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Two-neutron pairing enhancement factors

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The Spin Spectrometer was used to separate Dy ground-band and two-quasiparticle populations in one- and two-neutron transfer reactions with Sn and Ni projectiles. Transfer probabilities $P_{1n,2n}$ and two-neutron enhancement factors $F \equiv P_{2n}/P_{1n}^2$ were determined as a function of scattering angle. For the two-quasiparticle bands $F \simeq 7-20$, but for the ground band $F \simeq 30-500$, indicating large pairing effects in two-particle transfer to the ground band. The data also indicate larger enhancement factors in Sn than in Ni collisions.

The enhancement of two-nucleon transfer cross sections by factors of approximately 50 over that expected from uncorrelated transfer of two particles is well documented in (t,p) or (p,t) reactions on superfluid nuclei.[1] In the collision of two superfluid heavy ions it is expected that the enhancement could be considerably larger due to the strong pairing correlation in both interacting nuclei.[2] Various experiments have attempted to study two-particle transfer in the collision of two heavy nuclei[3–8] and typically have measured enhancement factors for these collisions which are comparable to those for (t,p) or (p,t) reactions. These experiments had low energy resolution, and thus there was little information as to which states were being populated in the reaction. In some cases these measured quantities have then been scaled up, based on indirect theoretical arguments about the number of states populated, to give enhancement factors of order 10^2–10^3. These numbers are not a direct measurement, however.

In this paper we report on the measurement of transfer probabilities with sufficient resolution to distinguish transfer to the ground-state band from transfer to other bands. We find that transfer to these two regions are distinct components of the total population, and that they have very different enhancement factors. The bulk of the reaction, $>80\%$, populates two-quasiparticle (2QP) bands with enhancements of $\simeq 7-20$, whereas the transfer to the ground band is found to have enhancement factors $\simeq 30-500$. Thus the *average enhancement* for all bands populated is small ($\simeq 50$), but the enhancement for the pairing rotational transition to the ground-state band is large, indicating that collisions between two heavy ions may approximate the scattering of two macroscopic superfluid objects.

The reactions studied were ^{162}Dy(^{116}Sn,^{118}Sn)^{160}Dy and ^{161}Dy(^{116}Sn,^{117}Sn)^{160}Dy at $E_{\rm lab}=637$ MeV; ^{162}Dy(^{58}Ni,^{60}Ni)^{160}Dy and ^{161}Dy(^{58}Ni,^{59}Ni)^{160}Dy at $E_{\rm lab}=345$ MeV. Experiments were performed using the Spin Spectrometer of the Holifield Heavy Ion Research Facility. The Spin Spectrometer consisted of eight Compton suppressed Ge detectors and 61 NaI elements (for the ^{116}Sn experiment) and four unsuppressed GeLi detectors and 66 NaI elements (for the ^{58}Ni experiment); it was operated in coincidence with four 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,[9–16] exit-channel states were identified by the discrete γ rays observed in highresolution Ge detectors, and the Spin Spectrometer was used to provide crucial information on entry-state energy and angular momentum. The Ge spectra were corrected, on an event-by-event basis, for Doppler shifts using the PPAC information. The timing of the NaI detectors was used to resolve neutrons from γ rays by time of flight and this was used to remove events corresponding to neutron multiplicity $K_n > 0$ from the data set to be discussed. Figure 1 shows the Q-value spectra determined from scattering angles and two-body kinematics gated on K_n for the reaction ^{162}Dy+^{116}Sn; this gating eliminates almost all events corresponding to large energy loss, such as those from deep inelastic scattering.

We gated on the projected total energy of the γ rays from the NaI elements of the Spin Spectrometer for the one- and two-neutron pickup reactions in order to approximately separate the direct population of the ground band from the population of excited states. A more detailed description of this gating method may be found in Ref. 14. Events labeled "G band" in the following discussion correspond primarily to transfer to the ground-state band of ^{160}Dy below spin 10, with negligible excitation in the exit-channel projectilelike ion. Events labeled "2QP" primarily correspond to transfer to excited 2QP DY states, with or without excitation of the projectilelike ion; a smaller component corresponds to simultaneous population of the ground band in Dy and excited states in Ni or Sn. Thus, those events labeled G band correspond to transfer reactions populating low-lying projectile and target states, while those labeled 2QP correspond to transfer reactions populating intrinsically excited states in the targetlike and/or projectilelike ion.

In the lower part of Fig. 2 we show the ratio $d\sigma/d\sigma_R$ of the particle singles events to the calculated Rutherford cross section for the reactions studied here. Subsequent analysis will be confined to that angular range where $d\sigma \simeq d\sigma_R$. Therefore, it is legitimate to assume Rutherford trajectories and introduce an experimental transfer probability P through the definition

$$P = [(1+\alpha)/\epsilon](Y/N_{\text{single}}) , \qquad (1)$$

where Y is the γ-ray yield of the $4^+ \rightarrow 2^+$ transition of ^{160}Dy, α and ϵ are, respectively, the internal conversion coefficient and the absolute detection efficiency of the Ge detectors for this transition, and N_{single} is the number of heavy-ion singles counts.

