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Dynamical Dipole mode in the ^{40,48}Ca +^{152,144}Sm fusion reactions at 11 MeV/nucleon

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Abstract

The excitation of the dynamical dipole mode along the fusion path was investigated in the formation of a heavy compound nucleus in the A=190 mass region. To form the compound nucleus, the ^{40}Ca + ^{152}Sm and ^{48}Ca + ^{144}Sm reactions were employed 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 The physical problem

The "Dynamical Dipole mode" (DD throughout the text) is a collective dipole oscillation that can be excited in N/Z asymmetric heavy-ion collisions. It develops along the symmetry axis of the deformed composite system, the dinucleus, and decays emitting prompt γ-rays in addition to those coming from the Giant Dipole Resonance (GDR) thermally excited in the hot compound nucleus (CN) [1–3]. The DD radiation is characterized by i) a centroid energy lower than that of the CN GDR in the same mass region due to the high deformation of the emitting source [2, 3] ii) an anisotropic angular distribution with respect to the beam axis since the oscillation is confined in the reaction plane [4] and iii) a γ yield that should depend on both the reaction dynamics and the symmetry term of the EOS [3].

The existence of the DD mode has been probed in deep inelastic and fusion-evaporation heavy-ion collisions [5–9]. 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 [6–8] 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. TDHF calculations [2] showed that the DD 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 the behavior of the DD in heavier systems than those studied before and to test its usefulness in super-heavy element production, we decided to study the DD in a composite system in the mass region A=190.

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

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 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 entrance channels populate the same CN 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. 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 excitation energy in both reactions, as explained in the following, and identical spin distribution: $L_{max} = 74\hbar$ for fusion and $L_{max} = 42\hbar$ for fusion-evaporation, according to PACE2 calculations [10] with a level density parameter a = A/9.5 MeV^{-1}, A being the CN mass. The γ-rays and the light particles were detected by using the MEDEA BaF_2 sphere [12], with a full azimuthal coverage in the polar angular range between 42° and 170°. They were identified by combining a pulse-shape analysis of the scintillator signal with a time of flight measurement (obtained with respect to 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 $\theta = 7°$ and subtending 7° in θ. The fission events were selected by detecting the two kinematically coincident fission fragments with position sensitive PPACs, centered at $\theta = 52.5°$ 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 and coincidence events between at least one fired BaF_2 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. Moreover, the trigger avoids to use any 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).

2.1 Results and discussion

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 (p, α) in coincidence with evaporation residues, while the pre-equilibrium neutron emission was estimated from our proton data and from systematics. These spectra were analyzed with a moving source fit where the particles were assumed to be emitted isotropically from two moving sources: 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 demonstrated that the two reactions lead to the formation of a CN with the same average mass and charge at the same average excitation energy. Hence, as in our previous works [7, 8], the only different parameter in the two reactions is the initial charge asymmetry. Therefore any difference in the γ-ray emission between the two reactions can be related to this quantity.

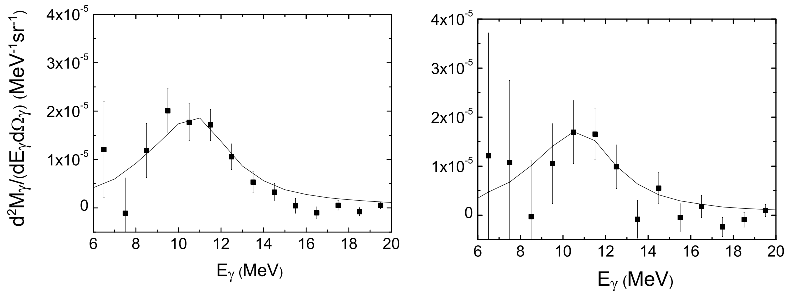

Figure 1: Difference between the charge asymmetric and charge symmetric reaction bremsstrahlung-subtracted center-of-mass γ-ray spectra for fusion-evaporation (left) and fission (right) events. The lines are described in the text.

