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B. G. Harvey

April 1975

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RECENT MULTINUCLEON TRANSFER EXPERIMENTS WITH HEAVY IONS AT BERKELEY[*]

B. G. Harvey
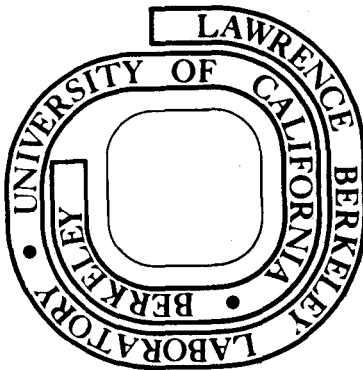
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I. INTRODUCTION. To talk about multinucleon transfer experiments at a confer-
ence devoted to the phenomenon of clustering is somewhat embarassing. In spite
of early hopes that heavy ion transfer reactions would contribute vast amounts
of new knowledge about clustering and correlations, the yield of definitive re-
sults is only just beginning to be harvested. The earliest good-resolution
transfer experiments were pioneering studies by the Yale group of transfer re-
actions such as $^{12}C(^{11}B,^{9}Be)^{14}N$ (1). The dark-ages then set in and it was not
until 1969 that the hunt for quartet states inspired the Saclay group to study
$(^{16}O,^{12}C)$ reactions in the A = 60 region (2). It was an invaluable secondary
result of this experiment to show that such 4-nucleon transfer work could in-
deed be done with heavy ion beams and that the difficulties of particle identi-
fication were by no means as great as had been feared. One other lesson was
learned - that much remained to be discovered about the dynamics of heavy ion
reactions before any unambiguous conclusions could be drawn from the results.

For this reason, and perhaps also because the experiments were easier,
several laboratories began, in the early 1970's, to study the transfer of
a single nucleon. Although the results make no direct contribution to our un-
derstanding of clustering phenomena they hopefully have laid a solid foundation
on which to build. The experiments of Kovar, Becchetti et al. (3) at the
Berkeley 88-Inch Cyclotron, combined with the theoretical work of de Vries (4)
and Nagarajan (5) showed that single particle spectroscopic factors for the re-
action $^{208}Pb(^{16}O,^{15}N)^{209}Bi$ could be reliably extracted only by the use of a fi-
nite range recoil DWBA calculation. Although these calculations have had many
successes, there are still unsolved problems such as a total failure to fit ex-
periment for the reaction $^{12}C(^{14}N,^{13}C)^{13}N$ (6), as shown in Figure 1. Neverthe-
less, the study of multinucleon transfer reactions has become in increasingly
popular, and it is about experiments of this type at the Berkeley 88-Inch Cyclo-
tron that this paper is devoted. First, though, the capital importance of in-
strumentation in this work must be emphasized both for the production and for
the detection and identification of heavy ions. It is now apparent that the
cross sections for many fascinating multi-nucleon transfer reactions will be no
greater than a few nb/sr. Beams of high intensity, and detection methods of
great selectivity are therefore essential. We must begin to think like high
energy physicists who spend a huge amount of effort on their particle detection
and identification systems.

II. TWO-NUCLEON TRANSFER REACTIONS. In a clear example of theory leading ex-
periment, it was shown by Ascuitto and Glendenning (7) that inelastic excita-
tions should play an important role in determining the cross sections and

angular distributions of two-neutron transfer reactions between vibrational
states of nuclei as modestly collective as the tin isotopes. Figure 2 shows a
comparison between coupled channel finite-range no-recoil Born approximation
(CCBA) calculations and experiments done at Oxford and Berkeley (8) for the re-
actions $^{18}O + ^{120}Sn \rightleftharpoons ^{16}O + ^{122}Sn$. Transitions between ground states in
either direction are time-reversed reactions, and happily the experimental and
theoretical results turn out to be identical. The $(^{16}O, ^{18}O)$ pick-up reaction to
both the ^{120}Sn ground and 2+ states has a typical bell-shaped angular distribu-
tion, but there is a destructive interference between direct and indirect paths
in the $(^{18}O, ^{16}O)$ stripping reaction which produces a smaller cross section and
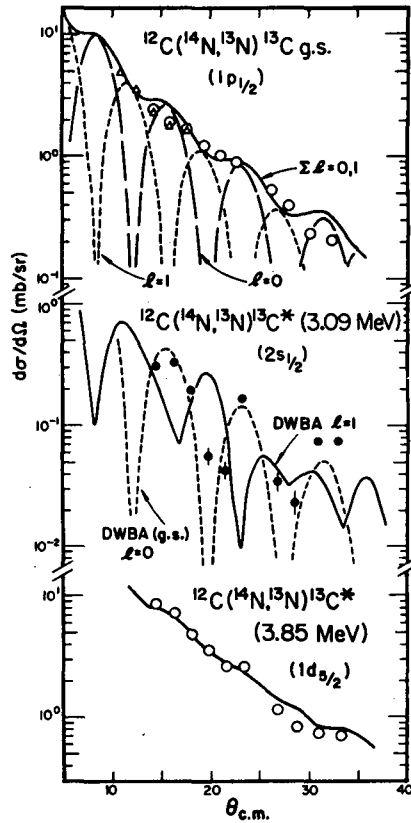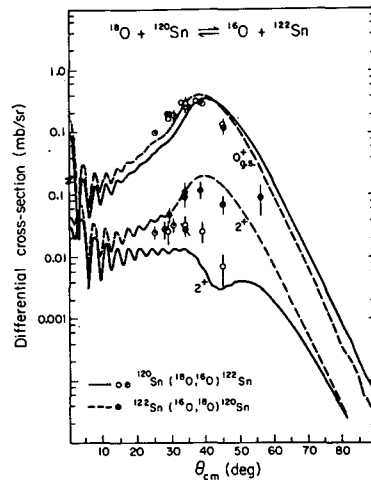a much flatter angular distribution.

