1

TWO AND FOUR NUCLEON TRANSFER REACTIONS INDUCED BY HEAVY IONS

M.-C. Mallet-Lemaire
D.Ph.N.B.E, CEN Saclay, B.P.n°2, 91190 Gif-sur-Yvette (FRANCE)

and

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720 U.S.A.*

ABSTRACT

Two nucleon transfer reactions induced by heavy ions have been particularly successful in pointing out contributions of inelastic two step processes. They provide a way to investigate the overlap between the wave functions of excited states of the target and residual nuclei. However, calculations of absolute cross sections must take into account sequential transfer. The studies of the $(^{16}O,^{12}C)$ reaction on 1s-0d and 0f-1p shell nuclei are reviewed. The relative spectroscopic factors are in good agreement with those of the $(^{6}Li,d)$ and $(^{12}C,^{8}Be)$ reactions, suggesting that this reaction is a good α transfer. However, some puzzling results are still not understood: excitation of unnatural parity states in s-d shell nuclei, the failure of EFR-DWBA calculations in reproducing the angular correlation measurements. Several experimental results showing that the $^{28}Si(^{18}O,^{14}C)^{32}S$ reaction is not a good α transfer will be presented.

INTRODUCTION

Multinucleon transfer reactions are studied to identify the multiparticle-multihole states in nuclei and obtain information on their nuclear structure--by comparing the selectivities of different reactions reaching the same residual nucleus. Such studies performed with light-ion induced reactions were reviewed by Fortune[1] at the Tokyo Conference. In their communication to the present Conference, the Los Alamos group[2] compared the selectivities of the $^{58}Ni(t,p)$ and $^{56}Fe(^{6}Li,d)$ reactions and from the differences found few levels of ^{60}Ni that could possibly correspond to proton excitation with two protons in the 0f5/2-1p shell and two proton holes in the 0f7/2 shell.

The availability of heavy ion beams has strongly increased the number of reactions that can be used to reach the same residual nucleus. Therefore, an enormous amount of experimental and theoretical work has been devoted to the study of heavy ion transfer reactions. To understand the mechanism of these reactions many one nucleon transfer data have been measured and analyzed, establishing the basic features of heavy ion reaction dynamics;[3,4] i) a strong dependence of the cross section on Q value and angular momentum matching conditions, and the evolution of the angular distributions from bell shapes to forward peaked cross sections with increasing incident energies.

*Present address.

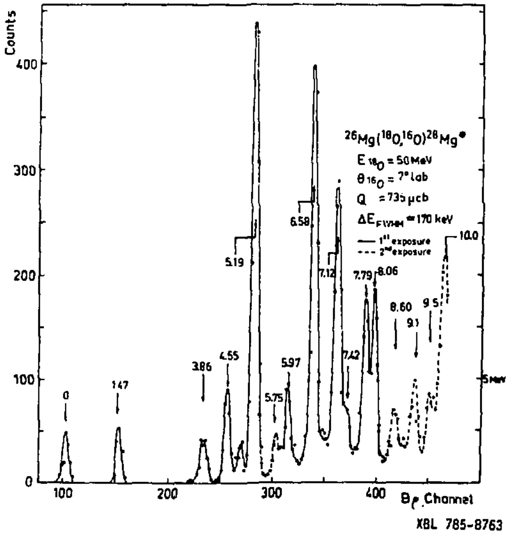
Low[5] discussed the validity of direct reaction theory to describe heavy ion few nucleon transfer reactions at the Caen Conference, showing that most of the features of the single nucleon transfer can be described in the framework of either Distorted Wave Born Approximation (DWBA) or Coupled Channel Born Approximation (CCBA) formalism. Here I discuss the studies of two and four nucleon transfer reactions induced by heavy ions which have been used to probe nuclear structure as well as to investigate the reaction mechanism.

TWO NUCLEON TRANSFER REACTIONS

The heavy ion induced two proton and two neutron transfer reactions have been measured on a large number of target nuclei and on a wide range of incident energies.[6-8] From these data I will discuss three main features: i) the selectivity of these reactions compared to light ion induced reactions, ii) the importance of inelastic two step process, and iii) the comparison of theoretical and experimental absolute cross sections.

HEAVY ION REACTION SELECTIVITY

Comparing the population of ^{28}Mg levels by the (^{18}O,^{16}O) reaction[9] (Fig. 1) and the (t,p) reaction[10] is an example of the relative



XBL 785-8763

Fig. 1. Energy spectrum of the ^{26}Mg(^{18}O,^{16}O)^{28}Mg reaction (Ref. 9).

selectivities of light and heavy ion reactions at tandem energies. In the excitation energy region where such comparison can be achieved (below 6 MeV), their selectivities appear to be very similar. In contrast, the recent study of the $^{26}Mg(\alpha,^{2}He)^{28}Mg$ reaction[11] (Fig. 2) shows a strong selectivity to high spin states ($5^-,6^+$). Such a selectivity to high spin states has also been observed with relatively high energy heavy ion beams (~10 MeV/nucleon) on light target nuclei (0p and 1s-0d nuclei).[12,13]

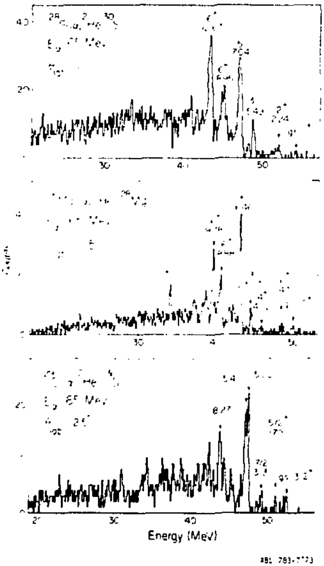


Fig. 2. Energy spectra of the $(\alpha,^{2}He)$ reaction on ^{26}Mg, ^{28}Si and ^{29}Si targets (Ref. 11).

For the light ion induced reactions, like the $(\alpha,^{2}He)$ reaction, the spins of the new states observed in ^{28}Mg have been assigned from the shape of the angular distributions.[11,14] In case of heavy ion induced reactions, the angular distributions are bell shaped at incident energies close to the Coulomb barrier.[9] At higher incident energies they display forward peaking and under favorable kinematic conditions they also display oscillations characteristic of the angular momentum transferred. A nice example of L dependence of heavy ion angular distributions has been reported for ^{50}Ti $0^+,2^+,4^+$ and 6^+ states populated by the $^{48}Ca(^{16}O,^{14}C)$ reaction at 56 MeV incident energy.[15] As the oscillations and L dependence observed in the above example arise from a dominance of the $|m| = L$ magnetic substate contribution for well matched transitions, they are observed only in these specific cases. If transitions are not well matched, the various magnetic substate contributions are equally important. The contributions of odd and even magnetic substates are out of phase, resulting in a strong damping of the oscillations and lack of L dependence.

