWBA calculations to extract spectroscopic factors. The exact-finite-range [EFR(q)] method of Ref. 2 was used for all transitions, using the code DWUCK5.[13] The light-particle structure was specified to $q=15$ fm^{-1}, as determined from electron scattering on ^{4}He (Ref. 14), or by realistic calculated wave functions for deuterium[15] for the (^{3}He,α) and (p,d) reactions, respectively.

Elastic scattering cross sections were measured for 35.19-MeV protons on ^{26}Mg and ^{27}Al and for 55.2-MeV ^{3}He on ^{26}Mg and ^{25}Mg. Optical-model parameters were varied to fit these data, with a normalization constant by which the data were multiplied. Only these renormalized data will be shown. Excellent fits were obtained in each case, with the optical parameters listed in Table I. These were used for the (p,d) and (^{3}He,α) DWBA calculations.

The ^{4}He optical-model parameters were taken from Ref. 16, as listed in Table I, while deuteron parameters are from Ref. 17. The real volume integrals listed in Table I show that the mass-3 and -4 parameter families are the same as those used in the (α,t) (Refs. 2 and 18) and (α,^{3}He)[4] studies in this mass region. These also maintain for all cases the standard of well matching,[19] with the radii near that selected for the bound state of the neutron to be picked up.

The potential well binding the neutron in the target to be picked up is taken to have the same geometrical parameters as used for other reactions in this mass region, $r_0=1.25$ fm, $a=0.65$ fm, with a spin-orbit potential 25 times the Thomas strength. The binding energy for all neutrons was taken to be that for removal to the ground state of the final nucleus. The inadequacies of this simple assumption will largely be mitigated when we compare spectroscopic factors for neighboring nuclei, as for 6^- transitions in ^{26}Al and $\frac{7}{2}^-$ transitions in ^{25}Mg.

Pickup spectroscopic factors are defined from[13]

$$\frac{d\sigma}{d\Omega}=C^2Ss\frac{d\sigma}{d\Omega}(DW)\ .$$

TABLE I. Optical-model parameters for the DWBA pickup calculations are listed. Those for ^{3}He and proton scattering on ^{26}Mg and ^{27}Al were determined in the course of the present work.

	$p+^{26}$Mg	$p+^{27}$Al	d^a+^{25}Mg	$d+^{26}$Al	^{3}He$+^{25}$Mg	^{4}He$^b+^{25}$Mg
V_R (MeV)	−41.44	−41.94	−78.4	−118.1	−116.0	−175.5
r_R (fm)	1.20	1.20	1.25	1.17	1.14	1.22
a_R (fm)	0.724	0.715	0.75	0.746	0.782	0.735
W_v (MeV)	−9.87	−7.77	0	−22.0	−20.6	−36.8
$4W_D$ (MeV)	27.32	26.04	60	0	0	0
r_W (fm)	1.13	1.13	1.34	1.52	1.59	1.35
a_W (fm)	0.478	0.480	0.68	0.81	0.762	0.732
V_{LS} (MeV)	−25.4	−28.6	0	0	0	0
r_C (fm)	1.2	1.2	1.25	1.4	1.4	1.40
J_{real} (MeV fm^3)/A_1A_2	423	421	450	382	371	455
Nonlocal (fm)	0.85	0.85	0.54	0.25	0.25	0.20

^{a}Reference 17.
^{b}Reference 16.

For pickup from a full shell to a single-hole state, this would give a spectroscopic factor $S=2j+1$. The isospin Clebsch-Gordan coefficients for $T=0$ and $T=1$ states of ^{26}Al and $T=\frac{1}{2}$ and $T=\frac{3}{2}$ states of ^{25}Mg are $C^2=1,\frac{1}{3}$ and $1,\frac{1}{4}$, respectively. The light-particle spectroscopic factor s is unity for pickup.

IV. RESULTS FOR ^{26}Mg$(p,d)^{25}$Mg and ^{26}Mg$(^3$He$,\alpha)^{25}$Mg

The $d_{5/2}$-neutron-hole states upon which the $T=0$, 1, and 2 6^- stretched states in mass 26 are based are primarily the ground state $(T=\frac{1}{2})$ and 7.79-MeV $(T=\frac{3}{2})$ state in ^{25}Mg.[9] Both are very prominent in the spectra of Figs. 3 and 5. Some $T=\frac{1}{2}$ $\frac{5}{2}^+$ pickup strength is also found in a number of known $\frac{5}{2}^+$ (for simply $l=2$) states.[9] Angular distributions for many of the known $T=\frac{1}{2}$ $\frac{5}{2}^+$ candidates and the one known $T=\frac{3}{2}$ transition are shown in Figs. 6 and 8 for the (p,d) and $(^3$He$,\alpha)$ reactions. As expected for a simple-hole picture, the ground state and 7.79-MeV states yield large spectroscopic factors, listed in Table II.

Although good fits are found for the strongest $\frac{5}{2}^+$ states, the agreement with the DWBA curves is less good for several others. Some known $l=2$ transitions[9] show flat angular distributions, as shown for the 5.52-MeV peak. A known $J=\frac{5}{2}$ state at 5.859 MeV (Ref. 9) shows a good fit to the (p,d) DWBA prediction, confirming an assignment of $J^\pi=\frac{5}{2}^+$. The $f_{5/2}$ curve shown is clearly not as seen in the data. All DWBA curves are for $d_{5/2}$ pickup, for the purpose of determining the distribution of the hole states for the 6^- stretched configurations.

