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TRANSFER INVOLVING DEFORMED NUCLEI

J.O. Rasmussen, M.W. Guidry, and L.F. Canto

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Transfer Involving Deformed Nuclei

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Transfer Involving Deformed Nuclei*

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We review results of 1- and 2-neutron transfer reactions at near-barrier energies for deformed nuclei. Rotational angular momentum and excitation patterns are examined. A strong tendency to populating high spin states within a few MeV of the yrast line is noted, and it is interpreted as preferential transfer to rotation-aligned states.

1. INTRODUCTION

How appropriate that we honor Niels Bohr with a symposium on "semiclassical descriptions." The resurgence of semiclassical methods in the last decade again reminds us of Niels Bohr's superb scientific instincts. Wave equations and the new quantum mechanics of the '20's may have appeared to supplant and replace the planetary orbital ideas of the Bohr atom but the success of newer semi-classical approaches reminds us that Niels Bohr was not far from the truth with his original intuition.

2. INELASTIC SCATTERING

For heavy ion nuclear reaction theory at Berkeley the introduction to treating quantum mechanics with equations of motion, rather than wave equations, came a little more than 10 years ago. The first speaker of this symposium, Bill Miller, generously shared his insights and coached our early efforts to adapt his semi classical methods with molecules[1] to the nuclear arena. The mass scales are the same but distance scales differ by five orders of magnitude and energy and moment-of-inertia scales by ten orders of magnitude. Remarkably, the most important dimensionless parameters remain quite comparable in magnitude. Our early work dealt with the rotational signatures accompanying pure Coulomb excitation by heavy-ion beams[2]. Independent work elsewhere[3] illuminates many aspects of the new methods. Although it was

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restricted to back-angle scattering (and for practical purposes is still so restricted for deformed nuclei), Miller's methods go beyond the perennially useful Winther-deBoer semiclassical codes[4] in that the dynamical effects of the quadrupole field on the trajectory are built in naturally. By testing numerically we found that the numerical improvement over Winther-deBoer codes (another form of semi-classical treatment where particles are put on symmetrized Rutherford hyperbolic trajectories) were <10-15% for sub-barrier pure Coulomb excitation, though if nature had provided somewhat larger quadrupole distortions, the Winther-deBoer method would be compromised. Where the new Miller methods proved superior was in near-barrier excitation, when the nuclear potential tail shifted orbits away from hyperbolic. It became possible to use the rotational signatures to explore the nuclear potential tail experimentally[5]. Fig. 1 shows a contour map of the nuclear potential tail, as deduced in this work.

Let us here make the distinction between the semiclassical "root-search" methods and "projection-integral" methods[6]. In the former one solves equations of motion for a spherical projectile on a spheroidal target at many different initial orientations of the body-axis with respect to the beam direction. The curve of final rotational angular momentum vs. initial orientation is plotted, analogous to a classical deflection function of deflection angle vs. impact parameter. Miller calls this the quantum number function.

In the root-search methods one then finds the roots for initial orientation angle(s) leading to the desired final rotational angular momentum (Fig. 2). Terms dependent on the derivative of the quantum function and with phases depending on the classical action integral in units of Planck's constant $\hbar$ are added to give the amplitude for the transition in question.

In the projection-integral methods one uses the Jacobian and phase information for all initial orientations within an integrand, and the amplitude of excitation to a particular rotational state

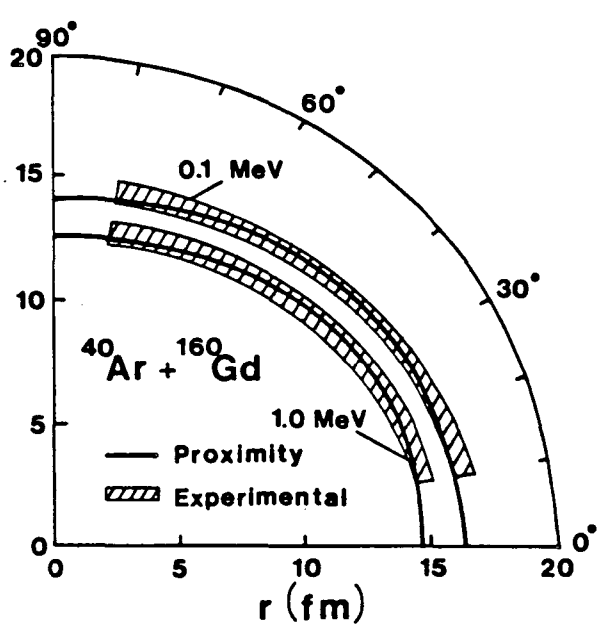

FIGURE 1
Contour map of the tail of the nuclear potential.

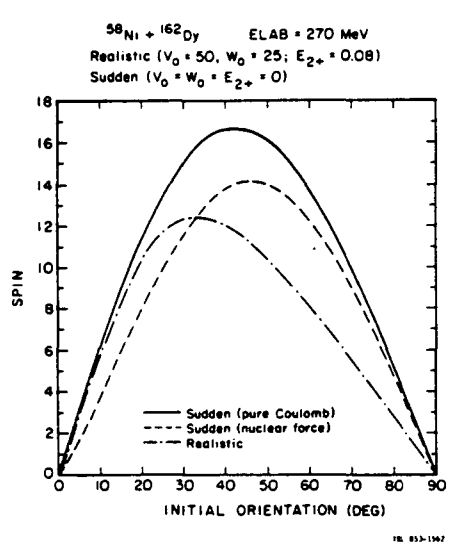

FIGURE 2
The quantum number function of rotational states.

is projected out by an angular integration with the Legendre function of the desired rotational state being within the integrand. The projection-integral methods, though complicated and not so graphic as the root-search methods, are equivalent to root-search and in some cases the preferred choice. Like the WKB methods to which they are clearly related these Miller orbital methods often seem to work better than originally expected.

