ALPHA CLUSTERING STUDIED WITH THE (^{6}Li,d) AND (d,^{6}Li) REACTIONS

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ABSTRACT

The systematics, throughout the periodic table, of the (^{6}Li,d) and (d,^{6}Li) reactions are reviewed. The α-spectroscopic factors extracted exhibit correlations with shell effects, nuclear pairing and nuclear deformation. The data are compared with calculations using SU3, pseudo-SU3, the jj-shell model, the pairing-vibration and boson-expansion models. Many, but not all of the experimental features are reproduced by existing models.

INTRODUCTION

Scientists have been studying α-clustering perhaps longer than any other aspect of nuclear physics. I refer, of course, to the early studies[1] of "α-rays" which actually predates discovery of other nuclear constituents. In recent years many research groups have turned to the study of direct α-transfer reactions specifically (^{6}Li,d) and (d,^{6}Li). This has been motivated to a large extent by the development of theoretical models, such as SU3 and the pairing-vibration model, which now permit quantitive comparisons of theory with experiment. Also, the study of nuclear reactions at high bombarding energies permit study of α-clustering throughout the periodic table and provides an overlap with α-knock-out reactions (A< 40), α-resonant scattering (A< 40), and α-decay (A>150).

ADVANTAGES - DISADVANTAGES

Why (^{6}Li,d) or (d,^{6}Li)? The advantages of these particular reactions are: 1) a large overlap of ^{6}Li→α+d (>50%), 2) diffractive, j-dependent angular distributions arising from a single, allowed ℓ-transfer, 3) favorable ℓ-transfer to $J^\pi = 0^+$ as well as high spin states i.e. a wide "Q-window", 4) no excited levels in the ejectile and 5) good energy resolution. Features (2) and (3) are particularly important as many "α-cluster" levels are $J^\pi = 0^+$. Also, the diffractive nature of the angular distribution is indicative of a direct α-cluster transfer. These features are illustrated in Figs. 1-3. Good energy resolution is essential in α-spectroscopy and often permits measurements of α-decay widths from line-widths, as for ^{12}C(^{6}Li,d)^{16}O shown in Fig. 3.

The disadvantages of the (^{6}Li,d) and (d,^{6}Li) reactions are: 1) the reactions are not particularly selective at low bombarding energies, 2) the exact shape of the angular distributions are often difficult to reproduce without ad hoc parameter adjustments, 3) large break-up ^{6}Li→α+d (Fig. 3), 4) contaminants (C,O, etc.) interfere with (^{6}Li,d) on heavy nuclei and conversely for (d,^{6}Li) on light

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nuclei. We illustrate (1) in Fig. 4. Note the population of both unnatural parity states and non α-cluster levels (2^+, 9.85 MeV; 4^+, 11 MeV).

At higher bombarding energies and/or heavier nuclei the reactions become selective (Figs. 3,5). Most of the cross section to non α-cluster states can be accounted for by compound nuclear processes (Fig. 2) although other non-direct mechanisms may also contribute. In this respect the (7Li,t) reaction appears to be much more favorable, at least for light nuclei[6-9]. The problems associated with fitting (^{6}Li,d) or (d,^{6}Li) angular distributions are illustrated in Fig. 6. One finds a rather strong dependence on various model parameters primarily the α+d and α+ target wavefunctions and the α-d interaction inducing the reaction. This affects mainly the absolute values of S_α (~X10) but fortunately has much less of an effect on the relative values of S_α (~X2) or the reduced α-widths, γ_α^2. In many aspects the (^{6}Li,d) and (d,^{6}Li) reactions are α-transfer equivalents of the (d,p) and (p,d) reactions, respectively. With suitable care one can extract reliable, albeit model dependent, "α-spectroscopic" factors.

In the following sections I will review some of the recent results obtained from study of the (^{6}Li,d) and (d,^{6}Li) reactions. Much of the early work in this field has been reviewed elsewhere[6-8] and will not be covered here. Also, many of the systematics noted below are also observed[6-10] in (^{7}Li,t) and (^{3}He,^{7}Be), etc.

SYSTEMATICS IN THE SD-SHELL

The mass region $16<A<70$ has been investigated extensively using both (^{6}Li,d) and (d,^{6}Li). The sd-shell is of particular interest as both SU3 and shell model calculations are available[11,12]. Recent results[13,14] are shown in Figs. 7 and 8. In most cases the agreement with theory, particularly SU3, is good especially when one considers the large variation in cross sections (~X 100 or more). The general features are reproduced, namely the decrease in S_α at mid shell, and the "blocking" of α-transfer in odd-A nuclei due to unpaired nucleons. The results tend to confirm the preference of α-clustering arising from particularly favorable combinations of nucleon shell-model orbitals such as $(p)^3$ (sd), $(p)^2$ $(sd)^2$, $(sd)^2$ $(pf)^2$, etc. There are notable discrepancies however. In several instances, ^{12}C(^{6}Li,d)^{16}O and ^{16}O(^{6}Li,d)^{20}Ne in particular, S_α(g.s.) appears to be enhanced relative to other members of the g.s. band. In general the overall agreement in light nuclei ($A<16$) is not as good as for heavier nuclei. This may be due to inadequacies associated with the very simple α+target wave functions employed, which neglect proper antisymmeterization, etc. In other nuclei many of the discrepancies for excited states are likely related to the simple nature of the theory which often assumes pure SU3 symmetry for certain states. Thus, (^{6}Li,d) and (d,^{6}Li) appear to provide suitable quantitative tests of α-cluster models in the sd-shell at least for relative S_α values. Attempts to extract absolute S_α values, utilizing finite-range DWBA have been hampered by the afore-

