Proton stripping to 6^- stretched states of ^{26}Al

R. J. Peterson, B. L. Clausen, and J. J. Kraushaar
Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309

H. Nann and W. W. Jacobs
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

R. A. Lindgren and M. A. Plum*
University of Massachusetts, Amherst, Massachusetts 01003
(Received 29 July 1985)

The (α,t) stripping reaction on ^{25}Mg was used to measure the $f_{7/2}$ proton spectroscopic factors for the $4^-;T=0$ (5.39 MeV), $6^-;0$ (6.89 and 7.53 MeV), and $6^-;1$ (9.26, 11.97, 12.40, and 12.55 MeV) states of ^{26}Al. The $T=1$ levels were identified with the aid of their analogs known in ^{26}Mg by inelastic electron scattering. Only 31% of the single particle strength is found for the two $6^-;0$ levels and only 59% is found for five $6^-;1$ levels. The lowest $6^-;1$ state has more than twice the spectroscopic factor of any of the others. Further 6^- candidate states are also examined.

I. INTRODUCTION

The 1-$\hbar\omega$ negative parity stretched states, formed by a particle-hole pair of maximum angular momentum, should be rather pure shell-model states simply due to the paucity of competing configurations that could couple to high spin. Deviations from this scheme are expected as collective effects spread and damp the simple configurations,[1-3] spreading the single particle strength among many states and decreasing the total strength observable to a reaction. Near ^{24}Mg, collective degrees of freedom are known to be very important, leading us to anticipate deviations from the shell model stretched state spectrum seen in more spherical nuclei. Indeed, while only one strong 6^- $d_{5/2}^{-1}f_{7/2}$ stretched state of each isospin, $T=0$ and $T=1$, is known and well-studied in ^{28}Si,[4-8] several $T=1$ 6^- states are known in ^{26}Mg.[9,10] The mass 26 system thus allows a more sensitive study of the damping of these simple states than would be possible for only one such state, as in mass 28.

In the simplest picture of only one-particle one-hole excitation from a closed shell the population of such 6^- states by inelastic scattering (or charge exchange) and by single nucleon stripping would be proportional to the same single particle amplitudes or spectroscopic factors.[6] Coherent collective effects will affect these two classes of reactions differently, since the stripping cross section is incoherent, being based on only a single hole state, the ground state of the odd-mass target. Comparison of an array of 6^- spectroscopic factors determined by the coherent (inelastic scattering) and incoherent reactions will indicate the damping due to the collective degrees of freedom.

We have used the ^{25}Mg$(\alpha,t)^{26}$Al reaction to populate the 6^- states of ^{26}Al. This reaction, which has a large momentum mismatch, was used to emphasize the $f_{7/2}$ stripping and enhance the 6^- states above the many other states at high excitation energies. A $T=0$ 6^- state in ^{26}Al has been observed,[11] but the $T=1$ 6^- states are best known through their analogs in ^{26}Mg.[9,10] The $T=2$ states of ^{26}Al are not accessible to proton stripping on ^{25}Mg.

Comparison of stripping and scattering reactions can be made through their comparisons to single particle predictions, after a comparison of each class of data to the appropriate reaction calculations. Although the (α,t) reaction is not the simplest stripping reaction, a good understanding of the mechanism is possible through either zero-range or exact-finite-range (EFR) distorted wave calculations. Such EFR calculations have been used for this reaction at the same beam energy for stripping to the 6^- states of ^{28}Si (Ref. 12) and for stripping to outer shells in heavy targets.[13] The present analysis will closely follow the ^{28}Si study to permit a systematic comparison of the same degree of freedom in two nearby $T=0$ nuclei.

II. THE EXPERIMENT

The 80.9 MeV ^{4}He beam from the Indiana University Cyclotron Facility was used for the present study, with the outgoing tritons momentum analyzed and detected in the QDDM spectrograph system, with a solid angle of 1.6 msr. Metallic foils of ^{25}Mg (enriched to 98.25% and 0.513 mg/cm^2 thick) and ^{24}Mg (99.92%, 0.78 mg/cm^2) were the targets, together with a natural carbon foil for calibration. The uniformity of the focal plane response was scanned using the ^{12}C$(\alpha,t)^{13}$N reaction to the 3.5 MeV state. Particle identification by the energy signal in a plastic scintillator behind the position sensitive focal plane detector was very clean, as no other reaction products were allowed on the focal plane by the high spectrometer magnetic field. A pulser signal introduced at the detector was both scaled directly and analyzed in the spectra to monitor the live time.

The energy resolution at small angles was 80 keV (FWHM), but this degraded at larger angles due to the kinematic broadening, which was not completely compen-

