Evolution of the prompt dipole γ-ray emission with incident energy in fusion reactions

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We investigated the prompt dipole γ-ray emission, related with entrance channel charge asymmetry effects, in the $^{32}S + ^{100}Mo$ and $^{36}S + ^{96}Mo$ fusion reactions at $E_{lab} = 196$ MeV and 214.2 MeV, respectively, with the aim to probe its evolution with incident energy. These reactions populate, through entrance channels having different charge asymmetries, the ^{132}Ce compound nucleus at an excitation energy of 117 MeV with identical spin distribution. Fusion events were selected by detecting high-energy γ rays in coincidence with evaporation residues. The center-of-mass differential γ-ray multiplicity spectra of the considered reactions were found to be identical within the experimental uncertainties in the whole energy range. This result, associated with that reported for the same reaction pair at higher beam energy where a larger giant dipole resonance yield was evidenced for the more charge asymmetric system, implies an increasing trend of the prompt dipole γ-ray emission with incident energy. Calculations based on a collective bremsstrahlung analysis of the reaction dynamics are presented and compared with the experimental findings.

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I. INTRODUCTION

In recent theoretical works [1–7] it was suggested that during the charge equilibration process taking place in the first stages of dissipative reactions between colliding ions with different N/Z ratios, a large amplitude dipole collective motion develops in the composite system, the so-called dynamical dipole mode. This collective dipole mode, gives rise to a prompt γ-ray emission that depends on the absolute value of charge that has to be shifted to restore the $(N_t + N_p)/(Z_t + Z_p)$ equilibrium ratio of the composite system, $N_t(N_p)$ and $Z_t(Z_p)$ being, respectively, the neutron and proton number of the target (projectile). Therefore, the prompt dipole γ-ray emission shows up in charge asymmetric collisions, in addition to the statistical one originating in the thermal excitation of the hot compound nuclei dipole vibration.

According to [4,6] this preequilibrium emission depends on the incident energy through its dependence on the initial isospin asymmetry, on the compound nucleus formation time, and on the giant dipole resonance (GDR) spreading width. It takes a maximum value in an appropriate energy region situated between the low incident energies near the Coulomb barrier and the higher ones near the Fermi energy domain, where it decreases.

As the prompt dipole γ-ray emission becomes comparable to the compound nucleus statistical emission under certain conditions, it could represent an interesting cooling mechanism to favor the formation of superheavy elements in hot fusion reactions. It is well known that the survival probability of these elements against fission is significantly affected by their excitation energy. The lowering of the compound nucleus excitation energy by ΔE ranging between 10 and 15 MeV (the energy approximately removed from the system with the emission of a preequilibrium dipole photon) results in an increase of its survival probability that can vary by a factor of 10 to 1000 [8]. In this respect, a systematic investigation of the prompt dipole γ-ray emission is of great interest, particularly when associated with the availability of exotic beams, which allow us to reach very large entrance channel charge asymmetries, maximizing thus this kind of emission.

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TABLE I. The percent increase of the intensity in the linearized γ-ray spectra at the compound nucleus GDR energy region for the more charge asymmetric system (the energy integration limits are given in the parenthesis), the compound nucleus excitation energy, the initial dipole moment $D(t=0)$, and the initial mass asymmetry Δ for each reaction.

Reaction	Increase (%)	E^*(MeV)	$D(t=0)$ (fm)	Δ	Reference
$^{40}Ca + ^{100}Mo$	16 (8,18)	71	22.1	0.15	[11]
$^{36}S + ^{104}Pd$		71	0.5	0.17	
$^{16}O + ^{98}Mo$	36 (8,20)	110	8.4	0.29	[12]
$^{48}Ti + ^{64}Ni$		110	5.2	0.05	
$^{32}S + ^{100}Mo$	1.6 ± 2.0 (8,21)	117	18.2	0.19	present
$^{36}S + ^{96}Mo$		117	1.7	0.16	work
$^{32}S + ^{100}Mo$	25 (8,21)	173.5	18.2	0.19	[13]
$^{36}S + ^{96}Mo$		173.5	1.7	0.16	

From an experimental point of view, various efforts have been devoted to verify the existence of entrance channel N/Z effects in the γ-ray emission during dissipative heavy-ion reactions. In these studies, the considered observable was the γ-ray multiplicity spectrum of the composite system, when formed at the same excitation energy and with identical spin distribution through different charge asymmetry entrance channels. In this way, data from inelastic [9,10] and fusion heavy-ion reactions [10–13] report an excess of dipole γ rays emitted during the more N/Z asymmetric reaction. This excess was related to the prompt dipole γ-ray emission predicted to take place during the charge equilibration process. To evaluate whether this emission depends on the incident energy, as predicted theoretically for fusion reactions, it was noticed in Ref. [13] that the existing data cannot be compared directly with each other as they concern results from reaction pairs at various incident energies but also have various initial dipole moment differences and various initial mass asymmetry differences. Then, many variables that influence the reaction dynamics and consequently the prompt dipole γ-ray emission change simultaneously. The proper way to investigate the incident energy dependence of the prompt dipole γ-ray emission is to study the same pair of reactions at different beam energies.

