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Prompt dipole γ-ray emission in fusionlike heavy-ion reactions

D. Pierroutsakou[1,a], A. Boiano[1], A. De Rosa[1,2], M. Di Pietro[1], G. Inglima[1,2], M. La Commara[1,2], Ruhan Ming[3,4], B. Martin[1,2], R. Mordente[1], A. Ordine[1], F. Rizzo[5,6], V. Roca[1,2], M. Romoli[1], M. Sandoli[1,2], F. Soramel[7,8], L. Stroe[9], M. Trotta[1,2,b], and E. Vardaci[1,2]

[1] INFN, Sezione di Napoli, Napoli, Italy
[2] Università di Napoli "Federico II", Dipartimento di Scienze Fisiche, Napoli, Italy
[3] China Institute of Atomic Energy, Beijing, PRC
[4] INFN, Laboratori Nazionali di Legnaro, Padova, Italy
[5] Università di Catania, Dipartimento di Fisica, Catania, Italy
[6] INFN, Laboratorio Nazionale del Sud, Catania, Italy
[7] Università di Udine, Dipartimento di Fisica, Udine, Italy
[8] INFN, Sezione di Udine, Udine, Italy
[9] NIPNE, Bucharest, Romania

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Abstract. The $^{32}S + ^{100}Mo$ and $^{36}S + ^{96}Mo$ fusionlike reactions were studied at incident energy of $E_{\rm lab} =$ 298 MeV and 320 MeV, respectively, with the aim of probing the influence of the entrance channel charge asymmetry on the dipole γ-ray emission. The excitation energy and spin distribution of the compound nucleus created in these reactions were identical, the only difference being associated with the unequal charge asymmetry of the two entrance channels. High-energy γ-rays were detected in an array of 9 seven-pack BaF_2 clusters. Coincidence with fusionlike residues detected in four PPAC ensured the selection of central reaction events. By studying the differential γ-ray multiplicity associated with the two reactions it was shown that the dipole strength excited in the compound nucleus increases with the entrance channel charge asymmetry. From the linearized spectra, the increase of the GDR γ-ray intensity was found to be $\sim 25\%$ for the more charge asymmetric system. The results are discussed and compared with those of previous data obtained at different incident energies.

PACS. 25.70.-z Low and intermediate energy heavy-ion reactions – 24.30.Cz Giant resonances – 23.20.-g Electromagnetic transitions – 25.70.Gh Compound nucleus

1 Introduction

During the very early stages of heavy-ion collisions when the charge equilibration takes place between colliding ions with different N/Z ratios, a collective dipole motion between protons and neutrons is excited giving rise to a prompt dipole γ-ray emission. Due to that process, it was suggested [1–7] that the dipole γ-ray emission in heavy-ion reactions should depend on the N/Z ratio of the colliding ions.

Since the prompt dipole γ-ray emission occurs when the composite system is still far from equilibrium, it is expected to be concentrated at energies lower than the ones corresponding to the dipole γ-rays coming from the thermal excitation of the dipole strength [2,5–8].

Experimentally, various works [9–11] investigated the pre-equilibrium dipole γ-ray emission in N/Z asymmetric deep-inelastic heavy-ion collisions, where it was shown that dipole γ-rays are emitted not only during the statistical decay of the complex fragments, but also from the very deformed composite system before fragmentation.

Indications of a pre-equilibrium dipole γ-ray emission can be found in incomplete fusion reactions for events where α-particles were detected at forward angles in coincidence with γ-rays [12].

