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Open problems in formation and decay of composite systems in heavy ion reactions

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Abstract. New highly exclusive experiments in the field of formation and decay of composite systems in heavy ion reactions are presented. Dynamical effects are reviewed in the light of recent works on the role of the N/Z asymmetry between projectile and target. The possibility of extracting directly from the experimental data the emission barrier of alpha particles emitted from highly excited nuclei is discussed. Finally, the first experimental evidence of double giant resonance excitation in fusion-evaporation reaction is presented.

Keywords. Heavy ion reactions; measured energetic gamma-rays; light charged particle spectra.

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1. Introduction

One of the fundamental problems in heavy ion physics is the description of formation and decay of hot composite nuclei that are populated in fusion reactions even at low or intermediate bombarding energies. In fact, despite the large experimental effort of several groups working in this field, clear answers to all the open questions are not yet available, mainly due to the unbalance between the complexity of the phenomena involved and the limitations in experimental data as well as to the correctness of the employed reaction models.

New exclusive experiments have been recently carried out by using complex detector arrays to shed new light in this field, by providing new high quality data sets. In particular, we will report here on recent collaborative experiments performed by our group to study the long-standing question related to the apparent lowering of the emission barrier in evaporative charged particle spectra and the possibility of detecting signal from rare states as the double giant dipole resonance in the decay of hot nuclei. Dynamical effects in the formation of the composite nuclear systems are also briefly discussed.

2. Entrance channel effects in the population of giant dipole resonance states

The giant dipole resonance (GDR) built on excited states of compound nuclei formed in heavy ion reactions has been proposed [1] as a probe of the fusion dynamics. In particular, it has been experimentally observed [2] that in mass symmetric fusion reactions the spectrum of the high energy γ-rays in the GDR region ($E_\gamma \geq 8$ MeV) could retain a signature of the emission from the intermediate di-nucleus before the equilibration of all the relevant degrees of freedom. This experimental observation is in agreement with calculations [3] based on dynamical models [4] which predict, under well defined conditions, a dependence of the fusion time τ_F on the mass asymmetry in the reaction entrance channel, being τ_F longer in the mass symmetric case. It has also been predicted [5,6] that a dynamical excitation of the GDR phonons could be possible in the initial stage of a heavy-ion collision between a target and a projectile with different neutron to proton (N/Z) ratios. This pre-equilibrium GDR emission would not depend only on the N/Z asymmetry in the reaction entrance channel but also on the beam velocity [5].

The first experimental evidence of this N/Z dependent pre-equilibrium GDR emission has been recently reported [7] for the ^{140}Sm compound nucleus populated by the two reactions 160 MeV ^{36}S + ^{104}Pd and 170 MeV ^{40}Ca + ^{100}Mo. These two entrance channels have similar mass asymmetries but different N/Z ratios for the target and the projectile. It was found that the high energy γ-ray spectrum in the N/Z asymmetric (^{40}Ca + ^{100}Mo) reaction exhibits a 16% intensity enhancement above $E_\gamma = 8$ MeV with respect to the N/Z symmetric (^{36}S + ^{104}Pd) one.

More recently, in an experiment performed at the GASP spectrometer at LNL, we have measured the high energy γ-ray spectra from the fusion-evaporation reactions 130 MeV ^{16}O + ^{98}Mo and 240 MeV ^{48}Ti + ^{64}Ni, populating the ^{114}Sn and ^{112}Sn compound nuclei at the excitation energy of 108 MeV [8]. The γ-ray intensity in the giant dipole resonance region ($E_\gamma \geq 8$ MeV) increases by $\sim$38% comparing the ^{48}Ti- to the ^{16}O-induced reaction.

The experimental results are consistent with detailed dynamical models calculations in which the effect of the direct GDR excitation in the intermediate di-nuclear system has been taken into account [9].

It has to be noted that the systems in which the effects related to the mass asymmetry in the entrance channel have been experimentally evidenced in the past exhibits also different N/Z ratios between projectile and target. Consequently, the interplay between the two effects has to be clarified.

