Suppression of Neutron Emission after Heavy-Ion Fusion: Is Shape Relaxation Affected by a Superdeformed Minimum?

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Neutron spectra as a function of spin and the neutron multiplicity distribution have been measured for the reaction 233-MeV ^{64}Ni + ^{92}Zr. The emission of two neutrons constitutes the strongest decay channel, in contrast to statistical-model calculations which predict the emission of three neutrons to be the strongest by more than one order of magnitude. This is possibly due to trapping in a super-deformed potential well, similar to that giving rise to fission isomers, as the compound nucleus relaxes from the highly distorted initial shape.

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An important facet of heavy-ion physics is the dynamics of ion-ion collisions. However, it is not yet clear how collision properties and nuclear-structure aspects govern the division of the total reaction cross section into the partial cross sections for complete fusion, incomplete fusion, fast-fission, deep-inelastic, and quasielastic reactions. To solve this problem it is important first to understand the dynamics of complete fusion at low incident energies without the complications introduced by the presence of other strongly competing reaction channels. In the initial stage of fusion, at the moment of contact between the interacting ions, the composite system is highly deformed. The relaxation of such a highly distorted shape towards the ground-state deformation represents an interesting case study in nuclear dynamics. Moreover, it may present an opportunity for exploring the structure of nuclei with high spin and temperature, perhaps at higher temperature than can be probed with conventional continuum γ spectroscopy. Several questions may be raised concerning, for example, the relaxation time for attaining the equilibrium shape, the nature of this equilibrium shape at high excitation energy, the influence of shell structure on the shape and relaxation time, and the temperature at which shell effects diminish.

A suitable compound system for study is one where the yrast line is known up to high spin and where there exists an appropriate entrance channel for bringing in sufficient angular momentum at moderate excitation energies. These conditions can be met in the rare-earth region. Here neutron evaporation is the predominant decay channel. Thus, neutron spectra and multiplicity distributions may prove useful for probing the early stages of the compound-nucleus deexcitation process, particularly when measured as a function of spin to select specific impact parameters.

In this Letter, we present the results from studying the system ^{64}Ni + ^{92}Zr with a 238-MeV-Ni beam from the Argonne superconducting linac. The effective beam energy is 233 MeV, which is a weighted average with the weight given by an estimated fusion cross section at each of the energies encountered within the 1-mg-cm^{-2} target. At this effective energy the compound nucleus ^{156}Er is formed at 46 MeV excitation energy and $l_{max} = 37\hbar$ (calculated with the Bass model[1]). We have measured neutron and gamma spectra in coincidence with the total gamma-ray energy. The neutrons were detected at 0° with a 12.5×5 cm NE213 liquid scintillator located 71 cm from the target and the neutron energy was determined by the time of flight with respect to the beam microstructure. Gamma spectra were measured with a Ge(Li) detector and 25×30 cm NaI detectors (with 10-cm-diam central collimators) positioned at 75 cm from the target at angles of 0° and 90°. Singles spectra were also recorded with the Ge detector. The sum energy was measured in a NaI spectrometer described by Khoo.[2]

The γ multiplicity as a function of sum energy was determined from the ratio of sum-energy spectra corresponding to threefold (sum-neutron-NaI) and twofold (sum-neutron) coincidences. The entry spin was determined by taking into account the average spin removed by a prompt γ

ray (1.21$\hbar$, determined from γ yields at 0° and 90°) and corrections for feeding of isomers. For events populating an isomer of spin I_{is} one obtains $I = 1.21(M_{90} - 4 - M_{is})/1.06 + I_{is}$. The multiplicity M_{90}, measured at 90°, is reduced by 4 to account for the typical number[3] of statistical transitions (which remove no angular momentum) and by M_{is}, the gamma multiplicity in the isomer decay. The factor 1.06 represents a correction for angular distribution effects. As a result, we obtain neutron spectra for different sum-energy slices corresponding to different entry line spins. The neutron spectra have been corrected for the efficiency response of the neutron detector[4] and have been transformed into the center-of-mass system. Measurements with an iron bar shadowing the neutron detector showed that neutrons which are first scattered before impinging on the detector constitute less than 15% of the total yield, are concentrated at low energy, and so have no significant contribution for energies above 2 MeV. Figure 1(a) shows the neutron spectra for different sum-energy slices. The "temperatures," obtained from fits to the exponential tails of the spectra, are shown in Fig. 1(b) as a function of the corresponding spins. (N.B. the temperature derived in this manner is characteristic of a measured spectrum and should not be equated with a nuclear temperature.) The spectra exhibit falling temperatures with rising spin. This is expected qualitatively because the energy above the yrast line is smaller at high spin. Similar results have been obtained by Cabot *et al.*[5] in the reaction ^{65}Cu + ^{87}Rb.

