Conf-8110181--4

CONF-8110181--4

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ALPHA-TRANSFER REACTIONS*

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Lectures presented at the
International Workshop on Nuclear Structure
Miramar, Trieste
Italy

October, 1981

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*Work performed under the auspice of the Office of High Energy and Nuclear Physics, Division of Nuclear Physics, U. S. Department of Energy under contract number W-31-109-ENG-38.

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ALPHA TRANSFER REACTIONS*

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1. INTRODUCTION

The interest in α-particle clustering in nuclei dates from the earliest days of nuclear physics with the discovery of the spontaneous emission of α-particles by heavy nuclei. The existence of preformed α-particles in nuclei was suggested by Gamow[1] in 1930 and the idea of an α-particle model of light nuclei was first proposed by Hafstad and Teller[2] in 1938. More recently, Morinaga has interpreted[3] some of the states of nuclei such as ^{8}Be, ^{12}C, ^{16}O, etc. in terms of α-particle clusters. The concept[4] of "quartets" received much attention during the 1970's and the idea of a definite α-cluster structure for subsets of nuclear excitations is still very much with us.

The availability of beams of heavy projectiles such as ^{6}Li, ^{7}Li, ^{12}C, ^{16}O, etc. provided natural tools for attempting the investigation of α-cluster effects by means of direct reaction spectroscopy. The hope has been of course that the distribution of α-cluster strength could be studied in a manner analogous to the probing of single particle degrees of freedom in one particle transfer reactions and pairing degrees of freedom in two particle transfer reactions. As is the case in all multiparticle transfer reactions, the sensitivity of the reaction strengths to *coherent* sums over many spectroscopic amplitudes has often made the interpretation of the experimental results rather difficult. Systematic features of the data have, however, suggested some schematic interpretations which have exposed much of the essential physics governing the distribution of α-transfer strength in the low-lying spectra of nuclei, and many of the overall features of α-particle transfer reactions are now at least qualitatively understood. The quantitative understanding of many of the experimental results as well as the experimental studies themselves in many cases leave considerable room for improvement and should therefore provide a fruitful area for further study.

In these lectures I will attempt to outline what I consider to be some of the essential features of the experimental results and theoretical interpretations. All of these topics are discussed in more detail in the literature and have been summarized in the several review articles that have appeared over the years.[5-9]

2. EXPERIMENTAL RESULTS

Many different reactions in which four particles are transferred have been used to study α-clustering effects in nuclei. Of these, the most thoroughly studied and understood over the entire periodic table is the (^{6}Li,d) α-particle stripping reaction and its inverse the (d,^{6}Li) reaction. There are several advantages to this reaction over other possible α-transfer reactions. In cases where the ^{6}Li induced reaction has been compared with others,[10] the results seem to be reasonably consistent and I will therefore confine the discussion in these lectures to (^{6}Li,d) and (d,^{6}Li) data.

A spectrum of the $^{16}O(^{6}Li,d)^{20}Ne$ reaction[11] at a bombarding energy of 32 MeV is shown in Fig. 1. The reaction is highly selective showing strong population of relatively few levels, despite the known complexity of the ^{20}Ne level scheme above 6 MeV. Particularly noticable is the strong population of the ground state rotational band (0^+, 0.0; 2^+, 1.63; 4^+, 4.25; 6^+, 8.78 and 8^+, 11.95 MeV) and the $K^{\pi}=0^-$ band (1^-, 5.79; 3^-, 7.17; 5^-, 10.26 MeV) which dominate the spectrum. Similar selectivity is seen on other s-d shell targets.

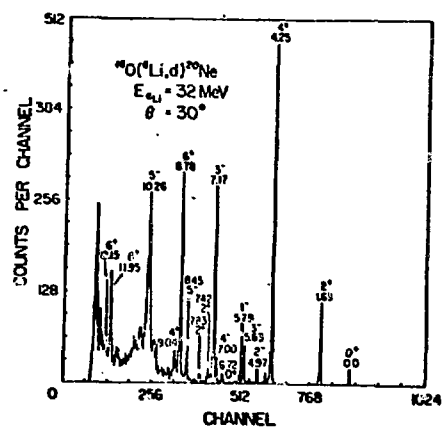

Fig. 1. Spectrum of the $^{16}O(^{6}Li,d)^{20}Ne$ reaction (Ref. 11).

On f-p shell targets, the reaction also shows strong selectivity although the cross-sections

are a factor of 5-10 smaller. A new feature that appears in this mass region is the frequent appearance of a strongly populated excited 0^+ state in the vicinity of 3-5 MeV. Spectra[12] for $^{54,56,58}Fe(^6Li,d)^{58,60,62}Ni$ are shown in Fig. 2.