3. Exploring the emission barriers in hot nuclei

In the past years a large effort has been devoted [10] to compare evaporative particle spectra with statistical model (SM) calculations for the emission from an hot equilibrated nucleus having the same size, diffusivity and shape as those for a corresponding cold nucleus. Generally, it is found that the reference calculations are not able to describe the experimental data. Consequently, modification of the parameters used in the calculations were introduced to simulate changes in shape and/or deformation of the emitter.

In the SM, the particle emission widths are determined by two major factors: the number of states in the exit channel ρ and the transmission coefficients T_l. The transmission coefficients are estimated by considering the inverse (the capture) reaction on cold nuclei, assuming that the emission barrier for cold and hot nuclei are identical. Deviations between experimental and calculated spectra at low particle energies have been taken as an indication of significant differences in shape or size between the hot and the cold nucleus.

After several years of work in this field it has been realized that the problem is hard to be solved by a simple comparison of the experimental spectra with the ones predicted by the statistical model. In fact, the region of the spectrum at low particle energies is extremely sensitive to the evaporation from the last steps in the decay chain, where the emitter is at low excitation energy [11]. It is therefore necessary to ascertain that reference calculations are able to describe this part of the decay chain. This has been verified only in few cases [12]. Furthermore, the decay of particle unstable intermediate mass fragments is also contributing to some extent to the yield in this region [13]. Furthermore, the distribution of the partial waves in the reaction entrance channel is very important and also small cross sections at high angular momenta might influence the shape of the alpha particle spectra. The diffusivity of the l-distribution and a correct estimate of the fusion-fission competition is, consequently, needed [14]. Finally, the angular momentum carried away by the evaporated particles is a crucial point when alpha particles are considered [15].

As a result, the progress obtained so far in the interpretation of the low energy part of the charge particle spectra is strongly model dependent and the difference between cold and hot rotating nuclei has still to be addressed in a full experimental way.

New data in this field have been recently obtained at the VIVITRON Tandem accelerator in Strasbourg, France, by studying charged particles-gamma coincidences in the ^{30}Si + ^{170}Er reaction at the bombarding energy of 165 MeV. The EUROBALL IV gamma-ray spectrometer, equipped with the DIAMANT ancillary detector for charged particles detection, was used.

The ^{30}Si + ^{170}Er reaction populates the ^{200}Pb compound nucleus at an excitation energy of 82 MeV. The known limiting angular momentum between fusion-evaporation and fusion-fission is $J_{\rm lim}{\sim}33\hbar$. Following statistical model predictions, the emission of an alpha particle is, in this case, characterized by an average dissipation of only $\Delta l = 2\hbar$. Furthermore, from the experimental alpha particle multiplicity it is estimated that more than one half of the emission takes place in the first step of the decay chain.

In the same experiment, we have also studied the companion reaction ^{29}Si + ^{170}Er at 149 MeV, which populates the compound nucleus ^{199}Pb at the excitation energy of 70.5 MeV with the same limiting angular momentum for the fusion-evaporation channel. Alpha particles from this reaction correspond, on average, to the evaporative cascade in ^{200}Pb where the alpha particle is emitted in the second or latest decay steps after one neutron emission.

In the data analysis, alpha particle measured in the DIAMANT detectors at backward angles were sorted in coincidence with discrete transitions in ^{191}Hg nuclei. This was necessary to avoid experimentally evidenced contaminations from incomplete fusion reactions [16].

By subtracting the spectrum of the ^{29}Si- from that measured in the ^{30}Si-induced reaction (with a proper normalization derived by the analysis of the gamma-ray spectra), the first chance alpha particle spectrum (indicated as DIFF) has been obtained, as illustrated in figure 1. Total and DIFF spectra for the ^{30}Si + ^{170}Er reaction are well reproduced by CASCADE calculations in which a substantial lowering of the emission barrier is introduced, via an empirically increased radius in the optical model potential used to compute the transmission coefficients. This method was already employed in several past works

