$I(p_\pi, \alpha_1, \alpha_2)$ has an anomaly starting with the ΣN threshold. Therefore, in Fig. 1(b) we have shown, by the dashed line, the values speculated from the calculation of $V_{\rm ph}|T_{\Lambda\Sigma}|^2$ above the ΣN threshold.

Now let us see where these peaks come from. We can see that the two peaks are essentially dependent on the character of $T_{\Lambda\Sigma}$, in which $\Sigma\Lambda$ conversion is explicitly taken into account, by plotting $V_{\rm ph}|T_{\Lambda\Sigma}|^2$ with respect to $M_{\Lambda N}$ as is shown in Fig. 1(c). The values calculated with potential set 1 are indicated by a solid line. Two peaks naturally and clearly appear. The $V_{\rm ph}|T_{\Lambda\Sigma}|^2$ calculated with potential set 2 is indicated by a dashed line in Fig. 1(c). Notice that the peak just above the ΛN threshold clearly appears while the peak just below the ΣN threshold does not appear.

Thus we can give physical meanings to the two peaks. Firstly, the two peaks are simultaneously explained by two-channel formalism and these peaks are essentially dependent on the character of $T_{\Lambda\Sigma}$. Secondly, the peak just below the ΣN threshold is mainly due to the Λp resonance; this peak would not be explained by kinematical effects alone. Thirdly, the peak just above the ΛN threshold is due to the two-channel final-state interaction or Λp final-state interaction associated with the $\Sigma\Lambda$ conversion process.

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Systematics of Ground-State α-Particle Spectroscopic Strengths for *sd*- and *fp*-Shell Nuclei*

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We present systematics of the ground-state α-particle spectroscopic strengths for nuclei from ^{20}Ne to ^{66}Zn, measured in the (^{6}Li,d) reaction. An oscillatory decrease from ^{20}Ne to ^{32}S, which is in excellent agreement with SU(3) theory, is followed by a striking and unexplained increase at ^{36}Ar and ^{40}Ca and then a decrease up to ^{52}Ti, after which there is again a rise.

Single-particle widths (spectroscopic strengths) of bound states in nuclei throughout the periodic table are well measured experimentally and to a considerable extent understood theoretically. The same has not been true experimentally until fairly recently and, in large measure, is still not true theoretically for α-particle spectroscopic strengths. In this Letter we present for the first time the detailed experimental systematics of the ground-state α-particle spectroscopic strengths for nuclei ranging from ^{20}Ne to ^{66}Zn. The results, in summary, are an oscillatory decrease from ^{20}Ne to ^{32}S whose details are in surprisingly good agreement with SU(3) theory, followed by a striking increase at ^{36}Ar and ^{40}Ca. The spectroscopic strengths then decrease to a minimum at ^{52}Ti, after which they rise again. This behavior in the upper half of the *sd* shell and lower half of the *fp* shell is not yet amenable to theoretical explanation.

The results were obtained from measurements of the (^{6}Li, d) reaction in the *sd* and *fp* shells[1-8] using the University of Rochester MP tandem Van de Graaff accelerator. A study similar to that discussed here, but using the (d, ^{6}Li) pickup reaction, was recently reported by Becchetti *et al.*[9] In the limited region of overlap with the present results, the agreement is good as discussed below.

The targets employed in the work reported here are ^{16,18}O, ^{20,21,22}Ne, ^{24,25}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40,42,44,48}Ca, ^{50}Ti, ^{50,52}Cr, ^{54,56}Fe, and ^{58,60,62}Ni.

The ^{6}Li bombarding energies were in all cases high enough to ensure that the reaction was predominantly direct: The energy was 32 MeV for most of the targets, 36 MeV for ^{24,25}Mg, 28 and 32 MeV for ^{36}Ar, and 28 MeV for the Cr, Fe, and Ni isotopes. Angular distributions, usually over the range of 5° to 60°, were obtained not only for the ground state, but also for several excited states of each of the final nuclei.

