Dynamical Dipole mode in heavy-ion fusion reactions


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Abstract. The excitation of the Dynamical Dipole mode along the fusion path was investigated for the first time in the formation of a heavy compound nucleus in the A∼190 mass region. The compound nucleus was formed at identical conditions of excitation energy and spin from two entrance channels having different charge asymmetry: the charge asymmetric 40Ca + 152Sm and the nearly charge symmetric 48Ca + 144Sm at Elab=11 and 10.1 MeV/nucleon, respectively. Both fusion–evaporation and fission events were studied simultaneously for the first time. The Dynamical Dipole mode excitation in the charge asymmetric channel was evidenced, in a model-independent way, by comparing the γ-ray multiplicity spectra and angular distributions of the two entrance channels with each other.

1 Introduction

The “Dynamical Dipole mode” (DD throughout the text), or pre-equilibrium Giant Dipole Resonance, 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 [1–5]. The DD radiation is characterized by the following characteristics: i) a centroid energy lower than that of the compound nucleus GDR in the same mass region indicating a high deformation of the emitting source [3, 4] ii) an anisotropic angular distribution with respect to the beam axis since the oscillation is confined in the reaction plane [6] and iii) a γ yield that should depend on both the reaction dynamics and the symmetry term of the nuclear matter Equation Of State [4].

From an experimental point of view, the DD excitation and subsequent γ decay has been observed in deep inelastic [5, 7–9] and fusion-evaporation heavy-ion collisions [9–16]. In some of the above-cited works [11–13], the first systematic study of its features as a function of the incident energy was performed in the 132Ce mass region in fusion-evaporation experiments. In those measurements, the DD was evidenced by employing a model independent method, the so-called difference technique, that consists in: (a) forming the same compound nucleus at identical conditions of excitation energy and spin from two entrance channels, a nearly charge symmetric and a charge asymmetric one; (b) obtaining the difference between the γ-ray spectra and angular distributions of the two channels for fusion-evaporation events. The resulting difference showed an excess of yield in the more charge asymmetric channel, ascribed to a pre-equilibrium effect, namely the DD excitation. A second campaign of experiments [15, 16] was performed to probe the DD excitation in the same composite system with a different method: the DD radiation was extracted by subtracting the γ-ray multiplicity spectrum of the compound nucleus, calculated by means of the statistical model code CASCADE [18], from the charge asymmetric reaction experimental γ spectrum. The CASCADE calculation used in the comparison was tested with a near-symmetric reaction leading to the same compound nucleus 132Ce.

The comparison of the two data sets [11–13, 15, 16] with each other and with the theoretical predictions, performed within a Boltzmann-Nordheim-Vlasov (BNV) transport model, based on a collective bremsstrahlung...
analysis of the entrance channel reaction dynamics [4], shows some discrepancies. On the one hand calculations, while being able to describe the phenomenon and absolute values of some observables, are not able to fully reproduce the existing experimental findings [14, 15]. On the other hand few experimental results exist reporting on the DD γ multiplicity and its angular distribution, that can be directly compared with calculations. These elements called for more experimental efforts to disentangle the influence of each reaction parameter on the DD features and to provide severe constraints to the theoretical models.

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 compound nucleus survival against statistical fission and thus, the formation of a super heavy element in hot fusion processes [4, 19]. TDHF calculations [19] 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 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 [17].

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 (INFN-LNS, Italy), impinging on a 1 mg/cm² thick self-supporting $^{152}$Sm ($^{144}$Sm) target enriched to 98.4%(93.8%) in $^{152}$Sm ($^{144}$Sm) at $E_{\text{lab}} = 440$ (485) MeV. Both entrance channels populate the same compound nucleus 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 compound nucleus had identical excitation energy in both reactions, $E' = (220\pm7)$ MeV, and identical spin distribution: $I_{\text{max}} = 74h$ for fusion and $I_{\text{max}} = 42h$ for fusion-evaporation, according to PACE2 calculations [20] with a level density parameter $a = A/9.5$ MeV$^{-1}$. A being the compound nucleus mass.

The γ-rays and the light charged particles were detected by using the 180 barium fluoride (BaF$_2$) modules of the MEDEA experimental apparatus [27] that covers the polar angular range between $\theta_{\text{lab}} = 30^\circ$ and $\theta_{\text{lab}} = 170^\circ$ and the full range in the azimuthal angle $\phi$. The MEDEA ball has an inner radius of 22 cm and covers a total solid angle of 3.7π sr. The apparatus operates under vacuum inside a large scattering chamber to allow a simultaneous detection of γ-rays and light charged particles. The discrimination between γ-rays and light particles was performed by combining a shape analysis of the BaF$_2$ signal with a time of flight (TOF) measurement, between each BaF$_2$ detector and the radiofrequency signal of the Cyclotron.

