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THE (d, ^{6}Li) REACTION ON ^{24}Mg, ^{26}Mg AND ^{28}Si AT 35 MeV

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Abstract: Data for the (d, ^{6}Li) reaction on targets of ^{24}Mg, ^{26}Mg and ^{28}Si have been obtained at 35 MeV bombarding energy. Angular distributions were measured for low-lying states in the residual nuclei. Zero-range distorted-wave Born approximation (DWBA) calculations have been used to analyze the data. The DWBA calculations account for the shapes of the experimental distributions reasonably well. The observation of significant population of unnatural parity states implies, however, that other transfer mechanisms may be important. The experimental spectroscopic factors are in qualitative agreement with those obtained from $SU(3)$ theory.

E | NUCLEAR REACTIONS ^{24}Mg, ^{26}Mg, ^{28}Si(d, ^{6}Li), E = 35 MeV; measured $\sigma(\theta)$. ^{20,22}Ne, ^{24}Mg levels deduced S_α. DWBA analysis

1. Introduction

In recent years α-particle transfer reactions have been used extensively as probes of α-clustering in nuclei. In such studies it is usually assumed that direct reaction theory (normally the distorted-wave Born approximation together with a simple cluster-type α-wave function) is adequate to describe the reaction mechanism. The nuclear structure information is then contained in a spectroscopic factor. Recently, the SU(3) shell model has been used to calculate theoretical α-spectroscopic factors for p and sd shell nuclei [1−3].

Since the early work of Daehnick and Denes [4], the (d, ^{6}Li) reaction has been considered a useful probe of α-particle correlations because of the pronounced deuteron plus α-cluster structure in ^{6}Li as discussed, for example, by Arima [5]. Some evidence has been presented which indicates that the reaction proceeds by a simple direct mechanism for deuteron energies as low as 15 MeV [ref. [6])]. On the other hand, Comfort *et al.* [7] have suggested that multistep processes may be important for targets in the sd shell at incident deuteron energies as high as 28 MeV.

The present work is part of a larger (d, ^{6}Li) study involving both p and other sd shell targets [8] and heavier targets covering a substantial portion of the periodic

table [9]). All of these studies have been done at 35 MeV bombarding energy using the 83 inch cyclotron at the University of Michigan. A preliminary report on the present work has been presented elsewhere [10]). In this paper we report the results of a study of (d, ^{6}Li) reactions on the sd shell targets ^{24}Mg, ^{26}Mg and ^{28}Si. Angular distributions were measured for low-lying states in the residual nuclei. A comparison is made between spectroscopic factors extracted from the experimental data with zero-range DWBA calculations and theoretical ones obtained from SU(3) calculations. Some attention is given to the suggestion that multi-step processes may be important for this reaction.

2. Experimental procedure

Targets were bombarded with a 35 MeV deuteron beam from the University of Michigan Cyclotron. The outgoing ^{6}Li ions from the (d, ^{6}Li) reaction were momentum analyzed in the focal plane of a magnetic spectrograph with a helical-cathode position-sensitive proportional counter of 50 cm length similar in basic design to that described by Lee, Sobottka and Thiessen [11]). The ^{6}Li ions were identified with a ΔE proportional counter which was located behind the position sensitive counter and operated in coincidence with it. The ΔE and position counters shared a common gas mixture of 80 % argon and 20 % CO_2 at one atmosphere absolute pressure. At forward angles kinematic broadening was compensated by moving the detection system inward to the effective focal plane. For lab scattering angles larger than about 25 °, it was not possible to correct completely for kinematic broadening due to the limited range of the detector movement.

The targets bombarded in this experiment were isotopically enriched ^{24}Mg and ^{26}Mg and natural SiO with thicknesses ranging from 96 to 476 $\mu g/cm^2$ with an uncertainty of ± 12 %, deduced from the energy loss of α-particles from an ^{241}Am source. Two of the target thicknesses were confirmed by elastic scattering of 35 MeV deuterons. The target materials were evaporated on 2.15 mg/cm^2 Au backings. Little background from the ^{197}Au(d, ^{6}Li)^{193}Ir reaction was observed with a pure Au foil at spectrograph field settings corresponding to the ^{6}Li ions of interest in the present experiments.

