Search for the Dynamical Dipole mode in the $^{192}$Pb mass region

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Abstract. The prompt $\gamma$ radiation originating from the dynamical dipole mode decay was investigated in the $^{192}$Pb composite system employing the $^{40}$Ca + $^{152}$Sm and $^{48}$Ca + $^{144}$Sm reactions at $E_{\text{lab}}$ = 11 and 10.1 MeV/nucleon, respectively. The $\gamma$-ray energy spectra at various polar angles were obtained for fusion-evaporation and fission events by detecting the high energy $\gamma$ rays with the MEDEA experimental apparatus in coincidence with evaporation residues and fission fragments. Preliminary results of this experiment show that the dynamical dipole mode survives in collisions involving heavier mass reaction partners than those studied previously. As a fast cooling mechanism on the fusion path, the prompt dipole $\gamma$ radiation could be of interest for the synthesis of super-heavy elements through "hot" fusion reactions.

1. Introduction

The dynamical dipole mode is a large amplitude collective dipole oscillation predicted to occur along the symmetry axis of the dinuclear system formed between interacting ions with a large charge asymmetry [1]. Its decay gives rise to a prompt $\gamma$ radiation expected to have the following characteristics: (i) it appears as an extra yield in the $\gamma$-ray energy spectra at a centroid energy lower than that of the Giant Dipole Resonance (GDR) thermally excited in the compound nucleus (CN) because it originates from a highly deformed dinuclear system; (ii) an anisotropic angular distribution due to the fact that the oscillation is confined in the reaction plane; (iii)
an intensity depending on the reaction dynamics and thus on the incident energy [2, 3] taking a maximum value in the energy region situated between the low incident energies near the Coulomb barrier and the higher ones near the Fermi energy domain, namely between 8 and 14 MeV/nucleon. As the prompt γ-ray emission related to the dynamical dipole mode decay may become comparable to the CN statistical γ emission, it could represent an interesting cooling mechanism of the composite system to facilitate the formation of super-heavy elements through "hot" fusion reactions. Super-heavy elements can be formed at low excitation energy because (1) smaller excitation energies have smaller fission probabilities and (2) the shell corrections, responsible for the stability of super-heavy nuclei, decrease with excitation energy. Thus, the lowering of the CN excitation energy by an amount ranging between 10 and 15 MeV (the energy approximatively removed from the system with the emission of a pre-equilibrium dipole photon) results in an increase of its survival probability against fission and thus in an increase of the evaporation residue cross section by a factor of ~10 [4]. This estimation is obtained in the framework of an "hybrid" statistical model of the CN decay in which the pre-equilibrium γ-ray emission is externally introduced while the fission width evolution is given by the diffusion model for fusion-fission dynamics described in [5]. However, the usefulness of the dynamical dipole mode in the super-heavy elements formation could be questionable by the prediction of [6] that the prompt dipole γ yield decreases in collisions involving heavy mass partners due to the fact that the reactions with small nuclei are less damped than those involving more nucleons.

In the last years, the existence of the dynamical dipole mode in heavy-ion deep inelastic [7, 8, 9] and fusion reactions [8, 10, 11] has been observed. In our previous campaign of experiments [12, 13, 14, 15] we performed the first systematic study of the dynamical dipole mode features as a function of the incident energy in the range between 6 to 16 MeV/nucleon in heavy-ion fusion-evaporation reactions that create compound nuclei in the 132Ce mass region. In those measurements, for each incident energy the 132Ce CN was formed at identical excitation energy and with identical spin distribution through different charge asymmetry entrance channels by using two reaction pairs: 32,36S+100,96Mo at E_{lab}= 6 and 9 MeV/nucleon and 36,40Ar+96,92Zr at E_{lab}= 16 MeV/nucleon. The dynamical dipole mode was evidenced through the observation of an excess of yield in the γ-ray energy spectrum of the more charge asymmetric system with respect to the charge symmetric one. This excess appeared at a centroid energy lower than that of the GDR and with an highly anisotropic angular distribution around 90° with respect to the beam direction [14, 15]. The angular distribution pattern was interpreted as a signature of the pre-equilibrium character of the dynamical dipole mode, confining its γ decay time scale at a very early stage of the reaction [14, 15]. Furthermore, the extracted dynamical dipole γ yield integrated over energy and over solid angle showed a maximum at E_{lab}~9 MeV/nucleon [15].