The ratio of $(^3$He$,\alpha)$ to (p,d) maximum cross sections for known $\frac{5}{2}^+$ states varies smoothly from 1.5 to 2.9 as the excitation energy in ^{25}Mg increases. Just this effect, but more dramatically, is predicted by the DWBA. These results are compared in Table II. Data for the 5.86- and 6.08-MeV peaks depart from this trend, giving, nonetheless, good $l=2$ DWBA fits for the (p,d) reactions.

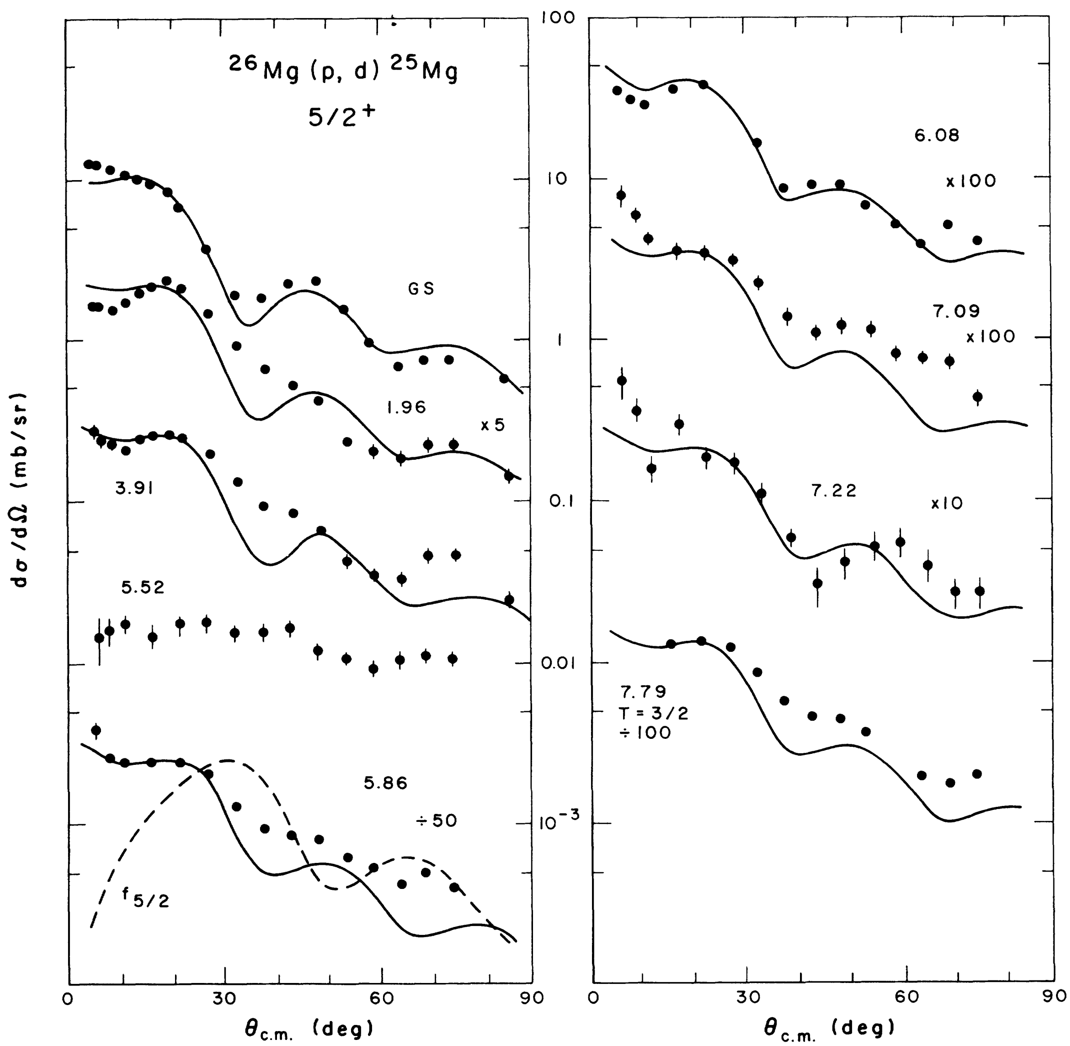

FIG. 6. Angular distributions and DWBA predictions for $d_{5/2}$ pickup by the ^{26}Mg$(p,d)^{25}$Mg reaction. Cross sections have been multiplied or divided by the factors shown for plotting purposes.

Pickup cross sections to known or possible $\frac{7}{2}^-$ states by the ^{26}Mg$(p,d)^{25}$Mg reaction are shown in Fig. 7, compared to $f_{7/2}$ DWBA curves. The strongest transitions, for 3.97- and 7.28-MeV peaks, have less structure than predicted, but excellent fits are found for the 6.91- and 6.96-MeV peaks. No spin assignments for these levels are given in Ref. 9. At 5.79 MeV this compilation lists a $\frac{7}{2}^-$ or $\frac{11}{2}^-$ state; only a poor fit is found to an $f_{7/2}$ pickup curve. For purposes of forming an estimate of the $f_{7/2}$ population in ^{26}Mg, the fits shown are used to extract the weak spectroscopic factors listed in Table II.

