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Entrance-channel effects in the population of superdeformed bands in ^{147,148}Gd

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Discrete superdeformed bands in ^{147,148}Gd have been populated with asymmetric and symmetric fusion-evaporation reactions. The yields of the superdeformed bands compared with the total yield of the channel exhibit a large increase for symmetric reactions. We suggest an explanation for this effect in terms of the competition between neutron emission and fission at the early stage of the deexcitation process of the composite system.

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In the last few years spectrometers comprising many Compton-suppressed HPGe detectors have observed γ rays emitted by superdeformed (SD) nuclei at high spin. Shortly after the first discovery [1] of a discrete SD rotational band, it was realized experimentally [2] and theoretically [3] that the strongest population of these bands occurred when the residual nucleus was produced relatively cold at very high spin. The yield of SD states in a particular residual nucleus then depends critically on the angular momentum and excitation energy of that residue; it therefore has a strong dependence on the reaction channel [4,5]. The broad features of these effects can be understood by noting that superdeformed states are populated in a narrow spin window, the upper edge is limited by the fission process while the lower edge is due to an unfavorable ratio of SD to normal-deformed level densities [5,6].

A few years before the first observation of a discrete SD band, it was suggested [7] that the decrease in evaporated neutron multiplicity for near symmetric heavy-ion fusion reactions could be explained by the existence of a long-lived SD composite system. This would imply that the yield of an SD band might depend on the entrance channel which would be in contradiction with the compound nucleus theory. No evidence for such entrance-channel effects was found in the first study of the SD band population in ^{152}Dy [8]. However, a more recent and detailed investigation has shown [9] that the SD band in ^{152}Dy is more strongly populated when a symmetric reaction is used. In the present work, we have studied the dependence of the population intensity of the discrete SD bands in ^{147,148}Gd [10,11] on the entrance-channel mass asymmetry.

In this study we have examined three fusion-evaporation reactions: ^{124}Sn+^{29}Si, ^{122}Sn+^{30}Si, and ^{76}Ge+^{76}Ge, populating ^{148}Gd and ^{147}Gd residues after the evaporation of four or five neutrons. Preliminary results of the first two experiments have been reported in [12]. The Si (155 MeV) and the Ge (319 MeV) beams were provided by the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at the Chalk River Laboratories. The targets consisted of two stacked foils of 400 μg/cm^2 each for Sn and 300 μg/cm^2 each for Ge. Emitted γ rays were detected with the 8π spectrometer [13], which comprises a ball of 71 bismuth germanate (BGO) elements surrounded by an array of 20 Compton-suppressed HPGe detectors. Doppler-shift corrections to the γ-ray energies registered by the HPGe detectors were performed on-line. The trigger to record an event on magnetic tape required at least two (Compton-suppressed)

HPGe detectors and a condition on the number, K, of BGO elements responding. For the $^{124}Sn+^{29}Si$ experiment, we required that $K \geq 12$. For the reactions leading to ^{147}Gd, the BGO ball was also used to select the $5n$ exit channel by exploiting the presence of a 550-ns ($\frac{49}{2}$) isomer in ^{147}Gd [14]. For these two reactions, the BGO multiplicity conditions were $K_{prompt} \geq 9$ and $K_{delayed} \geq 4$ and the isomer tagging efficiency was measured to be approximately 70%. A total of $\sim 2\times 10^8$ γ-γ coincidence events were recorded for the symmetric reaction ($^{76}Ge+^{76}Ge$), while each asymmetric reaction generated $\sim 5\times 10^8$ events. In the off-line analysis, $E_{\gamma 1}$-$E_{\gamma 2}$ coincidence matrices were constructed using more restrictive BGO multiplicity conditions chosen to suppress unwanted reaction channels.

The estimated excitation energy and maximum transferred angular momentum l_{max} calculated using the Bass potential [15] are presented in Table I. To make the most direct determination of the entrance-channel effect, the residual nucleus should be populated at a common excitation energy and at the same maximum angular momentum. Unfortunately, for the $^{122}Sn+^{30}Si$ and $^{76}Ge+^{76}Ge$ reactions these conditions can only be met at $l_{max}=44\hbar$ and $E^*=56$ MeV for the compound system; in which case the angular momentum would be too low to populate an SD band [5]. We have chosen the ^{30}Si and ^{76}Ge beam energies to produce the composite system at very similar excitation energies, therefore the l_{max} with the ^{76}Ge was higher than that with ^{30}Si. However, both maximum angular momenta were large enough to be in the region where the SD band intensity saturates due to the very strong competition with fission [5,6].

