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SEMICLASSICAL ASPECTS OF TRANSFER REACTIONS

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1. INTRODUCTION

The study of transfer reactions, in particular those induced by heavy ions, has profitted a great deal from semiclassical (or semi-quantal) analysis for both guidance and understanding. In this talk I will deal almost exclusively with reactions induced by heavy ions although many of the arguments can be applied to light-ion induced reactions as well. Furthermore, since reactions where large amounts of energy are lost will be discussed in other talks, I will confine myself to the so called quasielastic region, which about 10 years ago was envisaged as one of great simplicity. Subsequently, major experimental and theoretical advances have pointed out difficulties in understanding detailed aspects of certain reactions. Although important to understand, these relatively small number of problems have tended to overshadow the special role these reactions can play and the remarkable degree to which semiclassical models explain observed behavior. In the following I hope to show some of the unique aspects of these reactions, to demonstrate the variety of features which can be understood semiclassically, and to indicate where some open problems exist.

2. GENERAL SEMICLASSICAL ASPECTS

Collisions of high-energy heavy ions are characterized by large values of relative angular momenta and small de Broglie wavelengths. These features and the fairly large number of partial waves which contribute to transfer are ingredients which make discussion of trajectories and semiclassical approximations (use of asymptotic expressions and replacement of sums by integrals) valid and full quantum mechanical calculations tedious. Despite the enormous advance in computational techniques which now allow thousands of partial waves to be included in complete distorted wave calculations, the semiclassical results often provide better insight into observed physical processes. (I emphasize semi because in too many cases classical arguments have been used which have led to incorrect interpretations.) In the following, however, calculations with DWBA or coupled-channel codes will be compared to data, although I will not discuss details of these codes.

Two heavy ions which approach each other with a large impact parameter undergo only elastic scattering and Coulomb excitation since the nuclear force does not extend far enough to allow for significant transfer. Small impact parameters lead to compound nucleus formation and to large energy-loss collisions, thus it is the trajectories where the nuclear surfaces are near touching that will lead to simple transfer reactions (and nuclear inelastic scattering). This assumption leads to the conclusion that the partial waves involved in these reactions should be localized around that corresponding to the grazing trajectory.

In the mid 1960's, before large computer codes existed, semiclassical expressions for the cross section for angular momentum transfers L=0 were derived[1] under this assumption of localization around the grazing partial wave. While some important features could be shown, a great deal of the subtlety of L>0 transfer was lost. More recently these expressions have been generalized to allow for non-zero angular momentum transfers[2] (with projection M on the reaction normal). For the reaction a+A → b+B with Ja=Jb=JA=0 and JB=L the transition amplitude is

$$\alpha_L^M(\theta) \propto [\sin(\theta)]^{-\frac{1}{2}} \cdot$$

$$\{\exp[-\Gamma^2(\theta-\psi)^2/8]\exp[-i(l_0+1/2)\theta+i\pi/4]\exp[-((\Delta_0+M)/\gamma)^2]\cdot Y_L^M(\pi/2,\ (\pi-\theta)/2)+ \\ \exp[-\Gamma^2(\theta+\psi)^2/8]\exp[-i(l_0+1/2)\theta-i\pi/4]\exp[-((\Delta_0-M)/\gamma)^2]\cdot Y_L^M(\pi/2,\ (3\pi-\theta)/2)\} \tag{1}$$

and the cross section for angles $\theta > L/l_0$ is

$$d\sigma/d\Omega \propto [\sin(\theta)]^{-1}\cdot\sum_M |Y_L^M(\pi/2)|^2 \cdot$$

$$\{\exp[-(\gamma(\theta-\psi)/2)^2]\exp[-2(\Delta_0+M)^2/\gamma^2] + \exp[-(\gamma(\theta+\psi)/2)^2]\exp[-2(\Delta_0-M)^2/\gamma^2] + \\ 2(-1)^M\cdot\exp[-\gamma^2(\theta^2+\psi^2)/4]\exp[-2(\Delta_0{}^2+M^2)/\gamma^2]\cdot\sin[(2l_0+1)\theta+M\Delta\psi/2]\} \tag{2}$$

In both expressions Δ_0 *is the difference between the grazing partial waves in* the entrance (l_0^i) and exit channels (l_0^f), l_0 their average, ψ the grazing angle and Γ the number of partial wave contributing to transfer. The parameter γ depends upon the particle binding and is tied roughly to other parameters by $\Gamma \sim \frac{l_0}{\gamma}$. Because of the large charge of nuclei, the Coulomb force plays a major role and for trajectories dominated by this force the grazing partial wave is given by $l_0 = kR(1-2\,\eta/kR)^{\frac{1}{2}}$ and the grazing angle is $\psi = \tan^{-1} \eta_i/l_0^i + \tan^{-1} \eta_f/l_0^f$ where η is the Sommerfeld parameter. The expression for the cross section at small angles has also been derived[3] and has been used to show that cross sections can show an *L dependence when* $\Delta_0 \doteq 0$. In what follows I will compare the results of these simple expressions with experimental data.