A striking example is shown in Fig. 3, where excitation functions for inelastic excitation of rotational states in ^{160}Gd are calculated by the classical-limit method being discussed here, and by quantum-mechanical coupled-channels methods. Except for the classically-forbidden states the results are virtually identical. Even for the classically-forbidden states the small differences are due partially to non-essential approximations made to simplify the calculations. These results underscore the power of semiclassical methods in elucidating the essential physics of a problem. The coupled-channels calculations used ~2500 partial waves to calculate a point in Fig. 3. The classical limit method uses a few trajectories to accomplish the same thing. Repetition of the quantum-mechanical calculation using only that partial wave yields almost the same result as the full quantum mechanical calculation.

The extension of the methods from rotational inelastic scattering in the ground band to the prediction of rotational signatures for scattering to the octupole vibrational band was straightforward with the projection-integral method. The spherical harmonic Y_{30} was inserted into the projection integral as another factor[6]. This application has been slow to develop for lack of quantitative experimental data.

3. ONE-NEUTRON TRANSFER REACTIONS

Theoretical developments outlined above naturally led to attempts to apply the methods to predict rotational signatures accompanying transfer reactions on even-even deformed nuclei. With both collision partners heavy nuclei (hence, small wave- number changes, Sommerfeld parameter changes, etc.) a one-dimensional barrier penetration approach like that of Breit-Ebel[8] is possible, running trajectories for different initial orientations and considering the quantum-mechanical tunneling probability of a neutron at each point along the orbit. The tunneling can be expanded about the distance of closest approach of the two surfaces. In this approach the projection integral will be analogous to the one for octupole vibration mentioned above, except that the Y_{30} spherical harmonic is replaced by the Breit-Ebel tunneling amplitude times the surface Nilsson angular function of the active neutron orbital. It is still premature to apply the sophistication of projection integrals for transfer to deformed nuclei. We should first try to understand the emerging data in the simpler and more intuitive root-search framework.

In a deformed field the wavefunction for a particle at the nuclear surface will be concentrated in particular regions. Fig. 4 illustrates, for a typical orbit important for work we will discuss, the ^{161}Dy ground state neutron 5/2 + [642].

In the simple model for transfer employed in ref. 9 the probability of particle transfer as a function of orientation angle of the rotor depends on selecting an optimum orientation such that the nuclei overlap neither too weakly (suppressed barrier penetration) nor too strongly (suppres-

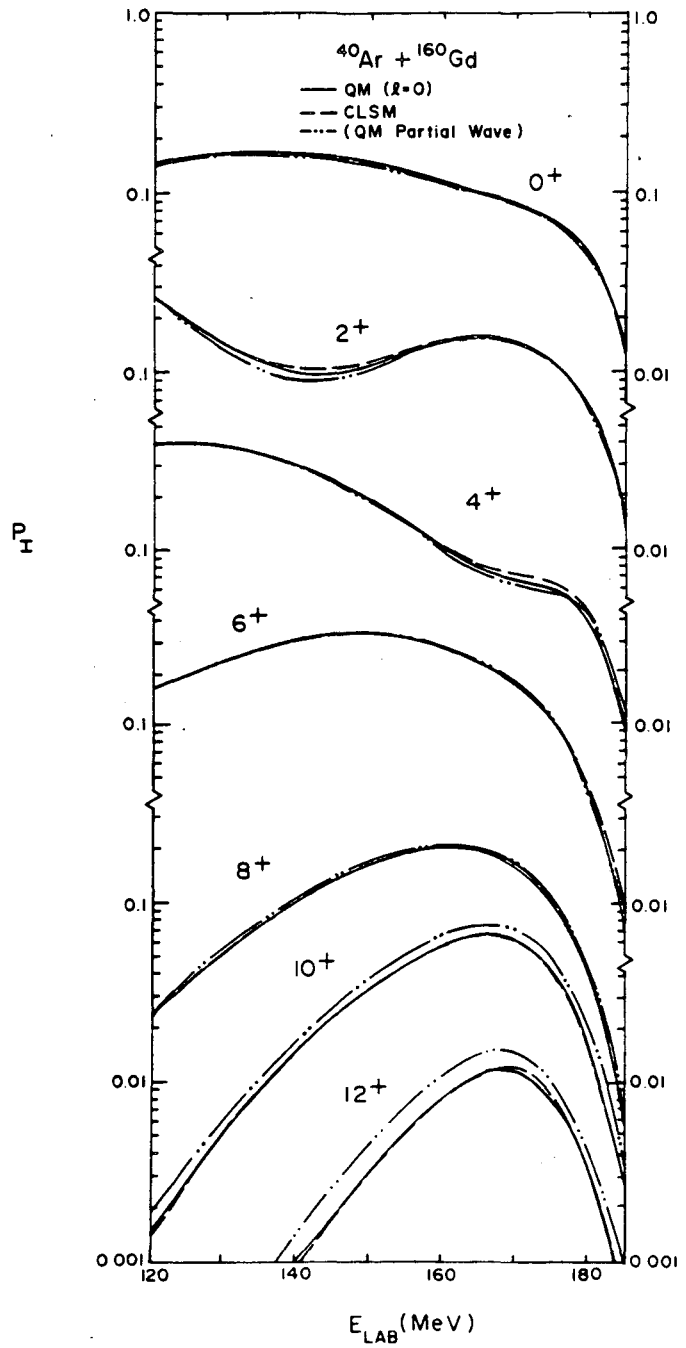

FIGURE 3
Comparison between quantum mechanical and classical-limit calculations of inelastic excitation functions of rotational states in ^{160}Gd.

sion by absorption into more complicated channels), and asking whether the relevant Nilsson orbit has lobes lying on the ion-ion axis for those orientations (see Fig. 5). If the Nilsson orbital of the transferred neutron has a dominant lobe on the surface, this fixes the process to a single root of the quantum number function and hence a fairly sharply defined value of Coulomb-excited rotational angular momentum. If there is more than one surface lobe of comparable strength, novel interference effects could arise.

