Unexpected Entrance-Channel Effects in the Decay of the Compound Nucleus ^{156}Er

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Angular momentum distributions for the dominant decay channels of ^{156}Er compound nuclei have been studied with the Darmstadt-Heidelberg "crystal ball" detector in nearly mass-symmetric (^{64}Ni + ^{92}Zr) and asymmetric (^{12}C + ^{144}Sm) entrance channels. Strong differences in the αn yield and $2n/3n$ cross-section ratios are observed at the same excitation energy (47 MeV) and spin in ^{156}Er. This effect indicates that there is memory of the entrance channel during the particle-evaporation stage of the compound-nucleus decay. The dominant exit channels do not exhibit high-angular-momentum components.

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Fusion of heavy ions near the barrier, although studied for many years, still has many open questions and puzzles. One of them is the well-established fact that statistical-model calculations systematically overpredict neutron-emission probabilities from some compound nuclei in the rare-earth region.[1,2] This feature seems to be more pronounced for mass-symmetric entrance channels. For example, in the fusion of ^{64}Ni + ^{92}Zr, neutron emission is suppressed.[3] In striking contrast there is excellent agreement between experimental and calculated values of the average number of emitted neutrons, when the same compound nucleus is formed in the mass-asymmetric channel ^{12}C + ^{144}Sm.[4]

In Ref. 3 it was speculated that the reduction of the neutron-evaporation probability may be understood in terms of a reduced effective temperature. The kinetic energy of the interacting ions may be tied up in deformation energy instead of being rapidly converted to heat. Such a situation may occur if the compound nucleus is trapped in a superdeformed minimum during the shape-relaxation process. Moreover, potential-energy-surface calculations[5] with shell corrections predict the existence of secondary minima with large deformation for some neutron-deficient rare-earth nuclei, including ^{156}Er. Direct evidence for superdeformed shapes has indeed recently been reported[6] for ^{152}Dy.

An alternative interpretation for the observed neutron suppression in terms of fusion-barrier fluctuations was suggested by Landowne *et al.*[7] Such fluctuations result in an increased width of the compound-nucleus spin distribution raising the rotational energy and reducing the temperature. Recently, average γ-ray multiplicities[8] as well as γ fold distributions[9] have been measured for various entrance channels leading to ^{160}Er at near-barrier energies and have been interpreted in terms of barrier fluctuations.

A distinction between the two interpretations can be made by measuring the angular momentum distributions for those evaporation residues which show anomalously enhanced yields. Moreover, comparisons should be made for nearly mass-symmetric and mass-asymmetric entrance channels leading to the same compound nucleus at the same excitation energy. Unfortunately, the angular momentum distributions will be rather different in the two cases. As a consequence, the decay of the compound nucleus formed via different entrance channels has to be compared for individual partial waves. This has become possible with the advent of new 4π γ-ray detection systems such as the Darmstadt-Heidelberg "crystal ball" detector.[10] In this Letter, we report on a study of the systems ^{64}Ni + ^{92}Zr and ^{12}C + ^{144}Sm, both leading to the compound nucleus ^{156}Er at an excitation energy of 47 MeV.

Isotopically enriched targets of 225-μg/cm^2 ^{92}Zr (95%) and 4-mg/cm^2 ^{144}Sm (96%) have been irradiated by pulsed 239-MeV ^{64}Ni beams and 73.5-MeV ^{12}C beams provided by the Heidelberg Tandem/Post-accelerator facility. The fusion products have been stopped in a ^{208}Pb backing evaporated onto the targets. Taking into account the energy loss in the target, both reactions lead to an effective excitation energy of 47 MeV in ^{156}Er with a spread of 3.4 MeV (^{64}Ni beam) and 5.6 MeV (^{12}C beam). The γ rays have been detected with the Darmstadt-Heidelberg crystal-ball detector, using 158 NaI modules subtending 97% of the full solid angle. Neutrons have been discriminated from γ rays via time of flight. The evaporation residues have been identified by their characteristic γ transitions observed in a germanium detector. Since the target contained only 1.1% of ^{94}Zr effects of target impurities can be neglected.