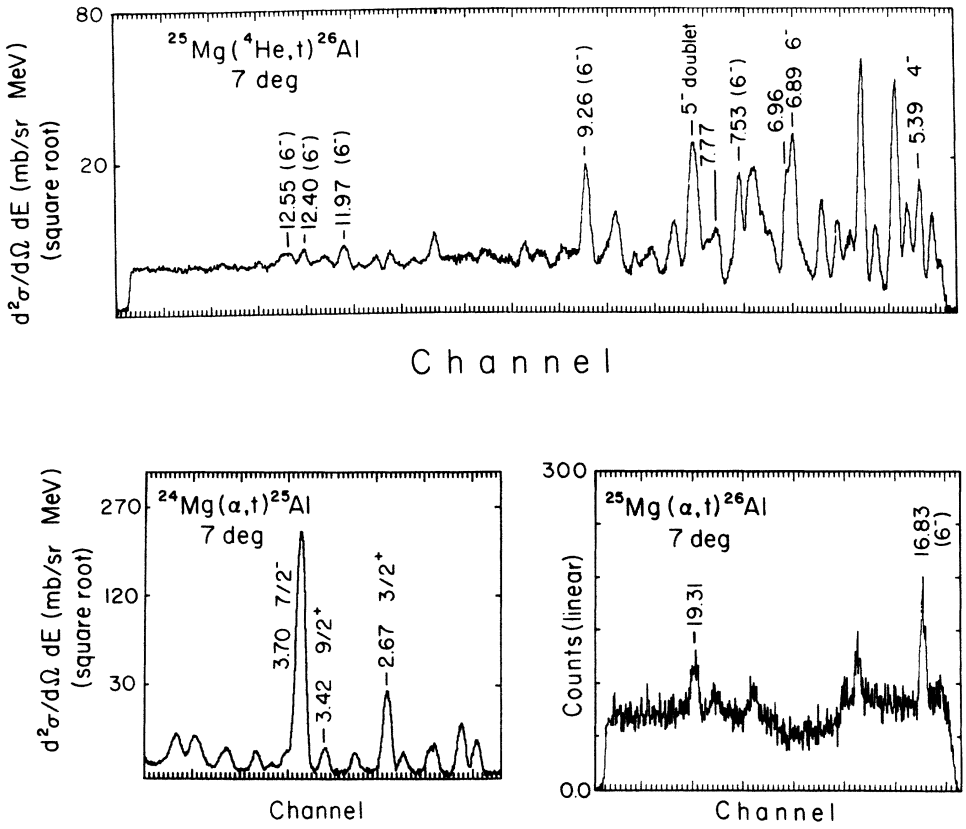

FIG. 1. Momentum spectra for the (α,t) proton stripping reaction on ^{24}Mg and ^{25}Mg are shown, with the vertical scale proportional to the square root of the cross sections, except for the insert at high excitation. These composite spectra are normalized from bite to bite by the overlapping regions. Excitation energies for the states of interest in the present work are given. The 12.55 MeV state is the lower one of two peaks; the other peak exhibits a steeply falling angular distribution inconsistent with $l=3$.

sated for by the spectrometer multipole fields. Energy calibration was accomplished for the lower states of ^{26}Al by the (α,t) reaction and the known levels of ^{25}Al (Ref. 14) and for the higher states by the levels of ^{13}N. All energy calibration comparisons were made at small angles with identical magnetic field settings for all targets. Due to the limited portion of the spectrum available for each setting of the spectrometer field, several overlapping spectra were required; some excitation energy calibrations were duplicated thereby. Composite spectra for both ^{25}Al and ^{26}Al are shown as Fig. 1. As expected for the (α,t) reaction, the $f_{7/2}$ stripping to the 3.696 MeV state of ^{25}Al (Ref. 14) is strongly emphasized.

In Fig. 1(b) there is no population of the analog in ^{26}Al of the 6^- state found at 18.1 MeV in ^{26}Mg. This confirms the $T=2$ assignment, as expected from inelastic scattering studies on ^{26}Mg.[9,15,10]

The normalization of the (α,t) cross sections was checked and adjusted slightly by measuring the elastic alpha particle scattering at 80.9 MeV on both ^{24}Mg and ^{25}Mg at angles between 31 and 34 deg. Near the elastic scattering maximum, comparison to elastic scattering optical model predictions (with the parameters described below) yielded a slight relative renormalization in the ^{24}Mg and ^{25}Mg target thickness. The elastic data are forced to match these predictions by increasing the ^{24}Mg target thickness by a factor of 1.06 and the ^{25}Mg thickness by 1.11. The stripping cross sections on the two targets may be compared with a relative uncertainty of $\pm 6\%$, from the scatter in the elastic scattering comparisons on the two targets (as normalized to the optical model). The absolute cross sections, from the known target thicknesses and solid angle, are known to $\pm 10\%$, consistent with the small readjustment used. This normalization uncertainty is compatible with the comparison between the elastic scattering data and calculations, where a scatter of $\pm 6\%$ was obtained for each target.

III. COMPARISON TO DWBA PREDICTIONS

All optical model parameters for the ^{4}He and for the triton were those used at the same beam energy for the ^{27}Al$(\alpha,t)^{28}$Si reaction, as listed in Table I of Ref. 12. The other important parameter set for stripping reactions is that to determine the potential binding the transferred nucleon. Inelastic scattering calculations based on the shell model also require that these parameters be specified. Since the magnitudes of the predictions can be quite sensitive to the radial wave functions, it is important to compare analyses only with consistent values. Disagreements

between spectroscopic factors for the 6⁻ states of ^{28}Si derived from proton stripping and inelastic scattering analyses may not be surprising, since the proton stripping calculations[12] were performed for a Woods-Saxon potential of radius $R=r_0A^{1/3}=1.25\ A^{1/3}$ fm and diffuseness $a=0.65$ fm, whereas harmonic oscillator radial wave functions were used for the proton[16,17] and electron[8] scattering analyses. As the states of interest are unbound, the differences in the radial matrix elements using these two methods can be great. Other analyses of reactions to these 6⁻ states of ^{28}Si used yet different parameters, as listed in Table I. No consistent comparison or sound structure deductions can be possible until a common parameter set is used for all reaction analyses. When consistency has been required, using oscillator wave functions, good agreement has been found between electron and pion scattering to the 6⁻ states of ^{28}Si.[18]

Fortunately, the desired geometrical parameters are not arbitrary, but can be determined by two means. One method, developed initially by Elton and Swift,[19] adds the distributions of nucleons bound in a well to match the measured total distribution of charge. For the neutron in ^{25}Mg, such an analysis has been carried out and used for the (p,d) pickup reaction at large momentum transfer.[20] The transverse electromagnetic form factor for the valence nucleon is also determined by the binding potential, and results have become available recently.[21] These $M5$ moment results are listed in Table I for ^{25}Mg and ^{27}Al. Unfortunately, these two reasonable schemes for ^{25}Mg disagree rather strongly, and the $M5$ (Ref. 21) and $M6$ analyses[10] do not give the same parameters. This negates the consistency hoped for in the analysis of Ref. 22, where a systematic reanalysis of stripping data was performed for test cases of odd nuclei with well-determined ground state distributions of magnetization.