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Fig. 1. Anomalous angular distribution for $^{12}C(^{14}N,$
$^{13}N)^{13}C$ $2s_{1/2}$ level at 3.09 MeV. The selection rules
allow only $\ell = 1$.

Fig. 2. Angular distributions for ground state and 2+
transitions in $^{18}O + ^{120}Sn \rightleftharpoons ^{16}O + ^{122}Sn$. The lines
are CCBA calculations.

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The energy spectra of the $^{122}Sn(^{16}O,^{18}O)^{120}Sn$ reaction show that the outgoing ^{18}O ion is about five times more likely to be in its 2_1^+ state than in its 0^+ ground state. In some $(^{18}O,^{16}O)$ reactions, the ^{16}O ion is much more likely to be observed in one of the (Doppler broadened) states near 6 MeV than in the ground state. There is no obvious reason why higher order inelastic plus transfer reactions should include inelastic excitations of the heavy nuclei but not of the incident or outgoing heavy ions. Indeed, very preliminary CCBA calculations by Glendenning and Wolshin (9) show that ion excitation may have very important consequences.

It thus seems, unhappily, that calculations for heavy ion transfers should in many cases be made with codes that include finite-range, full-recoil, sequential transfer and CCBA for a large number of states of all the four nuclei taking part in the reaction. This represents a challenge to theorists and programmers almost as difficult and expensive as the design and construction of heavy ion accelerators. The organization and funding of theoretical nuclear physics has certainly not adapted itself to these new needs and priorities.

The destructive (constructive) interferences to 2+ states observed experimentally in $^{120}Sn \rightarrow ^{122}Sn$ ($^{122}Sn \rightarrow ^{120}Sn$) are not general consequences of stripping (pick-up) reactions: they depend upon the nuclear model that decribes the 2+ states, in this case two-quasiparticle or RPA wave functions. We have also studied the reactions $^{148}Sm + ^{18}O \rightleftharpoons ^{150}Sm + ^{16}O$ (10). The target nuclei (N = 88 and 86) are just above the closed shell magic number N = 82, and have an open proton shell whereas the tin nuclei (N = 70 and 72) are close to the upper end of the N = 50 shell and are closed in protons. For the Sm targets, it is the two-neutron pick-up reaction that shows a destructive interference (Figure 3), which is just the opposite of what was observed for the Sn targets.

The explanation may be in the form of the direct and indirect amplitudes connecting the ground state of (A + 2) to the state J_A and the ground state of A to J_{A+2}, as shown in Figure 4. The amplitudes corresponding to steps 2 and 3 of Figure 4 are (7):

$$\beta_2(0_{A+2} \leftrightarrow J_A) \, \alpha \quad [V_a V_b \Psi_{ab} - U_a U_b \phi_{ab}]$$

$$\beta_3(0_A \leftrightarrow J_{A+2}) \, \alpha \quad -[U_a U_b \Psi_{ab} - V_a V_b \phi_{\alpha\beta}].$$

When the second term in the parenthesis is smaller than the first, β_2 (pick-up) is positive and β_3 (stripping) is negative. Since β_1 and β_4 are positive, the interference (for formation of the state J) is constructive for pick-up and destructive for stripping. This behavior should be observed for any nuclei for which a two-quasiparticle ($\phi=0$) description is adequate. It may be that the ϕ terms are much larger in the Sm case, leading to the opposite interference behavior, but there are no detailed structure calculations to substantiate this hypothesis. We have here a key to unlock much new nuclear structure information.