Figs. 1 to 5 show sample spectra obtained. Note the large contaminant peaks due to the presence of ^{12}C and ^{16}O on the targets. At certain angles the peaks due to these contaminants masked the peaks of interest and had to be subtracted from the spectra using the cross sections measured by VanderMolen *et al.* [8]). Uncertainties in this background subtraction were the dominant source of error in the determination of differential cross sections. The angular distribution ares shown in figs. 6–9. The error bars on the data points include statistical uncertainties and errors in background subtraction. Single targets were used throughout the measurement of a given angular distribution.
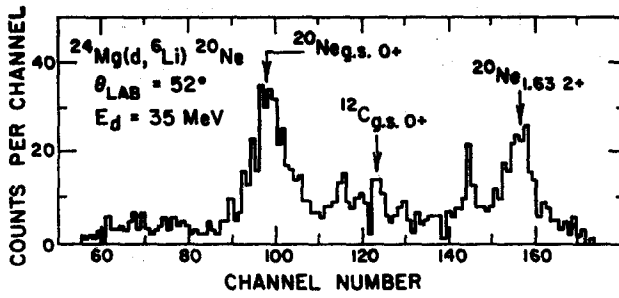
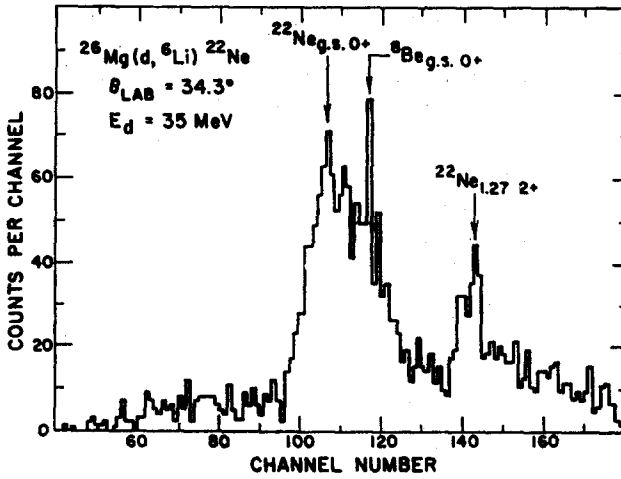Fig. 1. The ^{6}Li energy spectrum taken with a ^{24}Mg target showing the ground and first excited states of ^{20}Ne.

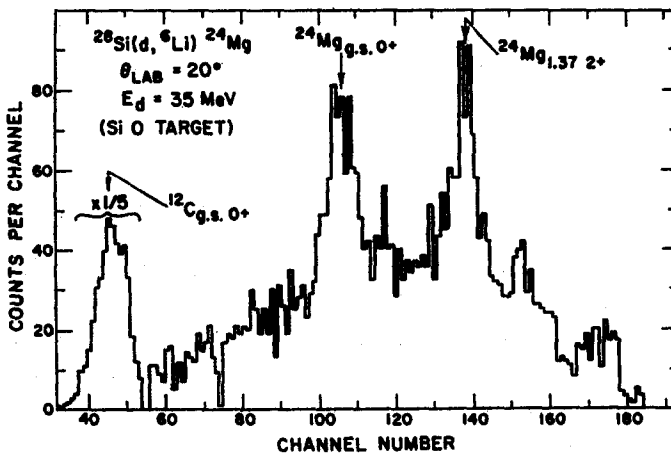Fig. 2. The ^{6}Li energy spectrum taken with a ^{26}Mg target showing the ground and first excited states of ^{22}Ne.