The angular distributions of the $^{26}Mg(^{18}O,^{16}O)^{28}Mg$ reaction have been measured at 50 MeV incident energy.[9] Those of the ground-state and first 2^+ excited state exhibit strong oscillations with a period of about 7 degrees which is characteristic of the grazing value ($\ell g \simeq 26$). For the states lying at high excitation energy, most angular distributions are like those of the 8.2 and 8.45 MeV states (Fig. 3). They exhibit no structure just a smooth decrease of the

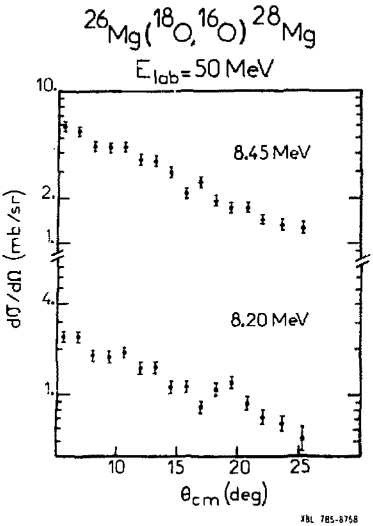


Fig. 3. Angular distributions of the $^{26}Mg(^{18}O,^{16}O)^{28}Mg$ reaction. (Ref. 9).

cross section to backward angles. Such lack of L dependence of the experimental angular distributions does not allow any spin assignment of the populated levels, and is clearly the main disadvantage of heavy-ion induced reactions over light-ion induced reactions.

Two-step Process

Two nucleon transfer reactions induced by heavy ions have demonstrated expecially well the contribution of two step processes where the transfer preceeds or follows inelastic excitation. An important feature of these reactions is that at incident energies not too high above the Coulomb barrier, the angular distribution of a two step transfer is markedly different from that of a one step direct transfer. Many two step contributions have been reported in recent experimental data (see Table I)[7,19-36]

Figure 4 shows the $^{76}Ge(^{16}O,^{18}O)^{74}Ge$ data measured at Brookhaven.[27] In this case, the ground-state angular distribution is bell shaped whereas that of the 2^+ state is forward peaked. These differences have been reproduced with EFR-CCBA calculations[28] using spectroscopic amplitudes determined from BCS-RPA wave functions. The direct contribution to the 2^+ state is completely suppressed by the structure of this state and its cross section comes from purely two step process. In such two step transition the transfer is associated with inelastic excitation produced either by nuclear or Coulomb interaction. As these two contributions have opposite signs, an interference which is always destructive occurs in the region of the grazing angle.

Angular distributions of the $^{74}Ge(^{18}O,^{16}O)^{76}Ge$ two neutron stripping reaction have also been measured (Fig. 5). The angular distribution of the ^{76}Ge ground-state is identical to that of the $^{76}Ge(^{16}O,^{18}O)^{74}Ge$ g-s transition, as expected from time reversed reactions. That of the ^{76}Ge 2^+, state exhibits a steep drop near the grazing angle followed by a plateau between 40° and 55°. The main features of such a peculiar shape are reproduced by a CCBA calculation.

Table I. List of reactions where inelastic two step processes have been pointed out.

Reactions	E_{lab} (MeV)	Ref.
$^{72,74,76}Ge(^{16}O,^{14}C)^{74,76,78}Se$	56	7,16,17,18
$^{64}Ni(^{16}O,^{14}C)^{66}Zn$	56	19
$^{116}Sn,^{16}O,^{14}C)^{118}Te$	64	20
$^{26}Mg(^{16}O,^{14}C)^{28}Si$	45	21
$^{62}Ni(^{12}C,^{10}Be)^{64}Zn$	48	22
$^{100}Mo(^{12}C,^{10}Be)^{102}Ru$	48	19
$^{186}W(^{12}C,^{10}Be)^{188}Os$	70	23
$^{120}Sn(^{18}O,^{16}O)^{122}Sn$	99	24,25
$^{122}Sn(^{16}O,^{18}O)^{120}Sn$	104	24,25,26
$^{74}Ge(^{18}O,^{16}O)^{76}Ge$	75	27,28
$^{76}Ge(^{16}O,^{18}O)^{74}Ge$	77·56	27,28
$^{148}Sm(^{18}O,^{16}O)^{150}Sm$	100	29
$^{150}Sm(^{16}O,^{18}O)^{198}Sm$		
$^{142}Nd(^{18}O,^{16}O)^{144}Nd$	98	30
$^{58,60,62,64}Ni(^{18}O,^{16}O)^{60,62,64,66}Ni$	65	31
$^{60}Ni(^{16}O,^{18}O)^{58}Ni$	73·2	31
$^{26}Mg(^{18}O,^{16}O)^{28}Mg$	50	9
$^{144}Nd(^{12}C,^{14}C)^{142}Nd$	78	32
$^{186}W(^{12}C,^{14}C)^{184}W$	70	33
$^{154}Sm(^{12}C,^{14}C)^{152}Sm$	65	34
$^{182}W(^{12}C,^{14}C)^{180}W$	70	34
$^{124}Te(^{12}C,^{14}C)^{122}Te$	70	35
$^{150}Sm(^{12}C,^{14}C)^{148}Sm$	78	36

By this analysis, it has been established that the ^{76}Ge 2^+, angular distribution results from an interference between the direct and indirect transitions. In addition, the ℓ distribution of the transfer cross section shows that the interference between the direct and indirect routes is respectively destructive or constructive depending on whether the two-step process is occurring via nuclear or Coulomb inelastic excitation.

It should be mentioned that the CCBA angular distributions shown in Figs. 4 and 5 for the two nucleon transfers have been performed using optical model parameters and deformation values which fit the experimental data on ^{18}O and ^{16}O elastic and inelastic scattering. As previously suggested by Glendenning and Wolschin[26] the coupling with the ^{18}O 2^+ state was found to modify significantly the angular distribution of the g-s to g-s transition. Neglecting this transition, the calculated grazing peak was shifted by 4 degrees to backward angles, producing a poorer agreement with the experimental data. The two-step route via the ^{18}O 2^+ state produces an enhancement of the forward angle cross-section, moving the grazing peak in this direction. The importance of the ^{18}O 2^+ coupling was expected in the $^{76}Ge(^{16}O,^{18}O)^{74}Ge$ two neutron pick-up reaction, as the transitions

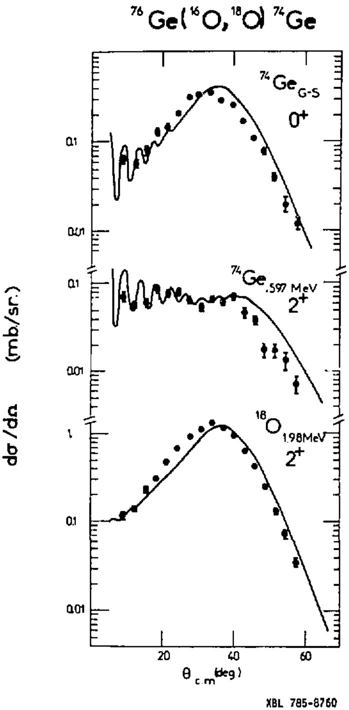


Fig. 4. EFR-CCBA analyses of the ^{76}Ge(^{16}O,^{18}O)^{74}Ge reaction (Ref. 28).