The first attempt toward this direction was undertaken in the present work, where the results concerning the reaction pair $^{32}S + ^{100}Mo$ and $^{36}S + ^{96}Mo$, at $E_{lab} = 196$ MeV and 214.2 MeV, respectively, are reported and compared with those of Ref. [13], where the same reaction pair was studied at higher incident energy. By studying the above reactions in this work the ^{132}Ce compound nucleus was formed through entrance channels having different charge asymmetries and thus different dipole moments [see Eq. (2)]. The initial dipole moment changes from 1.7 fm for the almost N/Z symmetric system $^{36}S + ^{96}Mo$ to 18.2 fm for the asymmetric one $^{32}S + ^{100}Mo$. The compound nucleus excitation energy in both reactions was equal to 117 MeV with the assumption of a nuclear reaction occuring at the center of the respective target. The chosen incident energies are the lowest ones that allow the critical angular momentum for fusion and for fusion-evaporation to be equal for both reactions with the values $L_{max} = 83\hbar$ and $L_{fus\text{-}evap} = 71\hbar$, respectively, according to PACE2 [14] calculations, avoiding thus, any difference in the compound nucleus spin distribution. There was only a small difference in the entrance channel mass asymmetry between the two reactions [see Eq. (3) and Table I]. However, as both systems were located above the critical curve in the fissility-mass asymmetry plane [15], dynamical effects influencing the compound nucleus statistical dipole γ-ray emission and associated with the initial mass asymmetry are negligible [16]. Therefore, as all the reaction parameters were kept identical, any difference in the γ-ray emission between the two reactions can be safely ascribed to the difference in the entrance channel charge asymmetry. As mentioned previously, the results of the present work can be directly compared with those obtained in Ref. [13] where the ^{132}Ce compound nucleus was formed at an excitation energy of 173.5 MeV. We remind that for this excitation energy an increase of the GDR γ-ray intensity of ~25% was found for the more charge asymmetric system in the bremsstrahlung-subtracted linearized spectra [13].

This article is organized as follows: in Sec. II the experimental techniques are reported. In Sec. III the center of mass differential γ-ray multiplicity spectra for fusion-evaporation events are presented. In the same section statistical model calculations are shown and the results of the present experiment along with those of previous works are discussed. In Sec. IV, theoretical analyses based on a collective bremsstrahlung approach are presented and compared with the experimental findings. Section V is devoted to the conclusions.

II. EXPERIMENT

The reactions were performed by using the pulsed beams of ^{32}S and ^{36}S provided by the heavy-ion 15 MV Tandem-XTU accelerator of the Laboratori Nazionali di Legnaro (Italy), impinging on 550 μg/cm^2 thick ^{100}Mo and ^{96}Mo self-supporting targets, isotopically enriched to 97.42 and 95.9%, respectively. The beam consisted of ~2 ns wide bunches with a 400 ns separation and it was measured in a Faraday cup shielded with lead and paraffin to reduce the background due to γ rays and neutrons. Beam current was about 10 nA.

The γ rays were detected by using six seven-pack clusters of BaF_2 scintillators situated at 28 cm from the target and at the following θ angles with respect to the beam direction:

70°, 90°, 110°, and 135°. The total solid angle covered by the BaF_2 detectors was 1.6 sr. The BaF_2 clusters were surrounded by a 3 mm thick lead shield that reduced the counting rate due to the low energy γ rays ($E_\gamma \leqslant 1$ MeV) to 50% and stopped the charged particles. The evaporation residues were detected by four position sensitive parallel plate avalanche counters (PPAC's) located symmetrically around the beam direction at 70 cm from the target. The PPAC's were centered at $\theta = 7°$ with respect to the beam direction, subtending 7° in θ. PACE2 calculations show that the evaporation residues of both reactions are distributed in an angular range up to 13° with a maximum at 4°. The total solid angle covered by the PPAC's was 0.089 sr. They provided the time of flight (TOF), the energy loss (ΔE), and the position of the reaction products.

The discrimination between γ rays and neutrons was performed by means of a measurement of their TOF relative to the beam burst.

The energy calibration of the γ-ray detectors was obtained by using the sources ^{60}Co, ^{88}Y, the composite source of $^{241}\mathrm{Am} + ^{9}\mathrm{Be}$, and the 15.1 MeV γ rays from the $p + ^{12}\mathrm{C}$ reaction. The time stability of the energy calibration was checked during the experiment by monitoring the stability of the peak corresponding to a radioactive source after each run.

Down-scaled single events together with coincidence events 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 cluster was greater than ~5 MeV. The threshold of each BaF_2 scintillator was set at ~100 keV. The coincidence request eliminated any cosmic ray contamination of the γ-ray spectra.

