Enhanced population of superdeformation in the mass $A=150$ region

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An enhanced population of the ^{149}Gd yrast superdeformed band has been observed in the reaction ^{124}Sn($^{31}P,p5n$) using the EUROBALL IV multidetector associated with an inner ball. This effect is explained as the consequence of a higher probability of trapping residual nuclei into the superdeformed well whose depth has been increased due to favorable temperature and of total energy and angular momentum selection with the inner ball.

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I. INTRODUCTION

One of the main open questions related to superdeformed (SD) bands remains the feeding mechanism. Experimentally, in the mass $A=150$ region, the intensity of the SD yrast states is 1–2 % of the population of the reaction channel in heavy-ion fusion-evaporation reactions. The combined results of many experiments using different arrays and entrance-channel mass asymmetries have shown that the yield of SD states in a particular residual nucleus depends critically on the angular momentum and excitation energy of that residue. The yield therefore shows a strong dependence on the characteristics of the reaction channel. In particular, an enhancement of the SD band population by a factor of 1.5–2.0 has been observed, relative to the normal deformed nuclear states, when populated via a mass-symmetric reaction versus a mass-asymmetric one [1–3]. All these differences in population have been reported using (*xn*) reaction channels and up till now no such systematic effect has been seen using (*pxn*) channels. Meanwhile some calculations [4] have suggested the importance of proton emission in the population of highly deformed nuclei, but only a few investigations have been made to observe a possible enhancement of SD band population in proton evaporation channels. Viesti *et al.* [5] have measured the feeding pattern of the yrast SD band in ^{152}Dy populated by the ^{120}Sn(^{37}C,$p4n$) reaction. Comparison with the results obtained in well-studied *xn* channels [2,6] gives the same values within the experimental uncertainties.

More recently, a study was made to determine whether the population of SD states in ^{193}Hg and ^{195}Hg could be enhanced by using ($\alpha5n$) reactions. The intensities of the two SD bands observed in ^{193}Hg were found to be reduced by a factor of 4 relative to the intensities observed in the reactions involving only neutron and γ emission [7].

Here we report results obtained for the population of the yrast SD bands in ^{150}Gd and ^{149}Gd observed in the ($p4n$) and ($p5n$) reaction channels. These results are by-products of our extended analysis of the properties related to SD bands present in the Tb nuclei using (*xn*) exit channels.

II. EXPERIMENT

The ^{149,150}Tb nuclei have been investigated using the EUROBALL IV array installed at the VIVITRON accelerator of the Institut de Recherches Subatomiques in Strasbourg. High-spin states of these nuclei observed, respectively, in the $6n$ and $5n$ channels were populated via the ^{124}Sn+^{31}P reaction at a beam energy of 167 MeV. Two self-supporting ^{124}Sn targets in a stack were used, with thicknesses of 350 and 420 μg/cm^2, respectively.

The EUROBALL IV array consisted of three types of Ge detectors: 30 high efficiency tapered detectors located on three rings at forward angles, 26 composite clover detectors each consisting of four crystals placed at medium angles, and finally 15 cluster detectors at backward angles, each formed by seven high efficiency encapsulated diodes in a common cryostat. The main new feature of EUROBALL IV is the presence of an inner ball of BGO detectors (210 crystals) in front of the BGO anti-Compton collimators. Together, with the Ge detectors (239 detectors), they form a device of 164 groups of detectors in terms of solid angle and efficiency allowing one to measure the multiplicity and the sum energy of γ rays emitted in a nuclear reaction.

A fold condition of four unsuppressed Ge detectors and 16 BGO ball elements firing in coincidence was required for selecting high multiplicity events and therefore to optimize the population of high-spin states in ^{150}Tb produced in the $5n$ channel. The population of the ^{149}Tb nucleus fed in the $6n$ channel amounts ≈69% of the $5n$ channel.

After Compton suppression, a total of 924×10^6 fourfold and higherfold events was obtained with a mean fold of 5.0. These data have been analyzed using a ''nonspiked'' database according to the procedure described in Ref. [8]. The search for weakly populated SD bands in (*xn*) and (*pxn*) channels was carried out by requiring three gates to be satisfied. A three-dimensional cube has also been investigated for supplementary analysis.