A powerful method for investigating the entrance channel charge asymmetry influence on the dipole γ-ray emission is to study and to compare the γ-ray energy spectra associated with heavy-ion reactions where the same composite system is formed from entrance channels having

[a] e-mail: pierroutsakou@na.infn.it
[b] *Present address:* INFN, Laboratori Nazionali di Legnaro, Padova, Italy.

different charge asymmetry. In this way, in refs. [13,14] an excess of dipole γ-rays emitted during the more N/Z asymmetric reaction was observed for fusion events at a compound nucleus excitation energy of 71 and 110 MeV, respectively. In ref. [15] the same effect was observed for deep-inelastic events but no such effect was seen for fast quasi-elastic collisions. As there was no reason to consider an inhibition of the composite system dipole strength in the more charge symmetric reactions of the previously mentioned works, the observed effect was attributed to an enhancement of the dipole strength excited in the more charge asymmetric reactions and it can be considered as a signature of the prompt dipole γ-ray emission. Therefore, it seems that the prompt dipole γ-ray emission occurs in all of the N/Z asymmetric dissipative heavy-ion collisions from fusion to deep-inelastic, although showing a decreasing trend with the centrality of the collision.

Recently, a dependence of the prompt dipole γ-ray emission on the incident energy was predicted and an appropriate region of incident energies, where this emission becomes stronger, was evidenced for fusion reactions [4,6].

In order to probe the N/Z effect on the dipole γ-ray emission in fusionlike reactions for a higher compound nucleus excitation energy than that of previous data, two systems were studied: ^{32}S + ^{100}Mo and ^{36}S + ^{96}Mo at $E_{\text{lab}} = 298$ and 320 MeV, respectively. All the relevant reaction parameters were kept constant, while the initial dipole moment changed 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 excitation energy of the ^{132}Ce compound nucleus created in both reactions was equal to 196 MeV. By taking into account the energy loss of the beams in the respective targets the compound nucleus excitation energy decreases to 194 MeV by assuming that the nuclear reaction occurs at the center of the target for both reactions. For the above calculation no pre-equilibrium light particle emission was taken into account. The critical angular momentum for fusion is $L_{\max} = 83\hbar$ according to PACE2 [16] calculations and the maximum angular momentum for fusion-evaporation is $L_{\text{fus-evap}} = 72\hbar$. The initial mass asymmetry in these reactions is very similar (see sect. 4), equal to 0.19 and 0.16 for the ^{32}S + ^{100}Mo and the ^{36}S + ^{96}Mo reaction, respectively. In addition, both systems are located above the critical curve in the fissility-mass aymmetry plane [17]; therefore effects associated with the mass asymmetry should be negligible.

Preliminary results concerning a part of the collected statistics during the above reactions were published in [18].

The present paper is organized as following: in sect. 2 the experimental techniques are discussed, in sect. 3 the differential γ-ray multiplicities in coincidence with fusionlike residues are presented. In sect. 4, statistical model calculations are performed for the more N/Z symmetric reaction and the results of the present experiment are discussed and compared with those of other works obtained at different incident energies. Finally the conclusions are drawn in sect. 5.

2 Experimental techniques

The reactions were performed by using the pulsed beams of ^{32}S and ^{36}S provided by the superconducting heavy-ion linear accelerator of the Laboratori Nazionali di Legnaro (Italy), impinging on 750 μg/cm^2 thick ^{100}Mo and ^{96}Mo self-supporting targets. The beam consisted of ~ 2 ns wide bunches with a 200 ns separation. The beam intensity was measured in a Faraday cup shielded with lead and paraffin to reduce the background due to γ-rays and neutrons.

The γ-rays were detected by using 9 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 taken to coincide with the Oz-axis: 70°, 90°, 115°, 125°, 135° and 155°. The total solid angle covered by the BaF_2 detectors was 2.39 sr. The BaF_2 clusters were surrounded by a 3 mm thick lead shield which reduced the counting rate due to the low-enegy γ-rays ($E_\gamma \leq 1$ MeV) to 50% and stopped the charged particles. The fusionlike residues were detected by 4 position-sensitive PPAC detectors located symmetrically around the beam direction at 70 cm from the target. The PPAC were centered at $\theta = 7°$ subtending 7° in θ. PACE2 calculations show that the fusion residues of both reactions are distributed in an angular range up to 15° with a maximum at 4.5°. The total solid angle covered by the PPAC was 0.089 sr. They provided the time of flight, the energy loss and the position of the particles.

