THE (d, ^{6}Li) REACTION ON ^{12}C, ^{16}O, ^{24}Mg, ^{40}Ca and ^{58}Ni AT 54.25 MeV

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The (d, ^{6}Li) reaction was studied at E_d = 54.25 MeV on the target nuclei ^{12}C, ^{16}O, ^{24}Mg, ^{40}Ca and ^{58}Ni. The data were analyzed with finite-range DWBA calculations. The absolute values of the α-cluster spectroscopic factors and the target mass dependence of the relative S_α were in agreement with those in the (p, pα) reaction at E_p = 100 and 157 MeV. The theoretical calculations of the relative S_α were in better agreement with the experimental data at higher energy than at the lower energies.

The four-nucleon pick-up reaction (d, ^{6}Li) is a useful probe for examining the relationship between the ground state of the target nucleus and the excited state of the residual nucleus in the α-cluster model. The pick-up reactions (d, ^{6}Li) and (^{3}He, ^{7}Be) have been investigated, and the relative spectroscopic factors extracted by using the DWBA prediction have been compared with model calculations. Most experimental studies of the (d, ^{6}Li) reaction have been done in the lower energies region $E_d \leqslant 35$ MeV [1–7]. In this region, some difficulties are caused by other reaction mechanisms; furthermore, observations are limited to the lower excitation states because of the Coulomb barrier of the excited channels. Recently, the (d, ^{6}Li) reaction has been studied on light targets at incident energies above 50 MeV [8–11]. In most of these studies, however, the experimental angular distributions have been fitted with a zero-range DWBA calculation in order to extract spectroscopic factors or have not been done. On the other hand, in order to obtain quantitative information on α-clustering in nuclei, quasi-free (p, pα) scattering has been studied on p and sd shell nuclei at E_p = 100 [12] and 157 MeV [13], respectively. There are, however, some differences in the spectroscopic factors between the transfer reactions and the (p, pα) reaction results. Stressing the importance of the 2p2n group inside nuclei, the (p, pα) reaction complements the 2p2n transfer reaction.

Furthermore, the relative spectroscopic factors extracted from the transfer measurements done up to now are also in some disagreement with the results of

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model calculations in the regions of p and sd shell nuclei.

In this work, (d, ^{6}Li) angular distributions were measured on five self-supporting targets, ^{12}C, ^{16}O, ^{24}Mg, ^{20}Ca and ^{58}Ni, with a 54.25 MeV deuteron beam from the RCNP-AVF cyclotron. Two ΔE–E counter telescope systems were used for detecting the emitted ^{6}Li ion; mass identification was obtained using a particle identification circuit. The angular distribution of elastically scattered deuterons from each target was measured in order to confirm the optical parameters in the incident deuteron channel. Three final states in ^{8}Be and ^{36}Ar, five in ^{12}C, four in ^{20}Ne, and seven in ^{54}Fe were identified, and the angular distributions were measured for these transitions in the range of 7.5–55° (lab).

An exact finite-range DWBA analysis was carried out, with the assumption of one-step α-cluster transfer, using the code DWBA-4 [6,14]. The deuteron optical model parameters were taken from the 52 MeV analysis of Hinterberger et al. [15]; these provided an adequate fit to the angular distributions of elastically scattered deuterons at E_d = 54.25 MeV. For the exit channel, we adopted the ^{6}Li optical parameters which Chua et al. [16] obtained from the analysis of ^{6}Li elastic scattering at 50.6 MeV. In this set, the radii were taken to be of the form $R = r_0 A^{1/3}$ in accord with folding models [17,18]; the depth of the real potential V_0 was adjusted within 20% of the original values of Chua et al. so as to reproduce the shapes of the observed angular distribuionts in the (d, ^{6}Li) reaction. The optical-model parameters for the excited states of the residual nuclei are the same parameters as those for the ground state in each nucleus. The effective interaction between the deuteron and α-particle was assumed to be of the Woods–Saxon form with V_0 = 37 MeV, R = 1.5 fm and a = 0.6 fm. The relative motion of the d and α in the two clusters in the ground state of ^{6}Li was assumed to be in the 2S state, and the spectroscopic factor was taken to be unity.

Fig. 1 compares the experimental with the calculated results. The solid lines are the results of the finite-range calculations and are normalized to the experimental data for extracting the α-cluster spectroscopic factor S_α. The spectroscopic factors, S_α, deduced from the present work are listed in table 1 together with the S values deduced from the (d, ^{6}Li) reaction at E_d = 28 and 35 MeV [2,3] and those from the (h, ^{7}Be) reaction at 70 MeV [19] and the (p, pα) reaction above 100 MeV [12,13].