3. DIRECT TRANSFER

Originally it was believed that the oscillatory term in eq. 2, which arises from the interference of trajectories from opposite sides of the nucleus, would be impossible to measure and so was averaged over. If this term is neglected in eq. 2 the cross section is expected to be bell shaped and centered at ψ or exponentially falling with angle depending on whether ψ is large or small. as can be seen in fig. 1 bell shaped behavior is found experimentally and both

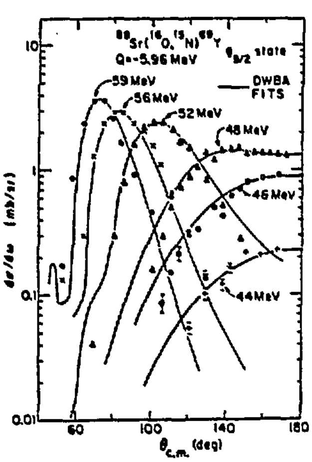


FIGURE 1

Angular distributions for the ^{88}Sr (^{16}O, ^{15}N) reaction as a function of energy (ref.4).

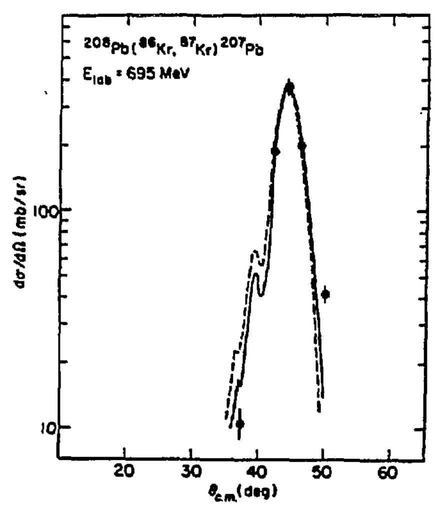


FIGURE 2

Angular distributions for the ^{208}Pb (^{86}Kr, ^{87}Kr) reaction. The grazing partial wave is roughly 400ħ (ref.5).

the grazing angle and the width of the angular distribution decrease with increasing energy. These effects are expected from eq. 2--the former because the grazing angle is roughly proportional to 1/E, the latter effect from a roughly constant Δr - region contributing to transfer so Γ (~ $k\Delta r$) increases with E and hence the angular width narrows. Perhaps the extreme, nearly classical, case of bell-shaped behavior is shown in fig. 2 where the width is $\Delta\theta \sim 5^0$!! For high-energy collisions on light nuclei (η small) exponentially falling cross sections are indeed observed[6]. Other features of the cross sections which can be successfully understood through simple matching conditions are the kinematic conditions (bombarding energy and Q value) for maximum cross-section and angular-momentum orientation[7,8].

As experimental techniques improved, it was discovered that the neglect of *the oscillating term in eq. 2 was in some cases unjustified* as several experiments demonstrated that some cross sections did oscillate[9]. It is amusing to note in retrospect the controversy which greeted the first suggestions that

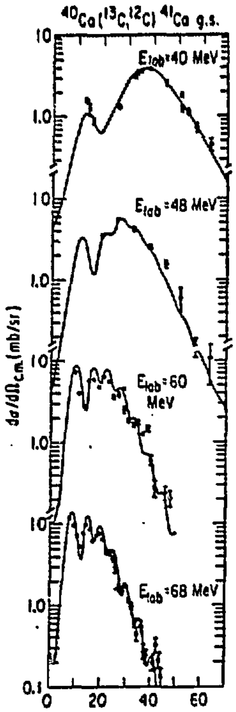


FIGURE 3

Angular distribution of the ^{40}Ca (^{13}C, ^{12}C) reaction as a function of energy (ref. 10).

