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Population of High Spin States in Very Heavy Ion Transfer Reactions - The Experimental Evidence

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I. Introduction

Transfer reactions have been studied for some time with light heavy ions such as oxygen.[1] Although states of spin I ~ 10 ħ are sometimes populated in such reactions, it is assumed that collective excitation is small, and the transferred particles are responsible for the angular momentum transfer.[2] In this paper we will discuss a qualitatively different kind of transfer reaction using very heavy ions (A > 40). In these reactions the collective excitation in both the entrance and exit channels is strong, and there may be appreciable angular momentum transfer associated with inelastic excitation. This type of reaction is illustrated highly schematically in fig. 1: strong inelastic excitation in the entrance channel, transfer of particles near the radial turning point, and strong exit channel inelastic excitation.

In this regime it should be possible to observe qualitatively new features not found in transfer reactions with light heavy ions or light ions. These have been discussed in the literature,[3-6] and fall into two general categories: 1) the strong collective excitation implies a localization in coordinates conjugate to quantum numbers which can take large values. For example, collective rotational excitation implies a localization in the orientation of a rotor in a transfer reaction. 2) The strong entrance and exit channel excitation implies that transfer can be induced between states which are collectively excited. For example, single-particle and pairing modes can be studied under the influence of high collective angular momentum.

In fig. 2 we show a recent estimate of the maximum collective angular momentum in some representative heavy ion systems near the classical turning point. The details may be found in ref. 7, but for our purposes we observe that these calculations indicate that transfer from states in the 15-20 ħ region for rare earths and 20-30 ħ in actinides should be feasible. We note that these calculations indicate only the maximum angular momentum at the turning point (the final angular momentum is likely to be more), and that they include only the angular momentum coming from the entrance channel inelastic excitation and not that coming from transferred particles.

II. General Features of Data

In this paper I would like to discuss a recent series of transfer experiments run by our group in collaboration with groups from Rochester, Oak Ridge, and St. Louis. Most data have been obtained at the Holifield Heavy Ion Facility (HHIRF) at Oak Ridge, but some experiments have also been done at Brookhaven, Daresbury, and GSI. A typical experimental arrangement is shown in fig. 3. The position-sensitive parallel-plate avalanche detectors (PPAD's) have no energy resolution, but are used to define the scattering angle and time of flight difference for target-like and beam-like ions. Gamma rays are detected in coincidence with the scattered ions in Ge detectors, which are often Compton suppressed. In the Oak Ridge experiments this apparatus is immersed in the Spin Spectrometer, which is used to record the total energy and multiplicity of the γ-ray cascade associated with a PPAD-PPAD-Ge coincidence.

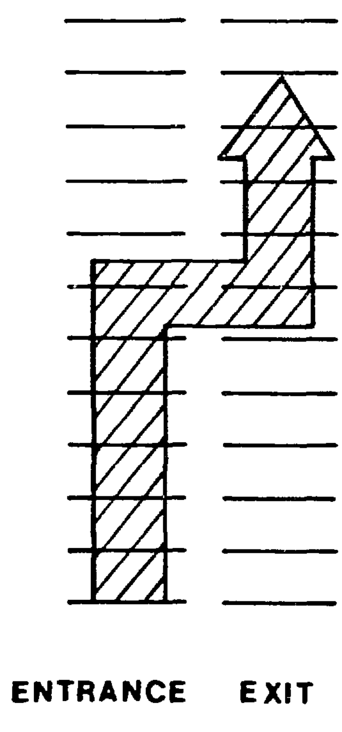

Fig. 1. Mechanism of transfer reaction with very heavy ions. The picture is schematic, since a variety of paths will actually contribute in a particular reaction (cf. fig. 2).

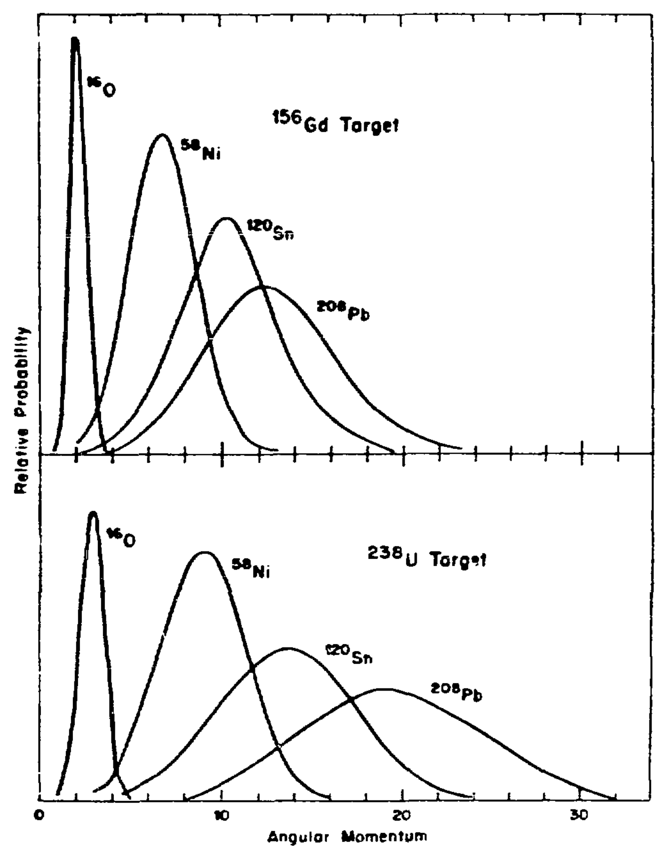

Fig. 2. The maximum angular momentum near the turning point for some heavy ion systems in grazing collisions (ref. 7).