TABLE I. Intensities of the different channels considered relative to the intensity of the $5n$ channel (line 1). In the rest of the table are given the population intensities of the corresponding yrast superdeformed bands measured with respect to the normal deformed (ND) channels in previous and the present work.

	^{150}Tb($5n$)	^{149}Tb($6n$)	^{150}Gd(p,$4n$)	^{149}Gd(p,$5n$)
$\sigma(\mathrm{ND}_i)/\sigma(5n)$	100(2)%	69(2)%	25(1)%	7.9 (0.5)%
$\sigma(\mathrm{SD}_i)/\sigma(\mathrm{ND}_i)$				
Previous works	1.0%	1.2%	1.0%	1.8%
This work	1.5 (0.3)%	2.0 (0.3)%	1.5 (0.3)%	6.5 (1.5)%

III. RESULTS AND DISCUSSION

All the SD bands previously assigned to ^{149,150}Tb nuclei [9,10] have been observed with some of them extended to higher frequencies. The yrast SD bands in ^{149}Gd and ^{150}Gd populated through the $(p5n)$ and $(p4n)$ exit channels, respectively, have also been observed. The assignment of these two bands to the Gd isotopes is based on the unambiguous observation in coincidence of known γ-ray lines of the corresponding nuclei.

The intensities of the ^{150}Gd and ^{150,149}Tb yrast SD bands, relative to the total population of the $(p4n)$, $5n$ and $6n$ channels, respectively, have been measured to be $\approx$1.5%, $\approx$1.5%, and $\approx$2%, respectively. These values are slightly higher but nevertheless still in agreement with the general trend of previous measurements [10,11] (see Table I). The observation of the SD band population enhancement is certainly due to the highfold requirement of the inner ball.

In order to investigate the population of the ^{149}Gd yrast SD band in the $(p5n)$ reaction channel compared to the population of the ^{150}Tb yrast SD band in the $5n$ reaction channel, we have produced the two spectra related to the yrast SD bands in ^{149}Gd and ^{150}Tb nuclei by requiring three gates to be satisfied among the same number of γ-ray transitions. Special care has been taken by applying the same SD gating conditions, namely, the same gate width for each SD γ ray and by avoiding strong contamination not only from these two SD bands but also from the yrast SD band in ^{149}Tb. These three SD bands have nearly identical transition energies in the 1.0–1.1 MeV energy range. The two spectra observed for ^{150}Tb and ^{149}Gd are presented in Fig. 1. A comparison of the two spectra shows that the ^{149}Gd yrast SD band population is surprisingly strongly favored in the $(p5n)$ channel with a ratio of $\approx$2.9 between the intensities of the two SD bands. The cross section of the $(p5n)$ channel relative to that of the $5n$ channel was estimated as 7.9(0.5)% taking into account the presence of the $J^{\pi}=49/2^{+}$ isomeric state (4 ns) in ^{149}Gd. The relative intensity of the yrast SD band in ^{149}Gd populated in the $(p5n)$ reaction has been measured to be 6.5(1.5)%. The cross section for populating this SD band in a $5n$ channel (^{124}Sn+^{30}Si) was previously reported to be 1.8% of the total yield of this nucleus [12]. According to these observations, the band was found in the present work to be populated $\approx$3.5 times more strongly in the $(p5n)$ reaction compared to the previous result observed in the $5n$ reaction channel. The strength of the yrast SD band in ^{149}Gd has also been measured [13] in the last reaction with the requirement of highfold selection ($K\geqslant 21$). In this case the intensity was approximately 2.5% of the total ^{149}Gd channel. We also were able to observe the second excited band in ^{149}Gd and an intensity of $\approx$40% compared to the present SD yrast band intensity was measured.

