DYNAMICAL DIPOLE MODE IN THE ^{192}Pb MASS REGION*

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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 $E_{\rm lab}$ = 11 and 10.1 MeV/nucleon, respectively. Both fusion-evaporation and fission events were studied simultaneously for the first time. 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.

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1. Introduction

In charge asymmetric heavy-ion collisions, a large amplitude collective dipole oscillation can develop along the symmetry axis of the dinuclear sys-

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tem due to the presence of a non vanishing dipole moment between the interacting ions [1–3]. This oscillation, called "dynamical dipole mode" (DD throughout the text), decays emitting prompt photons, in addition to those coming from the Giant Dipole Resonance (GDR) thermally excited in the hot compound nucleus (CN). The DD 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 [2, 3], *(ii)* an anisotropic angular distribution with respect to the beam axis because the oscillation is confined in the reaction plane [4], and *(iii)* a γ yield that depends on both the beam energy and the reaction dynamics [3].

Experimentally, the existence of the DD mode has been studied in deep inelastic [5–7] and fusion-evaporation heavy-ion collisions [6, 8–12]. In these measurements, an excess of γ-rays was observed in the GDR energy region for a charge asymmetric reaction, with respect to that of a more charge symmetric one forming the same CN at identical conditions [6, 8–11] or with respect to statistical model calculations [12]. This γ excess was attributed to the decay of the predicted DD. Although such γ excess constitutes one of the signatures of the DD radiation, angular distribution data are also important because, as explained in the following, they give information about the reaction dynamics and the DD lifetime.

The emission of DD γ-rays decreases the excitation energy of the nucleus reaching the statistical phase. As a fast cooling mechanism on the fusion path, it could, therefore, be of interest for the synthesis of super heavy elements through hot fusion reactions providing a way to cool down the hot fusion paths, so ending up with a larger survival probability. 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 larger ones. In order to understand if this pre-equilibrium effect survives in heavier systems than those studied up to now, we decided to investigate the DD in the mass region of the ^{192}Pb CN.

2. Experimental results for ^{192}Pb

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 $E_{\mathrm{lab}} = 440(485)$ MeV. Both entrance channels populate the same CN, ^{192}Pb, through a quite different initial dipole moment ranging from 30.6 fm for the ^{40}Ca + ^{152}Sm charge asymmetric reaction to 5.3 fm for the ^{48}Ca + ^{144}Sm more charge symmetric one. 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. Furthermore, the formed CN has identical spin distribution: $L_{\max} = 74\,\hbar$ for fusion and $L_{\max} = 36\,\hbar$ for fusion-evaporation, according to PACE2 calculations [13], and identical excitation energy of 236 MeV, evaluated using the empirical formula of [14]. The hypothesis of an equal CN excitation energy in the two reactions was verified experimentally in a first approach by considering a small part of the collected statistics. In this approach the proton energy spectra, taken at $\theta_{\rm lab} = 160^\circ$ with respect to the beam direction, in coincidence with evaporation residues and with fission fragments, were analyzed by means of a moving source fit in which the particles were assumed to be emitted isotropically from the hot CN. The extracted CN parameters (proton multiplicity M and emitting source apparent temperature T) were found to be equal within statistical uncertainties for both entrance channels ensuring us the same excitation energy of the CN in fusion evaporation and fission events. The M and T values for evaporation events are the following: $M = (2.42 \pm 0.18)$, $T = (3.45 \pm 0.06)$ MeV for the ^{40}Ca + ^{152}Sm reaction and $M = (2.14 \pm 0.38)$, $T = (3.38 \pm 0.11)$ MeV for the ^{48}Ca + ^{144}Sm one while for fission events: $M = (0.95 \pm 0.10)$, $T = (3.51 \pm 0.09)$ MeV for the ^{40}Ca + ^{152}Sm reaction and $M = (0.87 \pm 0.15)$, $T = (3.43 \pm 0.13)$ MeV for the ^{48}Ca + ^{144}Sm one. In a following step of our analysis, in order to extract the experimental value of the average excitation energy and average mass of the CN after pre-equilibrium particle emission (as done in our previous work [11]), the proton and alpha particle energy spectra collected at all angles will be analyzed by means of a moving source fit in which the particles are assumed to be emitted isotropically from two (four) moving sources in the case of evaporation (fission) events: the CN, the composite system before thermalization and, in case of fission events, also the excited fragments. From the above discussion we can conclude that all the parameters but the dipole moment (charge asymmetry) were kept identical in the two reactions, so that any difference in their γ-ray spectra and angular distributions can be safely ascribed to the difference in the entrance channel charge asymmetry.

The γ-rays and the light charged particles were detected by using the MEDEA experimental apparatus [15], made of 180 BaF_2 scintillators. 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 at $\theta = 7^\circ$ and subtending 7° in θ. PACE2 [13] calculations show that the evaporation residue angular distribution has a maximum at $\theta = 4.5^\circ$ and extends up to $\theta = 16^\circ$ for both reactions. That ensures us that we select experimentally the same compound nuclei in both reactions (about 70% of the whole evaporation residue cross section) avoiding thus any difference that could influence our results on the DD γ yield and angular distributions. The fission events were selected by detecting the two kinematically coincident fission fragments with position sensitive PPACs, centered at $\theta = 52.5^\circ$ symmetrically around the beam axis at 16 cm from the target covering 22° in both θ and ϕ and allowing the study of γ-ray — fragment angular correlations. Down-scaled single events together with coincidence events between at least one fired BaF_2 scintillator and a PPAC (two PPACs) for evaporation (fission) events were collected during the experiment. A coincidence event was accepted if the deposited energy in a BaF_2 detector was greater than ~ 5.5 MeV for γ-rays. 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 spectra as the double differential γ multiplicity is obtained from the ratio of the number of coincidences between γ-rays and evaporation residues (fission fragments) and the number of single events of evaporation (fission). Preliminary results of the experiment, concerning a partial statistics are shown in [16].