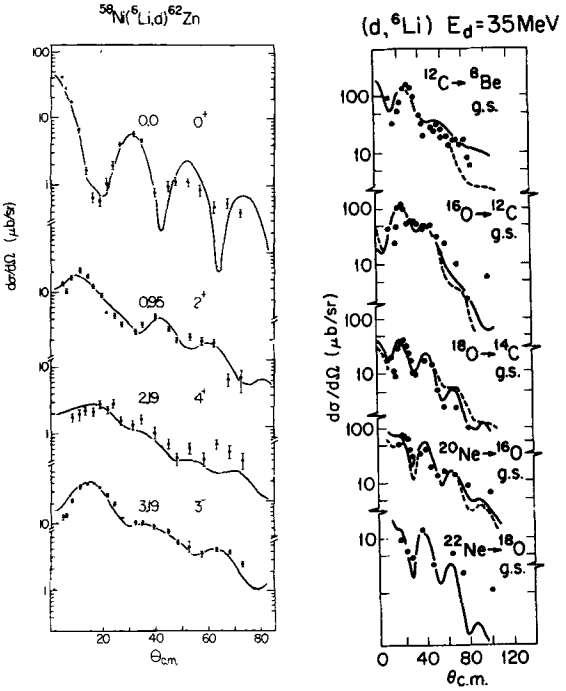


Fig. 1. J-dependence of (^{6}Li,d),(d,^{6}Li). (Refs. 2,13)

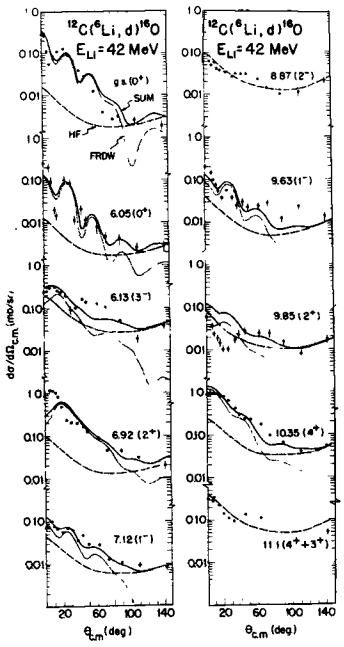


Fig. 2. Data and FRDW + HF calculations(Ref.3)

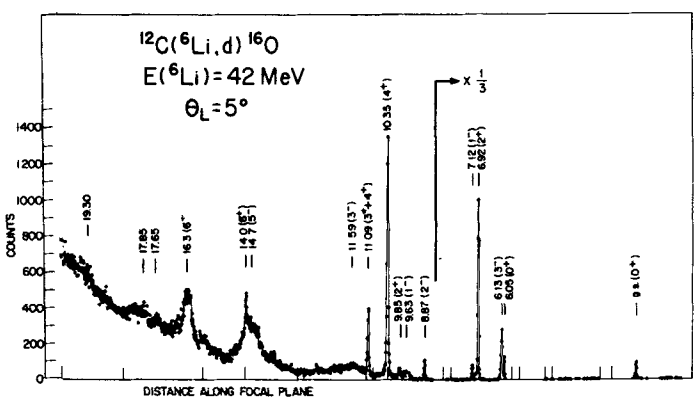


Fig. 3. Spectrum for ^{12}C(^{6}Li,d)^{16}O . Note scale change.(Ref.3).

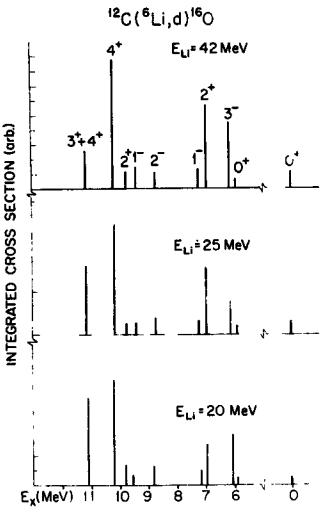


Fig. 4. Energy dependence of selectivity in (^{6}Li,d) (Refs. 3-7)

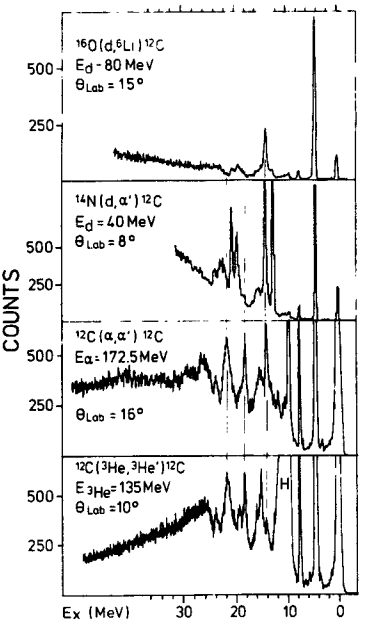
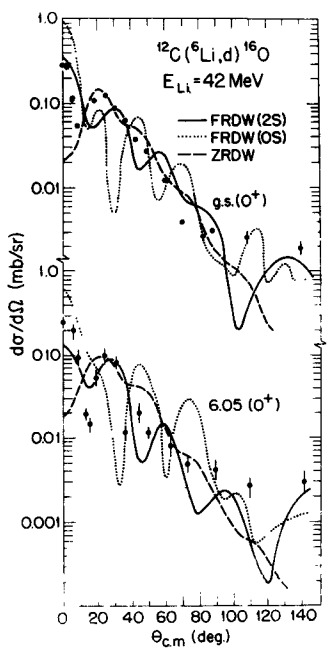


Fig. 5. Comparison of the selectivity of (d,^{6}Li) with other reactions .(Ref.5)



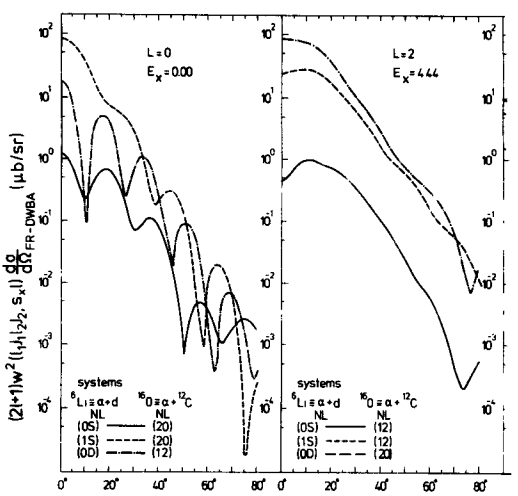


Fig. 6. Examples of model dependence of FRDW calculations.(Ref.3,5)