We shall present calculations using the same arbitrary bound state parameters used for the 80 MeV study of the ^{27}Al(α,t)^{28}Si reaction [$r_0=1.25$ fm, $a=0.65$ fm, and $\lambda=25$] (Ref. 12) to allow a consistent comparison, together with the parameters based upon, for instance, the scheme of Elton and Swift, as used in Ref. 20 (1.33, 0.70, 25) and an average of the similar parameters found for the $M5$ form factors of ^{27}Al and ^{25}Mg (Ref. 21) (1.09,0.72,14). The test case for these comparisons is the stripping to the $\frac{7}{2}^-$ state of ^{25}Al at 3.696 MeV, which is unbound to proton decay but has an observed width of only 0.3 keV.[14] The calculations to test the influence of the stripping state parameters treat this as a resonance using the method of Vincent and Fortune.[24]

These tests, and other calculated results for comparison to the data, were obtained with the zero-range DWBA code DWUCK4, with a finite-range parameter of 0.7 fm and nonlocal parameters of 0.85, 0.25, and 0.20 fm for the proton, triton, and ^{4}He. Spectroscopic factors are obtained by

$$\frac{d\sigma}{d\Omega}(\text{expt})=C^2SsD_0^2\frac{2J_f+1}{(2j+1)(2J_i+1)}\frac{d\sigma}{d\Omega}(\text{DW})$$

using a value[25] of $D_0=275$ MeV fm$^{3/2}$, for a single nucleon transfer, with a light-particle spectroscopic factor of $s=2$. On the ^{24}Mg target, the isospin coefficient is $C^2=1$, while for the ^{25}Mg target, $C^2=0.5$ for both $T=0$ and $T=1$ final states. It has been shown that with these parameters the zero range (ZR) calculations coincide with exact finite range (EFR) calculations for the (^{3}He,α) reaction over a wide range of energies.[25]

In Fig. 2 the (α,t) data for the strong $\frac{7}{2}^-$ transition in ^{25}Al are compared to the zero-range DWBA predictions, all with a constant spectroscopic factor of $S=0.31$ but with three sets of bound state parameters. Although the Elton and Swift set,[19] for instance, gives a cross section larger at 7 deg by 28%, these three average to be very near the results for the set used for the 80 and 65 MeV (α,t) analyses to ^{28}Si.[6,12] If treated improperly as a bound $\frac{7}{2}^-$ state, the predicted DWBA cross sections increase to 1.13 times the unbound state calculation, constant to within 1% for all three bound state geometries. This is similar to the factor of 1.33 found for a similar comparison at a lower beam energy for ^{28}Si.[6] As seen in Fig. 2 these variations have almost no effect on the shape of the predicted

TABLE I. Potential parameters binding the transferred proton in the (α,t) calculations or binding the excited nucleon for inelastic scattering are listed. The first set, from Ref. 12, was used for the present work, after comparisons to calculations with the other sets.

	r_0 (fm)	a (fm)	λ (Thomas)	$\frac{d\sigma}{d\Omega}(0°)$ (relative)	Ref.
(αt)	1.25	0.65	25	1.00	12
(α,t)	1.25	0.65	24	1.00	6
(e,e′)	$b=1.743$ fm		(harmonic oscillator)		8
(p,p′)	1.35	0.55	22.3	1.10	4
(π,π')	1.20	0.65	25	0.87	5
$M5$ (^{25}Mg)	1.06	0.72			21
(^{27}Al)	1.12	0.72			21
Average	1.09	0.72	14	0.72	
(p,d)	1.33	0.70	25	1.33	20
(p,p′)	$b=1.743$ fm		(harmonic oscillator)		23
^{26}Mg-$M6$	1.417	0.50	22.3	1.26	10
Average				1.04	

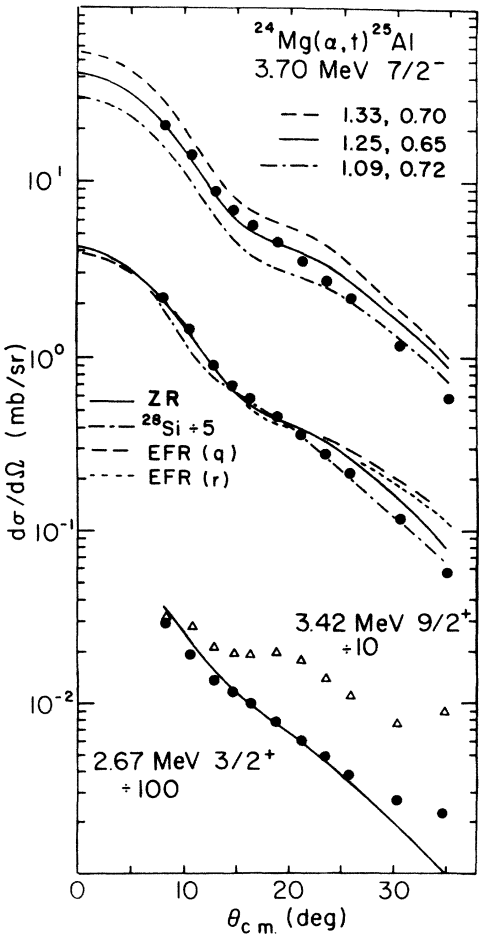

FIG. 2. In the upper part are shown proton stripping data to the $\frac{7}{2}^-$ state at 3.70 MeV in ^{25}Al, compared to zero-range DWBA predictions with three different geometrical parameter sets for the unbound transferred proton using $S=0.31$. In the lower part the same data are compared to the same solid curve as above, all divided by 10. The EFR calculations in momentum space yield the long dashed curve, with a bound state assumed as for the solid curve. The resulting spectroscopic factors are listed in Table II. The short-dash curve shows the EFR result using a radial form for the light particle. The dot-dash curve shows twice the sum (divided by 10 to be on the same scale) of the $T=0$ and $T=1$ 6^- cross sections for the ^{27}Al(α,t)^{28}Si reaction at the same beam energy (Ref. 12). The ^{25}Al Q value is very near the average of those for these transitions to ^{28}Si. The data at the bottom for the 3.42 MeV $\frac{9}{2}^+$ and 2.67 MeV $\frac{3}{2}^+$ data are compared to a curve averaging the $\frac{7}{2}^-$ 3.70 MeV data. Although the $d_{3/2}$ shape is similar to that for $f_{7/2}$, the $\frac{7}{2}^-$ state is ten times stronger due to the momentum mismatch in the (α,t) reaction.

cross sections. Also seen in Fig. 2 is a comparison of the $f_{7/2}$ data to ^{25}Al and the average of the $f_{7/2}$ stripping to the $T=0$ and $T=1$ 6^- states of ^{28}Si at the same beam energy. The Q values for these two states average quite closely to that for the $\frac{7}{2}^-$ state in ^{25}Al, and very similar shapes are seen.