The spectroscopic factors obtained for the 0^+, 2^+ and 4^+ states belonging to the ground state rotational band show generally larger values, suggesting that the configuration of an α-cluster coupled to the ground state band of a residual nucleus has large components in the ground state of 4n-target nuclei. For ^{8}Be, the relative spectroscopic factors S_α/S_α^{gs} agree fairly well with those calculated by Kurath [20]. But a DWBA calculation with the optical model parameters of ^{6}Li on ^{12}C does not closely reproduce the angular distributions for the excited 2^+ state of ^{8}Be. For the excited states of the ^{12}C nucleus, in particular the 4^+ state at 14.1 MeV, the relative spectroscopic factors disagree markedly with Kurath's calculations [20], which were made with the intermediate coupling shell model. In this calculation, two protons and two neutrons in the 1p shell are transferred to a state of zero spin and isospin, completely symmetric in the spatial coordinates. Such a simple configuration for the ground state band may be the source of the discrepancies between the theoretical and experimental values. The relative spectroscopic factors of the 0_2^+ state at 7.66 MeV and the 3^- state at 9.64 MeV in ^{12}C are about 0.16 and 0.1, respectively. The intermediate coupling shell model restricted to the 1p shell does not predict the 0_2^+ state and the 3^- state. When the ^{12}C states are described by the 3α-cluster model [21], the negative parity states in ^{12}C are not excited and the positive parity state at 7.66 MeV is excited only weakly in comparison with the excitation of the ground state band in α-particle pick-up from the pure closed shell configuration of ^{16}O. However, the values of the spectroscopic factors of both the 0_2^+ and the 3^- state are hardly negligible compared with those of the ground state band. This may indicate that the ground state of ^{16}O contains some deformed components which are 2p–2h and 3α in a line configuration. Recently, the (d, ^{6}Li) reaction on ^{16}O has been studied with a 80 MeV deuteron beam by Oelert et al. [22]. The relative spectroscopic factors obtained by analysis with a finite-range DWBA calculation are in agreement with our results. Several theoretical calculations of the relative spectroscopic factors of ^{20}Ne have also been carried out using the SU(3) model [21,23–26]. These give a good description of the ground state band and show that the state labeled $(\lambda, \mu) = (8,0)$ almost absorbs the α-cluster spectroscopic amplitude for