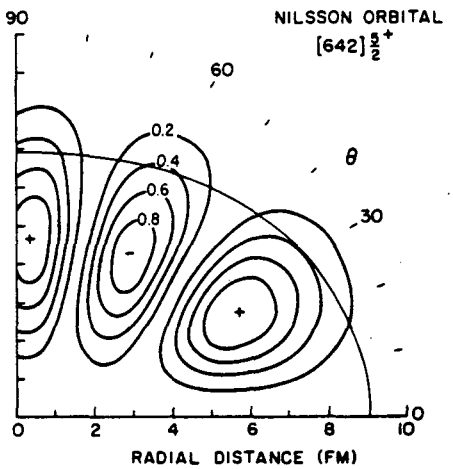

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FIGURE 4
Contour plot of the wave function of a neutron in the Nilsson orbital [642]5/2+.

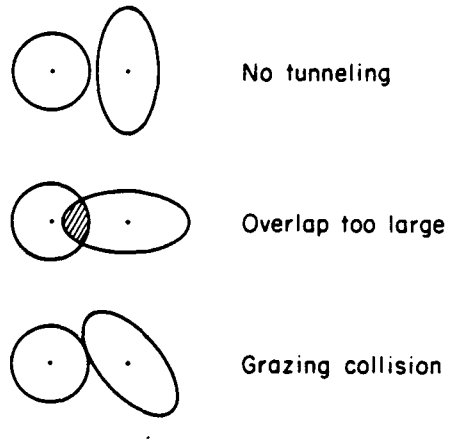

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FIGURE 5
Illustration of the optimal orientation at closest approach for transfer.

Several studies of neutron transfer with deformed nuclei have recently been reported. They generally employ high resolution gamma-ray or conversion-electron detection to identify products uniquely and to furnish information on the rotational angular momentum involved. Particle detectors do not have the mass-resolution nor energy-resolution to resolve clearly the final nuclei and the states populated for rare-earth and actinide deformed regions.

Himmele *et al.*[10] at GSI, Darmstadt, have used a novel method of conversion electron detection to study the system of ^{184}W on ^{238}U. Some of their results for 1- and 2-neutron transfer probabilities in both directions are shown in Fig. 6. The abscissa d_0 is the pure Coulomb distance of closest approach $D(A_1^{1/3} + A_2^{1/3})^{-1}$. Their tunneling slope parameters α are noted and not in the 2:1 ratio expected for 2- and 1-neutron transfer.

Macchiavelli *et al.*[11] at LBL, Berkeley, have used germanium gamma ray detection to study ^{132}Xe on ^{154}Sm, ^{176}Yb, and ^{171}Yb. Some of their results for 1- and 2-neutron transfer probabilities out of the rare-earth target are shown in Fig. 7. Note the nearly identical slopes for 1- and 2-neutron transfer, contrary to simplest expectation that the 2-neutron slope should be twice that of the 1-neutron transfer.

F.W.N. de Boer *et al.*[12] at GSI have bombarded ^{232}Th with ^{206}Pb and observed the 1- and 2-neutron transfer out of thorium. Fig. 8 shows the ratio of 2-neutron transfer to inelastic scattering for the 8+ to 6+ transition at two beam energies and several angles.

Let us look at some recent data[13] on primary populations in a one-neutron transfer reaction of a heavy deformed nucleus, namely, ^{58}Ni on ^{161}Dy. The odd neutron is in the 5/2 + [642] Nilsson orbital, plotted in Fig. 4. By use of the NaI-ball at Oak Ridge the total gamma multiplicity and total gamma energy in coincidence with particular Ge(Li) resolved gamma lines were obtained. Fig. 9 shows a contour plot of the deduced primary population density going into ^{160}Dy for the pick-up reaction on ^{161}Dy and the 2-neutron pick-up from ^{162}Dy. They show gen-

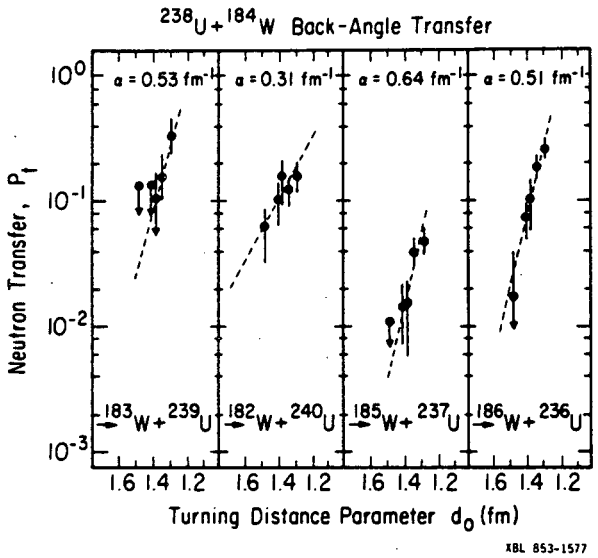

FIGURE 6
One- and two-neutron transfer probabilities in the collision of ^{238}U + ^{184}W (ref. 10) vs. parameter for distance of closest approach.