As the average between two reasonable schemes and for consistency with the previous (α,t) analyses,[6,12] we shall use only $r_0=1.25$ fm, $a=0.65$ fm, $\lambda=25$. This also gives a DWBA (α,t) prediction only 10% less than when the parameter set used for the ^{28}Si(p,p′) analysis[4] was employed. The parameter set used for the pion scattering analysis[5] gives DWBA predictions 13% less than the set selected for the (α,t) calculations. Although a variance of ±23% in the absolute predictions results from the choice of bound states among the six considered, much of this could be compensated for if the (α,t) spectroscopic factors are compared to scattering or charge exchange spectroscopic factors extracted by comparing data to reaction calculations with this same geometry. The relative DWBA zero degree predictions are listed in Table I, showing that the set adopted here gives a good average, even for the parameter sets selected only from electron scattering data.

At the bottom of Fig. 2 are seen comparisons of (α,t) data for the known[14] $\frac{3}{2}^+$ and $\frac{9}{2}^+$ states of ^{25}Al to the shape for the $\frac{7}{2}^-$ transition. Some danger of confusion between $d_{3/2}$ and $f_{7/2}$ stripping could be anticipated, but the (α,t) reaction gives much larger cross sections to the high spin states. Low spin states from $d_{3/2}$ stripping may also be expected to exhibit greater energy widths when highly unbound.

The code DWUCK5 was used to perform the EFR calculations, with the same parameters as above, but treating all unbound states as bound by 0.1 MeV. The influence of the correct unbound nature was assessed by comparison to the zero-range results, where unbound states gave predictions smaller than 0.1 MeV bound states by factors from 0.94 to 0.83 depending on the excitation energy. The light particle form factor is that used in (^{3}He,α) studies,[25] represented in momentum coordinates and specified out to $q=15$ fm^{-1}. The EFR (q) form used has $D(q=0)=-303.8$ MeV fm$^{3/2}$. Recent zero-range analyses of (α,^{3}He) reactions have determined that $D(q=0)$ has a magnitude of 290–310 MeV fm$^{3/2}$ (Ref. 26). At the smallest angle in the present experiment, 7 deg, $q^2=0.92$ fm^{-2}, and at the greatest angle, $q^2=4.45$ fm^{-2}; the $q=0$ value is clearly not sufficient to treat the (α,t) reaction.

The EFR (q) calculations are compared to the zero-range calculations and the data for the prominent $f_{7/2}$ transition to ^{25}Al in the middle of Fig. 2. The fit at large angles is not as good as that found with the ZR calculations. A spectroscopic factor of 0.32 is found for the calculations shown, whereas 0.31 was found for the ZR case.

In order to compare our results to those for the ^{27}Al(α,t)^{28}Si reaction,[12] we have also used a radial form for the "light" particle reaction, binding the transferred proton in a Woods-Saxon potential of radius $r_0=1.25$ fm, diffuseness 0.65 fm, and with 25 times the Thomas spin orbit coupling constant. These EFR (r) predictions are compared in the middle of Fig. 2 to the $\frac{7}{2}^-$ state data in ^{25}Al and to the other DWBA calculations. There is almost no difference between the two formulations of the EFR for the shape, but the radial formulation requires a spectroscopic factor only 85% as large as that in the momentum representation. In the radial form, the Fourier transform yields $D(q=0)=-304.4$ MeV fm$^{3/2}$, indicating that the different predictions are due to the larger values of q, such differences giving about 20%

differences among spectroscopic factors. Agreement among (α,t) reaction descriptions to this level of accuracy have been noted previously.[13,25,26]

Although only a small part of the total of unity for a single particle state, these spectroscopic factors are very near the value expected for a single Nilsson state in ^{25}Mg, $2/(2j+1)=0.25$. The Nilsson model has been found to work well for other stripping transitions to ^{25}Al.[27] All three forms of the DWBA calculations will be used for the ^{26}Al levels, although the EFR (q) method is based on the best description of the light system.

IV. RESULTS FOR ^{26}Al

A 6^- $T=0$ state at 6.95 MeV in ^{26}Al was found from the ^{24}Mg(α,d)^{26}Al reaction,[11] with an experimental resolution of 200 keV. In the present work, with 80 keV resolution, a doublet is found, at 6.888 and 6.961 MeV, with uncertainties of ± 6 keV. As seen in Fig. 3, both show $l=3$ angular distributions. Higher resolution studies of the ^{24}Mg(^{3}He,p)^{26}Al reaction[28] show that the 6.888 MeV state is a doublet, at 6.873 and 6.899 MeV (± 8 keV), while resonance reactions at low beam energies[14] locate states at 6.875 MeV (spin 2), 6.935 MeV [spin $(1,2)^+$], 6.964 MeV (spin 2^- or 3), and 6.999 MeV [spin $(1^+$-3)]. These results indicate that the 6.899 MeV state [in (^{3}He,p)] is the 6^- level, not seen in (p,γ) studies because of its high spin. If the nearest lower spin state at 6.875 MeV were contributing to the present data for our 6.888 MeV peak, it could not be detected by the peak shape. An $l=3$ population of the 6.961 MeV peak demands a negative parity, as for instance to a 2^- and 3^- doublet, consistent with the known spectroscopy. These results have been confirmed by recent ^{24}Mg(α,d)^{26}Al (Ref. 29) and ^{25}Mg(p,γ)^{26}Al (Ref. 30) measurements.