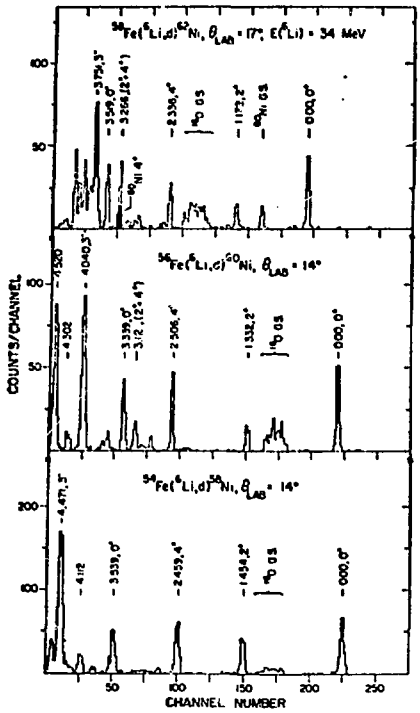

Fig. 2. Spectra for $Fe(^6Li,d)$ reactions (Ref. 12).

We see large cross-sections to the lowest 0^+, 2^+, 4^+ and 3^- states as well as the above mentioned excited 0^+ state. This selectivity is similar to that observed in two-particle transfer reactions such as (t,p) or (^3He,n) in this mass region.

For much heavier targets there are no (^6Li,d) data. The (d,^6Li) reaction has been extensively studied, however, by Becchetti, Janecke and collaborators. The example in Fig. 3 shows a spectrum of the $^{208}Pb(d,^6Li)$ reaction.[13] The cross-sections here are even smaller than for f-p shell nuclei and these measurements require large solid angle magnetic spectrometers. The selectivity in this spectrum is similar to that for f-p shell targets. For deformed heavy targets such as actinide nuclei, the pattern of cross-sections is more reminiscent of that seen in the s-d shell with strong population of the ground state rotational band.

The angular distribution shapes of (^6Li,d) and (d,^6Li) reactions are sensitive to the transferred angular momentum L, and as the four

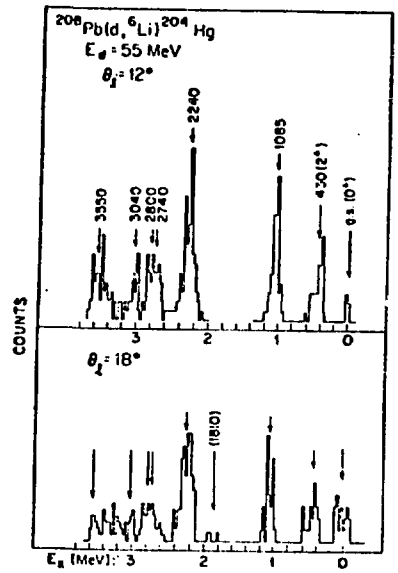

Fig. 3. Spectrum of the $^{208}Pb(d,^6Li)^{204}Mg$ reaction (Ref. 13).

transferred nucleons are assumed to have S=0, this in principle allows assignment of the J^π of the final state for reactions on spin zero targets. Examples of angular distributions for a variety of targets[11,13,14] and final state spins are shown in Figs. 4-6. The L=0 transitions are readily identified by their characteristic forward maxima and deep minima - reminiscent of L=0 angular distributions in (t,p) and (p,t) reactions. With increasing angular momentum transfer, the angular distribution shapes become less characteristic of L although plausible L-assignments can often be made based on the results of comparisons with DWBA calculations, they are necessarily far less certain that for the L=0 transitions. Again, this feature is similar to the case of two-particle transfer reactions.

3. DWBA AND SPECTROSCOPIC FACTORS

The ^6Li ground-state is to a good approximation described as a 0s α-particle and a deuteron in a relative s-state. Following Glendenning[15] we therefore write the cross-section for the transfer on a spin zero target

$$\frac{d\sigma}{d\Omega} \sim \left| \sum_N A_{NL} \beta_{NL} \right|^2$$

where the spectroscopic amplitude A_{NL} contains all the nuclear structure information and β_{NL} is the DWBA amplitude calculated using a cluster form-factor with N nodes, orbital angular

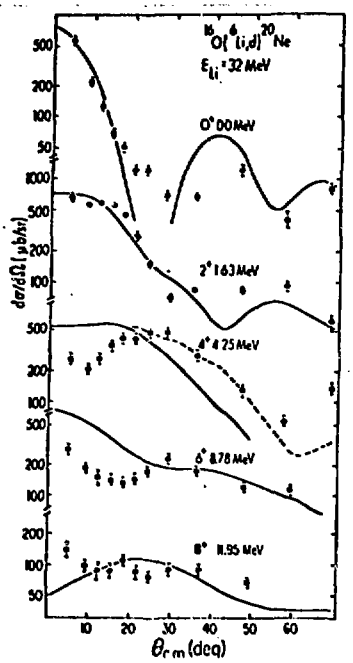

Fig. 4. Angular distributions for the $^{16}O(^6Li,d)$ ^{20}Ne reaction leading to the members of the ground-state rotational band (Ref. 11).

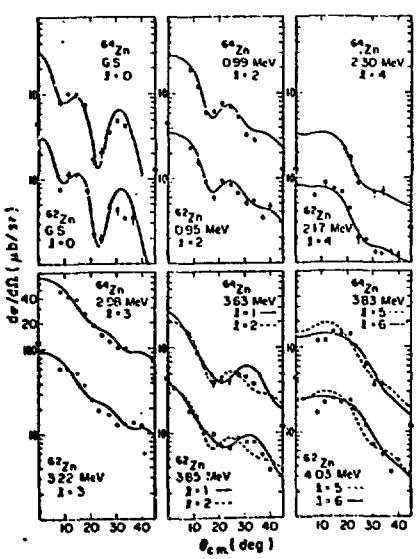

Fig. 5. Angular distributions for Ni(^{6}Li,d)Zn transitions to $J^\pi = 0^+, 1^-, 2^+, 3^-, 4^+$ and 5^- states (Ref. 14).