For $l=3$ pickup, only two states are available from the (^{3}He,α) spectra. Larger ratios of (^{3}He,α) to (p,d) cross sections are predicted for the 3.97-MeV state, and smaller for the 7.28-MeV state, as observed. The fits of the DWBA curves in (^{3}He,α) are not good; this is demonstrated in Fig. 9 by showing also $d_{5/2}$ pickup cross sections. The low-lying states are poorly matched by the

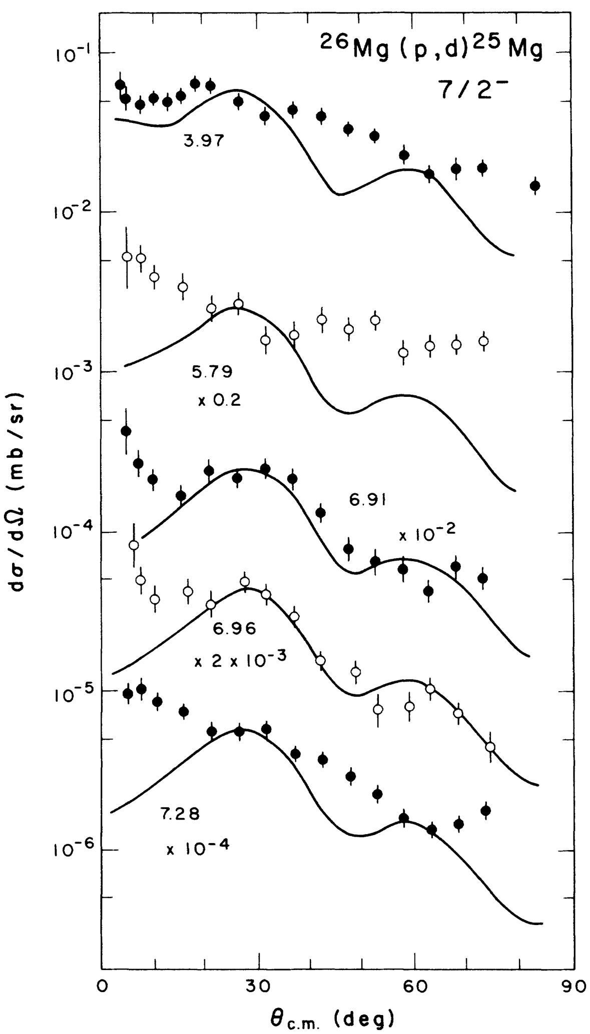

FIG. 7. Angular distributions and DWBA predictions for $f_{7/2}$ pickup by the ^{26}Mg$(p,d)^{25}$Mg reaction. Cross sections have been multiplied or divided by the factors shown for plotting purposes.

$l=3$ (^{3}He,α) calculations, but spectroscopic factors are estimated from the fits shown.

Data from the ^{26}Mg(^{3}He,α)^{25}Mg reaction to weak states at 5.75 MeV $(\frac{3}{2},\frac{5}{2})^+$, 5.79 MeV $(\frac{7}{2},\frac{11}{2})^-$, 6.91 MeV, and 6.96 MeV exhibit angular distributions that do not fall nearly as rapidly as the $l=2$ or $l=3$ DWBA curves. We are unable to provide spectroscopic factors for these states from these data, but ratios of (^{3}He,α) to (p,d) cross sections are listed in Table II. The small ratios of (^{3}He,α) to (p,d) cross sections lead to doubts on the $l=3$ pickup assignments.

Spectroscopic factors for $d_{5/2}$ states are in good agreement between the (p,d) and (^{3}He,α) data to low-lying states. The (p,d) results will be used, since these will be compared to (p,d) results for pickup from ^{27}Al. We point out the great difference in the momentum transfer provided by our two pickup reactions, and the agreement between the results establishes the reliability of the reaction calculations.

Only 12% of the total $d_{5/2}$ $T=\frac{1}{2}$ hole strength is fragmented into the weaker states, with spectroscopic factors also listed in Table II. The (p,d) spectroscopic factors were used for this value. The total strength of 2.60 is less than the expected value of 6 from the simple-shell model. The ground-state strength is slightly greater than expected ($\frac{2}{6}$) from the Nilsson model and in adequate agreement with other determinations.[9] We conclude that the $T=\frac{1}{2}$ $d_{5/2}$ $K=\frac{5}{2}$ hole state may be taken to be the ^{25}Mg ground state.

No other prominent $l=2$ peaks are found near the ^{25}Mg 7.79-MeV $T=\frac{3}{2}$ $\frac{5}{2}^+$ state. Proton pickup from ^{26}Mg finds the second $T=\frac{3}{2}$ $\frac{5}{2}^+$ state at 2.91 MeV, with only 10% of the strength to the lowest $T=\frac{3}{2}$ peak.[20] The expanded spectrum in Fig. 4 confirms that no prominent $\frac{5}{2}^+$ candidates lie near the 7.787 MeV peak. We conclude that the 7.79 MeV state may be taken as the $K=\frac{5}{2}$, $T=\frac{3}{2}$ $d_{5/2}$ hole for forming stretched states. The (p,d) spectroscopic factor is greater than found for the ground state, but less in the (^{3}He,α) results, but both are large, as expected.