A strong interference effect has also been observed in the reaction ^{144}Nd $(^{12}C,^{14}C)^{142}Nd$ (2_1^+) (11). An energy spectrum of levels in ^{142}Nd (N=82) is shown in Figure 5. The 0_1^+, 0_2^+ and 2_2^+ states are believed to be predominantly two-neutron holes in the N=82 closed shell plus two neutrons in the next shell. These states are therefore readily accessible by two-neutron pick-up from ^{144}Nd, and as Figure 5 shows, they are strongly excited. The 2_1+ state, however, is dominantly a proton particle-hole quadrupole vibration so that the direct two-neutron pick-up is strongly inhibited and indirect paths become relatively important.

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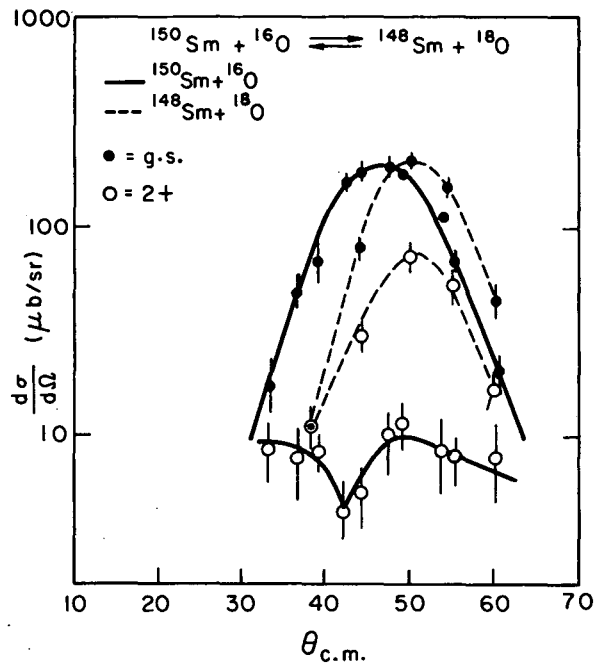
Fig. 3. Angular distributions for $^{148}Sm + ^{18}O \rightleftharpoons ^{150}Sm + ^{16}O$ showing destructive interference for the pick-up reaction to the 2+ level of ^{148}Sm.
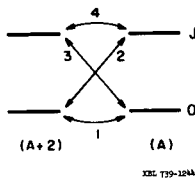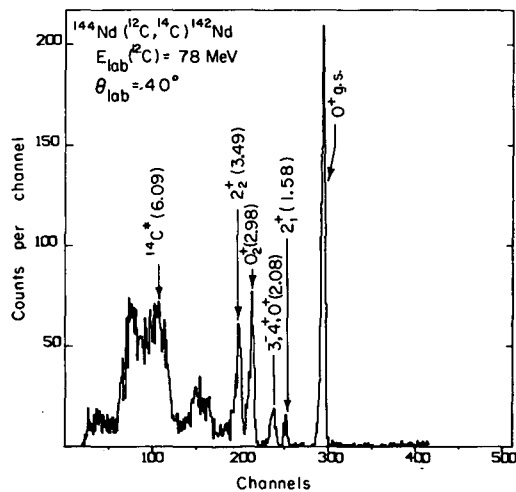

Fig. 4. Direct and indirect routes in two-neutron pick-up and stripping. In stripping to state J, route 3 is direct and in pick-up 2 is direct.

Fig. 5. Energy spectrum of $^{144}Nd(^{12}C,^{14}C)^{142}Nd$ showing weak excitation of the 2_1+ state.

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Figure 6 shows that the angular distribution for the 2_1+ state is much flatter than the typical bell-shaped curves for the 0_1, 0_2 and 2_2 states. The solid lines in the figure are the results of finite range CCBA calculations.

In the absence of a beam of ^{14}C ions, the reverse two-neutron stripping reaction was studied by $^{142}Nd(^{18}O,^{16}O)^{144}Nd$, whose 2_1+ state is, in lowest order, simply two neutrons beyond the N=82 closed shell. Figure 7 shows that the state is indeed strongly excited.

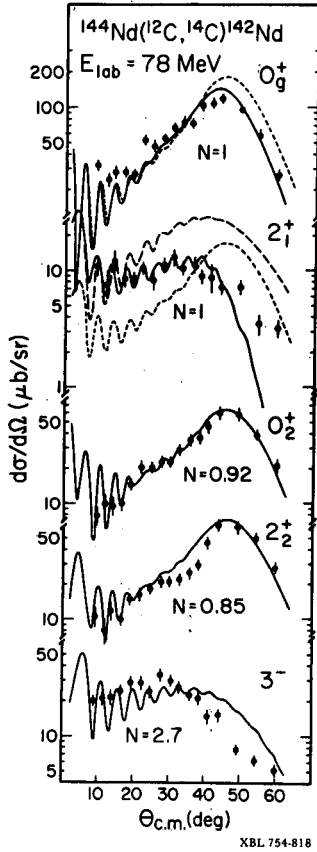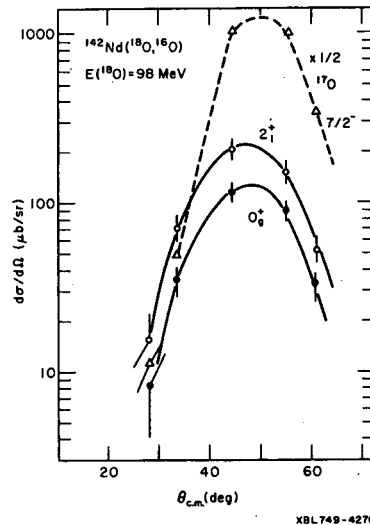Fig. 6. Angular distributions for $^{144}Nd(^{12}C,^{14}C)^{142}Nd$ showing anomalous angular distribution for the 2_1+ level.

