we accept that the three jets are quark, antiquark, and gluon, the effect would indicate that the gluon carries color. Although this is probably believed or assumed by anyone likely to read this paper, a further piece of direct evidence that hadronic forces are described by a non-Abelian theory is not to be disregarded.

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[1]For recent reviews, see *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan 1978*, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of Japan, Tokyo, 1979), especially the talks of Session A12 and the plenary talks of R. Sosnowski, G. Veneziano, and R. D. Field.

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Massive Transfer Accompanying Proton, Deuteron, and Triton Emission in Heavy-Ion Reactions

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Fast, forward-peaked protons, deuterons, and tritons observed in the reactions of 135- and 165-MeV ^{14}N ions with $^{152,154}Sm$ and 166-MeV ^{19}F ions with ^{148}Nd are shown to originate in massive-transfer reactions. These reactions are also demonstrated to have merit as probes of angular momentum space in nuclei at very high spin.

The production of high-energy forward-peaked light fragments in heavy-ion–induced reactions has been known.[1,2] Recent α-γ coincidence experiments have demonstrated that for projectile energies in the range 6–10 MeV/nucleon many of the observed α particles result from massive-transfer reactions.[3,4] In these reactions a light fragment of the projectile escapes while the remaining projectile mass fuses and initiates a (fragment, xn) reaction. In this Letter, we report on a number of particle-γ coincidence experiments which show for the first time that forward-peaked protons, deuterons, and tritons observed in such reactions also originate in a massive-transfer process. These results establish the general nature of the massive-transfer process and also demonstrate the potential associated with the use of these reactions as a probe of nuclei in angular momentum space.

We have performed p-, d-, t-γ coincidence experiments with 135-MeV and 165-MeV ^{14}N beams. The targets used were self-supporting ^{152}Sm and ^{154}Sm foils with thickness 3.5 and 5.0 mg/cm^2, respectively. Similar experiments were performed with a 166-MeV ^{19}F beam using a 2.4-mg/cm^2 ^{148}Nd target. The bombarding energies were chosen so that, after proton, deuteron, or triton emission, significant production of the same residual nucleus, ^{158}Er, would occur. A summary of the reaction systems is given in Table I. Particles were detected in a ΔE-E counter telescope consisting of 400-μm and 5-mm Si detectors with 300-mm^2 area at 19° and 8 cm from the target. At each bombarding energy an

TABLE I. Reaction data, yrast transition intensities in ^{158}Er, and critical angular momenta for massive transfer.

Reaction	Beam Energy (MeV)	E_{part}[a] (MeV)	Yrast Transition 4→2	6→4	8→6	10→8	12→10	14→12[b]	16→14	18→16	20→18	22→20	24→22	26→24	Transferred Fragment	ℓ_{cr}[c]
^{148}Nd(^{19}F,p8n)	166	14-24	100	104(9)	82(14)	76(12)	59(13)	107(12)	42(15)	45(10)	36(12)	38(14)	40(14)		^{18}O	60
^{154}Sm(^{14}N,p9n)	165	14-21	100	102(10)	78(12)	76(12)	51(15)	57(11)	51(11)	47(13)	54(16)	36(12)	17(10)	24(13)	^{13}C	57
^{154}Sm(^{14}N,d8n)	165	12-42	100	94(10)	82(12)	64(10)	60(15)	62(10)	18(5)	21(6)	32(10)				^{12}C	52
^{154}Sm(^{14}N,t7n)	165	24-52	100	106(13)	91(13)	63(11)	55(17)	71(13)	24(11)	26(12)					^{11}C	45
^{152}Sm(^{14}N,p7n)	135	15-25	100	106(8)	83(7)	68(6)	45(10)	61(9)	29(4)	26(6)	25(7)	20(7)			^{13}C	48
^{152}Sm(^{14}N,d6n)	135	22-36	100	95(10)	70(11)	67(10)	45(13)	54(10)	28(8)	26(10)					^{12}C	43
^{152}Sm(^{14}N,t5n)	135	30-52	100	109(12)	90(13)	68(11)	53(13)	59(11)	28(11)	30(12)	25(12)				^{11}C	38
^{122}Sn(^{40}Ar,4n)[d]	166			100	101(3)	78(3)	66(3)	50(3)	50(3)	44(3)	45(3)	44(3)	38(5)	24(4)		60[e]

[a]Given transition intensities are for γ rays coincident with indicated particle with this range of energies.
[b]Uncorrected for interfering line.
[c]Critical angular momentum for fusion of the massive fragment.
[d]Ref. 5, corrected for internal conversion.
[e]Critical angular momentum for fusion of the projectile.

appropriate amount of Al absorber was placed in front of the counter telescope to remove the scattered beam.