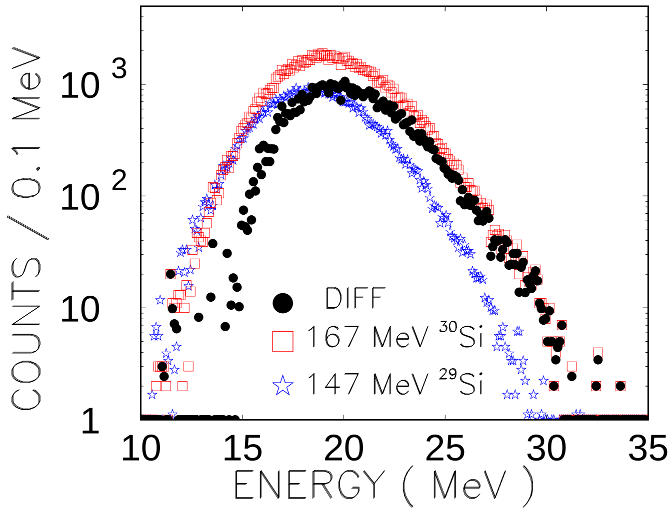

Figure 1. Alpha particle spectra measured at backward angles in the 167 MeV ^{30}Si + ^{170}Er and 149 MeV ^{29}Si + ^{170}Er reactions. DIFF indicates the difference spectrum. For details see the text.

(see for example [12]). The experimental spectra are also reproduced fairly well by calculations in which the single angular momentum $\langle J \rangle = 22\hbar$, corresponding to the average value for the fusion-evaporation channel, is employed, as documented in figure 2. In this case it is also possible to derive from the CASCADE calculations the energy spectra of the first chance alpha particles as a function of the angular momentum $\Delta J (\Delta J = 22 - J_{\rm fin})$ dissipated in the particle emission, as shown in figure 3.

We have tried here to attack again the problem of determining experimentally the emission barrier in hot nuclei and its angular momentum dependence by applying, in the case of the first chance evaporative alpha particle spectra, the 'second derivative' analysis proposed by Rowley, Satchler and Stelson for extracting barrier distributions $D(B)$ from the sub-barrier fusion cross section σ_f[17]:

$$D(E) = \frac{1}{\pi R^2} \frac{{\rm d}^2(E\sigma_f)}{{\rm d}E^2}. \tag{1}$$

In fact, following Blatt and Weisskopf [18] and Thomas [19], the rate $R_x d\epsilon$ for the emission from the nucleus 1 of a particle x having kinetic energy between ϵ and $\epsilon + d\epsilon$, and populating the nucleus 2 at (E_2, J_2, π_2) is:

$$R_x d\epsilon = \frac{\rho_2(E_2, J_2, \pi_2)}{2\pi\hbar\rho_1(E_1, J_1, \pi_1)} \sum_{S=|J_2-s|}^{J_2+s} \sum_{l=|J_1-S|}^{J+S} T_l^x(\epsilon) d\epsilon, \tag{2}$$

where s and l are the spin and the orbital angular momentum of the particle and $\rho_i(E_i, J_i, \pi_i)$ is the level density of the nucleus i. From this expression a more simple formula can be obtained when angular momentum effects are negligible:

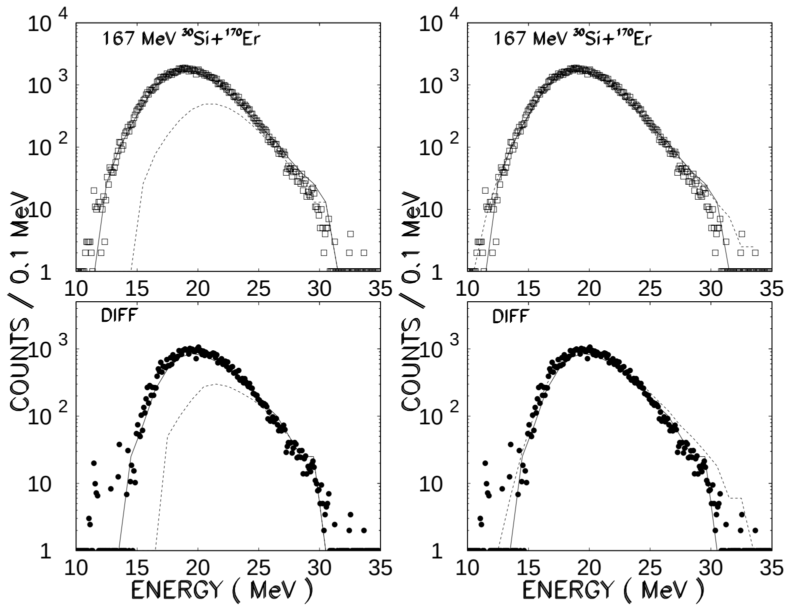

Figure 2. Left: Comparison of the total and the difference alpha particle spectra from the 165 MeV ^{30}Si + ^{170}Er reaction with prediction from the CASCADE statistical model calculations using standard (dotted lines) and adjusted (solid lines). Optical model potential for the evaluation of the transmission coefficients. Right: Comparison between the experimental spectra and CASCADE calculation with adjusted optical model potential with entire compound nucleus angular momentum distribution (solid line) or the single value $J = 22\hbar$ (dotted line).

$$R_x d\epsilon = \text{constant}\ \epsilon\ \sigma_C^x(\epsilon)\rho_2(\hat{E} - \epsilon)d\epsilon, \qquad (3)$$

where $\hat{E} = E_1 - S_x - B_x$ is the maximum available excitation energy in the nucleus 2 after the emission of the particle x and $\sigma_C^x(\epsilon)$ is the cross section for the fusion of the particle x on the nucleus 2.

It seems, therefore, that the energy distribution of the evaporated alpha particles, after a correction for the level density (ρ_2), can be used to extract, by the second derivative method, the barrier distribution.

In the present work we have extracted the level density from the CASCADE code for the average angular momentum ($J_2 = 20\hbar$) in the daughter nucleus. Computed values were fitted by an exponential function and this function, properly matched to the high energy part of the alpha particle spectrum, was used to correct the experimental spectrum.

The ρ_2-corrected spectrum is shown in the upper panel of figure 4. The same procedure was applied for comparison to the predicted spectra from CASCADE. The ρ_2-corrected spectrum is supposed to be now proportional to the term $\epsilon\ \sigma_C^x(\epsilon)$ of eq. (3). The second derivative was then computed, as shown in the medium panel of figure 4, in which the experimental barrier obtained in this way is compared with CASCADE predictions for the different ΔJ values carried away by alpha particles. This comparison demonstrates that, as expected, several ΔJ might contribute to the effective barrier, ranging from 0 to $10\hbar$.

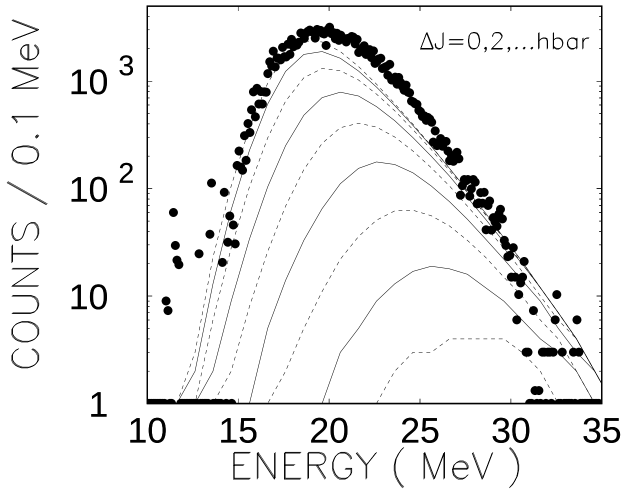

Figure 3. DIFF alpha particle spectrum compared with predictions from CASCADE calculations as a function of the angular momentum Δl dissipated in the evaporations $(\Delta J = 0, 2, 4, \ldots, \hbar)$.

This observation suggests some care in comparing the result from this experiment with the pioneering work of Vaz and Alexander [20] where the so called experimental barriers were extracted by analysing experimental alpha-nucleus fusion data but in the hypothesis of $l = 0$ collisions.

