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Abstract. The excitation of the Dynamical Dipole mode along the fusion path was investigated for the first time in the formation of a heavy composite system in the $A{\sim}190$ mass region, in fusion–evaporation and fission events. The composite system was formed at identical conditions of excitation energy and spin from two reactions with different charge asymmetry: the charge asymmetric ^{40}Ca + ^{152}Sm and the nearly charge symmetric ^{48}Ca + ^{144}Sm at $E_{lab}=11$ and 10.1 MeV/nucleon, respectively. In this paper, we report the results on fusion evaporation events and the preliminary analysis on fission channel.

1. Introduction

During the charge equilibration mechanism taking place in the first stages of dissipative reactions between colliding ions with different N/Z ratios, a large amplitude dipole collective motion develops in the composite dinuclear system, the so-called "Dynamical Dipole mode" (DD), or pre-equilibrium Giant Dipole Resonance (GDR). The DD gives rise to a prompt γ-ray emission [1, 2, 3, 4, 5, 6], characterized by: i) a centroid energy lower than that of the compound nucleus (CN) GDR in the same mass region indicating a high deformation of the emitting source [3, 4], ii) an anisotropic angular distribution with respect to the beam axis since the oscillation is confined in the reaction plane [7] and iii) a γ yield that should depend on both the reaction dynamics and the symmetry term of the nuclear matter Equation Of State (EOS), that is acting as a restoring force [4].

Experimentally, the DD excitation has been observed in deep inelastic [5, 8, 9, 10] and fusion-evaporation heavy-ion collisions [10, 11, 12, 13, 14, 15, 16, 17], while the first systematic study of its incident energy dependence was performed in an experimental campaign [12, 13, 14, 15] for the ^{132}Ce CN. In this case, the DD was evidenced with a model independent method, the so-called "difference technique", consisting in: (a) forming the same CN at identical conditions of excitation energy and spin from two entrance channels, a nearly charge symmetric and a

charge asymmetric one; (b) obtaining the difference between the γ-ray spectra and angular distributions of the two channels for fusion-evaporation events. The DD was evidenced through the observation of an excess of yield in the γ-ray energy spectrum of the more charge asymmetric system at a centroid energy lower than that of the CN GDR and with a higly anisotropic angular distribution, presenting a maximum around 90° with respect to the beam direction.

At the moment very few data exist on the DD γ multiplicity and on its angular distribution that can be directly compared with theoretical calculations. Furthermore, calculations are not able to simultaneously reproduce all the existing experimental findings. The emission of DD γ-rays decreases the excitation energy and the initial temperature of the nucleus reaching the statistical phase. This cooling mechanism could be suitable to favour the CN survival against statistical fission and thus, the formation of a super heavy element in hot fusion processes [4, 19]. In order to investigate the behavior of the DD in heavier systems than those studied before and to test its usefulness in superheavy element production, we decided to study the DD in a composite system in the mass region A=190 [18].

2. The experiment: ^{40,48}Ca+^{152,144}Sm at 11 MeV/nucleon

We performed the experiment by using the ^{40}Ca (^{48}Ca) pulsed beam provided by the Cyclotron of the Laboratori Nazionali del Sud (INFN-LNS, Italy), impinging on a 1 mg/cm^2 thick self-supporting ^{152}Sm (^{144}Sm) target enriched to 98.4%(93.8%) in ^{152}Sm (^{144}Sm) at E_{lab} = 440 (485) MeV. Both reactions populate the same composite system through a quite different initial dipole moment, 30.6 fm for the ^{40}Ca + ^{152}Sm charge asymmetric reaction and 5.3 fm for the ^{48}Ca + ^{144}Sm more charge symmetric one, while the mass asymmetry of the two entrance channels is very similar, namely 0.22 (0.18) for the ^{40}Ca + ^{152}Sm (^{48}Ca + ^{144}Sm) system. The formed system had identical excitation energy in both reactions, E^* = (220±7) MeV, and identical spin distribution: L_{max} = 74$\hbar$ for fusion and L_{max} = 42$\hbar$ for fusion-evaporation, based on PACE2 calculations [20] with a level density parameter a = A/9.5 MeV^{-1}, A being the CN mass.