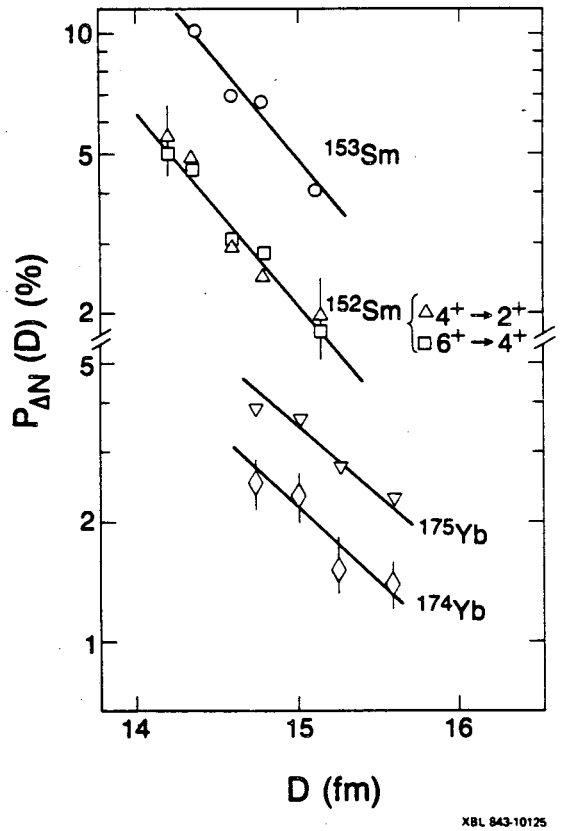

FIGURE 7
One- and two-neutron transfer for probabilities from rare-earth targets (ref. 11) vs. distance of closest approach.

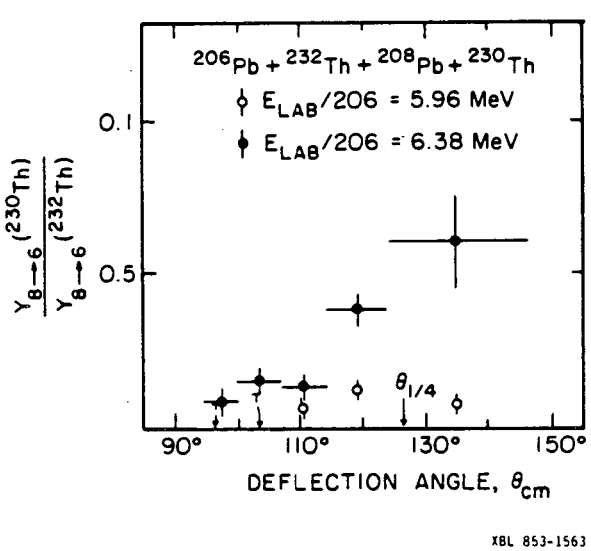

FIGURE 8
Ratio of 2-neutron transfer to inelastic scattering for the 8^+ to 6^+ transition of the ground rotational band.

erally a "cool" process, with population concentrating at or slightly above the yrast envelope for lower spins and tailing to several MeV excitation at the highest spins. That the population contours smear below the yrast line is a reflection of the finite resolution of the system.

The pattern seen in Fig. 9 can be understood in simple terms. In Fig. 10 we show the total energy of the initial system ^{58}Ni + ^{161}Dy with ^{58}Ni in its ground state and ^{161}Dy on its yrast line, and the final system ^{59}Ni + ^{160}Dy with ^{59}Ni in its ground state and ^{160}Dy in its yrast line. The transfer is most likely to occur near the point of closest approach. A reasonable estimate of the average angular momentum at the turning point for the ^{161}Dy is $I^{\pi} \sim 17/2^{+}$ A cranked shell model calculation indicates that the $\Omega = 5/2^{+}$ unpaired particle is carrying ~4 units of aligned angular momentum for this state. Thus, an average value of the core angular momentum is ~4 at transfer. We assume the transfer of the particle to be a first-order process, so the transfer must proceed to states in ^{160}Dy which also have ~4 units of core angular momentum.

Two general functions limit the regions which the transfer from the ^{161}Dy $17/2^{+}$ state can populate in Fig. 10. First, there is a Q-window which favors population of a horizontal band centered at the energy of the $17/2^{+}$ state. This window is ~5 MeV wide and approximately Gaussian. Second there is a binding energy effect. The removal of more tightly bound particles from ^{161}Dy requires penetration of a larger barrier. This yields a factor decreasing exponentially in the square root of the separation energy of the transferred neutron. We show as contours in Fig. 10 the product of these two factors for a transfer assumed to proceed from the ^{161}Dy $17/2^{+}$ state. They conspire to force transfer to states lying relatively near the ^{160}Dy yrast line. Once the transfer is made, then the final nucleus ^{160}Dy may receive further collective excitation, provided the state populated is in a collective band. In Fig. 11 a cranked shell model calculation is