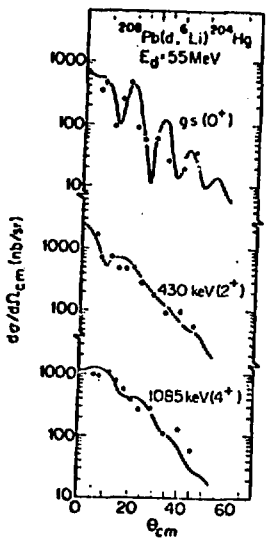

Fig. 6. Angular distribution for $J^\pi = 0^+, 2^+$ and 4^+ states populated in the $^{208}Pb(d,^6Li)^{204}Hg$ reaction.

momentum L and a fall off at large radii corresponding to the α-particle separation energy in the final state. For a 0s α-particle and assuming the same oscillator size parameter for the projectile and target N and L are determined by the expression

$$2N + L = Q = \sum_{i=1}^{4} q_i$$

where q_i equals the number of oscillator quanta transferred by the ith particle in the cluster. (This relationship arises simply from the conservation of energy). If all configurations corresponding to a given final state involve the same number of oscillator quanta or in other words if all configurations are contained within the same combination of major shells we may rewrite the above expression for the cross-section as

$$\frac{d\sigma}{d\Omega} \sim |A_{NL}|^2 |\beta_{NL}|^2$$

or

$$\frac{d\sigma}{d\Omega} = |A_{NL}|^2 \sigma_{DWBA}$$

where σ_{DWBA} is the cluster DWBA cross-section. We thus effectively define a cluster spectroscopic factor which provides a measure of the

intrinsic strength of a given transition independent of the experimental conditions.

It is well known that there are significant deficiencies in the above procedure. More sophisticated analyses do not however alter the qualitative significance of the results obtained as above.

The DWBA cross-sections can either be calculated in the zero-range approximation in which case an unknown overall normalization factor appears resulting in only the relative values of the spectroscopic factors having any significance or finite-range calculations can be performed for which a knowledge of the relative α-d wavefunction in the projectile is required. In principle, the latter procedure does lead to absolute values of the α spectroscopic factor although comparison with values obtained from α-decay widths[16] indicates some problems in this area. One important point in the calculation of DWBA cross-sections is the sensitivity of the final results in the optical potentials - particularly for the ^{6}Li. Different potentials have been shown to produce quite different Q and energy dependencies of the calculated cross-sections which may result in spurious variation in the extracted spectroscopic factors, particularly over a wide range of masses. This point has not been sufficiently investigated either experimentally by the measurement of ^{6}Li elastic scattering on the appropriate targets or theoretically. In many cases, however, different sets of data and different DWBA analyses do lead to consistent sets of relative spectroscopic factors. As an example of this, values obtained[17-19] from the ^{40}Ca(^{6}Li,d)^{44}Ti reaction at three different bombarding energies and with somewhat different DWBA analyses are shown in Table I. The overall agreement is remarkably good - despite the above mentioned difficulties.

4. THE STRUCTURE AMPLITUDE A_{NL}

The structure amplitude A_{NL} contains all the relevant nuclear structure information. It may be written as a sum of products of two factors

$$A_{NL} = \left(\frac{B}{B-4}\right)^{Q/2} \sum_{\Gamma} \langle \psi_B \| \chi^+(\Gamma) \| \psi_A \rangle \, G(\Gamma|\alpha)$$

where B is the mass of the final nucleus and the two terms in the sum are the coefficient of fractional parentage and the overlap of the transferred nucleons with the α-particle in the projectile. The label Γ serves to specify the exact nature of the transferred nucleons in the basis in which the initial and final state wave functions are written. It is emphasized here that the sum over Γ is a coherent one and the resulting value of A_{NL} depends not only on the magnitudes of the various terms in the sum but also on their relative phases. It is therefore clear that a suitable choice of basis functions

TABLE I. Comparison between ^{40}Ca(^{6}Li,d)^{44}Ti results at 28, 32 and 34 MeV bombarding energy.

E_x (MeV)	L	S_α 28 MeV[a]	32 MeV[b]	34 MeV[c]
0.0	0	1.0	1.0	1.0
1.08	2	0.46	0.33	0.49
1.90	0	0.25	0.27	0.28
2.45	4	0.29	0.16	0.29
2.53	2	0.26	0.25	0.38
2.89	2	0.046	-	0.036
3.36	4	0.24	0.12	0.23
3.76	1	0.17	-	0.088
3.94	3	0.052	-	0.072
4.02	6	0.34	(0.11)	0.17
4.11	2	0.15	0.20	0.17
4.83	0	0.67	1.35	1.04
5.06	2	0.072	-	0.10
5.21	4	0.046	-	0.078
5.32	4	0.083	0.09	0.14
6.03	4	-	-	0.29
6.20	6	-	-	0.22
	7	-	-	0.15
6.31	0	-	-	0.15
	1	-	-	0.48
6.45	8	0.72	-	0.99
7.28	2	-	-	0.82
7.51	2	-	-	0.93
	8	-	-	0.97
7.61	2	-	-	1.80
7.99	8	-	-	1.20
8.48	0	-	8.0	-
	6	-	-	0.65
8.90	4	-	-	1.25
	5	-	-	0.43

[a] Reference 17.
[b] Reference 18.
[c] Reference 19.

can result in a considerable simplification in the calculation of the spectroscopic amplitude and can lead to a more transparent understanding of the physical significance of the experimental results. In the following sections we discuss the calculation of A_{NL} in three models. The j-j coupled shell model, the SU(3) model and the pairing vibration model.