The inequality of spectroscopic factors for the predominant $T=\frac{1}{2}$ and $T=\frac{3}{2}$ $\frac{5}{2}^+$ states could reflect the inadequacy of the binding-energy scheme used for this work; alternatives are discussed in Ref. 21. This is most marked for the (^{3}He,α) results. The worst consequence of this fault would be inconsistent spectroscopic factors for $T=0$ and $T=1$ final states in ^{26}Al, since these are based differently upon the $\frac{5}{2}^+$ hole states. An EFR analysis for proton pickup to the $T=\frac{3}{2}$ ground state in ^{25}Na finds a spectroscopic factor of 2.02.[22]

The small fragmentation of $d_{5/2}$ strength that is seen can be compared to the expectations of the Nilsson scheme. The ground state is due to pickup from the [202 $\frac{5}{2}$] orbital, while the 1.96-MeV $\frac{5}{2}^+$ state is part of the [211 $\frac{1}{2}$] orbital, as assigned from previous stripping data,[9] and the 3.91-MeV $\frac{5}{2}^+$ state is from the [220 $\frac{1}{2}$] orbital. For a deformation $\beta=+0.3$, the tabulated single-particle coefficients give predicted spectroscopic factors of 2.0, 0.51, 1.4 for the ground, 1.96- and 3.91-MeV states.

Measured results (Table II) are 2.27, 0.11, and 0.067. This failure of the simple Nilsson scheme has been pointed out before[23] and is improved by Coriolis band mixing.

The spectra in Figs. 3 and 5 show fairly strong excitations of the $\frac{7}{2}^+$ (1.61-MeV) and $\frac{9}{2}^+$ (4.71-MeV) states, which would require $2\hbar\omega$ admixtures into the ^{26}Mg ground state for a one-step pickup reaction. These states were also seen in the work of Alons *et al.*[24] and were successfully fit in magnitude by a coupled-channel calculation in which both $d_{5/2}$ pickup and rotational inelastic scattering are allowed. These two states are particularly strong since they are members of the $K=\frac{5}{2}^+$ ground-state band. Alons *et al.* did not carry through two-step calculations for negative-parity states, but their DWBA analysis gave a spectroscopic factor of 0.07 to fit the magnitude of the $\frac{7}{2}^-$ 3.97-MeV peak. This is about three times larger than found in the present work, carried out at a higher beam energy.

From the pickup reactions to ^{25}Mg, we draw three important conclusions. First, the $d_{5/2}$ hole strength is not significantly fragmented, but gathered into single states of $T=\frac{1}{2}$ and $\frac{3}{2}$. Second, the $d_{5/2}$ fragmentation that we do observe is somewhat as expected from the Nilsson scheme with a deformation near 0.3. Third, multistep reaction mechanisms are not required to account for $f_{7/2}$ neutron pickup from ^{26}Mg, since good fits are found for both (p,d) and $(^3\text{He},\alpha)$ reactions with the simple first-order DWBA. These conclusions make possible a more reliable analysis for the 6^- states made by pickup from ^{27}Al.

From the spectroscopic factors observed for the $\frac{7}{2}^-$ states, occupations of Nilsson orbits can be determined and will be compared in Sec. VI to results for 6^- states from the $^{27}\text{Al}(p,d)^{26}\text{Al}$ reaction.

V. $^{27}\text{Al}(p,d)^{26}\text{Al}$ RESULTS

From earlier $^{25}\text{Mg}(\alpha,t)^{26}\text{Al}$ stripping data and other sources, two $T=0$ and four $T=1$ 6^- states are known in ^{26}Al.[2] From electron scattering[3] and $^{25}\text{Mg}(\alpha,{}^3\text{He})^{26}\text{Mg}$ stripping,[4] ten $T=1$ 6^- states are known in ^{26}Mg. In a companion paper on results from high-resolution $^{25}\text{Mg}(^3\text{He},d)^{26}\text{Al}$ measurements,[25] further information is available. Due to the high density of states in doubly odd ^{26}Al, we used only the high-resolution (p,d) pickup reaction to study the 6^- states. Some results on 5^- states were also analyzed.

In Fig. 10 the pickup data to the states found at 6.884 ± 0.005 MeV and 7.527 ± 0.010 MeV are compared to DWBA cross sections. The spin of a level at a 6.892-MeV state is determined by (p,γ) spectroscopy,[7] and the isospin is also known from the $^{24}\text{Mg}(\alpha,d)^{26}\text{Al}$ reaction.[12]

TABLE II. Spectroscopic factors for neutron pickup to $\frac{5}{2}^+$ and $\frac{7}{2}^-$ states in ^{25}Mg from the (p,d) and $(^3\text{He},\alpha)$ reactions. Sums and centroids are computed assuming that all doubtful states are $\frac{5}{2}^+$ or $\frac{7}{2}^-$. For the 5.859-MeV state, the parity is determined from the present work.

Ex [b] (MeV)	J^{π} [a]	Present work	$S(p,d)$	$S(^3\text{He},\alpha)$	$\sigma(^3\text{He},\alpha)/\sigma(p,d)$ Data	$\sigma(^3\text{He},\alpha)/\sigma(p,d)$ DW
0	$\frac{5}{2}^+$	$\frac{5}{2}^+$	2.27	2.24	1.4	1.49
1.965	$\frac{5}{2}^+$	$\frac{5}{2}^+$	0.11	0.066	1.2	1.94
3.908	$\frac{5}{2}^+$	$\frac{5}{2}^+$	0.062	0.037	1.54	2.55
3.971	$\frac{7}{2}^-$	$\frac{7}{2}^-$	0.022	0.012	2.8	5.32
5.794	$(\frac{7}{2},\frac{11}{2})^-$	$\frac{7}{2}^-$	0.004		0.9	5.85
5.858	$\frac{5}{2}$	$\frac{5}{2}^+$	0.031	0.032	3.5	3.33
6.083	$(\frac{3}{2},\frac{5}{2})^+$	$\frac{5}{2}^+$	0.11	0.12	3.7	3.36
6.919		$\frac{7}{2}^-$	0.013		1.2	6.32
6.951		$\frac{7}{2}^-$	0.013		1.2	6.32
7.084	$(\frac{3}{2},\frac{5}{2})^+$	$\frac{5}{2}^+$	0.0095			3.66
7.222	$(\frac{3}{2},\frac{5}{2})^+$	$\frac{5}{2}^+$	0.0064			3.77
7.283	$\frac{7}{2}^{-\text{c}}$	$\frac{7}{2}^-$	0.032	0.010	2.0	6.53
7.87	$\frac{5}{2}^+;\frac{3}{2}$	$\frac{5}{2}^+$	3.50	1.21	2.9	8.42
$\Sigma(d_{5/2},T=\frac{1}{2})$			2.60/6	2.50/6		
$\bar{E}(d_{5/2},T=\frac{1}{2})$ MeV			0.53			
$\Sigma(f_{7/2},T=\frac{1}{2})$			0.084/8	0.022/8		
$\bar{E}(f_{7/2},T=\frac{1}{2})$ MeV			6.45			