Recently, new results appeared [16] on the dynamical dipole mode excited during the 16O+116Sn charge asymmetric reaction at E_{lab}=8 and 15.6 MeV/nucleon that populates also the 132Ce CN. In this work a different method was used: the dynamical dipole mode γ decay was evidenced by subtracting from the charge asymmetric reaction experimental γ-ray spectrum the statistical spectrum calculated with the code CASCADE [17] for a 132Ce CN formed at an excitation energy that was evaluated from the light charged particle energy spectra. With this method, the centroid of the extracted dynamical dipole mode was found to be equal to that of the CN GDR, the associated angular distribution studied in a rather narrow interval ranging from 120° to 160° with respect to the beam axis was found to be slightly anisotropic around 90° while the dynamical dipole γ yield obtained at 16 MeV/nucleon was found to be comparable to that of the 36Ar+96Zr reaction at the same incident energy in spite of the smaller initial dipole moment of the 16O+116Sn system. The comparison of the two data sets with each other and with the theoretical predictions proves that further investigation is needed from both the theoretical and the experimental point of view to shed light on the interplay between the different parameters that influence the dynamical dipole mode features.
2. The dynamical dipole mode in the mass region of the $^{192}\text{Pb}$

In order to examine the possibility to take advantage of the dynamical dipole mode $\gamma$ decay in the formation of super-heavy elements and to verify experimentally if this pre-equilibrium effect survives in heavier systems than those studied up to now, we extended our investigation of the dynamical dipole mode in the mass region of the $^{192}\text{Pb}$ CN, formed at an excitation energy of 236 MeV, employing the $^{40}\text{Ca}+^{152}\text{Sm}$ and $^{48}\text{Ca}+^{144}\text{Sm}$ reactions at $E_{lab}=440$ MeV and 485 MeV, respectively.

![Figure 1. Bidimensional plot of the energy loss ($\Delta E$) of the reaction products detected in the PPACs for the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction as a function of their time of flight (TOF). The plot in the right-hand side is obtained by requiring a coincidence between two PPACs. The fusion-evaporation events (left-hand side) and the mass symmetric fission events (right-hand side) included in the displayed contours were considered during the analysis.](image_url)

The reactions were performed by using the pulsed beam of $^{40}\text{Ca}$ and $^{48}\text{Ca}$ delivered by the Superconducting Cyclotron of the Laboratori Nazionali del Sud (Italy), at $E_{lab}=11$ and 10.1 MeV/nucleon, respectively. The beam impinged on a 1 mg/cm$^2$ thick $^{152}\text{Sm}$ and $^{144}\text{Sm}$ target. The above reactions form the same CN, $^{192}\text{Pb}$, with identical spin distribution ($L_{max}=74\hbar$) according to PACE2 calculations [18], at an excitation energy of 236 MeV, evaluated using the empirical formula of ref. [19]. As a first approach, we analyzed the proton energy spectra collected at $\theta_{lab}=160^\circ$ with respect to the beam direction, where emission from solely the CN is expected and the claim of identical excitation energy of the CN in the two reactions was confirmed. However, the CN effective excitation energy will be extracted experimentally by analyzing the energy spectra of all the light charged particles detected at different polar angles as in our previous works [14, 15]. While the entrance channel mass asymmetries of the considered reactions are similar with each other, namely 0.22 and 0.18 for the $^{40}\text{Ca}+^{152}\text{Sm}$ and $^{48}\text{Ca}+^{144}\text{Sm}$ reaction, respectively, the initial dipole moment is quite different for the two systems and it changes from 30.6 fm for the more charge asymmetric system, $^{40}\text{Ca}+^{152}\text{Sm}$, to 5.3 fm for the charge symmetric one. Therefore, in this experiment all the reaction parameters were kept identical except for the initial dipole moment (as in our previous experiments). The dynamical dipole mode was investigated in both fusion-evaporation and fission events for the first time.

The $\gamma$-rays and the light charged particles were detected by using the 180 barium fluoride (BaF$_2$) modules of the MEDEA experimental apparatus (for details see [20]) that covers the polar angular range between $\theta_{lab}=30^\circ$ and $\theta_{lab}=170^\circ$ and the full range in the azimuthal angle $\phi$. The discrimination between $\gamma$-rays and light charged particles was performed by combining a pulse shape analysis of the BaF$_2$ signal with a time of flight measurement between each BaF$_2$ detector and the radiofrequency signal of the Cyclotron. The fusion-evaporation residues were detected by four position sensitive Parallel Plate Avalanche Counters (PPACs) located symmetrically around the beam direction at 70 cm from the target and covering the angular
Figure 2. Bidimensional plots obtained for a BaF$_2$ scintillator in the ring centered at $\theta_{lab}=97^\circ$. The $\gamma$-ray events considered in the analysis are obtained by applying the displayed contours to both these plots. Left-hand side: ”Fast component vs Total energy”. Right-hand side: ”Time of Flight vs Total energy” conditioned by the contour on $\gamma$-rays shown in the left hand-side panel.

range from $\theta=3^\circ$ to $10.5^\circ$. The fission events were identified by detecting the two kinematically coincident fission fragments with position sensitive PPACs, centered at $\theta=52.5^\circ$ symmetrically around the beam axis, positioned such that allowed the measurement of $\gamma$-rays emitted parallel ($0^\circ$) or perpendicular ($90^\circ$) to the spin axis of the composite system.

Figure 3. $\gamma$-ray spectrum obtained in coincidence with fusion-evaporation residues for the $^{48}$Ca+$^{144}$Sm reaction compared with the theoretical spectrum (solid line) calculated with the code CASCADE and folded by the response function of the experimental apparatus.