The energy calibration of the BaF$_2$ detectors was obtained by using the composite sources of $^{241}$Am + $^9$Be ($E_{\gamma}=4.43$ MeV) and $^{238}$Pu + $^{13}$C ($E_{\gamma}=6.13$ MeV) and the 15.1 MeV γ-rays from the $p + ^{12}$C reaction at $E_p = 25$ MeV. The charged particle calibration was deduced from the γ calibration as described elsewhere [21]. The time stability of the energy calibration was checked during the experiment by monitoring after each run the stability of the peak corresponding to a radioactive source.

The fusion-evaporation residues were detected by four Parallel Plate Avalanche Counters (PPACs) located symmetrically around the beam direction at 70 cm from the target in an annular configuration. The PPACs were centered at an angle $\theta_{\text{lab}} = 7^\circ$ with respect to the beam direction, subtending $7^\circ$ in $\theta$ and covering a total solid angle of 0.089 sr. The PPACs provided the energy loss ΔE and the TOF of the reaction products with respect to the radiofrequency signal of the accelerator. 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 $\theta$ and $\phi$ and allowing the study of γ-ray - fragment angular correlations. The PPACs gave information on the energy loss ΔE, the TOF and the $x$ and $y$ positions of the fragments that allowed to reconstruct angles, masses and velocity vectors of the fragments in the laboratory and the center-of-mass reference frame. Both evaporation residues and fission fragments were selected by applying appropriate contours in the relative bi-dimensional plots (ΔE, TOF) of the PPACs.

Down-scaled single PPAC events together with coincidence ones between a PPAC and at least one fired BaF$_2$ scintillator 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 (charged particle) spectra as the double differential γ (charged particle) multiplicity is obtained from the ratio of the number of coincidences between γ-rays (charged particles) and evaporation residues (fission fragments) and the number of single events of evaporation (fission).

3 Analysis and Results

The experiment was designed in such a way to form the same compound nucleus at identical excitation energy from the two entrance channels by taking into account incomplete fusion events [22]. These events are characterized by emission of pre-equilibrium light particles that reduces the compound nucleus average mass, average charge and average excitation energy and cannot be discarded in the TOF spectrum of the reaction products because they have overlapping velocity distributions with those of the complete fusion events [23].

Therefore, in the present work, 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 ($\alpha$-particles and protons) detected in coincidence with evaporation residues and fission fragments while the pre-equilibrium neutron emission was estimated from our proton data and from existing neutron emission studies (see [17] and references therein). Here, we will present the light charged particle analysis for evaporation residues events.

3.1 Fusion–evaporation results

In Figure 1 the laboratory proton multiplicity spectra obtained with BaF$_2$ scintillators centered at polar angles 51.5$^\circ$ $< \theta_{lab} < 159.7^\circ$, in coincidence with the evaporation residues are reported for the $^{40}$Ca + $^{152}$Sm reaction. These spectra were analyzed by means of a moving source fit in which the particles were assumed to be emitted isotropically from two moving sources: a slow source describing the statistical evaporation from the hot compound nucleus and an intermediate-velocity (between the compound nucleus and the projectile velocity) source related to the pre-equilibrium particles emitted by the composite system before thermalization. The energy distribution of the evaporated particles was parameterized, in the source rest frame, adopting a surface-type Maxwellian distribution, while the distribution of the pre-equilibrium particles was taken to be that for volume emission from a thermal source (see [17] for more details). The same procedure was adopted for the $\alpha$-particles.

The result of the simultaneous fit is shown with solid lines in panel (a) of Figure 1 for proton events and the relative contributions of the two sources are reported in panel (b) of the same figure for a backward and a forward angle, with the slow (intermediate-velocity) source component represented with a dotted (dashed) line.

To evaluate the average energy taken away by pre-equilibrium neutrons, not detected in the present experiment, we assumed that their energy spectra were very similar to the proton ones, apart from the Coulomb barrier. Then, the average kinetic energy of a pre-equilibrium neutron was taken to be that of a pre-equilibrium proton minus the Coulomb barrier while the pre-equilibrium neutron multiplicity was deduced by that of pre-equilibrium protons multiplied with the N/Z ratio of the compound nucleus. The adopted pre-equilibrium neutron multiplicity is in agreement within errors with neutron emission studies performed at similar center-of-mass incident energy above the Coulomb barrier [24].