[a]Reference 8.
[b]Results from the (p,d) spectra.
[c]Sato *et al.*, private communication.

A 7.529-MeV 6^- state[7] is also seen in the (α,d) reaction[26] and hence has $T=0$ but is also matched by a weak $M6$ transition in ^{26}Mg (Ref. 3) and thus has some $T=1$ strength. We identify the 6.892- and 7.529-MeV 6^- states with the 6.884- and 7.527-MeV levels in our pickup spectra.

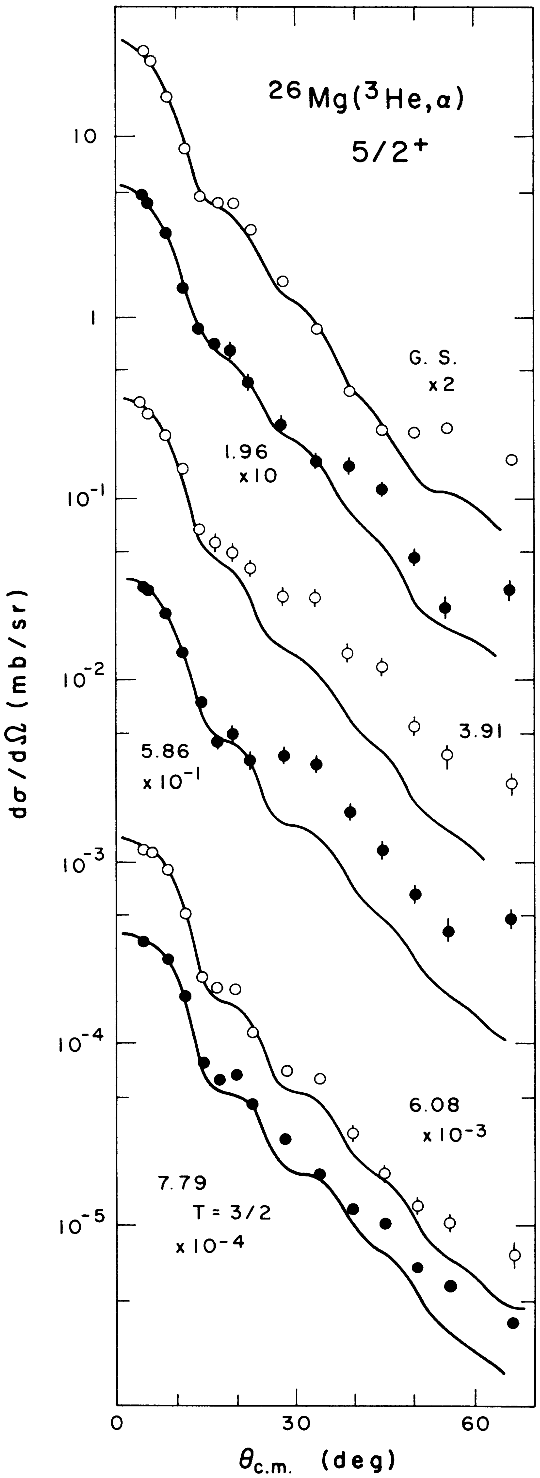

FIG. 8. Angular distributions and DWBA curves from the ^{26}Mg(^{3}He,α)^{25}Mg reaction for $d_{5/2}$ pickup. Cross sections have been multiplied or divided by the factors shown for plotting purposes.

An adequate fit to the $f_{7/2}$ pickup calculation is found for the 6.88-MeV 6^- state, with $S=0.0039\pm0.0007$, with eight expected for a full $f_{7/2}$ shell or $\frac{13}{6}$ to 6^- states alone. The fit to the 7.53-MeV cross section is not good, perhaps indicating a more complex structure, as hinted at by the isospin confusion. The fit shown yields $S=0.0063$.

Pickup data to the first definite $T=1$ 6^- state in ^{26}Al at 9.26 are shown in Fig. 10. The DWBA curve matches the featureless shape observed and yields $S=0.033$. The sum of cross sections to the 7.53- and 9.26-MeV 6^- states is more like the DWBA shape than either alone. Since the sum of cross sections cancels interference terms for two-state mixing, this may be a sign that these levels are mixed. In a companion paper on the ^{24}Mg$(\alpha,d)^{26}$Al reaction,[12] this point will be examined in greater detail. A weak (α,d) population of the 9.26-MeV state is observed, giving definite proof of at least isospin mixing. Higher-lying 6^- states in ^{26}Al could not be observed.