Fig. 3. The ^{6}Li energy spectrum taken with a SiO target showing the ground and first excited states of ^{24}Mg.
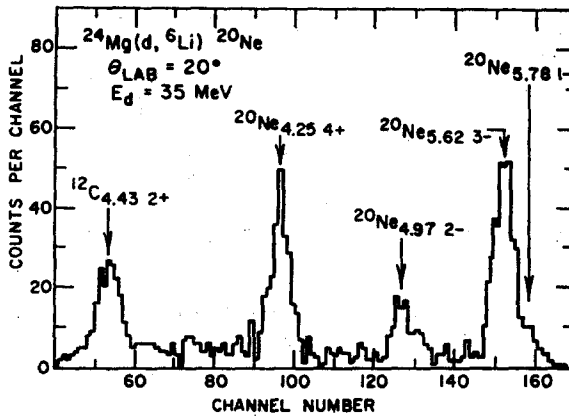
Fig. 4. The ^{6}Li energy spectrum taken with a ^{24}Mg target showing excited states of ^{20}Ne including unnatural parity state (2$^-$).
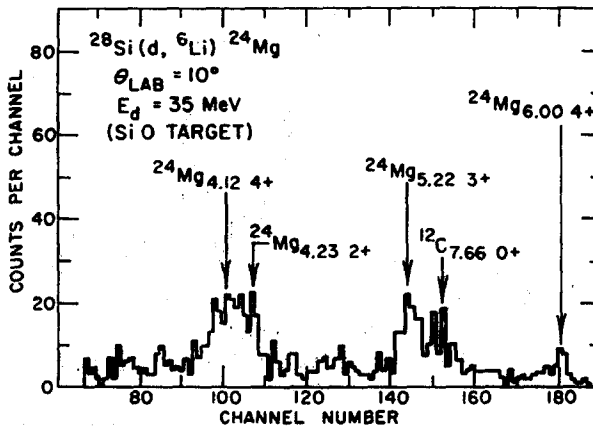

Fig. 5. The ^{6}Li energy spectrum taken with a SiO target showing excited states of ^{24}Mg including unnatural parity state (3$^+$).

3. DWBA calculations

Zero-range DWBA calculations were employed to extract spectroscopic factors from the experimental angular distributions using the code DWUCK [12]). A few finite-range calculations were also made utilizing the codes LOLA [13]) and MERCURY [14]). An important ingredient in any DWBA calculation is the para-metrization of the potential wells for the distorted waves and the bound state wave functions. The optical model parameters used in the present work are shown in table 1 along with the appropriate definitions. The parameters for the incident deuteron channel are those of Newman et al. [15]). and have a surface absorption term while for the outgoing ^{6}Li channel the parameters are those of Chuev et al. [16]) which have volume absorption. In these calculations the bound state wave functions were the

usual Woods-Saxon wave functions in which the transferred α-particle is bound to a core in a single-particle-type "cluster" state. The radius of this potential well was in all cases set equal to $1.3A^{\frac{1}{3}}$ fm (where A is the mass of the binding core) with a diffuseness parameter of 0.73 fm. The number of radial nodes, N, in the cluster wave function was obtained from the relation:

$$2N+L = \sum_{i=1}^{4} (2n_i + l_i),\tag{1}$$

where the sum is over the four nucleons transferred, L is the orbital angular momentum of the cluster, and n_i and l_i are the number of radial nodes and orbital angular momenta (shell-model quantum numbers in a notation for which the sd shell is denoted 1s0d) of the individual nucleons. The depth of the Woods-Saxon potential

TABLE 1

Optical model parameters used in distorted wave analysis

	V_r (MeV)	r_r (fm)	a_r (fm)	W_v (MeV)	r_i (fm)	a_i (fm)
^{6}Li+^{16}O	252	1.3	0.7	13	1.75	1.2
^{6}Li+sd shell nuclei	262	1.2	0.71	16	1.75	1.15
	V_r	r_r	a_r	W_s	r_i	a_i
d+^{20}Ne	93.48	1.047	0.814	41.6	1.385	0.714
d+^{24}Mg	93.98	1.059	0.79	45	1.37	0.725
d+^{26}Mg	93.98	1.059	0.79	45	1.37	0.725
d+^{28}Si	93.98	1.059	0.79	45	1.37	0.725