In fig. 4 a spectrum typical of this kind of experiment is shown for the reaction ^{58}Ni + ^{161}Dy (E_{Lab} = 270 MeV) gated near the grazing angle. In addition to the inelastic transitions in ^{161}Dy we observe very strong transitions in the ground band of ^{160}Dy, corresponding to the 1-neutron pickup ^{161}Dy (^{58}Ni, ^{59}Ni) ^{160}Dy to high spins in ^{160}Dy. These lines are present only near the grazing angle, confirming their origin in a transfer reaction. Several important features may be noted: (1) High spin states are observed; (2) Transfer is very strong; (3) Only a few channels are strongly populated; (4) The spectral quality is comparable to that for Coulomb excitation reactions.

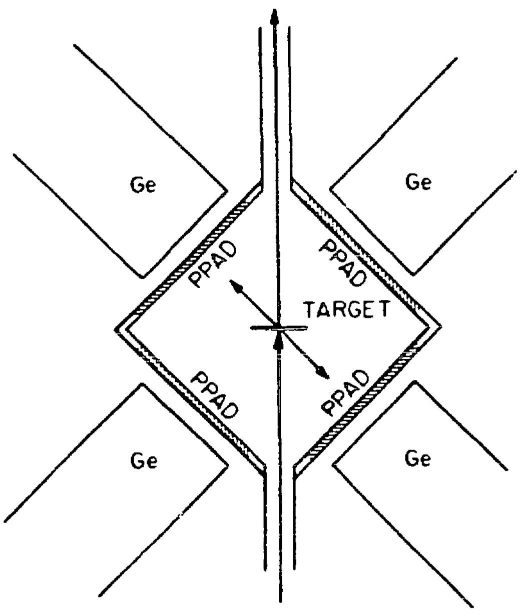

Fig. 3 A typical experimental set up. The particle detectors are normally placed inside the Spin Spectrometer.

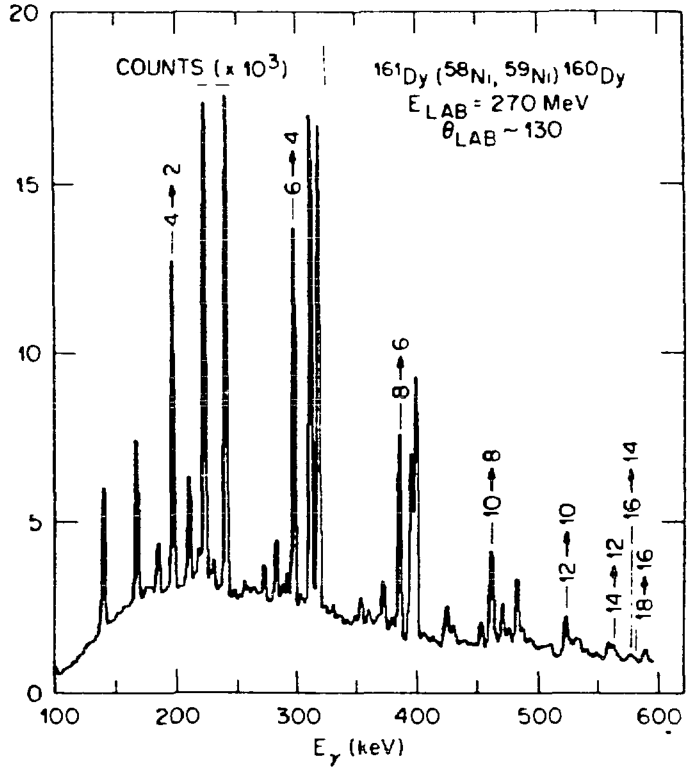

Fig. 4. A representative γ-ray spectrum (not Compton suppressed) near the grazing angle (θ_{Lab} ~ 130°) for ^{58}Ni + ^{161}Dy at E_{Lab} = 270 MeV. The strong unmarked lines correspond to inelastic excitation. The ground band of ^{160}Dy is marked.

In fig. 5 a representative total energy vs multiplicity (E,M) plot is shown for the reaction ^{161}Dy (^{58}Ni, ^{59}Ni) ^{160}Dy. The multiplicity shown is that of the Spin Spectrometer, and doesn't include the gating γ-ray detected in the Ge detector. The solid lines are total energy-multiplicity contours gated on the strong ground-band transitions in the ^{160}Dy transfer product. The light dashed contour is the 10% contour gated on the strong ^{161}Dy inelastic scattering lines. The total energy and multiplicity plots are constructed from the experimental total pulse height spectra and γ-ray fold through an unfolding procedure correcting for the response of the Spin Spectrometer.[8] An approximate yrast line for ^{160}Dy (with ^{59}Ni in its ground state) is sketched as the heavy dashed line. A related angular momentum scale valid only for ^{160}Dy yrast transitions is shown for reference below the multiplicity axis. For example, excitation of the ^{160}Dy 4^+ state with ^{59}Ni left in its ground state yields a multiplicity ~ 0 in the Spin Spectrometer since one transition yields the gating γ-ray detected in the Ge detector, and the $2^+ \rightarrow 0^+$ transition is almost entirely converted. Events lying below the yrast line reflect the finite resolution of the Spin Spectrometer, which is typically 30% in both total energy and multiplicity for these experiments.