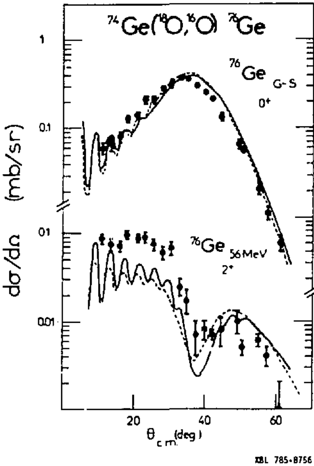


Fig. 5. EFR-CCBA analyses of the ^{74}Ge(^{18}O,^{16}O)^{76}Ge reaction (Ref. 28).

corresponding to the ^{18}O excited in its 2^+ state are favored by a factor of 3.5 compared to those where the ^{18}O is left in its ground-state.

In most of the analyses, only the two step process via the excitation of the first 2^+ excited state of the target and residual nucleus has been included. However, recent study of the ^{150}Sm(^{16}O,^{18}O)^{148}Sm reaction[36] suggests that other two step routes [i.e., $0_g^+(A) \rightarrow 0_2^+(B) \rightarrow 2_1^+(B)$] make extremely important contributions to the 2_1^+ cross sections. This is in agreement with the previous ^{150}Sm(p,t)^{148}Sm data where the $0_g^+ \rightarrow 0_2^+(B)$ cross section is 3 times as large as the $0_g^+ \rightarrow 2_1^+$ cross section. In the case of the ^{76}Ge(^{16}O,^{18}O) reaction discussed previously, recent ^{76}Ge(p,t) results show that all the excited states are much less populated than the g-s and 2_1^+ states.[37]

Other interesting features have been pointed out by Baltz and Kahana[31] in their EFR-CCBA analysis of the ^{58,60,62,64}Ni(^{18}O,^{16}O) and ^{60}Ni(^{16}O,^{18}O) reactions.

• Two step contributions via the ^{18}O excited states 4_1^+, 0_2^+ and 2_2^+ are small.

• Surface transparent potentials are strongly favored to reproduce both the angular distribution shapes and the cross-section magnitudes. Cross sections calculated with strong absorbing potentials are by an order of magnitude smaller than those obtained with surface transparent potentials. In addition to this potential dependence, they noticed that the calculations were sensitive to the choice of parameters used to describe the form factor of the inelastic excitations. To minimize these effects, EFR-CCBA calculations of the transfer data should always be carried out simultaneously with a coupled channel analysis of the elastic and inelastic data.

• The potential dependence of the EFR-CCBA calculation should be energy dependent. At low energy, the reaction should be less sensitive to the absorption due to the Coulomb repulsion. With increasing incident energies more direct channels become open, increasing the surface absorption strength. Therefore, it would be interesting to study from the experimental data such energy dependence of two step processes.

In addition in reproducing the marked shape difference of the angular distribution observed experimentally between different final states, EFR-CCBA calculations reproduce better the relative intensities than DWBA calculations do (Table II).[9,19] However, in their analysis of the $^{116}Sn(^{16}O,^{14}C)^{118}Te$ reaction,[20] Lepine et al. have shown that the importance of coupling effects on the relative populations may strongly depend on the wave functions used.

Table II. Comparison between experimental and theoretical cross-sections calculated with EFR-DWBA and EFR-CCBA formalism.

Reaction	E_{MeV}	$R = \sigma_{exp}/\sigma_{theory}$		
$^{64}Ni(^{16}O,^{14}C)^{66}Zn$ [a]	56	g.s., 0^+	1.04 MeV, 2^+	2.83 MeV, 3^-
DWBA		27	75	224
CCBA		35	35	35
$^{100}Mo(^{12}C,^{10}Be)^{102}Ru$ [a]	48	g.s., 0^+	0.475 MeV, 2^+	2.0 MeV, 3^-
DWBA		47	873	289
CCBA $0^+ - 2^+$, $0^+ - 3^-$		28	28	28
CCBA 0^+, 2^+, 3^-		58	36	20
$^{26}Mg(^{18}O,^{16}O)^{28}Mg$ [b]	50	g.s., 0^+	1.47 MeV, 2^+	
DWBA		10	186	
CCBA		20	13	

a) Ref. 19
b) Ref. 9

It must be emphasized that two step contributions were also seen in (p,t) reactions. In these light ion experiments, however, the direct and indirect angular distributions differ only in the extreme forward region, making the existence of such process more difficult to establish from the data. In contrast, for heavy-ion reactions at properly chosen incident energies, the shape difference is so well marked that an examination of the data is generally sufficient to discriminate between the two reaction mechanisms. Such inelastic two step process offer a unique way to investigate the overlap between the structures of two excited states.

Comparison between Experimental and Theoretical Absolute Cross Sections

A common problem of two nucleon transfer reactions is that the theoretical cross sections generally underestimated the experimental data by one or two orders of magnitude. In dealing with comparison of absolute cross sections, it is necessary to compare the method used for the calculations. For instance, the no recoil approximation overestimates the cross section by a factor of 4 compared to the exact finite range calculations. The cluster EFR-CCBA calculations underpredict the two neutron transfer cross sections by a factor 2.3 for the ^{74}Ge(^{18}O $\leftrightarrow$ ^{16}O) case and a factor of approximately 3 for the Ni(^{18}O $\leftrightarrow$ ^{16}O) reactions. To estimate the importance of microscopic form factors Baltz and Kahana[31] compared the EFR-DWBA cross section of the ^{58,60}Ni(^{18}O,^{16}O)^{60,62}Ni$_{g-s}$ transition calculated with a cluster approximation to the results of Bayman[38] obtained with a microscopic form factor. The agreement in angular distributions between these two calculations is remarkable. The cross section magnitude is overestimated by 30% with the cluster approximation.

Recent work[39-42] has shown that the difficulty of too small cross sections is partly due to the contribution of sequential transfer. Indeed the EFR-DWBA calculations of the ^{48}Ca(^{18}O,^{16}O) reaction performed by the Texas group show that: i) simultaneous transfer cross-sections can be increased by a factor 2 by using extended shell model wave functions and taking into account of the residual interaction between the two nucleons transferred, ii) the contribution of sequential transfer (^{18}O,^{17}O$_{g-s}$)(^{17}O$_{g-s}$,^{16}O) has a cross section as large as that of simultaneous transfer, and iii) the cross sections of sequential and simultaneous transfer add coherently to reproduce the experimental cross sections. Such calculations[42] have been extended to the 3. MeV 2^+ state of ^{50}Ca showing that for all the states the sequential two step cross section is important. For simultaneous transfer, the DWBA cross sections exhibit a shift of the grazing peak towards larger angles with increasing excitation energy of the residual nucleus while the experimental data do not. The inclusion of the sequential two step process seems to remedy this discrepancy.