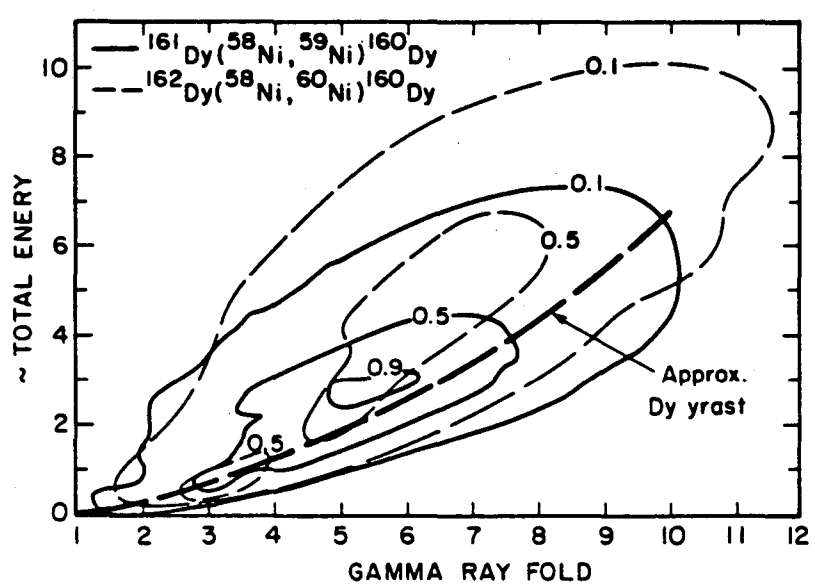

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FIGURE 9

Contour plots of the primary population density going into ^{160}Dy, for the 1-neutron pick-up reaction on ^{161}Dy and 2-neutron pick-up from ^{162}Dy. The abscissa is the "fold" or raw gamma multiplicity. Preliminary Monte Carlo corrections show for this case that "fold" and multiplicity are about the same in the region of the peaks.

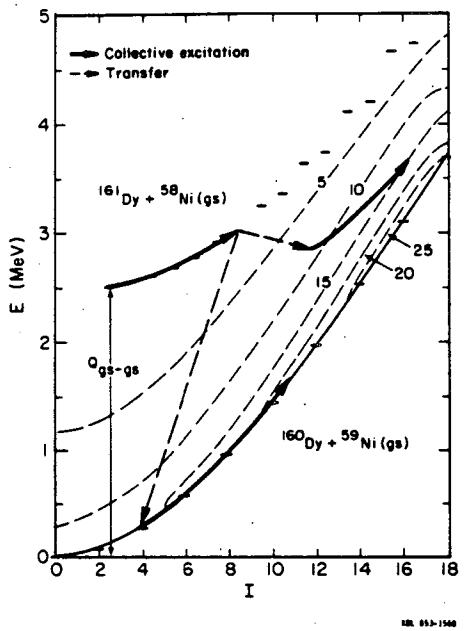

FIGURE 10
Evolution of the one-neutron transfer on the E vs. I plane. For details see the text.

shown of the lowest bands which can be formed in ^{160}Dy by removing a neutron from ^{161}Dy. Comparing Figs. 10 and 11 we see that there are no states other than the ground band lying in the energy window at low spins. (We omit collective bands such as the γ-band from this discussion.) At spins $I \geqslant 10$ the 2QP bands begin to fall within the window. Analysis of the cranked shell model calculation shows considerable alignment such that the core = 4 states in the low-lying 2QP bands lie mostly in the $I \sim 10$-14 region. Thus the reaction is favored to proceed backwards in spin to populate the ground band near $I \sim 4$, followed by collective excitation after the transfer; or forward in spin to the 2QP states near the yrast line having core angular momentum $I \sim 4$, followed by collective excitation after the transfer. Fig. 11 illustrates. Notice that the lower slope of the 2QP bands with respect to the ground band has two implications for the post-transfer collective excitation of the 2QP bands. The flatter slope means the collective excitation will be less hindered by finite adiabaticity than for the ground band. Second, the flatter slope means that once the 2QP bands are populated by transfer, the exit-channel collective excitation will tend to bring this population even closer to the yrast line.

Particle-rotor calculations[14] suggest that for $i_{13/2}$ orbits the pickup of a single neutron from ^{161}Dy will have largest spectroscopic factors for the maximally aligned states. This would also tend to force the 2QP population to the right in Fig. 10. However, the calculations of ref. 14 assumed a strong-coupled ^{161}Dy state, and they should be repeated to assess the importance of alignment on that orbit in the present context.

Based on these ideas we offer the following interpretation of Fig. 9: The peak at lower multiplicity corresponds primarily to direct transfer to the ground band of ^{161}Dy, with the ^{59}Ni left in its ground state or low-lying excited states. The larger peak near multiplicity 6 and just above the ^{160}Dy yrast line represents strong population of low-lying 2QP states in the transfer, with Ni