$U(r) = -V_r(1+e^x)^{-1} - iW_v(1+e^x)^{-1} + iW_s d/dx(1+e^x)^{-1}$, with $x = (r-r_0 A^{\frac{1}{3}})/a_0$ where A is the target mass and r_0, a_0 are r_r, a_r or r_i, a_i. Here $U_C(r)$ is the Coulomb potential for a uniformly charged sphere of radius $R_C = 1.3A^{\frac{1}{3}}$ fm. For the bound state Woods-Saxon potential $R = 1.3A^{\frac{1}{3}}$ fm with a diffuseness of 0.73 fm, where A is the mass of the residual nucleus.

well was adjusted to give the known α-particle separation energy. Thus, $2N+L$ for the bound state of the α-particle in the target nucleus was set equal to eight for all positive parity states under the assumption that four valence sd shell nucleons were transferred. For the negative parity odd-J states in ^{20}Ne, the assumption was made that one p-shell and three sd shell nucleons were picked up so that $2N+L = 7$. For the finite-range calculations, the bound state of the $d+\alpha$ system in ^{6}Li must be specified. For this system we set $N = 1$ and $L = 0$. A justification of these quantum numbers is given by Kurdyumov et al. [17]).

4. Results

The measured angular distributions and zero-range DWBA calculations are displayed in figs. 6–8. The DWBA curves have been normalized using spectroscopic
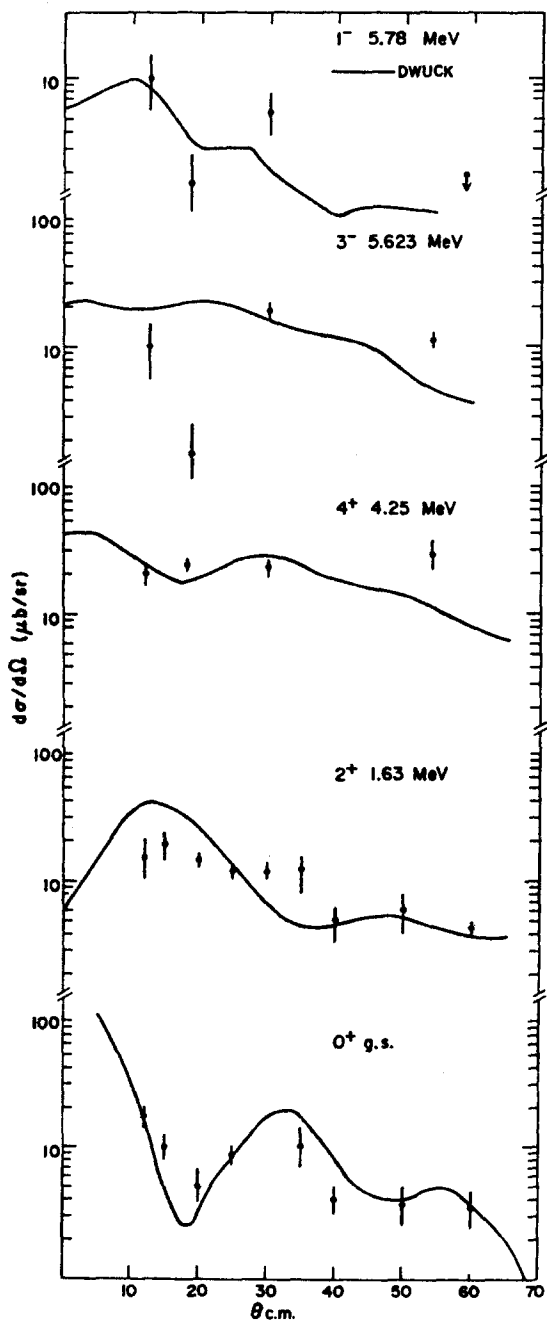
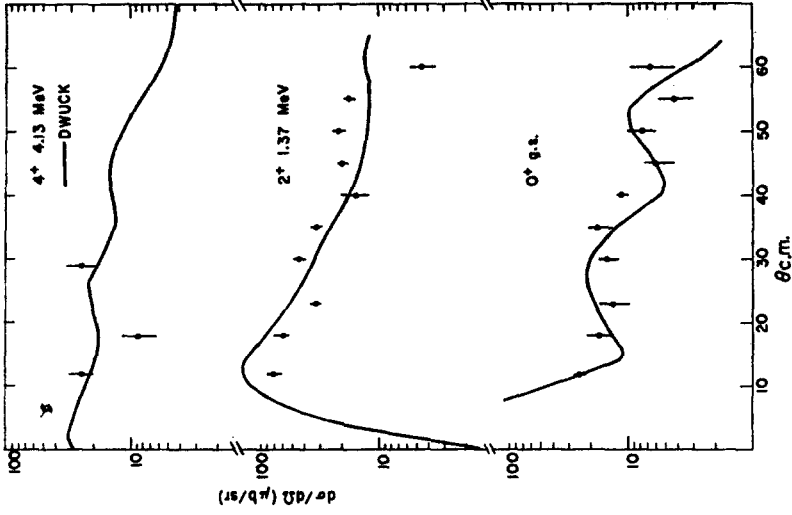Fig. 6. Angular distributions for the ^{24}Mg(d, ^{6}Li)^{20}Ne reaction.