In the lower panel of figure 4, the experimental barrier extracted from this experiment are compared with $\Delta J = 0$ results from CASCADE and the results from [20]. It is immediately noticed that the CASCADE results obtained for default standard statistical model transmission coefficients gives a barrier too high with respect to Vaz-Alexander results.

This means that the O.M. average potentials used in CASCADE are not correct, producing in any case the apparent need of a barrier lowering. This fact does not account for all the observed shift. The empirically adjusted O.M. potentials produce an $\Delta J = 0$ barrier that is well below the Vaz-Alexander estimate for cold nuclei. This means that the present experimental result demonstrates definitively the difference between barriers in cold and hot nuclei. A more quantitative analysis is in progress.

4. Searching for DGDR in hot nuclei

The recent observation of the double giant dipole resonance (DGDR) in heavy ion and pion induced reactions has attracted considerable interest [21]. The observed resonance energy and width are in good agreement with the representation of the DGDR as a multi-phonon state formed by non-interacting harmonic oscillators. The main interest in the study of the properties of these multi-phonon states is in the search for phonon–phonon interaction and anharmonic effects.

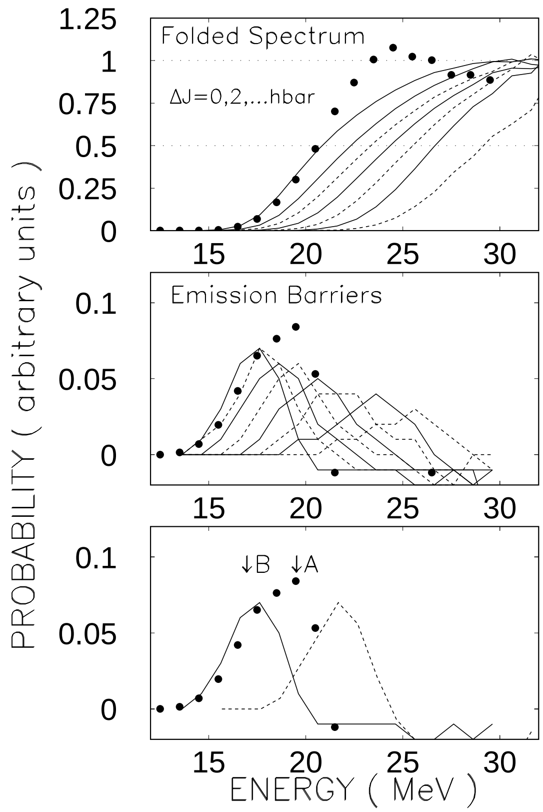

Figure 4. ρ_2-corrected DIFF spectrum (dots) compared with predictions from CASCADE calculations (lines) as a function of the angular momentum ΔJ dissipated in the evaporations ($\Delta J = 0, 2, 4, \ldots, \hbar$) (upper panel). Comparison between the second derivative of the ρ_2-corrected DIFF spectrum with the CASCADE predictions (middle panel). In the lower panel the same experimental distribution is compared with the CASCADE predictions for $\Delta J = 0$ using standard and adjusted optical model potentials. In the same lower panel the arrows mark the Vaz-Alexander [20] estimate for cold (A) and hot (B) nuclei.

In this respect, an interesting field of investigation is represented by the possible dependence of the anharmonicity on the nuclear temperature and its correlation with the observed DGDR parameters. Detailed theoretical predictions show, indeed, a positive correlation between temperature, strength and width of the resonance [22]. The available experimental data about DGDR are related to resonances built on the ground state of nuclei, excited by inelastic collisions, electromagnetic excitation or pion-induced double charge-exchange reactions. Therefore, a direct test of the theoretical predictions is not possible at this stage.

A natural way to study temperature effects on the DGDR would be the use of heavy-ion induced fusion-evaporation reactions, once the possibility to discriminate the DGDR contribution from the bulk of the compound nucleus decay will be demonstrated.