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

The energy calibration of the γ-ray detectors was obtained by using the sources ^{60}Co, ^{88}Y and the composite sources of ^{241}Am + ^{9}Be and of ^{238}Pu + ^{13}C. The time stability of the energy calibration was checked during the experiment by monitoring the stability of the peak corresponding to a radioactive source.

Divided 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 ~ 6 MeV and for some runs of the ^{36}S + ^{96}Mo reaction greater than ~ 7 MeV. The threshold of the BaF_2 scintillators was set at ~ 100 keV. The coincidence request eliminated any cosmic-ray contamination of the γ-ray spectra.

3 Data analysis and results

In fig. 1 a bidimensional plot of the energy loss *versus* the time of flight (TOF) of the particles detected in one of the PPAC for the ^{32}S + ^{100}Mo reaction is presented. In the figure, both 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 considering the fact that the beam bunches had a 200 ns separation. In fig. 1 the arrow at large TOF

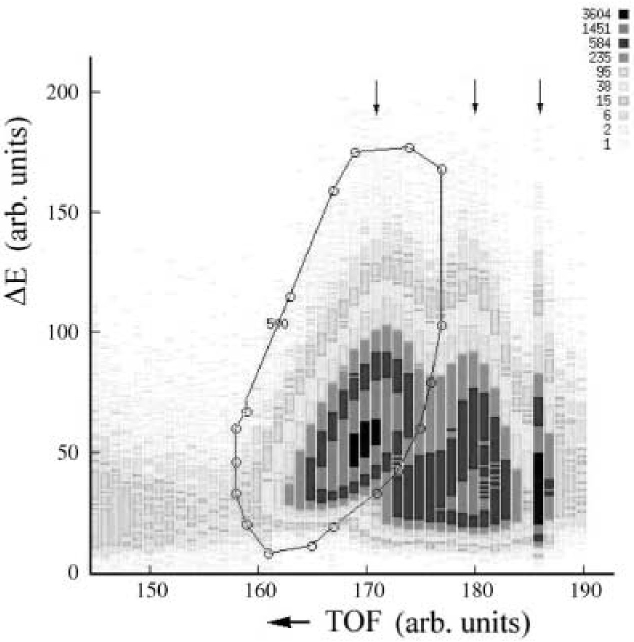

Fig. 1. Bidimensional spectrum of the energy loss ΔE of the particles detected in one of the PPAC (single and coincidence events) for the $^{32}S + {}^{100}Mo$ reaction as a function of the time of flight (TOF). The arrows indicate the reaction mechanisms described in the text.

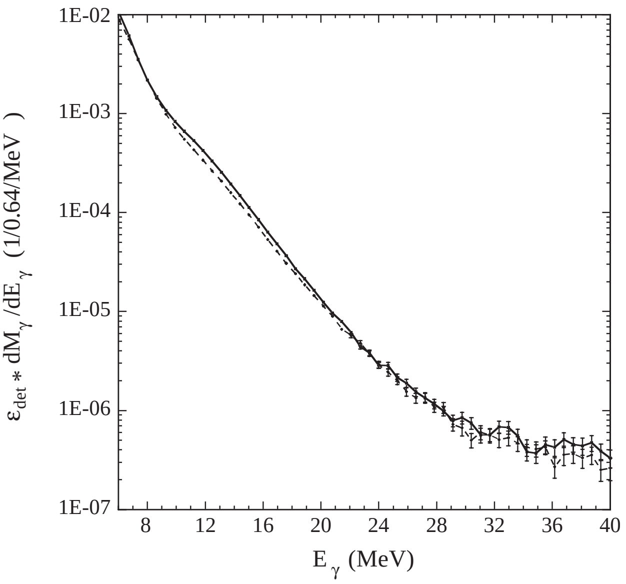

Fig. 2. Experimental γ-ray spectrum of the $^{32}S + {}^{100}Mo$ (solid line) and of the $^{36}S + {}^{96}Mo$ (dashed line) reaction for fusionlike events and for all of the BaF_2 scintillators in the center-of-mass frame.

