out for lower momentum, $p_2 \sim 150$ MeV/c, in Ref. 10 is not affected by this mechanism. In Ref. 7 another example is discussed where the dominant pion-nucleon rescattering amplitude is slightly modified by the double-pion-photoproduction amplitude.

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Evidence for "Massive Transfer" in Heavy-Ion Reactions on Rare-Earth Targets

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Particle-γ coincidence experiments have been performed to study heavy-ion–induced reactions at 6–9 MeV/nucleon which lead to fast α particles. Experimental evidence is presented that the α particles are emitted in a new class of reaction called "massive transfer" which involves fusion of the remaining projectile mass. Such reactions are shown to occur with large cross section. High-spin states in the residual nuclei are populated, but side-feeding γ-ray intensities are distinctly different from those observed in (HI, $xn\gamma$) reactions [HI is heavy ion].

Heavy-ion reactions are classically divided into distinct categories based on impact parameter. Direct reactions occur in grazing collisions and result in few-nucleon transfer. Smaller impact parameters produce deep-inelastic collisions—the probability of occurrence increasing rapidly with higher projectile mass and energy. Such collisions are characterized by dissipation of a large amount of kinetic energy into internal excitations and usually include mass flow between target and projectile. The interaction times are not long enough for equilibration to occur, however, and before a compound nucleus can be formed, disruption of the system comes about. For even smaller impact parameters complete fusion does occur, followed by formation of a compound nucleus.

It has long been known that in reactions induced with heavy ions lighter than Ar an abundance of light fragments ($A \leq 4$) are produced with energies much higher than those expected from evaporation.[1-3] The angular distributions of these light particles are strongly peaked in the forward direction, suggesting that they originate in a direct interaction.[1,2] In this Letter, we present experimental evidence that these fast light particles are emitted in reactions which lead to fusion of the remaining projectile mass and that these reactions occur with rather large cross section. These "massive transfer" reactions form a new class of reactions which form a bridge between the complete fusion process and deep-inelastic and direct processes.

To study this reaction we performed a series of coincidence studies between γ rays and "direct" α particles. Several combinations of incident heavy ions and targets, as summarized in Table I, were studied to provide a sufficient amount of data from which to draw conclusions. The γ-ray spectra are used to identify the specific residual nucleus produced in the massive transfer reaction.

TABLE I. Reaction data, coincident transition intensities, and classical estimates of the transferred angular momentum for massive transfer reactions.

No.	System	E_{lab} (MeV)	E_α [a] (MeV)	Transferred fragment	Residual nucleus	Transition intensity $4\to2$	$6\to4$	$8\to6$	$10\to8$	$12\to10$	$14\to12$	$16\to14$	$18\to16$	$20\to18$	L_t ($\hbar$)
1	$^{159}Tb+^{10}B$	75	35–41	^{6}Li	^{162}Er	0.99(7)	≡1.0	0.91(7)	0.73(6)	0.47(5)	0.18(4)	0.18(4)			12
2	$^{154}Sm+^{12}C$	85	28–33	^{8}Be	^{158}Dy	1.01(6)	≡1.0	0.94(6)	0.91(7)	0.80(6)	0.68(6)	0.46(6)	0.31(5)	0.18(6)	21
3	$^{154}Sm+^{12}C$	109	42–56	^{8}Be	^{158}Dy	0.89(7)	≡1.0	0.99(13)	1.06(9)	0.74(8)	0.95(9)[b]	0.42(7)	0.32(9)		25
4	$^{159}Tb+^{14}N$	115	35–39	^{10}B	^{164}Yb	0.98(11)	≡1.0	0.94(14)	0.85(11)	0.74(14)	0.63(14)	0.36(10)	0.20(7)		34
5	$^{153}Eu+^{19}F$	112	23–29	^{15}N	^{164}Yb	≡1.0	1.07(9)	0.92(15)	0.94(10)	0.73(12)	0.57(10)	0.37(7)	0.28(9)	0.23(10)	38
6	$^{152}Sm+^{20}Ne$	119	23–27	^{16}O	^{164}Yb	1.03(10)	≡1.0	1.07(13)	0.81(13)	0.51(11)	0.42(11)	0.19(8)			40
7	$^{152}Sm+^{20}Ne$	151	24–31	^{16}O	^{162}Yb	≡1.0	0.86(9)	0.73(9)	0.36(8)	0.19(7)					60

[a] The given transition intensities were extracted from γ rays in coincidence with α particles having these energies.
[b] Doublet.

Beams employed were ^{10}B, ^{12}C, ^{14}N, ^{19}F, and ^{20}Ne with energies in the range 6–9 MeV/nucleon. Self-supporting rare-earth metallic targets were used ranging in thickness from 0.5–3 mg/cm^2. α particles were detected in two Si surface-barrier detectors, each 1 mm$\times$3 cm^2 and positioned 9 cm from the target at $\pm 19°$ to the beam direction. The total solid angle subtended was approximately 74 msr. The maximum energy loss by protons in each detector was 12 MeV. Scattered beam was removed by an Al absorber placed in front of each detector. Coincidences were demanded between either Si detector and the γ rays observed with a 50-cm^3 Ge(Li) detector placed at 90° to the beam direction and 5 cm from the target.