In the case of the ^{48}Ca(^{16}O,^{14}C)^{50}Ti reaction, it has been found that the sequential two step process has the dominant contribution to the cross section, but the cross sections calculated in this way must still be normalized by a factor 10 to 25 to the experimental cross sections. The angular distributions of sequential and simultaneous transfer are very similar for the $^{48}Ca(^{18}O,^{16}O)$ and $^{48}Ca(^{16}O,^{14}C)$ reactions, but differ for the $^{12}C(^{18}O,^{16}O)^{14}C$ reaction.[41,42] In the calculations of these three cross sections it has also been found that g-s to g-s transitions generally give the dominant contribution to the cross section with the exception of the $^{48}Ca(^{18}O,^{16}O)^{50}Ca$ reaction for which the process via the ^{17}O $1/2^+$ intermediate state is also strong.[42]

FOUR NUCLEON TRANSFER REACTIONS

Four nucleon correlations in nuclei are one of the most interesting aspects of multinucleon transfer reactions. From the spectroscopic factors calculated by Kurath[43] (Table III), it is seen that the lithium-induced reactions are the best processes to study α clustering in nuclei. Indeed, these last years, many interesting results have been collected via the $(^6Li,d)$ and $(^7Li,t)\alpha$ stripping reactions as well as the $(d,^6Li)$ and $(^3He,^7Be)\alpha$ pick-up reactions.[44,45]

Table III. The S_α spectroscopic factors of various 2p-2n transfer reactions (Ref. 43).

Reactions	E_{xc}	L = 0	L = 1	L = 2	L = 4
$(^{16}O,^{12}C)$	0.0	0.23			
$(^{16}O,^{12}C^*_{2^+})$	4.43			1.3	
$(^{12}C,^{8}Be)$	0.0	0.557			
$(^{15}N,^{11}B)$	0.0			0.41	
$(^{14}N,^{10}B)$	0.0			0.012	0.68
$(^{14}N,^{10}B^*_{1^+})$	0.72	0.004		0.125	
$(^{10}B,^{6}Li)$	0.0	0		0	0.0027
$(^{6}Li,d)$	0.0	1.125			
$(^{7}Li,t)$	0.0		1.191		

The availability of heavy ion beams allowing investigation of the 2p-2n transfer reactions from a wide variety of projectiles, has stimulated interest in studying four nucleon correlations in nuclei. The $(^{16}O,^{12}C)$ transfer has received the largest interest. This reaction was first systematically studied at Saclay, on fp shell target nuclei.[46] The corresponding spectra clearly displayed a strong selectivity to states lying in an excitation energy region where the number of levels is known to be high. However, at that time the counter telescope technique used to detect the ^{12}C led to energy spectra with rather poor energy resolution ($\approx$ 250 keV), and the low counting rate prevented systematic measurement of the angular distributions. Presently, the magnetic spectrometer allows measurement of energy spectra with an energy resolution of about 60-100 keV--similar to that used in studies of the $(^6Li,d)$ reactions, so that individual levels of the two reactions can be compared. Furthermore, the solid angle of these spectrometers makes it possible to measure the angular distributions of the individual levels for a quantitative analysis.

Whether the four nucleons transferred in the (^{16}O,^{12}C) reaction behave like an α particle has been much discussed[47,48] as the (^{16}O,^{12}C) α spectroscopic factor is rather small. However, shell model calculations performed by Kurath and Towner[49] show that at the nuclear surface the contribution of 0s relative motion should dominate, while all the other components of relative motion should have small contributions. As it is now well established that heavy-ion induced reactions occur at the nuclear surface, one can expect that the (^{16}O,^{12}C) reaction will behave like a good α transfer. To check this hypothesis several experiments have been carried out to compare the (^{16}O,^{12}C) and the (^{6}Li,d) reactions. I will review the results obtained with the (^{16}O,^{12}C) reaction on (1s-0d) and (1p-0f) target nuclei and how they do compare with the (^{6}Li,d) data.

Some experiments have also compared 2p-2n transfer reactions induced by different projectiles on the same target nucleus. The purpose of such studies is to determine if the heavy-ion induced reactions can be described in terms of "α transfer" and used as an alternative to the lithium-induced reactions.

The (^{12}C,^{8}Be) reaction has a larger α spectroscopic factor than the (^{16}O,^{12}C) reaction. However, its use is still very recent due to the fact that ^{8}Be is unstable and has to be detected as two correlated α particles. Another, disavantage of this reaction is its poor energy resolution (180-300 keV) so that generally the angular distribution measurements have been limited to the g-s and 1st excited state. The spectroscopic factors extracted from these data will be compared to those obtained from the (^{16}O,^{12}C) and (^{6}Li,d) data.

Studies of the other 2p-2n heavy-ion induced reactions, such as (^{13}C,^{9}Be), (^{14}N,^{10}B), (^{18}O,^{14}C), and (^{20}Ne,^{16}O), have been restricted to the measurement of a few energy spectra. I will discuss the comparison of the ^{28}Si(^{16}O,^{12}C) and ^{28}Si(^{18}O,^{14}C) reactions at 60 MeV incident energy for which angular distributions to individual levels have been measured, so that quantitative comparison can be achieved.

Selectivity of the (^{16}O,^{12}C) Reaction

An energy spectrum of the ^{58}Ni(^{16}O,^{12}C)^{62}Zn reaction measured at 60 MeV incident energy[50] with the Saclay QDDD is shown in Fig. 6. The 60 keV energy resolution allowed identification of 13 levels between 3.19 and 6.30 MeV excitation energies. In the region below 4.5 MeV excitation energy, where both the (^{16}O,^{12}C) and (^{6}Li,d) reactions excite well separated transitions, the selectivity of these two reactions to individual transitions appears to be very similar. Such similarities have also been observed by comparing these two reactions on ^{40}Ca,[51] ^{24}Mg [52] and ^{28}Si,[52,53] and for other 0f-1p shell target-nuclei.[2]

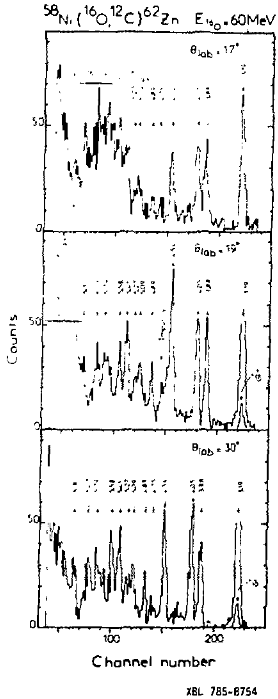


Fig. 6. Energy spectrum of the $^{58}Ni(^{16}O,^{12}C)^{62}Zn$ reaction (Ref. 50).