Fig. 7. Angular distributions for $^{142}Nd(^{18}O,^{16}O)^{144}Nd$ showing strong excitation and "normal" shape for the 2_1+ level.

Two points are worth making about these interference experiments. First, the theoretical fits to the angular distributions are impressively good, in general much better than one obtains with light ions. Second, destructive interference provides a sensitive test of the nuclear wave functions since the shape as well as the magnitude of the angular distribution depends critically upon the amplitudes of the interfering reaction pathways.

III. THREE NUCLEON TRANSFER REACTIONS. Three nucleon transfer reactions are being studied in several laboratories, but it is the pioneering work of the Oxford group (12) that has shown how they may be used to locate cluster states of light nuclei. As had been found much earlier in np transfer (α,d) studies (13), the reactions are often so selective in the states that they populate that a large amount of nuclear structure information, and even spin and parity assignments, can be obtained just by looking at the spectra. Much can be understood by the application of Brink's rules (14) for matching of linear and angular momentum. For a high transfer probability, these conditions must be approximately satisfied:

$$\Delta k = k - \lambda_1 / R - \lambda_2 / R \approx 0$$

$$\Delta L = (\lambda_2 - \lambda_1) + \frac{1}{2} k_o (R_1 - R_2) + Q_{eff} R / \hbar v \approx 0$$

$$\ell_1 + \lambda_1 = \text{even}, \quad \ell_2 + \lambda_2 = \text{even}.$$

Here, $k_o = mv/\hbar$ where m is the mass of the transferred nucleon or cluster and v is its velocity relative to the target nucleus at the point of transfer, $\ell_1 \lambda_1$ and $\ell_2 \lambda_2$ are the orbital angular momenta of m in the initial and final states and λ's are projections of the ℓ's on a z-axis perpendicular to the scattering plane. R_1 and R_2 are the two nuclear radii and $R = R_1 + R_2$. The effective Q-value, Q_{eff}, is defined by

$$Q_{eff} = Q - (z_1^f z_2^f - z_1^i z_2^i) e^2 / R.$$

In the experiments many years ago at the old 60-Inch Cyclotron and more recently at the Berkeley 88-Inch Cyclotron, we found that the (α,d) reaction on light nuclei very strongly selected the state $(d_{5/2})^2_{5+}$. In heavier nuclei, the states $(f_{7/2})^2_{7+}$ and $(g_{9/2})^2_{9+}$ were strongly excited. When the target nucleus had spin J, multiplets of strong states appeared which were assigned the configurations $[J \otimes (d_{5/2})^2_{5+}]$. The np pair is transferred in a state of relative motion L = 0, S = 1, T = 0, i.e. a deuteron-like state. At sufficiently high energies, similar results were obtained with (^{3}He,p) and no evidence came to light for the transfer of a T = 1 pair in (^{3}He,p). It is instructive to use the second of Brink's rules to look at the reaction ^{12}C(α,d)^{14}N, 5^+, 9 MeV, even though the results should not be taken too seriously when half the incident ion is transferred. For 50 MeV α-particles, the three terms in the ΔL rule are:

$$\Delta L = \lambda_2 - 0.8 - 5.9.$$

The high negative value of Q (and hence of Q_{eff}) drives the reaction towards the population of a final state with a large value of λ_2 and hence of ℓ_2. For $(d_{5/2})^2_{5+}$, $\ell_2 = 4$, and this value gives a small value of Δk, 0.8 fm^{-1}.

The reaction $^{12}C(^{12}C,^9Be)^{15}O$ has been studied by the Oxford group (12) and at several energies up to 187 MeV (15.6 MeV/nucleon) at Berkeley. The spectrum at 187 MeV is shown in Figure 8, where the high selectivity and low density of populated states is very evident. The strong states at 12.87 and 15.08 MeV have been interpreted by Brink and coworkers (12) as ^3He cluster states with spins $11/2^-$ and $13/2^+$ respectively. Buck, Dover and Vary (15) have calculated the spectrum of states for three and four nucleon clusters in a potential obtained by folding the cluster and core mass densities. The $11/2^-$ state (also observed in $^{12}C(^{12}C,^9B)^{15}N$) is assigned N, L = 0,5: it is one of the two states that are strongly excited in $^{13}C(\alpha,d)^{15}N$ and it has the dominant shell model configuration $[(d_{5/2})^2_{5+} \otimes p_{1/2}]_{11/2^-}$. The $13/2^+$ state is assigned N,L = 0,6 with dominant shell model configuration $[d_{5/2})^2_{5+} \otimes d_{3/2}]_{13/2+}$. This configuration can of course be excited in three-nucleon transfer to a ^{12}C core, but it should not be (and is not) excited in $^{13}C(\alpha,d)^{15}N$.

