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Evidence for oscillating two-neutron transfer probabilities at large radial separation in heavy-ion reactions

C. Y. Wu,[(a),*] X. T. Liu,[(a)] W. J. Kernan,[(b)] D. Cline,[(b)] T. Czosnyka,[(b),†] M. W. Guidry,[(a),(c)] A. E. Kavka,[(b)] R. W. Kincaid,[(a)] B. Kotlinski,[(b)] S. P. Sorensen,[(a),(c)] and E. Vogt[(b)]

[(a)]*Department of Physics, University of Tennessee, Knoxville, Tennessee 37996*

[(b)]*Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627*

[(c)]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830*

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The populations of the ground-state band and the two-quasiparticle bands in ^{160}Dy were approximately separated for two-neutron pickup reactions using ^{58}Ni and ^{116}Sn ions. The two-quasiparticle transfer probability falls exponentially at large distance, but the ground-band two-neutron transfer exhibits apparent oscillations which are interpreted as the interference between scattering from different spatial orientations of deformed nuclei. These results appear to resolve the heavy-ion two-neutron transfer slope anomaly.

Several groups have investigated one- and two-nucleon heavy-ion transfer probabilities as a function of radial separation between the ions in the collision.[1-7] At large ion-ion separations the radial behavior of the form factor is governed by the exponential form of the bound-state wave functions and the probability for transfer is expected to be

$$P \sim e^{-\alpha R_{\min}}, \tag{1}$$

where $\alpha = 2(2\mu E_B)^{1/2}/\hbar$, E_B is the effective mean binding energy and μ the reduced mass of the transferred particles, and $R_{\min}$ is the classical distance of closest approach, which can be related to the scattering angle for sub-barrier reactions. Assuming E_B to be the average separation energy and Eq. (1) to be valid, one expects that the one- and two-neutron transfer slope parameters α are related by

$$\alpha_{2n} \simeq 2\alpha_{1n} \tag{2}$$

for transfer between low-lying states, irrespective of whether the two neutrons are transferred as a cluster or sequentially.

For a variety of heavy-ion reactions the data exhibit an exponential dependence on the distance of closest approach as given in Eq. (1). The one- and two-neutron transfer slope parameters obey Eq. (2) when both collision partners are spherical,[1,2] whereas a large departure from the expected behavior is observed for neutron transfer reactions with very heavy ions in which at least one of the collision partners is deformed;[3,4,6,7] in these cases $\alpha_{2n} \simeq \alpha_{1n}$.

This puzzling behavior has been observed for many deformed systems, and we will term it the two-neutron transfer (TNT) slope anomaly. Initial attempts to explain the anomaly invoked large intrinsic excitation energies ($\simeq$10 MeV) associated with the TNT process. In Ref. 7 we demonstrated that this explanation of the TNT slope anomaly in terms of intrinsic excitation was not likely to be correct, and that the slope anomaly exhibits a pronounced dependence on the angular momentum of the state populated in the transfer. In this paper, we report on the apparent resolution of this puzzle: *The slope anomaly results from a superposition of two independent components of the transfer population.* The first component dominates the transfer cross section near the grazing angle and is associated with population of two-quasiparticle bands. The radial dependence of the probabilities for this component is in reasonably good agreement with Eqs. (1) and (2). The second component is associated with transfer to the ground-state rotational band. It is a small fraction of the transfer cross section at the grazing angle, but accounts for about half the total two-neutron transfer at large distances. This component exhibits a slowly decaying oscillation, in disagreement with Eqs. (1) and (2).

The experiments were carried out by bombarding 540–600 μg/cm^2 self-supporting ^{162}Dy targets with 285 and 345 MeV ^{58}Ni and 637-MeV ^{116}Sn ions in the spin spectrometer of the Oak Ridge National Laboratory Holifield Heavy-Ion Research Facility. The target was enriched to 96.26% ^{162}Dy with a 0.80% ^{160}Dy contamination. The spin spectrometer comprised 4–14 Ge detectors (most of them Compton-suppressed) and 55–66 NaI elements operated in coincidence with two position-sensitive parallel-plate avalanche counters (PPAC's), which were used to measure the scattering angles and time of flight for beamlike and targetlike ions in kinematic coincidence. As discussed in previous publications,[7-10] exit channels were identified by the discrete γ rays observed in the high-resolution Ge detectors while the NaI elements of the spin spectrometer provided information on the entry states.