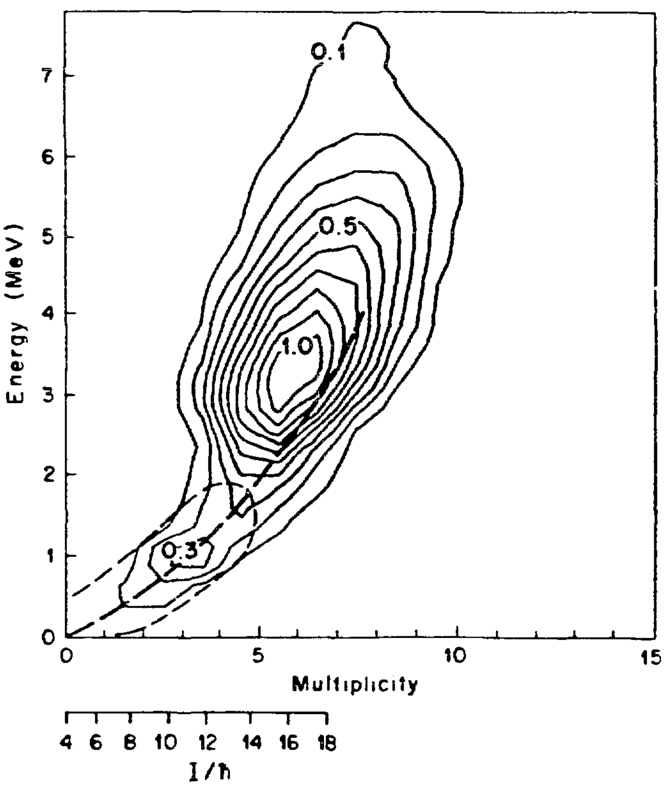

Fig. 5 Total energy vs. multiplicity for ^{161}Dy(^{58}Ni,^{59}Ni)^{160}Dy (solid contours) and ^{161}Dy (^{58}Ni, ^{58}Ni')^{161}Dy (dashed contour). The heavy dashed line is an approximate ^{160}Dy yrast line.

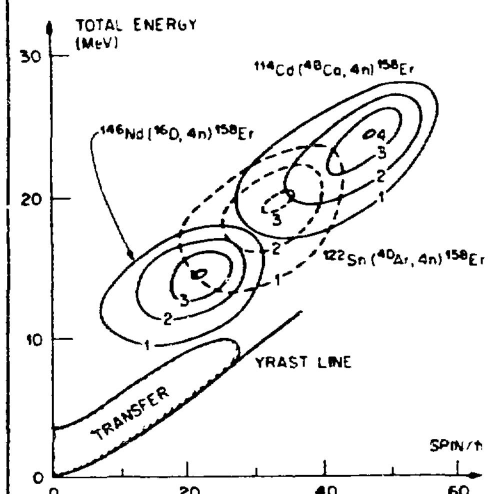

Fig. 6 Total energy vs spin predicted for entry distributions in some (heavy ion, xn) reactions, and the general region being populated in transfer reactions with very heavy ions.

Several interesting features are evident in fig. 5. (1) the transfer (E,M) distribution has two maxima; (2) the lower multiplicity transfer maximum approximately coincides with the single maximum for inelastic scattering; (3) the transfer population of ^{160}Dy is remarkable cold, lying mostly within an MeV of the yrast line; (4) high angular momenta (I ~ 20ħ) appear to be populated.

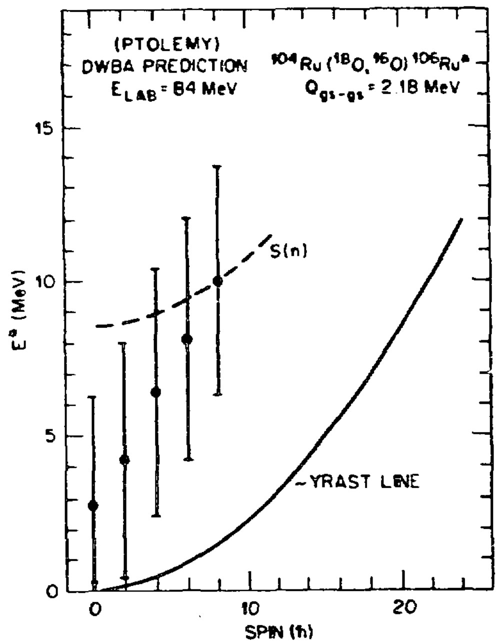

Fig. 7 A DWBA prediction of the optimal Q-windows for excitation of various spin states in ^{106}Ru (ref.9).