The γ-rays and the light charged particles were detected by using the BaF$_2$ detectors of the MEDEA setup [26], covering the polar angular range θ_{lab} = 42.4° − 170° and the full range in the azimuthal angle. It operates in vacuum to allow a simultaneous detection of γ-rays and charged particles. The discrimination between γ-rays and light particles was performed by combining a shape analysis of the BaF$_2$ signal with a time of flight (TOF) measurement, between each BaF$_2$ and the radiofrequency signal of the Cyclotron.

The fusion-evaporation residues (ER) were detected by four Parallel Plate Avalanche Counters (PPACs) located symmetrically around the beam direction at 70 cm from the target. The PPACs were centered at θ_{lab} = 7° with respect to the beam direction, subtending 7° in θ and covering a total solid angle of 0.089 sr. The PPACs provided the energy loss ΔE and the TOF of the reaction products. The fission events were selected by detecting the two kinematically coincident fission fragments (FF) with position sensitive PPACs, centered at θ_{lab} = 52.5° symmetrically around the beam axis, at 16 cm from the target covering 22° in both θ and ϕ. The PPACs gave information on the energy loss ΔE, the TOF and the position (x,y) of the FF that allowed to reconstruct angles, masses and velocity vectors of the fragments in the laboratory and the center-of-mass reference frame. Both ER and FF were selected by applying appropriate contours in the relative bi-dimensional plots (ΔE, TOF) of the PPACs.

Down-scaled single PPAC events together with coincidence ones between a PPAC and at least one fired BaF$_2$ were collected during the experiment. The energy threshold in a BaF$_2$ detector was set at ∼5.5 MeV. The coincidence request eliminated any cosmic ray contamination of the γ-ray spectra. By using the above trigger there are no normalization factors in the γ-ray (charged particle) spectra as the double differential γ (charged particle) multiplicity is obtained from the ratio of the number of coincidences between γ-rays (charged particles) and ER (FF) and the
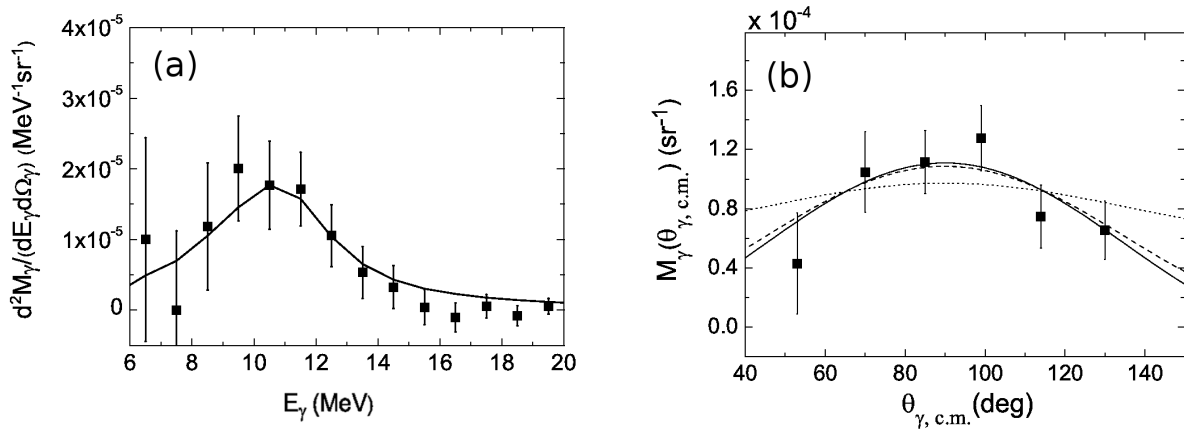
Figure 1. (a) The symbols represent the DD γ-ray spectrum for fusion-evaporation events. The line is a Lorentzian curve folded by the experimental set up response function. (b) 9 MeV$\leq E_\gamma \leq$15 MeV DD γ-ray angular distribution, corrected for the detection efficiency. The lines represent different Legendre polynomial fits, obtained by using different a_2 values. See the text for details.

number of single events of ER (FF).

