CHARGED PARTICLES IN COINCIDENCE WITH SUPERDEFORMED STATES: A TEST OF THE COMPOUND NUCLEUS DECAY AT LARGE ANGULAR MOMENTA * **

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The reaction $^{37}Cl+^{120}Sn$ at 187 MeV bombarding energy has been investigated in a coincidence experiment between charged particles and γ-rays at the GASP spectrometer. The population of the superdeformed (SD) band of ^{152}Dy has been studied in the $p4n$ and $d3n$ channels. Alpha particle spectra in coincidence both with normal deformed (ND) and SD bands of ^{150}Tb have been measured. A clear difference is observed between the two spectra, that in coincidence with the SD states being shifted to lower energies. This effect is understood in terms of different angular momentum regions from which the ND and SD states originate. The standard statistical model fails to describe the angular momentum dependence of the alpha particle energies. The use of statistical model in the region where the fission-evaporation competition is strongly affected by dynamical effects is discussed.

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1. Introduction

The studies of nuclei at high excitation energy (E_x) and angular momentum (J) identify a research field in nuclear physics active since long time [1, 2]. These studies have generally benefited from the availability of heavy ion beams, to produce of compound systems at different (E_x, J) in such a way that the effects related to both parameters could be discriminated and studied separately. The basic question to be answered in this field is “How do excited rotating nuclei compare to cold (ground-state) nuclei?” [3]. In this respect, several attempts to derive quantitative information about the

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emission barrier (and from this parameter about the average shape of the emitter) by analyzing the inclusive charged particle spectra found a severe limitation in the intrinsic complexity of the decay cascade [4].

The study of correlations between particle evaporation and the states in the final evaporation residues (ER) is possible today with the advent of large γ-ray arrays. This opens also new possibilities in this field and renews the interest on the study of the evaporative spectra. Decay paths can be, in fact, selected with this technique by triggering on discrete γ-rays. The exclusive spectra obtained in this way may help in solving the ambiguities in the interpretation of the evaporation process based on inclusive data. Furthermore the possibility exists to correlate the evaporation spectra to discrete γ-rays from the decay of high spin states, filtering during the process only the high angular momentum component of the compound nucleus decay. Finally, various bands can be selected with shapes ranging from spherical to superdeformed ones (SD) in the same final nucleus. The latter possibility seems to be of extreme interest. In fact it is generally accepted that the particle evaporation process from the compound nucleus is chaotic and that only in the near-yrast γ cascade, where the feeding of different classes of states takes place, the ordered motion is restored [5]. The sensitivity of the particle spectrum to the feeding of specific states in the residual nuclei can be taken as an indication that additional degrees of freedom might be important in the evaporation process or that particular regions of the phase space open to the decay populate preferentially some selected structures in the final cold nucleus. This is important for the understanding of the feeding mechanism of SD states.

We present here results from experiments in which correlations have been measured between charged particles and discrete γ-rays. In particular we have pushed forward this technique studying those decays, as the alpha particle emission, which have been proposed in the past as a sensitive probe for the deformation of the emitting nucleus [6].

2. Experimental details

The experiment was performed at the XTU Tandem facility of the Laboratori Nazionali di Legnaro using a beam of 187 MeV ^{37}Cl (intensity ~ 3 pnA) and targets made of two foils (0.5 mg/cm^2 + 0.4 mg/cm^2) of ^{120}Sn. Gamma-rays were detected using the GASP spectrometer [7]. Charged particles were detected with the ISIS silicon ball which is made of 40 ΔE–E telescopes (130 μm and 1000 μm thick, respectively) covering a geometrical solid angle of about 90% of 4π. The event trigger was determined by any three or more Compton suppressed Ge detectors and five or more BGO scintillators of the GASP inner ball firing in coincidence with the charged particle detectors. A total of $\sim 1 \times 10^9$ events in coincidence with charged particles were recorded, being the statistics for protons and alpha particles roughly equal. The spectra obtained in this study are those measured in the first forward ring of the silicon ball (six telescopes at $\theta_{\rm lab} \sim 34°$) for which the threshold due to the thickness of the ΔE detector is unimportant. The energy spectra of the telescopes were summed, after gain matching.