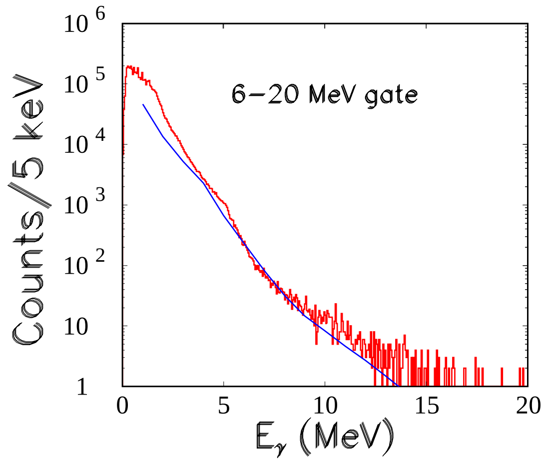

Figure 5. Comparison between the experimental spectrum (gate 6–20 MeV on the inclusive matrix) and predictions from statistical model (CASCADE) folded with the calculated Cluster response function (line). For details see the text.

From the experimental point of view, fusion-evaporation reactions have been intensively employed in the past to study GDR in hot nuclear systems, mainly with the detection of energetic γ-rays emitted in the decay of the resonance [23]. As demonstrated in an earlier experiment performed with the TAPS detector system, the DGDR can be tagged by detecting the two coincident energetic photons emitted in the decay of the two one-phonon states [24].

This possibility has been recently demonstrated by a re-analysis of a large data set from the EUROBALL III array, in which a number of HPGe cluster detectors [25] are employed. The analysed data set was originally obtained in a search for hyperdeformed states in the reaction 187 MeV ^{37}Cl + ^{120}Sn that populates the compound nucleus ^{157}Ho at an average excitation energy of $E_x = 83$ MeV. Results from this experiment have been already published [26].

The re-analysis was focused on events in which two energetic ($E > 8$ MeV) photons are emitted, searching for the decay of the DGDR built on highly excited states. It is found that the shape of the gamma ray spectrum obtained by requiring the coincidence with a second photon having energy in the range $E =$ 6–20 MeV is roughly accounted for by statistical model predictions, as shown in figure 5. This demonstrates that such two-photons events are produced essentially in the fusion-evaporation reaction.

The shape of the inclusive spectrum of γ-rays in coincidence with photons in the range 8–20 MeV, shown in the middle panel of figure 6, is characterized by regions showing different effective temperatures. The events associated by a low effective temperature are supposed to be emitted at the end of the particle evaporation phase. The events characterized by a very high effective temperature are thought to be emitted at the top of the de-excitation cascade. Those events, are strongly suppressed when a coincidence with charged particles is required.

The events in which two photons in the GDR region ($E > 8$ MeV) are required, are characterized by a multiplicity value which is larger than the estimated upper limit for the

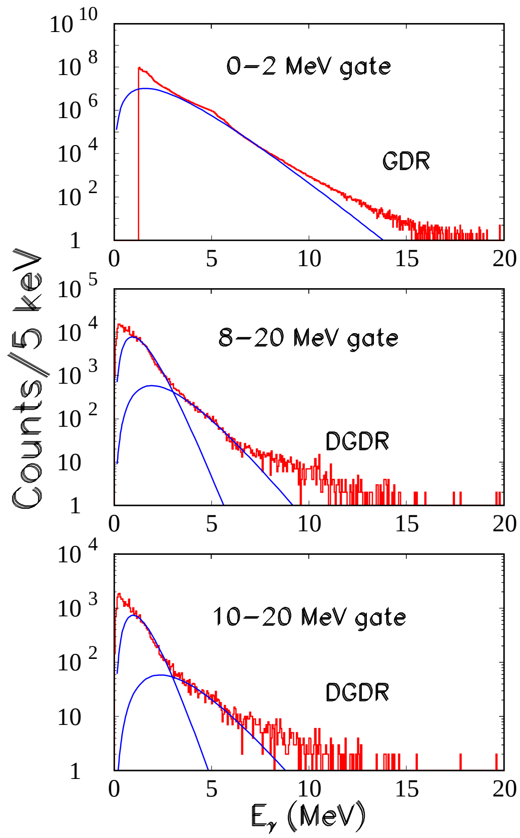

Figure 6. Gamma-ray spectra obtained by setting gates on one axis of the inclusive (symmetric) gamma–gamma matrix. Only coincidences between Cluster detectors have been considered. Lines are results from fits to the experimental data.

emission of two uncorrelated photons in the same de-excitation cascade. This evidence supports strongly the attribution of such events to the decay of the double giant resonance built on highly excited states. Moreover, the sum spectrum of the two photons events shows the well known line-shape of a giant dipole resonance in hot systems, with the centroid energy twice the one for a single GDR (see figure 7).