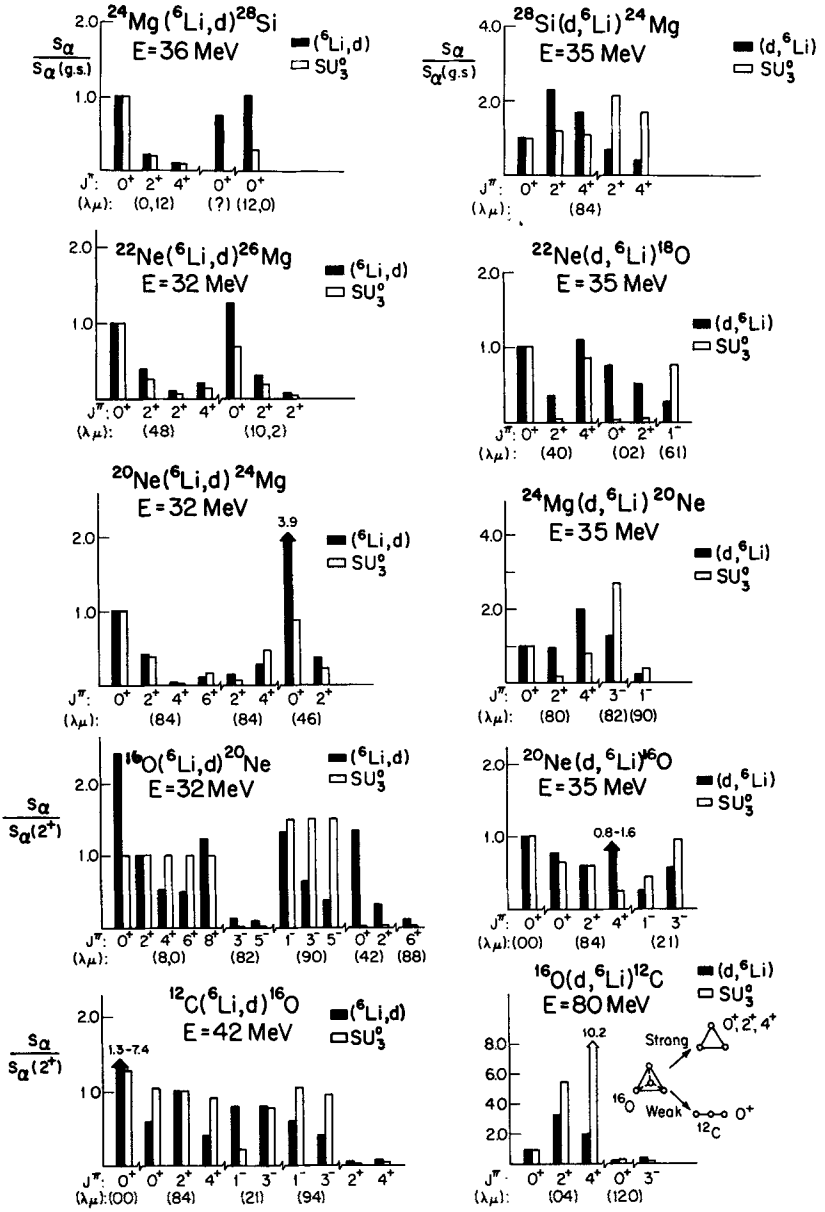


Fig. 7. Comparison of experimental and calculated(SU3) alpha - spectroscopic factors. (Refs.3,5,11,13,14). Note S_α scale.

mentioned sensitivity to some of the parameters (Fig. 6) but the values extracted[3,14] appear to be comparable to values extracted from α-resonance work and knock-out reactions ($0.1<S_\alpha<1.0$).

Additional sd-shell data are presented in the contributions to this conference.

FP SHELL

Recent (^{6}Li,d) results are displayed in Figs. 9 and 10 (See also contributed papers). One observes features similar to those seen in the sd-shell e.g. the experimental S_α distribution for ^{40}Ca(^{6}Li,d)^{44}Ti (Fig. 10) resembles that for ^{16}O(^{6}Li,d)^{20}Ne. Both show enhancement to the 0^+ g.s. and an excited 0^+ state. The latter in ^{44}Ti ($E_x \doteq 4.8$ MeV) is thought to be a proton pairing vibration. With the exception of the 0^+ states, an $(fp)^4$ shell model calculation accounts satisfactorily for the relative S_α values in ^{44}Ti (Fig. 10).

An analysis of data for Ni and Zn is displayed in Table I. One- and two-phonon states are rather weak in both (^{6}Li,d) and (d,^{6}Li) data[2,15,16]. One can treat Ni and Zn as pseudo sd-shell nuclei ($\tilde{O}$, $\tilde{N}e$). The relative S_α thus obtained agree surprisingly well[17] with an $(fp)^4$ shell model calculation[18] and the experimental data for particular nuclei, but there are discrepancies for S_α (g.s.). The inferred absolute S_α tend to be larger (by X2 to X10) than calculated values unless one makes adjustments to the α+ target or optical-model parameters.

PAIRING VIBRATION AND BOSON EXPANSION MODELS

Many of the features observed for $J^\pi = 0^+$ states populated in (^{6}Li,d) and (d,^{6}Li) closely parallel those observed in two-nucleon transfer. The connection appears explicitly in the expressions derived by Kurath and Towner[19] and others which consider α-transfer amplitudes as an appropriate coupling of di-neutron and di-proton amplitudes (Fig. 11). Betts[20] has exploited this "factorization" to extend the pairing-vibration (PV) model to include α-transfer, with the relative di-neutron and di-proton amplitudes taken from (p,t), (t,p) and (^{3}He,n) experiments. Application of this model to fp-shell nuclei is shown in Figs. 12 and 13. The predicted selectivity and systematics appear to be born out by experiment, with a few exceptions observed[16] mainly in (d,^{6}Li). Even in the PV model the ^{44}Ti(g.s.) S_α still appears to be greatly enhanced relative to other nuclei, however. A quantitative comparison with the PV model is given in Table II.and in the section on nuclei $90 < A < 132$.