A typical γ-ray spectrum observed in coincidence with α particles is shown in Fig. 1. The data were obtained in the bombardment of ^{159}Tb with a 75-MeV ^{10}B beam. The range of α-particle energies gated (35–41 MeV) was chosen to optimize the production of ^{162}Er. This range was determined by projecting the α particles in coincidence with the discrete lines in ^{162}Er. This spectrum, as well as the spectrum in coincidence

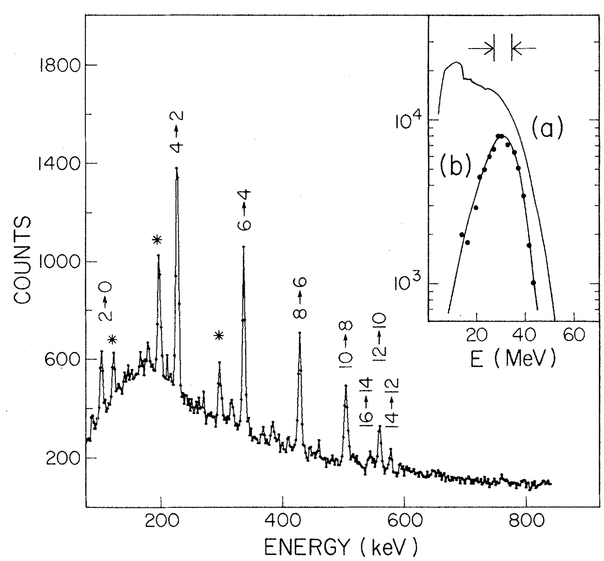

FIG. 1. γ-ray spectrum in coincidence with 35–41-MeV α particles observed in the bombardment of ^{159}Tb with 75-MeV ^{10}B ions. Labeled peaks are in ^{162}Er. Asterisks mark ^{161}Er γ rays. The particle spectra in the inset are in coincidence with (a) any γ ray, (b) ^{162}Er γ rays. The α-particle gate optimizing observation of ^{162}Er transitions is also indicated. The particle energies in the inset have not been corrected for the effects of a 48-mg/cm^2 Al absorber.

with any γ ray, is shown in the inset in Fig. 1. The structure below 12 MeV in the total spectrum arises mainly from detection of protons. The fact that spectrum (b) in the inset shows no peak corresponding to protons indicates that the nucleons are emitted as only an α particle and not also as $2p2n$.

The cross sections for these reactions have not been measured absolutely. However, an estimate can be made from analyzing the singles γ-ray spectrum, since the same Ge(Li) detector records both the (HI,xn) and (HI,αxn) products. For example, in the bombardment of ^{159}Tb with 75-MeV ^{10}B, the cross section for the production of the $^{163-165}$Yb products is collectively taken to be 1 b. With this assumption the yields of $^{160-162}$Er indicate a combined cross section of about 300 mb for the massive transfer reactions which produce fast α particles. For the remaining systems we have studied, a similar analysis gives cross section estimates in the 100–300-mb range. These numbers are qualitatively in agreement with the values given by Britt and Quinton,[1] who reported the cross sections for the production of direct α particles to be in the 150–850-mb range for the bombardment of Au and Bi targets with 7–10-MeV/nucleon ^{12}C, ^{14}N, and ^{16}O projectiles. This seems to suggest that a large fraction of the observed fast α particles originate in massive transfer reactions.

The observed yrast transitions in the residual nuclei and their relative intensities are summarized in Table I. In some systems states as high as $20\hbar$ are observed. A surprising feature of these data is the constancy of the intensity for γ rays originating from states as high as the 10^+ yrast state. This constancy has already been noted in a single case,[3] namely, for the ^{166}Yb γ rays in coincidence with fast α particles observed in bombardment of ^{159}Tb with 95-MeV ^{14}N ions.

In ordinary (HI,$xn\gamma$) reactions the intensity decreases as the spin increases, an indication of side feeding. The side-feeding intensities for the systems studied are shown in Fig. 2 and are obtained from the differences between the observed intensities of successive transitions in the yrast band. To exclude experimental uncertainties smoothed curves are used in this procedure. The constancy of observed transition intensity is emphasized by the absence of side feeding to the lower spins. In some cases the side-feeding function is a high, narrow peak, as in the case of ^{162}Er transitions observed in the ^{159}Tb + 75-MeV ^{10}B system. This means that side feeding occurs principally to one or two yrast levels and, consequently, the higher-spin yrast states are not easily seen. It should be noted that the side feeding in the residual nucleus ^{164}Yb produced in three different reactions is essentially the same, indicating the dominance of nuclear structure.