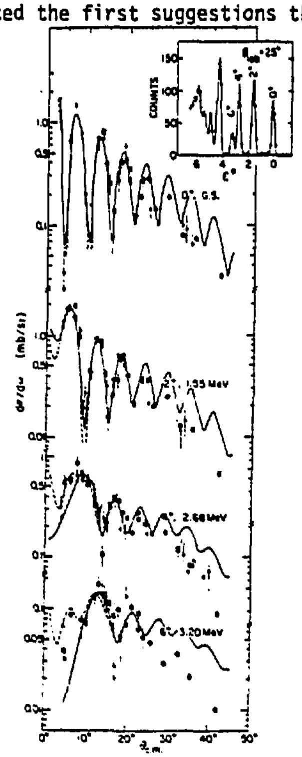


FIGURE 4

Angular distributions for various states in the $^{48}Ca(^{16}O,\ ^{14}C)$ reaction (ref. 11).

such oscillations should exist. Shown in fig.3 is the evolution of the cross section from bell shaped to oscillatory behavior for the (^{13}C, ^{12}C) reaction as a function of energy. Oscillating cross sections were not only fun to measure, but also gave information on the grazing partial wave (the period is $180°/(l_0+.5)$) and the angular-momentum transfer since it was found that the most forward peak for well matched conditions ($l_0^i = l_0^f$) occurred at an angle characteristic of L (see fig.4), the larger the value of L the larger the angle of the first bump (as in light-ion reactions).

Inspection of eq. 2 shows that the magnitude of the oscillating term depends on exponential factors involving the products $\Gamma^2\psi^2$ and $\frac{\Delta_0^2}{\gamma^2}$ which must be small in order that the oscillations be observable. Thus the matching of the grazing angular momenta should be $\Delta_0 \approx 0$ and the product $\Gamma\psi$ must also be small to observe oscillations at all. This second condition can be achieved by choosing a reaction with a steeply falling bound-state wave-function (strong binding or massive transfer) giving Γ small and by arranging kinematic conditions such that ψ is small, which is most easily obtained for light systems. As the mass of the projectile-target combinations increase the Coulomb repulsion also increases so that the interference pattern is substantially damped. For these systems at very high energies ψ can be made small, but l_0 and Γ become so large that oscillations will have a small magnitude, even if the extremely rapid period ($180/l_0$) could be observed. Thus the observation of oscillatory angular distributions for heavy systems will be a very difficult experimental challenge.

The expected orientation of the transferred angular momentum (eq.2) for moderate energy collisions is schematically indicated

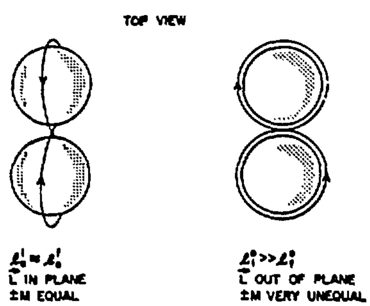


FIGURE 5

Schematic representation of the transfer orbits for two kinematic conditions.

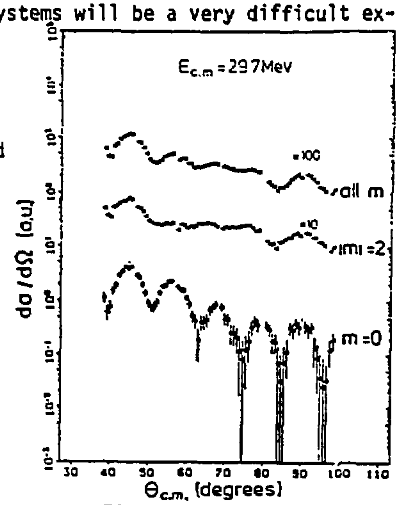


FIGURE 6

Partial cross sections for different M transfers in $^{12}C + ^{12}C$ inelastic scattering (ref. 12).

in fig.5. L will lie preferentially in the reaction plane when $l_0^i = l_0^f$ (M=0) and will be normal to the reaction plane when l_0^i and l_0^f differ substantially (|M|=L). A number of recent measurements of the M population have shown again the remarkable success of semiclassical expressions. The partial cross sections for different M from ^{12}C + ^{12}C inelastic scattering are shown in fig.6 and it can be seen the one for M=0 oscillates most strongly. Since this reaction is dominated by nuclear inelastic scattering the assumption of localization going into eq.2 is met and we see that M=0 cross section oscillates more strongly for two reasons. The factor which tends to damp the oscillating term for M > 0 factors out of the expression for M=0 and only affects the cross-section magnitude. The M= ± 2 cross sections also have a relative phase which tends to smooth out the oscillations.

Even the relative phases of the amplitudes can be understood semiclassically. In recent transfer experiment[13] these phases were determined from an alpha-particle correlation-measurement from unbound states of ^{20}Ne. Shown in fig.7 are the results for the phases of the M amplitudes for the 3-state relative to M=+3 as a function of scattering angle.