4.1. The j-j Coupled Shell Model

The application of this model to α-transfer has been discussed in detail by Kurath and Towner[20] and is important not so much because of its use in providing numbers for comparison with experiment but rather that it reveals certain properties of the coefficients of fractional parentage and overlap factors which can be more fully exploited by more schematic models. It does,

however, also provide the framework for calculation of α-particle spectroscopic factors in any given case - provided appropriate shell-model wavefunctions for the initial and final states are available.

The Overlap $G(\Gamma|\alpha)$

Consider two protons occupying orbitals $(q_1\ell_1 j_1)$ and $(q_2\ell_2 j_2)$ and two neutrons in orbits $(q_3\ell_3 j_3)$ and $(q_4\ell_4 j_4)$. In the internal α-particle wavefunction both neutrons and protons are in spatially symmetric 0s states with intrinsic spin zero, and only that component of the original couplings which satisfies this requirement will contribute.

Therefore, the general specification $(j_1 j_2 J_\pi, j_3 j_4 J_\nu)$ will only contribute to 0s α-transfer if $J_\pi = L_\pi$, $\ell_1 + \ell_2 + L_\pi$ = even and similarly for the neutrons. The evaluation of the overlap factor then requires transformation from the j-j to the L-S coupling scheme followed by three Moshinsky transformations (or projections à la Bayman and Kallio[21]) to convert to 0s states for all the internal coordinates as illustrated schematically in Fig. 7. The result is,

$$G(\Gamma|0s) = \begin{Bmatrix} \ell_1 & \frac{1}{2} & j_1 \\ \ell_2 & \frac{1}{2} & j_2 \\ L_\pi & 0 & L_\pi \end{Bmatrix} \langle 0sQ_\pi L_\pi, L_\pi | q_1\ell_1 q_2\ell_2 L_\pi\rangle$$

$$\begin{Bmatrix} \ell_3 & \frac{1}{2} & j_3 \\ \ell_4 & \frac{1}{2} & j_4 \\ L_\nu & 0 & L_\nu \end{Bmatrix} \langle 0sQ_\nu L_\nu, L_\nu | q_3\ell_3 q_4\ell_4 L_\nu\rangle$$

$$\langle 0sQL, L | Q_\pi L_\pi Q_\nu L_\nu L\rangle$$

This result can be written

$$G(\Gamma|0s) = \langle 0sQL, L|Q_\pi L_\pi Q_\nu L_\nu L\rangle$$

$$G(L_\pi j_1 j_2, 0s, Q_\pi L_\pi)$$

$$G(L_\nu j_3 j_4, 0s, Q_\nu L_\nu)$$

where the proton and neutron overlap factors are just those which occur in two nucleon transfer for projection onto a 0s state for the relative motion of the identical nucleons. The implication of this result is that we expect

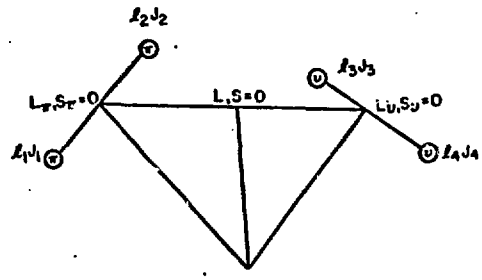

Fig. 7. Schematic illustration of the coordinate systems for transforming into relative and center-of-mass motion in the calculation of the overlap factor.

some of the features of two-particle transfer reactions to appear in α-transfer reactions. For example, two-neutron transfer in the f-p shell the cross-section for $(p_{3/2})^2$, $L_\nu=0$ transfer is approximately six times larger than for $(f_{7/2})^2$, $L_\nu=0$. In α-transfer such a favoring would enter quadratically in comparing $(p_{3/2})^4$ with $(f_{7/2})^4$ transfer.

The Parentage $\langle\psi_B \| \chi^+(\Gamma) \| \psi_A\rangle$

The effect of the initial and final nuclear states is contained in the parentage amplitude. If the nucleus B can be represented by a single term

$$\psi_B = [\psi^{J_p} \times \psi^{J_n}]^{J_B}$$

with a similar representation of nucleus A - the α-parentage amplitude for the case $\Gamma = (j_1 j_2 L_\pi j_3 j_4 L_\nu)$ becomes

$$\langle\psi_B \| \chi^+(\Gamma) \| \psi_A\rangle = \sqrt{(2J_p+1)(2J_n+1)(2J_A+1)(2L+1)}$$

$$\begin{Bmatrix} J_p & J_n & J_B \\ \bar{J}_p & \bar{J}_n & J_A \\ L_\pi & L_\nu & L \end{Bmatrix} \langle\psi^{J_p} \| \chi^+(L_\pi j_1 j_2) \| \psi^{\bar{J}_p}\rangle$$

$$\langle\psi^{J_n} \| \chi^+(L_\nu j_3 j_4) \| \psi^{\bar{J}_n}\rangle$$

a product of two two-particle coefficients of fractional parentage.

