DYNAMICAL DIPOLE MODE IN FUSION HEAVY-ION REACTIONS IN THE MASS REGION OF A = 192

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The dynamical dipole mode was investigated in the mass region of the ^{192}Pb compound nucleus, by using the ^{40}Ca + ^{152}Sm and ^{48}Ca +^{144}Sm reactions at E_{lab} = 11 and 10.1 MeV/nucleon, respectively. The γ-ray energy spectra at various polar angles were obtained for fusion-evaporation and fission events by detecting the high energy γ-rays with the MEDEA experimental apparatus in coincidence with evaporation residues and fission fragments. Our results show that the dynamical dipole mode survives in reactions involving heavier nuclei than those studied previously. However, its yield is lower than that expected within BNV calculations.

1. Introduction

In charge asymmetric heavy-ion collisions, a large amplitude collective dipole oscillation can develop along the symmetry axis of the dinuclear system due to the presence of a non vanishing dipole moment between the interacting ions [1]. This oscillation, called "dynamical dipole mode" (DD), decays emitting prompt photons in addition to those coming from the Giant Dipole Resonance (GDR) thermally excited in the hot compound nucleus (CN).

The dynamical dipole radiation presents i) a lower centroid energy than that of a statistical GDR built in a spherical nucleus of similar mass due to the high deformation of the emitting source and ii) an anisotropic angular distribution around 90° with respect to the beam axis. Moreover, its intensity depends on the interplay between different parameters: 1) initial dipole moment, 2) reaction dynamics (incident energy, centrality, mass asymmetry) and 3) the symmetry term of the nuclear matter Equation of State (EOS) acting as a restoring force [3, 4].

2. Experimental results for ^{192}Pb

The emission of dynamical dipole γ-rays decreases the excitation energy and hence the initial temperature of the nucleus reaching the statistical phase. This cooling mechanism could be suitable to favour the production of super-heavy elements in "hot" fusion reactions. However, TDHF calculations [2] showed that the prompt dipole γ yield decreases as the mass of colliding ions increases since the reactions with small nuclei are less damped than those involving more nucleons. In order to understand if this pre-equilibrium effect survives in heavier systems than those studied previously and to test the usefulness of the dynamical dipole in super-heavy element production, we decided to investigate this collective oscillation in the mass region of the ^{192}Pb CN.

The experiment was performed by using the ^{40}Ca(^{48}Ca) pulsed beam provided by the Superconducting Cyclotron of the Laboratori Nazionali del Sud (LNS, Italy), impinging on a 1 mg/cm^2 thick ^{152}Sm(^{144}Sm) target at E_{lab} = 440(485) MeV. According to PACE2 calculations [5], the ^{192}Pb CN was formed in the two reactions with identical spin distribution (L_{max} = 74ħ) at the excitation energy of 236 MeV, evaluated with the empirical formula of [6]. The entrance channel mass asymmetry was 0.22 and 0.18 for the ^{40}Ca + ^{152}Sm and

^{48}Ca + ^{144}Sm reaction, respectively, while the initial dipole moment was 30.6 fm for the more charge asymmetric system and 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. The prompt dipole was studied in both fusion-evaporation and fission events for the first time. The γ-rays and the light charged particles were detected by using the MEDEA experimental apparatus [7], made of 180 BaF_2 scintillators, that covers the polar angular range from θ_{lab} = 30° to 63.1° and the full range in the azimuthal angle φ. The discrimination between γ-rays, light charged particles and neutrons was performed by combining a pulse shape analysis of the BaF_2 signal with a time of flight measurement between each scintillator 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 range from θ_{lab} = 3° to 10.5°. The fission events were selected by detecting the two kinematically coincident fission fragments with position sensitive PPACs, centered at θ_{lab} = 52.5° symmetrically around the beam axis at 16 cm from the target, and covering the angular range from θ_{lab} = 41.9° to 63.1°. These PPACs were positioned such to allow the study of γ-ray - fragment angular correlation. The hypothesis of equal CN excitation energy in the two considered reactions was verified by analyzing the proton energy spectra collected at θ_{lab} = 160° with respect to the beam direction, where emission from exclusively the CN is expected. However, the CN excitation energy, found with the empirical formula of [6], will be compared with the experimental value extracted by analyzing the energy spectra of all the light charged particles detected at different polar angles as done in our previous works [11,12].

2.1. *γ-ray spectra*

All the collected statistic has been analyzed for the BaF_2 modules placed in the rings from θ_{lab} = 83° and θ_{lab} = 130°. The γ-ray spectra of the two reactions and their relative difference in fusion-evaporation and fission events are presented in Fig. 1, while in [8,9] we showed preliminary results of this experiment, concerning a smaller part of the data.

We remind that no normalization of the γ-ray spectra was done, because we measured the double differential γ-ray multiplicity for fusion- evaporation and fission. In both channels, an excess of γ-rays in the more charge asymmetric reaction was observed in the energy range $8<E_\gamma<14$ MeV. This excess, related to the dynamical dipole mode decay, was reproduced by means of a lorentzian curve folded by the experimental apparatus response function [10]. We found the centroid energy E_{DD} = 10.5 MeV, the width Γ_{DD} = 3.5 MeV and a very similar DD yield for both fusion-evaporation and fission channels as expected for a pre-equilibrium effect. Moreover, it is interesting to note that E_{DD} is lower than E_{GDR} = 13 MeV, the centroid energy of the GDR excited in the CN, confirming the high deformation of the emitting source in agreement with previous works [11,12]. The E_{GDR} was obtained by fitting the experimental γ-ray spectrum for the charge symmetric reaction, ^{48}Ca + ^{144}Sm, with the theoretical spectrum calculated by means of the code CASCADE [13] and folded by the response function of the experimental apparatus [10].