and large energy losses (left hand side of the figure) corresponds to residues coming from complete fusion, while the middle arrow at intermediate TOF and smaller energy losses indicates peripheral collision events. The arrow at small TOF (right hand side of the figure) indicates events where the projectile was elastically scattered by the target. Notice that, the elastically scattered beam particles were discarded by the electronic threshold of the PPAC since they were associated with very low energy loss signals, however, some events coming from the pile-up of the ΔE signals are still present in fig. 1. In this analysis only the fusionlike events included in the contour of fig. 1 were retained. Fortuitous coincidences within the same beam bunch can take place between a fusionlike residue registered by the PPAC and a γ-ray originating in a peripheral reaction event and detected by a BaF_2 scintillator, or between a fusionlike residue and a γ-ray coming from different fusionlike events. These coincidences, which could influence the present analysis, are estimated to be $\sim 1\%$ of the real coincidences and cannot be discarded.

At the present beam energies, the incomplete fusion cross-section represents about 25%–30% of the total fusion cross-section [19]. The incomplete fusion events cannot be discarded in the time of flight spectrum because they have overlapping velocity distributions with those of the complete fusion reactions [20].

In the analysis, the differential γ-ray multiplicity spectrum of each BaF_2 scintillator was considered separately. The differential γ-ray multiplicity obtained with all of the BaF_2 detectors in coincidence with fusionlike residues, in the center-of-mass reference frame, is plotted in fig. 2. The solid and the dashed line correspond to the $^{32}S + {}^{100}Mo$ and the $^{36}S + {}^{96}Mo$ reaction, respectively. The spectra were integrated in 4π by assuming isotropic emission in the center-of-mass frame. $\varepsilon_{\rm det}$ is the energy-dependent efficiency of the experimental apparatus. From this figure, one can see that the γ-ray multiplicity related with the ^{32}S-induced reaction is clearly larger than that of the ^{36}S-induced one in the energy region $E_\gamma = 9$–21 MeV.

The γ-ray spectra at E_γ greater than 20 MeV are mainly feeded by the nucleon-nucleon Bremsstrahlung mechanism [21] which can be reproduced in the nucleon-nucleon center-of-mass frame by an exponential function. To evaluate the contribution of this process in the spectra, only the data obtained with the scintillators situated at $\theta = 90°$ with respect to the beam direction, where the Doppler effect is negligible, were considered. Then, the experimental differential γ-ray multiplicity spectra of the two reactions were fitted from 30 to 40 MeV with an exponential function. The inverse slope of the spectra was found to be $E_0 = (7.4 \pm 1.6)$ MeV and $E_0 = (6.6 \pm 1.7)$ MeV for the $^{32}S + {}^{100}Mo$ and the $^{36}S + {}^{96}Mo$ reaction, respectively, in good agreement with the systematics for Bremsstrahlung spectra. In fig. 3 are reported the data at $\theta = 90°$ together with the associated bremsstrahlung contribution, shown by the solid ($^{32}S + {}^{100}Mo$) and the dashed ($^{36}S + {}^{96}Mo$) lines.

The spectra at $\theta = 90°$, resulting after the subtraction of the Bremsstrahlung component, are presented in fig. 4 by using the same lines as in fig. 3. The error bars include both the statistical uncertainties and the errors due to the subtraction of the Bremsstrahlung component. Also in this figure, a clear difference between the data appears, the larger γ-ray multiplicity being associated with the more N/Z asymmetric reaction.