Combining the above results we can write the spectroscopic amplitude as

$$A_{NL} = \left(\frac{B}{B-4}\right)^{Q/2} \sum_{L_\nu L_\pi} \langle 0sQL,L|Q_\pi L_\pi Q_\nu L_\nu,L\rangle$$

$$\sqrt{(2J_p+1)(2J_n+1)(2J_A+1)(2L+1)} \begin{Bmatrix} J_p & J_n & J_B \\ \bar{J}_p & \bar{J}_n & J_A \\ L_\pi & L_\nu & L \end{Bmatrix}$$

$$\sum_{j_1 \geq j_2} \langle \psi^{J_p} \| \chi^+(L_\pi j_1 j_2) \| \psi^{\bar{J}_p} \rangle G(L_\pi j_1 j_2, 0s, Q_\pi L_\pi)$$

$$\sum_{j_3 \geq j_4} \langle \psi^{J_n} \| \chi^+(L_\nu j_3 j_4) \| \psi^{\bar{J}_n} \rangle G(L_\nu j_3 j_4, 0s, Q_\nu L_\nu)$$

The last two factors in this equation are exactly the structure amplitudes of Glendenning for 0s transfer of two nucleons and this therefore illustrates the sensitivity of α-transfer to the same types of correlations important in two-particle transfer reactions in a quantitative as well as in a qualitative sense. We note here, however, that one should not expect α-transfer reactions to populate only those states which are strongly excited in two particle transfer reactions but there are additional degrees of freedom or classes of states which cannot be excited in two-particle transfer but may still be excited in α-transfer reactions.

The seemingly simplicity of the above expressions is marred by the realization that few nuclear states have wavefunctions which contain only a small number of j-j coupled components and that the type of cluster states of most interest in α-transfer reactions will be exceedingly complex in this basis. For example, within the shell model space of the $1f_{7/2}$, $2p_{3/2}$, $2p_{1/2}$ and $1f_{5/2}$ orbits there are 70 possible J=0 configurations for two protons and two neutrons and although 75% of the total L=0 α-cluster strength is contained within 16 of them, the evaluation of the spectroscopic amplitudes is a formidable task. Such calculations have only been performed in a few cases. The agreement between theory and experiment is however quite reasonable as is illustrated in Table II where the experimental results for ^{44}Ti and ^{62,64}Zn are compared within shell model predictions.[22] The problem being of course that it is not easy to associated disagreement between theory and experiment with specific features of nuclear structure.

TABLE II. Experimental and shell-model alpha spectroscopic factors.[22]

State		S_{exp}	$S_{shell\ model}$
E(MeV)	J^π(B)		
0.00	$0^+(^{44}Ti)$	0.054	0.019
1.08	2^+	0.025	0.024
2.45	$4^+ + 4^{+a}$	0.029	0.024
3.36			
4.01	6^+	0.019	0.018
4.09	2^+	0.0081	0.0071
4.83	0^+	0.036	0.029
5.21	$4^+ + 4^{+a}$	0.0070	0.0062
5.31			
6.51	8^+	0.039	0.015
0.00	$0^+(^{62}Zn)$	0.020	0.013
2.36	0^+	0.0024	0.00002
0.95	2^+	0.0072	0.0072
1.80	2^+	0.0003	0.00011
2.19	4^+	0.0017	0.0009
	4^+		0.0005
0.00	$0^+(^{64}Zn)$	0.34	0.0065
1.91	0^+	very weak	0.0005
0.99	2^+	0.0088	0.0026
1.80	2^+	weak	0.0009
2.31	4^+	0.0010	
2.79	4^+	weak	

[a] Here two states are observed whereas only a single state is predicted by the shell model. In this case the experimental strength is the sum over the two levels.

4.2. The SU(3) Model

The advantages of this model in the study of clustering in nuclei were first pointed out by Bayman and Bohr.[23] They considered a system of particles in a harmonic oscillator basis where all but the last two neutrons and two protons fill the lowest available oscillator orbits. If the remaining four particles are in the next oscillator orbits, if they are in a state which is completely symmetric under space exchange and if the internal motion of the four particles is such that they are in a 0s state, then the wavefunction for these four particles is identical to the so-called leading representation of the SU(3) group for four particles in a given oscillator shell. Thus, if the nuclear wave functions for a nucleus with four nucleons outside an inert core is expanded onto an SU(3) basis then, to a good approximation, the α-transfer spectroscopic factor is proportional to the square of the amplitude of the leading SU(3) representation.