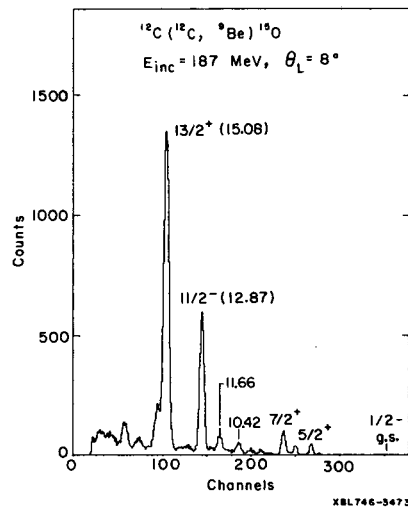Fig. 8. Spectrum of $^{12}C(^{12}C,^9Be)^{15}O$ at 187 MeV (lab) showing strong excitation of states believed to be of high spin.

Brink's rules require that the transfer probability between a given pair of states should be a function of the particle energy and of any other parameters that affect the values of Δk and ΔL. The Oxford group (12) has shown how to make a semiclassical calculation of the dependence of the transfer probability P on Δk and ΔL:

$$p \; \alpha \; \exp\left[-\left(\frac{R\Delta k}{\pi}\right)^2 - \left(\frac{\Delta L}{\sqrt{\gamma R}}\right)^2\right]$$

where $\gamma^2 = 2m\varepsilon/\hbar^2$ and ε is the average of the cluster binding energies in the initial and final states. Figure 9 shows the results of a calculation of the relative cross sections for three states in $^{12}C(^{12}C,^9Be)^{15}O$ with experimental points from Berkeley (16). There is such good general agreement that one may look forward to finding and assigning many more cluster states in light nuclei by making cross section measurements at several energies. It would obviously be desirable to use beams of up to 20-30 MeV/nucleon, and this will be done in the Berkeley 88-Inch Cyclotron by accelerating $^{12}C(5+)$ ions which would give a maximum energy of 24 MeV per nucleon (290 MeV).
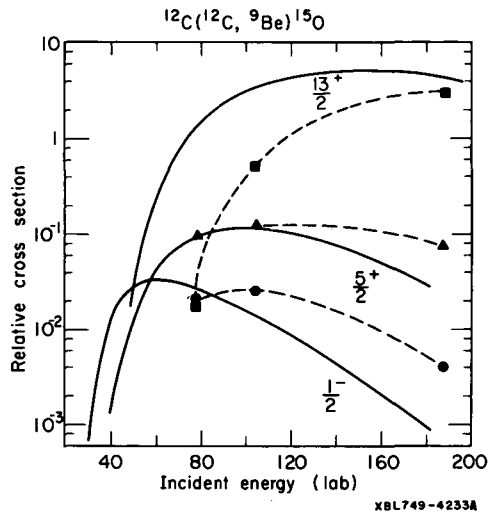
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$^{12}C(^{12}C, ^9Be)^{15}O$

Fig. 9. Relative cross sections (points) and semi-classical calculations for the reaction $^{12}C(^{12}C,^9Be)^{15}O$.

The three-neutron transfer reactions $^{26}Mg(^{11}B,^8B)^{29}Mg$ and $^{28}Si(^{11}B,^8B)^{31}Si$ were studied with 86 MeV ^{11}B ions (17) primarily to measure the mass of ^{29}Mg, about which there had been some controversy. The cross sections are very small-only 15 nb/sr for the ground state of ^{29}Mg. Again, this can be understood qualitatively from Brink's rules. For the reaction with a ^{26}Mg target, $\Delta L \approx -5$, mainly due to the large negative value of $Q_{eff}(-19.72)$ and hence of the term $Q_{eff}R/\hbar v$ in the ΔL rule.