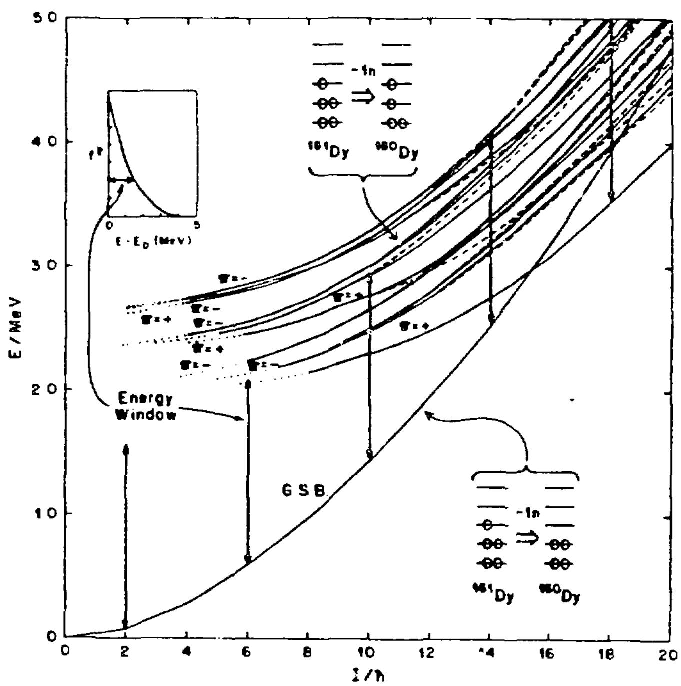

Fig. 8 Low-lying bands in ^{160}Dy which can be formed by removing a single neutron near the Fermi surface from ^{161}Dy. The bands were constructed from a Cranked Shell Model calculation.

Let's recall that these (E,M) distributions are quite different from those expected for other kinds of reactions with such heavy projectiles. For example, in fig. 6 the expected entry distributions for some (heavy-ion, xn) reactions are compared to those for the transfer data being discussed here. Let's also note that these results differ appreciably from those expected for transfer reations with light heavy ions where the angular momentum transfer comes primarily fro the transferred particles. For example, in fig. 7 we see that the

DWBA prediction for optimal Q-matching in an oxygen transfer reaction quickly favors excitation of states in the vicinity of the nucleon binding energy with transfer of just a few units of angular momentum. This is due to the tradeoff of L-window against Q-window in this case.

III. Schematic Model for 1-Particle Transfer

The general structure observed in fig. 5 can be understood in terms of a simple model. First, recall the band structure expected for deformed nuclei given by basic models of high-spin physics. Fig. 8 shows a Cranked Shell Model[10] calculation for low-lying bands in ^{160}Dy including the ground band and 2-quasiparticle (2QP) bands for which one of the quasiparticles is in the $\Omega = 5/2^+$, $i_{13/2}$ neutron orbit (the unpaired neutron orbit in the ground state of ^{161}Dy). Thus, these bands contain the low-lying states in ^{160}Dy easily formed by removing a neutron from ^{161}Dy, as illustrated schematically in the insets to fig. 8.

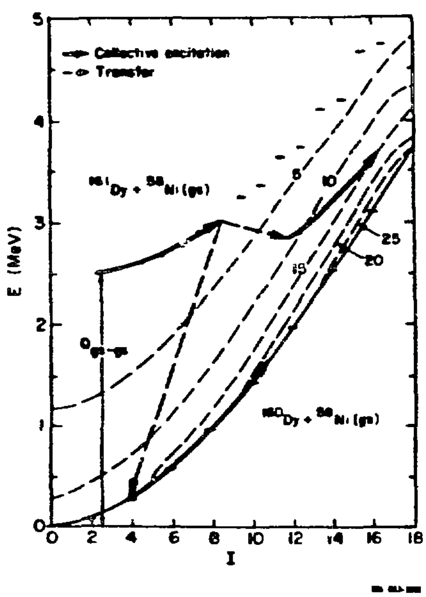

Fig. 9. Evolution of a 1-neutron transfer reaction in the energy-angular momentum plane.

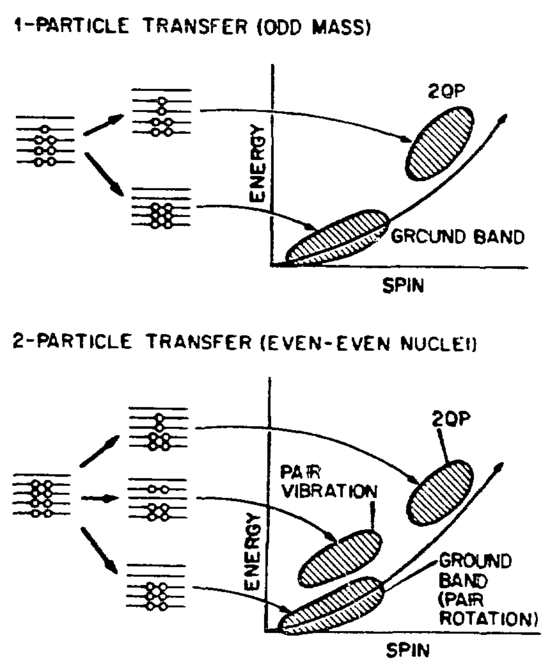

Fig. 10. A schematic picture of one-and two-particle transfer reactions populating even-even nuclei.