The upper part of Fig. 2 shows one- and two-particle transfer probabilities as a function of scattering angle. The ground band and 2QP probabilities were separated by gating on the projected total γ-ray energy, as indicated previously. Because of the strong Coulomb excitation present in these reactions, the 4^+ yield is expected to incorporate $>90\%$ of the total population and thus should be an excellent approximation to the total transfer probability. Analysis of the inelastic excitation allowed us to determine an angle-dependent correction to the effects of an incomplete separation of the populations of the ground band and the 2QP bands. At the grazing angle, for example, this factor was ~ 2.7 and 2.3, respectively, for one- and two-neutron transfer channels populating the ground band, while there was a correction of about -10% to -18% for the population of the 2QP bands. (The ground-band population in the one-neutron transfer channel may be overestimated by $\sim 25\%$ due to ignoring the contamination from the 2QP population.)

Note that the exponential falloff of the probability for transfer to the 2QP bands at large separation distances has a slope consistent with the expected exponential radial dependence of the bound-state wave functions. On the other hand, the ground-band population for two-particle

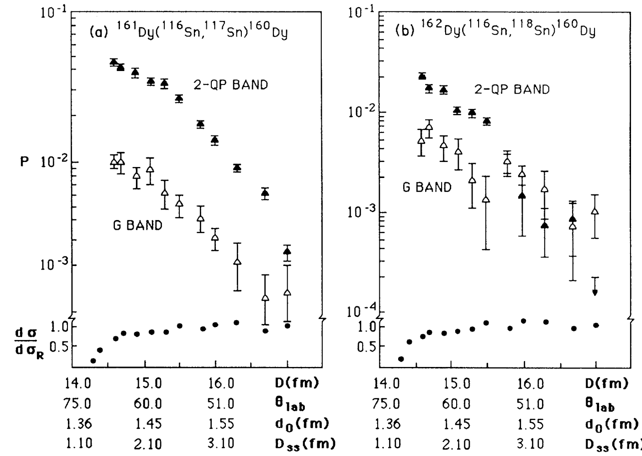

FIG. 2. Probabilities for one- and two-neutron pickup to the ground band and 2QP bands in ^{160}Dy. The quantity $d\sigma/d\sigma_R$ is the ratio of the quasielastic events relative to the calculated Rutherford cross section. The radial separation scale was derived from the scattering angles assuming classical Rutherford trajectories; $D \equiv d_0(A_1^{1/3}+A_2^{1/3})$ is the closest approach distance assuming Rutherford trajectories; $D_{ss} \equiv D - 1.25(A_1^{1/3}+A_2^{1/3})$ is an approximate measure of surface-surface distance at closest approach.

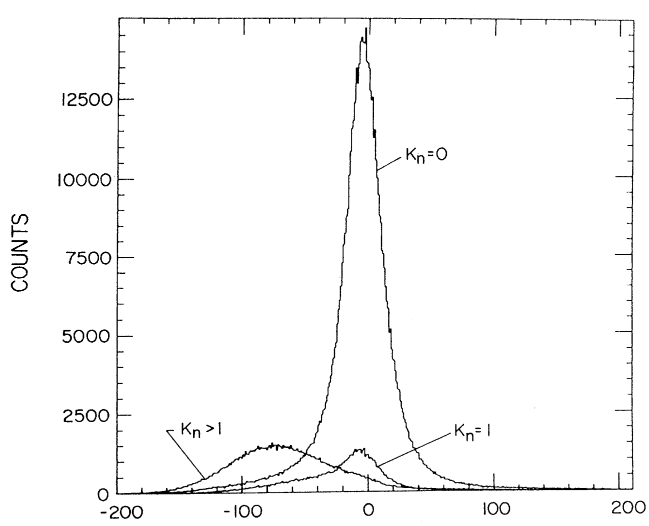

FIG. 1. Q-value spectra gated on neutron multiplicity K_n for the ^{162}Dy+^{116}Sn reaction.

transfer appears to oscillate, and the envelope of the oscillation decays very slowly relative to that expected from binding-energy arguments. As we have discussed separately,[14] this behavior can be interpreted as an orientation angle interference effect for the deformed rotor and accounts for the "slope anomalies" observed earlier in heavy-ion two-neutron transfer reactions.[4,12]

Figure 3 shows the enhancement factor F for transfer to the ground-band and 2QP bands as a function of separation distance at the classical point of closest approach. Various definitions exist in the literature for such an enhancement factor; we have taken the simplest:

$$F = P_{2n}/P_{1n}^2 , \quad (2)$$

where the one- and two-neutron probabilities are denoted by P_{1n} and P_{2n}, respectively. This definition ignores possible differences in ground-state Q values and the number of states involved in the two reactions. Some caution should be used in comparing this number directly with enhancement factors defined in simpler transfer reactions where fewer states are involved, as we discuss further below.