The distributions of the number of responding crystal-ball detectors ("fold distributions") were deconvoluted using a response function measured in the experimental geometry. Since the fold distributions exhibit widths typically 3 times larger than the experimental resolution, the shape of the γ multiplicity distributions can be accurately determined. To obtain evaporation-residue spin distributions the assumption is made that the γ radiation only consists of stretched quadrupole ($\Delta I = 2$) and dipole ($\Delta I = 1$) transitions and of four statistical transitions which are assumed to remove $0.3\hbar$ each. The average spin ΔI_{ns} per nonstatistical photon was determined by fitting the γ-ray angular distributions with a series of Legendre polynomials. The attenuation coefficient $\alpha_2 = 0.75$ reported[11] for ^{154}Er has been used. The multiplicity-to-spin conversion is described in detail by Fischer *et al.*[12] Since most of the residues have isomeric states,[11] distributions for individual decay branches populating or bypassing isomers have been summed to obtain the spin distribution for a given residue. For $I > 8\hbar$ the assumption of stretched transitions should be quite reliable and the uncertainty in spin is estimated to be ±10%. It should be noted that a relative comparison of the two entrance channels is less sensitive to possible systematic errors in the determination of the absolute spin values.

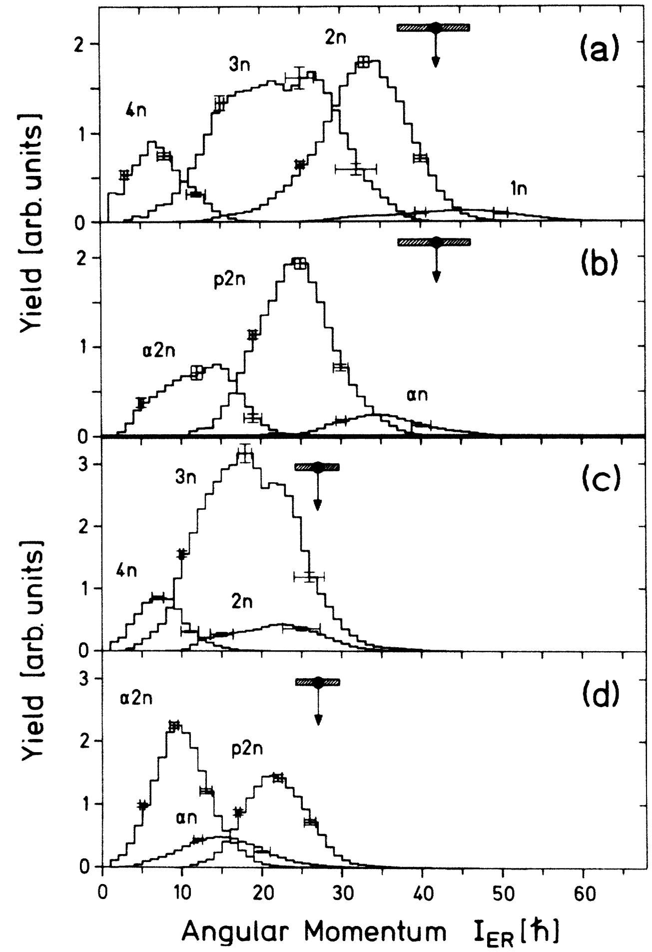

FIG. 1. Evaporation-residue angular momentum distributions for ^{156}Er formed in (a),(b) ^{64}Ni + ^{92}Zr and (c),(d) ^{12}C + ^{144}Sm. The arrows indicate the limiting compound-nuclear angular momenta derived from measured evaporation-residue sections (Ref. 4) assuming a sharp-cutoff angular momentum distribution.

Figure 1 shows the measured evaporation-residue spin distributions for the various exit channels produced in ^{64}Ni + ^{92}Zr [Figs. 1(a) and 1(b)] and ^{12}C + ^{144}Sm [Figs. 1(c) and 1(d)]. For reference we have also indicated the limiting angular momentum $l_{1/2}$, determined from the measured evaporation-residue cross section[4] within the sharp-cutoff approximation. Numerical results from the analysis are listed in Table I. The angular momentum removed by evaporated particles has been obtained from statistical-model calculations with the code HIVAP.[13] For most decay channels, this correction is rather small (Table I). For the Ni-induced reaction, the $1n$ and αn channel originate to a large part from compound nuclear spins above $l_{1/2}$. In contrast to predictions of calculations including barrier fluctuations, at least 90% of the total yield is concentrated below $42\hbar$ even allowing for an uncertainty in the absolute spin scale of 10%. As a consequence there is no significant influence of barrier fluctuations on the average particle multiplicities.