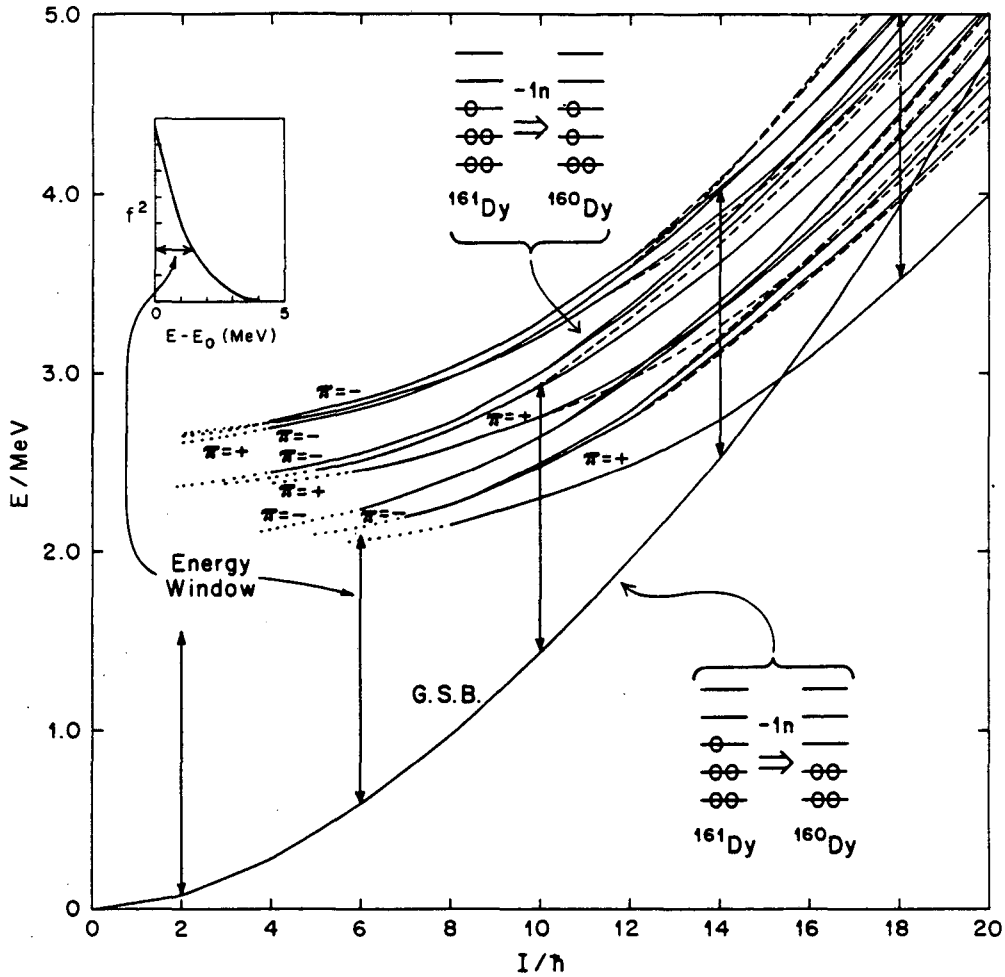

FIGURE 11

Levels of a Cranked Shell model calculation, where the excited bands plotted have one or both odd neutrons in the [642]5/2$^+$ orbital of the ^{161}Dy ground state. The signs label parities, while the dashed and solid branches are the levels of different signature. The inset plots the energy rate factor, which is the product of an exponentially decreasing neutron penetrability and the Q-window factor.

left in low-lying states. These states have large alignments, since a least one of the quasiparticles is in the orbit arising from the $\Omega = 5/2$, $i_{13/2}$ orbit. The addition of the angular momentum associated intrinsically with the transfer to aligned states accounts for the multiplicity (spin) gap between the lower and upper peaks.

4. TWO-NEUTRON TRANSFER REACTIONS

Now consider 2-neutron transfer. Fig. 9 shows a superposition of the total energy and multiplicity plots for the reactions ^{161}Dy(^{58}Ni,^{59}Ni)^{160}Dy and ^{162}Dy(^{58}Ni,^{60}Ni)^{160}Dy (ref. 13 and unpublished). In this case the data have not been corrected for response of the Spin Spectrometer, except to shift the energy scale to approximately compensate for detection efficiency. However, the only significant effect of this omitted correction would be to improve the resolution. In particular the axis labeled "fold" may be read as "multiplicity." An approximate Dy yrast