By using the parameters extracted from the fitting procedure, the average excitation energy of the composite system after pre-equilibrium particle emission was deduced to be $E^*=(219.6\pm6.8)$ MeV for the $^{40}$Ca + $^{157}$Sm and $E^*=(220.5\pm6.6)$ MeV for the $^{40}$Ca + $^{144}$Sm reaction. The average total mass and average total charge lost in each reaction were found to be: $\Delta A=3.2\pm0.6$ and $\Delta Z=1.5\pm0.2$ for the $^{40}$Ca + $^{152}$Sm system and $\Delta A=3.4\pm0.5$ and $\Delta Z=1.6\pm0.2$ for the $^{40}$Ca + $^{144}$Sm one. We considered, thus, that two units of charge and three units of mass were carried away from the initial composite system leading to the $^{189}$Hg nucleus in both reactions. The average total momentum removed from the system was obtained by taking the product of the pre-equilibrium particle momentum with its multiplicity and then summing over particle types. This allowed us to derive the linear momentum transfer along the beam direction that was $\sim 97\%$ in both reactions.

This analysis ensured us that the two reactions lead to the formation of the same compound nucleus $^{189}$Hg with the same average excitation energy, giving us confidence that any difference between the $\gamma$-ray spectra and $\gamma$-ray
The angular distributions of the two reactions is related to an entrance channel effect.

After the evaluation of the excitation energy of both reactions, shown above, the incoherent bremsstrahlung component considered to originate primarily in neutron-proton (np) collisions and dominant for \( E_\gamma > 30 \text{ MeV} \), must be evaluated and subtracted from the data. An equal bremsstrahlung component is expected for the two reactions because of their very similar beam energy and size of the reaction partners and of the same temperature of the composite system \([25, 26]\). This is confirmed by the data of the two reactions, that are equal within errors for \( E_\gamma > 20 \text{ MeV} \). The np bremsstrahlung component was deduced by fitting simultaneously the center-of-mass fusion-evaporation \( \gamma \)-ray spectra of the two reactions at different polar angles in the energy range \( 30 \text{ MeV} < E_\gamma < 40 \text{ MeV} \). The fit was performed assuming an exponentially decreasing behavior in the \( nn \) center-of-mass system.

In the left-hand side panel of Figure 2 we display the center-of-mass bremsstrahlung-subtracted \( \gamma \)-ray multiplicity of the two reactions for fusion-evaporation events. The solid (dashed) lines represent the charge asymmetric \( ^{40}\text{Ca}+^{152}\text{Sm} \) (nearly charge symmetric \( ^{48}\text{Ca}+^{144}\text{Sm} \)) reaction. The difference between the data of the two reactions, shown in the right-hand side panel of the figure, evidences an excess of \( \gamma \)-rays in the more charge asymmetric reaction, concentrated in the energy range \( E_\gamma = 8-15 \text{ MeV} \). This excess can only be related to the DD excitation in the composite system of the \( ^{40}\text{Ca}+^{152}\text{Sm} \) reaction because of its larger charge asymmetry.

The DD \( \gamma \) spectrum in fusion-evaporation events is shown in Figure 2 (symbols in panel (b)) and can be reproduced well by means of a Lorentzian curve folded with the response function of the MEDEA apparatus \([28]\) (solid line), with the DD centroid energy \( E_{\text{DD}} = 11 \text{ MeV} \) and the width \( \Gamma_{\text{DD}} = 3.5 \text{ MeV} \). Since the DD centroid energy reflects the emitting source deformation, it is interesting to compare it with the centroid energy of the GDR, \( E_{\text{GDR}} \), obtained by means of a statistical model calculation. We notice that \( E_{\text{DD,exp}} \) is 3 MeV lower than \( E_{\text{GDR}} \), indicating a high deformation of the emitting source during the DD \( \gamma \) emission. This result is in excellent agreement with expectations for a dipole oscillation along the symmetry axis of a deformed dinucleus during the early moments of the reaction \([3, 4, 5, 19, 29, 30]\) and with previous experimental works on lighter systems \([10, 11, 13, 14, 19]\).

The DD \( \gamma \)-ray angular distribution provides important information, since it is a sensitive probe of the fusion dynamics and of the DD lifetime. Indeed, the amount of anisotropy, if present, is related to the interplay of the rotation angular velocity of the dinuclear system during the prompt DD emission and the instant at which this emission occurs \([6, 13, 14]\).