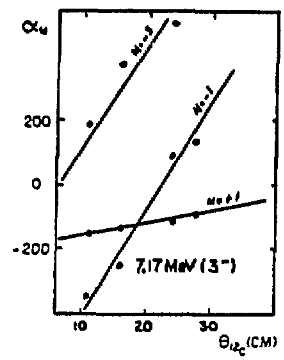


FIGURE 7

Deduced phases of the transition amplitudes relative to M=+3 as a function of scattering angle for the $^{16}O+^{16}O \rightarrow {}^{12}C+^{20}Ne(3^-)$ reaction (ref. 13).

Under the kinematic conditions of the experiment $|\Delta_0| >> L$ so from eq. 1 the expected relative phases for negative M are

$$\phi_M-\phi_L = (2l_0+1)\theta - (|M|+L)\frac{\theta}{2} + (|M|+L)\frac{3\pi}{2} - \frac{\pi}{2} + (L-M)\,\Delta\psi$$

and for positive M

$$\phi_M-\phi_L = (M-L)\frac{\theta}{2} + (L-M)(\frac{3\pi}{2} + \frac{\Delta\psi}{2})$$

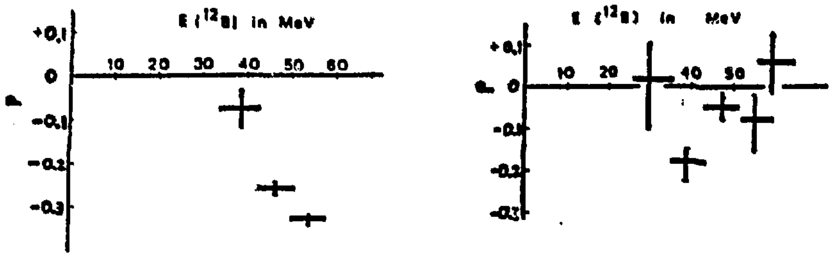


FIGURE 8
Polarization of ^{12}B following the (^{13}C, ^{12}B) reaction on two targets (ref. 15).

The large difference in slope between $\pm M$ in these expressions agrees quantitatively with what is observed. Another similar experiment[14] has emphasized that correlation measurements can be crucial in obtaining spin information from featureless cross sections.

The orientation of the angular momentum has also been investigated through measurements of the polarization of the ejectile in the (^{13}C, ^{12}B) reaction on two different targets[15]. For small energy losses the ^{12}B polarization differed significantly depending on the target (fig. 8). The observation can be explained, at least qualitatively, if account is taken of the different nuclear structure of the targets.

TABLE

Target	State	P_{max} (^{12}B)
	1/2 -	- 1.0
Cu	3/2 -	- 0.5
	5/2 -	- 1.0
	9/2 +	- 0.14
Mo	7/2 +	- 0.96
	5/2 +	- 0.36

Shown in the table are the *maximum* possible ^{12}B polarizations for valence orbitals of the targets. Clearly the measured polarization near the ground state will be smaller for Mo than Cu. Not all the results of heavy-ion induced transfer are so successfully understood. There are many cases of apparent simplicity which do not behave properly. The grazing angle for many-proton transfers have been observed to be more forward than calculated and a number of transfers gave anomalous spectroscopic factors. Another special problem is illustrated in fig. 9 where two simultaneously measured reactions on Ca targets are shown. The (^{13}C, ^{12}C) reactions (L=4) are seen to agree well with the expectations of theory and, as expected, the (^{13}C, ^{14}N) reactions (L=1) oscillate with the same period. The theoretical curve, which agrees with what is expected semiclassically, is out-of-phase with the data, however. This behavior has been observed for several cases[17], all L=1. To add to the puzzle, other one-proton pickup reactions between the *same* states fit

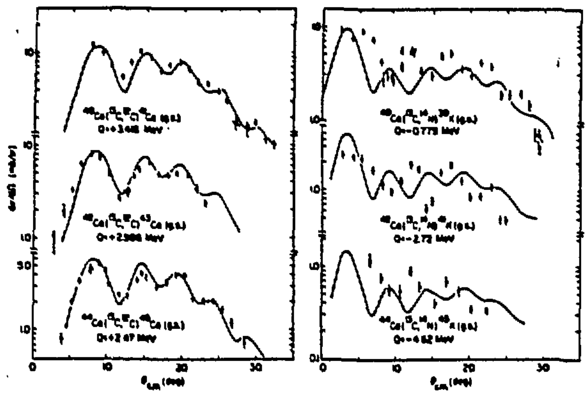


FIGURE 9
Comparison of the $(^{13}C, ^{12}C)$ and $(^{13}C, ^{14}N)$ reactions on various Ca targets (ref. 16).

