

Nuclear dissipation and the feeding of superdeformed bands

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Statistical model calculations including nuclear dissipation were performed to calculate the high-energy γ -ray spectrum following the reaction $^{16}\text{O} + ^{159}\text{Tb}$. Including dissipation changes the spin population distribution leading to evaporation residues and fission. The calculations show that a larger fraction of the highest partial waves contributes to evaporation residues than standard statistical model calculations predict (an increase of 65% for spins $> 65\hbar$). This effect is shown to provide an explanation for enhanced feeding of superdeformed bands which are populated by the highest partial waves leading to evaporation residues.

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One of the main still open questions related to superdeformed bands is the feeding mechanism. Experimentally it has been determined that the population of superdeformed bands is unexpectedly large (1–2% of the total population) and that they are populated only over a narrow region of the highest spins of the evaporation population [1–4]. In most cases the high-spin limit of the evaporation residue population is determined by the competition with fission (fission cutoff). A number of aspects of the feeding of superdeformed bands have been investigated theoretically [5–7], but one aspect that has not been explored is how the high-spin cutoff due to fission might be influenced by dynamical effects in the fission process. Recent observations [8,9] of enhanced neutron and γ -ray emission prior to fission have been explained by taking nuclear dissipation effects [10] into account; fission is slowed down due to the dissipation and this allows for additional evaporation of light particles and γ rays prior to scission. The population distribution in mass and excitation energy of the primary fission fragments are affected by this phenomenon. On the average the fission fragments will have a lower mass and less excitation energy. It is conceivable that other properties of the compound nucleus decay might also be affected by the inclusion of these dissipation effects.

In the present paper we show results from statistical model calculations with and without nuclear dissipation and discuss the differences in the initial spin distribution leading to evaporation residues and fission. Differences in these distributions are, of course, expected to be most pronounced in the region where the residue cross section decreases and the fission cross section increases with spin, that is, in the vicinity of the fission cutoff. We suggest a modification in the competition between fission and evaporation as a function of spin resulting from nuclear dissipation which may influence the population of superdeformed bands.

The most complete theoretical investigation of the feeding of superdeformed bands is a statistical model calculation by Schiffer and Herskind [7] that included both normal and superdeformed states. Important parameters in the code are the level density of the superdeformed states, the crossing point at which superdeformed states become yrast, and the barrier between the normal and superdeformed potential well. The calculation also allows for mixing (tunneling) between the normal and superdeformed shapes and includes the effects of changes in giant dipole resonance splitting as a function of deformation. Although the calculations by Schiffer and Herskind can reproduce the shape of the feeding distribution of the superdeformed bands as a function of excitation energy, they underpredict the overall yield. A change of the primary spin distribution leading to evaporation residues in the range where the superdeformed states are populated would certainly influence the results of these calculations.

We analyzed high-energy γ -ray spectra in coincidence with fission fragments emitted following the reaction $^{16}\text{O} + ^{159}\text{Tb}$. Details of the experimental setup and the statistical model calculations are provided elsewhere [11]. In order to describe the γ -ray spectra, nuclear dissipation had to be included in the calculation. Dissipation results in a reduction of the asymptotic fission width relative to the conventional Bohr-Wheeler value (Γ_f^{BW}) given by the Kramers relation [12]. In addition, the fission width (Γ_f) becomes time-dependent reflecting transient effects in the buildup of the fission probability [13]. These two effects were approximated by the relation [13]

$$\Gamma_f(t) = \Gamma_f^{\text{BW}}(\sqrt{1+\gamma^2} - \gamma)[1 - \exp(-t/\tau_f)] .$$

The nuclear dissipation coefficient γ , and τ_f , the fission decay time, can be approximately related by [13,14] $\tau_f = 10^{-21} \gamma \ln(10B_f/T)$, where B_f is the fission barrier and T the temperature of the system. These dissipation

effects were included in a modified version of the statistical model code CASCADE [15,16,14]. The fits to the γ -ray spectra [11] required a nuclear dissipation coefficient of $\gamma=10$, which is consistent with results in heavier mass systems [14].

CASCADE calculations for each initial spin value were then performed with standard statistical model parameters and with the inclusion of dissipation effects in order to extract the evaporation and fission cross section as a function of spin.

The results of these calculations are shown in Fig. 1. The total fusion cross section (solid) is partitioned between the fission and evaporation residue cross section. The distribution of fission cross section for the calculation including dissipation (short-dashed) is shifted to lower spins compared to the standard calculation (dotted), whereas the tail of the evaporation residue (dissipation, long-dashed) extends to higher angular momenta than the standard calculation (dot-dashed). Figure 2(a) shows the relative contribution of the evaporation cross section to the total fusion cross section of the standard calculation (dashed) compared to the calculations including dissipation mechanisms (solid). This figure clearly shows the enhancement of the evaporation residue cross section due to nuclear dissipation. This effect appears to be relatively small, but because the feeding of the superdeformed bands corresponds to $\sim 1\%$ of the total residue population [7] even a small change of the population distribution can yield an important increase in the population of the superdeformed bands.