3. Analysis and Results

The experiment was designed in such a way to form the same composite system at identical excitation energy in both reactions by taking into account the pre-equilibrium particle emission. That reduces the CN average mass, average charge and average excitation energy and cannot be discarded in the TOF spectrum of the reaction products because they have overlapping velocity distributions with those of the complete fusion events [21, 22]. Therefore, in the present work, the average excitation energy, the average mass and the average charge of the composite system, after pre-equilibrium particle emission, were evaluated by studying the energy spectra of the light charged particles (α-particles and protons) detected in coincidence with ER and FF, while the pre-equilibrium neutron emission was estimated from our proton data and from existing neutron emission studies (see [18]).

3.1. Fusion–evaporation results

The light particle spectra detected by BaF$_2$ scintillators in coincidence with the ER were analyzed assuming that particles have been emitted isotropically from two moving sources: a *slow* one describing the statistical evaporation from the hot CN and an *intermediate-velocity* (between the CN and the projectile velocity) one due to the pre-equilibrium particles emitted by the composite system before thermalization (see [18]). To evaluate the average energy taken away by pre-equilibrium neutrons, not detected in this experiment, we assumed that their energy spectra were very similar to the proton ones, apart from the Coulomb barrier. Then, the average kinetic energy of a pre-equilibrium neutron was taken to be that of a pre-equilibrium proton minus the Coulomb barrier while the pre-equilibrium neutron multiplicity was deduced by that of pre-equilibrium protons multiplied with the N/Z ratio of the CN. The adopted pre-equilibrium neutron multiplicity is in agreement within errors with neutron emission studies performed at similar center-of-mass incident energy above the Coulomb barrier [23]. We found that two units of charge and three units of mass were carried away from the initial composite system leading to the ^{189}Hg nucleus in both reactions, with the same average excitation energy E^*=(220±7)

MeV, giving us confidence that any difference between the γ-ray spectra and γ-ray angular distributions of the two reactions is related to an entrance channel effect.

After the evaluation of the excitation energy of both reactions, the incoherent bremsstrahlung component considered to originate primarily in neutron-proton (np) collisions and dominant for $E_\gamma > 30$ MeV, must be evaluated and subtracted from the data. An equal bremsstrahlung component is expected for the two reactions because of their very similar beam energy and size of the reaction partners and of the same temperature of the composite system [24, 25]. The np bremsstrahlung component was deduced by fitting simultaneously the center-of-mass fusion-evaporation γ-ray spectra of the two reactions at different polar angles in the energy range 30 MeV$<E_\gamma<$40 MeV. The fit was performed assuming an exponentially decreasing behavior.

The difference between the center-of-mass bremsstrahlung-subtracted γ-ray spectra of the two reactions for fusion-evaporation events (symbols in panel (a) of Figure 1) shows an excess of γ-rays in the more charge asymmetric channel, between 8 and 15 MeV. This can only be related to the DD excitation in the composite system of the ^{40}Ca+^{152}Sm reaction because of its larger charge asymmetry. This spectrum is reproduced well by means of a Lorentzian curve folded with the response function of the apparatus [27] (solid line), with the DD centroid energy $E_{DD} = 11$ MeV and the width $\Gamma_{DD} = 3.5$ MeV. E_{DD} is 3 MeV lower than E_{GDR} (obtained by using Cascade code [28]), indicating a high deformation of the emitting source during the DD γ emission. This result is in excellent agreement with expectations for a dipole oscillation along the symmetry axis of a deformed dinucleus during the early moments of the reaction [4, 3, 29, 5, 30, 4, 19] and with previous experimental works on lighter systems [11, 19, 12, 14, 15].