Bennett and Fulbright have extended a more general model, the interacting boson approximation (IBA), to α-transfer with the results shown in Fig. 14. Many of the overall trends for 0^+ 2^+ and 4^+ states are reproduced, but again ^{44}Ti(g.s.) appears to be an exception.

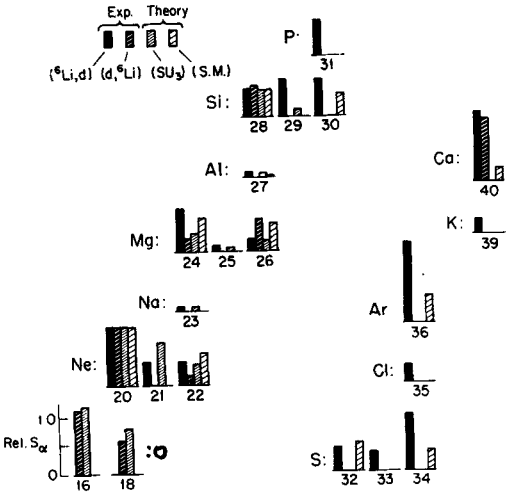


Fig. 8. Systematics of S_{α}(g.s.) in the sd-shell: theory and experiment. (Refs. 11-14).

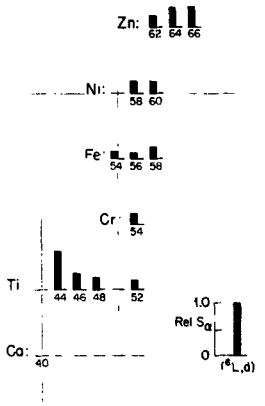


Fig. 9. Systematics of S_{α} in fp shell. (Refs.2,15)

Table I

Comparison of Shell Model α-Spectroscopic Factors with the Pseudo-SU_3 Approximation

k	L	S_α(pseudo SU_3)[a] $(d_{5/2}^{\sim} d_{3/2}^{\sim} s_{1/2}^{\sim})$	$S_\alpha(f_{5/2}p_{3/2}p_{1/2})$[b] shell model	S_α(exp.)[c]
		$\frac{^{58}Ni(0^+) \to ^{62}Zn(L^+)[(40)\cdot(82)]}{(^{18}O \to ^{22}Ne)}$		
1	1	1.00 (0.010)	1.00 (0.019)	1.00 (0.02)
0	2	0.70	0.70	0.36
1	3	0.26	0.29	0.06
2	3	0.004	0.001	0.02
2	4	0.046	0.029	
		$\frac{^{60}Ni(0^+) \to ^{64}Zn(L^+)[(42)\cdot(10,0)]}{(^{20}O \to ^{24}Ne)}$		
1	1	1.00 (0.0039)	1.00 (0.018)	1.0 (0.03)
0	2	0.59	0.59	0.26
1	3	0.11	0.18	0.03

Numbers in columns 1 and 2 give α-strengths relative to the ground state transitions. Numbers in parentheses give the absolute ground state predictions.

[a] Hecht, et al (17)

[b] Bennett, Fulbright, van Hienen, Chung, and Wildenthal.

[c] Ref. 18

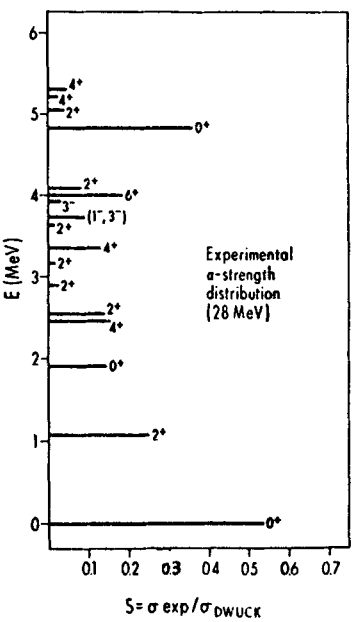


Fig. 10. Alpha transfer strength from $^{40}Ca(^6Li,d)^{44}Ti$. (Ref.2).

Table II
Comparison of (6Li,d) and PV model. (Ref.20)

^{62}Zn				^{64}Zn			
E_x (MeV)	J^π	S_α (Expt.)	S_α (Calc)	E_x (MeV)	J^π	S_α (Expt.)	S_α (Calc)
0.00	0^+	1.0[a]	1.0[a]	0.00	0^+	0.95[b]	0.95[b]
0.95	2^+	0.23[b]	0.23[b]	0.99	2^+	0.21[b]	0.21[b]
1.81	2^+	0.004	0.002	1.80	2^+	0.01	0.001
2.17	4^+	0.04	0.004	1.91	0^+	<0.02	0.01
2.33	0^+	<0.10	0.02	2.30	4^+	0.02	0.002
3.22	3^-	0.27[b]	0.27[b]	2.98	3^-	0.24[b]	0.24[b]
3.85	(1^-)	0.30[c]	0.006	3.63	(1^-)	0.24[c]	0.003
4.03	(5^-)	0.10[c]	0.008	3.83	(5^-)	0.07[c]	0.004

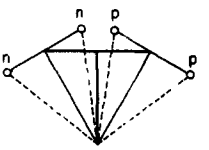
a) Normalized to 1.0 for ground state of ^{62}Zn

b) Experimental value used in calculation to obtain one-phonon strength.

c) Unbound states. S_α extracted by extrapolation from bound form factor.