The side feeding occurring in ordinary (HI,$xn\gamma$) is also contrasted with that observed in the (HI, $\alpha xn\gamma$) massived transfer reaction in Fig. 2. The dahsed line corresponds to the side feeding for the reaction ^{159}Tb(^{10}B, $5n\gamma$)^{164}Yb at 70 MeV. This is compared with the data obtained in the massive transfer of ^{10}B which occurs in the system ^{159}Tb + 115-MeV ^{14}N. The ^{10}B which fuses in the latter case also carries an energy of about 70 MeV in the lab, since the separation energy of an α particle from ^{14}N is 11.6 MeV and the most favorable α energy for producing ^{164}Yb is 33 MeV. The shapes of the side-feeding functions are very different, with the ordinary (HI,xn) results showing considerable side feeding to the low-spin states. This suggests that while a ^{10}B fuses in both cases, the most nearly head-on collisions are not contributing to the massive transfer process. If the massive transfer reactions localize the angular momentum distribution at high l values, thus acting as a filter for impact parameters, they might serve as a highly selective probe of nuclei at high angular momentum.

A model for a massive transfer reaction recently proposed by Kishimoto and Kubo seems con-

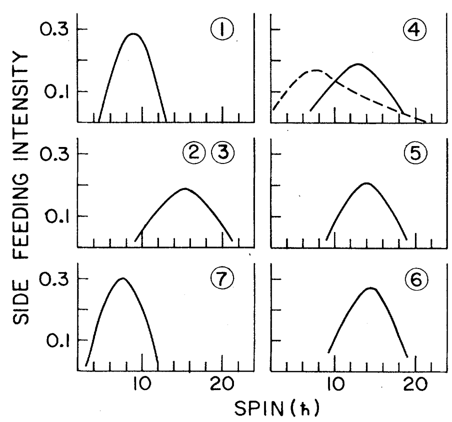

FIG. 2. Side-feeding intensities in yrast bands of residual nuclei formed in massive transfer reactions. The circled numbers refer to the number of the reaction in Table I. The intensities are normalized in the same way as Table I. The dashed curve is the side feeding observed in the reaction ^{159}Tb(^{10}B, $5n\gamma$)^{164}Yb at 70 MeV.

sistent with the experimental data.[4] In this model the α particle is emitted in a direct process without ever being absorbed by the target nucleus. The reaction occurs only over a small range of impact parameters. The remainder of the incident heavy ion fuses with the target. Smaller impact parameters would lead to complete fusion, while larger ones would result in the transfer of only a few nucleons. Thus the angular momentum distribution of the residual nuclei is very localized at high l values. Since low angular momentum transfers do not contribute, the lack of side feeding to the lower-spin states is naturally explained.

We stimate the angular momentum L resulting from the capture of a massive fragment by the classical expression

$$L = (R/\hbar)[2\mu(E_{\text{c.m.}} - E_S - E_P - V]^{1/2},$$

where μ is the reduced mass of the transferred fragment, $E_{\text{c.m.}}$ is the projectile energy in the center-of-mass system, E_S is the energy required to separate the α particle or other light fragment from the projectile, E_P is its kinetic energy, V is the potential barrier, and R, the strong absorption radius, is taken to be[5] $1.07(A_1^{1/3}+A_2^{1/3})+3$ fm. The most probable value of E_P is determined experimentally. The corresponding value of L is called L_t. The values calculated in this way are given in Table I and differ considerably in some cases from the highest observed spin.

The differences cannot be attributed to the angular momentum carried away by the evaporated neutrons and statistical γ rays. The latter are usually assumed to be dipole and to produce on the average little net change in the angular momentum, while evaporation calculations performed by us using the code GROGI2 indicate that the net loss in angular momentum is about one unit per evaporated neutron. This implies that a series of unresolved stretched quadrupole transitions may be required to account for most of the angular momentum imbalance. In the usual picture, these would occur in a series of rotational bands which run parallel to the yrast line. It should be noted, however, that the observed γ-ray intensities remain constant to approximately the same spin value ($\sim 8\hbar$) in the various systems independent of projectile or its energy. In addition, the yrast band in ^{164}Yb, which was observed in massive transfer reactions with ^{14}N, ^{19}F, and ^{20}Ne ions on various targets, is observed to lowest spin in the ^{20}Ne reaction, even though L_t is highest for that reaction. More surprising are the data obtained by increasing the ^{20}Ne energy to 151 MeV. The highest spin observed in the residual nucleus is actually lower ($12\hbar$) despite the apparently large increase in input angular momentum. These observations seem to suggest that the extra angular momentum is being dissipated prior to or just after the statistical cascade, that the succeeding cascade paths remain essentially the same, and that the entry into the yrast band therefore occurs at about the same place.

As noted earlier, massive transfer reactions involving α-particle emission occur only for projectiles lighter than Ar. This implies that projectile structure plays an important role in the reaction. Although they are not α-particle nuclei, ^{10}B, ^{14}N, and ^{19}F must have a large α-particle component in their structure.

To summarize, we provide experimental evidence in support of a new type of reaction called massive transfer. The cross sections for such reactions leading to fast α particles are found to be very large. The side-feeding intensities in the residual nuclei are different from those observed in ordinary (HI,$xn\gamma$) reactions, suggesting that the smallest impact parameters do not contribute to massive transfer.

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