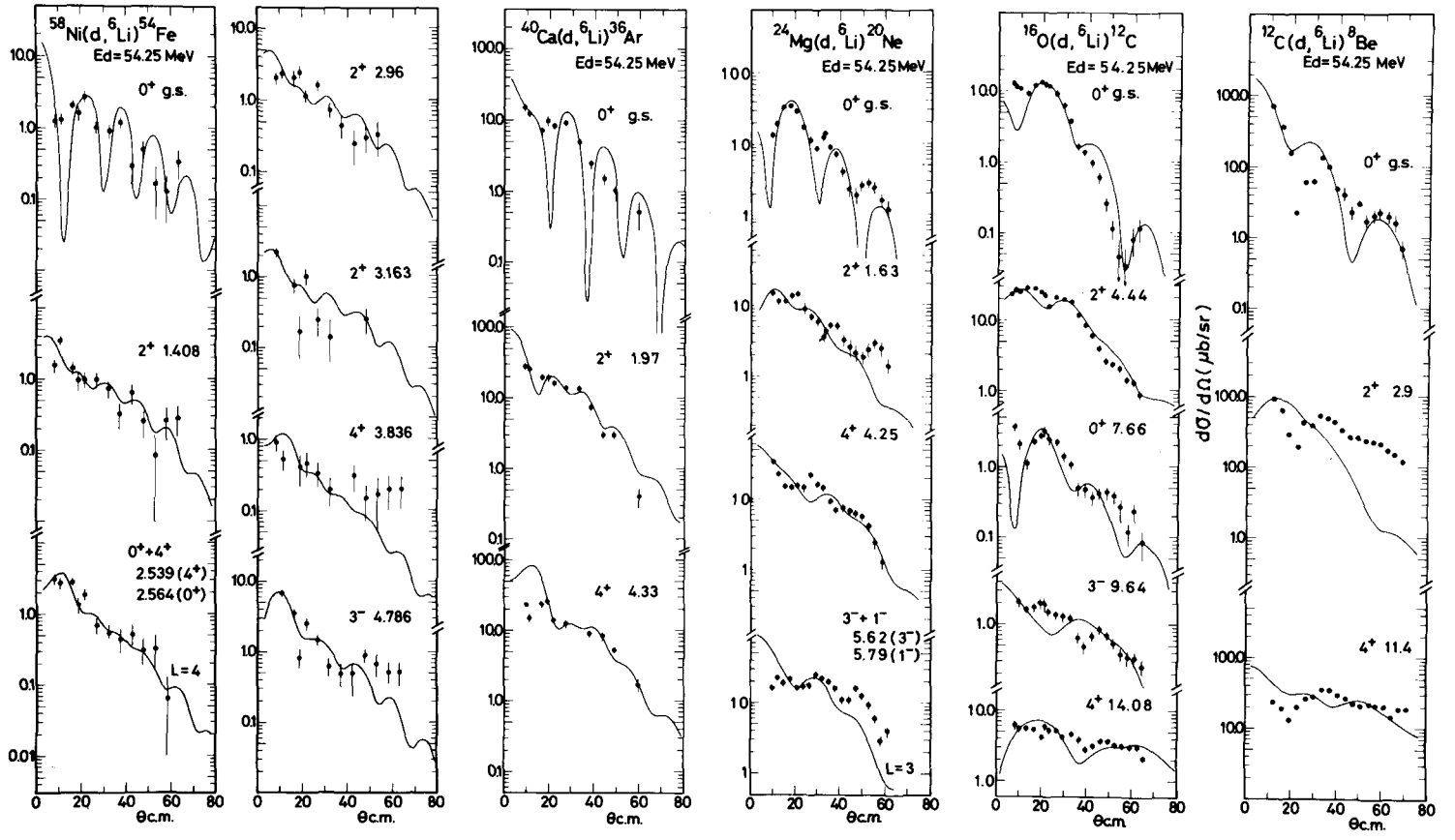

Fig. 1. Angular distributions for the (d, ^{6}Li) reaction on ^{12}C, ^{16}O, ^{24}Mg, ^{40}Ca and ^{58}Ni at 54.25 MeV as compared with finite-range α-transfer DWBA calculations. The solid lines are the results of calculations.

Table 1
α-cluster spectroscopic factors derived from the present (d, ^{6}Li) data by use of a FR-DWBA analysis. The last six columns give pertinent data and theoretical predictions from the literature.

Residual nucleus		(d, ^{6}Li) present work		(d, ^{6}Li) ref. [3]	(d, ^{6}Li) ref. [2]	(d, ^{6}Li) ref. [22]	(h, ^{7}Be) ref. [19]		(p, pα) refs. [12,13]				Theory
		E_d = 54 MeV		35 MeV	28 MeV	80 MeV	E_h = 70 MeV		E_p = 100, 157 MeV				
E_x	J^π	S_α	S_α/S_α^{gs}	S_α/S_α^{gs}	S_α/S_α^{gs}	S_α/S_α^{gs}	S_α	S_α/S_α^{gs}	S_α	S_α/S_α^{gs}			S_α/S_α^{gs}
^{8}Be													
0.0	0^+	0.79	1.0				3.0	1.0	0.59				1.0[a]
2.9	2^+	1.08	1.37				6.5	2.16					1.28
11.4	4^+	1.27	1.61				2.2	0.74					1.38
^{12}C													
0.0	0^+	0.57	1.0			1.0	2.9	1.0					1.0[a]
4.4	2^+	1.50	2.28			3.18	5.9	2.03					5.54
7.7	0^+	0.09	0.16			0.18							
9.6	3^-	0.05	0.09			0.56							
14.1	4^+	0.83	1.46			1.90							10.16
^{20}Ne													
0.0	0^+	0.34	1.0	1.0			0.013	1.0	0.23	1.0	1.0[b]	1.0[c]	1.0[d,e]
1.6	2^+	0.16	0.47	0.90			0.026	2.0	0.20	0.87	0.13	0.12	0.14
4.2	4^+	0.25	0.74	4.14			0.019	1.5			0.83	0.80	0.80
5.6	3^-	0.45	1.6	1.24									2.70
^{36}Ar													
0.0	0^+	0.50	1.0		1.0		0.12	1.0	0.50	1.0			
2.0	2^+	1.08	2.16		2.13		0.12	1.0	0.90	1.8			
4.4	4^+	1.15	2.30		3.52								
^{54}Fe													
0.0	0^+	0.067	1.0		1.0		0.01	1.0					
1.4	2^+	0.034	0.51		0.64		0.008	0.7					
2.5	4^+	0.033	0.49		0.77		0.008	0.7					
3.0	2^+	0.040	0.60		0.50								
3.8	4^+	0.010	0.15										
4.8	3^-	0.070	1.04										

[a] Ref. [20]. [b] Ref. [21]. [c] Ref. [23]. [d] Ref. [24]. [e] Ref. [25].