III. EXPERIMENTAL RESULTS

The fusion events were selected offline in the bidimensional plot of the ΔE versus the TOF of the reaction products detected in each PPAC. In Fig. 1 such a bidimensional plot for the $^{36}\mathrm{S} + ^{96}\mathrm{Mo}$ reaction is presented, where single and coincidence events with the BaF_2 scintillators are included. The stop of the TOF was given by the radiofrequency signal of the accelerator. A relative calibration of the reaction product TOF with respect to the one of the elastically scattered projectile was performed by using the fact that the beam bunches had a 400 ns separation.

In Fig. 1 the arrow at large TOF (left-hand side of the figure) corresponds to residues coming from fusion-evaporation, whereas the middle arrow at intermediate TOF indicates peripheral collision events and/or fission events. The arrow at small TOF (right-hand side of the figure) indicates events where the projectile was elastically scattered by the target. Even if the elastically scattered beam particles were discarded by the electronic threshold of the PPAC's because they were associated with very low ΔE signals, events coming from the pile-up of the ΔE signals remain in Fig. 1. Fortuitous coincidences within the same beam bunch can take place between an evaporation residue registered by the PPAC's and a γ ray originating in a peripheral reaction or fission event and detected by a BaF_2 scintillator or between an evaporation residue and a γ ray coming from different fusion-evaporation events. These coincidences that could influence the present

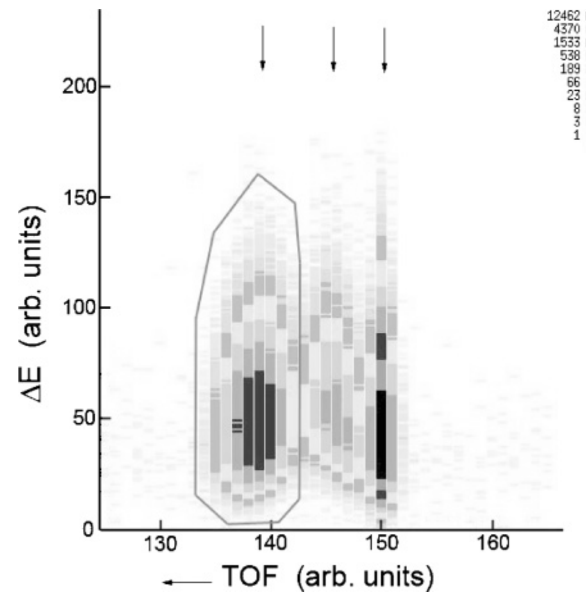

FIG. 1. Bidimensional spectrum of the energy loss (ΔE) of the reaction products detected in one of the PPAC's (single and coincidence events) for the $^{36}\mathrm{S} + ^{96}\mathrm{Mo}$ reaction as a function of their time of flight (TOF). The arrows indicate reaction mechanisms described in the text.

analysis, are estimated to be less than ~1% of the real coincidences and cannot be discarded. In this analysis only the fusion events included in the contour shown in Fig. 1 were retained.

At the present beam energies, the incomplete fusion cross section should be small, representing no more than 15% of the total fusion cross section [17]. This kind of events cannot be discarded in the TOF spectrum of the reaction products because they have overlapping velocity distributions with those of the complete fusion reactions [18]. In incomplete fusion events the emission of preequilibrium light particles lowers the excitation energy, the mass and the charge of the compound nucleus. It has been seen, in inclusive particle measurements over a wide range of bombarding energies and target-projectile combinations, that the preequilibrium particle emission is insensitive to the details of target and projectile nuclei and that a scaling of the preequilibrium particle multiplicity with the bombarding energy above the Coulomb barrier can be assumed (see Ref. [18] and references therein). In this hypothesis, the average excitation energy loss resulting from preequilibrium particle emission is found to be approximately 0 for both reactions by using the empirical relation given in Ref. [19]. Thus we can consider that, on average, for the present incident energies there is no loss of excitation energy, of mass and of charge in the creation of the compound nucleus.

The differential γ-ray multiplicity spectrum of each BaF_2 cluster was reconstructed by summing the energy deposited in each detector. If the fired detectors were isolated or if they formed small clusters located far from one another we assumed that one γ ray of the cascade was detected in each isolated detector or in each small cluster and the energy of each γ ray was reconstructed. The differential γ-ray multiplicity obtained with all of the BaF_2 detectors in coincidence with

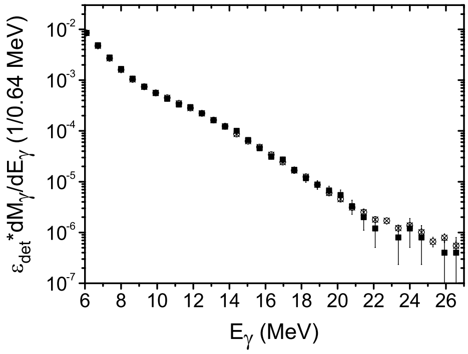

FIG. 2. Experimental γ-ray multiplicity spectrum of the $^{32}S + ^{100}Mo$ (squares) and of the $^{36}S + ^{96}Mo$ (circles) reaction for fusion events and for all of the BaF_2 scintillators in the center-of-mass frame.