The expression for the spectroscopic amplitude thus becomes

$$A_{NL} = \left(\frac{B}{B-4}\right)^{Q/2} \langle\psi_B \| \chi^+(\Gamma=(Q,0)) \| \psi_A\rangle G(\Gamma=(Q,0)|\alpha)$$

where $(\lambda,\mu) = (Q,0)$ signifies the most symmetric state in Elliot's SU(3) scheme.[24] We see that the coherent sum present in the expression for A_{NL} in the j-j coupled shell model is replaced by a single term. The application of this model is particularly sppealing in the case of s-d shell nuclei which are known to be reasonably well described in terms of the SU(3) scheme.[25] The application of this model was first reported by Ichimura *et al.*[26] who give an explicit form for the overlap factors.

The parentage coefficients can be expressed in terms of SU(6)/SU(3) and SU(3)/R(3) coupling coefficients which have been tabulated by Draayer[27] and Hecht and Braunschweig.[28] The calculation of spectroscopic amplitudes for transitions with pure SU(3) configurations is therefore a relatively simple procedure.

For example, in ^{20}Ne we expect two $K^\pi=0^+$ rotational bands with SU(3) representations (λ,μ) = (8,0) and (4,2) arising from $(sd)^4$ configurations. We associate these model states with the ground state rotational band and the band based on the 6.72 MeV 0^+ state. It is expected on the basis of the above discussion that the ground-state rotational band will carry all the α-stripping strength for this configuration of nucleons. Comparison with experiment indicates that the selectivity expected on the basis of the SU(3) model is indeed observed. More detailed comparison of the extracted spectroscopic strengths for stripping and pickup given in Table III however shows significant discrepancies. This approach does nevertheless provide a relatively simple basis in which the experimental results can be expressed in terms of a few degrees of freedom.

4.3. The Pairing Vibration Model

The utility of Elliot's SU(3) model as a description of nuclear states decreases with increasing mass - largely due to the increased splitting between spin-orbit partners. The concentration of cluster strength in the most symmetric SU(3) state has been used to calculate α-particle spectroscopic amplitudes although the expansion of realistic wavefunctions on an SU(3) basis becomes more and more complex. It was realized that for heavier nuclei there were some striking correspondences between α-particle and two-particle transfer reactions populating the same final nucleus, a result which suggested that some of the schematic models which had given insight into pair transfer might be useful in discussing α-transfer.

TABLE III. Results of ^{16}O(^{6}Li,d)^{20}Ne and ^{24}Mg(d,^{6}Li)^{20}Ne reactions.

		Stripping[11]		Pickup[29]	
E_x(MeV)	J^π	S_{exp}	$S_{SU(3)}$	S_{exp}	$S_{SU(3)}$
0.0	0^+	1.00	1.0[a]	1.00	1.0[a]
1.63	2^+	0.41	1.0	0.83	0.13
4.25	4^+	0.22	1.0	1.00	0.80
8.78	6^+	0.20	1.0	1.92	1.84
11.95	8^+	0.51	1.0	-	-
5.62	3^-	0.06	0.0[b]	3.08	2.65[b]
8.45	5^-	0.04	0.0	1.08	0.51
5.79	1^-	0.54	1.50[c]	0.25	0.0[c]
7.17	3^-	0.26	1.50	0.0	0.0
10.26	5^-	0.45	1.50	0.0	0.0
6.72	0^+	0.56	0.0[d]	0.03	0.26[d]
7.42	2^+	0.13	0.0	0.21	0.0

Assuming $(\lambda\mu)$ = (0,0) and $(\lambda\mu)$ = (8,4) for the ^{16}O and ^{24}Mg ground states respectively.

[a] $(\lambda\mu)$ = (8,0).
[b] $(\lambda\mu)$ = (8,2).
[c] $(\lambda\mu)$ = (9,0).
[d] $(\lambda\mu)$ = (4,2).

Examples of this correspondence are shown in Figs. 8 and 9. The former of these shows a

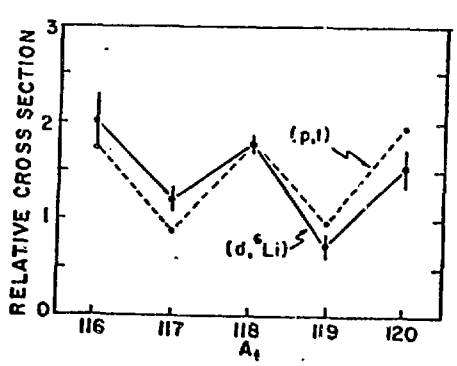

Fig. 8. Cross-sections for L=0 transitions in Sn(d,^{6}Li) reactions showing the blocking of strength for odd-mass targets. The dashed line shows (p,t) results for the same targets (Ref. 30).

comparison of (p,t) and (d,^{6}Li) cross-sections for odd and even Sn targets.[30] We see that the "blocking" of the two-neutron transfer strength due to the presence of the odd neutron is also manifest in the four-particle transfer data. Similarly, Fig. 9 shows a comparison[31] of (t,p)

and (^{6}Li,d) reactions populating final states in ^{44}Ca. Both spectra are dominated by population of the ground-state and an excited 0^+ state at 5.86 MeV - the so-called neutron pairing vibration.