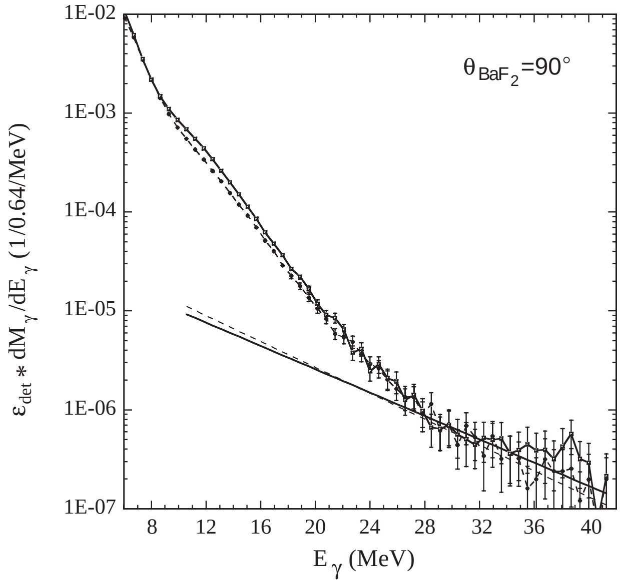

Fig. 3. Experimental γ-ray spectrum of the ^{32}S + ^{100}Mo (solid line) and of the ^{36}S + ^{96}Mo (dashed line) reaction for fusionlike events obtained with the BaF_2 scintillators situated at $\theta = 90°$ with respect to the beam direction and the corresponding Bremsstrahlung contribution indicated with the same lines.

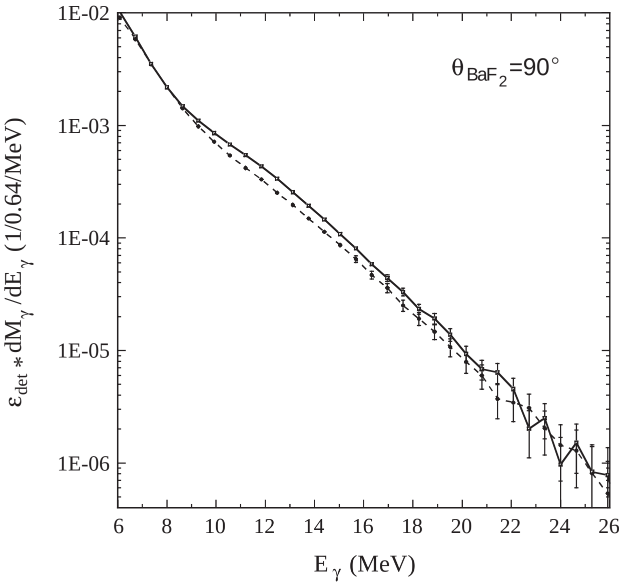

Fig. 4. Bremsstrahlung subtracted experimental γ-ray spectrum in coincidence with fusionlike residues of the ^{32}S + ^{100}Mo (solid line) and of the ^{36}S + ^{96}Mo (dashed line) reaction obtained with the BaF_2 scintillators situated at $\theta = 90°$ with respect to the beam direction.

This excess of γ-rays associated with the more charge asymmetric system, cannot be due to the contamination of neutrons, since the discrimination of γ-rays and neutrons is very good by using the BaF_2 scintillators. Furthermore, the maximum angular momentum for fusion-evaporation is identical in both reactions, therefore the excess cannot be ascribed to an angular momentum difference. The uncertainty in the excitation energy of the compound nucleus, due to the beam energy uncertainty and to the energy loss of the projectile in the target, is estimated to be $\sim$ 4 MeV if the total thickness of the target is considered. CASCADE calculations [22] show that such an uncertainty cannot cause the observed difference in the experimental γ-ray spectra.

In conclusion, the difference between the Bremsstrahlung subtracted experimental γ-ray spectra, can be attributed to the initial dipole moment difference between the two reactions. Then, also for the present excitation energy, the dipole γ-ray emission from the compound nucleus was found to increase with the entrance channel charge asymmetry.

4 Discussion

As pointed out in sect. 3, a part of the fusion cross-section corresponds to incomplete fusion. In incomplete fusion events the emission of pre-equilibrium light particles lowers the excitation energy, the mass and the charge of the compound nucleus. It has been seen that the pre-equilibrium particle emission is insensible to the details of target and projectile and that a scaling of the pre-equilibrium particle multiplicity with the bombarding energy above the Coulomb barrier can be assumed (see [20] and references therein). By using the empirical relation given in [23], the average excitation energy of the compound nucleus for all the fusionlike events is lowered from the complete fusion value of 194 MeV to 173.5 MeV, while its average charge and average mass are lowered by 1 and 2 units, respectively, for both reactions. Notice that also the initial dipole moment difference between the two reactions can be somewhat diminished from its initial value of 16.5 fm due to the light particle pre-equilibrium emission. However, this cannot be evaluated easily, as we do not know from which of the two colliding ions the pre-equilibrium light particles are emitted. Nevertheless, the conclusions of the paper remain valid even by taking into account such a decrease.