3. Coincidences with H isotopes

Several experiments performed so far did not find a clear dependence of the shapes of the particle spectra on the excited states having different deformations in the ER [8–12]. For example, the proton spectra in coincidence with transitions in the SD bands of ^{133}Nd [11] and ^{152}Dy nuclei [12] were found to be similar to those in coincidence with transitions in the normal deformed (ND) bands. We have continued this study by comparing

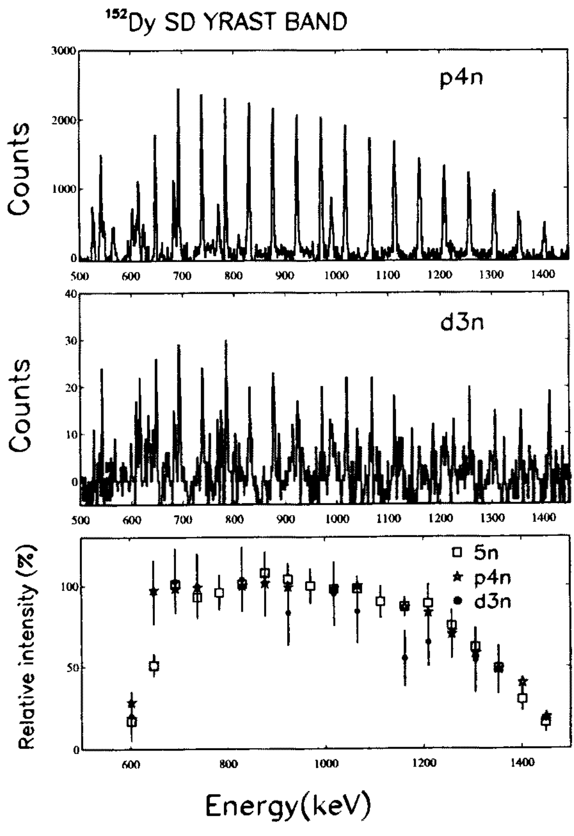

Fig. 1. The yrast Sd band in ^{152}Dy.

the population of SD bands in decay channel in which charged particles are evaporated with that, from the commonly used xn channels. The use of pxn decay channel in studying high spin structures was proposed because of the expected change in the macroscopic fission barrier ($\Delta B \sim +1$ MeV for $\Delta Z = -1$) and of the predicted sensitivity of charged particles to the lowering of the Coulomb barrier induced by deformation [13].

The yrast SD band in ^{152}Dy as populated via proton ($p4n$ channel) or deuteron ($d3n$ channel) evaporation shows a feeding pattern which compares well with earlier experimental data from the (^{36}S,xn) [14] and the (^{48}Ca,xn) [15] reactions, as shown in Fig. 1. The measured intensity, relative to that of the ND ^{152}Dy states is SD/ND = 1.1 ± 0.1% for the $p4n$ channel and SD/ND ∼ 0.7 for the $d3n$ channel. The value for the $p4n$ channel fits nicely in the systematics of Ref. [14].

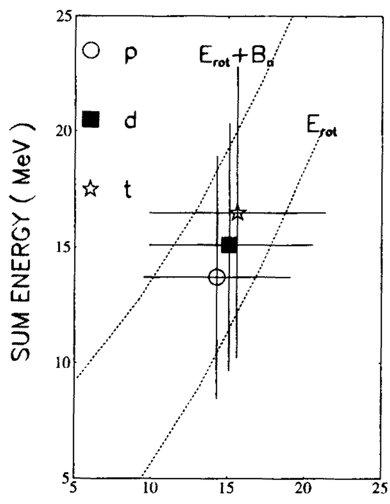

Fig. 2. Entry states in ^{152}Dy after emission of $p4n$, $d3n$ and $t2n$.