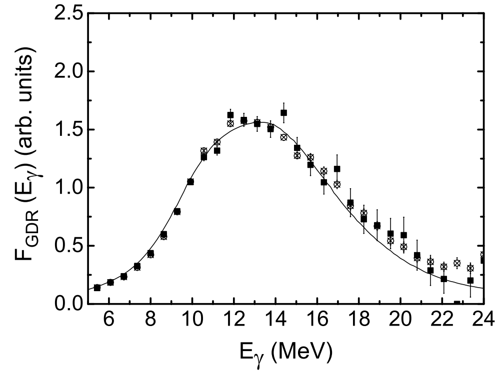

FIG. 3. Center-of-mass linearized data of the $^{32}S + ^{100}Mo$ (squares) and $^{36}S + ^{96}Mo$ (circles) reaction. The solid line is a linearized theoretical γ-ray spectrum calculated with the CASCADE code. The data as well as the theoretical spectrum were divided by the same constant strength function.

evaporation residues, in the center-of-mass reference frame, is plotted in Fig. 2. The Doppler shift correction was made by assuming emission from a source moving with the center-of-mass velocity. The squares and the circles correspond to the $^{32}S + ^{100}Mo$ and the $^{36}S + ^{96}Mo$ reactions, respectively. The spectra were integrated in 4π by assuming an isotropic emission in the center-of-mass frame.

Different mechanisms may feed the γ-ray spectra at E_γ greater than 20 MeV, the nucleon-nucleon bremsstrahlung mechanism being the dominant one [20]. At the present incident energies this contribution to the spectra can be neglected.

From Fig. 2, one can see that the γ-ray multiplicity is identical for both reactions within the experimental uncertainties in the whole energy range.

To emphasize the details in the GDR energy region, a linearization procedure of the experimental γ-ray spectra was performed. In this way, the exponential behavior due to the nuclear level density is eliminated from the data. The γ-ray spectra associated with the two reactions (Fig. 2) were linearized by dividing them by the same theoretical γ-ray spectrum, calculated with the CASCADE code [21], where a constant dipole strength and a level density parameter $a = A/8\,\mathrm{MeV}^{-1}$ were considered. Moreover, the constant strength theoretical γ-ray spectrum was folded by the experimental setup response function by using the GEANT code [22]. The linearized data of the $^{32}S + ^{100}Mo$ ($^{36}S + ^{96}Mo$) reaction are displayed by the squares (circles) in Fig. 3. The solid line in the same figure corresponds to a linearized theoretical γ-ray spectrum obtained with the CASCADE code and folded by the experimental setup response function. In this calculation the level density parameter was $a = A/8\,\mathrm{MeV}^{-1}$, whereas the dipole strength function was taken as a Lorentzian function with centroid $E_{\mathrm{GDR}} = (14.3 \pm 0.2)$ MeV, width $\Gamma_{\mathrm{GDR}} = (10 \pm 0.5)$ MeV and strength $S_{\mathrm{GDR}} = (1 \pm 0.1)$ of the energy-weighted sum rule.

Also from Fig. 3 it can be seen that there is no difference between the linearized data of the two reactions within the error bars.

The result of the present work is different from that obtained at higher beam energy for the same reaction pair [13], where an increase of the GDR γ-ray intensity of $\sim$25% was found for the more charge asymmetric system in the bremsstrahlung-subtracted linearized spectra. To our knowledge, this is the first experiment where the evolution of the prompt dipole γ-ray emission with incident energy can be seen clearly. For the studied reaction pair and for the investigated energy region, it presents an increasing trend with incident energy.

For completeness, we cite in Table I all the experiments where fusion reactions were investigated. The first column of the table shows the different reaction pairs, the second column presents the percent increase of the intensity in the linearized γ-ray spectra at the compound nucleus GDR energy region for the more charge asymmetric system. The percent increase can be written as follows:

$$Increase(\%) = \frac{a-b}{b} \times 100, \qquad (1)$$

with a and b equal to the following integral: $\int_{E_1}^{E_2} F_{\mathrm{GDR}}(E_\gamma)dE_\gamma$ for the reaction with the larger and smaller entrance channel charge asymmetry, respectively. The energy integration limits are shown in parenthesis in Table I. E^* in the third column of Table I corresponds to the compound nucleus excitation energy; $D(t=0)$ is the initial dipole moment for each reaction given by the following relation:

$$\begin{aligned} D(t=0) &= \frac{NZ}{A}\,|R_Z(t=0) - R_N(t=0)| \\ &= \frac{r_0\left(A_p^{1/3} + A_t^{1/3}\right)}{A} Z_p Z_t \left|\left(\frac{N_t}{Z_t}\right) - \left(\frac{N_p}{Z_p}\right)\right|, \end{aligned} \qquad (2)$$

where R_Z and R_N are the center-of-mass coordinates of protons and of neutrons, respectively. $A = A_p + A_t$ is the mass of the composite system, $N = N_p + N_t$ ($Z = Z_p + Z_t$) its neutron (proton) number, whereas the indices p and t refer to the projectile and target, respectively. To obtain the $D(t=0)$ values of Table I, $r_0 = 1.2$ fm was used.