The DD γ-ray angular distribution is a sensitive probe of the fusion dynamics and of the DD lifetime. Indeed, the amount of anisotropy, if present, is related to the interplay of the rotation angular velocity of the dinuclear system during the prompt DD emission and the instant at which this emission occurs [7, 14, 15]. Panel (b) of Figure 1 displays the fusion-evaporation γ-rays angular distribution with respect to the beam axis for the difference between the reactions, integrated over energy from 9 to 15 MeV and corrected for the detection efficiency, i.e. the DD γ-ray angular distribution. The lines describe the angular distribution of the emitted γ-rays given by the Legendre polynomial expansion $M_\gamma(\theta_\gamma) = M_0[1 + Q_2 a_2 P_2 cos(\theta_\gamma)]$, where a_2 is the anisotropy coefficient and Q_2 is an attenuation factor for the finite γ-ray counter [31] (0.98 in our case). The DD γ-ray angular distribution is very anisotropic around 90° and can be reproduced well with $a_2 = -1$ (solid line) that describes an emission from a dipole oscillation along the beam axis. The dashed line corresponds to a value of $a_2 = -0.84$ obtained within BNV calculations [4] for evaporation events, while the dotted one shows a more isotropic angular distribution ($a_2 = -0.25$). The above a_2 values indicate a preferential oscillation axis of the DD along an axis that has not rotated much on the reaction plane during the DD lifetime, confirming the pre-equibrium nature of this emission. This is in agreement with our previous results for evaporation events [14, 15] and with theoretical expectations [7].

By taking into account the DD γ-ray angular distribution ($a_2 = -1$) for evaporation events and the response function of the experimental setup, the DD yield, integrated over energy and over angle, is $(1.2 \pm 0.2)*10^{-3}$ [18]. The experimental results were also compared with BNV calculations. These calculations reproduced all the DD features, except for the yield that is overestimated. This discrepancy suggests that BNV calculations do not take into account some aspects of the reaction dynamics which could inhibit the DD γ-ray emission. An ingredient neglected is the deformation of the ^{152}Sm target ground state that could influence the DD excitation mechanism. Calculations are under way to evaluate this point.

3.2. Fission: preliminary results
As mentioned before, FF were detected by two position-sensitive PPACs placed at $\theta_{lab} = 52.5°$. The information obtained from these detectors were the ΔE, TOF and x, y positions of the

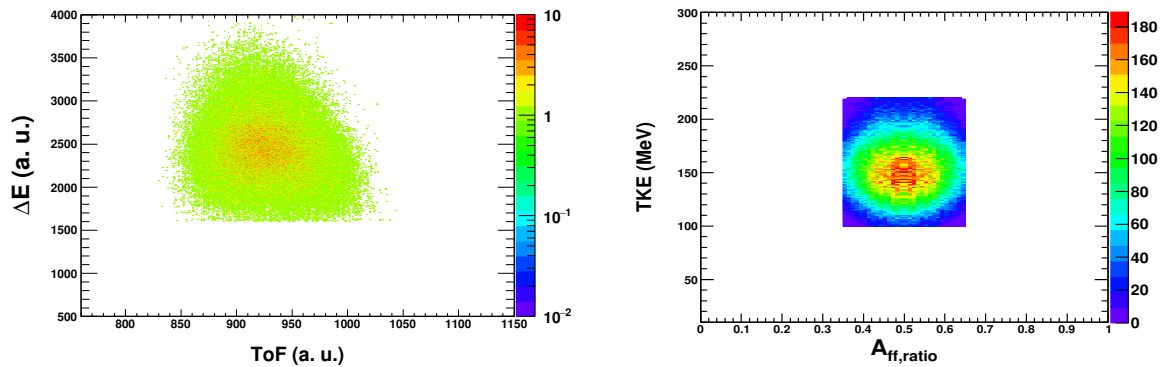**Figure 2.** ΔE vs TOF (left-hand side) and TKE vs composite system mass ratio (right-hand side) bidimensional plot for a PPAC at $\theta_{lab} = 52.5°$ in the ^{40}Ca + ^{152}Sm fission reaction. Here, only coincidence events between the two PPACs at $\theta_{lab} = 52.5°$, after the selection procedure, are shown. See the text for details.