Two SD bands are known in ^{147}Gd [10]. Their population intensities are given in Table I for both symmetric and asymmetric reactions. We have used the total data set (isomer tagged and prompt events) to extract the population ratios, with an exception for the first SD band in ^{147}Gd populated with the $^{76}Ge+^{76}Ge$ reaction. Because the transition energies of the lowest SD band in ^{147}Gd are nearly identical with those in ^{148}Gd [10], a reliable intensity value could not be derived from the total data set for the symmetric reaction where a larger Doppler broadening of the peak widths occurred due to the large recoil velocity of the residues. In Table I it can be seen that the intensity ratio compared to the channel population is $\sim 60\%$ greater for both SD bands in ^{147}Gd when a symmetric reaction is employed. The relative intensity of the first SD band for the $^{76}Ge+^{76}Ge$ reaction was extracted from the isomer tagged data set assuming that this enhancement factor is unaffected by the tagging process. The 919-keV transition ($\frac{51}{2}^+ \rightarrow \frac{49}{2}^+$) was used to obtain the normal-deformed state intensities. This transition represents 27% of the $\frac{49}{2}$ isomer feeding [16] which collects 80% of the total yield of the nucleus.

The population intensity of the yrast SD band in ^{148}Gd is also given in Table I. The normal-deformed state intensities were obtained from the $\gamma 337$:$\gamma 959$ coincidence, which was measured to represent $15\% \pm 2\%$ of the total yield of the nucleus in agreement with Ref. [17]. For the symmetric reaction, it was possible to isolate the ^{148}Gd from ^{147}Gd by requiring a very large BGO multiplicity ($K \geq 26$) in the data analysis. The corresponding spectrum is presented in Fig. 1 together with the spectrum of the first SD band in ^{147}Gd gated by the detection of the 550-ns isomer decay. One notices that the energy of the γ rays are similar for both bands. However, a careful examination reveals that the spectra are not cross contaminated. Gamma-ray spectra measured with the asymmetric reactions may be found in Ref. [12]. The enhancement factor for the symmetric reaction in the $4n$ exit channel is even larger than that observed in the $5n$ channel leading to ^{147}Gd.

Setting gates on the fold K introduces a bias to the observed relative intensity of the SD bands. To remove this bias, one has to measure the K distribution associated with the normal-deformed and SD transitions, and then, from these distributions, calculate the intensity ratios selected by the specific K window used in the analysis. Unfortunately, in the present work it was not possible to obtain a clean K distribution for the SD bands since both SD bands have similar γ-ray energies. However, from previous experiments performed with the 8π spectrometer in this mass region [4,12], it is known that the K distribution has approximately the same shape for the normal-deformed and SD exit channels, with a shift of one or two units to higher fold in the SD case. We have assumed that this is also true in the present experiment to calculate the relative intensity of the SD bands unbiased by the K selection; the uncertainty on the magnitude of the shift was included in the calculation of the errors given in Table I.

TABLE I. Calculated excitation energy and maximum angular momentum at the center of the target for the different reactions assuming that a kinetic energy of 13 MeV was carried away by the neutron cascade; the numbers in parentheses correspond to the spread in excitation energy and angular momentum due to the energy loss of the beam in the target. The measured relative population intensities of the SD bands are also presented.

	Excitation energy (MeV)			I_{SD}/I_{normal} (%)	
Reaction	Compound	Residue	l_{max} ($\hbar$)	Band I	Band II
$^{122}Sn(^{30}Si,5n)^{147}Gd$	83(2)	31(2)	65(1)	1.3(2)	0.5(1)
$^{76}Ge(^{76}Ge,5n)^{147}Gd$	84(3)	32(3)	79(3)	2.1(3)	0.8(2)
$^{124}Sn(^{29}Si,5n)^{148}Gd$	87(2)	37(2)	65(1)	0.8(2)	[a]
$^{122}Sn(^{30}Si,4n)^{148}Gd$	83(2)	39(2)	65(1)	0.5(2)	[a]
$^{76}Ge(^{76}Ge,4n)^{148}Gd$	84(3)	41(3)	79(3)	1.9(5)	[a]

[a]An excited SD band in ^{148}Gd has been reported in Ref. [12] but its intensity is too weak to be extracted accurately.

