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Dynamical Dipole mode in heavy-ion fusion reactions

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Abstract. In this work we give evidence for the first time of the Dynamical Dipole mode in a heavy system in the A$\sim$190 mass region, in both fusion–evaporation and fission events. The ^{40,48}Ca + ^{152,144}Sm reactions at E_{lab}=11(10.1) MeV/nucleon were employed. 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) is a collective oscillation of protons against neutrons with a dipole spatial pattern inside the atomic nucleus. It is a pre-equilibrium phenomenon, being excited along the fusion path of nuclei with a different ratio of neutrons and protons and decaying through emission of prompt γ-rays [1, 2, 3, 4]. The DD radiation is characterized by i) a centroid energy lower than that of the compound nucleus (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 [5] 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 [4, 6, 7, 8, 9, 10]. 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 [7, 8, 9] or with respect to statistical model calculations [10]. This γ excess was attributed to the decay of the predicted DD. The emission of DD γ-rays decreases the excitation energy and 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 [11] 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 [12].

2. The experiment: ^{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. The formed CN had identical excitation energy in both reactions, $E^* = (220\pm7)$ MeV, and identical spin distribution: $L_{max} = 74\hbar$ for fusion and $L_{max} = 42\hbar$ for fusion-evaporation, according to PACE2 calculations [13] 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 [14], with a full azimuthal coverage in the polar angular range between 42° and 170°. 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 θ = 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. The analysis of the light charged particles energy spectra in evaporation events demonstrated that the two reactions lead to the formation of the same CN with the same average excitation energy (see [12]). Therefore any difference in the γ-ray emission between the two reactions can be related to an entrance channel effect.

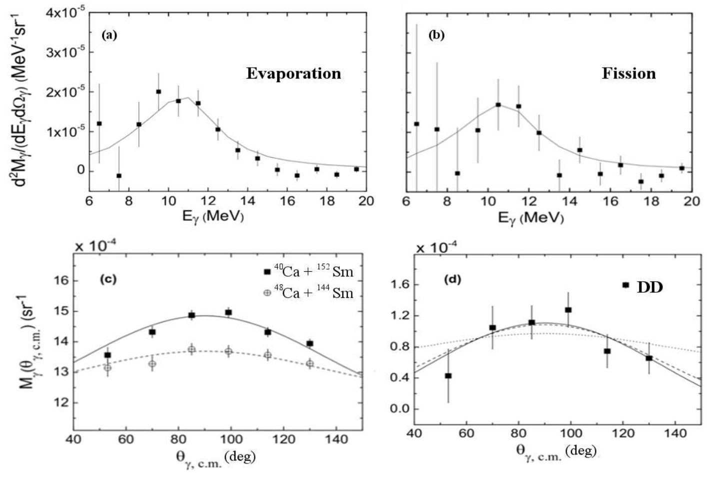

Figure 1. Difference between the charge asymmetric and charge symmetric reaction center-of-mass bremsstrahlung-subtracted γ-ray spectra for fusion-evaporation (a) and fission (b) events. (c) 9 MeV$\leq E_\gamma \leq$15 MeV γ-ray angular distribution of the ^{40}Ca+^{152}Sm (squares) and ^{48}Ca+^{144}Sm (circles) reactions, corrected for the detection efficiency. (d) Angular distribution of the difference between the data of panel (c). The lines are described in the text.

Panels (a) and (b) of Figure 1 show the difference between the center-of-mass bremsstrahlung-subtracted γ-ray spectra of the two reactions in coincidence with the evaporation residues and fission fragments, respectively. The data show an excess of γ-rays in the range E_γ=8-15 MeV in the charge asymmetric channel. This excess can only be related to the DD excitation in the composite system of the ^{40}Ca+^{152}Sm reaction because of its larger charge asymmetry. The DD γ spectrum (symbols in panels (a) and (b)) can be reproduced well by means of a Lorentzian curve folded by the experimental setup response function [15] (lines in the figure), with the DD centroid energy E_{DD} = 11 MeV and the width Γ_{DD} = 3.5 MeV, in both exit channels. 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, confirming the high deformation of the emitting source during the DD γ emission. This result is in agreement with expectations [2, 3] and with previous works [7, 8, 9].

Panels (c) and (d) of Figure 1 display the fusion-evaporation γ-rays angular distribution with respect to the beam axis for the two reactions (c) and for their difference (d), integrated over energy from 9 to 15 MeV and corrected for the detection efficiency. The lines 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 [16] (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. By using the same argument as previously for the spectra, the observed difference in the γ-ray angular distribution of the two systems can only be ascribed to entrance channel effects, namely the DD excitation. Consequently, the experimental angular distribution of the difference between the data of panel (c) (panel (d)) is very anisotropic around 90° and can be reproduced well with a_2 = -1 (solid line) that describes an emission from a dipole oscillation along the beam axis. The dashed line corresponds to a value of a_2 = -0.84 obtained within BNV calculations [3] for evaporation events, while the dotted one shows a more isotropic angular distribution (a_2 = -0.25). The above a_2 values indicate a preferential oscillation axis of the DD 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 for evaporation events [9] and with theoretical expectations [5]. By taking into account the 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 ± 0.2)*10^{-3} [12]. 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 BNV calculations, based on a collective bremsstrahlung approach of the entrance channel reaction dynamics. These calculations give centroid energy, width and angular distribution of the DD in good agreement with those of the experiment. However, the theoretical DD yield for evaporation events overpredicted the data, calling for further investigation to clarify this aspect.

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