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Dynamical Dipole mode in heavy-ion fusion reactions in the ^{192}Pb mass region

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Abstract. 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. Both fusion–evaporation and fission events were studied simultaneously for the first time. Our results for evaporation and fission events (preliminary) show that the dynamical dipole mode survives in reactions involving heavier nuclei than those studied previously.

1. Introduction

In N/Z asymmetric heavy-ion reactions, it is possible to excite a collective dipole oscillation that can develop along the symmetry axis of the dinuclear system [1, 2, 3]. This oscillation, called "Dynamical Dipole mode" (DD throughout the text), decays emitting prompt dipole γ-rays, 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 is predicted to depend on both the beam energy and the reaction dynamics [3].

Experimentally, the existence of the DD mode has been studied in deep inelastic and fusion-evaporation heavy-ion collisions [5, 6, 7, 8, 9]. 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, 7, 8] or with respect to statistical model calculations [9]. This γ excess was attributed to the decay of the predicted DD.

The emission of DD 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 processes. 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 before and to test its usefulness in super-heavy element production, we decided to study 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_{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 had identical spin distribution: $L_{max} = 74\hbar$ for fusion and $L_{max} = 36\ \hbar$ for fusion-evaporation, according to PACE2 calculations [10] by using a level density parameter of a = A/8, A being the compound nucleus mass, and identical excitation energy, as explained in the following.

The γ-rays and the light charged particles were detected by using the MEDEA experimental apparatus [12], made of 180 BaF$_2$ scintillators. 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) placed symmetrically around the beam direction at 70 cm from the target at $\theta = 7^\circ$ and subtending 7° in θ. 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. 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 [13].

2.1. γ-ray spectra and angular distributions

The average excitation energy and the average mass of the composite system after pre-equilibrium particle emission were evaluated by studying the energy spectra of the light charged particles (p, α) detected in coincidence with evaporation residues. These spectra for the BaF$_2$ rings placed from $\theta = 51.5^\circ$ to $\theta = 159.7^\circ$ were analyzed in the framework of a two moving source scenario: a *slow* source simulating the statistical evaporation from the hot CN and an *intermediate-velocity* (between the CN and the projectile velocity) source related to the pre-equilibrium particles emitted by the composite system before thermalization. The analysis confirmed us that the two considered reactions lead to the formation of a CN with the same average mass at the same average excitation energy. Therefore, as in our previous works [7, 8], all the parameters except the dipole moment were kept identical in the two reactions, so that any difference in their γ-ray spectra and angular distributions can be attributed to the difference in the entrance channel charge asymmetry. 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_γ = 8-15 MeV as can be seen in the left-hand side of Figure 1 where the difference between the spectra of the two systems is shown 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 [14] (line in the figure) with a centroid energy E_{DD} = 11 MeV and a width Γ_{DD} = 3.5 MeV, for both exit channels. It is interesting to note that E_{DD} is lower than the ground state GDR centroid energy $E_{GDR} \sim$ 13.5 MeV for a mass in the region of 192. This result confirms the high deformation of the emitting source, in agreement with expectations [2, 3] and with our previous works [7, 8].

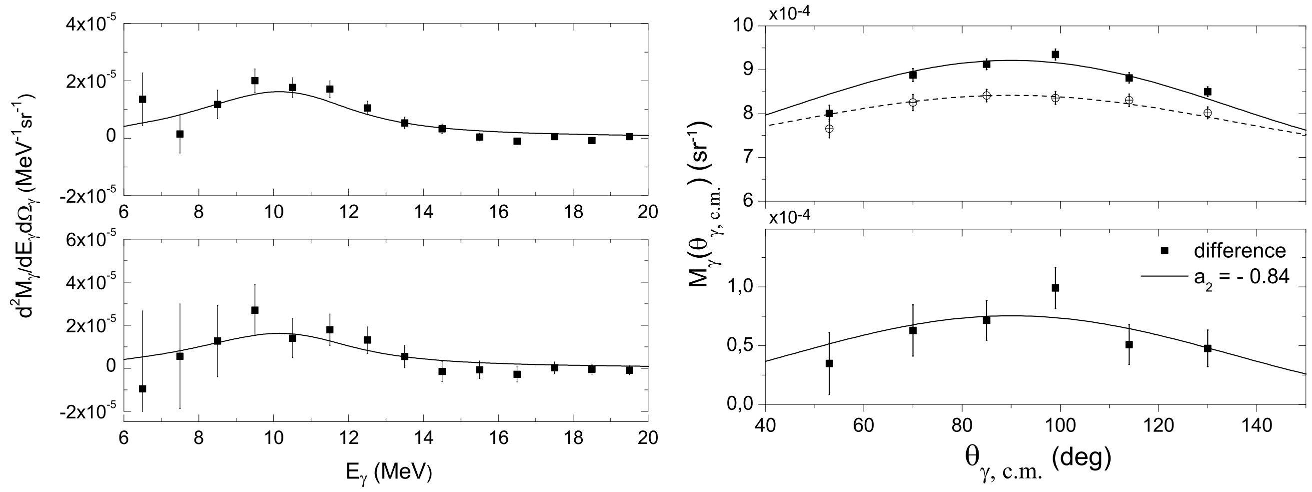

Figure 1. (Left-hand side) Difference between the charge asymmetric and charge symmetric reaction center-of-mass γ-ray spectra for fusion-evaporation (top) and fission (bottom) events. The solid lines in both panels are described in the text. (Right-hand side) Center-of mass angular distribution of the γ-rays in evaporation events for the two reactions (top) and of their difference (bottom) in the energy interval $10 \leq E_\gamma \leq 14$ MeV corrected by the experimental setup efficiency. The lines are described in the text.

Although such γ excess constitutes one of the signatures of the DD radiation, the angular distribution is also an important observable since it gives information about the reaction dynamics and 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-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 10 to 14 MeV, after the subtraction of (nn)-bremsstrahlung component, and was corrected by the experimental setup efficiency. The lines in both panels of the above figure describe the angular distribution of the emitted γ-rays given by the Legendre polynomial expansion $M_\gamma(\theta_\gamma) = M_0[1 + Q_2 a_2 P_2 cos(\theta_\gamma)]$, 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 [15]. From a best fit to the data, shown with a solid (dashed) line for the ^{40}Ca+^{152}Sm (^{48}Ca+^{144}Sm) reaction, we obtained a_2 = -0.17 ± 0.05 for the ^{40}Ca+^{152}Sm reaction and a_2 = -0.10 ± 0.03 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 around 90°. The data can be reproduced with a_2 = -0.84 (solid line), obtained within the BNV theoretical calculations as mentioned in the following, 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. 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 can confine the γ-emission time scale at the very beginning of the reaction. This result is in agreement with our previous results [8] for evaporation events corresponding to small impact parameters. By taking into account the DD γ-ray angular distribution and the response function of the experimental setup, we deduced the DD yield, integrated over energy and over angle: 1.38 ± $0.14*10^{-3}$ and 1.4 ± $0.4*10^{-3}$ for evaporation and fission events, respectively, where the quoted errors are statistical. A 3% systematic error in the BaF_2 scintillator efficiency introduces a ± $4*10^{-5}$ error, smaller than the statistical one. We notice that the extracted DD yield is the same, within errors, in evaporation and fission events.

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 DD in good agreement with those of the experiment. However, the theoretical γ yield overestimates the data, an aspect that should be further investigated.

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