The population above $60\hbar$ relative to the total evaporation residue cross section increases from 8% for the standard calculation to 10% for the dissipation calculation. Above $65\hbar$ the evaporation residue cross section increases from 1.7% to 2.8%. Figure 2(b) shows the ratio of the effective total evaporation residue population calculated using dissipation and the standard calculation for spins above a given spin. For example, the population increases above $60\hbar$ and $65\hbar$ are 25% and 65%, respectively, as indicated by the dashed lines. With this result we

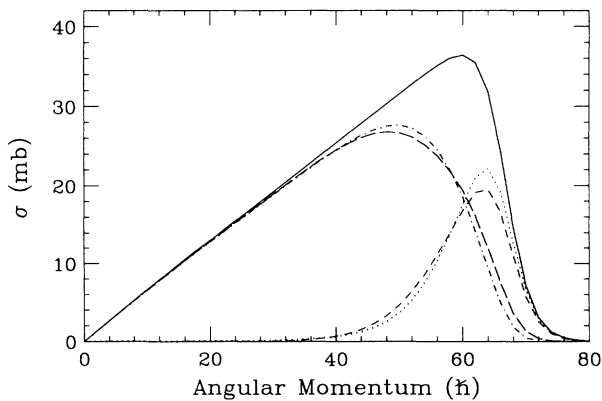


FIG. 1. Spin distributions for $E_{\text{beam}} = 160$ MeV: total fusion (solid), evaporation residues (dot-dashed) and fission (dotted) calculated with the standard statistical model and evaporation residues (long-dashed) and fission (short-dashed) calculated by including nuclear dissipation.

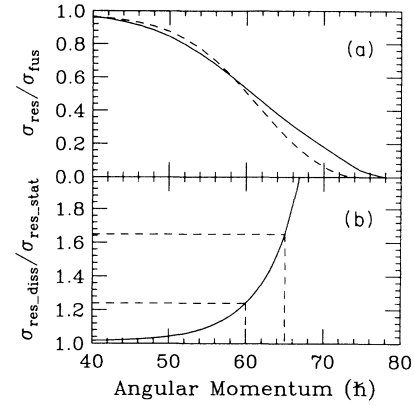


FIG. 2. (a) Relative evaporation residue cross section for the standard (dashed) and dissipation (solid) calculations. (b) Ratio of dissipation to standard calculation of evaporation residue cross-section population above a given spin.

can estimate the increase of the superdeformed band population from the calculations of Schiffer and Herskind [7] for ^{152}Dy . They show that the population originates from a narrow spin window ($\sim 16\hbar$) bounded by the fission limit at high spin and the yrast crossing to the normal deformed band at low spin. Our calculation with dissipation yields an enhancement above $65\hbar$ that implies an approximate increase of 20% in the total superdeformed population. This enhancement is purely due to the additional high-spin population that does not fission. Other factors like the depth of the minimum of the superdeformed band which is a function of spin might further enhance the population.

A word of caution is in order concerning the way nuclear dissipation was included in the calculation for the $^{16}\text{O} + ^{159}\text{Tb}$ reaction. Since the fission cross section which has been measured (~ 280 mb) [17] has to be reproduced, one has to compensate the fission probability reduction in the early stages of the decay. This can be achieved, for example, by reducing the overall fission barrier, as was done in the present calculations, or by increasing the level-density ratio for fission with respect to neutron evaporation, a_f/a_n . This will increase the fission probability at lower angular momenta and, therefore, produces a shift of evaporation residues to higher values. We believe that this admittedly *ad hoc* procedure will reflect the important physical effects; however, a full dynamical treatment of the fission would certainly be preferable.

This paper has discussed the influence of one aspect of dissipative dynamics in the decay of highly excited compound nuclei on the population of superdeformed states. Dissipative effects can, however, influence the formation as well as the decay of the compound nucleus. It is worth considering whether such influences on the fusion process might also lead to observable effects on the superdeformed band population.

Dissipative effects can delay the coalescence of reactants in heavy-ion fusion just as they delay fission. In calculations employing dissipative dynamics [18,19] a "fusion time" can be defined as the time required, after contact, for the thermal energy to reach some specified

fraction of its final value. It is found [19,20] that this time is a strong function of the entrance channel asymmetry. It is largest for nearly symmetric entrance channels at bombarding energies near the Coulomb barrier, and increases with increasing angular momentum. For different entrance channels with bombarding energies chosen to produce the same compound system at the same excitation energy (if the Z of the compound nucleus is greater than ~ 60), fusion times can be almost 10 times longer for mass symmetric entrance channels than for very asymmetric ones. The time scales involved are similar to those involved in fission ($\sim 10^{-20}$ s). It is obviously possible for particle and γ -ray emission to occur during the coalescence process just as it does prior to fission, thus leading to differences in the decay of the same composite system at the same spin and excitation energy. Such effects have probably already been observed experimentally [21–24]. These entrance channel dependent effects of dissipation are unlikely to directly affect the superdeformed band population, since the time scale for feeding yrast or near-yrast states is orders of magnitude longer than the fusion time; however indirect effects are possible. It is generally assumed that the cutoff in evaporation residues at high spins by fission is a property of the compound nucleus and hence independent of en-

trance channel. It is at least plausible that the extended time required for fusion could modify the subsequent competition between fission, particle, and γ -ray emission, to make this spin cutoff entrance channel dependent. We therefore suggest that recent observations of entrance channel dependent feeding of superdeformed bands [25] could be due to indirect effects of dissipative dynamics.

In conclusion, we have discussed the possible implications of dynamical effects on nuclear structure experiments, and in particular, on the feeding of superdeformed bands. Accurate measurements of the angular momentum distribution leading to evaporation residues should be extremely interesting not only in studying the possible enhancement of the feeding of superdeformed bands from very high angular momenta but also because they may provide more insight into the detailed process of nuclear dissipation.

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