Furthermore the average entry states in the ^{152}Dy nucleus populated by $p4n$, $d3n$ and $t2n$ emission have been determined (see Fig. 2). The location of the entry states in the yrast plane depends on the phase space open to a given decay, taking into account the energy and the angular momentum dissipated in the particles emission. As shown if Fig. 2, the net result for this particular reaction is that the emission of heavy hydrogen clusters produces an increase of the average angular momentum of the entry states. The entry states associated to the emission of d ant t particles are located, however, at a slightly larger excitation energy relative to the RLDM predicted yrast line. This increase of the excitation energy of the entry states might be responsible of the apparent decrease of the relative population of the yrast SD band evidenced in this work. We note also that the fluctuations associated to the particle emission process seems to increase with the mass of the cluster. Bars in Fig. 2 indicate, in fact, the width [FWHM] of the distributions in fold and sum energy measured in the GASP inner ball.

4. Coincidences with alpha particles

The γ-ray spectra in coincidence with alpha particles and associated with long γ-ray cascades selected in the inner ball (fold $k > 10$ and sum energy $H > 14$ MeV) are very clean and show practically only the residual nuclei ^{149,150}Tb. The spectrum of the known yrast SD band in ^{150}Tb [16, 17] extracted from the γ-γ-γ data in coincidence with α-particles is shown in Fig. 3. The intensity of the band is $\sim 0.7\%$ of the ^{150}Tb total population, a figure which compares well with the data of the (^{31}P,5n) reaction reported in Ref. [17]. The feeding pattern of the band seems to be scarcely affected by the reaction used.

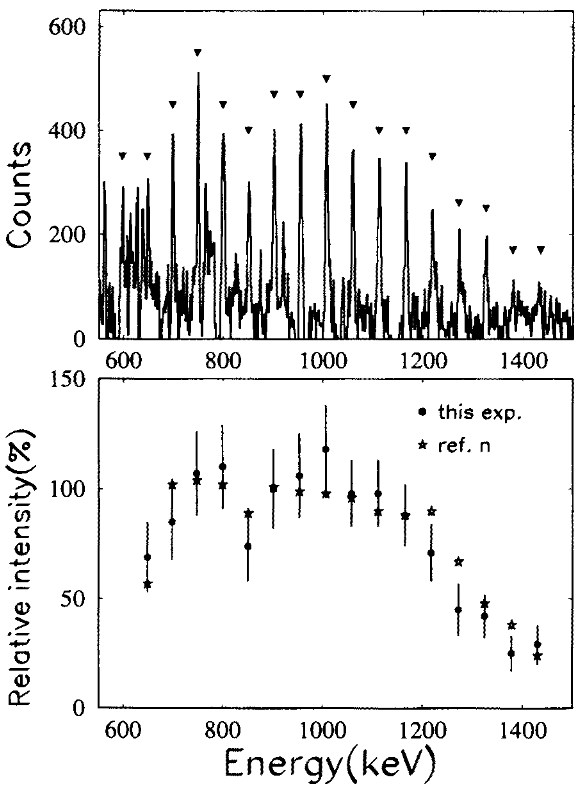

Fig. 3. The yrast Sd band in ^{150}Tb.

The α particle spectra in coincidence with ND states in ^{149,150}Tb nuclei and with the yrast SD band of ^{150}Tb are shown in Fig. 4. For comparison, Monte Carlo CASCADE Statistical Model calculations [18,19] are presented in the same figure. The spectral shapes of the alpha particles in coincidence with ND states are reproduced by calculations in which standard input parameters are used, with the exception of the emission barrier which is lowered. This is achieved by increasing the radius in the Optical Model potential ($r = 1.2 \times r_0$, where r_0 is the radius of the spherical nucleus). In the past the radius expansion has been introduced often in order to simulate the emission from a deformed nucleus [19]. This empirical adjustment of the emission barrier is not needed in the $A \sim 160$ mass region when heavy ion reactions at low excitation energy and moderately low spin ($J \leq 50\hbar$) are considered. On the contrary it increases to a large value, (corresponding to $r = 1.3 \times r_0$) for reactions induced by heavy ions at ~10 AMeV [20]. Furthermore we note that the Statistical Model predictions in Fig. 4 are relative to calculations using a maximum angular momentum for fusion $J = 68\hbar$ and diffuseness $\Delta = 3.5\hbar$, without explicitly introducing the fission competition. A decrease of the mean alpha particle energy associated with the ^{149}Tb nucleus in comparison to ^{150}Tb is evident from Fig. 4, well accounted for by the statistical model calculations.