fragments. The position signals from the PPACs were transformed event by event to polar and azimuthal angles (θ, ϕ). From TOF and angles of the FF, velocity vectors, masses and Total Kinetic Energy (TKE) were obtained by using kinematical considerations. Moreover, an iterative procedure was done to compensate for the energy losses in the target, assuming that the reaction takes place at the middle of the target.

By applying appropriate conditions in the bidimensional plot (ΔE, TOF) of the PPACs and selecting the same mass and TKE distributions for two coincident FF, the observables of the two reactions can be compared properly. Figure 2 shows the resulting ΔE vs TOF (left-hand side) and TKE vs composite system mass ratio (right-hand side) bidimensional plots for a PPAC in the charge asymmetric reaction, where only coincidence events between the two PPACs are considered.

As done in fusion-evaporation, we evaluated the average excitation energy and the mass of the composite system in fission events (selected as mentioned above) in both reactions, by studying the pre-equilibrium particle emission. Protons and α-particles detected in coincidence with FF were extracted for several polar angles with respect to the beam direction and analyzed by means of a multiple-source least-squares fit where the particles are assumed to be emitted isotropically (in the respective center of mass reference frame) from four moving sources. In this case, the light particle spectra were supposed to originate from: 1) the emission of fast particles of non-statistical origin (the *intermediate-velocity* source) from the composite system before reaching the equilibration, 2) the statistical particle emission from the CN (the *slow* source) before fission and 3-4) the statistical particle emission of the two excited FF. From this analysis, the pre-equilibrium particle emission was found to be lower than in evaporation events, showing a dependence from the impact parameter of the selected channel [32]. Furthermore, we demonstrated that the composite system was formed in both reactions with the same average excitation energy and mass.

After applied the selection procedure of fission events in the two reactions, γ-ray - fission events were determined with a triple coincidence between γ-rays detected by MEDEA detetector and two FF detected by the PPACs. Since the evaluation of the pre-equilibrium particle emission in fission events proved that the composite system was formed in both reactions with the same average excitation energy and average mass, we are entitled to compare the γ-ray spectra of both reactions. This comparison showed that there is also in this channel a γ-ray excess between 8

and 15 MeV, in the more charge asymmetric reaction. This excess should be ascribed to the only different parameter between the two reactions, namely the initial charge asymmetry. A more accurate analysis is under way to obtain the γ-ray angular distribution in fission events and to understand the DD dependence from the impact parameter.

4. Conclusion

The present results on the pre-equilibrium GDR radiation in ^{40}Ca + ^{152}Sm fusion-evaporation reaction allows to take a step forward in the study of superheavy element formation, demonstrating that the DD γ radiation, a possible cooling mechanism of the composite system along the fusion path, survives in heavy composite systems in the fusion-evaporation channel.

Furthermore, we proved the DD excitation also in fission events. This observation provides inedited information on the DD excitation at higher partial waves.

By using the prompt DD radiation as a probe and with the advent of more intense radioactive beams, new possibilities for the investigation of the EOS symmetry energy at sub-saturation density are foreseen [7]. Indeed, radioactive beams are expected to maximize the difference of the DD yield between the different prescriptions of the symmetry energy dependence on density and to allow a clear experimental discrimination [7, 33].

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