A gas cell was used for the measurements on ^{16}O, ^{20,21,22}Ne, ^{32}S, and ^{36}Ar targets; for ^{16}O and ^{32}S, solid targets were also employed. The active volume of gas could be estimated to an accuracy of about 20%, which represents the major source of error in the corresponding absolute cross-section determination. The ^{18}O target contained a known amount of ^{16}O, which provided an easy means of getting the ^{18}O(^{6}Li, d)^{22}Ne absolute cross section. Except for ^{32}S and the Ca isotopes, all the other targets were self-supporting. Elastic scattering at forward angles was used to determine to an accuracy of about 20% the absolute cross sections for these nuclei. For the gold-backed S and Ca targets, elastic-scattering peaks could be resolved well enough to yield an accuracy of about 30% in absolute cross sections. A remeasurement using gas targets of SO_2 and ^{36}Ar gave absolute cross sections for the (^{6}Li, d) reactions on ^{16}O, ^{32}S, and ^{36}Ar which agreed within the quoted accuracy with the earlier values.

In work already published,[1-8] the angular distributions for transitions to states in some of the final nuclei were fitted by distorted-wave Born-approximation (DWBA) calculations by use of either the zero-range code DWUCK[10] or the exact-finite-range code LOLA[11] with the assumption of a cluster-transfer mechanism. The ratios $(d\sigma/d\Omega)_{\text{expt}}/(d\sigma/d\Omega)_{\text{DWBA}}$ gave the α-particle spectroscopic strengths. In studying systematics over a wide range of nuclei, special attention must be paid to the accuracy of the absolute cross-section measurements (discussed above) and to the consistency of the analysis, including the choice of optical-model potentials and bound-state parameters.

For reactions on all the sd-shell targets, a single set of ^{6}Li and deuteron optical-model parameters proved sufficient to fit the angular distributions, by use of the code LOLA. This was true not only for the ground states, but also for several excited states. The ^{6}Li potential used was the one employed by Strohbusch *et al.*[4] and depends on A only through the usual $A^{1/3}$ dependence of the radii for the real and imaginary potentials; the deuteron potential used[12] had a mild Z and A dependence. The bound-state well had a radius of $1.3A_t^{1/3}$ fm and a diffuseness of 0.65 fm. Calculations with the same set of optical and bound-state parameters also provided good fits to the ground-state angular distributions for the transitions ^{40,42,44,48}Ca(^{6}Li, d), ^{50}Ti(^{6}Li, d), and ^{62}Ni(^{6}Li, d), but not for the transitions on Cr, Fe, and ^{58,60}Ni targets. The angular distributions for the transitions on Cr, Fe, and Ni targets were fitted by DWUCK calculations using the set II optical-model parameters of Fulbright *et al.*[5] (They have also been fitted by LOLA calculations[6] in which the bound-state radius was varied from one target to another and which therefore were not used in the present analysis.) The strengths extracted thereby were multiplied by a constant factor to ensure consistency with the results for the other transitions. This constant factor was determined from cases where both sets provided equally good fits to the measured angular distributions, viz., the (^{6}Li, d) transitions on ^{50}Ti and ^{62}Ni. It was verified in these and a number of other cases that the ratios of extracted strengths for different states remained essentially the same when different optical potential sets which fitted the measured angular distributions were used. Despite this, however, it must be admitted that the relative spectroscopic strengths in the region $A_f = 54$ to 64 are less certain than for the lighter nuclei.