Panels (a) and (b) of Figure 3 display the fusion-evaporation \( \gamma \)-rays angular distribution with respect to the beam axis for the two reactions (a) and for their difference (b), integrated over energy from 9 to 15 MeV and...
corrected for the detection efficiency. The lines describe the angular distribution of the emitted $\gamma$-rays given by the Legendre polynomial expansion $M_\gamma(\theta, \phi) = M_0[I_0(1 - Q_2a_2P_2\cos(\theta))]$, where $a_2$ is the anisotropy coefficient and $Q_2$ is an attenuation factor for the finite $\gamma$-ray counter (0.98 in our case). From a best fit to the data, shown with a solid (dashed) line for the $^{40}\text{Ca}+^{152}\text{Sm}$ ($^{48}\text{Ca}+^{144}\text{Sm}$) reaction, we found $a_2 = -0.13 \pm 0.03$ for the $^{40}\text{Ca}+^{152}\text{Sm}$ reaction and $a_2 = -0.06 \pm 0.02$ for the $^{48}\text{Ca}+^{144}\text{Sm}$ one. By using the same argument as previously for the spectra, the observed difference in the $\gamma$-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 (a) and (b) 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 $a_2 = -0.04$ obtained within BNV calculations [4] 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, confirming the pre-equilibrium nature of this emission. This is in agreement with our previous results for evaporation events [13, 14] and with theoretical expectations [6].

By taking into account the DD $\gamma$-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 $(1.2 \pm 0.2) \times 10^{-3}$ [17]. The experimental results on the DD in $^{40}\text{Ca}+^{152}\text{Sm}$ reaction were compared with BNV calculations. 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. The results of the present work suggest that BNV calculations do not take into account some aspects of the reaction dynamics which could inhibit the pre-equilibrium $\gamma$-ray emission. An ingredient neglected in the present calculations is the deformation of the $^{152}\text{Sm}$ target ground state that could influence the DD excitation mechanism. Calculations are under way to evaluate this point.

### 3.2 Fission: preliminary results

As mentioned before, fission fragments were detected by two position-sensitive PPACs placed at $\theta = 52.5°$. From TOF and position information of the fragments, velocity vectors, masses and Total Kinetic Energy (TKE) in the laboratory and in the center-of-mass reference frame were obtained by using kinematical considerations. Moreover, an iterative procedure was done to compensate for the energy losses in the target, assuming that the reaction takes place at the middle of the target.

By applying appropriate conditions in the bidimensional plot ($\Delta E$, TOF) of the PPACs and selecting the same mass and TKE distributions for two coincident fission fragments, the observables of the two reactions can be compared properly.

As done in fusion-evaporation, the evaluation of the pre-equilibrium particle emission in coincidence with fission fragments demonstrated that the compound nucleus was formed in both reactions with the same average excitation energy and mass in fission events. From this analy-
sis, the pre-equilibrium particle emission was found to be lower than in evaporation channel, showing a dependence from the impact parameter [32].

γ-ray - fission events were selected with a triple coincidence between γ-rays detected by MEDEA detector and two fission fragments (selected with the already mentioned conditions) detected by the PPACs. The comparison of the fission γ-ray spectra of the two reactions showed that there is a γ-ray excess coming from the more charge asymmetric reaction, in the energy range Eγ = 8-15 MeV, but with a yield lower than the fusion-evaporation channel one. This preliminary outcome confirms the DD excitation also in fission events due to the entrance channel charge asymmetry effect but the reduced yield reflects the dependence on the impact parameter and, therefore, on the related reaction mechanism [8, 9].

A more accurate analysis is under way to compare these results and to investigate the impact parameter dependence of the pre-equilibrium emission in both light particles and γ-rays.

3.3 Conclusion

The present work allows to take a step forward in the study of superheavy element formation, demonstrating that the DD γ radiation, a possible cooling mechanism of the composite system along the fusion path, survives in heavy composite systems in fusion-evaporation channel. However, in order to predict evaporation residue cross sections by taking into account the isospin degree of freedom, an appropriate theoretical model is needed together with a large body of data of the DD energy- and angle-integrated multiplicity in composite systems formed under various reaction conditions.

Besides the superheavy element quest, we found that also in fission events the DD is excited with a lower yield. This preliminary observation, never observed before, provides inedited information on the DD excitation at higher partial waves.

The use of radioactive ion beams will offer the opportunity of very large entrance channel charge asymmetries, thus, maximizing the prompt dipole γ-ray and, therefore, will allow us to probe the density dependence of the symmetry energy in the Equation of State at nuclear densities lower than the saturation one, where the dynamical dipole mode is active [6].

References