FACTORIZATION OF THE OVERLAP FACTOR

$$G^2(\Gamma|\alpha) = g^2(\gamma_n|O_s)\,g^2(\gamma_p|O_s)$$



$$g^2(\gamma_n|O_s) \sim \frac{S_{EXP}}{S_{PV}}(t,p)$$

$$g^2(\gamma_p|O_s) \sim \frac{S_{EXP}}{S_{PV}}(^3He,n)$$

Fig. 11. Factorization of alpha transfer amplitudes. (Refs.19,20)

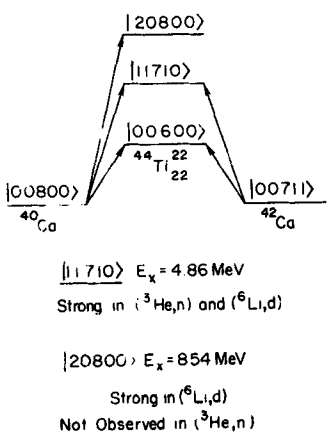


Fig. 12. Predictions of PV model. (Ref. 20)

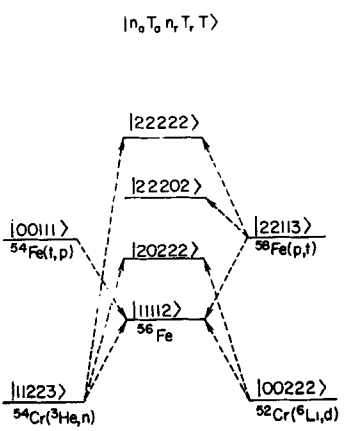


Fig. 13. Application of PV in fp shell. (Ref. 20)

NUCLEI 90<A<132

Most data in this region are from (d,^{6}Li). The surprising aspect is that the α-transfer cross sections[10,22,23] do not drop much from A=40 to A=150 (Fig. 15). In fact the (d,^{6}Li) cross sections for some of the Sm and Nd isotopes are actually larger than for many sd- and fp-shell nuclei. Not coincidentally many nuclei, A>140 are unstable to α-decay i.e. $Q_{\alpha}>0$, including ^{208}Pb. The data (Fig. 15) exhibit correlations with shell closures and deformation.

The Sr-Zr and Cd-Sn-Te regions are of interest in that extensive data[24,25] for (p,t), (t,p) and (^{3}He,n) are available permitting application of the pV models. The (d,^{6}Li) data (Fig. 16 and ref. 26) indicate a high degree of selectivity with excitation of proton and neutron pairing vibrations and again weak population of one-and two-phonon vibrations (0^{+}, 2^{+}, 4^{+}). The deduced S_{α} values are displayed in Fig. 17 and compared with the corresponding two nucleon transfer amplitudes. In agreement with factorization and the PV model, Sn(g.s.)→Cd(g.s.) scales with (p,t) and (t,p) including the X 1/2 blocking in odd-A nuclei[25], indicating that the di-proton pair acts as a spectator in these closed proton shell nuclei. The 0^{+} proton-pairing vibration in Sn although observed in Te(d,^{6}Li) as expected from the PV model, is suppressed with increasing neutron number, unlike (^{3}He,n), indicating an additional correlation between the transferred di-nucleon pairs. The (d,^{6}Li) strengths to the 0^{+}_{2} as well as the 5^{-} and 7^{-} levels are strongly correlated with the relative energy of the levels, suggesting an "α-condensation" effect. Microscopic calculations[26] based on BCS wavefunctions, indicate that most of the preferred transitions are of the form (L_{π}= 0) ⊗ (L_{ν} = J) or (L_{ν} = J) ⊗ (L_{π} = 0) with $J^{\pi} = 0^{+}$ or J corresponding to the "stretched" configuration, such as (2d 3/2, 1h 11/2) $J^{\pi} = 7^{-}$. This accounts for many of the systematics with increasing neutron number.

NUCLEI A>132

Data obtained[28] for rare earth nuclei are shown in Fig. 17 and the corresponding S_{α} are displayed in Fig. 18 and compared with two nucleon transfer[29]. Again many of the features of α-transfer in spherical nuclei can be correlated with two-nucleon transfer, however a striking transition occurs in strongly deformed nuclei. In these nuclei as in the sd shell the g.s.→g.s. α-transfer is suppressed with the (d,^{6}Li) cross sections (and S_{α}) spread among members of the g.s. rotational band, and perhaps spherical 0^{+} excited states. Clearly, however, both di-nucelon pairs are active participants. The angular distributions (Fig. 20) however, also exhibit effects possibly due to inelastic excitations[28].

Spectra and angular distributions[30] for ^{208}Pb(d,^{6}Li)^{204}Hg are shown in Figs. 21 and 22. The states populated strongest appear to be $J \geq 3$, probably 4^{+} and 3^{-} or if not the latter perhaps a high spin "stretched" configuration. The distribution of the 0^{+} - 2^{+} - (4^{+}) S_{α} strengths are not unlike those for ^{16}O(d,^{6}Li). The limited data[23,16,30] for ^{238}U(d,^{6}Li) and ^{232}Th (d,^{6}Li) appear consistent

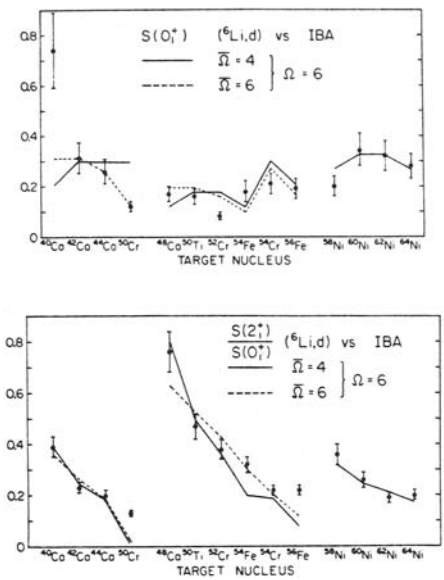


Fig. 14. Results of an IBA analysis in the fp shell.(Ref.21).