Figure 1 displays the spectroscopic strengths extracted for the various ground-state transitions plotted versus the mass A_f of the final nucleus, all normalized relative to unity for the transition ^{16}O(^{6}Li, d)^{20}Ne(g.s.). The crosses represent ex-

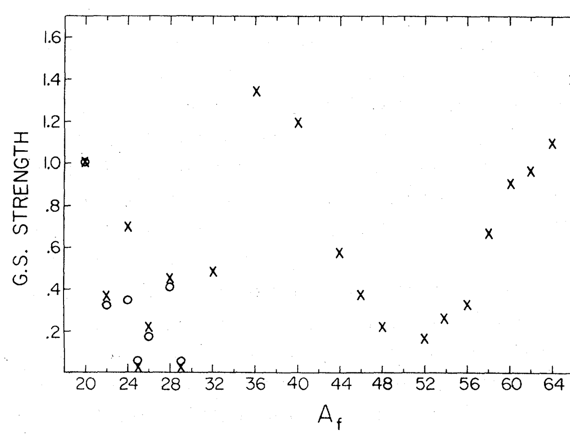

FIG. 1. Ground-state α-particle spectroscopic strength, measured in the (^{6}Li,d) reaction, plotted as a function of the mass A_f of the final nucleus populated.

perimental strengths and the open circles are the SU(3) predictions for nuclei in the lower half of the *sd* shell (as discussed below). At mass 54, there are actually two experimental points lying on top of one another because the ^{50}Ti(^{6}Li, *d*) and ^{50}Cr(^{6}Li, *d*) ground-state transitions had equal strengths. The maximum in the mass region 36–40 is not a result of the DWBA calculation. This is demonstrated by the fact that the measured differential cross sections at the second maximum in the angular distributions for the ground-state transitions show a trend similar to that of the extracted ground-state strengths. For final nuclei of ^{20}Ne, ^{32}S, ^{36}Ar, ^{40}Ca, and ^{52}Ti, the cross sections measured at 32 MeV are 30, 6, 15, 16, and 3.5 μb/sr, respectively. It is also interesting to note that the peak ground-state differential cross sections measured at Centre d'Etudes Nucléaires de Saclay[13] in the (^{16}O, ^{12}C) reaction on various *fp*-shell targets show a minimum in the mass-50 region similar to that observed in the present extracted strengths.

For $L=0$ transfers in the cluster approximation, the number of nodes in the radial wave function of the transferred α particle is $n-1=4$ for $(2s1d)^4$ and $n-1=6$ for $(1f2p)^4$, and these were the numbers used in our analysis of data on the *sd*-shell and *fp*-shell targets, respectively. For both the reactions ^{32}S(^{6}Li, *d*)^{36}Ar and ^{36}Ar(^{6}Li, *d*)^{40}Ca, therefore, the spectroscopic strengths given in Fig. 1 are those corresponding to $n-1=4$. Particle-hole admixtures in the ^{40}Ca ground-state wave function would effectively *increase* the number of nodes in the wave function of the transferred α particle and thereby *decrease* the extracted spectroscopic strength. With Gerace and Green's wave function[14] for ^{40}Ca and certain extreme assumptions about the effects of the various contributions, the quoted strength can be reduced by as much as a factor of 3. Since the particle-hole admixtures presumably decrease as one moves away from the closed shell, their effect becomes less for the ^{32}S(^{6}Li, *d*)^{36}Ar case.

As noted above, the uncertainty in the experimental strengths due to errors in absolute cross-section measurement should be less than 30%. The considerably larger range of variation in the observed strengths for the various nuclei is therefore significant as indicating systematic variations in α-particle spectroscopic strengths among the nuclei studied. While it is conceivable that altering some parameter like the bound-state radius in the analysis would cause a systematic increase or decrease of the extracted strength as a function of target mass, it is unlikely that this would account for the maximum observed at $A\sim 40$ and the minima at $A\sim 28$ and ~ 52. The results indicate a real nuclear-structure effect.

The strengths extracted from the (^{6}Li, *d*) reaction on targets of ^{24}Mg, ^{36}Ar, ^{54}Fe, and ^{56}Fe agree closely with the strengths extracted by Becchetti *et al.* from the (*d*, ^{6}Li) reaction on ^{28}Si, ^{40}Ca, ^{58}Ni, and ^{60}Ni, the numbers being 0.45, 1.59, 0.67, and 0.92 and 0.38, 0.92, 0.63, and 0.93, respectively. This agreement provides a check on the accuracy of the various absolute cross-section measurements and on the consistency of the analyses.