The timing of the NaI detectors was used to discriminate between the neutrons and γ rays, and a neutron multiplicity (K_n) was established; K_n is expected to be a sensitive indicator of the internal excitation energy of the reaction products. The total kinetic energy loss (TKEL) was also deduced from the particle detector information assuming two-body kinematics. Although the resolution of the TKEL is limited to about 30 MeV by the target thickness, that is sufficient to distinguish the quasielastic from

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the deep inelastic events. Only events with $K_n = 0$ and TKEL > -50 MeV are included in the following discussion, which insures that the analysis focuses on quasielastic events. We estimate that uncertainties associated with this gating introduce errors of 10% or less in the quantities to be discussed.

Typical Doppler-shift-corrected Ge spectra are dominated by the discrete transitions of ^{162}Dy from the inelastic channel for distant collisions. For grazing collisions, discrete transitions of ^{160}Dy from the two-neutron pickup reaction channel were seen up to $\simeq 16^+ \rightarrow 14^+$ with an intensity about 5% of that for the inelastic channel. Figure 1 shows the sum-energy spectra of the NaI elements of the spin spectrometer gated on the ground-band $4^+ \rightarrow 2^+$ transitions in the Ge spectrum for both ^{162}Dy (inelastic channel) and ^{160}Dy (two-neutron pickup-reaction channel). Two distinct areas are observed for the two-neutron transfer channel. The discrete states observed in the lower-energy region (< 1.5 MeV), which resemble those of the inelastic channel, correspond to the population of the ground-state band and the continuous structure in the higher-energy region corresponds primarily to the population of two-quasiparticle (2-qp) states.[8]

The ratio of the particle singles events relative to the calculated Rutherford cross section for the present experiments is illustrated in Figs. 2(a) and 2(b). The discussion will be limited to those scattering angles where it is clear that the ratio is nearly unity and the classical Rutherford trajectory is valid. Then the transfer probability can be defined as

$$P = [(1+\epsilon)/\varepsilon](Y/N_{\mathrm{single}}) , \qquad (3)$$

where Y is the γ-ray yield of the $4^+ \rightarrow 2^+$ transition of ^{160}Dy, ϵ and ε are, respectively, the internal conversion coefficient and the absolute efficiency of the Ge detectors for this transition, and N_{single} is the number of heavy-ion singles counts. Shown in Figs. 3(a)–3(c) are the resulting transfer probabilities versus the distance of closest approach assuming Rutherford trajectories. The $d\sigma/d\sigma_{\mathrm{Rutherford}}$ information was lost for the case shown in Fig. 3(b). It was assumed that the reaction at 345 MeV corresponds to Rutherford scattering for classical closest-approach separations larger than 14 fm. It has been shown to be the case for those separations at 285 MeV [Fig. 2(a)]. The absolute scale was established by comparing the observed inelastic excitation with a Coulomb excitation calculation for forward scattering angles.

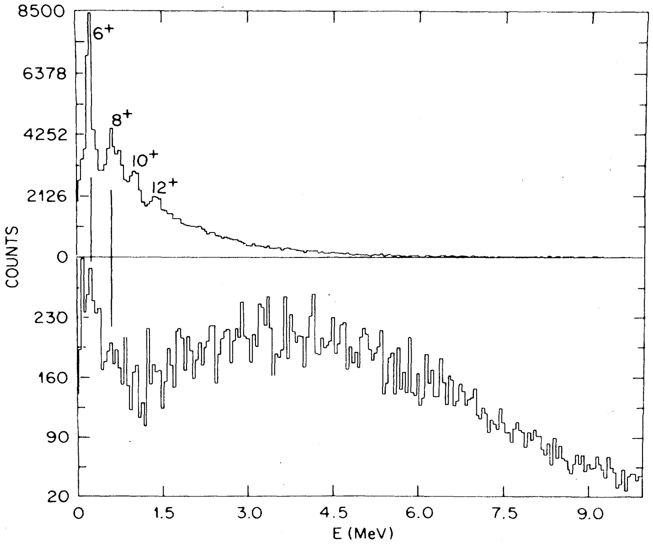

FIG. 1. Projected total γ-ray energies for the inelastic channel (top) and two-neutron pickup reaction channel (bottom) for ^{58}Ni + ^{162}Dy at 285 MeV.