Known[7] 5^- states at 7.548, 8.011, and 8.067 MeV must also be populated by $l=3$ pickup. Data shown in Fig. 10 are fit by $f_{7/2}$ curves, with spectroscopic factors larger

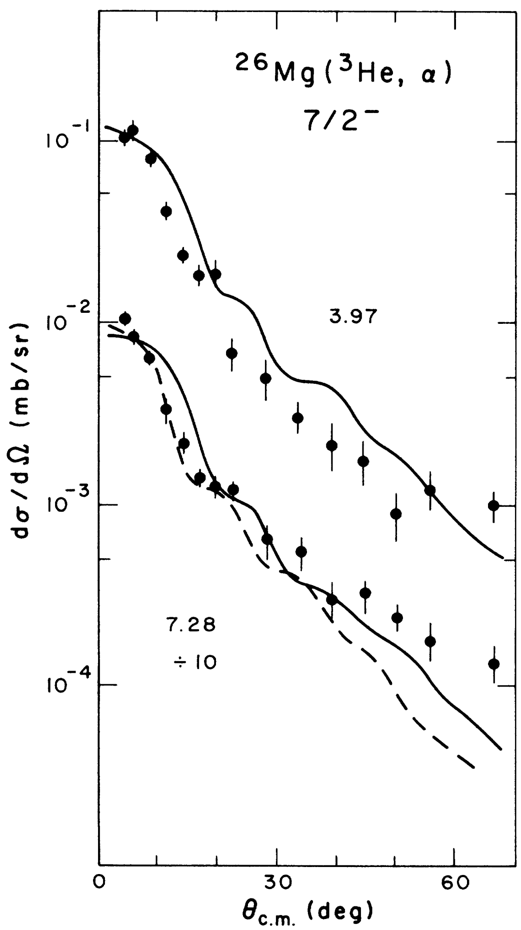

FIG. 9. Angular distributions for $f_{7/2}$ pickup by the ^{26}Mg(^{3}He,α)^{25}Mg reaction, with $f_{7/2}$ DWBA results shown by the solid curves. The dashed curve shows a $d_{5/2}$ prediction for comparison. Cross sections have been multiplied or divided by the factors shown for plotting purposes.

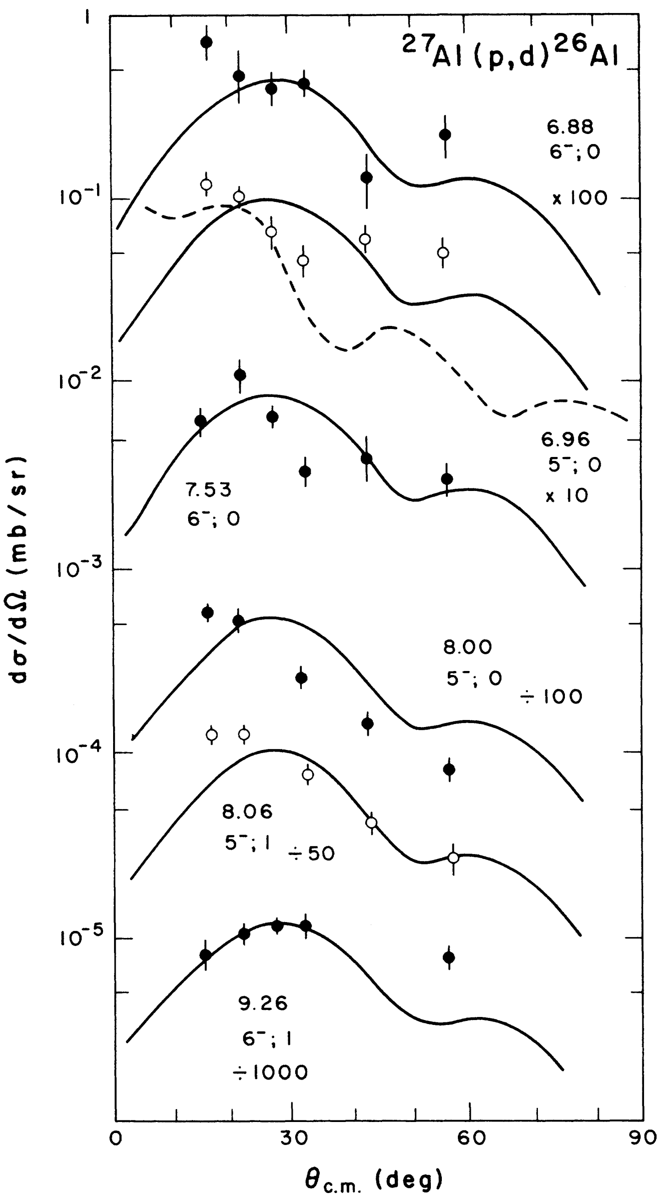

FIG. 10. Angular distributions for weak 5^- and 6^- transitions in the ^{27}Al$(p,d)^{26}$Al reaction are compared to solid DWBA curves for $f_{7/2}$ pickup. A dashed curve shows the $d_{5/2}$ expectation for comparison. Cross sections have been multiplied or divided by the factors shown for plotting purposes.

than found for the 6^- states. Both members of the 8.0-MeV doublet, with isospins from (α,d) results,[12] have spectroscopic factors near 0.05. Although the fits are not good, neither is that by an $l=2$ curve.