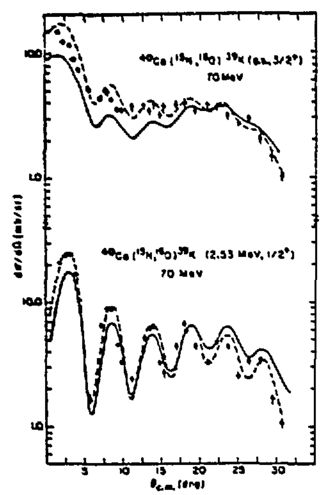


FIGURE 10
Angular distributions for L=1 transfers in the $^{40}Ca(^{15}N, ^{16}O)$ reaction (ref. 18).

theory very well (see fig. 10) so that the effect is likely to be a somewhat subtle one. There are only two independent M transfers for L=1 so an inversion of the population of the partial cross sections is required to explain the anomalous cases. The problem with the data of fig. 9 and other L=1 reactions has been around for a long time with many proposed solutions but none is satisfactory. I suspect the answer lies in the calculation of "recoil", but the problem is still wide open and needs a solution.

These problems coupled with a lack of much new spectroscopic information from transfer reactions led to a period of disillusionment, which was perhaps natural in light of the overwhelming enthusiasm found in the early to mid 1970's. However, there were other early observations in the experimental work which were not used to full advantage until recently. Strong selectivity was seen in two-and three-particle transfer with targets of mass less than ^{16}O [6]. State assignments were suggested on the basis of shell-model calculations and semiclassical reaction theory, but unfortunately there was no direct experimental evidence other than a strong state was seen near the calculated energy. It was believed for heavier targets the increased level density would prohibit such studies and the observed selectivity on heavy targets did not seem to be as strong as on light targets. It had been observed that transfer with the (^{16}O, ^{15}N) and (^{12}C, ^{11}B) reactions to known final states in heavy nuclei produced considerably stronger cross sections to $j=l+1/2$ states than to $j=l-1/2$ states[19], in contrast to light-ion single-particle reactions where these cross sections are equal. As will be seen below this observation is generally not the case but is dependent upon kinematic conditions. The choice of conditions can be tuned to produce very different and much more dramatic effects than were seen in the early work.

The reasons for the j selectivity in heavy-ion reactions arise from three factors: the difference between incoming and outgoing grazing angular momenta, the fact that the bound states in the projectile are not $s_{1/2}$ in most heavy-ion projectiles, and that there is almost no evidence that the intrinsic spin of the transferred nucleon changes during transfer. From angular-momentum conservation the allowed angular-momentum transfer is limited to $|j_1-j_2| < L < |j_1+j_2|$ where j_1 and j_2 are the total spins of the nucleons in the projectile and target. With no spin flip L is also limited to $|l_1-l_2| < L < |l_1+l_2|$. Finally in most cases of high selectivity the natural-parity transfer dominates ($(-1)^{l_1+l_2} = (-1)^L$). Since $l_1>0$ the selection rules are different from light ions.

It has often been erroneously suggested that, because heavy ions bring in a large amount of angular momentum, large L transfers are naturally favored. This This is not the case - to assure high L transfer Δ_0 must be large (see eq. 2). Consider the special case of (^{16}O, ^{15}O) reactions to final states of $j = l+1/2$ (j>) and $j = l-1/2$ (j<). The transferred neutron begins in ^{16}O in a $p_{1/2}$ orbit so the favored L values to these final states are $L = l+1$ and $L = l-1$ respectively. The very negative Q value leads to the condition $|\Delta_0| \gg L$ so that from eq. 2 we can see that the most important value of M will be M = L (for cases where there is no strong far-side contribution) and that the larger L transfers have the largest cross section. With this kinematic condition and the assumption that the intrinsic spin does not flip, it can be shown j> states should be very strongly favored over j< states. On the other hand if the neutron began in a $p_{3/2}$ orbit as in ^{12}C, which has a similar large negative Q value, the results are quite different and in fact j< is favored over j>. This arises both from the different allowed L values and angular-momentum coupling. Shown in figure 11 are the cases of (^{16}O, ^{15}O) and (^{12}C, ^{11}C)