The ^8B spectra are shown in Figure 10. In ^{31}Si, the observed states at 0 and 3.15 MeV have the dominant configurations $(s_{1/2})^2 (d_{3/2})$ and $(s_{1/2})^2 (f_{7/2})$. Thus the three neutron transfer appears to select states with the configuration $[L = S = 0, T = 1) + 1$ neutron]. States at 0.75 MeV (1/2+) and 1.70 MeV (5/2+), accessible only through their $(s_{1/2}) (d_{3/2})^2$ components, are absent. The importance of sequential transfer remains an open question. As so often happens, the reaction mechanism can best be tested by measuring the excitation of levels of known configuration. Nuclear structure theory, nuclear reaction theory and experiment can advance only hand in hand for mutual support.
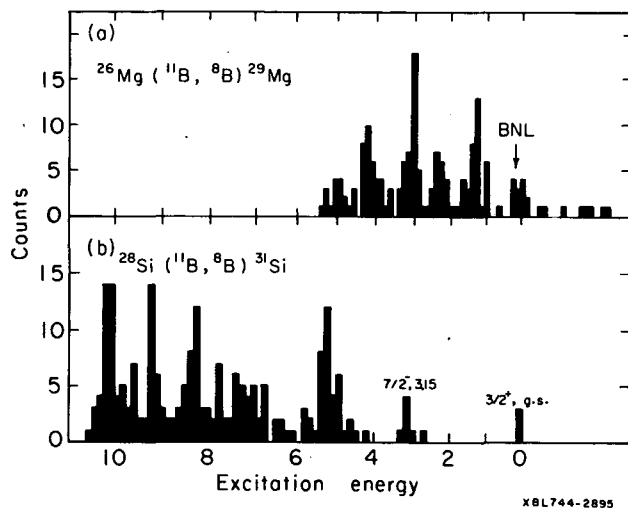

Fig. 10. ^8Be spectra from $^{26}Mg(^{11}B,^8B)^{29}Mg$ and $^{28}Si(^{11}B,^8B)^{31}Si$ at E = 86 MeV (lab) and 11° (lab).

IV. FOUR-NUCLEON TRANSFERS: Recent work has shown that the two break-up α-particles from ^{8}Be can be detected and identified with an initial ^{8}Be nucleus (18). It is therefore possible to use the reactions $(\alpha, ^8\text{Be})$ and $(^{12}\text{C}, ^8\text{Be})$ to study four-nucleon pick-up and stripping reactions. The large α-decay width of ^{8}Be suggests that the reactions should really test the α-particle cluster configuration of the target or final nucleus. It should be possible to learn something more by comparing the reactions $(\alpha, ^8\text{Be})$ and $(\alpha, 2\alpha)$ on the same target nucleus.

Before drawing any conclusion, it is necessary to insure that $(\alpha, ^8\text{Be})$ is a direct reaction at the α-energy to be used. Wozniak, Jelley, and Cerny (19) investigated the reaction $^{12}\text{C}(\alpha, ^8\text{Be})^8\text{Be}$ at five energies between 63.2 and 67.3 MeV (lab) and found that the differential cross section over the peak at 35° (c.m.) was a slow and smoothly decreasing function of α-particle energy. Moreover, the reactions $^{16}\text{O}, (\alpha, ^8\text{Be})^{12}\text{C}$, $^{24}\text{Mg}(\alpha, ^8\text{Be})^{20}\text{Ne}$ and $^{28}\text{Si}(\alpha, ^8\text{Be})^{24}\text{Mg}$ failed to populate any of the well-known unnatural parity states in ^{12}C, ^{20}Ne or ^{24}Mg, and the angular distributions were often highly oscillatory. The $(\alpha, ^8\text{Be})$ reaction therefore appears to be largely direct.

The reaction $^{16}\text{O}(\alpha, ^8\text{Be})^{12}\text{C}$ (72 MeV) gave a strongly oscillatory cross section for the ^{12}C ground state, but less so for the ^{12}C 4.43 MeV 2+ state. The relative strengths of these states were in rough agreement with Kurath's prediction (20) that ^{16}O looks much more like $(^{12}\text{C}(2^+) + \alpha)$ than $(^{12}\text{C}(\text{g.s.}) + \alpha)$ as shown in Figure 11 and Table 1.

Table 1. Relative α-spectroscopic factors from $^{16}\text{O}(\alpha, ^8\text{Be})^{12}\text{C}$ and $^{16}\text{O}(\alpha, 2\alpha)^{12}\text{C}$.

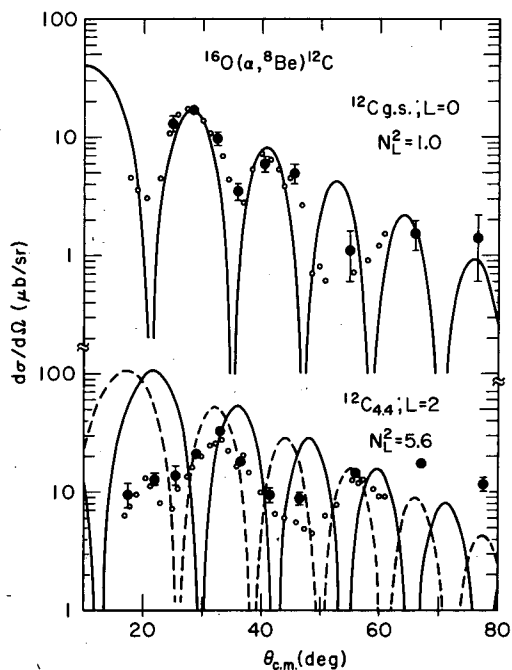| ^{12}C level		Relative spectroscopic factors		
		Theory (20)	$(\alpha, ^8\text{Be})$	$(\alpha, 2\alpha)$ (21)
0+	0 MeV	1.00	1.00	1.00
2+	4.43 MeV	5.56	3.4	0.24