The α-spectrum in coincidence with the yrast SD band of ^{150}Tb has been derived from the γ-γ-E_α cube, using only the SD band transitions with energies of 954, 1007, 1112, 1166, 1219 and 1272 keV. The average energy of this spectrum is $\langle E_\alpha \rangle = 25.06 \pm 0.01$ MeV, which is about 2 MeV lower than that derived for the ND states of ^{150}Tb.

In order to explain the shift in energy between the alpha particles associated with the ND and SD bands we have explored their angular momentum dependence and how this is reflected by the average energy $\langle E_\alpha \rangle$. For this purpose, we have extracted the k-fold distributions from the GASP inner ball of the events associated with the spectra of Fig. 4 by double gating on a γ-γ-k cube. The fold distributions themselves do not exhibit sizeable differences when selecting ND ($\langle k_{\rm ND} \rangle = 18.3$) and SD ($\langle k_{\rm SD} \rangle = 18.6$) transitions in the ^{150}Tb nucleus. This does not imply a similarity in the associated angular momentum, because the average multipolarity of the gamma-rays cascade in coincidence with ND and SD states is not the same [21].

The feeding of the yrast SD band of ^{150}Tb is known to occur at spins $I_{\rm ER} \sim 48 - 58\hbar$. Therefore, we may associate to the measured mean fold $\langle k_{\rm SD} \rangle$ in coincidence with the SD band an angular momentum of at least $I_{\rm ER} \sim 53\hbar$. Taking into account a correction $\Delta J \sim 8\hbar$ for the angular momentum carried away by the alpha particles, the average value of the compound nucleus angular momentum correlated with the SD spectrum is estimated to be $\langle J_{\rm SD} \rangle \geq 61\hbar$. On the other hand, the value $\langle k_{\rm ND} \rangle = 18.3$ for

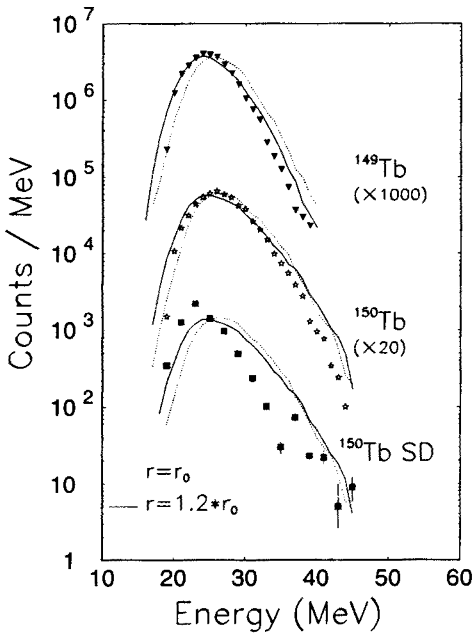

Fig. 4. Alpha particle spectra in coincidence with ^{149}Tb and ^{150}Tb

the ND states of ^{150}Tb nucleus can be associated with a much lower angular momentum value, $\langle J_{\rm ND}\rangle \approx 47\ \hbar$, using an empirical spin-fold calibration for ND states in this mass region.

We have then derived the α spectra feeding the ND states in ^{150}Tb for three different fold conditions $k = 11 - 15$, $k = 16 - 20$ and $k = 21 - 25$, which correspond roughly to $J_{\rm ND} \approx 35\hbar$, $46\hbar$ and $59\hbar$, respectively. In Fig. 5 the latter spectra are compared with the total α-particle spectrum with no condition in fold (solid line). The energy distribution exhibits, with increasing fold, a shift toward lower energies becoming also narrower. Qualitatively, the same effect was observed in the proton spectra of Refs [8, 9, 12] where it was reproduced by Statistical Model calculations and explained in terms of the reduction of the thermal energy available to the decay chain when increasing the fold k (or equivalently the angular momentum).