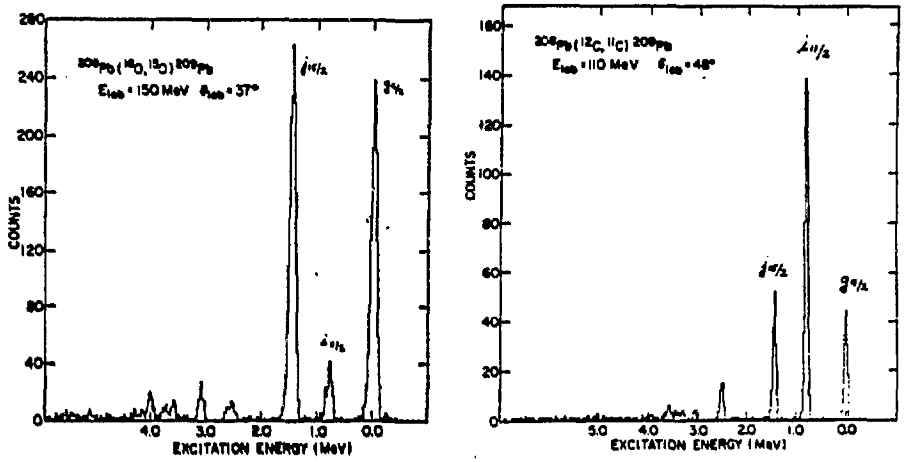


FIGURE 11A FIGURE 11B

Comparison of the yields of the (^{16}O, ^{15}O) and (^{12}C, ^{11}C) reactions on ^{208}Pb at the grazing angle (ref. 20).

reactions on ^{208}Pb which demonstrate that these conclusions are experimentally achieved. This is in contrast to the findings of many experiments because the kinematic mismatch condition $|\Delta_0|>L$ has not been realized in those cases. The remarkable selectivity for these particular reactions is energy dependent and is maximal at about 10MeV/nucleon. Let me emphasize that semiclassical calculations pointed to these reactions as being the most selective and give the bombarding energy for maximum selectivity.

The strong selectivity demonstrated in fig. 11 has been used recently to locate previously unknown high-spin states in deformed and spherical nuclei despite the fact that the cross sections are bell shaped. In both cases level-densities in the region of interest are high so that one might think that heavy-ion reactions with their relatively poor resolution would be unusable. The extreme selectivity of the reaction coupled with gamma-ray coincident measurements, however, has made the discovery of new states of high spin possible.

Consider first the well deformed Er nuclei. In this region the role of the $i_{13/2}$ neutron orbital is expected to play a major role in high-spin-state structure. There are several of these states which would be rather low lying, but had not been seen or were misidentified in light ion experiments. The use of the (^{16}O, ^{15}O) and (^{12}C, ^{11}C) reactions identified the 13/2+ member of the 9/2 [624] band and the 9/2- member of the 7/2 [514] band in $^{167,169,171}Er$

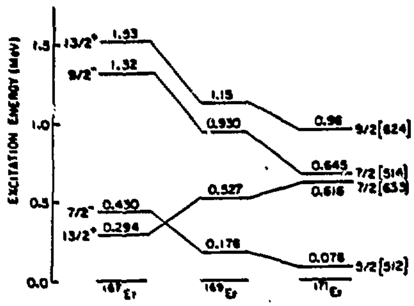


FIGURE 12
Results for high spin states seen in the Er nuclei via transfer reactions (ref. 21).

nuclei (see fig. 12). In ^{171}Er the coincident gamma-ray spectra confirmed the assignment of 13/2+ to states at 971 and 616 keV and allowed a measurement of the strong effects the Coriolis force causes in mixing the K quantum number of these states[22].

In the near-spherical final nucleus ^{144}Nd high-spin states are expected to be shell-model like. In this region of the periodic table the (^{16}O, ^{15}O) reaction strongly favors transfer to $f_{7/2}$ and $i_{13/2}$ orbitals which, coupled to the 7/2- ^{143}Nd ground state, produces multiplets of $f_{7/2}$**2 and $f_{7/2}$- $i_{13/2}$ in ^{144}Nd. The $i_{13/2}$-$f_{7/2}$ multiplet extends to spin 10^- with the highest spin state expected to be purest. The 10^- state is generally not yrast so is often missed in experiments involving compound-nuclear formation. There is no such restriction in particle transfer and that state should be the strongest in the spectrum. Figure 13 shows how selective the reaction is even up to an excitation energy of 4MeV where the density of levels is very high.

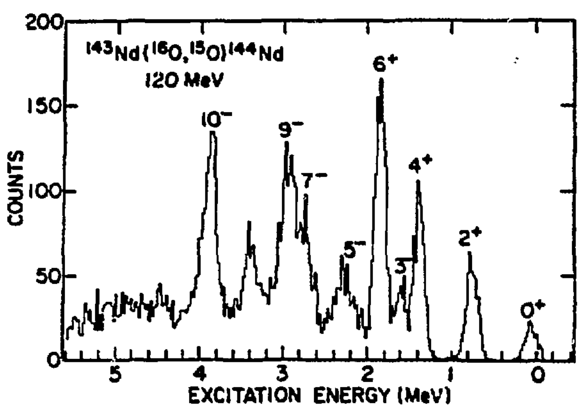


FIGURE 13
Particle spectrum of the ^{143}Nd (^{16}O, ^{15}O) reaction (ref. 23).