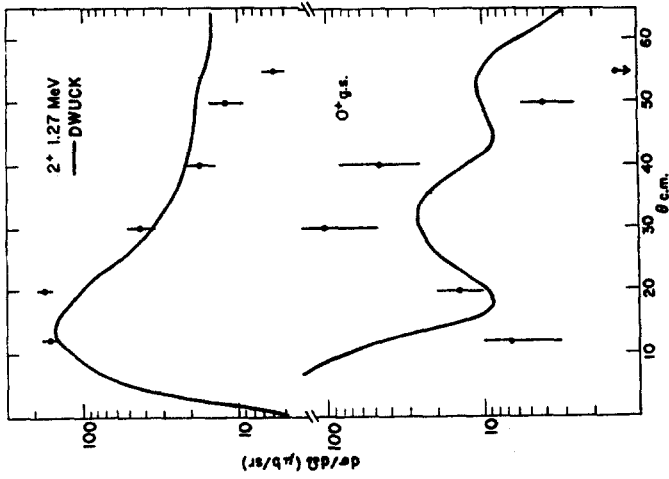Fig. 8. Angular distributions for the ^{28}Si(d, ^{6}Li)^{24}Mg reaction.

Fig. 7. Angular distributions for the ^{26}Mg(d, ^{6}Li)^{22}Ne reaction.

factors extracted by averaging over all data points in a given angular distribution. The angular distributions for the 2^+ 4.23 and 4^+ 6.00 states in ^{24}Mg are not shown; they are similar to that of the 4^+ 4.13 state.

The zero-range calculations are in qualitative agreement with the shapes of the experimental angular distributions, though by no means is this agreement good in all cases. For the most part, the more prominent maxima and minima of the calculations and the experimental angular distributions coincide.

TABLE 2

Spectroscopic factors

Reaction	$(\lambda_i \mu_i) \rightarrow (\lambda_f \mu_f)$ [a]	S_α (theory)	S_α (exp.) [b]
^{24}Mg(d, ^{6}Li)^{20}Ne			
0^+ g.s.	(84) $\rightarrow$ (80)	0.35	0.21
2^+ 1.63	(84) $\rightarrow$ (80)	0.05	0.19
4^+ 4.25	(84) $\rightarrow$ (80)	0.28	0.87
3^- 5.62	(84) $\rightarrow$ (82)	0.95	0.26
1^- 5.78	(84) $\rightarrow$ (90)	0.13	0.04
^{26}Mg(d, ^{6}Li)^{22}Ne			
0^+ g.s.	(48) $\rightarrow$ (82)	0.18	0.66
	(10,2) $\rightarrow$ (82)	0.12	
2^+ 1.27	(48) $\rightarrow$ (82)	0.14	1.19
	(10,2) $\rightarrow$ (82)	0.005	
^{28}Si(d, ^{6}Li)^{24}Mg			
0^+ g.s.	(0,12) $\rightarrow$ (84)	0.41	0.52
2^+ 1.37	(0,12) $\rightarrow$ (84)	0.50	1.17
4^+ 4.12	(0,12) $\rightarrow$ (84)	0.44	0.87
2^+ 4.24	(0,12) $\rightarrow$ (84)	0.87	0.32
4^+ 6.00	(0,12) $\rightarrow$ (84)	0.70	0.20

Both the theoretical and experimental spectroscopic factors are normalized such that $S_\alpha = 1$ for the ^{20}Ne g.s. [ref. [8]].