Also shown in fig. 8 is an energy window which limits the states which can be populated. This energy window is the product of a Gaussian Q-window and a factor decreasing exponentially in $(B + \delta)^{1/2}$, where B is the binding energy for a nucleon and δ is the excitation energy with respect to the yrast line of the state populated in ^{160}Dy. A useful and accurate estimate of the fullwidth at 1/e for the Q-window is b ~ $(Z_1 Z_2/\mu)$ MeV, which can be derived from semiclassical considerations. In this formula Z_1 and Z_2 are atomic numbers, and μ is the reduced mass for the heavy ion system.

Fig. 9 illustrates the proposed mechanism for the 1-neutron pickup reaction. In the explanation we will assume that the Ni-like ion remains in its ground state, or low-lying excited states. The data on which fig. 5 is based support this assumption. Shown are the experimental yrast lines for these systems with this assumption, plotted on a mass scale with the mass of ^{160}Dy(g.s.) + ^{58}Ni(g.s.) as the origin. In the entrance channel the ^{161}Dy is inelastically excited (predominantly by Coulomb excitation) to an average angular momentum ~ 17/2 at the turning point (cf. fig. 2) where particle transfer is assumed to take place. The contours of the energy window are shown as dashed lines in fig. 9. Thus kinematics and binding energies favor the population of ^{160}Dy states lying within this window. A cranked shell model calculation indicates that at I = 17/2 the core angular momentum in ^{161}Dy is ~ 4-6 ħ, with the remainder primarily carried by alignment of the unpaired particle. If the transfer operator is approximately one-body, the transfer cannot change the core angular momentum, so the transfer must proceed to states in ^{160}Dy with a core angular momentum R ~ 4-6. Analysis of the calculation used to construct fig. 8 shows that there are two general regions within the energy window which satisfy this condition: The ground band around I = 4-6, and the 2-quasiparticle bands near I ~ 10-12 (the average alignment in these bands is i ~ 6). Thus the transfer can proceed to the two regions indicated by the dashed arrows in fig. 9. Both regions are expected to involve states within collective bands, so exit channel inelastic excitation will further excite the ^{160}Dy nucleus as indicated by the heavy lines lying to the right in fig. 9. The flatter slope of the exit channel excitation in the 2QP bands reflects the structure of fig. 8.

Thus, at least schematically, two regions of the (E,M) plane should be populated in the 1-neutron transfer reaction, (fig. 10) the ground band at an angular momentum comparable to that for inelastic excitation, and 2QP bands at higher angular momentum, with the difference in angular momentum between the two regions approximately given by the average aligned angular momentum in the 2QP bands. The data of fig. 5 are qualitatively and quantitatively in agreement with this picture. For example, the gap between the two maxima is just 6 units of angular momentum, as expected from the analysis given above.

IV. Two-Particle Transfer Reactions

A simple schematic model for 2-particle transfer is outlined in fig. 10. For the two-particle transfer beginning from an even-even deformed nucleus two pairs of particles may be broken in the transfer leading to population of 2QP states. Alternatively, pairs may be transferred, leading either to population of the ground band of the daughter (pairing rotational transition), or to bands built on excited pairs (pairing vibrational transition). In all cases we expect the reaction to populate rotational bands of states, due to the strong entrance and exit channel inelastic excitation.

It should be obvious from these considerations that the experimental measurement of the patterns illustrated in fig. 10 constitutes a probe of the pairing structure of the nuclei involved in the collision. This is particularly true of the 2-particle transfer reaction. For example, in the presence of extremely strong pairing, the pairing rotational transition (strong pairing collectivity) would be dominant. As pairing is weakened, strength would be shifted to the pairing vibrational transition (still weakly collective in the pairing degrees of freedom) and to the 2QP transitions (non-collective with respect to pairing). Furthermore, we might expect the influence of angular momentum on pairing to manifest itself in these patterns. For example, a loss of pairing at higher angular momenta might lead to a depletion of the higher-spin part of the pairing rotational population and a corresponding enhancement of the higher-spin portions of the pairing vibrational and 2QP populations. These observations would clearly be complementary to those we have already proposed concerning the population of discrete states in these reactions as a measure of pairing correlations.[4)]

V. Pairing Correlations and Heavy-Ion Transfer

With the previous section as introduction, I would now like to turn to a subject which has a long history in heavy-ion nuclear physics, the attempt to study pairing correlations through the enhancement of 2-particle transfer between heavy ions. Probably everyone is familiar with the general argument. In (t,p) or p,t) reactions on "superfluid" nuclei the transfer rates are enhanced by ~ 50 over uncorrelated single-particle rates, and the enhancement is ascribed to coherent pairing effects. If both collision partners were superfluid, as is possible in a heavy ion collision, considerably more dramatic effects might be expected.

Such effects are often discussed in terms of an "enhancement factor" which may be defined in a variety of ways, but which is generally of the form $F \sim P_2/(P_1)^2$ where P_2 is the probability for 2-particle transfer, and P_1 is the probability for 1-particle transfer. Thus F is a measure of whether 2-particle transfer is more likely than the product of two uncorrelated 1-particle transfers. Similar considerations can be applied to the probabilities for multiple-pair transfer.

A serious problem with such measurements is that the mere observation of enhancement factors is not necessarily an indicator of pairing effects. For example, large 2-particle cross sections might be because of enhanced tunneling of quasiparticles, due to some combination of excitation before transfer and a large density of 2QP states available satisfying kinematic constraints in the reaction. Von Oertzen has discussed this problem in some detail.[11] From fig. 10, it is clear that inclusive cross section measurements can tell us nothing about pairing since such measurements cannot distinguish the enhancement due to pairing from other sources.