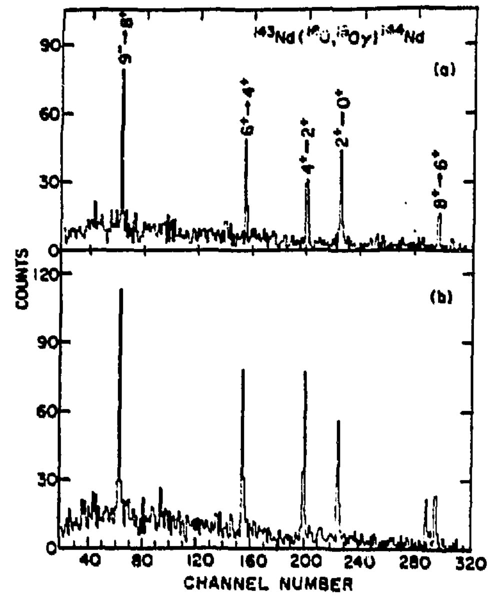


FIGURE 14
Gamma-ray spectra in coincidence with the peaks labelled 9^- and 10^- in fig. 13 (ref. 23).

The gamma-ray spectra in coincidence with the peaks labelled 9^- and 10^- are shown in fig. 14. The 9^- peak gives gamma rays known from other work[24] and confirms its assignment. The 10^- gamma ray spectrum is nearly identical except for a gamma ray of precisely the energy difference between the two states. Spectroscopic values together with the decay of this state exclusively to the 9^- strongly indicates that it is the 10^- member of the $i_{13/2}-f_{7/2}$ multiplet.

4. MULTISTEP TRANSFER

Finally, let me conclude with some beautiful effects which occur as a result of a feature of heavy ions which was originally feared would limit their usefulness: the large multistep transfer caused by strong Coulomb excitation in nuclei with collective states. Early theoretical work predicted that precisely because of this effect exotic interference patterns between direct and indirect transfer routes should be seen to states not easily reached by direct transfer[25,26]. The combination of high-resolution beams and particle spectrometers enabled measurements of two-particle transfer in deformed nuclei

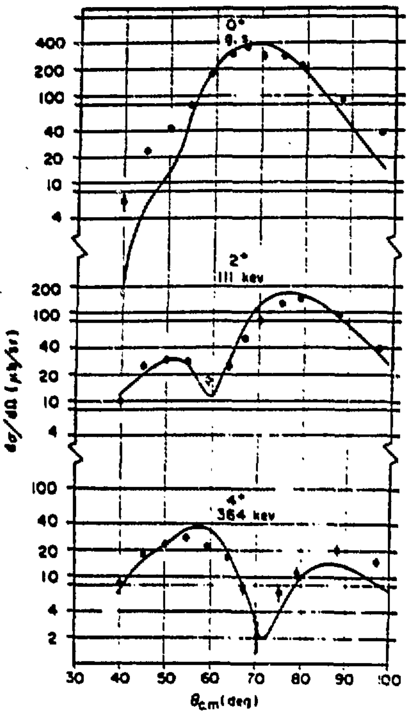
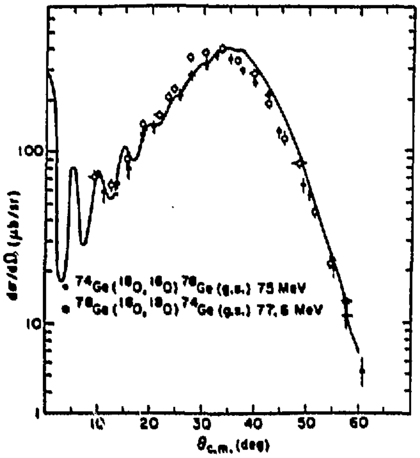


FIGURE 15

Interference pattern between direct and indirect transfer routes in the $^{186}W\ (^{12}C,\ ^{14}C)$ reaction (ref. 27).

(fig. 15) and strong interference effects near the grazing angle for the 2^+ and 4^+ states were seen and reproduced theoretically. Note that the first excited state is only 111 keV from the ground state.