In Fig.1 we show two bidimensional plots of the energy loss ($\Delta E$) of the reaction products as a function of their time of flight (TOF). In the left hand-side panel the plot is obtained from one of the PPACs employed for fusion-evaporation events while the right hand-side panel refers to fission events obtained requiring a coincidence between two PPACs in the $^{48}$Ca+$^{144}$Sm reaction. In our analysis we retained the events inside the selected areas that indicate fusion-evaporation events (left hand-side panel) and mass symmetric fission events (right hand-side panel). A relative TOF calibration was achieved by considering the distance between the elastic peaks observed during two runs characterized by fixed delays in the radiofrequency signal. In Fig. 2 the bidimensional plots ”Fast component vs Total energy” (left-hand side) and ”Time of Flight vs Total energy” (right-hand side) conditioned by the contour on $\gamma$-rays seen in the left hand-side
panel are presented for a BaF$_2$ detector in the ring centered at $\theta_{lab} = 97^\circ$ for the $^{48}$Ca+$^{144}$Sm reaction. By applying contours to both these planes, an unambiguous discrimination between $\gamma$-rays, protons and alpha particles is achieved.

About half of the collected statistics has been analyzed for BaF$_2$ detectors in the rings situated at $\theta_{lab} = 82^\circ$, $97^\circ$ and $112^\circ$ with respect to the beam direction and is shown in the present paper while in ref. [22, 23] we presented preliminary results of the same experiment, concerning a smaller part of the collected statistics. In Fig. 3 the obtained experimental $\gamma$-ray spectrum for the charge symmetric reaction, $^{48}$Ca + $^{144}$Sm, is shown with the points while the theoretical spectrum calculated by means of the code CASCADE [17] and folded by the response function of the experimental apparatus [21] is displayed with the line. The parameters used in this calculation are: a CN mass $A=192$ with an excitation energy $E^*_G=236$ MeV and a level density parameter $a=A/11$ MeV$^{-1}$. The GDR strength function was taken to be a lorentzian curve with centroid energy $E_{GDR}=13$ MeV, width $\Gamma_{GDR} = 12$ MeV and strength $S_{GDR}=100\%$ of the E1 energy-weighted sum-rule strength throughout the calculation. We notice that a good agreement is obtained between the data and the stational $\gamma$-ray spectrum.

![Image]

**Figure 4.** Left hand-side: experimental $\gamma$-ray spectrum of the charge symmetric and charge asymmetric reactions (top) and their difference (bottom) for fusion-evaporation events. Right hand-side: the same spectra as in the left hand-side for mass symmetric fission events by requiring a coincidence between the two PPACs.

In the left hand-side panel of Fig. 4 we present the experimental $\gamma$-ray spectrum of the charge symmetric and charge asymmetric reactions (top) and their difference (bottom) for fusion-evaporation events while in the right hand-side panel we show the same spectra for symmetric fission events by requiring a coincidence between the two PPACs. By comparing the corresponding $\gamma$-ray spectra of the two reactions for fusion-evaporation and fission events an excess of $\gamma$-rays in the more charge asymmetric reaction was observed, concentrated in the energy range $E_\gamma=8-13$ MeV. This excess is related to the dynamical dipole mode $\gamma$ decay. It is worth noting that, also in this case, the centroid energy of the dynamical dipole mode is lower than that of the CN GDR, $E_{GDR}=13$ MeV, suggesting a large deformation of the emitting source. Moreover, we notice that the dynamical dipole $\gamma$ yield obtained in fusion-evaporation events is comparable with that obtained in fission events as is expected for a pre-equilibrium $\gamma$-ray emission.
In order to reduce the error bars of the present analysis and to draw definite conclusions, all the statistics collected during the experiment will be analyzed while the angular distributions for evaporation events and the γ-ray fragment angular correlations for fission events will be extracted. The experimental findings will be compared with theoretical predictions performed within a BNV transport model, based on a collective bremsstrahlung analysis of the entrance channel reaction dynamics [3].

As a very first conclusion we can claim that the dynamical dipole mode survives in composite systems in the mass region $A \sim 190$ at the studied incident energy of $\sim 11$ MeV/nucleon. However, its yield is comparable with that obtained for reactions leading to $A \sim 130$ composite systems at incident energies ranging from 9 to 16 MeV/nucleon but having a lower initial dipole moment. This observation supports the theoretical prediction that the heavier mass of the reaction partners causes a decrease of the dynamical dipole γ yield.

3. Conclusion
In this contribution we presented preliminary results on the investigation of the dynamical dipole mode in reactions involving heavier mass reaction partners than those studied previously that form composite systems in the mass region of $^{192}$Pb. We show that the dynamical dipole mode survives in these heavy systems, though its yield does not increase as expected by increasing the dipole moment between the reaction partners. That could be a signature of the role played by the mass of the reaction partners. Because of its prompt nature, the dynamical dipole mode $\gamma$ decay could represent a new cooling mechanism of the composite system, becoming thus of interest for the synthesis of super-heavy elements.

The advent of intense radioactive beams will help in maximizing the charge asymmetry between the colliding ions, shedding thus new light on different interesting aspects that could be investigated using the prompt dipole radiation as a probe, like the investigation of the symmetry energy at sub-saturation density [24].

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