The fifth column of Table I shows the initial mass asymmetry Δ of the corresponding reaction:

$$\Delta = \frac{R_t - R_p}{R_t + R_p}, \qquad (3)$$

with R_t and R_p the target and projectile radii.

From Table I we see that the extra dipole radiation is only partially related to the larger value of the initial dipole moment. The difference in mass asymmetry is also playing an important role (e.g., see the different "increase" in the systems listed in the first two rows) . We note the larger extra dipole γ yield in the case of Ref. [12], where in fact we have a smaller difference in the initial dipole moments *but* a much larger difference in mass asymmetries. This is a clear indication of the effect of the fusion dynamics. A faster fusion process, for the collision with the larger mass asymmetry, will imply a faster start up of a collective dipole mode in the dinuclear system. Thus, we will have a relatively large dipole amplitude, not much reduced with respect to the initial value $D(t=0)$. This mechanism, that in fact is also behind the increase of the dynamical dipole contribution with increasing incident energy discussed here, is shown in detail from the calculations of the next section.

IV. CALCULATIONS

To understand the origin of the observed experimental differences for the $^{32}S + ^{100}Mo$ and $^{36}S + ^{96}Mo$ reaction pair we compared the dynamical dipole mode in the entrance channel for the considered systems at incident energy of 6 and 9 MeV/nucleon in the framework of a BNV transport model [4].

Within this model, the dynamics of dissipative reactions is described in a microscopic approach based on semiclassical transport equations where mean field and two-body collisions are treated in a self-consistent way (see details in Ref. [3]). Realistic effective interactions of Skyrme type are used. The numerical accuracy of the transport code has been largely improved to have reliable results also at low energies, just above the threshold for fusion reactions [3,4,23]. The resulting physical picture is in good agreement with quantum Time-Dependent Hartree-Fock calculations [5]. In particular, we studied in detail how a collective dipole oscillation develops in the entrance channel [4].

First, during the *approaching phase*, the two partners, overcoming the Coulomb barrier, still keep their own response. Then follows a *dinuclear phase* when the conversion of relative motion energy in thermal motion starts to take place, mainly because of nucleon exchange. The composite system is not thermally equilibrated and manifests, as a whole, a large amplitude dipole collective motion. Finally, during the third phase, a thermally equilibrated nucleus is formed, *the compound nucleus*, with consequent statistical particle/radiation emission.

In the second *(dinuclear)* phase, preequilibrium collective dipole radiation can be emitted. We can directly apply a bremsstrahlung *("bremss")* approach to estimate this contribution [6] [24].

The total photon emission probability from the dipole mode oscillations, as given by the bremsstrahlung formula, can be expressed as follows ($E_\gamma = \hbar\omega$)

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 |X''(\omega)|^2, \qquad (4)$$

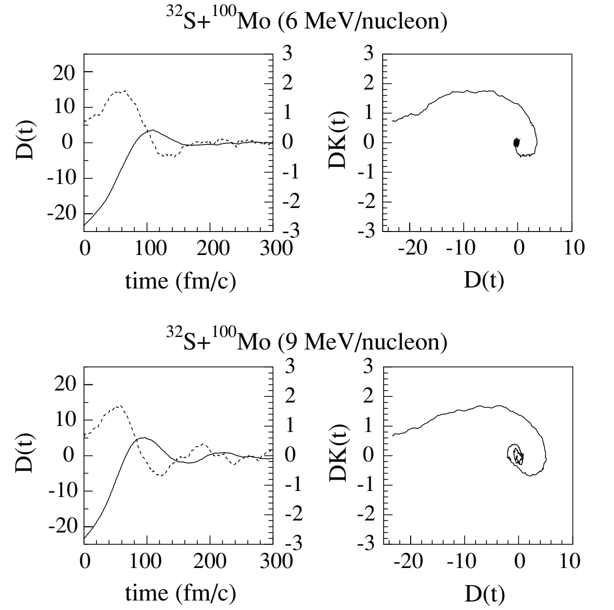

FIG. 4. The time evolution of the dipole mode in r-space $D(t)$ (solid lines, in fm units) and p-space $DK(t)$ (dashed lines, in fm^{-1}) and the correlation $DK(t)$ *vs* $D(t)$ at incident energy of 6 and 9 MeV/nucleon for $b = 2$ fm.

where $X''(\omega)$ is the Fourier transform of the acceleration $X''(t)$ associated with the distance between the centers-of-mass of protons (Z) and neutrons (N), $X = R_Z - R_N$. $A = N + Z$ is the composite system mass. Thus following the time evolution of the dipole mode along the fusion dynamics it is possible to evaluate, in absolute values, the corresponding preequilibrium photon emission probability [6].