Fig. 11. Angular distributions for $^{16}\text{O}(\alpha, ^8\text{Be})^{12}\text{C}$ at $E_\alpha = 65$ MeV. The solid lines are results of a diffraction calculation.

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In contrast with this work, the reaction $^{16}O(\alpha,2\alpha)^{12}C$ was studied at $E_\alpha = 90$ MeV by Sherman and Hendrie (21). For this and many other targets, the ground state was much more strongly populated than the 2_1+ state, as Figure 12 and Table 1 show, and this result is in apparent disagreement with all available two-body final state reactions. However, the 90 MeV $(\alpha,2\alpha)$ results are in agreement with Kenefick's work at 70 MeV and with a $(p,p\alpha)$ experiment at $E_p = 160$ MeV (22).

It is clear that the knock-out reactions and the pick-up reactions are probing different parts of the bound α-particle momentum distribution. Wozniak (19) pointed out that near the quasi-elastic angle the $(\alpha,2\alpha)$ reaction is sensitive to much smaller recoil momenta than those explored by the small-angle $(\alpha,^8Be)$ reaction.

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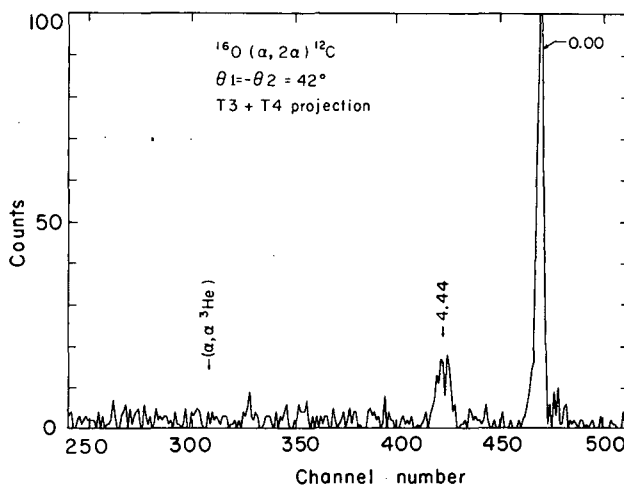
Fig. 12. Energy spectrum (sum of two α's) for $^{16}O(\alpha,2\alpha)^{12}C$ at $E_\alpha = 90$ MeV (lab), showing strong excitation of ^{12}C ground state.

V. MANY-NUCLEON TRANSFERS: It has always been the great hope of heavy ion reaction afficionados that it would be possible to study two-body final states arising from the transfer of very large numbers of nucleons. Such reactions might, for example, make it possible to reach superheavy nuclei, to measure their masses and excited states in a way that is virtually independent of their half-lives. Cross sections of even a tiny fraction of a nanobarn would compete very favorably with those anticipated for the compound nucleus reactions that have so far been used to synthesize elements up to Z = 106. Results so far have not been encouraging, perhaps because the right kinematic conditions have not been explored and because very low background detectors are essential.

It might be expected that the target nucleus will suck in the largest amount of the incident heavy ion when the two bodies remain in contact (i.e. within the range of nuclear forces) for the longest possible time. If this is true, the most favorable kinematic conditions would be achieved just at the Coulomb barrier. If the α-particle were observed at 180°, there would be no angular momentum mismatch.

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We therefore looked for α-particles from the reaction ^{208}Pb(^{20}Ne,α)^{224}Th at E = 99 MeV, i.e. slightly above the Coulomb barrier, using a ^{208}Pb target that was about 7 MeV thick for ^{20}Ne ions. We observed no α's at all in the first 5 MeV of excitation of ^{224}Th under conditions where one event would have corresponded to 70 nb/sr. However, at the observation angle of 110° (lab), the angular momentum mismatch is already about 30$\hbar$ and it would be interesting to repeat the experiment at an angle very near 180°.