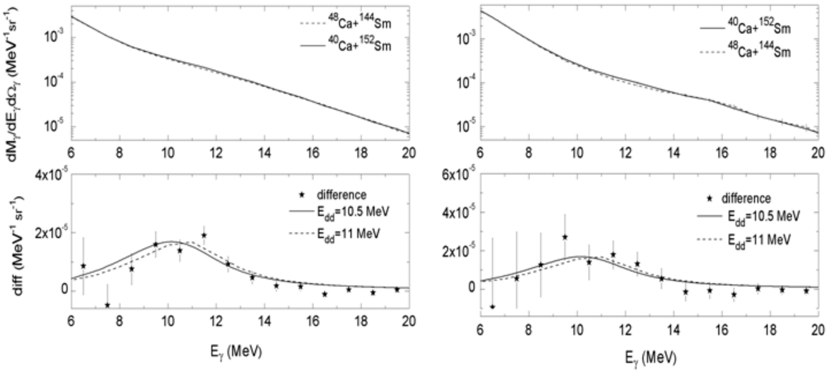

Figure 1. Experimental γ -ray spectrum of the charge symmetric and charge asymmetric reactions (top) and their difference (bottom) for fusion-evaporation events (left-hand side) and for mass symmetric fission events (right-hand side) obtained by requiring a coincidence between the two kinematically coincident fragments. The lines in the bottom reproduce the data as described in the text.

2.2. *Fusion - evaporation γ-ray angular distribution*

The angular distribution of the dynamical dipole γ-rays is a sensitive probe of the fusion dynamics and of the dynamical dipole lifetime. This is related to (a) the rotation angular velocity of the dinuclear system during the prompt dipole emission and (b) the instant at which this emission occurs.

We display in Fig. 2 the center-of-mass angular distribution with respect to the beam direction of the observed evaporation γ–rays for the $^{40;48}$Ca + $^{152;144}$Sm reactions (top) and for their difference (bottom) integrated over energy range from 9 to 16 MeV, after the subtraction of *nn-bremsstrahlung* component. These data are corrected by the experimental setup efficiency obtained from the experimental set up response function [10]. The lines in both panels of the above figure describe the angular distribution of the emitted γ-rays given by the Legendre polynomial expansion $M(\theta) = M_0 [1 + Q_2 a_2 P_2 cos(\theta_\gamma)]$, where a_2 is the anisotropy coefficient and Q_2 is an attenuation factor for the finite γ-ray counter, which, for the present geometry, was found to be 0.98 [14]. The coefficient M_0 and a_2 were obtained from a best fit to the data.

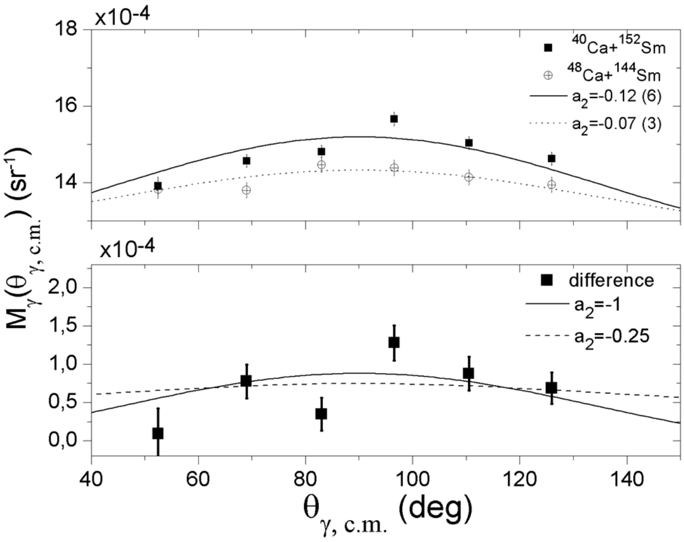

Figure 2. (Left) Center-of mass angular distribution of the γ -rays for the ^{40}Ca + ^{152}Sm (solid squares) and ^{48}Ca + ^{144}Sm (open circles) reactions and (Right) of their difference in the energy interval $9 \leq E_{\gamma,cm} \leq 16$ MeV corrected by the experimental setup efficiency. The lines are described in the text.

The solid and dashed lines in the bottom of Fig. 2 are a fit of the ^{40}Ca + ^{152}Sm and ^{48}Ca + ^{144}Sm angular distribution, respectively. The charge asymmetric (solid squares) reaction displays a more anisotropic angular distribution around 90° than the charge symmetric one (open circles). Since we have the same compound nucleus, with the same excitation energy and angular momentum, such a difference should be ascribed to entrance channel effects. The experimental angular distribution of the difference, that is the DD angular distribution, can be reproduced with $a_2 = -1$ (solid line), that is compatible with an emission from a dipole oscillation along an axis that has performed a small rotation with respect to the beam axis. This confines the γ-emission time scale at the very beginning of the reaction, in agreement with our previous results [11,12].

The present experimental findings on the prompt dipole radiation in ^{40}Ca + ^{152}Sm reaction were compared with preliminary calculations performed within the BNV transport model framework and based on a collective bremsstrahlung approach of the entrance channel reaction dynamics [3]. These calculations give centroid energy, width and angular distribution of the dynamical dipole in good agreement with those of the experiment. However, the theoretical γ yield overestimates the data and this aspect should be further investigated.

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