For the ^{27}Al$(p,d)^{26}$Al reaction, the $5^+;0$ ground state is the strongest transition, and the most likely second step for sequential excitation of the 6^- stretched states is inelastic scattering. For all $T=1$ final states, this path is isospin forbidden for the deuteron final state. For $T=0$ 6^- and 5^- states, only the single-particle isoscalar $E1$ and $E3$ inelastic scattering can occur. The single-particle $E1$ mode is particularly strongly suppressed, and the $E3$ strength is systematically weak in the middle of the *s-d* shell.

Multistep mechanisms are particularly important when a large momentum transfer may be shared between two steps of smaller momentum transfer. For the present work on ^{27}Al, the Q values are such that the 6^- states are excited only with low momentum transfer. The particularly fine fit for the pickup to the lowest $6^-;0$ state at 6.89 MeV, and the clear $l=3$ pattern seen and predicted, differ from the case for the higher states. At the 35.2-MeV beam energy of the present work, the momentum transfer to the 6.89-MeV state is very nearly zero, encouraging a good DWBA reaction mechanism.

In general, we suggest that multistep excitations of the high-spin states of negative parity in ^{26}Al will be negligible. Any specific calculations for a transition to a doubly odd nucleus would be very complicated and dependent upon the assumptions, and so none have been performed.

VI. DISCUSSION

The pickup reactions do indeed find weak but definite admixtures of $f_{7/2}$ strength in the ground state of ^{26}Mg, and this strength does not populate a single final state. This thus provides the means to fragment the strength for simple particle-hole stretched transitions. These results will be analyzed in the deformed shell model or Nilsson scheme, as has been used for other nuclear-reaction studies in this mass region,[24,27,28] but not yet for the $f_{7/2}$ or 6^- states. Although this scheme fails to match in detail the single-nucleon stripping to the *s-d* shell bands, we shall apply it for the less well-known $f_{7/2}$ shell structures for simplicity and to relate neighboring odd and even nuclei.

TABLE III. Spectroscopic factors for the ^{27}Al$(p,d)^{26}$Al reaction are listed for 5^- and 6^- states. Stripping spectroscopic factors for ^{26}Al and for mirror $T=1$ states in ^{26}Mg are shown for comparison.

Ex Present	Ref. 7	$J^\pi;T$	$S(p,d)$	$S(\alpha,t)^a$	$S(\alpha,{}^3\text{He})^b$
6.884	6.892	$6^-;0$	0.0039	0.16	
7.528	7.529	$6^-;0$	0.0063	0.15	
7.562	7.548	$5^-;0$	0.031	0.15	
8.001	8.011	$5^-;0$	0.044	0.14	
8.065	8.067	$5^-;1$	0.051	0.19	0.21
9.260		$6^-;1$	0.033	0.20	0.13

[a]Reference 2.
[b]Reference 4.

TABLE IV. Occupation numbers θ^2 for Nilsson orbitals of stretched configurations are listed for the (p,d) pickup reaction, with eight for a full $f_{7/2}$ shell. Two 5^- states are found near 8 MeV, probably very mixed.

	Ex	$J^\pi;T$	K	$\theta^3[303]$	$\theta^2[312]$
^{25}Mg					
	3.97	$\frac{7}{2}^-;\frac{1}{2}$	$\frac{7}{2}^-$	0.088	
	7.28	$\frac{7}{2}^-;\frac{1}{2}$	$\frac{5}{2}^-$		0.16
^{26}Al					
	6.88	$6^-;0$	6	0.018	
	7.53	$6^-;0$	5		0.064
	7.56	$5^-;0$	5		0.31
	8.00	$5^-;0$	?		0.45
	8.06	$5^-;1$	5		0.52
	9.26	$6^-;1$	6	0.15	

In the Nilsson scheme, the $(f_{7/2})^2$ configuration mixed into the ground state of ^{27}Al will be distributed over several orbitals, with pickup strength to several 5^- and 6^- states. For each orbital, the occupation θ^2 will be determined from

$$S=6\theta^2\,|c_j|^2(\tfrac{5}{2}\tfrac{5}{2}\tfrac{7}{2}\Omega\,|\,J_fK_f)^2/(2J_f+1)\ .$$

For pickup from ^{26}Mg, $S=2\theta^2|c_j|^2$. The Nilsson single-particle amplitudes are $|c_j|^2$, and $f_{7/2}$ pickup from a full Nilsson orbital will find θ^2 of unity or $S=2$, much as found in Table II for the $\frac{5}{2}^+$ ground state of ^{25}Mg.

For $f_{7/2}$ pickup, we take a deformation of $\beta=-0.3$ to reproduce the level order of negative-parity states in ^{25}Mg and the Nilsson coefficients $|c_j|^2$ from Ref. 29. Although this deformation is not of the same sign as that of the ground-state prolate band in mass 25, two-nucleon transfer data have previously found bands of s-d shell nucleons to have either sign of deformation.[28] For the 3.97-MeV ($K=\frac{7}{2}^-$) and 7.28-MeV ($K=\frac{5}{2}^-$) states, we find $\theta^2=0.088$ and 0.16, respectively, to match the observed spectroscopic factors.

The same calculation is used for pickup from ^{27}Al to the 6^- and 5^- states of ^{26}Al, and the listed K values in Tables III and IV were assumed. Greater occupation strength in the [303] orbit is found in the $T=1$ 6^- peak than in the $T=0$, while the ^{25}Mg result is the average of those. Occupation of the [312] orbit is seen to be greater in ^{27}Al than in ^{26}Mg, judging by the 5^- strength at 7.56 MeV. Much larger occupations are shown by the 5^- peaks than the 6^-.