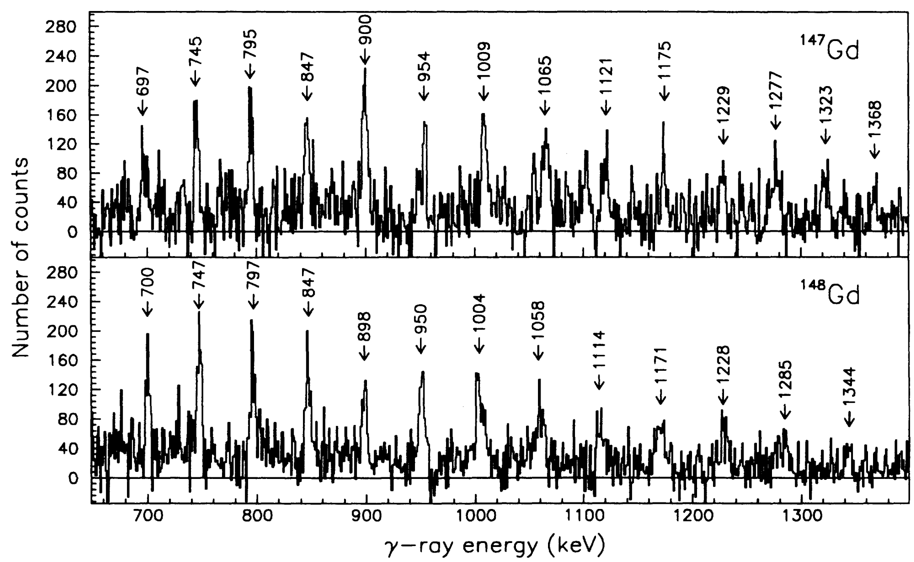

FIG. 1. Gamma-ray spectra for superdeformed bands measured in the $^{76}Ge+^{76}Ge$ reaction. The spectrum of the yrast SD band in ^{148}Gd has been obtained requiring a BGO ball multiplicity of $K \geq 26$, while the first SD band in ^{147}Gd has been isolated by tagging on the 550-ns isomer.

As recently observed [9] in ^{152}Dy, the discrete SD bands in ^{147}Gd and ^{148}Gd are more strongly populated when mass-symmetric projectile-target combinations are used. Moreover, the observed entrance-channel effect seems to be more pronounced when the number of evaporated neutrons is smaller. These facts suggest that in the case of symmetric reactions a dynamical process favors particle evaporation over the fission decay channel. That is to say there is some delay in the fission process associated with a compound system formed by symmetric partners compared with the same system formed by asymmetric partners. As proposed in Refs. [9,18], the observed entrance-channel effect might also be explained by a longer fusing time for the symmetric reactions; during which time, particles could be emitted from the very deformed composite system. Both interpretations imply that for the symmetric entrance channel there is an increase in the effective maximum angular momentum at which the evaporation residues are produced. In other words, the γ-ray multiplicity distribution (or K distribution) should have a tail at the highest values. This tail should be principally observable in the K distribution associated with the SD bands; as previously explained, it was not possible to measure such distributions in the present experiment. A nucleus populated in this high-spin region has a higher probability of decaying into the discrete SD bands and consequently the relative yields of these bands are larger. Thus the measurement of the SD band intensities may provide a sensitive probe of the reaction dynamics at the fission threshold. The intensity distribution along the SD bands should also depend on the entrance channel; in particular, the mean spin of feeding should be shifted to higher values in the case of symmetric reactions. Unfortunately, the relatively large Doppler broadening prevents a reliable measurement of the SD intensity pattern and we will have to wait for the next generation of γ-ray spectrometers to address this question.

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