[a]) These are the SU(3) quantum numbers for the target nucleus $(\lambda_i \mu_i)$ and for the residual nucleus $(\lambda_f \mu_f)$ which were assumed to completely describe these nuclei in the calculations of the theoretical spectroscopic factors. In the case of ^{26}Mg, two different representations were used: (48) (oblate) and (10, 2) (prolate).

[b]) These are experimental spectroscopic factors obtained with the zero-range DWBA code DWUCK.

Finite-range calculations were attempted for only a few cases because of the extensive computer time required. The same optical model and bound state parameter sets were used as in the corresponding zero-range cases. The calculations yielded approximately the same relative cross sections for the various states as the zero-range calculations. However, the oscillations in the calculated angular distributions were out of

of phase by about 12° with the zero-range results and the experimental data using either LOLA or MERCURY. These two finite-range DWBA codes gave essentially identical results. The failure of our finite-range calculations may have been due to an inadequate description of the cluster structure of ^{6}Li, the effective interaction, or the distorted waves. The radius r_0 of the Woods-Saxon potential for the d + α system was adjusted over a range from 1.1 fm to 1.6 fm with no improvement, however.
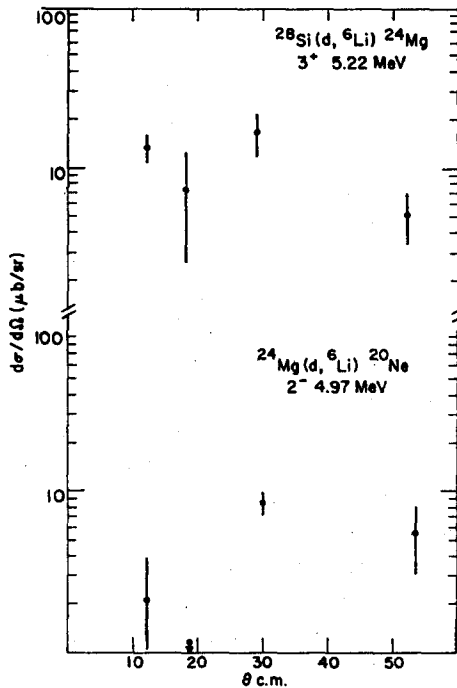

Fig. 9. Angular distributions for unnatural parity states.

Table 2 shows the experimental and theoretical spectroscopic factors, S_α. All spectroscopic factors have been normalized relative to the ^{20}Ne(d, ^{6}Li)^{16}O$_{g.s.}$ reaction [8]), to facilitate the comparison with the theoretical values obtained by Hecht and Braunschweig [2]) and Draayer [3]). Absolute spectroscopic factors may be obtained, for example, by multiplying the relative values reported here by 0.23, which is the absolute value given by Ichimura et al. [1]) for ^{20}Ne → ^{16}O$_{g.s.}$ + α. The theoretical values shown in table 2 are those obtained from first order SU(3) calculations in which the states in both the target and residual nuclei are assumed to be pure SU(3) states without consideration of any representation mixing effects. For the ^{24}Mg target the 3$^-$ and 1$^-$ states are poorly resolved experimentally so that it is probably only meaningful to consider the sum of their S_α values. For the case of the ^{26}Mg target, the 0$^+$ and 2$^+$ states of ^{22}Ne were both populated more strongly than pre-

dicted. The theoretical values listed for this transition are those for the two leading SU(3) representations $(\lambda\mu)$ of ^{26}Mg corresponding to the two shape extremes [(48) oblate and (10, 2) prolate]. The ground state of ^{26}Mg is not a pure SU(3) state so that other contributions corresponding to shapes intermediate between these two extremes may be present and could possibly account for the large observed yields [18]). The 4^+ and 2^+ states in ^{24}Mg at about 4 MeV in excitation are also poorly resolved, so one should compare the experimental and theoretical values for the sum of the spectroscopic factors obtained for these two states.