The correlation between $\langle E_\alpha\rangle$ and the average angular momentum (stars) is reported in Fig. 6, where the value in coincidence with the SD band (heavy dot) is also included. The experimental data feature a continuous decrease of the average energy with increasing angular momentum without a marked distinction between the ND and SD data. Furthermore, from the CASCADE calculations reported also in Fig. 6 (triangles), it appears clearly that the Statistical Model does not describe correctly the angular momen-

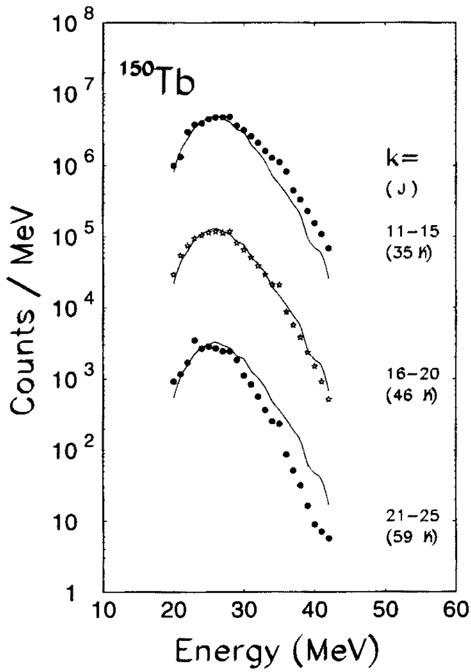

Fig. 5. Alpha particle spectra in coincidence with ^{150}Tb and for different values of the fold k in the inner ball.

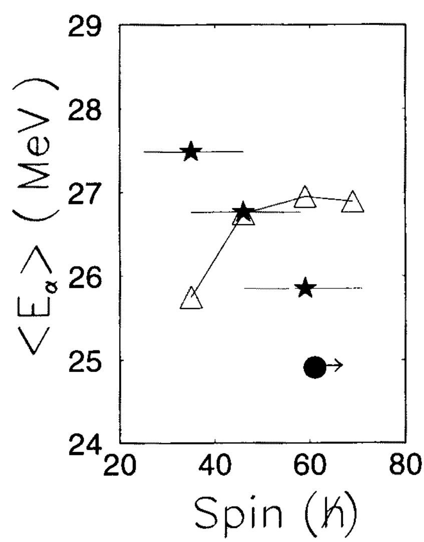

Fig. 6. Average energies of the alpha particles versus angular momentum. For details see text.

tum dependence of $\langle E_\alpha \rangle$, being the average energy predicted to increase with the angular momentum.

5. The alpha emission from high angular momenta

In the classical Statistical Model approach, the energy of the charged particles emitted from an equilibrated compound nucleus depends on the nuclear temperature T of the daughter nucleus, on the emission barrier B and on the channel orbital angular momentum. The energy associated to the orbital angular momentum is often indicated as the so-called spin-off contribution [22]. In the actual CASCADE Statistical Model calculations the barrier B does not depend on the angular momentum of the compound nucleus, whereas the balance between the reduction of T with increasing angular momentum and the spin-off depends on the phase space open to the decay. Results reported in Fig. 6 suggest that the reduction in thermal energy is overwhelmed in the CASCADE statistical model by the spin-off contribution.

Furthermore it has to be noticed that the CASCADE code does not contain a self-consistent, complete treatment of the nuclear deformation effects on the particles decay. It is well known, indeed, that many quantities in the calculations (as the moment of inertia, the yrast lines, the transmission coefficients and the level densities) strongly depend on the emitter deformation. Among those parameter, only the yrast line has in the CASCADE a well defined dependence on the angular momentum induced deformations, following the RLDM predictions. All other parameters are kept at some 'effective' values which are independent from the angular momentum. This means that a detailed description of the angular momentum induced effects can be obtained only evaluating the relative change of the 'effective' values as a function of the spin. An example of this procedure would be the extraction of an effective barrier for each fold windows in Fig. 5 by fitting the corresponding spectrum.