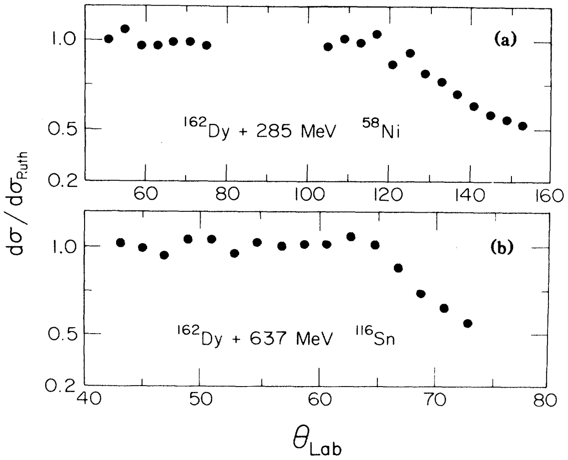

FIG. 2. The ratios $d\sigma/d\sigma_{\mathrm{Rutherford}}$ as a function of the scattering angle.

Coulomb excitation calculations indicate that the sum of probabilities for states with spin above 4^+ in the inelastic channel accounts for about 70–90% of the total population for the grazing angle region, so the yield of $4^+ \rightarrow 2^+$ should sample the true probabilities. That is, the collective excitation is assumed to be so strong that transfers to the ground-band 0^+ and 2^+ states have small probabilities. The data were corrected for target contamination of ^{160}Dy, which was measured by Coulomb excitation to be $0.13 \pm 0.02\%$. The magnitude of corrections for the probabilities ranged from $\simeq 60\%$ for the case of the ground-state band population in Fig. 3(a) at large separation to negligible for the case in Fig. 3(c) for grazing collisions. The contamination originating from one-neutron transfer reactions on the target impurity ^{161}Dy (1.22%) accounted for less than 10% of the yield in the two-neutron transfer channel according to a similar experiment on a ^{161}Dy target, and was neglected. The large number of Ge detectors effectively averaged over the γ-ray angular distributions and no correction was made for nonisotropy of γ rays; we estimate less than a 1% error introduced by this assumption.

The population of 2-qp bands was approximately separated from that of the ground-state band by gating on the summed NaI energy; the boundary between these gates varied from 1.1 to 1.4 MeV for cases shown in Fig. 3. The population of the ground-state band should include Dy states up to 8^+ or 10^+ for the above gates for events where the projectilelike ion is in the ground state.

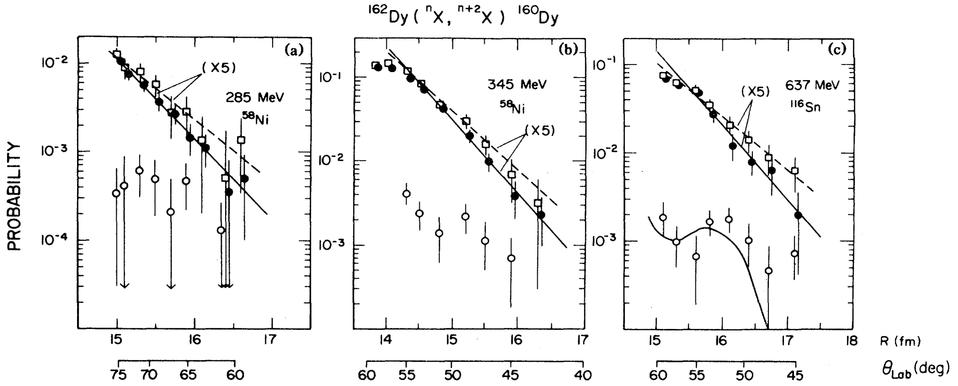

FIG. 3. Radial behavior for two-neutron transfer reactions. Shown for each case are the probability for two-neutron transfer to the ground-state band (open circles), the 2-qp bands (closed circles), and the sum of these two (open squares). The probabilities are defined in Eq. (3), and the distance is determined from the measured scattering angle assuming classical Rutherford trajectories. The dashed and solid lines are the best fits of straight lines through the data for total and 2-qp, respectively. The slope parameters for the total and 2-qp are 1.5 ± 0.2 and 1.9 ± 0.2, 1.6 ± 0.2 and 2.0 ± 0.2, and 1.3 ± 0.1 and 1.9 ± 0.3 for (a), (b), and (c), respectively. The undulating solid curve in (c) is the summed probability of 4^+, 6^+, and 8^+ from the calculation of Ref. 11. All probabilities are plotted on an absolute scale, but displaced by the factors shown for clarity.