Figure 2 shows the neutron multiplicity distribution which was deduced from the yields of $^{(156-x)}$Er observed in the Ge spectra. Here x is the number of neutrons emitted from the compound nucleus. The solid bars indicate predictions of the statistical-model code CASCADE.[6] The code has been modified to include enhancement of collective $E2$ transitions parallel to the yrast line[3] and $E1$ deexcitation through the giant dipole resonance[7,8] (GDR). The $E1$ strength was given by the energy-weighted sum rule,[8] which yielded agreement for Γ_γ observed in neutron capture[8] and yielded a "GDR bump" in the γ spectrum of similar strength to that observed[7] in (^{40}Ar, xn) reactions. The yrast lines for even-A nuclei in our calculation follow that in ^{154}Er, where states up to spin 36 are known[9]; in odd-A nuclei the yrast line is 1 MeV lower at equivalent spin values larger than 10$\hbar$. It is obvious from Fig. 2 that the statistical model underestimates the ratio R of $2n$ to $3n$ emission by a factor of 20. In contrast, in the case of ^{16}O-induced reactions leading to heavier Er compound nuclei, the model predicts neutron multiplicity distributions in

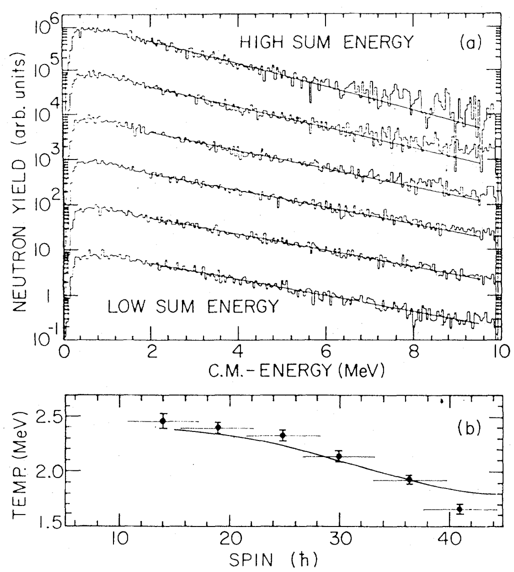

FIG. 1. (a) Neutron spectra, measured at 0°, for six consecutive gamma-ray sum-energy slices. The straight lines represent fits with an exponential function in the energy interval spanned by the lines. Deviations from the exponential shape at high sum energy are due to contamination from isomeric gamma rays. (b) "Temperatures," derived from the fits in (a), as a function of mean entry line spin corresponding to the different sum slices. The solid line represents results from similar fits to neutron spectra obtained in CASCADE calculations, using the elevated (dashed) yrast line in Fig. 3 and a level-density parameter $a = A/16$ (see text).

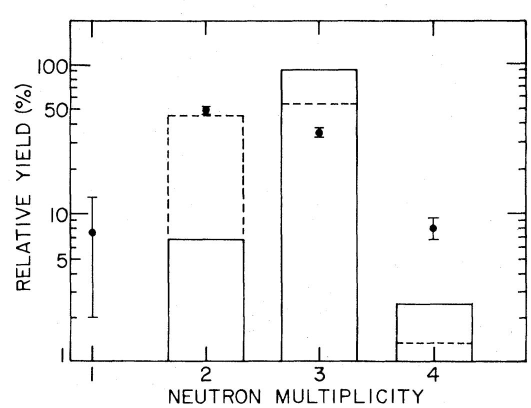

FIG. 2. Comparison of experimental (circles) neutron multiplicity distribution with those from statistical-model calculations using the normal (solid bars) and elevated (dashed bars) yrast lines of Fig. 3.

excellent agreement with experiment.[10] In the following we discuss possible reasons for the failure of the model for ^{64}Ni-induced reactions.

At the low beam energy used here (close to the Coulomb barrier) incomplete-fusion reactions or preequilibrium processes should not contribute to the formation of the Er isotopes. This is confirmed by the lack of any significant high-energy tail in the neutron spectra. As a consequence, the failure of the statistical-model calculation may be attributed to an inadequate choice of the relevant parameters. In an attempt to reproduce R we have performed calculations with enhanced $E1$ strengths and have found that it is necessary to increase the strength ~200 times over that given by the energy-weighted sum rule.[8] Besides being unreasonable, such an enhancement leads to a high-energy tail in the gamma spectrum well in excess of that which is observed experimentally.[7] We have also performed calculations with level-density parameters a between $A/6$ and $A/16$, which is the range usually given in the literature. (A more detailed discussion on the level densities used in the calculation is given by Pülhofer.[6]) R was found to be rather insensitive to variations in a. In contrast, the neutron temperatures do depend sensitively on the choice of a and can be reproduced with $a = A/12$; however, R is too low by a factor of 20 (Fig. 2). Calculations with larger l values, $l_{max} = l_{gr} = 41\hbar$ (Wilke *et al.*[11]) and $l_{max} = 47\hbar$, underestimate R by factors 10 and 5, respectively. (The latter l_{max} value is already larger than indicated by the experimental spin distribution.) Even combining the increased l_{max} of $41\hbar$ with an enhancement of the GDR $E1$ strength by a factor of 10 still underestimates R by a factor of 7.