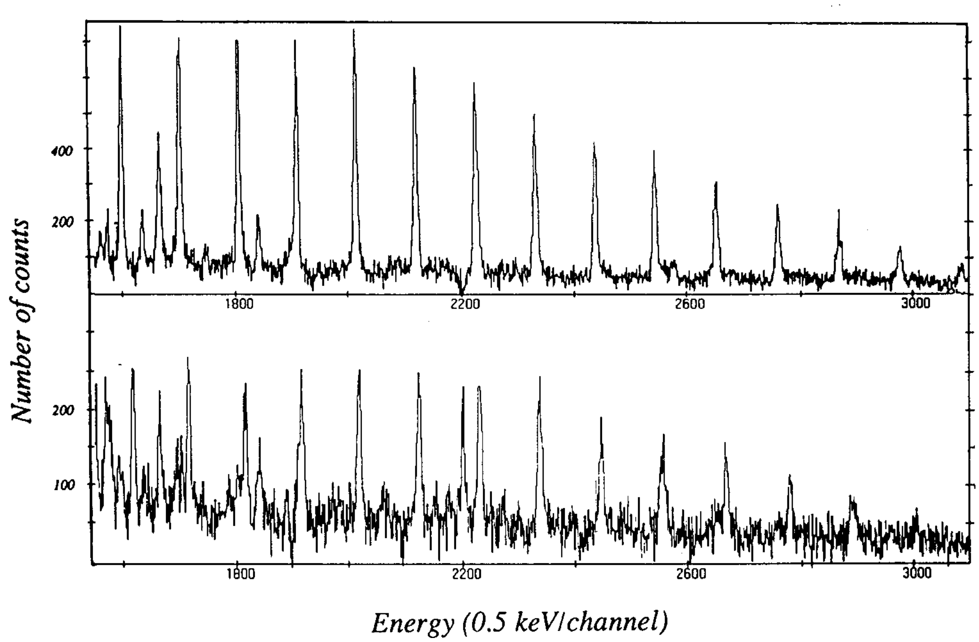

FIG. 1. Coincidence spectra representing the yrast superdeformed bands in ^{150}Tb (upper part) and in ^{149}Gd (lower part) obtained by summing all possible three gates on these bands. Careful gating conditions have been applied in the 1.0–1.1 MeV energy range where the bands have nearly identical γ-ray energies.

Theoretical calculations [14] of nuclear level densities as a function of quadrupole deformation indicate that at very high spins and low excitation energies, there is a strong tendency for the side feeding of SD bands to increase as the temperature of the residual nucleus decreases. This is due to a favorable competition of the level density factor in the superdeformation range over the normal deformation one. The effect of temperature on the formation of SD states has been observed experimentally [15] by producing residual nuclei at the same angular momentum but at different excitation energies. The conclusion was that a necessary criterion for population of SD states is that these residual nuclei must be formed at low excitation energy relative to the yrast SD line. In our case, the large difference in population of yrast SD bands in ^{149}Gd and ^{149}Tb after evaporation of the same number of nucleons implies that the total available thermal excitation energy of the compound nucleus is not shared in the same way among the evaporated nucleons. The $(p5n)$ reaction with a larger dissipation of excitation energy in the proton decay leads the entry states closer to the SD yrast line. In addition, the highfold requirement involves a decrease of the available excitation energy above this last line. On the contrary, there is no differences in population of the yrast SD bands in ^{150}Gd and ^{150}Tb. In this case the number of evaporated nucleons is decreased to five units (one neutron less), leading to higher excitation energy in the final nucleus. The calculated probability of populating the discrete SD band in ^{149}Gd has been obtained as a function of the initial spin and the excitation energy above the band [16]. This probability increases with decreasing temperature U_0 at a given spin and can reach $\sim$5% for spins 60 to 65 $\hbar$ and for U_0 between 2 and 4 MeV. Therefore, the enhanced population of the yrast SD band in ^{149}Gd can be explained by the fact, that for the first time we are able to reach a higher probability of trapping this nucleus in a SD well, this probability depending critically on the well depth and consequently on the temperature associated with the entry distribution for SD states.

IV. SUMMARY

In summary, the enhanced feeding of the yrast SD band in ^{149}Gd by the $(p5n)$ channel is a new significant indication that the population of superdeformed states depends strongly on the excitation energy of residual nuclei relative to the yrast line. In order to obtain the highest population, the cascade of evaporated nucleons has to approach the minimum of the SD well as close as possible and therefore take advantage of the quite favorable ratio of SD to normal deformed level densities. Total energy versus angular momentum selection associated with proton tagging could be an interesting criterion for discovering weak excited SD bands or hyperdeformed bands.

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