The two-neutron transfer probability to 2-qp bands falls exponentially with radial distance at large separations in all three cases, and the experimental slope parameters ($\simeq 2.0$) approach the values ($\simeq 2.4$) expected using two-neutron separation energies in Eq. (1). In contrast, the transfer probability to the ground band exhibits an oscillatory behavior. This behavior is well reproduced [see Fig. 3(c)] by the calculations of Landowne, Price, and Esbensen,[11] who have interpreted the oscillation as the interference between different spatial orientations of the deformed nucleus in the transfer process. Such interferences were predicted for these reactions in Ref. 12. If, instead, one attempts to fit the form (1) to these data, the slope parameters vary from 0 to 0.78.

The calculations appear to underestimate the transfer probability at the large distance. However, we note that this conclusion rests primarily on a single data point at $\simeq 17.1$ fm in Fig. 3(c), and that there is an uncertainty of about 0.2 fm in R due to the finite angular resolution of the detectors. We conclude that the quantitative agreement between the calculation and the data is satisfactory, except possibly at the largest distances (corresponding to probabilities $\sim 10^{-3}$). It would be interesting to investigate the transfer at even larger separations to see if the ground-band transfer continues to decay as slowly as suggested in Fig. 3.

A comparison of the total, ground-band, and 2-qp curves in Fig. 3 indicates the source of the apparent slope anomaly reported in earlier TNT measurements: those inclusive experiments failed to resolve the ground-band and 2-qp components. The 2-qp component decays with the simple behavior expected from Eqs. (1) and (2), presumably because the 2-qp population is a superposition of many excited states which washes out interference effects. The ground-band component retains interference effects because it is dominated by only a few states [cf. the calculation of Ref. 11 presented in Fig. 3(c)]. It is clearly inappropriate to apply the simple formulas (1) and (2), which result essentially from binding energy arguments, to the ground-band transfer where the nuclear structure (deformation) is asserting itself in the form of interference effects. It has previously been established[7–10] that the 2-qp transfer tends to populate higher angular momentum states than the ground-band transfer. Therefore, these results also give an explanation for the disappearance of the slope anomaly as the angular momentum of the states populated in the transfer reactions increases.[7] Finally, we note that a recent application of these same techniques to Sn + Sn two-neutron transfer indicates no slope anomaly[13] (see also Refs. 1 and 2). This is consistent with the present interpretation of the anomaly as an interference effect specific to the structure of deformed nuclei.

In conclusion, we have shown that the large-distance probabilities for two-neutron transfer in the reactions ^{162}Dy(^{58}Ni, ^{60}Ni)^{160}Dy and ^{162}Dy(^{116}Sn, ^{118}Sn)^{160}Dy exhibit the expected exponential dependence for transfer to the two-quasiparticle bands, but oscillations, interpreted as an interference between scattering from different spatial orientations of deformed nuclei, are observed for transfer to the ground band. We suggest that the superposition of these two disparate behaviors is a plausible explanation for all previously reported anomalies in two-neutron transfer reactions with heavy ions on deformed nuclei.

Finally, we remark that it is not surprising that Eqs. (1) and (2) sometimes fail; rather the surprise is that such a prescription works as often as it does. We might expect that whenever detailed nuclear structure influences transfer reactions Eqs. (1) and (2) may fail, both for one- and two-particle transfer. We have demonstrated a specific example here; it is of considerable interest to see if there are others since such behavior indicates that the reaction is sensitive to more than gross binding energy and kinematic matching effects.

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[*] Present address: Nuclear Structure Research Laboratory, University of Rochester, Rochester, NY 14627.

[†] Present address: Heavy Ion Laboratory, University of Warsaw, Hoza 69, 00-681 Warszawa, Poland.

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