The proton spectra obtained at 19° in coincidence with yrast transitions in ^{158}Er and ^{159}Er are shown in Fig. 1 for the 165-MeV ^{14}N case. There are two groups of particles associated with each residual product, possibly indicating competition between distinct reaction channels. The higher-energy peak is attributed to protons emitted in the nonequilibrium massive-transfer process while the lower one corresponds to ordinary nucleon evaporation.

The combined thickness of the ΔE detector and the Al absorber (75 mg/cm^2) used to stop the scattered beam results in a proton detection threshold of 9 MeV. A statistical-model calculation using GROGI2 predicts the evaporated-proton spectrum to peak at about 10 MeV. As shown in Fig. 1, the residual product ^{158}Er is as likely to be formed by evaporation as by massive transfer. It should be noted that the observed energy difference between the high- and low-energy proton peaks must be compensated by the kinetic energy of evaporated neutrons and/or the energy available for γ decay of the residual nucleus.

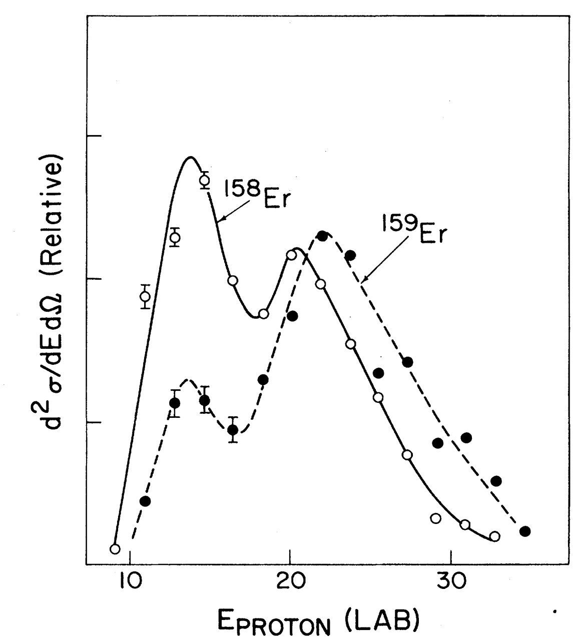

FIG. 1. Energy spectra of protons (lab) coincident with discrete ^{158,159}Er γ-ray transitions observed in the 165-MeV ^{14}N bombardment of ^{154}Sm. Protons of energy below 9 MeV were not detected. Representative errors are shown. The ordinate is linear.

The spectra of protons, deuterons, and tritons coincident with any γ-ray for the 135-MeV ^{14}N irradiation, shown in Fig. 2, are broad and extend to energies well above those typical of evaporation. The detection threshold energies for deuterons and tritons are 12 MeV and 14 MeV, respectively. The discontinuity observed at higher energy in these spectra corresponds to penetration of the 5-mm Si(Li) detector by each specific particle. Protons (dueterons, tritons) above 32 MeV (43 MeV, 52 MeV) exit from this detector. The numbers of deuterons and tritons relative to protons were found to increase markedly at forward angles, as observed also for other systems.[2] The abundance of these complex clusters at forward angles is not expected from a preequilibrium model (where nucleon emission should be favored) but is consistent with the projectile breakup process which occurs in massive transfer.

Spectra of ^{158}Er γ rays were obtained in coincidence with each outgoing particle. The appropriate energy gate for the particle was determined from the energy spectrum coincident with discrete transitions. The γ rays coincident with 30–52-MeV tritons are shown in Fig. 3 for the 135-MeV ^{14}N irradiation. The principal reaction channel is $^{152}Sm(^{14}N, t5n)^{158}Er$.

The intensities of the ^{158}Er yrast transitions coincident with particles are summarized in Table I for each combination of outgoing-particle and projectile energy. Transitions from states with spins in the vicinity of $20\hbar$ were generally observed with the highest spin, $26\hbar$, visible in the $(^{14}N, p9n)$ reaction at 165 MeV. Sidefeeding was found to be strongly restricted in all cases to the four yrast states with spins in the range $(8-14)\hbar$. Such localization has been reported for other systems.[3,4] The lack of sidefeeding to lower-spin states has been taken as evidence that the input angular momentum is limited to a rather narrow range.[3,4] This behavior is quite different from that which results from ordinary (heavy ion, xn) reactions.