TABLE I. Relative yields (normalized to 100%), average multiplicities (including prompt and delayed γ rays), average evaporation residue spins, and calculated angular momentum removed by particles. The statistical error of $\langle M_\gamma \rangle$ is negligible. Systematic errors in $\langle I_{\mathrm{ER}} \rangle$ are estimated to ±10%. Errors in the relative yield include statistical errors as well as systematic error introduced through corrections for efficiency and decay-time distributions.

	$^{64}\mathrm{Ni}+{}^{92}\mathrm{Zr}$				$^{12}\mathrm{C}+{}^{144}\mathrm{Sm}$			
Exit channel	Relative yield (%)	$\langle M_\gamma \rangle$	$\langle I_{\mathrm{ER}} \rangle/\hbar$	$\langle l_{\mathrm{part.}} \rangle/\hbar$ [a]	Relative yield (%)	$\langle M_\gamma \rangle$	$\langle I_{\mathrm{ER}} \rangle/\hbar$	$\langle l_{\mathrm{part.}} \rangle/\hbar$ [a]
$1n$	3 ± 1	27.0	43 ± 4	1.1	< 1	. . .	. . .	. . .
$2n$	24 ± 3	22.2	32 ± 3	1.7	6 ± 1	15.0	21 ± 2	0.9
$3n$	31 ± 6	13.6	22 ± 2	2.0	48 ± 10	11.1	18 ± 2	1.5
$4n$	7 ± 2	6.7	7 ± 1	0.6	7 ± 1	6.8	7 ± 1	−0.2
$p2n$	23 ± 5	13.7	24 ± 2	2.3	14 ± 3	11.9	21 ± 2	2.1
αn	3 ± 1	20.3	34 ± 3	4.7	6 ± 1	9.6	15 ± 2	0.4
$\alpha 2n$	9 ± 2	10.8	12 ± 1	0.8	19 ± 4	9.2	10 ± 1	−0.2

[a] From calculations with HIVAP (Ref. 13).

However, the measured l distributions do not necessarily rule out such fluctuations since there is the possibility that the highest partial waves may be depleted by fission.

An unexpected and striking dependence on the entrance-channel mass asymmetry is observed for the charged-particle evaporation channels (Fig. 1): In the $^{12}\mathrm{C}$-induced reaction, 90% of the αn yield originates from partial waves below $20\hbar$. The $^{64}\mathrm{Ni}$-induced reaction does not populate the αn channel in this l range at all. Instead, it feeds the high-spin isomers in $^{151}\mathrm{Dy}$. As a result, the αn yield is concentrated at spin values above $25\hbar$.

Entrance-channel effects are also observed for the neutron-evaporation channels, relevant for the discussion of neutron suppression. At high spin values Fig. 1 shows a strong $2n$ yield for the $^{64}\mathrm{Ni}$-induced reaction; for the $^{12}\mathrm{C}$-induced reaction the $3n$ channel predominates over the whole range of spin values. This feature is further illuminated by comparing σ_{2n}/σ_{3n}, the ratio of cross sections corresponding to emission of 2 and 3 neutrons, for the two entrance channels as a function of compound-nucleus spin (Fig. 2). The comparison of the experimental $2n/3n$ yields is restricted to a limited spin range where the distributions for both reactions have sufficient yield. The spread due to the conversion from γ multiplicity into compound-nucleus spin is less than $5\hbar$, deduced from a Monte Carlo simulation of the decay cascade. Thus, there is no significant contribution of high partial waves to lower spins, which would otherwise distort the yield ratio. At low spins in the selected spin range the σ_{2n}/σ_{3n} ratios agree within the errors and are consistent with statistical-model calculations. However, for spins above $24\hbar$ there is a steep rise in this ratio for the $^{64}\mathrm{Ni}$-induced reaction as compared to the $^{12}\mathrm{C}$-induced reaction.