A theoretical explanation of the observed behavior involves the calculation of α-particle spectroscopic strengths. Such calculations have been done for nuclei in the lower half of the *sd* shell, where the SU(3) model provides a good description of initial and final nuclear states. The open circles in the figure were obtained by combining the SU(3)$\supset$R(3) relative spectroscopic strengths tabulated by Draayer[15] with the SU(6)$\supset$SU(3) coefficients of fractional parentage calculated by Hecht and Braunschweig[16]; the pure SU(3)-SU(4) symmetry limit was used for the initial and final nuclear wave functions. The calculated strengths agree remarkably well with the measured values. Only for $^{20}\mathrm{Ne}+\alpha\rightarrow{}^{24}\mathrm{Mg}$ is the observed strength significantly larger than predicted; this may signal the presence of α clustering beyond that available within a single-major-shell description of the relevant initial and final nuclear eigenstates. The odd-A strengths are shifted down by a factor of 5 to 10 from the neighboring even-A values; this represents a fragmentation of L-transfer strength due to couplings. The predicted strengths for transitions to the ground states of ^{21}Ne, ^{23}Na, and ^{27}Al are 0.74, 0.02, and 0.14, respectively; these have not been included in the figure because the corresponding reactions have not yet been performed at a high bombarding energy. For the ^{36}Ar(^{6}Li, *d*)^{40}Ca ground-state strength, the SU(3) calculation predicts an upper limit of 0.39 if the ground states are taken to be free of particle-hole admixtures.

Shell-model calculations involving many shells but restricted to seniority-zero configurations were required to explain (p, t) and (t, p) transitions to ground states of Ca and Ni isotopes.[17] This suggests that theoretical calculations to explain the present (^{6}Li, *d*) systematics may likewise require multishell configurations, a nontrivial task indeed!

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Polarization Effects in the Final-State Interaction Region of the *p-d* Breakup Reaction*

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The angular distributions of the vector analyzing power have been measured in the reactions ^{2}H$(p,p)np$ and ^{1}H$(d,p)np$ at 22.7 and 45.4 MeV, respectively, corresponding to the same center-of-mass energy. Significant analyzing powers were found in the production of final-state np pairs with low relative energies, and the angular distributions show a remarkable similarity to those of the corresponding elastic scattering.

We report in this Letter on the first significant polarization effects observed in the final-state interaction (FSI) region of the p-d breakup reaction.

Among the experimental observables in the three-nucleon system, the elastic cross section, inelastic cross section, and elastic analyzing power have been extensively investigated.[1] Inelastic analyzing powers comprise one class of observables which has received very little attention. That is, only a few experiments have been done which even show the presence of polarization effects, and theoretical interpretation and predictions via exact three-body calculations have not, as yet, been made. The three-nucleon calculations, based on the Faddeev equations with separable potentials for the $^1S_0$, $^3S_1$-$^3D_1$, and P-wave components of the nucleon-nucleon interaction,[2,3] have provided predictions of the vector and tensor polarizations which are in good agreement with the experimental data in the elastic channel,[4-6] whereas the S-wave forces alone had been sufficient to give agreement with the differential cross-section data. Similarly, calculations which have been successful in fitting inelastic cross-section data have been restricted to two-nucleon S-wave interactions[7] and, thus, cannot predict analyzing powers for incident polarized protons or deuterons.

Perhaps the first polarization effects seen in the breakup reaction for the production of final-state np pairs with low relative energy were those observed by Arvieux *et al.* in the reaction ^{2}H$(p, 2p)n$ at 10.5 MeV.[8] Their measurements at three angles of the proton analyzing power $A_y(\theta)$ for the transition to the np FSI region showed $A_y(\theta) \leq 0.05$, within the errors of ± 0.02 to ± 0.03. They had noted, for comparison, the similarity of the trend of their measurements to that of the elastic-channel analyzing power at 11.0 MeV. Blyth *et al.*[9] have reported on the determination of the deuteron vector analyzing power at several