The measurement of the angular distributions of individuals levels of ^{62}Zn populated by the $(^{16}O,^{12}C)$ reaction has been performed at two incident energies 46 and 60 MeV. At the lowest energy they are bell shaped with a maximum moving from 65° c.m. for the ground state to 75° c.m. for the 3^- state. Such a move of the grazing angle to backward angles for increasing excitation energy is expected for a direct transfer. At 60 MeV incident energy, these angular distributions are forward peaked (Fig. 7). The ground state and 2_1^+ state display oscillations with a 6° c.m. period, while the 3^- state has no structure at all.

EFR-DWBA Analysis of the $(^{16}O,^{12}C)$ Reactions

The DWBA angular distributions of the $(^{16}O,^{12}C)$ reaction are generally analyzed with the EFR-DWBA codes such as SATURN-MARS of K. S. Low and T. Tamura or LOLA of R. DeVries. With the two assumptions of a os relative motion (n=0, l=0) between the transferred particles and a single N value for the description of the center of mass motion, the cross section can be factorized as follows:

$$\frac{d\sigma}{d\Omega}(\theta) = N S_\alpha^{ab} S_\alpha^{BA} \left[\frac{d\sigma}{d\Omega}(\theta)\right]_{DWBA}$$

where S_α^{ab} and S_α^{BA} are respectively the spectroscopic factors relative to the light system (a-b) and to the heavy system (B-A). The normalization factor N has been introduced to take into account that for heavy ion reactions the DWBA calculations are generally unable to reproduce absolute cross sections. Because of this normalization problem, only relative spectroscopic factors can be extracted from comparison of experimental and DWBA cross sections. If in addition the

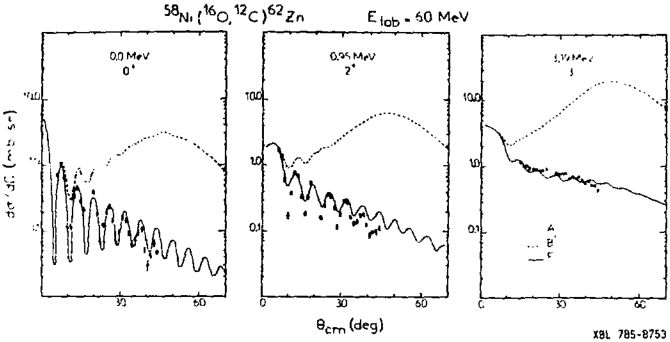


Fig. 7. EFR-DWBA analysis of the $^{58}Ni(^{16}O,^{12}C)^{62}Zn$ reaction. The optical potential set F is a surface transparent type potential (Ref. 50).

spectroscopic factors are known from shell model calculations, one can determine how far the normalization factor N is from the ideal value of 1. The two main uncertainties encountered in the DWBA analysis are: the choice of the optical model parameters, and the choice of the parameters used to calculate the bound-state wave functions.

Despite the efforts of both theorists and experimentalists to determine an optical potential describing heavy ion interaction, the characteristics of such a potential are not yet well established. This is due to the fact that at low incident energies, the elastic scattering data are only sensitive to the extreme tail of the potential. Consequently, many ambiguities have been found between families of optical model parameters able to reproduce the experimental elastic scattering angular distributions; potentials with very different geometries and absorptive properties have been obtained.

Previous studies of multinucleon transfer reactions[7,31] have already pointed out that the transfer differential cross-section shapes are very sensitive to the absorption at the nuclear surface. A coherent description of these reactions and of the elastic scattering strongly favors the use of surface transparent potentials.

DWBA analysis of the $^{58}Ni(^{16}O,^{12}C)^{62}Zn$ reaction has been performed at 46 and 60 MeV incident energies. The ^{16}O optical potentials used have been determined by fitting the elastic scattering data at each of these energies. Since no optical model parameters were available for the exit channel, the same parameters were used in the exit and entrance channels. At 60 MeV incident energy only the surface transparent potential (Fig. 7) provides a fairly good fit to the experimental data, while all the others produce bell shape angular distributions. At 46 MeV incident energy, such surface transparent potential, as well as the others, failed to reproduce the experimental data.

As pointed out by Glendenning[54] such a systematic discrepency between DWBA and experimental cross sections is difficult to understand in terms of two step process via inelastic excitations of the target or residual nucleus. Indeed as has been seen in the analysis of the two-nucleon transfer data, the importance of such two step processes depends on the strength of the inelastic excitations of the intermediate states as well as on the parentage amplitudes involved in the direct and two step processes. The relative strengths and phases of the parentage amplitudes are not expected to be similar for different final states. Therefore such coupling to low lying collective states will not lead to a systematic effect. A possible explanation[55] of the failure of DWBA calculations at low energies is that the weakly bound state wave function is modified by the field of the approaching nucleus. Such polarization effect, calculated for one nucleon transfer reaction in the two center shell model, allows the transfer to take place at larger impact parameters and shifts the distribution to smaller angles. Whether, during the time of a typical reaction, the shell model states undergo an adiabatic polarization depends on the ratio of the transition time to the nuclear period, so that the effect should decrease with incident energy.

Figures 8 and 9 show that the angular distributions[53] of the $^{28}Si(^{16}O,^{12}C)^{32}S$ reaction measured at 60 MeV incident energy are fairly well reproduced with a surface transparent potential. These transfer data are a good challenge to all the potentials which have been recently proposed to describe the $^{16}O + ^{28}Si$ elastic scattering. The potential E-18 determined by Cramer et al[56] in their analysis of the elastic scattering data on a wide range of incident energies (33-215.2 MeV) failed to reproduce the transfer data. The weakly absorbing potential determined by Schkolnik et al.[57] also failed; the one proposed by Auerbach et al.,[58] readjusted to fit the 60 MeV elastic scattering data, provides fits equivalent to those shown in Fig. 8.

For all the L=2 transitions, the DWBA calculations exhibit oscillations whose amplitude is too small compared to the experimental data. This is understandable in terms of misrepresentation of the cross-section contribution for a particular m-substate. Each magnetic substate makes a significant contribution to the final cross section. The strong oscillations have different phase for each magnetic substate, and this results in a final angular distribution that is not strongly oscillatory. Since the DWBA cross sections vary rapidly with small changes in bound-state radii, the spectroscopic factor product $S_{\alpha}^{ab}\ S_{\alpha}^{AB}$ cannot be entirely determined unless the bound-state parameters are very well known.

DeVries[50] has shown that for transfer reactions induced by heavy ions at incident energies close to the Coulomb

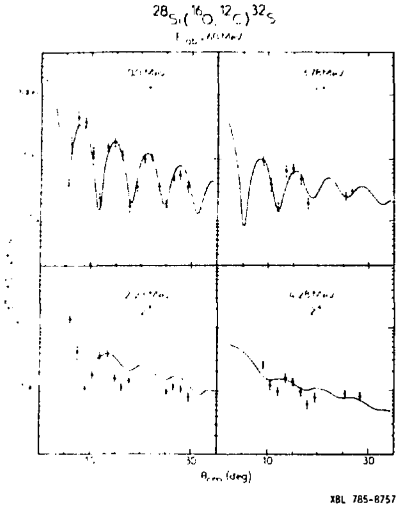


Fig. 8. EFR-DWBA analysis of the $^{28}Si(^{16}O,^{12}C)^{32}S$ reaction (Ref. 53).

barrier, the Coulomb term in the interaction potential is important. The DWBA cross sections are strongly affected by the introduction of such Coulomb interaction, but neither the shapes nor the relative spectroscopic factors are sensitive to this effect.