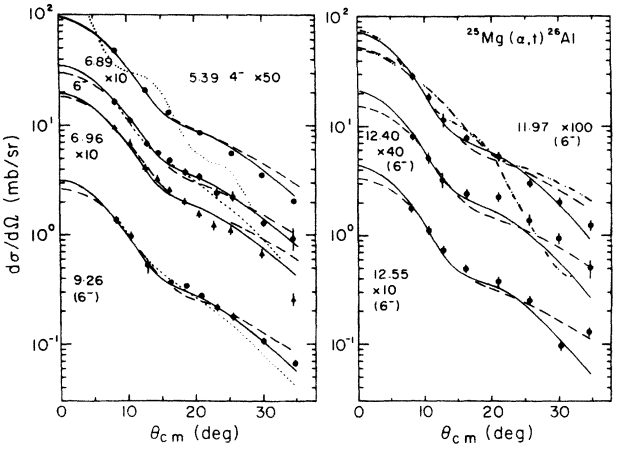

FIG. 3. Data for stripping to the known 4^- and 6^- $T=0$ states of ^{26}Al are compared to zero-range DWBA predictions as the solid curves, also compared to the data for the unresolved members of the 6.96 MeV doublet. Error bars are shown to encompass the results of peak fitting with a range of background and peak shape assumptions for the three highest states. The dotted curves compared to the 6.89 and 9.26 MeV data are taken from the shape to the $\frac{7}{2}^-$ state in ^{25}Al. EFR (q) calculations yield the dashed curves compared to the data. For the 5.39 MeV 4^- state, an $l=1$ ($2p_{3/2}$) ZR prediction is shown as the dotted curve, with a spectroscopic factor of 0.59. The shape of this prediction is nothing like that for the data. For the 11.97 MeV state ZR $l=4$ ($g_{9/2}$) and $l=2$ ($d_{3/2}$) predictions are shown as double dot-dash and dot-dash curves, respectively.

The spectroscopic factor for the 6^- 6.888 MeV state is 0.17 from the zero-range fit shown in Fig. 3, and 0.16 from the EFR (q) fit, with the DWBA calculations computed as for the $\frac{7}{2}^-$ state in ^{25}Al, with a reduction to the cross section by a factor of 0.86 to account for the unbound state. If the full stripping strength to an empty shell for a $T=0$ 6^- state was present, the normalization used here would yield a unit spectroscopic factor. Also shown in Fig. 3 is the comparison to the data for the $\frac{7}{2}^-$ transition to ^{25}Al. The 6^- cross section is a factor of 0.080 times this cross section, which ratio becomes 0.071 after correction within the DWBA for the difference in Q values. The 6.961 MeV member of the doublet has a zero range spectroscopic factor of $(2J_f+1)S=1.27$ and the EFR value is 1.26. These results are summarized in Table II. Although $l=2$ angular distributions are rather similar to $l=3$, the large cross sections and narrow widths for these steps preclude this possibility.

At 5.394 MeV in ^{26}Al a 4^- state is known[14] to be populated by an $l=1$ transition in the (d,nγ) reaction. At low momentum transfers, as in that (d,n) experiment, the lowest allowed angular momentum is expected to dominate, in contrast to the highest allowed value expected for the present work at large momentum transfer, as shown below. The $P_{3/2}$ shape compared to the 4^- data in Fig. 3 does not fit at all, whereas the $l=4$ curve matches the observed shape. Since no analog is known[14] in ^{26}Mg, we interpret this 5.39 MeV state to have $T=0$. Data for the (α,t) reaction to this 4^-;0 state, at 5.386 ± 0.006 MeV, are shown in Fig. 3, with the expected $l=4$ comparison yielding $S(\text{EFR})=S(\text{ZR})=0.10$, a smaller fraction of the allowed strength than found for the lowest 6^- stretched state. The $l=4$ transfer is also noted in the equal shapes for the 4^- and 6^- angular distributions.

The $T=1$ 6^- states of ^{26}Al are not known, but are located in the present work by comparison to their known[9,10] mirror states in ^{26}Mg. Since several states near the expected locations can be seen in the spectrum of Fig. 1, it is also demanded that the angular distributions match the DWBA predicted shapes and not exceed, state by state, the unitary limit for spectroscopic factors. Low spin states of negative parity will be short-lived and wide, so we also demand that the 6^- candidate states be narrow. Angular distributions are shown in Fig. 3 for four such states, with excitation energies and widths (after quadratic subtraction of the instrumental width) listed in Table II. All the other states seen clearly above 11.5 MeV excitation in Fig. 1 have widths of over 100 keV, except as noted below. A DWBA calculation for the width of a proton $f_{7/2}$ single particle state at an excitation energy of 12.4 MeV in ^{26}Al gives an expected width of 540 keV, whereas a $d_{3/2}$ single particle state would have twice this width, but only four percent of the $f_{7/2}$ differential cross section. For equal spectroscopic factors, $f_{7/2}$ transitions are much stronger than $d_{3/2}$ transitions. Any strong $d_{3/2}$ states

TABLE II. Excitation energies and spectroscopic factors, computed both in ZR and EFR, are listed for the states of interest in ^{25}Al and ^{26}Al. The 6^- $T=1$ results from proton and electron scattering on ^{26}Mg are also listed, from Refs. 9 and 10. A similar experiment and analysis for ^{28}Si yielded $S(4^-;0)=0.18$, $S(6^-;0)=0.21$, and $S(6^-;1)=0.29$ (Ref. 12). The results labeled EFR (q) use the momentum form factor for the light particle, while those labeled EFR (r) use the radius form, as in Ref. 12.

^{24}Mg(α,t)^{25}Al State (MeV)	J_f^π	j	S(ZR)	S(EFR) (q)	S(EFR) (r)				
3.70	$\frac{7}{2}^-$	$f_{7/2}$	0.31	0.32	0.27				
^{25}Mg(α,t)^{26}Al (MeV)	$J_f^\pi;T$	j	S(ZR)	S(EFR) (q)	S(EFR) (r)	Γ (keV)	^{26}Mg (MeV)	$\frac{d\sigma}{d\Omega}$ [a] (μb/sr)	$B(M6)$[b] oscillator
5.386±0.006	$4^-;0$	$f_{7/2}$	0.095	0.101	0.091				
6.888±0.006	$6^-;0$	$f_{7/2}$	0.17	0.16	0.15				
6.961±0.006		$f_{7/2}$	$1.27/2J_f+1$	$1.26/2J_f+1$	$1.15/2J_f+1$				
7.527±0.008	$6^-;0$	$f_{7/2}$	0.15	0.15	0.13		7.54		(1.0%)
8.002±0.008[c]	$5^-;1$	$f_{7/2}$	0.14	0.14	0.12				
8.058±0.008[c]	$5^-;1$	$f_{7/2}$	0.21	0.19	0.17				
9.264±0.005	$6^-;1$	$f_{7/2}$	0.20	0.20	0.17	59	9.18	45	7.2%
11.969±0.005	$(6^-;1)$	$f_{7/2}$	0.085	0.080	0.072	57	11.98	47	
12.404±0.005	$(6^-;1)$	$f_{7/2}$	0.070	0.065	0.061	57	12.49	40	9.5%
12.547±0.005	$(6^-;1)$	$f_{7/2}$	0.063	0.058	0.050	55	12.86	50	4.2%
16.83±0.16	$(6^-;1)$	$f_{7/2}$	0.17	0.14	0.13		16.5		14.1%
$\Sigma S(6^-;1)=0.59$ (ZR)				$\Sigma S(6^-;0)=0.32$ (ZR)					
$=0.54$ (EFR) (q)				$=0.31$ (EFR) (q)					
$=0.49$ (EFR) (r)				$=0.28$ (EFR) (r)					