Another case of the special nature of the interference of direct and indirect routes is shown in fig. 16. Here the reactions $^{74}Ge+^{18}O \leftrightarrow ^{16}O+^{76}Ge$ are compared at the same center of mass bombarding energy. For the ground-state transitions, which are direct transfers, the reactions are time reverses and the cross sections are identical as expected. The 2^+ states in the two reactions are populated weakly by direct transfer and indirectly via inelastic excitation followed by transfer (and vice versa). The large difference in the cross section for the 2^+ states near the grazing angle is caused by the interference of the direct and indirect routes. In the stripping case it is destructive and in the pickup constructive. The difference is very sensitive



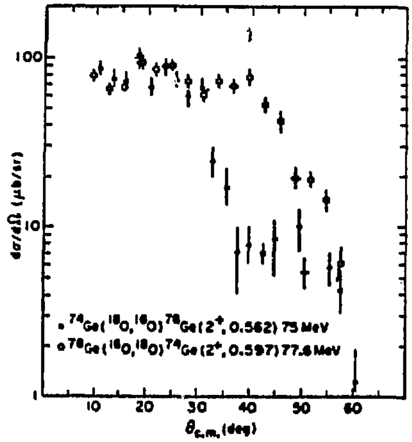


FIGURE 16A FIGURE 16B

Angular distributions for the ^{74}Ge + ^{18}O $\leftrightarrow$ ^{16}O + ^{76}Ge reactions at the same center of mass energy (ref. 28).

to the spectroscopic nature of the states and provides a very sensitive test for nuclear structure theory.

5. CONCLUSION

In this rather limited view of the vast amount of work that has gone into transfer experiments I have tried to emphasize certain distinctive features of heavy ion induced transfer, which makes them complementary to light ions, and to demonstrate how valuable semiclassical analysis has been for understanding them and for guiding directions in the field. Clearly there are areas which have not been addressed where heavy ions can play a unique role. Quasielastic transfer is certainly not without complications and experiments may require considerably more sophistication than has generally been made, but there are still interesting areas in both spectroscopy and reaction-mechanism studies which should be investigated. I might comment that in the area of cluster transfer, experiment continues far ahead of theory. I am optimistic about the future of the field and hope that I have demonstrated why.

ACKNOWLEDGEMENT

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REFERENCES

1) V. Strutinski, Sov. Phys. JETP 19 (1964) 1401. W.E. Frahn and R.H. Venter, Nucl. Phys. A59 (1964) 651. A. Dar, Phys. Rev. 139 (1965) 1193.

2) P.D. Bond, Phys. Rev. C22 (1980) 1539.

3) S. Kahana et al. Phys. Lett. 50B (1974) 199.

4) N. Anantaraman, Phys. Rev. C8 (1973) 2245.

5) A.J. Baltz et al. Phys. Rev. C29 (1984) 2392.

6) N. Anyas-Weiss et al. Phys. Rep. C12 (1974) 201.

7) P.J.A. Buttle and L.B.J. Goldfarb, Nucl. Phys. A176 (1971) 299.

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

9) C. Chasman et al. Phys. Rev. Lett. 31 (1973) 1074.

10) P.D. Bond et al. Phys. Lett. 47B (1973) 231.

11) W. Henning et al. Phys. Rev. Lett. 32 (1974) 1015.

12) D. Konnerth et al. Proceedings of XV Masurian Summer School on Nucl. Phys., Mikolajki (1983) to be published.

13) F. Pougheon et al. Nucl. Phys. A325 (1979) 481.

14) W.C.M. Rae and R.K. Bhomik, Nucl. Phys. A420 (1984) 320.

15) N. Takahashi et al. Proceedings of the International Conference on Nucl. Phys., Florence (1983) vol. 1, p. 582.

16) P.D. Bond et al. Phys. Rev. Lett. 36 (1976) 300.

17) R.M. DeVries et al. Phys. Rev. Lett. 32 (1974) 680.

18) P.D. Bond et al. Phys. Rev. C19 (1979) 2160.

19) D.G. Kovar et al. Phys. Rev. Lett 29 (1972) 1023.

20) P.D. Bond et al., to be published.

21) P.D. Bond et al. Phys. Rev. Lett. 46 (1981) 1565.

22) A.J. Kreiner et al. Phys. Rev. C25 (1982) 866.

23) M.T. Collins et al., to be published.

24) L.E. de Geer et al. Nucl. Phys. A259 (1976) 399.

25) R.J. Ascuitto and N.K. Glendenning, Phys. Lett. 47B (1973) 332.

26) R.J. Ascuitto and J. Vaagen, Proceedings of the International Conference on Reactions Between Complex Nuclei Nashville (1974) North-Holland, p.257.

27) K. Erb et al. Phys. Rev. Lett. 33 (1974) 1102.

28) P.D. Bond et al. Phys. Rev. C16 (1977) 177.