Therefore, one should not rely heavily upon comparison of absolute values of spectroscopic factors as long as the DWBA cross sections have not been calculated in a consistent way. However, since the relative cross sections vary little with changes in bound-state parameters or optical model parameters, the relative spectroscopic factors can be reliably extracted and compared between different reactions.

Spectroscopic factors

The spectroscopic factors relative to the ground state are listed in Table IV, for better comparison with the results obtained in the analysis of other transfer data. These spectroscopic factors are generally in good agreement with those derived from the $(^6Li,d)$ reactions[48,52,60,61] with two main exceptions the 2_1^+ state in ^{44}Ti, and the 5.01 MeV 3^- state of ^{32}S. In the latter case, spectroscopic factors have not been extracted from the $(^6Li,d)$ data. The values $\sigma_{rel}/(2\ell+1)$ have been listed where σ_{rel} is the relative magnitude of the peak in the $(^6Li,d)$ cross-section to a particular state. In such comparisons between spectroscopic factor values, one should be careful about the quality of the DWBA fits. For the starred cases quoted in Table IV, the spectroscopic factors have been extracted with poor DWBA fits, so that their meaning is highly questionable.

Data about the $(^{12}C,^8Be)$ reactions generally have been limited to the ground state and 2^+ first excited state,[62,63] for which agreement with the $(^6Li,d)$ and $(^{16}O,^{12}C)$ results is generally good. For ^{44}Ti the situation is confusing, as different data lead to different results.

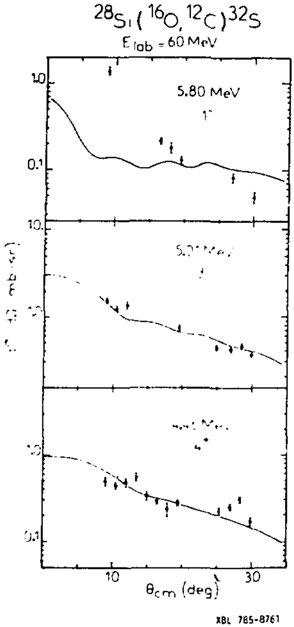


Fig. 9. EFR-DWBA analysis of the $^{28}Si(^{16}O,^{12}C)^{32}S$ reaction (Ref. 53).

Shell model calculations[64] of $^{62}Zn_{g-s}$ and ^{62}Zn $2^+{}_1$ spectroscopic factors have been performed assuming these states described with a $(2p3/2)^4$ configuration around a ^{58}Ni core. The ratio $S_\alpha(^{62}Zn\ 2^+{}_1)/S_\alpha(^{62}Zn_{g-s})$ predicted by these calculations is .55, in agreement with the 0.40 value derived from the DWBA analysis of the experimental data. The products $N\ S_\alpha{}^{(A-B)}\ S_\alpha{}^{(b-a)}$ have been determined by comparing the experimental to the DWBA cross sections. They are quoted in parentheses in Table IV for the g-s transitions. These values correspond to the use of the following bound-state parameters: $R = 1.25\ A_c{}^{1/3}$ fm and $a = 0.65$ fm in the DWBA calculations. Using the theoretical spectroscopic factors S_α from Bennett[64] for the (^{58}Ni - ^{62}Zn) system and Kurath[49] for the (^{16}O - ^{12}C) system, a normalization factor of 5 is obtained for the $^{58}Ni(^{16}O,^{12}C_{g-s})^{62}Zn_{g-s}$ transition at 60 MeV incident energy.

<u>Puzzling experimental results observed in various studies of the ($^{16}O,^{12}C$)</u>

• <u>Excitation of unnatural parity states:</u> The study of the $^{24}Mg(^{16}O,^{12}C)^{28}Si$ and $^{28}Si(^{16}O,^{12}C)^{32}S$ reaction[52] has clearly pointed out the population of unnatural parity states. Such transitions are forbidden in a pure direct α transfer on a 0^+ target. The excitation of such levels with significant cross section implies either than the four nucleons are transferred in a relative motion different from Os[(Op) for instance] or multistep contributions via the inelastic excitation of either the target or the residual nucleus.

• <u>Polarization of ^{20}Ne in the $^{16}O(^{16}O,^{12}C)$ reaction.</u>[65] A recent study of the $^{16}O(^{16}O,^{12}C)^{20}Ne$ reaction performed at Orsay[65] shows i) the angular distributions are accurately described by EFR-DWBA calculations assuming an α transfer, and ii) the relative spectroscopic values of the g-s rotational band are close to 1 as expected from the theoretical values calculated with SU3 wavefunctions for ^{20}Ne. The ^{12}C-^{16}O angular correlations of the sequential reaction $^{16}O(^{16}O,^{12}C)^{20}Ne^* \rightarrow \alpha + {}^{16}O$ have been measured both in the reaction plane and in a plane perpendicular to it for several excited states.

Table IV Comparison of relative spectroscopic factors for different 2p-2n reactions.

			(^{16}O,^{12}C)					(^{6}Li,d)		(^{12}C,^{8}Be)		(^{18}O,^{14}C)
Residual nucleus	E_{xc}	J^π	46 MeV[a]	60 MeV[a]				28 MeV[f]		55 MeV[h]		
^{62}Zn	0.0	0^+	1(.0085)	1(.015)				1	1	1		
	0.95	2^+	.42	.40				.36	.29	.35		
	3.19	3^-	.36	.55				.39	.37			
			36 MeV[h]	42 MeV[h]	48 MeV[h]	53 MeV[h]	60 MeV[c]	$\frac{c_{rel}}{2J+1}$	b		c	60 MeV[c]
^{32}S	0.0	0^+	1(5.2)	1(2.1)	1(1.1)	1(.75)	1(7.8)	1		1		1(1.17)
	2.24	2^+	.42	.50	.51	.46	.36	.56		.30		.47
	3.78	0^+		.75			.51	.67				-
	4.28	2^+		.065*			.14	-				.01
	4.46	4^+		.16*			.22	.27				.02
	5.01	3^-		.33	.34	.35	.38	.91		.14*		.20
	5.8	1^-		(1.5*)	1.73			2.36				.09*
			36 MeV[h]	42 MeV[h]	48 MeV[b]	56 MeV[h]	56 MeV[d]	$\frac{c_{rel}}{2J+1}$[b]	S	65 MeV[h]		
^{28}Si	0.0	0^+	1(4.9)	1(1.72)	1(1.)	1(1.06)	1.(1.2)	1	1	1		
	1.78	2^+	.20	.20	.20	.22	.26	.22	.21	.19		
	4.43	2^+		4.6	6.4	6.1	5.33					
	4.98	0^+		.52	.53			.89	.7			
	6.69	0^+			1.76			1.1	1			
	7.91	2^+			.14							
			42 MeV[e]					36 MeV[e]		45 MeV[i]	56 MeV[h]	
^{44}Ti	0.0	0^+	1					1		1	1*	
	1.08	2^+	.83					.32		.78	.22*	
	2.6	4^+	-									
	3.34	4^+	.15					.22		.55*		