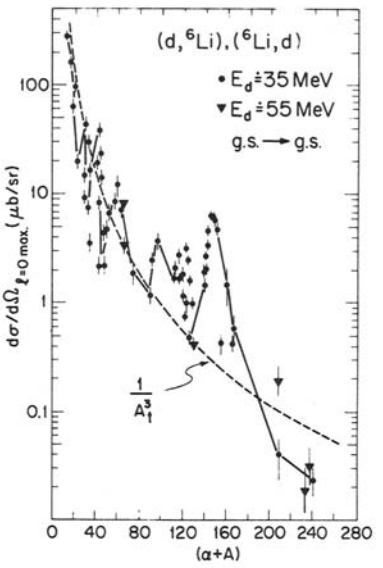


Fig. 15. Cross section vs. mass. (Refs. 2-16,22-30)

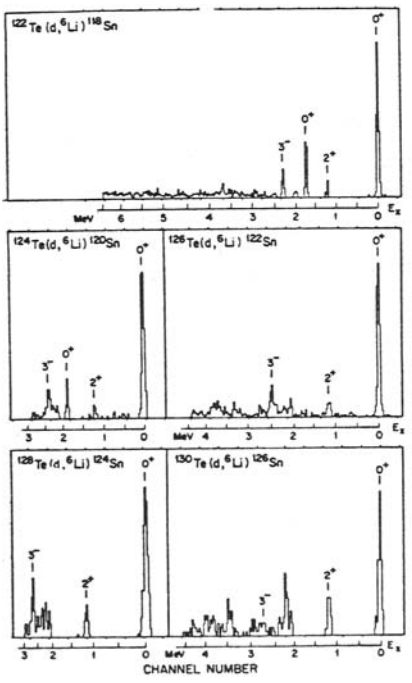


Fig.16. Data for Te(d,^{6}Li).(Ref.26).

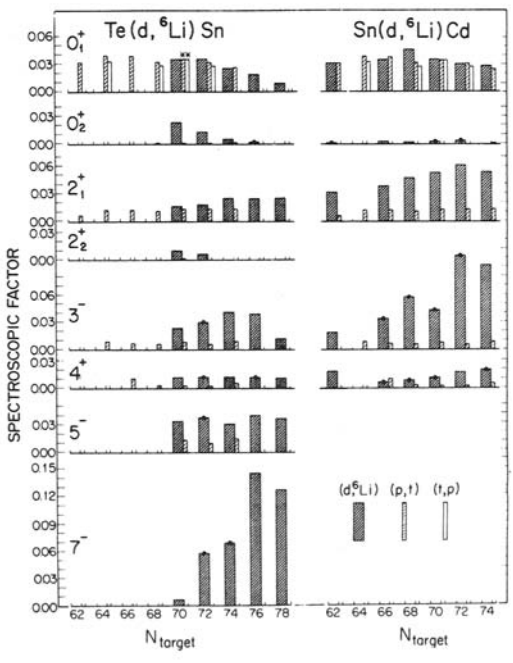


Fig. 17. S_α for Sn-Cd (Ref. 26)

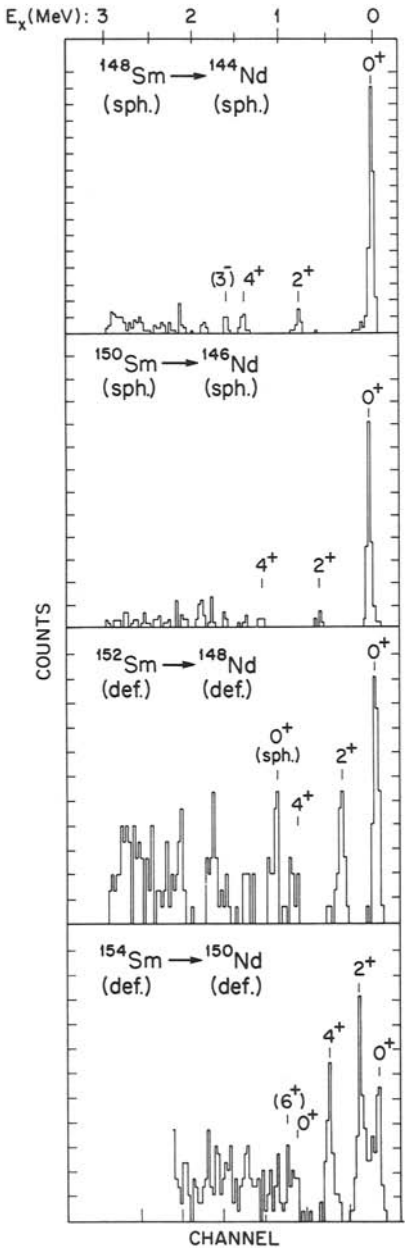


Fig. 18. Spectra for Sm(d,^{6}Li) (Ref. 28)

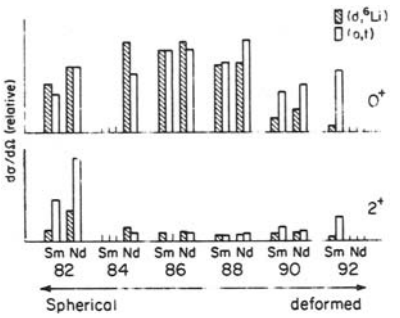


Fig. 19. S_{α} systematics for Sm-Nd compared with (p,t). (Ref.28)

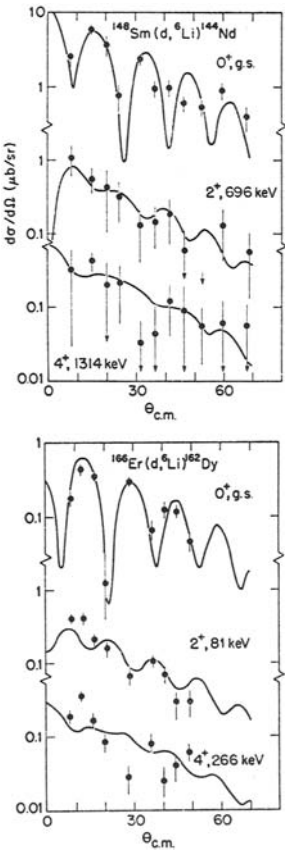
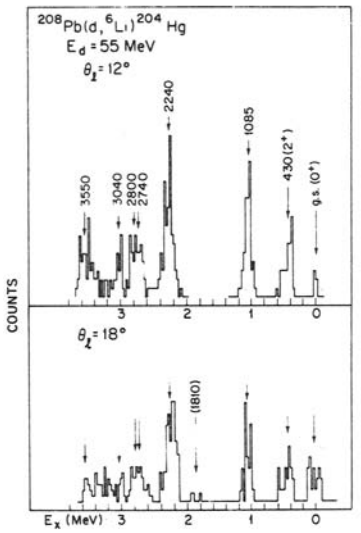


Fig. 20. Angular distributions for rare-earth nuclei. (Ref.28)