Massive transfer is believed to occur at or near the critical angular momentum l_{cr} for complete fusion of the projectile.[3,4] For the 135- and 165-MeV ^{14}N beams this quantity was $56\hbar$ and $64\hbar$, respectively, while for the 166-MeV ^{19}F case it was $70\hbar$. If the heavy projectile fragment is to fuse, it also must not exceed its associated critical angular momentum. The values of l_{cr} for the ^{13}C, ^{12}C, ^{11}C, and ^{18}O massive fragments are given in Table I to provide some estimate of the transferred angular momentum. The largest value occurs at each bombardment energy for the massive transfer of the heaviest fragment. While

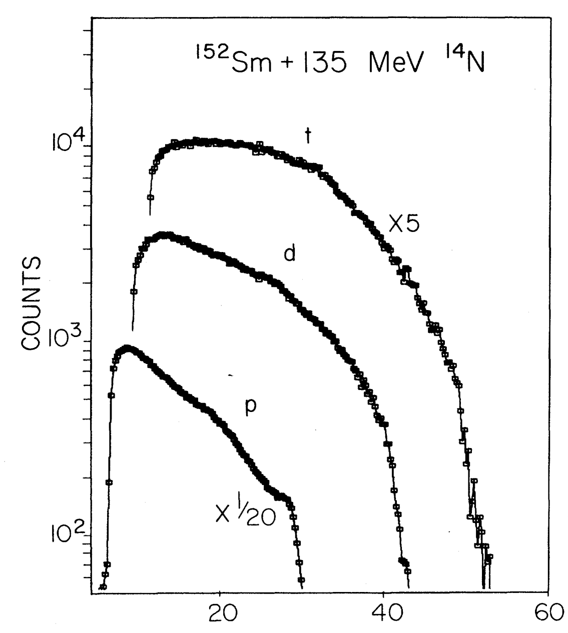

FIG. 2. Proton, deuteron, and triton spectra coincident with any γ ray. The energy scale has not been corrected for the effect of a 54-mg/cm^2 Al absorber.

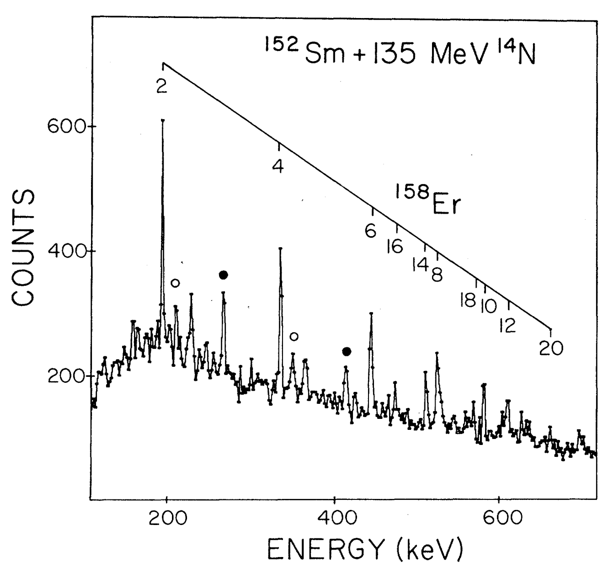

FIG. 3. Spectrum of γ rays coincident with 30–52-MeV tritons. Yrast transitions in ^{158}Er are labeled with the spin of the initial state. γ rays assigned to ^{157}Er and ^{159}Er are marked by closed and open circles, respectively.

for each case neutron evaporation carries away slightly different amounts of angular momentum, the residual product ^{158}Er is produced with somewhat different values of initial average angular momentum and excitation energy. In this way we have been able to use the massive-transfer process as a probe of various entry points into ^{158}Er.

Using ^{14}N beams, the intensities of the coincident γ rays are very similar for five of the six cases we have studied. This indicates that the entry point, while different for each of these cases, had essentially no effect on eventual population of yrast states. Although entry into the numerous rotational bands which run parallel to the yrast line may have occurred at different high-spin values, the eventual decay of these bands into the yrast states at much lower spins was unaffected.

The sixth case, the p-γ data for 165-MeV ^{14}N bombardment, corresponded to larger angular momentum transfer and produced qualitatively different results. Population of the yrast states above spin $14\hbar$ was enhanced by about a factor of 2. The ^{19}F experiment was performed to confirm this result, and yielded the same enhanced high-spin population. This pattern of γ-ray intensities was observed also in the ^{122}Sn(^{40}Ar, $4n$) ^{158}Er reaction when a multiplicity filter was used to select events of higher multiplicity.[5]

It has been suggested in recent theoretical work[6] that at very large rotational frequencies nuclei will tend toward oblate shapes under the influence of centrifugal forces. For a given nucleus, the path followed in deformation space, however, is also strongly affected by the quantal shell structure. A recent calculation of nuclear equilibrium shapes by Andersson *et al.*[6] indicates that, while ^{158}Er has a prolate ground state, it assumes an oblate yrast shape near $I = 50$. The inclusion of finite nuclear temperature by Kishimoto[7] yielded a similar result. Bohr and Mottelson[8] have noted that nuclei which take on such an oblate shape at high angular momentum are characterized by rapid cooling to the yrast line, that is, by an absence of the strong $E2$ radiation parallel to the yrast line which is typical of prolate nuclei. It is quite possible that the enhanced high-spin population observed in our data results from such passage through an oblate coupling scheme. Recent observations of unusually large population of high-spin states in ^{152}Dy and ^{154}Er have also led to speculation that this results from such an oblate shape.[9,10]

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