Notes. The data quoted with a star correspond to poor DWBA fits. The absolute spectroscopic factors of the g-s transition are quoted in parentheses when known.

a) Ref. 50 d) Ref. J. R. Erskine et al., Phys Rev. Lett 34 (1975) 680. g) Ref. 61
b) Ref. 52 e) Ref. 48 h) Ref. 62
c) Ref. 53 f) Ref. 60 i) Ref. 63

The population of various magnetic substates $|P_j^m|^2$ on a quantization axis perpendicular to the reaction plane has been extracted from the data with a least square method. This clearly establishes a strong polarization of the ^{20}Ne* on an axis perpendicular to the reaction plane (Fig. 10), since the population for m=j is by far the largest. The EFR-DWBA calculations cannot reproduce the experimental angular correlations.

Comparison of the ^{28}Si(^{18}O,^{14}C) and ^{28}Si(^{16}O,^{12}C) reactions

The energy spectrum (Fig. 11) of the ^{28}Si(^{18}O,^{14}C) reaction[53] clearly show the excitation of the ^{32}S T=1 state lying at 7.12 MeV excitation energy. Such ΔT=1 transition is forbidden in a pure α transfer.

The experimental angular distributions of the low lying states could be fitted with EFR-DWBA calculations only with optical model parameters modified from those determined by an optical model

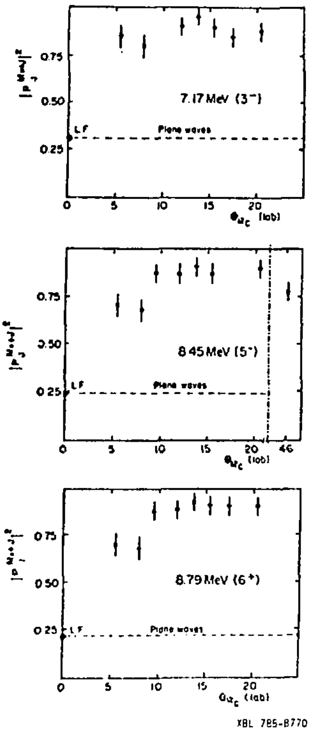


Fig. 10. Angular distribution for the population of the m=j magnetic substate of ^{20}Ne states populated in the $^{16}O(^{16}O,^{12}C)^{20}Ne \rightarrow \alpha + ^{16}O$ sequential reaction (Ref. 65).

analysis of the entrance channel elastic scattering data. This difference with the $^{28}Si(^{16}O,^{12}C)$ reaction measured at the same incident energy is not understood. Therefore, the goal of the experiment to determine the ratio of spectroscopic factors $S_{\alpha}(^{18}O,^{14}C)/S_{\alpha}(^{16}O,^{12}C)$ could not be achieved. The relative spectroscopic factors of the 4.28 MeV 2^+ state and 4.46 MeV 4^+ states are 10 times smaller than those obtained with the $(^{16}O,^{12}C)$ data.

CONCLUSION

The study of two nucleon transfer reactions induced by heavy ions has pointed out important contributions of two step processes where the transfer is proceeding via target and residual nucleus inelastic excitation. At incident energies not too high above the Coulomb barrier, such processes produce clear shape changes between different final state angular distributions. At higher incident energy, the angular distributions are forward peaked and display oscillations for both mechanisms. Nevertheless the failure of DWBA theory in reproducing the cross section of different final states with the same normalization factor is partly removed by using EFR-CCBA formalism. Such inelastic two step processes provide a unique way of testing the overlap between the wave functions of excited states of target and residual nuclei. However to reproduce the absolute values of the experimental cross sections, sequential transfer has to be taken into account together with simultaneous transfer.

Most of the experimental data relative to the $(^{16}O,^{12}C)$ reaction suggest that this 2p-2n transfer is proceeding via the transfer of an α particle as well as the $(^{6}Li,d)$ reaction. Further investigation of the few cases where deviations have been observed should be done. As

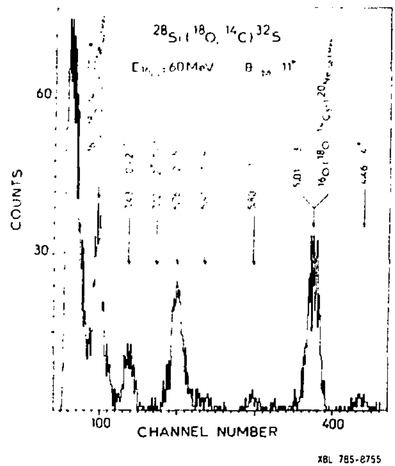


Fig. 11. Energy spectrum of the $^{28}Si(^{18}O,^{14}C)^{32}S$ reaction (Ref. 53).

excitation of unnatural parity states has been observed only in the case of light-deformed target or residual nuclei, it can be connected to inelastic two step contributions. It should be noticed that such excitation of unnatural parity states has also been observed in the studies of the $(^{6}Li,d)$ reaction on 1s-0d shell target nuclei.

Heavy ion projectiles cannot compete with light ion induced reactions as far as the L dependence of the angular distributions is concerned. In addition, much experimental work remains to be done before completely understand the reaction mechanism. For example, resonance like structures were recently discovered in the excitation function of the $^{24}Mg(^{16}O,^{12}C)^{28}Si$[66] reaction at the incident energies: 47, 52 and 57 MeV in a region where the reaction was assumed to be purely direct.

There have been speculations about the possibility of observing enhanced multi pair transfers between two superfluid nuclei.[67] Search for such a nuclear Josephson effect is a particularly interesting field which can only be achieved with heavy ion projectiles. To get a realistic estimate of the cross section of multi pair transfer reactions, it is important to include in the calculations all the informations derived from the studies of heavy ion two nucleon transfer reactions.

ACKNOWLEDGMENTS

I would like to thank Mrs Faraggi for fruitful discussions during the writing of these notes. My particular thanks go to my collaborators: G. Berg, B. Berthier, J. Gastebois, J. Fouan and J. P. Le Fèvre at Saclay and M. Bernas, F. Pougheon, P. Roussel, M. Stephan, M. Langevin and G. Rotbard at Orsay. I would also like to thank the other groups who gave me their data prior to publication and from whom I took many ideas: R. de Meyer et al., F. Pougheon et al. and M. C. Mermaz et al.

This work was supported by the Nuclear Physics Division of the Department of Energy.