Thus, we conclude that any change of parameters within reasonable limits is not able to reproduce consistently the neutron multiplicity distribution and the shape of the neutron spectra at the same time. The suppression of the third neutron suggests that the available free energy for neutron emission, i.e., the energy above the compound-nucleus yrast line, is smaller than expected by roughly half of a neutron binding energy. This is borne out by the measured average γ sum energy (16 MeV), which exceeds by 5 MeV the value expected from the calculated neutron multiplicity distribution and is consistent with that expected from the measured distribution. Experimental indications for large deformations have been reported[12] in the Pd region, while several calculations[13,14] have suggested that in the Er nuclei of interest there exists at high spin a superdeformed well with $\epsilon \sim 0.6$, which arises from shell effects and which is related to those which give rise to fission isomers. The existence of a barrier between the domains of normal and superdeformed shapes may affect the shape relaxation of the initially highly distorted compound nucleus, possibly leading to trapping in the superdeformed minimum for an interval comparable to typical neutron emission times (10^{-19}–10^{-17} s). The available energy for neutron decay is then measured with respect to this minimum and is correspondingly decreased from its nominal value. In this event neutron emission will be suppressed, with the excitation energy being removed by γ emission instead. To test this conjecture we have performed a calculation employing an elevated yrast line (dashed in Fig. 3) which was constructed to roughly follow (for $I > 10$) the superdeformed minima in ^{156}Er calculated by Åberg.[13] Good agreement for both R (Fig. 2) and neutron temperatures (Fig. 1) was obtained. To reproduce the neutron temperatures a value of $a = A/16$ was found necessary, a value similar to that used[15] to account for γ multiplicities observed in (^{3}He, α) reactions.

In all calculations the yield for one-neutron

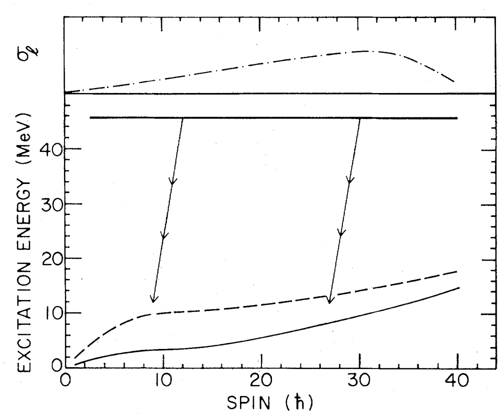

FIG. 3. Angular momentum distribution (top) and yrast lines used in CASCADE calculations. The yrast lines shown are for even-A nuclei; the solid one is similar to that of ^{154}Er (Ref. 9), while the dashed one approximately follows the superdeformed minima calculated for ^{156}Er by Åberg (Ref. 13) for $I > 10$. The yrast excitation energies of odd-A isotopes are 1 MeV lower than those of even-A isotopes for $I > 10$. The thick horizontal bar indicates the initial compound-nucleus energy and the arrows illustrate the average energy and angular momenta removed by neutron emission, demonstrating that there is easily sufficient excitation energy to emit three neutrons.

emission was significantly smaller than observed. On the other hand, the cross section for emission of four neutrons can be reproduced if better account is taken of the energy spread in the target than through the use of an effective beam energy. With the normal yrast line (Fig. 3) the sum of the partial cross sections in each of five slices of the target gives 1–4 neutron yields of 0, 5%, 90%, and 5%. With the elevated (dashed) yrast line of Fig. 3 a decrease in the four-neutron emission cross section would result; however, this yrast line is inappropriate for describing this cross section since it originates primarily from lower l values, for which the superdeformed minimum barely exists.[13]

To summarize, we have measured neutron spectra for ^{156}Er compound nuclei as a function of angular momentum and have determined the neutron multiplicity distribution. The neutron temperatures provide sensitive information on level densities, and together with other available data (on the yrast line[9] and γ-decay strength[7]) provide tight constraints on the parameters used in statistical-model calculations. Such calculations are unable to reproduce the measured neutron multiplicity distribution unless an yrast line elevated with respect to the known one is employed. This raises the possibility of superdeformed shapes at high spin and energy occurring for a time interval comparable to typical neutron emission times ("deformation traps"). This suggestion is clearly speculative at this point, but it can be subject to many further experimental tests. Since the initial deformation of the fusing system may be varied by choosing different entrance channels, the neutron multiplicity distribution for a given spin interval should depend on the mass asymmetry of the entrance channel, in contrast to the Bohr independence hypothesis. Another consequence of the existence of deformation traps may be a strong enhancement of fusion-fission. In addition, both the entry line (locus of maximum population in an E vs I plot prior to γ decay) and the γ-decay spectrum should reflect an excess energy release through γ emission over the more normal case. Finally, we hope to stimulate theoretical calculations on the shape relaxation time of the compound nucleus, particularly in the presence of a superdeformed well.

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