Figure 13 shows a spectrum of α-particles from ^{12}C(^{20}Ne,α)^{28}Si at 100 MeV (lab) (23). Preliminary results indicate that the angular distribution is not of the 1/sinθ form that would be expected from the decay of a high spin (~26$\hbar$) compound nucleus. Both at 100 MeV and 93 MeV, several peaks are observed in the spectrum at ^{28}Si energies up to 28 MeV. If these prove to correspond to the ^{12}C + ^{16}O orbiting molecular states observed in heavy ion scattering, the massive transfer reaction will truly have come of age as a tool for the study of nuclear structure.
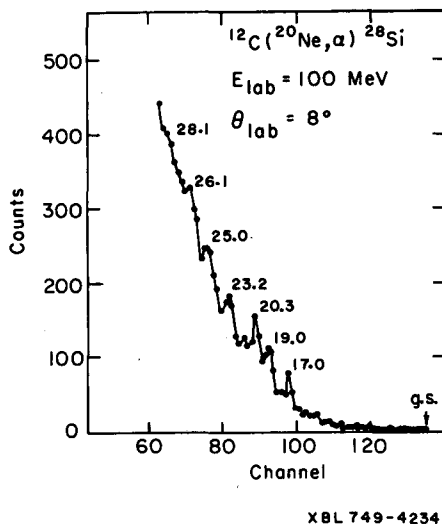

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Fig. 13. α-particle spectrum from ^{12}C(^{20}Ne,α)^{28}Si at 100 MeV (lab) and 8° (lab).

FOOTNOTE AND REFERENCES

1.   M. W. Sachs, C. Chasman and D. A. Bromley, Phys. Rev. 139 B92 (1965); J. Birnbaum, J. C. Overley and D. A. Bromley, Phys. Rev. 157 787 (1967); J. E. Poth, J. C. Overley and D. A. Bromley, Phys. Rev. 164 1295 (1967).

2.   J. C. Faivre, H. Faraggi, J. Gastebois, B. G. Harvey, M. C. Lemaire, J.M. Loiseaux, M. C. Mermaz and A. Papineau, Phys. Rev. Lett. 24 1188 (1970).

3.   D. G. Kovar et al. Phys. Rev. Lett. 30 1075 (1973).

4.   R. M. De Vries, Phys. Rev. C8 951 (1973).

5.   M. A. Nagarajan, Nuc. Phys. A196 32 (1972), A209 485 (1973).

6. R. M. De Vries, M. S. Zisman, J. G. Cramer, K. L. Lin, F. D. Becchetti, B. G. Harvey, H. Homeyer, D. G. Kovar, J. Mahoney and W. von Oertzen, Phys. Rev. Letters 32 680 (1974).

7. R. J. Ascuitto, and N. K. Glendenning, Phys. Lett. B47 332 (1973).

8. B. G. Harvey, D. L. Hendrie, U. Jahnke, L. Kraus, C. F. Maguire, J. Mahoney, D. K. Scott, K. Yagi and N. K. Glendenning, LBL 3415 (1974), to be published.

9. N. K. Glendenning and G. Wolshin, private communication (Mar. 1975).

10. C. F. Maguire, B. G. Harvey, D. L. Hendrie, H. Homeyer, U. Jahnke, J. Mahoney and D. K. Scott, 1974 Ann. Rep. LBL Nuclear Chemistry Division, to be published.

11. K. Yagi, D. L. Hendrie, L. Kraus, C. F. Maguire, J. Mahoney, D. K. Scott, Y. Terrien, T. Udagawa, K. S. Low and T. Tamura, LBL Report 2982 (Dec. 1974), to be published.

12. N. Anyas-Weiss et al., Phys. Reports 12 No.3, 201 (1974).

13. C. C. Lu, M. S. Zisman and B. G. Harvey, Phys. Rev. 186 1086 (1969).

14. D. M. Brink, Phys. Lett. 40B 37 (1972).

15. B. Buck, C. B. Dover and J. P. Vary, preprint Dec. 1974.

16. D. K. Scott, D. L. Hendrie, U. Jahnke, L. Kraus, C. F. Maguire, J. Mahoney, Y. Terrien and K. Yagi, Report LBL 3445 (to be published).

17. D. K. Scott, B. G. Harvey, D. L. Hendrie, L. Kraus, C. F. Maguire, J. Mahoney, Y. Terrien and K. Yagi, Report LBL 2996 (Sept. 1974). Submitted to Phys. Rev. Lett.

18. G. J. Wozniak, N. A. Jelley and J. Cerny, Phys. Rev. Lett. 31 607 (1973).

19. G. J. Wozniak, Ph.D. Thesis, Report LBL 2999, (Aug. 1974).

20. D. Kurath, Phys. Rev. C7 1390 (1973).

21. J. D. Sherman, Ph.D. Thesis, Report LBL 1690 (Mar. 1973). J. D. Sherman and D. L. Hendrie, to be published.

22. B. Gottschalk and S. L. Kannenberg, Phys. Rev. C2 24 (1970).

23. D. K. Scott, D. L. Hendrie, U. Jahnke, L. Kraus, C. F. Maguire, J. Mahoney, Y. Terrien and K. Yagi, unpublished work.