In our simulations the preequilibrium dipole photon emission probability for the almost charge symmetric system $^{36}S + ^{96}Mo$ was found to be so small than it can be neglected. Therefore, here we focus our study on the results concerning the N/Z asymmetric reaction $^{32}S + ^{100}Mo$. In Fig. 4 (left-hand side column) we draw for the impact parameter $b = 2$ fm the time evolution of the dipole moment in the r-space (solid lines), $D(t) = \frac{NZ}{A}X(t)$, and in the p-space (dashed lines), $DK(t) = \Pi(t)/\hbar$, where $\Pi = \frac{NZ}{A}(\frac{P_Z}{Z} - \frac{P_N}{N})$, with P_Z (P_N) the center-of-mass in momentum space for protons (neutrons), is just the canonically conjugate momentum of the X coordinate, see [4,6]. On the right-hand side column of Fig. 4, the corresponding correlation $DK(t)$ *vs* $D(t)$ in the phase space for $b = 2$ fm is shown as well. We choose the origin of time at the beginning of the *dinuclear* phase (touching configuration). The "spiral-correlation" in the right-hand side column of the figure denotes the collective nature of the mode. In fact, it corresponds to a "coherent" out-of-phase oscillation of the two dipoles, in r and p-space, in presence of some damping [5,6]. When the center of the spiral curve is reached, charge equilibration is finally achieved. The spiraling trend starts when the collective dipole response of the system is triggered. That occurs with some delay with respect to the touching configuration ($t = 0$), necessary for the creation of the dinuclear mean field and depending on the reaction dynamics. The collective dipole response starts at $t \sim 30$ fm/c for

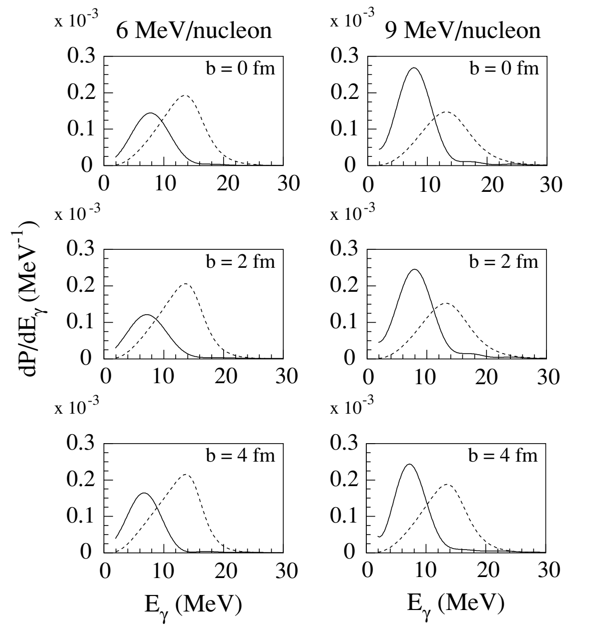

FIG. 5. The bremsstrahlung spectra for the $^{32}S + ^{100}Mo$ system at incident energy of 6 and 9 MeV/nucleon (solid line) and the first step statistical spectrum (dashed line) for three impact parameters.

6 MeV/nucleon, whereas it starts earlier, at $t \sim 20$ fm/c, for 9 MeV/nucleon. We note from the Fig. 4 (left-hand side column) that at the start up of the collective dipole response, the absolute value of $D(t)$ is already reduced with respect to the geometrical value at the touching point, $D(t = 0)$, because meanwhile some charge equilibration has taken place through incoherent exchange of nucleons. This is the reason why the dinucleus dipole yield is not simply given by the "static" estimation, being largely influenced by the reaction dynamics. This point is further discussed at the end of the section.

From the bremsstrahlung formula [Eq. (4)] we can deduce the photon emission probability from the preequilibrium dipole mode. The corresponding bremsstrahlung spectra obtained at the two incident energies are compared in Fig. 5 for impact parameters $b = 0, 2,$ and 4 fm (solid lines). An enhanced emission at higher energy is evident. In all cases, as a reference, the first step statistical spectrum (dashed line) [6] is also included. The latter is just the product of the statistical γ-decay rate, times the mean life time of the equilibrated source.