REFERENCES

1. T. Fortune, Proceedings of the International Conference on Nuclear Structure, Tokyo, September 5-10, 1972.
2. D. L. Hanson, N. Stein, J. W. Sunier and C. W. Woods; Contribution to this Conference, Phys. Rev. Lett. 38, 587 (1977).
3. D. G. Kovar, Proceedings of Conference on Reactions between Complex Nuclei, Nashville, vol. 2, 235 (1974).
4. A. J. Baltz, Symposium on Macroscopic features on Heavy Ion Collisions, Argonne, Illinois, vol. 1, 65 (April 1976).
5. K. S. Low, European Conference on Nuclear Physics with Heavy Ions, Caen, p.75 (1976).
6. Previous reviews of these data can be found in the following conference proceedings; reactions induced by heavy ions, ed. By R. Bock and W. R. Herring (North-Holland, Amsterdam 1970); Symposium on heavy in reactions and many particle excitations (Saclay, 1971) J. Phys. 32 (1971) C5; ORNL Heavy ion summer study (Oak Ridge, 1972); Symposium on heavy ion transfer reactions (Argonne, March 1973); International conference on nuclear physics (Munich, 1973); Reaction between complex nuclei, ed. by R. L. Robinson, F. K. McGowan, J. B. Ball, J. M Hamilton (North-Holland, Nashville 1974) 235.
7. M. C. Lemaire et al., Phys. Rev. C10, 1103 (1974).
8. M. Conjeaud et al., Nucl. Phys. A250, 182 (1975).
9. M. Bernas et al., Contribution to the Fourth EPS Nuclear Physics Division Conference, Florence (1977); Contribution to the International Conference on Nuclear Structure Tokyo (1977).
10. R. Middleton and J. Pullen, Nucl. Phys. 51, 77 (1964).
11. R. Jahn et al., Contribution to this Conference, submitted to Phys. Rev. C.
12. N. Anyas-Weiss et al., Phys. Reports C12, 202 (1974).
13. K. Nagatani, Proceedings of the 4th EPS Nuclear Physics Division Conference, Florence (1977); Phys. Rev. C17, 586 (1978).
14. R. J. de Meijer et al., Phys. Rev. C16, 2442 (1977).
15. Y. Eisen et al., Phys. Rev. C13, 699 (1976).
16. M. E. Cobern et al., Phys. Rev. C13, 1200 (1976).
17. T. Tamura et al., Phys. Lett. 51B, 116 (1974).
18. T. Udagawa et al., Phys. Lett. 57B, 135 (1975).
19. M. C. Mermaz et al., Phys. Rev. C15, 307 (1977).
20. A. Lepine et al., Nucl. Phys. A289, 187 (1977).
21. B. Sorensen, Phys. Lett. 32, 71 (1974).
22. A. Greiner, thesis, Orsay (1976).
23. R. J. Ascuitto et al., Phys. Lett. 55B, 289 (1975).
24. D. K. Scott et al., Phys. Rev. Lett. 34, 895 (1975).
25. R. S. Ascuitto et al., Phys. Lett. 47B, 332 (1973).
26. N. K. Glendenning and G. Wolschin, Phys. Rev. Lett. 34, 1642 (1975).

27. P. D. Bond et al., Phys. Rev. C16, 177 (1977).
28. M.-C. Lemaire and K. S. Low, Phys. Rev. C16, 183 (1977).
29. B. Sorensen, Phys. Lett. 66B, 119 (1977).
30. K. Yagi et al., preprint.
31. A. J. Baltz and S. Kahana; Phys. Rev. C17, 555 (1978).
32. K. Yagi et al., Phys. Rev. Lett. 34, 96 (1975).
33. K. A. Erb et al., Phys. Rev. Lett. 33, 1102 (1974).
34. D. L. Hanson et al., Nucl. Phys. A269, 520 (1976).
35. R. J. Ascuitto et al., Nucl. Phys. A273, 230 (1976).
36. C. F. Maguire et al., Phys. Rev. Lett. 40, 358 (1978).
37. D. Ardouin et al., Rapport interne (SNN-780).
38. B. F. Bayman, Phys. Rev. Lett. 32, 71 (1974).
39. T. Kammuri et al., Contribution to the INS-IPCR Symposium on Cluster Structure of Nuclei and Transfer Reactions Induced by Heavy Ions, Tokyo (1975) 560, Phys. Lett. 51B, 442 (1974).
40. N. Ichimura, Contribution to the INS-IPCR Symposium on Cluster Structure of Nuclei and Transfer Reactions Induced by Heavy Ions. Tokyo (1975) 547.
41. D. H. Feng, et al., Phys. Rev. C14, 1484 (1976); Nucl. Phys. A274, 262 (1976).
42. T. Takemasa and H. Yoshida, to be published.
43. D. Kurath, Phys. Rev. C7, 1390 (1973).
44. K. Bethge, Ann. Rev. Nucl. Science 20, 255 (1970).
45. Y. Strohbush, Proceeding of the INS-IPCR Symposium on Cluster Structure of Nuclei and Transfer Reactions Induced by Heavy Ions, Tokyo (1975), 506.
46. H. Faraggi et al., Phys. Rev. C4, 1375 (1971); Ann. Phys. (N.Y.) 66, 1375 (1971); Phys. Rev. Lett. 24, 1188 (1970).
47. D. Robson, Comments on Nucl. Part. Phys. 5, 16 (1972).
48. R. M. DeVries, Phys. Rev. Lett. 30, 666 (1973).
49. D. Kurath and I. Towner, Nucl. Phys. 222, 1 (1974).
50. G. P. A. Berg et al., submitted to Physical Review C.
51. J. R. Erskine et al., Phys. Lett. 47B, 335 (1973).
52. J. C. Peng et al., Nucl. Phys. A264, 312 (1976).
53. G. P. A. Berg et al., to be published.
54. N. K. Glendenning, private communication.
55. G. Delic et al., Phys. Lett. 69B, 20 (1977).
56. J. G. Cramer et al., Phys. Rev. C14, 2158 (1976).
57. V. Shkolnik et al., Proc. on Macroscopic Features of Heavy Ion Collisions Argonne, vol. II (1976) 761.
58. E. H. Auerbach et al., Symposium on Heavy Ion Elastic Scattering Rochester, N.Y., October 1977.
59 R. H. DeVries, Phys. Rev. C11, 2105 (1975).
60. H. W. Fulbright et al., Nucl. Phys. A284, 329 (1977).
61. J. P. Draayer et al., Phys. Lett. 53B, 250 (1974).
62. E. Mathiak et al., Nucl. Phys. A259, 129 (1976).
63. G. R. Morgan and N. R. Fletcher, Phys. Rev. C16, 167 (1977).
64. C. L. Bennett, Nucl. Phys. A284, 301 (1977).
65. F. Pougheon et al., Proceedings of the Florence Conference (1977) p.52-53; J. Phys. (Paris) Lett. 21, 417 (1977).
66. M. Paul et al., Phys. Rev. Lett. 40,1310 (1978).
67. R. A. Broglia et al., Phys. Lett. 73B, 401 (1978).