2.1. γ-ray spectra and angular distributions

By comparing the center-of-mass double differential γ-ray spectra of the two reactions for fusion-evaporation and fission events an excess of γ-rays in the more charge asymmetric reaction was observed, concentrated in the energy range $E_\gamma = 8$–14 MeV as can be seen in the left-hand side of Fig. 1, where the difference between the spectra of the two systems is showed for evaporation (fission) events in the top (bottom). This excess is related to the DD decay and can be reproduced by means of a lorentzian curve folded by the experimental apparatus response function [17] (line in the figure) with a centroid energy $E_{\rm DD} = 10.5$ MeV and a width $\Gamma_{\rm DD} = 3.5$ MeV, for both exit channels. It is interesting to note that $E_{\rm DD}$ is lower than the CN GDR centroid energy $E_{\rm GDR} = 13$ MeV (obtained with a CASCADE calculation [18] of the ^{48}Ca+^{144}Sm reaction). This result confirms the high deformation of the emitting source, in agreement with expectations [2, 3] and with our previous works [10, 11]. By integrating over energy the difference between the γ-ray spectra of the two reactions for the BaF_2 rings situated at polar angles from $\theta = 51.5^\circ$ to $\theta = 128.5^\circ$ and by taking into account the response function of the experimental set up [17] we obtain for the DD yield: $(8 \pm 1) \times 10^{-5}\,{\rm sr}^{-1}$ for evaporation events and $(10 \pm 3) \times 10^{-5}\,{\rm sr}^{-1}$ for fission events, with the quoted errors being statistical. A 3% error in the BaF_2 scintillator efficiency gives a $\pm 0.3 \times 10^{-5}\,{\rm sr}^{-1}$ error in the above values of the DD multiplicity, smaller than the statistical error.

The angular distribution of the DD γ-rays is a sensitive probe of the fusion dynamics and of the DD 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 [4]. We display in the right-

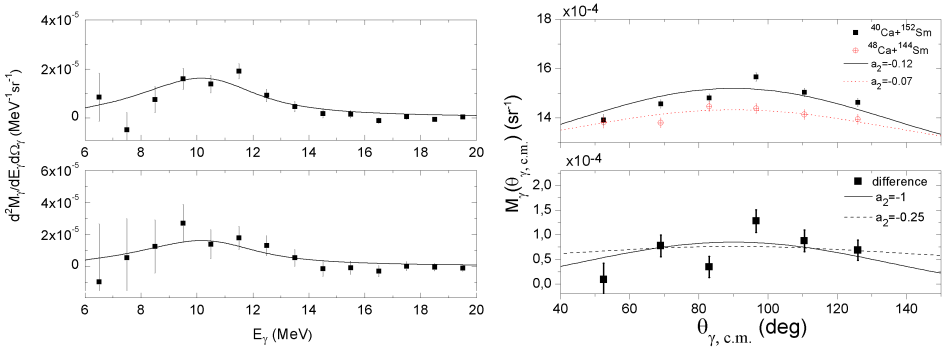

Fig. 1. (Left-hand side) Difference between the charge asymmetric and charge symmetric reaction center-of-mass γ-ray spectra for fusion-evaporation (top) and fission (bottom) events. The solid lines in both panels are described in the text. (Right-hand side) Center-of mass angular distribution of the γ-rays for the two reactions (top) and of their difference (bottom) in the energy interval $9 \leq E_\gamma \leq 16$ MeV corrected by the experimental setup efficiency. The lines are described in the text.

hand side of Fig. 1 the center-of-mass angular distribution with respect to the beam direction of the γ-rays detected in coincidence with evaporation residues for the ^{40,48}Ca + ^{152,144}Sm reactions (top) and for their difference (bottom). The double differential γ-ray multiplicity was integrated over energy from 9 to 16 MeV, after the subtraction of (nn)-bremsstrahlung component, and was corrected by the experimental setup efficiency. The γ-ray angular distributions are reproduced by means of 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, which, for the present geometry, is 0.98 [19]. A best fit to the data is shown in the figure (solid line for the ^{40}Ca+^{152}Sm reaction and dashed line for the ^{48}Ca+^{144}Sm one). The charge asymmetric reaction (squares) displays a more anisotropic angular distribution around 90° than the charge symmetric one (circles). Since we have the same CN, with the same excitation energy and spin distribution, such a difference is related to entrance channel effects.

As a consequence of the above, the experimental angular distribution of the difference (squares in the bottom of the figure) is very anisotropic with a maximum at 90°. The data 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. The dashed line obtained with $a_2 = -0.25$, corresponds to a more isotropic angular distribution and is also showed in the figure for comparison. Although we are not able to evaluate the rotation angle of the DD axis around the beam direction when the DD oscillation is completely damped, due to the large statistical errors, we have an indication that confines the γ-emission time scale at the very beginning of the reaction. This result is in agreement with our previous results [11] for evaporation events corresponding to small impact parameters.

Preliminary calculations of the DD in the ^{40}Ca+^{152}Sm reaction at $E_{\rm lab} = 11$ MeV/nucleon for different impact parameters within a BNV transport model, based on a collective bremsstrahlung analysis of the entrance channel reaction dynamics [3, 20], give centroid energy, width and angular distribution that are in good agreement with those obtained in the experiment. However, the theoretical γ yield overestimates the data. This last point should be further investigated in order to verify if it is due to the heavier mass of the colliding nuclei as predicted in the TDHF calculations of [2].

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