A further question relates to the use by itself of a Statistical Model code in the angular momentum region where the competition between fusion and evaporation is strongly affected by the fission dynamics [23]. This effect would likely change the angular momentum distribution as well as the deformation of the emitters ending to the evaporation residue channel, thus influencing the charged particles spectra. A recent measurements of the neutron pre-scission emission for the 187 MeV ^{37}Cl on ^{120}Sn reaction [24] shows clearly this effect. In fact an increase of a factor two in the probability of emitting neutrons in coincidence with fission fragments is experimentally evidenced respect to the Statistical Model estimates. This increase calls for a fission delay of 30×10^{-21} s, which in turn implies an increase of ~ 40

mb in the evaporation residue cross section for the extreme angular momenta around $J \sim 75\ \hbar$. This means that the population of the highly deformed ER is enhanced when fission dynamics is taken into account. The latter effect would again have a strong influence on the spectra of the alpha particles.

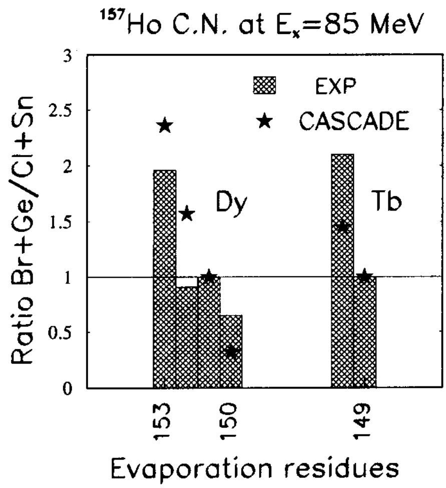

Fig. 7. Ratio of the yields for different ER populated using mass symmetric and asymmetric reaction entrance channels.

As a further example of how the competition between evaporation and fission extends up to very high angular momenta, we show in Fig. 7 results from the comparison of the ER yields obtained by populating the same compound nucleus (^{157}Ho at $E_x = 84$ MeV of excitation energy) by using the ^{37}Cl+^{120}Sn and the ^{81}Br+^{76}Ge entrance channels. Using the mass symmetric reaction, the limiting angular momentum for fusion is raised from $J_{\rm crit} = 77\hbar$ to $J_{\rm crit} = 94\hbar$. In the case of a sharp cut-off between evaporation and fission it is expected that the ratio between the yields relative to the two entrance channels is close to the unity, depending only on the differences in the distributions of the partial waves in the entrance channels. This is indeed shown experimentally in the case of those decay channels which lie at moderate angular momenta, far from the region of the fission-evaporation competition. Looking to the channels at high angular momenta, which are characterized by the minimum number of evaporated particles, a strong deviation from the unity value is found. This demonstrates that there is a contribution to the evaporation residue channels also from the angular momentum region at $J \geq 70\hbar$ which is normally considered completely committed to fission.

6. Conclusions

We have reported here results from a correlation experiment between charged particles and γ-rays. Our attention was mainly focussed on the emission of heavy hydrogen clusters and alpha particles, in view of their predicted sensitivity to angular momentum induced effects.

Among the results reported here, it seems that the α energy spectra in coincidence with a given decay channel are, as those of protons, affected by the different selection of the γ-ray fold k and therefore of the angular momentum. In contrast with earlier investigations of the proton spectra, a clear difference in energy is observed between the α spectra in coincidence with states having different deformation in the decay channel populating the ^{150}Tb nucleus, the SD channel being shifted to lower energies. Despite the uncertainties in deriving the angular momentum from the measured k-fold in the case of the ND and SD structures, the present work strongly suggests that the bulk of this effect is related to the differences in the angular momenta associated with the two classes of states.

The standard Statistical Model (the CASCADE code) fails in reproducing quantitatively and qualitatively the angular momentum dependence of the α spectra. A further lowering of the emission barriers, with respect to the Optical Model ones, seems to be required to empirically describe the spectra at the higher angular momenta. The failure of the statistical model predictions was not evidenced in earlier studies because of the lower sensitivity of the energy spectra of protons to angular momentum induced effects (as the spin-off energy and changes in the emission barrier).

The modelling of the decay at large angular momenta, especially in the region of competition between evaporation and fission should be further pursued by using codes treating in a complete and self-consistent way the emission from an elongated nucleus. Such calculations, as those of Ref. [23], would provide the tools to analyze highly exclusive data as those reported in this work. This will be particularly important for the understanding of the feeding mechanism of the SD bands and of the dynamics of the fission process.

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