A model which has provided extremely useful in the understanding of two-particle transfer data in the Ca-Ni region is the pairing-vibration model with isospin. This model was first proposed by Bohr[32] and Nathan.[33] The ground-state of the "doubly-magic" nucleus ^{56}Ni is taken as the vacuum 10>. Monopole pairing-vibration states are then formed by the successive action of the boson creation operators a^+ and r^+ each of which creates a pair of highly correlated particles or holes in orbits largely above or below the vacuum. Each of these pairs carries spin 0 and isospin 1. The states of the model are characterized by the number of addition and removal phonons, their isospin, the total isospin and its z-projection

$$\psi = |n_a T_a n_r T_r T\ T_z\rangle$$

Within the model there are three possible[34] ways in which an α-particle may be transferred. Namely, as two addition phonons, an addition and a removal phonon or as two removal phonons

$$\chi^+(\Gamma) = \begin{cases} [a^+ \otimes a^+]^{0^+,T=0} & \Gamma = aa \\ 2[a^+ \otimes r]^{0^+,T=0} & \Gamma = ar \\ [r \otimes r]^{0^+,T=0} & \Gamma = rr \end{cases}$$

Evaluation of the spectroscopic amplitudes for transitions between pairing vibrational states then leads to the following expressions for the three different types of transition.

$$|n_a T_a n_r T_r T\ T_z\rangle \rightarrow |n_a+2\ T_a n_r T_r T\ T_z\rangle$$

$$S_\alpha = N\left(\frac{B}{B-4}\right)^Q (n_a+T_a+3)(n_a-T_a+2)\ G^2(aa|\alpha)$$

$$|n_a T_a n_r T_r T\ T_z\rangle \rightarrow |n_a+1\ T'_a n_r-1\ T'_r T\ T_z\rangle$$

$$S_\alpha = 4N\left(\frac{B}{B-4}\right)^Q \begin{Bmatrix} T'_a & T'_r & T \\ T_r & T_a & 1 \end{Bmatrix}^2 [(n_a+T_a+3)(T_a+1)\delta(T'_a,T_a+1) + (n_a-T_a+2)T_a\delta(T'_a,T_a-1)]$$
$$[(n_r-T_r)(T_r+1)\delta(T'_r,T_r+1) + (n_r+1_r+1)T_r\delta(T'_r,T_r-1)]$$
$$G^2ar|\alpha)$$

$$|n_a T_a n_r T_r T\ T_z\rangle \rightarrow |n_a T_a n_r-2 T_r T\ T_z\rangle$$

$$S_\alpha = N\left(\frac{B}{B-4}\right)^Q (n_r+T_r+1)(n_r-T_r)\ G^2(rr|\alpha)$$

where the factors $G^2(\Gamma|\alpha)$ reflect the microscopic structure of the pair addition and removal phonons.

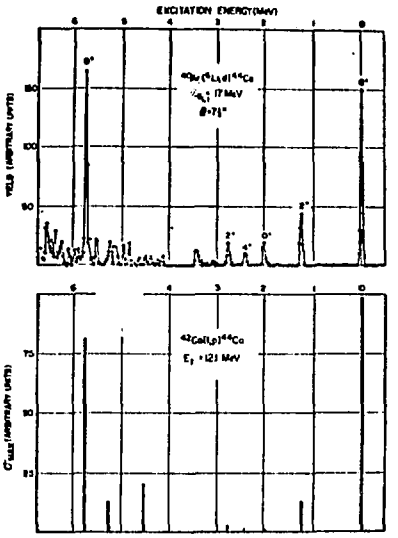

Fig. 9. Comparison of the ^{40}Ar(^{6}Li,d)^{44}Ca and ^{42}Ca(t,p)^{44}Ca reactions showing the strong population of the neutron pairing vibration near 6 MeV (Ref. 31).

If the pairing vibration scheme does in fact provide a good description of 0^+ states then it follows that there are stringent selection rules for α-transfer between these states.

Figure 10 shows the spectrum of pairing vibration states for ^{44}Ti and indicates allowed transitions for α-stripping on ^{40}Ca, two-proton stripping on ^{42}Ca and two-neutron pickup on ^{46}Ti. Experimentally the situation is in reasonably good agreement with the expectations. The (^{6}Li,d) reaction shows strong L=0 transitions to the ground state and an excited 0^+ state at 4.84 MeV both of which are strongly excited in the ^{42}Ca(^{3}He,n) reaction. The ^{46}Ti(p,t) reaction shows no appreciable strength to excited 0^+ states. It had been originally suggested that the |20800> pairing vibration state occurred at 8.55 MeV where an L=0 transition had been reported[17] in the ^{40}Ca(^{6}Li,d)^{44}Ti reaction. Further investigation[19] of this reaction failed to show such a state and indeed the identification of this double pair excitation is one of the outstanding questions in the f-p shell. In ^{44}Ti such a state may well be

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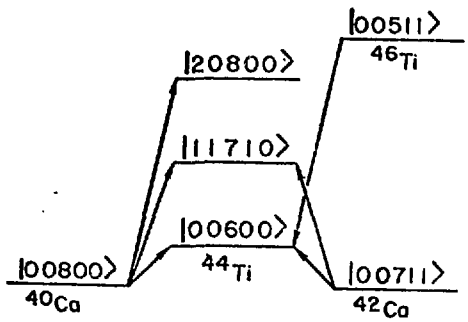

Fig. 10. Pairing-vibration selection rules for 0^+, T=0 states in ^{44}Ti populated in two and four particle transfer reactions.

unbound to α-particle emission and therefore rather broad and difficult to observe experimentally. For the heavier Ti isotopes, however, systematics suggest that this type of state may be bound and therefore observable experimentally in a transfer reaction.