5. Summary and conclusions

We have performed recently, in collaborative experiments, new investigations in the field of formation and decay of highly excited compound nuclei. Powerful arrays, as GASP and EUROBALL were used in this campaign. The obtained results are providing new insight into the open problems in this field.

The presence of dynamical effects in the formation stage of the compound nucleus has been firmly demonstrated in the past by comparing entrance channels with different mass

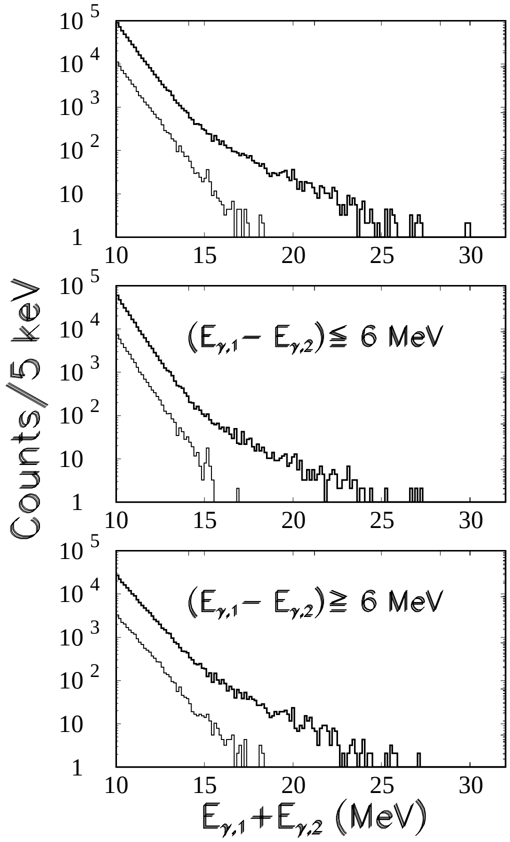

Figure 7. Sum energy spectra $(E_{\gamma,1} + E_{\gamma,2})$ obtained without (upper panel) and with (medium and lower panel) conditions on the difference between the coincident gamma-rays $(E_{\gamma,1} - E_{\gamma,2})$. In each panel the upper (thick line) histogram refers to inclusive events, the lower (thin line) to coincidences with protons.

asymmetry [2]. More recently, the dependence of the dipole emission on the N/Z difference between projectile and target have been evidenced in fusion-fission reactions at low energies [7]. Our recent data [8] confirm this effect. This finding is also supported by model calculations [9]. It seems, therefore, that the unfolding of the effects related to the N/Z and those related to the mass asymmetry in the entrance channels has to be fully performed also for past experiments.

By a re-analysis of a large data set from the EUROBALL III spectrometer, we have presented for the first time evidence for DGDR events in fusion-evaporation reaction. This opens the possibility to study temperature effect on two phonon states.

Finally, the long-standing question relative to the difference between the emission barriers in cold and hot nuclei has been addressed experimentally by using a subtraction technique of highly exclusive alpha particle spectra. In this way the first chance alpha particle spectra has been determined. This spectrum has been corrected for the effects related to the level density and, finally, analysed applying the ‘second derivative’ analysis proposed by Rowley, Satchler and Stelson [17]. The results reported in this work support strongly the possibility of extracting, in this way, the experimental emission barrier in hot nuclei.

This experimental campaign is still in progress. New experiments in the field of formation and decay of hot nuclei have been recently performed by our group at the charged particle detector array 8πLP and the neutron array recently commissioned at the Laboratori Nazionali di Legnaro.

Acknowledgements

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