To make definitive statements about pairing effects in heavy ion collisions the preceding discussions suggest that a minimal requirement is a measurement which distinguishes quasielastic from deep inelastic processes and which gives (1) the energy of states populated in transfer; (2) the angular momentum of states populated in transfer. Since no measurement previously reported satisfies these criteria (those of ref. 11 come closest), we would contend that the question of pairing enhancement in heavy ion transfer is still an open one. We would like to suggest that the kind of total energy - multiplicity measurement just described is the key to resolving this problem.

In Fig. 11 some total energy-multiplicity diagrams are shown from a very recent series of one-and two-neutron pickup reactions using ^{116}Sn beams on a set of Dy isotopes. Before continuing, let me insert a caveat or two. First, these data are very recent. They are not fully analyzed, and they represent only a portion of the total statistics. Second, these distributions are only approximately corrected for the response of the Spin Spectrometer. Based on past experience we expect the response unfolding will primarily sharpen the distributions, enhancing details with little change in the gross structure. Some approximate yrast lines are sketched in fig. 11. These also should be considered only a rough guide at this stage of the analysis.

Notice that global features of fig. 11 are similar to those of fig. 5. The distributions are primarily concentrated near the yrast line. Although it is not yet clear whether there are separated peaks as in fig. 5, the long ridges in several of the diagrams suggest that such structure could emerge with full statistics and correction for the Spin Spectrometer response. Although there is a tail of the distribution which appears to extend to somewhat higher energy and multiplicity in the two-particle case than in the 1-particle case, there are significant portions of the 2-particle transfer population which come as low, or even lower in energy and multiplicity than the 1-particle distributions. In fact the maxima for the two-particle transfers generally lie in the same region as those for the corresponding inelastic excitations (not shown).

Thus, we offer the following tentative interpretation of the 2-particle transfers shown in fig. 11. The maxima below M ~ 6 (at least their lower portions) correspond to pairing rotational population of the ground band of the Dy daughter, and is the portion of the cross section which is most sensitive to pairing correlations. The remainder of the population represents some mixture of 2QP and pairing vibrational

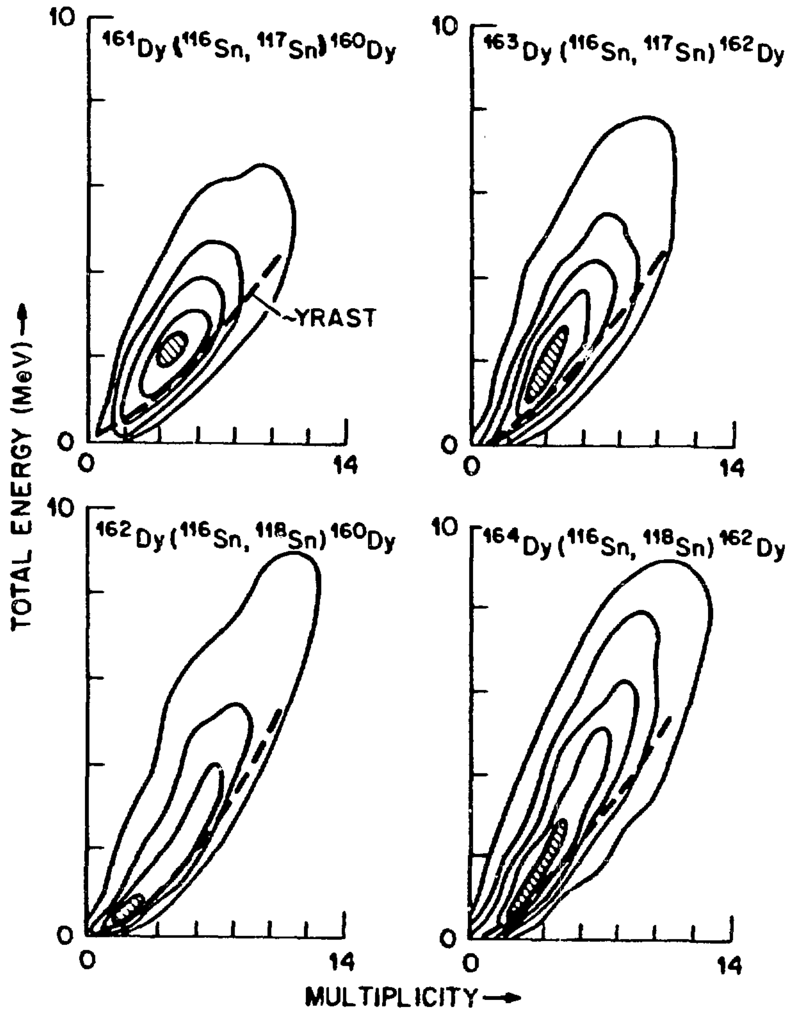

Fig. 11. Some approximate total energy-multiplicity plots for Sn reactions. The Sn laboratory energy was 638 MeV, and the lab grazing angle was ~ 70°. These results are based on a partial data analysis, and are not yet fully corrected for the response of the Spin Spectrometer.

transitions, or perhaps even more complicated processes in the higher energy-higher multiplicity tail. This portion of the population is much less dependent on the pairing.