Another simple expectation based on this model is the absence of excited 0^+ strength for α-stripping on targets with N and Z both >28 as illustrated in Fig. 11 for the ^{58}Ni(^{6}Li,d) and

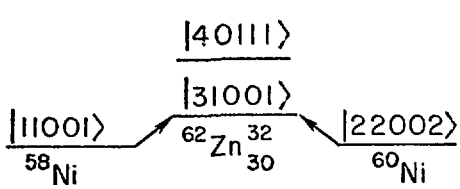

Fig. 11. Pairing-vibration selection rules for 0^+, T=1 states in ^{62}Zn populated in two and four particle transfer reactions.

^{60}Ni(^{3}He,n) reactions leading to ^{62}Zn. The experimental results are in agreement with this expectation.

A quantitative comparison[34] between the experimental ground-state α-transfer strengths and the values calculated using the above pairing vibration expressions is given in Table IV and shows quite reasonable agreement. There are three separate normalizations in this comparison, one for each of the three possible transfers of the two neutrons and two protons (Γ = rr, ar and aa). In principal they may be obtained by utilizing the factorization property of the overlap integral

$$G^2(\Gamma|\alpha) = G^2(\gamma_{\nu\nu}|0s)\, G^2(\gamma_{\pi\pi}|0s)$$

and obtaining the values of the overlap factors for the neutron and proton pairing phonons from a comparison of two-neutron and two-proton transfer data with the pairing vibration model.

The results of this procedure are illustrated[34] in Fig. 12 where now only one overall normalization is used over the entire range of data. Once again the overall agreement is rather good although it must be pointed out that different DWBA prescriptions can alter the overall mass dependence of the experimental values considerably.

TABLE IV. Comparison of experimental results with monopole pairing vibration model.[34]

Target	Final	S_α Expt	S_α PV
Γ = rr			
^{40}Ca(00800)	^{44}Ti(00600)	8.9	9.0
^{42}Ca(00711)	^{46}Ti(00511)	3.0	6.4
^{44}Ca(00622)	^{48}Ti(00422)	1.8	4.1
^{50}Cr(00311)	^{54}Fe(00111)	1.0[a]	1.0[a]
Γ = ar			
^{48}Ca(00444)	^{52}Ti(11334)	1.0[a]	1.0[a]
^{50}Ti(00333)	^{54}Cr(11223)	1.0	0.7
^{54}Fe(00111)	^{58}Ni(11001)	0.9	0.2
^{56}Fe(11112)	^{60}Ni(22002)	1.2	0.4
Γ = aa			
^{58}Ni(11001)	^{62}Zn(31001)	1.0[a]	1.0[a]
^{60}Ni(22002)	^{64}Zn(42002)	1.1	1.4
^{62}Ni(33003)	^{66}Zn(53003)	1.2	1.7

[a]Normalized.

The basic ideas of the monopole pairing vibration model have been extended to include higher multipole phonons and this model has been used to study the population of two phonon states in the Zn isotopes.[14] These states are of particular interest in that they constitute a class of states that might be expected to be strongly excited in an α-transfer reaction and yet are inaccessible in two particle transfer reactions. Surprisingly, both experimentally and in the model, such transitions are found to be extremely weak - a result which arises largely from the dominance of the strength of monopole phonon transfer over other multipoles. The implication of this result is that, with the

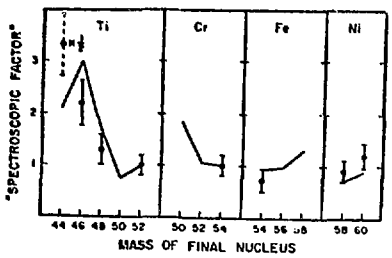

Fig. 12. Comparison between experimental spectroscopic factors for ground state transitions between f-p shell nuclei and the values expected from the pairing vibration model.

exception of the double monopole pair excitation mentioned previously, we should expect a much stronger correspondence between two-particle transfer reactions populating $T = T_z$ states and four-particle transfer reactions in this mass region than might have been initially expected.

The extension of the pairing vibration model to much heavier nuclei where it is no longer necessary to work in an isospin representation is trivial and although there are no detailed comparisons with data in the vicinity of ^{208}Pb where the model might be expected to work well there has been some effort[35] to locate the double pairing vibration or so-called "α-vibration".[36]

5. SUMMARY AND CONCLUSIONS

In these lectures I have attempted to summarize some of the features of α-transfer reactions and the various model interpretations. I feel that at least some of the rules of some of the games that can be played are clear but much further work is necessary before it can be stated that a quantitative understanding of the experimental results have been obtained. Naturally, whole subjects have been left unmentioned. I apologize for such omissions and hope that subsequent speakers will do them justice.

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*This work was performed under the auspices of the Office of High Energy and Nuclear Physics, Division of Nuclear Physics, U. S. Department of Energy under contract number W-31-109-ENG-38.

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