[a]Reference 9, proton scattering peak cross sections.
[b]Reference 10, as fractions of the $T=1$ single particle value, evaluated with harmonic oscillator radial wave functions as in Table I.
[c]These two states formed a doublet. To split it a 56 keV energy separation was assumed (Ref. 32).

would thus be much wider than the $f_{7/2}$ states of interest. If these were $d_{3/2}$ transitions to the highest spin states, 4^+, very large spectroscopic factors would be required, as discussed in more detail below. These tests result in four acceptable states, coinciding closely with their mirrors in ^{26}Mg.

In electron scattering a 6^- state has also been found at 13.00 MeV in ^{26}Mg.[10] In this region of ^{26}Al we see a very small sharp peak calibrated to be at an excitation of 13.06±0.01 MeV, with a spectroscopic factor not in excess of 0.01.

Recent ^{24}Mg(α,d)^{26}Al work has located two additional 6^- $T=0$ candidates, located at 7.50 and 7.86 MeV.[29] The stripping data to a sharp peak at 7.527±0.008 MeV are seen in Fig. 4 to agree with the $f_{7/2}$ shape, yielding a spectroscopic factor of 0.15. A state at 7.86±0.01 MeV also shows an $f_{7/2}$ shape, as in Fig. 4, but exhibits an intrinsic width of 80 keV, precluding a 6^- spin assignment. A sharp state at 7.79±0.02 MeV has a stripping angular distribution inconsistent with $f_{7/2}$ transfer.

Our spectra did not cover the range of excitations between 13 and 16 MeV, but a sharp state is found in higher excitation spectra at 16.83±0.16 MeV, with the large uncertainty due to the lack of calibration spectra and the need to extrapolate the calibration from lower excitations A complex containing a 6^- $T=1$ state in ^{26}Mg is located by electron scattering at 16.5 MeV,[10] so we compare our data to the $f_{7/2}$ prediction as in Fig. 4. The shape and narrow width are consistent with a 6^- spin, providing a spectroscopic factor of 0.14 in the EFR (q) method.

Spectroscopic factors for these 6^- states are listed in Table II, with a sum over the five $T=1$ states of 0.59 (in zero range) or 0.54 computed in the momentum form of the EFR or 0.49 computed in the radial form,[12] where a total of one would be expected for stripping into an empty shell. Also shown in Table II are the maximum cross sections for the ^{26}Mg(p,p′) reaction to the mirror $T=1$ 6^- states.[9] The latter are much more nearly equal than are the proton stripping spectroscopic factors, where the lowest 6^- state is the strongest by a large margin. The $M6$ strengths from electron scattering on ^{26}Mg are also listed[10] as computed using harmonic oscillator potentials to generate bound nuclear wave functions.

If these 6^- candidate transitions were due to $d_{3/2}$ stripping to 4^+ states, the smaller DWBA predictions and statistical factors would be such that spectroscopic factors would be greater by a factor of 18 than those listed in Table II for 6^- states. Even the weakest of these then

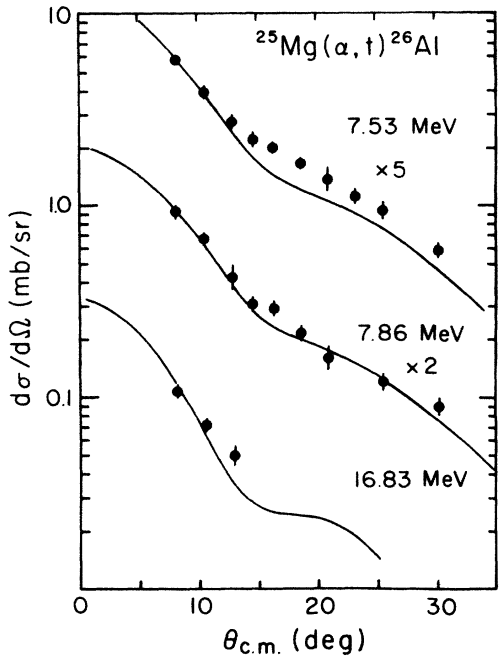

FIG. 4. Candidates for further 6^- states in ^{26}Al yield (α,t) data compared to the unbound zero range DWBA curves shown. The 7.53 and 7.86 MeV states are seen in (α,d) on ^{24}Mg (Ref. 29). The 7.86 MeV state is too broad to be of spin as high as 6^-. A 16.5 MeV 6^- $T=1$ state is known from electron scattering on ^{26}Mg (Ref. 10).

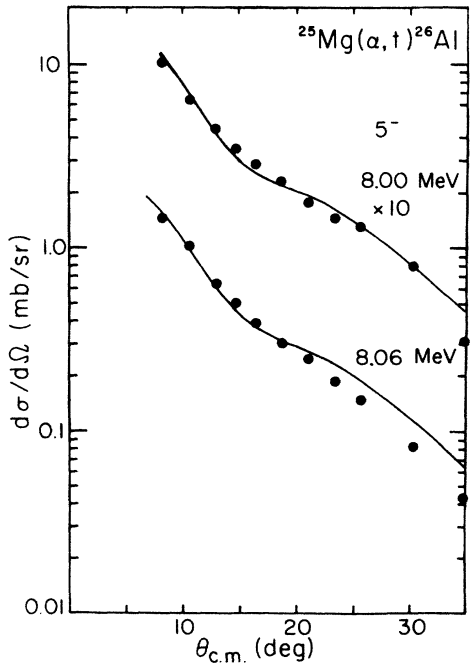

FIG. 5. Candidates for 5^-;1 states in ^{26}Al yield (α,t) data compared to the unbound zero range DWBA curves shown. The two states are seen in (p,γ) on ^{25}Mg. Spin assignments are from Ref. 30.