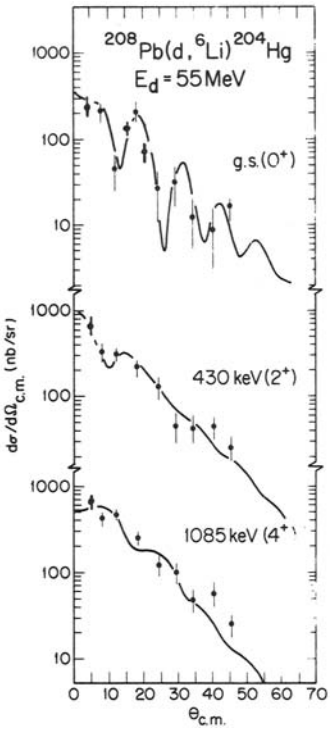


Fig. 22. Data and FRDW for ^{208}Pb (Ref. 30)

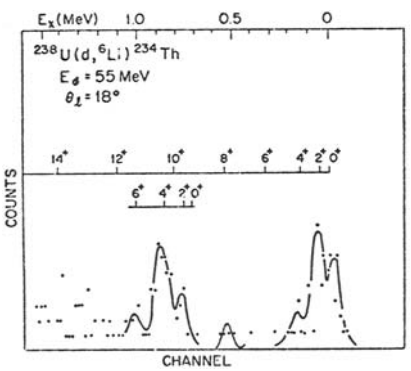


Fig. 21. Spectra for (d, ^{6}Li) on ^{208}Pb and ^{238}U. (Ref.30)

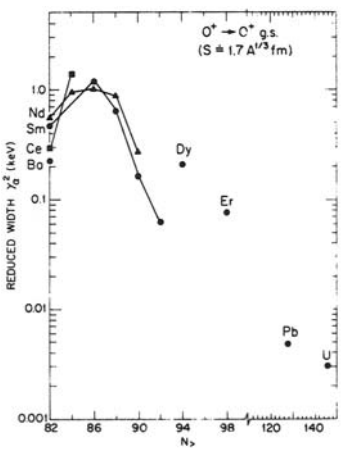


Fig. 23. Systematics of alpha widths from (d,^{6}Li). (Ref. 28)

with data for rare-earth deformed nuclei : suppressed g.s.→g.s. strength with a resulting spread in strength over the g.s. rotational band and excited states(Fig. 21).

ALPHA WIDTHS AND "ABSOLUTE" S_α VALUES

The quantity better determined in analyses[28] of (^{6}Li,d) and (d,^{6}Li) is the reduced α width γ_α^2, rather than S_α. Although in principle one can determine absolute γ^2 values from finite range DWBA, the present parameter uncertainties introduce considerable error (~X5). An alternate procedure is to renormalize the reaction data to one or more known α-decay widths, e.g. ^{148}Sm or ^{238}U. Results are shown in Table III and Fig. 23. The systematics deduced from (d,^{6}Li) correlate well with α-decay, including the branching ratios. Unlike α-decay studies one can also infer "α-decay" properties for nuclei considered stable, i.e. T 1/2 >10^9 years, such as ^{208}Pb (see Table III). The α-widths extracted for heavy spherical nuclei, such as ^{208}Pb, may be useful in extrapolation of α-decay properties to super heavy nuclei (A>300) as they may be more relevant than those obtained from other nuclei (e.g. deformed transuranic nuclei).

The absolute S_α values deduced from normalization to α-decay are typically 0.05 (^{120}Sn), 0.08 (^{148}Sm), 0.01 (^{208}Pb) and<0.01 for deformed nuclei (^{154}Sm, ^{238}U), while the values from FRDW are X1 to X10 times larger. In any event, the absolute S_α values are not significantly smaller than those for many sd- or fp-shell nuclei, i.e. $0.01<S_\alpha<0.1$. and are significantly larger than most shell model predictions[3], viz. $10^{-4}<S_\alpha<10^{-2}$.

SUMMARY

The (^{6}Li,d) and (d,^{6}Li) reactions appear to provide an effective means of investigating α-clustering phenomena, with good energy and spin resolution, over the entire periodic table. The data indicate many systematics, some of which can be understood with present models. Non-direct processes can be significant at low bombarding energies, however. Also, further work better establishing the parameters to be used in the reaction analyses, primarily those for the α+d and α+target wavefunctions and the α-d interaction is needed to fully exploit the data available.

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Table III

Comparison of experimental α-decay half-lives $T_{\frac{1}{2}}$ and branching ratios β with values deduced from (d, ^{6}Li) reaction data for α-unstable target nuclei

Target parent	Residual daughter	J^π	E_x (keV)	Q_α (keV)	Reaction [a]		Decay [b]	
					log $T_{\frac{1}{2}}$ (y)	β (%)	log $T_{\frac{1}{2}}$ (y)	β (%)
^{142}Ce	^{138}Ba	0^+	0	1362	25.81	100		
		2^+	1426	[c]				
^{144}Nd	^{140}Ce	0^+	0	1902	15.45	100	15.32±0.08	100
		2^+	1596	306		[d]		unobserved
^{146}Nd	^{142}Ce	0^+	0	1164	35.00	100		
		2^+	641	523				
^{148}Sm	^{144}Nd	0^+	0	1974	15.90 [a]	100	15.90±0.01	100
		2^+	696	1278				unobserved
		4^+	1314	660				unobserved
^{150}Sm	^{146}Nd	0^+	0	1440	28.34	100		
		2^+	454	986				
^{160}Dy [e]	^{156}Gd	0^+	0	451	104.15	100		
^{166}Er	^{162}Dy	0^+	0	822	65.90	100		
		2^+	81	741		$\approx 2\times10^{-8}$		
		4^+	266	556				
		6^+	549	273				
^{208}Pb [e]	^{204}Hg	0^+	0	519	129.72	100		
^{238}U [e]	^{234}Th	0^+	0	4266	10.91	75	9.65±0.01	77±4
		2^+	48	4218		24		23±4
		4^+	160	4106		0.58		0.23±0.07
		6^+	310	3956		0.02		unobserved

[a]) Normalized such that $\gamma_\alpha^2(s)$ is the same for the (d, ^{6}Li) reaction and the α-decay of ^{148}Sm with $T_{\frac{1}{2}} = 8.0\times10^{15}$ y. Estimated uncertainty is ±1 in log $T_{\frac{1}{2}}$.