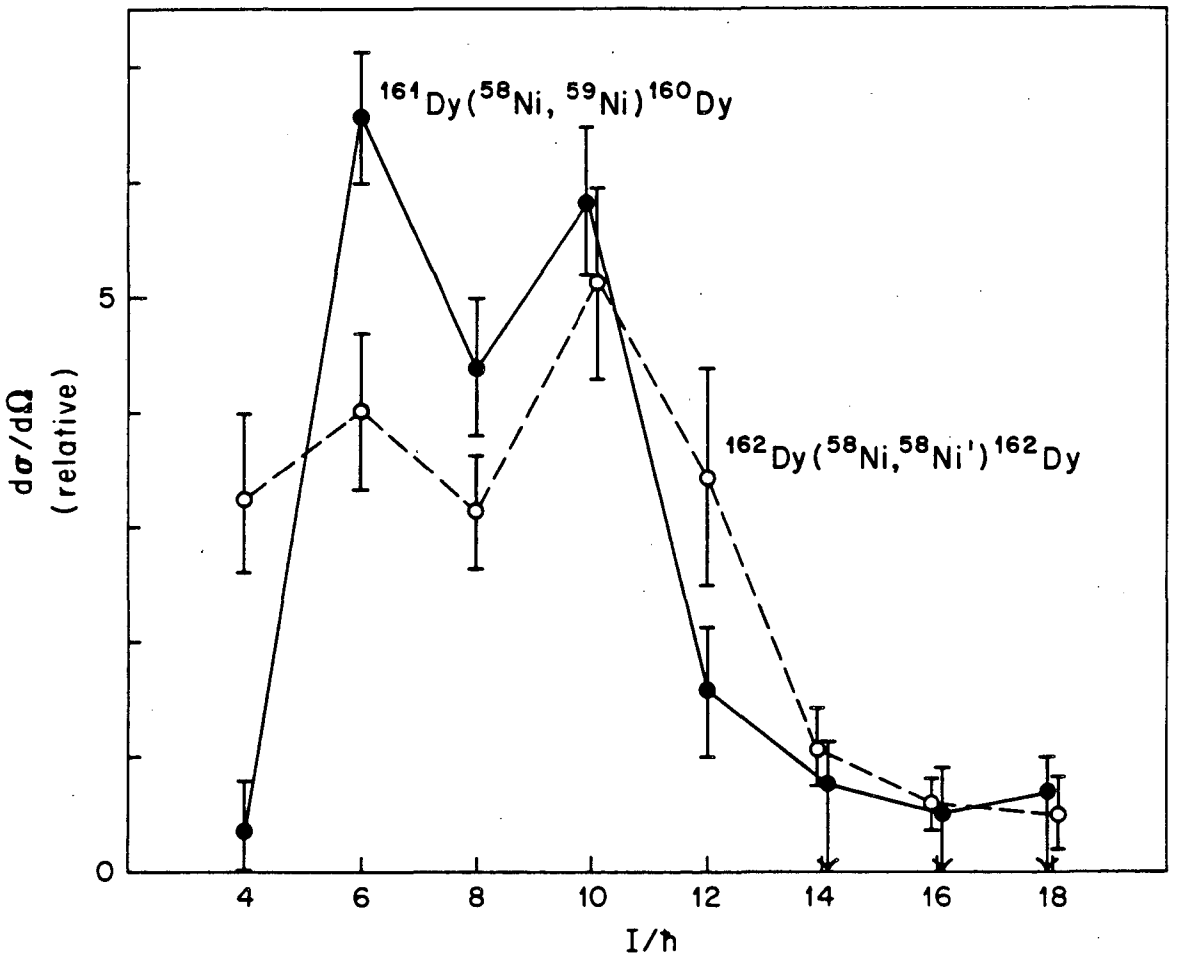

FIGURE 12
Rotational Population signature for 1n transfer and for inelastic scattering.

line assuming no excitation of Ni is shown.

It is immediately clear that both distributions display the same general features: a secondary maximum near multiplicity ~3 (that this is a maximum is more apparent in the unfolded spectrum. Figs. 9 shows the similarity for one- and two-neutron transfer of a primary maximum at larger multiplicity, and a distribution with most of the population within 2-3 MeV of the yrast line. However, there are also obvious differences between the two. The 2-particle transfer distribution peaks at higher multiplicity and total energy and exhibits a tail of events extending to even higher multiplicity and total energy.

We may interpret the 2-particle distribution in the same manner as we just interpreted the 1-particle case. However, there will be some differences. First, the ground-state Q-value is +5.7 MeV in this case, compared to +2.5 MeV in the 1-particle transfer. Second, if we assume the transfer to proceed by the lowest possible order, it is no longer necessary that any 2-QP states populated in ^{160}Dy involve the cranked shell model orbit arising from the $\Omega = 5/2$ orbit. However, the other lightly bound neutron orbitals also have major lobes at intermediate latitude (45° ± 20°), so large Coulomb excitation is favored. Third, the yrast line of ^{162}Dy is more parallel to the ^{160}Dy yrast line than is the ^{161}Dy yrast line. These differences will tend to force the 2-QP

population to higher energy and to higher angular momentum in the 2-particle case relative to the 1-particle case, as suggested by Fig. 9.

Thus, the lower peak of the $^{162}Dy \rightarrow {}^{160}Dy$ distribution represents direct population of the ground band, and the upper peak represents population of 2-quasiparticle states. We interpret the extension of the $^{162}Dy \rightarrow {}^{160}Dy$ distribution to higher energies and multiplicities than the $^{161}Dy \rightarrow {}^{160}Dy$ case as primarily a Q-value effect, but more detailed calculations and other experiments may be needed to confirm this.

Based on this analysis, some qualitative remarks are in order concerning the use of heavy-ion reactions to study pairing enhancements and the conjectured collapse of pairing in heavy nuclei. Related comments have been made by others.[15] These results illustrate clearly that a measurement of total 2-particle transfer cross section has very little to say about pairing (we use the term to mean L = 0 pairing). In the case discussed here, there is significant 2-particle transfer, but the larger portion of it appears to be transfer to excited states involving broken pairs. Only the part of the population in the weaker low-multiplicity peak is likely to be related to the traditional picture of enhanced pair transfer (pairing rotational transitions) between two pairing condensates.

In fact, we may conjecture that a measure of the importance of pairing in a heavy deformed nucleus is afforded by comparing the total energy-multiplicity distribution for inelastic scattering to that for 2-particle transfer. If the transfer proceeds through the exchange of $L \sim 0$ pairs, the transferred particles contribute little to the angular momentum, and the range of angular momenta and energy populated in the transfer should be comparable to that of inelastic scattering. If the reaction involves transfer of broken pairs, we may expect a distribution extending to higher energy and multiplicity than that for inelastic scattering. Thus, a significant deviation of the transfer distribution from the corresponding inelastic distribution, once corrections for effects such as differing Q-windows are applied, may be a clear signal of the suppressed importance of pairing.

5. ROTATIONAL SIGNATURE FOR TRANSFER TO HIGH-SPIN STATES

By gating in the (E,M) plane to exclude the feeding from the quasicontinuum, a Ge spectrum may be constructed for direct population of the Dy yrast states. The cross sections for direct population of individual yrast states may be deduced from this Ge spectrum by correcting for feeding beginning at the highest state seen. Some results are shown in Fig. 12 (ref. 13) along with the corresponding cross sections for the inelastic scattering reaction $^{162}Dy(^{58}Ni,^{58}Ni')^{162}Dy$, which should be quite similar to that expected for $^{160}Dy(^{58}Ni,^{58}Ni')^{160}Dy$. As the $2^+ \rightarrow 0^+$ transition is highly converted, only states with $I^{\Pi} \geqslant 4^+$ are shown.