Except for the ^{26}Mg target, the agreement between the experimental spectroscopic factors extracted from the data using the zero-range DWBA analysis and the theoretical spectroscopic factors obtained from SU(3) theory is within a factor of three. States with small predicted S_α are usually weakly populated whereas states with large predicted S_α are prominent. It appears, therefore, that the SU(3) model can account for most of the observed cross sections and hence most of the α-particle correlations present in these nuclei.

Fig. 9 shows the angular distributions for the unnatural parity states observed in this experiment. These states cannot be populated in a simple one-step pickup of an α-particle. Unnatural parity states have been seen in other (d, ^{6}Li) studies at bombarding energies below and above 35 MeV. Comfort *et al.* [7]) at 28 MeV bombarding energy observed both of the unnatural parity states seen in the present work. McGrath *et al.* [19]) observed the 2^- state at 4.97 MeV in ^{20}Ne at 55 MeV bombarding energy. In both of these instances the strengths of the unnatural parity states relative to other states was nearly the same as that observed in the present work ($\approx 1 : 3$). The significant population of unnatural parity states in the (d, ^{6}Li) reaction casts doubt on the validity of the simple α-transfer assumption. However, the agreement between experiment and theory obtained in the present work suggests that while other transfer mechanisms are important for reactions leading to unnatural parity states their contribution to the population of natural parity states may be small. The fact that Djaloeis *et al.* [20]) did not see the 2^- state in ^{20}Ne at 80 MeV bombarding energy suggests that higher bombarding energies may be desirable.

5. Comparison of spectroscopic factors with those obtained in other transfer reaction experiments

Comfort *et al.* [7]) report spectroscopic factors for the lowest 0^+, 2^+ and 4^+ states in ^{20}Ne populated by the ^{24}Mg(d, ^{6}Li)^{20}Ne reaction at 28 MeV to be 1, 0.3 and 0.8, respectively. The values obtained in the present experiment at 35 MeV were 1, 0.89 and 4.2, if one renormalizes so that the ground state has an S_α value of unity. The uncertainties in the extraction of spectroscopic factors are fairly large but may not be large enough to rule out significant discrepancies between the results of the two experiments done at different bombarding energies. The observed angular distributions in ref. [7]) have shapes similar to those observed in the present work.

Another pickup reaction which has been used to study α-particle correlations in nuclei in this mass region is (^{3}He, ^{7}Be). Detraz *et al.* [21]) studied this reaction at 30 MeV on targets of ^{20}Ne and ^{28}Si. They obtained a value of S_α equal to 0.6 for the ^{28}Si(^{3}He, ^{7}Be)^{24}Mg ground state relative to the ^{20}Ne(^{3}He, ^{7}Be)^{16}O ground state. This agrees quite well with the present result of 0.52. Audi *et al.* [22]) also studied the (^{3}He, ^{7}Be) reaction at 26 MeV on targets of ^{20}Ne and ^{28}Si. Four different optical parameter sets were used in conjunction with the finite-range code LOLA. The average spectroscopic factor for these four parameter sets for the ^{24}Mg ground state relative to the ^{16}O ground state was 0.28, which is consistent with the present result.

It is interesting to compare the present results with those obtained from studies of the reciprocal reaction (^{6}Li, d). Draayer *et al.* [23]) have studied the ^{24}Mg(^{6}Li, d)^{28}Si reaction for low-lying states in ^{28}Si at a ^{6}Li bombarding energy of 36 MeV. The spectroscopic factors for the two lowest excited states relative to the ground state obtained using finite-range DWBA were in quite good agreement with the calculations in ref. [3]), and are therefore consistent with the results reported here for the (d, ^{6}Li) reaction.

6. Conclusions

The experimental data analyzed using zero-range DWBA calculations yields spectroscopic factors in qualitative agreement with the theoretical values obtained from the SU(3) model without representation mixing. The zero-range calculations are in overall agreement with the shapes of the observed angular distributions. The observation of the unnatural parity states raises some doubt concerning the reliability of extracting α-spectroscopic factors using DWBA theory, but it is difficult to estimate the extent to which the processes responsible for populating unnatural parity states also contribute to the natural parity states.

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