$(sd)^4$. The S_α of the 3^-, $(\lambda, \mu) = (8, 2)$ state of ^{20}Ne, calculated using $(1p)^1(2s, 1d)^3$ pick-up, is 2.7 times [24,25] that of the ground state, and the value of $S_\alpha^{3^-}/S_\alpha^{gs}$ deduced from the present data, is 1.6. In general, the theoretical values obtained from the SU(3) scheme are in better agreement with the relative spectroscopic factors for the states in ^{20}Ne obtained from the present analysis than with those obtained from the data at E_d = 35 MeV [3]; they disagree, however, with the results from the (h, ^{7}Be) reaction [19]. For ^{36}Ar and ^{54}Fe, the relative spectroscopic factors of the ground state band at E_d = 54 MeV almost agree with those at E_d = 28 MeV [2]. In table 1, our results can also be compared with those obtained from the study of the (p, pα) reaction at 100 and 157 MeV. The absolute values of S extracted from the experimental data are in good agreement between the (p, pα) and the transfer reaction results at higher energy.

Fig. 2 shows the target mass dependence of the α-cluster spectroscopic factors together with those obtained from the study of the (p, pα) reaction. The magnitude of S_α normalized to the ^{8}Be ground state for the lowest 0^+, 2^+ and 4^+ levels generally decreases with target mass, but is obviously enhanced at ^{40}Ca. These results are in good agreement with those of the (p, pα) reaction. The 3^- states in ^{12}C and ^{36}Ar are populated

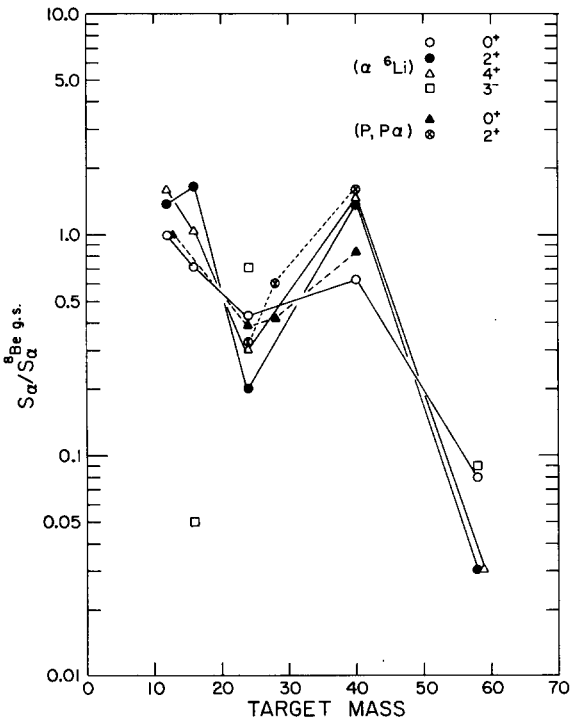

Fig. 2. Target mass dependence of the α-cluster spectroscopic factors for the ground state and the first excited 2^+, 4^+ and 3^- states together with those obtained from the study of the (p, pα) reaction. The magnitude of S_α is normalized to ^{8}Be ground state.

weakly, while the 3^- states in ^{20}Ne and ^{54}Fe are excited with appreciable strengths. In particular, the 3^- state of 4.18 MeV in ^{36}Ar did not have a measurable cross section. This result agrees with the result of Martin et al. [2] at E_d = 28 MeV. It was suggested that the strength for the L = 3 pick-up of one nucleon from the $f_{7/2}$ shell and another three from the sd shell is very weak compared with the strength of the L = 3 pick-up of an α-particle from the ^{16}O ground state that contains a certain amount of 2p–2h admixture.

In summary, the absolute values and the target mass dependence of S_α extracted from the present data in the (d, ^{6}Li) transfer reaction at higher energy are in agreement with those in quasi-free (p, pα) scattering, in spite of the uncertainties involved in the DWIA or DWBA treatment. In the analysis, the optical model parameters obtained from the analysis of deuteron and lithium elastic scattering were highly regarded for all the DWBA calculations that hold the optical model; furthermore the spectroscopic factors, in particular, are very sensitive to the choice of ^{6}Li optical parameters. Thus the quality of the fit of the experimental data with DWBA calculations is not always good.

The theoretical calculations of the relative spectroscopic factors S_α are in better agreement with the experimental data at higher energy than at lower energy. This supports the hypothesis α-transfer and the direct nature of the (d, ^{6}Li) reaction at higher energy.

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