exceeds the sum rule limit of unity. This great enhancement of $l=3$ over $l=2$ cross sections is not found for the (^{3}He,d) reaction. At 35 MeV, a study of the ^{27}Al(^{3}He,d)^{28}Si reaction found $d_{3/2}$ transitions to 4^+ states to be weaker than $f_{7/2}$ transitions to 6^- states by a factor of about 1.3, for equal spectroscopic factors.[30] These (^{3}He,d) results did not show striking differences between the shapes for $l=2$ and $l=3$ transitions. At a 60 MeV ^{3}He energy, a published ^{27}Al(^{3}He,d)^{28}Si spectrum[31] indicates that the ratio of the cross section to the prominent 11.89 MeV $l=2$ (Ref. 30) state and that to the 11.57 MeV $l=3$ 6^- state is much the same as seen at 35 MeV. The present (α,t) reaction is thus particularly well suited to studies of stretched states, enhancing the highest allowed l transfer greatly above competing values.

The enhancement of high l transfers in the (α,t) reaction would suggest sensitivity to $l=4$ transitions, at $2\hbar\omega$ beyond the s-d shell. In Fig. 2 a known $\frac{9}{2}^+$ state shows an angular distribution distinct from that of any of our 6^- candidates. At higher excitation, Fig. 3 shows a $g_{9/2}$ prediction for the 11.97 MeV state, as computed in zero range. The fit is somewhat inferior to that for $f_{7/2}$ stripping. For the maximum $J_f=7^+$, a spectroscopic factor of 0.022 is obtained from this $g_{9/2}$ comparison. We consider the presence of such $2\hbar\omega$ modes unlikely at the excitation energies observed for our 6^- $1\hbar\omega$ candidates, but the (α,t) reaction is surely sensitive to the presence of such single particle strength. The $d_{3/2}$ DWBA shape compared to the 11.97 MeV data does not match the observed shape, especially at large angles. All of the shapes for 6^- candidates show shapes very consistent with this 11.97 MeV example.

Very recent (p,γ) resonance studies have located two 5^- $T=1$ states in ^{26}Al, at 8.002 and 8.058 MeV.[32] A single broad (α,t) stripping peak at the proper excitation was split by demanding the observed separation. The data and $f_{7/2}$ unbound zero range DWBA curves are compared in Fig. 5, showing adequate fits. Spectroscopic factors are listed in Table II. This (p,γ) work also confirms our 6^- assignments to the states calibrated by us at 6.888 ± 0.006 MeV and at 7.527 ± 0.008 MeV.

V. DISCUSSION

Each DWBA method used here to extract proton spectroscopic factors suffers from an incompleteness. The DWUCK4 calculations use only an approximation, albeit a well demonstrated one, for the finite sizes of the light particles in the reaction. The DWUCK5 calculations do not include the unbound nature of the final states, which are sharp due to their high spin. However, since the spectroscopic factors from the two methods differ but little in magnitude and show almost no difference in relative values, it must be concluded that the values listed in Table II are reliable measures of the incoherent 6^- proton spectroscopic factors. The EFR calculations using the radial method and parameters of Ref. 12 give spectroscopic factors about 10% less, but since the Fourier transform resulting from this computation is in poorer agreement with the charge form factor of ^{4}He,[25] the present results will be used, resulting from a momentum-space EFR method.

The $T=1$ 6^- states, five in number, give 54% of the sum rule spectroscopic strength, confirming that the simple shell model strength is not concentrated. This result is a bit more than the spectroscopic sum for proton stripping to the single 6^- $T=1$ state of ^{28}Si, averaging over two (α,t) (Refs. 6 and 12) and one (^{3}He,d) (Ref. 30) measurements to give 0.35. Further 6^- states in ^{26}Mg are known from electron scattering.[10]

The lowest known 6^- $T=0$ state in ^{26}Al at 6.89 MeV yields $S=0.16$, about half the proton spectroscopic factor obtained (0.32) in one (α,t) analysis for ^{28}Si,[6] but near that in Ref. 12 (0.21) and much less than found (0.43) for the (^{3}He,d) reaction on ^{27}Al.[30] Ciangaru *et al.*[12] report work at the same beam energy, analyzed by the same methods as in the present work. Their results for the single 4^- $T=0$ state of ^{28}Si yielded $S=0.18$, compared to 0.10 in the present work for ^{26}Al. If the 7.53 MeV state in ^{26}Al is also considered, the summed strength found is 31% of the single particle value for 6^- $T=0$ states.

As expected for the distributing influence expected for a Nilsson scheme for the deformed ^{25}Mg target, the present work finds the incoherent proton spectroscopic factors to be less concentrated than in ^{28}Si. In this Nilsson scheme, the 6^-;1 spectroscopic factors are to be given by

$$S(K)=|c_{7/2}|^2\times 6(\tfrac{5}{2}\ \tfrac{5}{2}\ \tfrac{7}{2}\ \Omega\,|\,6K)^2/13\ ,$$

using the Clebsch-Gordan coefficient. At a deformation $\beta=+0.3$, the single-particle coefficients may be taken from Davidson.[33] In general, the larger projections K on the symmetry axis yield the largest spectroscopic factors.

A single $K=6$ 6^- state is predicted to have $S=0.462$, nearly twice the value found for the lowest $T=1$ 6^- state at 9.26 MeV ($S=0.20$). It is also calculated that the stronger of two $K=5$ states would have $S=0.26$ and the strongest of three $K=4$ states would have $S=0.126$. These predictions depart from the observed near equality of the three observed 6^- $T=1$ spectroscopic factors for 11.97, 12.40, and 12.55 MeV. Mixing of the K values for these states is indicated, whereas the more distant 9.26 MeV state could be regarded as of a pure value of K. The known and unknown 6^- $T=0$ states have little space in the spectrum, making K mixing more likely, and it is not surprising that $S=0.16$ for the state at 6.89 MeV, less than expected for a $K=6$ or a $K=5$ level, and equal to the spectroscopic factor for the 6^- $T=0$ candidate at 7.53 MeV.[29,30]

The electron scattering study found a very weak 6^- candidate at 7.54 ± 0.02 MeV in ^{26}Mg,[10] closely matched with the 7.53 MeV state in the present work for ^{26}Al, identified as having $T=0$ by the (α,d) result of Ref. 29. These isospins are clearly inconsistent, and more detailed spectroscopic studies will be needed before the results of the several experiments may be compared in this region of excitation. The rather high-lying 6^- $T=1$ candidate at 16.83 MeV seems to exhaust the same fractions of the single particle value for both (α,t) ($S=0.14$) and electron scattering[10] (14%).