It is known[23] that band mixing increases the single-particle strength to the band heads beyond the expectations of the Nilsson coefficients, so the present 6^- results may be overestimates of the true $f_{7/2}$-shell occupations. Since only 6^- states may truly be stretched, the excessive occupations for the 5^- cross sections are not a major worry. More complex structures, perhaps involving the $d_{3/2}$ shell, may concentrate an excess of strength in the band heads for both the $T=0$ and $T=1$ 5^- states.

The simple single-particle model provides but three available 6^- states in ^{26}Al, one of $T=0$ and two of $T=1$. Two $f_{7/2}$ Nilsson orbits, as found in the ^{26}Mg ground state, can give 6^- states by unblocked promotions to the $d_{5/2}$ shell, and $d_{5/2}$ nucleons may also be promoted from the pure-hole states we observe into both $\Omega=\frac{7}{2}^-$ and $\frac{5}{2}^-$ orbits, largely empty. These effects multiply the number of 6^- states by four. A total of eight $6^-;1$ states is known by electron scattering on ^{26}Mg, exactly as expected by this counting, and the transition strengths exhaust 74% of the $T=1$ $M6$ sum-rule strength for ten $d_{5/2}$ nucleons in the ground state.[7] Since the present results find but 1% of the ^{26}Mg ground-state nucleons to be $f_{7/2}$, the expected sum strength decreases by only this amount. Only very minor quenching of the single-particle strength is provided by the observed $f_{7/2}$ content.

An analysis of neutron or proton stripping to the $T=1$ 6^- states in mass 26 can account for seven such states by a full array of $K=0-6^-$ projections, but this decomposition is not unique, especially for the very weak states. Pickup data to these weak levels could not be obtained. With this many Nilsson orbitals, yet more 6^- states could be constructed.

VII. CONCLUSION

Our measurements of $f_{7/2}$ pickup from ^{26}Mg and ^{27}Al show evidence of weak occupation in these ground states from the $f_{7/2}$ shell. The splitting and distribution, observed for two nuclei, are roughly consistent with the expectations of the deformed-shell model. The $f_{7/2}$ occupation is not sufficient to give any significant quenching of $(d_{5/2}^{-1}f_{7/2})$ particle-hole excitations, as for the sum of electron scattering yields to the array of 6^- stretched states. This $f_{7/2}$ occupation is, however, very effective at providing further 6^- states, which then mix with and spread the $M6$ strength among the several 6^- states observed by electron scattering and by other light-ion reactions.

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[1] V. R. Pandharipande, C. N. Papanicolas, and J. Wambach, Phys. Rev. Lett. 53, 1133 (1984).

[2]R. J. Peterson *et al.*, Phys. Rev. C **33**, 31 (1986).
[3]M. A. Plum, Ph.D. thesis, University of Massachusetts, 1985 (unpublished).
[4]J. J. Kraushaar *et al.*, Phys. Rev. C **34**, 1530 (1986).
[5]G. Adams *et al.*, J. Phys. G **10**, 1747 (1984).
[6]P. M. Endt, C. Alderliesten, and P. de Wit, Phys. Lett. **173B**, 225 (1986).
[7]P. M. Endt, P. de Wit, and C. Alderliesten, Nucl. Phys. **A459**, 61 (1986).
[8]B. L. Clausen, R. J. Peterson, and R. A. Lindgren, Phys. Rev. C **38**, 589 (1988).
[9]P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978).
[10]S. Kato, T. Hasegawa, and M. Tanaka, Nucl. Instrum. Methods **154**, 19 (1978).
[11]M. H. Tanaka, S. Kubono, and S. Kato, Nucl. Instrum. Methods **195**, 509 (1982).
[12]M. Yasue *et al.* (unpublished).
[13]DWUCK5, an exact-finite-range DWBA code written by P. D. Kunz, University of Colorado (unpublished).
[14]J. R. Shepard, W. R. Zimmerman, and J. J. Kraushaar, Nucl. Phys. **A275**, 189 (1977).
[15]G. R. Smith *et al.*, Phys. Rev. C **30**, 593 (1984).
[16]M. Yasue *et al.*, Nucl. Phys. **A391**, 377 (1982).
[17]C. M. Perey and F. G. Perey, At. Data Nucl. Data Tables **17**, 1 (1976).
[18]C. Ciangaru *et al.*, Phys. Rev. C **29**, 2017 (1984).
[19]R. M. Del Vecchio and W. W. Daehnick, Phys. Rev. C **6**, 2095 (1972).
[20]E. Kramer, G. Mairle, and G. Kaschl, Nucl. Phys. **A165**, 353 (1971).
[21]H. Ohnuma *et al.*, J. Phys. Soc. Jpn. **36**, 1245 (1974); **42**, 382 (1977).
[22]K. I. Pearce *et al.*, Nucl. Phys. **A467**, 215 (1987).
[23]P. Wasielewski and F. B. Malik, Nucl. Phys. **A160**, 113 (1971).
[24]P. W. F. Alons *et al.*, Nucl. Phys. **A351**, 77 (1981).
[25]R. J. Peterson *et al.*, Phys. Rev. C **38**, 1130 (1988).
[26]Y. Kadota *et al.*, Nucl. Phys. **A458**, 523 (1986).
[27]R. J. Peterson and R. A. Ristinen, Nucl. Phys. **A246**, 402 (1975).
[28]N. Takahashi *et al.*, Phys. Rev. C **23**, 1305 (1981).
[29]J. P. Davidson, *Collective Models of the Nucleus* (Academic, New York, 1968).