[b]) Data from refs.

[c]) ^{142}Ce cannot α-decay to excited states in ^{138}Ba.

[d]) Blank spaces indicate $\beta \ll 10^{-15}$ %.

[e]) Data from ref.

DISCUSSION

Pilt, McMaster University:

Regarding the statement that simple SU(3) does not always do a very good job for some (d,^{6}Li) reactions in sd-shell nuclei, I think it fair to point out that one can do much better by adding only one or two additional SU(3) representations to the wave functions. This is still much simpler than in the jj shell model where one needs very many components.

Becchetti:

Quite true. The SU(3) calculations shown were zero-order ones (single $\lambda\mu$) and apparently are not quite complete enough. As I mentioned, a good description of (d,^{6}Li) for both ground state and excited states depends on the model used for the target ground state, unlike (^{6}Li,d). Even simple back-of-the-envelope SU(3) does quite well considering the small basis used.

Neudatchin, Moscow State University:

I suspect there should exist the specific quasi one α-particle surface states with rather large S_α values if the orbital momentum value is high, something like 20. It is possible now to try to observe them?

Becchetti:

In principle, yes. In practice high bombarding energy will be required (E > 100 MeV) to overcome momentum mismatching. It will likely not be possible to assign spins unless one does an angular correlation experiment however. We have evidence (Fig. 17 and 21) that $(L_\pi = 0) \otimes (L_\upsilon = J_{max})$ are excited in heavy nuclei.

Neudatchin, Moscow State University:

Are some indications of sequential transfer present?

Falk:

There are no analyses that I am aware of that give compelling evidence for the presence of a sequential process in (p,α) reactions.

Stein, Los Alamos Scientific Laboratory:

I wish to comment first on the previous question concerning the possible existence of α-cluster states. We have performed some experimental comparisons in ^{58,60}Ni between (^{6}Li,d) and (^{16}O, ^{12}C) spectra and find essentially the same results for the two reactions, despite the fact that quite different angular momentum selectivity should apply in the two cases. Thus there does not yet seem to be evidence in these two nuclei for high spin α-cluster states up to about 7 MeV of excitation. Perhaps we must search at higher energies.

I would now like to ask the two speakers if they would agree

that the bulk of the 3-particle transfer data show essentially single-particle spectra and the bulk of the 4-particle transfer data show essentially 2-nucleon transfer spectra. It seems to me that one should seek the 3- and 4-particle cluster states through the way in which (α,p) and (^{6}Li,d) spectra, for example, deviate from one- and two-nucleon transfer spectra.

Falk:

As far as the 3-nucleon transfer is concerned, I think your statement is correct, but very clearly the coupling of neutrons to 2^+, 3^- etc. is very important in order to be able to explain the relative strengths that one observes.

Stein, Los Alamos Scientific Laboratory:

But one sees no new states, except for a few high spin states. One doesn't see a triton spectrum, or states which one can look at as triton cluster states.

Becchetti:

In terms of the spectator problem, I think there are indications, there are mass regions, mainly at the doubly magic nuclei and far away from the doubly magic nuclei, where the spectator model doesn't work. I think that at higher bombarding energies one is going to see new phenomena.

Sarma, Bhabha Atomic Research Center:

I agree with Dr. Becchetti that the ^{6}Li wave function has to be correctly put in. We have estimated the effect of a better wave function and find that the spectroscopic factor may change by 20-50%. However this has to be included in the standard codes.

Janecke, University of Michigan:

I believe it is generally agreed that α-particle spectroscopic factors extracted from experiment are strongly model-dependent. I therefore urge experimentalists to include in their tables a column with reduced widths γ_α^2, which are far less model-dependent. We are using a channel radius of $1.7A^{1/3}$ which takes us into the region where, at our bombarding energies, the α-particle is picked up, and we therefore consider our values most reliable for this channel radius. Even as new ways of analyzing α-decay and/or α-transfer independent of channel radii become available (D. Jackson), my suggestion should still be worthwhile in the interim period.

Robson, Florida State University:

I am somewhat surprised that you take the DWBA analysis for Li induced reactions so seriously. Since ^{12}C is strongly deformed a CCBA calculation may be necessary.

Holmgren, University of Maryland:
In the (p,pα) and (α,2α) reactions we find that the reactions are limited to the very low density region of the nuclear matter distribution. In the case of the (^{6}Li,d) and (d,^{6}Li) the reactions may also be restricted to the extreme surface and the spectroscopic factors obtained may only reflect the properties of nuclear matter in this region.

Janecke:
I agree in principle but there are no indications in our data such as strange angular distributions which mandate the need for a CCBA treatment.

Becchetti:
Yes, this is correct, and is the reason many of us prefer the use of α reduced-widths rather than "S_α". The α-transfer reactions take place at about $R = 1.7\ A^{1/3}$ fm ($\rho_{nucl.} \lesssim 10\%$). I would argue, however, that α-clustering in the low-density regions of nuclei is still of interest.

Ajzenberg-Selove, University of Pennsylvania:
I would like to ask Dr. Falk if the relative strengths in (p,α) and (d,^{3}He) reactions, shown in one of his early figures, were based on experimental data.

Falk:
These were the ratios of experimental data and a simple distorted wave calculation.

Ajzenberg-Selove, University of Pennsylvania:
Was this done at a particular energy for the deuterons and for the protons, and have you tried to see whether changing the energy of both of the incident particles would have an effect on the relative strengths?

Falk:
No I haven't done that. These were data analysed by Smits, the (p,α) data were taken at Groningen, the (d,^{3}He) elsewhere. Only one set of analyses was done.

Siemssen, Groningen:
Perhaps I could mention that the (d,^{3}He) data are very insensitive to the incident energy. Both the absolute and the relative spectroscopic factors are stable. For the (p,α) there were measurements at two different energies and the relative spectroscopic factors were very much the same.