In fig. 12 the total energy - multiplicity diagrams for the transfer ^{162}Dy → ^{160}Dy induced by Ni and Sn projectiles are shown. A striking feature may be noted. The relative population of the region that we interpret as the ground band

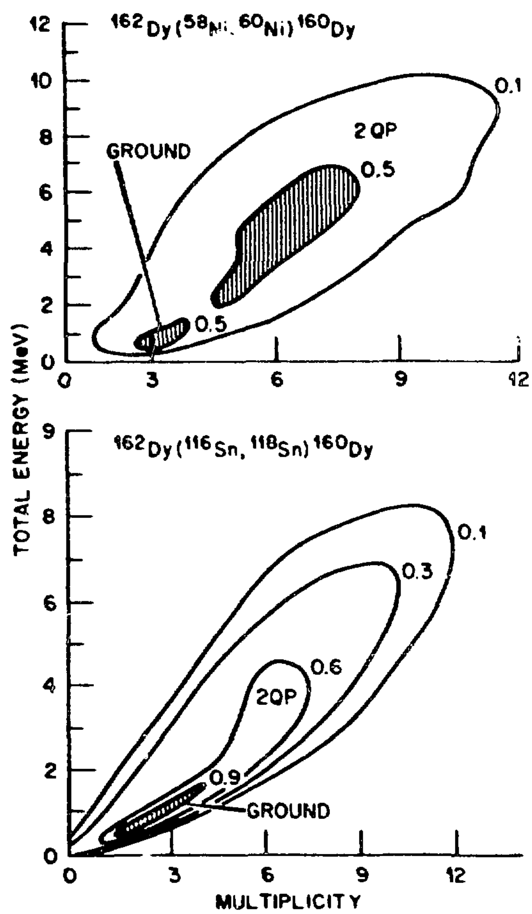

Fig. 12. Comparison of total energy - multiplicity for the two-particle transfer reaction ^{162}Dy → ^{160}Dy induced by 285 MeV ^{58}Ni and 638-MeV ^{116}Sn projectiles. The results are based on a partial data analysis and are not yet fully corrected for Spin Spectrometer response.

is considerably enhanced relative to the 2QP region in the Sn case when compared to the Ni case. In light of the preceding discussion an immediate interpretation presents itself. The Sn projectile is expected to have stronger pairing correlations than the Ni projectile. Thus, the enhancement of the ground band (pairing rotational) transition in the Sn reaction at the expense of 2QP transitions is a measure of the pairing enhancement of the 2-particle transfer. Furthermore, consulting fig. 2 we surmise that fig. 12 contains information about the Dy pairing primarily in the spin 6-8 region for the Ni data, and the spin 8-14 region for the Sn data.

However, it is too early to draw quantitative conclusions. First, the same reservations about partial data sets and incomplete Spin Spectrometer response corrections noted for fig. 11 apply to fig. 12 as well. Second, the energy window discussed earlier is at least partially responsible for the differences between the Ni and Sn data of fig. 12. This is primarily because the ground-ground Q is 5.7 MeV for the Ni reaction and 1.7 MeV for the Sn reaction. Preliminary estimates indicate that a factor of 2-3 for the 2QP to ground band ratios could come from pure Q-window effects when comparing the Ni and Sn data.

When the analysis is complete and kinematical factors are accounted for, we expect the data of figs. 11-12, coupled with cross sections for 2-particle transfer to discrete states which are currently being analyzed, to provide a measure of the superfluid enhancement of heavy-ion 2-particle transfer, and an indication of the effect of collective angular momentum on pairing correlations in deformed nuclei. We suggest that this is the first measurement sufficiently exclusive to provide such information for heavy-ion reactions.

VI. Rotational Signatures for Transfer to Discrete States

It has been argued that the pattern of probabilities for excitation of members of rotational bands (rotational signatures) in very heavy ion transfer reactions would be a sensitive probe of nuclear structure.[3,4] In the experiments previously described, it has been possible to measure the cross section for transfer to high-spin members of the yrast bands of deformed nuclei. The result of such a measurement is shown in fig. 13 for the reaction ^{161}Dy (^{58}Ni, ^{59}Ni) ^{160}Dy.

The key to this measurement was the use of particle-γ coincidence methods, with a banana gate placed on the yrast region of the total energy-multiplicity plane to suppress side-feeding of the yrast line in the γ-ray cascade. Once the feeding is restricted to the E2 yrast cascade, the cross sections for populating individual yrast states in the transfer can be deduced starting at the top of the cascade and correcting the measured peak areas for such things as Ge efficiencies and feeding from the preceding transition in the cascade. Such methods have been used with considerable success in heavy ion Coulomb excitation and inelastic scattering experiments.[12] The vital new ingredient is the use here of the Spin Spectrometer to suppress sidefeeding from the quasi-continuum, which is a much more serious problem for transfer than for Coulomb excitation or inelastic scattering.