The resolution of the Spin Spectrometer is insufficient to separate the ground and first two excited states of ^{58}Ni. Therefore, Fig. 12 represents the cross section for populating Dy ground band states when either the $p_{3/2}$, $f_{5/2}$, or $p_{1/2}$ Ni orbital is populated.

The most striking feature of the transfer cross sections is the dramatic suppression of the 4^+ state relative to that seen in inelastic scattering. We note also that the E-M distributions in Fig.

9 support (at lower resolution) the suppression of low spin states in the transfer data. Such a minimum is too deep to be explained by the standard interferences giving the oscillating cross sections for inelastic scattering. A possible explanation is the geometrical surface form factor for transfer discussed in ref. 9. Population of the ground band of ^{160}Dy requires pickup of the [642] $5/2^+$ neutron from ^{162}Dy, if we assume a Nilsson model. For maximum transfer probability from this orbit, the combination of damping by the imaginary potential, barrier penetration effects, and distribution of the single-particle wavefunction on the surface should favor a collision between the heavy ions with approximately a 45° angle between the symmetry axis of the rotor and the line joining the ions at closest approach, thus enhancing high collective angular momentum transfer and suppressing population of low spin states. This is a plausible explanation for the extremely low 4^+ cross section shown in Fig. 12.

6. EVIDENCE FOR TRANSFER TO HIGHLY EXCITED STATES

There have been several two-nucleon transfer studies involving spherical single-closed-shell nuclei (Sn on Sn neutron transfer[15] and 50-neutron isotones on each other to give proton transfer,[16] including single and multiple), and we shall mention and contrast the neutron transfer work later. First, let us look at the data for deformed nuclei. Himmele *et al.*[10] have reported studies on 1- and 2-neutron transfer in both directions for W-184 on U-238. They identify products by the conversion electrons from the first-excited state of the backward-going W nucleus, and may also select on events with considerable excitation of the uranium by measuring coincidences with forward-going fission products. Macchiavelli *et al.*[11] reported 1- and 2-neutron transfer with ^{132}Xe on Sm and Yb isotopes. They observe discrete gamma rays of the rotational bands of product nuclei in coincidence with the projectile-like product measured in position-sensitive detectors. In both of the above studies it was possible to plot the logarithm of the ratio of transfer probability to inelastic scattering. The horizontal axis is the distance of closest approach, calculated classically from Rutherford hyperbolic trajectories. In the W + U work the back angle was fixed, and several bombarding energies near barrier were used. In the Xe + R.E. work the bombarding energy was fixed, but the gamma spectra could be analyzed as a function of angle of the Xe outgoing particle. Fig. 7 is from Macchiavelli *et al.*, and Fig. 6 is adapted from Himmele *et al.* Whether one considers sequential neutron transfer or simultaneous transfer as a "di- neutron" cluster the simplest theory predicts that the slope of the 2-neutron probability should be twice as steep as the 1- neutron transfer, assuming both have Q-values near zero. This factor of two is not seen in either of the above studies , the slopes for the two different processes being generally comparable. In both these papers the slope problem is explained in terms of "intermediate states with 6-12 MeV excitation energy."

At first thought the notion that the two neutrons to be transferred somehow selectively get such an amount of the translational kinetic energy concentrated on them seems most curious. Obviously it could not be a random thermal excitation to concentrate this much energy on the transferring nucleons. We were at first attracted to the idea that pairing forces can explain the slope problem. To be sure if one simply thinks of simultaneous transfer as a dineutron, with its

energy gain from the pairing force the same whether inside or outside a nucleus, the slope is the same. However, if one thinks of the neutrons to be transferred as less tightly correlated inside the nucleus than they are by geometrical constraint while tunneling the barrier between the two nuclei, then the energy gain from turning on a pairing force could be greater in the barrier than out. The pure pairing explanation for the slope similarities should, however, equally well apply to deformed or spherical single-closed-shell nuclei. Yet in the case of Sn + Sn the 2:1 slope relationship expected from simple considerations holds,[15] and in the 50-neutron isotone proton transfer various ratios are obtained.[16] In the Sn + Sn case the expected slope relationship sets in only at rather larger turning distances than measurable in the studies on deformed nuclei. Thus, we do not know how significant the differences are. In refs. 10 and 11 the slope problem was said to arise from a selective excitation of the transferred neutron pair to 6-12 MeV of excitation energy. These numbers should not be taken literally, since the model implies this excitation energy is independent of distance-of-closest approach. While incipient neck formation or cluster break-up could provide selective excitation at the interface, the evidence is too sparse to draw conclusions at present.

7. CONCLUSION

There clearly are interesting data beginning to come from transfer reactions on deformed nuclei using heavy ions. It would appear from the discussion contained here that to extract much quantitative information from such experiments the particle-γ coincidence spectra being recorded must be supplemented by information on the region of the energy-angular momentum plane being populated by the reaction. At present the best techniques for doing that seem to involve the "crystal ball" NaI (or bismuth germanate) arrays capable of detecting total γ-ray energy and multiplicity.

By employing such methods it seems that a quantitative spectroscopy is possible, which can provide important information about the effect of collective excitation on single-particle motion and pairing in nuclei. In the experiments done to date, and in those to be done in the future, the suggestion of which experiments to do and the interpretation of the resulting data depend crucially on the physical insight afforded by semiclassical methods.

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