The coherent spectroscopic factors to be extracted from the 6^- analogs in ^{26}Mg by inelastic proton or electron scattering will be more nearly equal, since the cross sections are nearly equal to the several states.[9] Zamick[3] has pointed out that for $K=6$, the incoherent stripping spectroscopic factor would be $\frac{6}{13}$ of the single particle value, while the coherent scattering strength $B(M6)$ would be $\frac{2}{13}$ times the single particle value. Relative to the other three 6^-;1 states, the lowest state (9.26 MeV) is very closely three times as strong in the (α,t) results, just as expected for $K=6$.

We conclude that the ensemble of stretched states available in $A=26$ does provide a more valuable tool for understanding the damping of such simple degrees of freedom than is possible for only a single stretched state (of each isospin) in $A=28$. A particular Nilsson model with $K=6$ for the lowest $T=1$ stretched state agrees in detail with the comparison between stripping and scattering relative strengths, but the higher 6^-;1 states will need an analysis that includes K mixing, and a more complete understanding of the location of the $f_{7/2}$ strength to 6^- states is necessary.

Since but two 6^- $T=0$ states are reliably known, the (α,t) analysis for these states is less complete. New spectroscopic studies of the ^{24}Mg(α,d)^{26}Al, ^{26}Mg(^{3}He,t)^{26}Al, and ^{26}Mg(p,n)^{26}Al reactions would be needed to locate further 6^- $T=0$ states before we could determine further spectroscopic factors.

The DWBA methods used in the present work have been thoroughly tested, and good consistency is found for the parameter set chosen. A test of the $f_{7/2}$ Nilsson spectroscopic factor for ^{25}Al was successful. We conclude that the absolute spectroscopic factors, from either the ZR or EFR calculations, are reliable to about $\pm29\%$, formed of 10% uncertainty in the normalization of the data, 23% for the variance due to the choices of bound state geometry, and 15% as the extreme uncertainty between EFR (q) and EFR (r) methods. This confirms that much of the stripping strength to the simple 6^- stretched states is not located, as the present work finds at most 54% of the $T=1$ and 31% of the $T=0$ sums. In ^{26}Mg, the five $T=1$ states listed in Table II exhaust 36% of the extreme single particle $T=1$ strength from electron scattering, and a total of 64% is found for ten $T=1$ states.[10] Rather similar total strengths are thus found by the two reactions, but the analyses use rather different binding potentials.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation and U.S. Department of Energy. We wish to thank M. Yasue and P. M. Endt for their latest spectroscopic results for ^{26}Al.

*Present address: MS H841 MP-10, Los Alamos National Laboratory, Los Alamos, NM 87545.

[1]A. Amusa and R. D. Lawson, Phys. Rev. Lett. **51**, 103 (1983).
[2]G. F. Bertsch, P. F. Bortignon, and R. A. Broglia, Rev. Mod. Phys. **55**, 287 (1983).
[3]L. Zamick, Phys. Rev. C **29**, 667 (1984).
[4]G. S. Adams *et al.*, Phys. Rev. Lett. **38**, 1387 (1977).
[5]C. Olmer *et al.*, Phys. Rev. Lett. **43**, 612 (1979).
[6]M. Yasue *et al.*, Nucl. Phys. **A391**, 377 (1982).
[7]R. O. Nelson, E. G. Bilpuch, C. R. Westerfeldt, and G. E. Mitchell, Phys. Rev. C **30**, 755 (1984).
[8]S. Yen *et al.*, Phys. Rev. C **27**, 1939 (1983).
[9]D. F. Geesaman *et al.*, private communication.
[10]M. A. Plum, Ph.D. thesis, University of Massachusetts, 1985 (unpublished).
[11]E. Rivet, R. H. Pehl, J. Cerny, and B. G. Harvey, Phys. Rev. **141**, 1021 (1966).
[12]C. Ciangaru *et al.*, Phys. Rev. C **29**, 2017 (1984).
[13]S. Gales *et al.*, Phys. Rev. C **21**, 94 (1985).
[14]P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978).
[15]R. A. Lindgren *et al.*, Bull. Am. Phys. Soc. **27**, 697 (1982).
[16]S. Yen *et al.*, Phys. Lett. **105B**, 421 (1981).
[17]N. M. Hintz *et al.*, Phys. Rev. C **30**, 1976 (1984).
[18]J. A. Carr *et al.*, Phys. Rev. C **27**, 1636 (1983).
[19]L. R. B. Elton and A. Swift, Nucl. Phys. **A94**, 52 (1967).
[20]G. R. Smith *et al.*, Phys. Rev. C **30**, 593 (1984).
[21]T. W. Donnelly and I. Sick, Rev. Mod. Phys. **56**, 461 (1984).
[22]A. E. L. Dieperink and I. Sick, Phys. Lett. **109B**, 1 (1982).
[23]C. Olmer *et al.*, Phys. Rev. C **29**, 361 (1984).
[24]C. M. Vincent and H.T. Fortune, Phys. Rev. C **2**, 782 (1970).
[25]J. R. Shepard, W. R. Zimmerman, and J. J. Kraushaar, Nucl. Phys. **A275**, 189 (1977).
[26]S. Gales *et al.*, Phys. Lett. **144B**, 323 (1984).
[27]R. J. Peterson and R. A. Ristinen, Nucl. Phys. **A246**, 402 (1975).
[28]R. R. Betts, H. T. Fortune, and D. J. Pullen, Phys. Rev. C **6**, 957 (1972).
[29]Y. Kadota and M. Yasue, private communication.
[30]H. Nann, Nucl. Phys. **A376**, 61 (1982).
[31]K. A. Snover *et al.*, Phys. Rev. C **27**, 493 (1983).
[32]P. M. Endt, P. deWitt, and C. Alderliesten, private communication.
[33]J. P. Davidson, *Collective Models of the Nucleus* (Academic, New York, 1968), p. 191.