At surface-surface distances smaller than $D_{ss} \simeq 3$ fm (see the caption of Fig. 2) the 2QP enhancements are typically $F \simeq 7-10$, but the corresponding ground-band enhancements are $F \simeq 50-80$ for Sn projectiles and $F \simeq 30-50$ for Ni projectiles, suggesting pairing effects in the transfer to the ground-state band of ^{160}Dy. At surface-surface distances larger than $\simeq 3$ fm the enhancements increase to $F \simeq 500$ for the ground band in the Sn reaction and $F \simeq 100$ in the Ni reaction. This increase in F at large separation for the ground band is associated with oscillations of the two-neutron transfer probability, as illustrated in Fig. 2(b).

Thus, the two-particle enhancement factors for heavy-ion collisions have a dramatic dependence on intrinsic excitation energy, and a failure to resolve this energy dependence may lead to misleading conclusions. For example, if the ground and 2QP populations are summed and a total enhancement factor computed, we find $F \simeq 50$. This is an order-of-magnitude lower than the ground-band enhancements shown at large separation in Fig. 3.

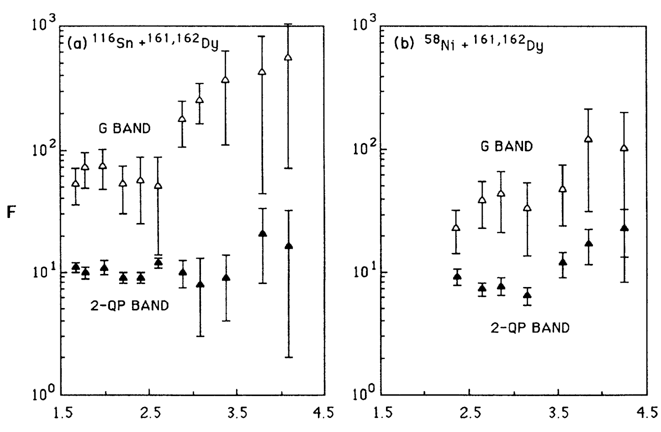

FIG. 3. Two-neutron enhancement factors constructed from transfer probabilities using the definition (2).

In separate publications,[15,16] we describe the extraction of an enhancement factor for ground-to-ground state transfer in Sn + Sn collisions. In that case the definition of the enhancement factor is similar to the traditional definition (e.g., Ref. 8). Nevertheless, we find there enhancement factors of order 1000, which are comparable with the largest factors reported here. This suggests that the traditional definition and the alternative definition employed here for the enhancement factor may agree numerically within a factor of about 2.

Finally, we wish to emphasize that the most important result of the present work—that two-particle transfer to low-lying states is strongly enhanced relative to that for states at only 1–2 MeV excitation energy—is rather stable against uncertainties in the definition and measurement of the enhancement factor. However, one should exercise caution in using "enhancement factors" as *quantitative* measures of correlations in the sort of experiment discussed here. Such simple concepts only have well-defined meanings when there is one clearly specified initial state and one final state. *The data presented here suggest strong correlations; the way to extract these correlations is by comparing realistic calculations of the cross sections with the data.* Such calculations are technically feasible, but they generally have not been done in any systematic fashion. Therefore, we are forced to resort to qualitative concepts such as enhancement factors in analyzing data which contain nuclear structure information that cannot be easily extracted by other means. It is to be hoped that data of the sort presented here will spur theoretical development in a field where experiments are now very far ahead of theory.

In summary, we have presented substantial evidence that the pairing enhancement of two-particle transfer in the collision of two heavy ions is appreciably larger than the corresponding enhancement in light-ion reactions. The decisive step was the use of the Spin Spectrometer to separate ground-band transfer from that populating two-quasiparticle bands. The ground-band enhancements are found to range between 50 and 500 for Sn projectiles, and 20–100 for Ni projectiles as a function of scattering angle, whereas the two-quasiparticle enhancements range only between about 7–20 in the corresponding angular range. Separate work on Sn + Sn collisions finds ground-state enhancement factors comparable with those reported here for Sn + Dy collisions. Thus, the enhancement factors imply a significantly larger role for pairing in transfer to low-lying states relative to excited states, and for Sn projectiles compared with Ni projectiles. The enhancements are found to vary substantially with scattering angle, with greater enhancements for the largest separations measured in the present experiment. This fluctuation can be interpreted as an interference between transfer amplitudes associated with different rotor orientation angles.[14]

These results suggest that the collision of two heavy nuclei with structures far from closed shells may be reasonably approximated as the collision of two superfluid pieces of matter if attention is focused on transitions to low-lying states. The marked difference between the ground-band and two-quasiparticle band enhancements calls into question any discussion of nuclear pairing effects based on heavy-ion reactions which fail to resolve the states lying below about one MeV from higher-lying states—a category which includes all previous attempts to measure the enhancement factors. Multielement 4π γ-ray detectors such as the Spin Spectrometer currently provide the only method whereby the required resolution can be obtained for very heavy ions like Sn.

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