Because the Spin Spectrometer has finite resolution, the total energy-multiplicity gating just described may not suppress all side feeding. The error bars in fig. 13 include an estimate of the uncertainity introduced by side feeding which circumvents the gating requirements. For the 14^+, 16^+, and 18^+ states the sidefeeding uncertainty is as large as the measurement itself, so those relative cross sections should be viewed as upper limits. Because the energies of the first two excited states of ^{59}Ni lie within the total energy uncertainty, fig. 13 actually represents the rotational signature for populating the yrast band of ^{160}Dy in the 1-neutron pickup reaction when the ^{59}Ni is simultaneously populated in its ground or first two excited states.

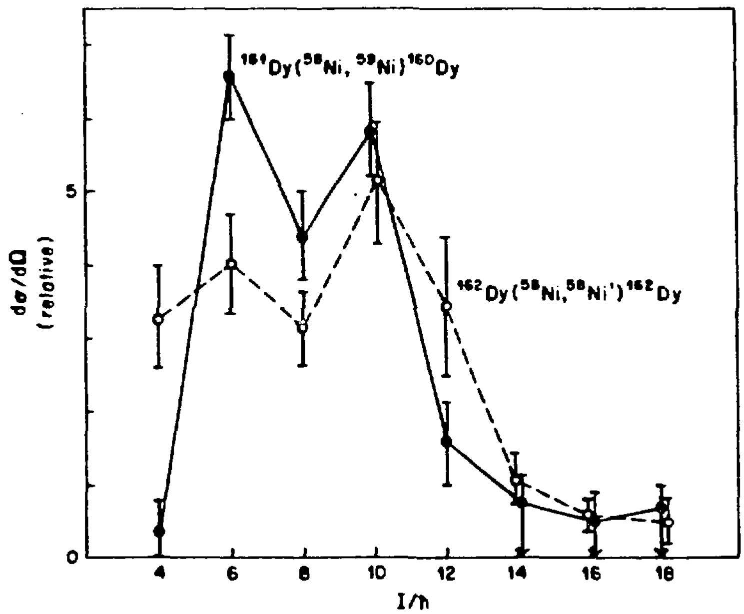

Fig. 13. Rotational signatures for the transfer reation ^{161}Dy (^{58}Ni, ^{59}Ni)^{160}Dy (E_{Lab} = 270 MeV) and for the inelastic scattering reaction ^{162}Dy (^{58}Ni, ^{58}Ni)^{162}Dy (E_{Lab} = 285 MeV). In both cases the relative cross section is integrated over the grazing angle region.

Comparing the transfer rotational signature in fig. 13 to the inelastic scattering signature, the most striking difference is the strong suppression of the 4^+ for the transfer. This suppression is much larger than expected from simple inelastic interference effects. A partial explanation may lie in the transfer energy window which would enhance higher spins over lower spins, but the difference between the 4^+ and 6^+ states appears to be too dramatic to arise solely from this. A more interesting prospect is that the pattern in fig. 13 for the transfer reaction results from the effect of the orientation angle dependent formfactor on the deformed nuclear surface which was discussed extensively in ref. 3. From the discussions of refs. 3-6, a transfer formfactor peaked near a polar angle of ~ 45° on the deformed nuclear surface would favor high-spin and suppress low-spin collective excitation, and could account for the pattern seen in fig. 13. We need more examples, and detailed calculations like those in refs. 3-6 to be certain.

VII. The Transition from Quasielastic to Deep Inelastic Reactions.

The spectrum shown in fig. 4 appears, at first glance, to be rather simple. However, under more stringent gating requirements many of the small peaks sitting just above background become more prominent and a variety of channels more complicated than inelastic scattering or 1-neutron transfer may be identified. For example, fig. 4 subject to the requirement that the multiplicity > 10 reveals the presence of ground state rotational bands for a whole series of Er isotopes. These appear to result from transfer reactions in which two protons are transferred to the heavy fragment, with several neutrons transferred simultaneously to the lighter fragment (particle evaporation may also be taking place).

The total energy and multiplicity associated with these multiparticle transfer channels appears to be intermediate between those of the simple transfer reactions discussed earlier and a component observed in the data with large multiplicity and total energy which is in coincidence with few discrete lines. This latter component is assumed to be deep inelastic in nature. Thus, these multiparticle channels appear to be a bridge between simple quasielastic processes and strongly damped ones, and are an extremely interesting subject for future study.

VIII. Summary

Before summarizing, let me mention what I consider to be the major problems still to be resolved for these reactions. We need 1) more complete understanding of how the energy and angular momentum are shared between the spherical and deformed collision partners, (2) more experience in relating multiplicity to angular momentum, and (3) a quantitative theoretical apparatus to analyze these data. These are serious questions which will be addressed further in future work. However, they do not appear to represent intractable obstacles to these studies.

In summary, we are seeing population of high-spin states with large cross section in very heavy ion transfer reactions. The spectra are remarkably clean. The data suggest that the 1 and 2 neutron transfer is occurring through a rather gentle mechanism with low total energies, little neutron emission, and near Rutherford trajectories. The transfer reactions exhibit striking multiplicity and total energy distributions which suggest direct population of both ground bands and 2QP bands. A separate multiparticle transfer component is observed which seems to provide a link between quasielastic and deep inelastic reactions. Most importantly, it appears that a quantitative study of nuclear structure is possible for these reactions. Two specific examples discussed here were evidence for an orientation angle-dependent formfactor for the transfer, and evidence for 2-particle enhancement due to the pair field.

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