The total contribution from the dynamical dipole mode is calculated by integrating over the energy in the resonance region for each impact parameter and summing over the impact parameters leading to fusion with the corresponding geometrical weights. The γ-ray multiplicity obtained in this way for the preequilibrium dipole mode is 1.03×10^{-3} $\gamma/$*fusion* and 1.75×10^{-3} $\gamma/$*fusion* for incident energy of 6 and 9 MeV/nucleon, respectively. The theoretical ratio $C_{\rm th}$ of total preequilibrium to total statistical GDR γ-ray multiplicity, the latter calculated by means of the CASCADE code and integrated between 8 and 21 MeV, can be compared to the corresponding experimental quantity, $C_{\rm exp} = (c - d)/d$ with c and d equal to the following integral: $\int_8^{21} (\varepsilon_{\rm det} * dM_\gamma/dE_\gamma)\, dE_\gamma$, for the $^{32}S + ^{100}Mo$ and $^{36}S + ^{96}Mo$ reaction, respectively. $\varepsilon_{\rm det}$ appearing in the integral is the energy dependent efficiency of the experimental apparatus.

The theoretical value, $C_{\rm th}$, varies from 0.04 (6 MeV/nucleon) to 0.08 (9 MeV/nucleon), in reasonable agreement with the experimental one, $C_{\rm exp}$, which varies from 0.015 ± 0.020 (present study) to 0.13 (from data of Ref. [13]). The given uncertainties on the values of both the $C_{\rm exp}$ and the percent increase (see Table I) are of statistical nature.

Therefore, a clear energy dependence of the dynamical dipole contribution is evidenced theoretically: the increase is almost 100% passing from 6 to 9 MeV/nucleon. A possible explanation of this effect relies on the difference in the fusion dynamics, as already noted in the comments to the Table I at the end of the previous section and when describing Fig. 4. At lower incident energy we have a slower fusion process, as can be seen in Fig. 6 where the neck dynamics density plots projected on the reaction plane at 6 and 9 MeV/nucleon are reported. The collective dipole oscillations in the dinuclear

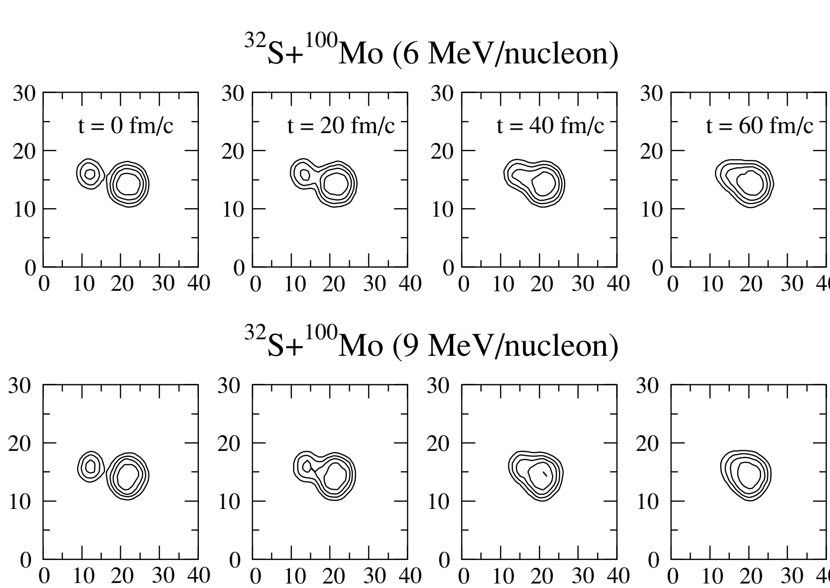

FIG. 6. Density plots of the neck dynamics for the $^{32}S + ^{100}Mo$ system at incident energy of 6 and 9 MeV/nucleon. Projections on the reaction plane: the abscissa represents the beam axis (units in fm).

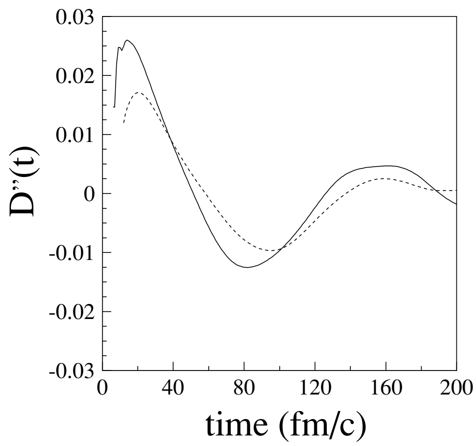

FIG. 7. Time evolution of the dipole acceleration $D''(t)$ (in c^2/fm) in the entrance channel for the $^{32}S + ^{100}Mo$ system at incident energy of 6 MeV/nucleon (dashed line) and 9 MeV/nucleon (solid line) for $b = 2$ fm.

system are allowed to develop once the neck between the colliding nuclei becomes wide enough to make possible the "organization" of a dinuclear mean field. Then, the presence and persistence of a narrow neck for a longer period at 6 MeV/nucleon, delays the start up of the isovector collective response which occurs at $t \sim 30$ fm/c, when some charge equilibration has already taken place through incoherent nucleon exchange. That leads to a reduced dipole moment amplitude $D(t)$ with respect to the initial value $D(t = 0)$ at the touching configuration and, thus, to a reduced collective dipole response (see the less persistent oscillations in the left-hand side column of Fig. 4). As a consequence, at lower incident energy we get a reduced amplitude for the dipole acceleration, with a corresponding smaller bremsstrahlung radiative emission [see Eq. (4)]. On the contrary, at higher beam energy, a faster disappearence of the neck leads to physical conditions that favor an early and complete collective isovector response (we remind its start up at $t \sim 20$ fm/c). The time evolution of the dipole acceleration at the two energies, reported in Fig. 7, supports this scenario. We see that at 9 MeV/nucleon this quantity presents a larger amplitude (solid line) in the early stage of the reaction, which will also lead to more persistent dipole oscillations. Both effects contribute to the enhancement of the total bremsstrahlung yield for the higher incident energy.