The independence hypothesis[14] implies a complete loss of memory for all details of compound-nucleus formation which do not involve the basic conservation laws. Therefore, at given spin and excitation energy the relative intensities of two decay channels (e.g., σ_{2n}/σ_{3n}) should not depend on the entrance-channel mass asymmetry. The striking displacement of the αn spin distribution in the Ni-induced reaction as well as the observed different spin dependence of σ_{2n}/σ_{3n} for the two entrance channels suggests that there is memory of the entrance channel during the particle-evaporation stage of the compound-nucleus decay. This unexpected experimental result can be understood within the context of trapping in a superdeformed minimum during compound-nuclear shape re-

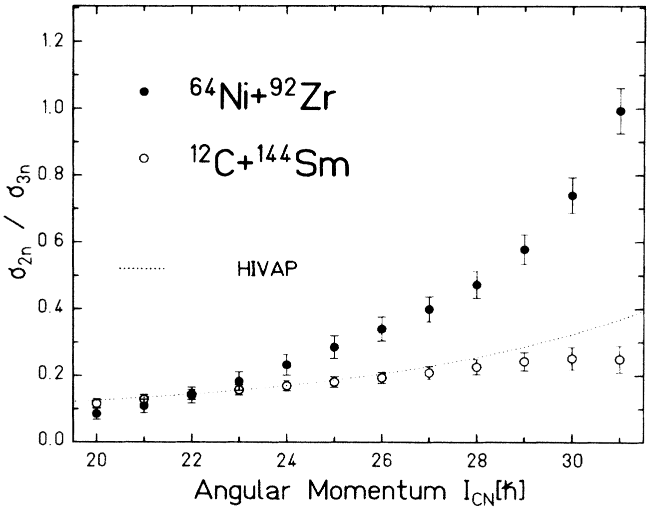

FIG. 2. Ratio of $2n/3n$ yields for $^{64}\mathrm{Ni}+{}^{92}\mathrm{Zr}$ and $^{12}\mathrm{C}+{}^{144}\mathrm{Sm}$ as a function of compound-nucleus spin. The systematic uncertainty in the absolute spin scale is estimated to be ±10%. In a relative comparison of the two entrance channels the cross-section ratios are less sensitive to such errors. Results are compared with a statistical-model calculation [HIVAP (Ref. 13)], which predicts identical ratios for both reaction channels.

laxation. It is only when the compound nucleus is formed from nearly symmetric mass partners that it has a sufficiently large initial deformation to relax subsequently through shapes corresponding to those at a superdeformed minimum. The large deformation energy necessary to excite such states would lead to a significant decrease in temperature and reduce particle multiplicities as observed, if the deformation is trapped until γ emission sets in. The effect increases strongly with rising spin which is in qualitative agreement with results from cranked-shell-model calculations, which predict more pronounced superdeformed minima for higher spins.

The observed effects cannot be accounted for by preequilibrium emission since neutron spectra measured for this system show no evidence for such processes.[3] Moreover, the incident energies (6.1 MeV/u for ^{12}C and 3.7 MeV/u for ^{64}Ni) are well below the known onset of this reaction mechanism.[15] A possible impact of incomplete fusion on the αn channel in the C-induced reaction—although unlikely because of the low incident energy—will be investigated in a future experiment.

In summary, unexpected entrance-channel effects have been observed in the decay of the compound nucleus ^{156}Er. For the same excitation energy and spin the multiplicities of emitted particles depend on the entrance-channel mass asymmetry. The spin distributions for the dominant evaporation residues do not show high-l tails which might otherwise have provided an explanation for the suppression of neutrons in the $^{64}\mathrm{Ni}+^{92}\mathrm{Zr}$ reaction. Thus, the original speculation of trapping in a superdeformed minimum[3] still qualifies for further examination. Whether the observed entrance-channel effect is indeed related to the nuclear structure of light Er nuclei is presently being investigated in a comparative study of different entrance channels leading to the heavier isotopes ^{160}Er–^{164}Er where superdeformation is not predicted.

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