By comparing the bremsstrahlung-subtracted center-of-mass γ-ray spectra, an excess of γ-rays in the more charge asymmetric reaction was observed, concentrated in the energy range E_γ = 8-15 MeV. This can be seen in Figure 1 where the difference between the spectra of the two reactions is displayed for evaporation (fission) events in the left (right) side. This excess is related to a pre-equilibrium effect caused by the large charge asymmetry of the ^{40}Ca+^{152}Sm reaction, namely to the DD γ decay, and can be reproduced by means of a lorentzian curve folded by the experimental apparatus response function [13] (line in the figure). The DD centroid energy E_{DD} and width Γ_{DD} used to reproduce our data are $E_{DD} = 11$ MeV and $\Gamma_{DD} = 3.5$ MeV, in both exit channels. It is interesting to note that E_{DD} is lower than the centroid energy of the GDR built on the ground state of a nucleus of similar mass, $E_{GDR} = 14$ MeV. This result confirms the high deformation of the emitting source at the moment of the DD γ emission, in agreement with expectations [2, 3] and with our previous works [7, 8].

A clear confirmation of the pre-equilibrium nature of the DD comes from the γ-rays angular distribution for evaporation events. This is related to the interplay between the rotation angular velocity of the dinuclear system

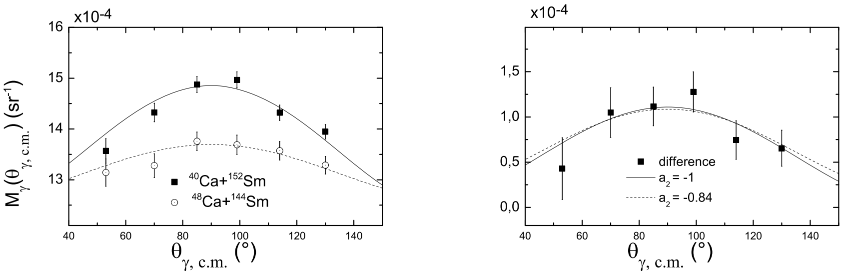

Figure 2: Center-of mass angular distribution of the evaporation γ-rays for the two reactions (left) and of their difference (right) in the energy range 9-15 MeV corrected by the experimental setup efficiency. The lines are described in the text.

during the DD emission and the instant when this emission takes place [4]. Figure 2 displays the center-of-mass angular distribution with respect to the beam direction of the fusion-evaporation γ-rays for the ^{40,48}Ca+^{152,144}Sm reactions (left) and for their difference (right), integrated over energy from 9 to 15 MeV and after the subtraction of (nn)-bremsstrahlung component. The angular distribution was corrected by the experimental setup efficiency. The lines in both panels of figure 2 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 [14] (0.98 in our case). 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 found a_2 = -0.13 ± 0.03 for the ^{40}Ca+^{152}Sm reaction and a_2 = -0.06 ± 0.02 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. Consequently, the experimental angular distribution of the difference (shown in the right-hand side of the figure 2) is very anisotropic around 90°. The data can be reproduced well with a_2 = -1 (solid line) that results in an angular distribution of the $sin^2(\theta_\gamma)$ form of emission from a dipole oscillation along the beam axis. The dashed line in the figure gives the DD angular distribution with a_2 = -0.84 obtained within BNV calculations for impact parameters integrated up to 2 fm (evaporation events). The above a_2 values indicate a preferential oscillation axis of the DD, triggered at the early stage of the fusion path, along an axis that has not rotated much on the reaction plane during the DD lifetime.

Our data therefore suggest that the DD γ-emission time scale is confined at the beginning of the reaction, in agreement with our previous results [8] for evaporation events and with theoretical expectations [4].

By taking into account the an 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}. The analysis for the DD angular distribution for fission events is under way.

The experimental results on the DD in ^{40}Ca+^{152}Sm reaction were compared with calculations performed within the BNV transport model 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 for evaporation events overestimates the data. This aspect should be further investigated.

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