V. CONCLUSIONS

The prompt dipole γ-ray emission, occuring in fusion reactions and related with charge asymmetry effects in the entrance channel, could represent a new cooling mechanism of the composite system. The first step to maximize this kind of emission is the use of suitable reactions having large charge asymmetry between the colliding ions. Moreover, for a given charge asymmetry, entrance channels with large mass asymmetry should be preferred to mass symmetric ones as they are associated with a faster reaction dynamics and consequently with a larger preequilibrium dipole emission. Finally, according to recent theoretical predictions [4,6], another parameter affecting the prompt dipole γ-ray emission is the incident energy.

The present work was motivated mainly by the above predictions and by the lack of any associated experimental evidence. In this respect we presented an investigation of the prompt dipole γ-ray emission evolution with incident energy by studying the fusion reactions $^{32}S + ^{100}Mo$ and $^{36}S + ^{96}Mo$ at $E_{\text{lab}} = 196$ MeV and 214.2 MeV, respectively. In the above reactions the ^{132}Ce compound nucleus was formed with identical spin distribution at the same excitation energy of 117 MeV from different charge asymmetry entrance channels. The center-of-mass differential γ-ray multiplicity spectra associated with the two reactions were found to be identical within the experimental uncertainties in the entire energy range. The same conclusion is drawn also by looking at the respective linearized spectra where the details in the GDR region are clearly seen. The present result can be directly compared with that obtained in Ref. [13] for the same reaction pair at higher incident energy. Although in that work an increase of the GDR γ-ray intensity of $\sim 25\%$ was found for the more charge asymmetric system in the bremsstrahlung-subtracted linearized spectra, at the present incident energy no difference was seen between the data. Thus, it is shown that for the studied reaction pair and for the investigated energy region, the prompt dipole γ-ray emission presents an increasing trend with incident energy.

Calculations performed within the BNV transport model framework and based on a collective bremsstrahlung approach predict a lower dynamical dipole yield at lower incident energy related to a slower neck dynamics that obstructs a full collective response. The variation of the theoretical ratio of the total preequilibrium to the total statistical GDR γ-ray multiplicity with incident energy is found to be in good agreement with that of the corresponding experimental ratio of the total extra dipole γ-ray multiplicity from the N/Z asymmetric system to the total statistical GDR γ-ray multiplicity associated with the N/Z symmetric one.

To map the behavior of the prompt dipole γ-ray emission in the whole incident energy region the present study should be extended for the same reaction pair to incident energies larger than those of Ref. [13]. From a theoretical point of view we expect a "rise and fall" of the fast dipole radiation with the beam energy (see also Ref. [6]). At low energies, just above the fusion threshold, the fusion dynamics is very slow and the collective dipole mode of the dinuclear mean field will start when the initial dipole amplitude is much reduced via incoherent nucleon exchange. At high beam energies, above (15–20) MeV/nucleon, the extra dipole radiation is expected to be hindered by a faster damping of the dinuclear collective dipole mode and by a larger preequilibrium neutron emission from the most neutron-rich partner that will reduce the initial dipole amplitude of the dinuclear system.

As a fast cooling mechanism on the fusion path, the prompt dipole radiation could be also of interest for the synthesis of superheavy elements. We remind the competition between hot fusion (larger compound nucleus formation probability) *vs* cold fusion (larger compound nucleus survival probability) production mechanisms. The entrance channel charge asymmetry could provide a way to cool down the hot fusion paths, so ending up with a larger survival probability. The present work shows that the prompt dipole radiation yield decreases at low incident energies, thus becoming less important in the typical bombarding energy range for the superheavy element formation through hot fusion reactions. However, to draw reliable conclusions about this point, the evolution of the prompt dipole radiation with beam energy should also be explored for compound nuclei heavier than the one of our work, as in that case projectile-target combinations with larger charge and mass asymmetries can be used which might result in a significant preequilibrium dipole yield also at low beam energies.

The search of suitable reactions and incident energy domains that maximize the prompt dipole γ-ray emission is a very interesting field of research and it can be further pursued by making use of the available radioactive beams. However, experiments induced by such beams suffer from low statistics, thus very powerful detection systems are required to ensure the appropriate accuracy for this kind of exclusive measurements.

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