In previous works [13,14] investigating the dependence of the dipole γ-ray emission on the entrance channel charge asymmetry, a linearization procedure of the experimental γ-ray spectra was performed in order to eliminate the exponential behaviour due to the nuclear level density from the data and to emphasize the details in the GDR region. Then, for comparison purposes, the same linearization procedure was adopted in the present paper. The Bremsstrahlung subtracted γ-ray spectra associated with the two reactions (fig. 4) were linearized by dividing them by the same theoretical spectrum, calculated with the CASCADE code. In this calculation a constant dipole strength was considered and the compound nucleus average excitation energy, average mass and average charge were lowered as decribed previously. Moreover, the theoretical γ-ray spectrum was folded by the experimental set-up response function by using the code GEANT [24]. The linearized γ-ray spectra are displayed in fig. 5. The squares represent the data of the ^{32}S + ^{100}Mo reaction,

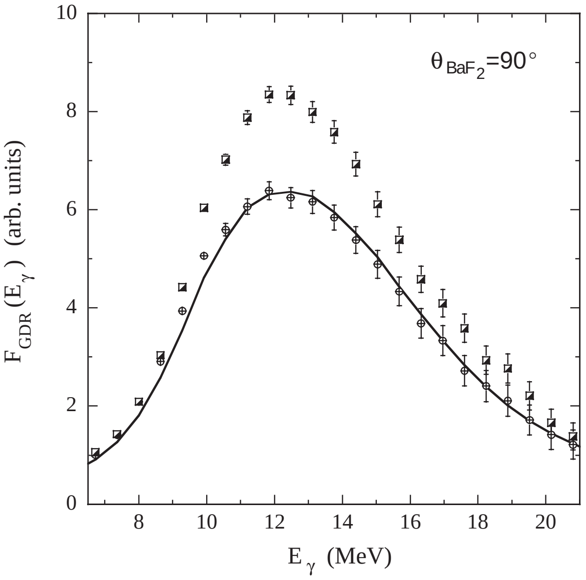

Fig. 5. Linearized Bremsstrahlung subtracted experimental γ-ray spectrum of the $^{32}S + {}^{100}Mo$ (squares) and $^{36}S + {}^{96}Mo$ (circles) reactions. The solid line shows the linearized theoretical γ-ray spectrum for the $^{36}S + {}^{96}Mo$ reaction, calculated with the CASCADE code and folded by the experimental set-up response function.

while the circles those of the $^{36}S + {}^{96}Mo$ one. It is to be noticed that this linearization procedure is somewhat arbitrary for the data of the more N/Z asymmetric reaction, since the composite system is not equilibrated during the emission of the prompt dipole γ-rays. Therefore, the shape of the pre-equilibrium part of the γ-ray spectrum resulting from the above linearization (squares in fig. 5) should be considered with caution.

In order to reproduce the γ-ray spectrum of the $^{36}S + {}^{96}Mo$ reaction, calculations were performed with the CASCADE code at the lowered compound nucleus average excitation energy, average mass and average charge. In fig. 5 the solid line respresents the linearized theoretical γ-ray spectrum folded by the experimental set-up response function by using the code GEANT. The used statistical model parameters are: $E_{GDR} = 14$ MeV, $\Gamma_{GDR} = 12$ MeV, $S_{GDR} = 0.85$ TRKSR, $a = A/8$ MeV^{-1}.

One can see that the calculations reproduce well the data, then, the hypothesis of an average pre-equilibrium emission of 2 nucleons is reasonable and the used empirical relation of [23] is a good approximation of the average excitation energy taken away by the pre-equilibrium particles.

If the linearized spectra of fig. 5 are integrated over the range $E_\gamma = 8$–21 MeV an increase of the γ-ray intensity of $\sim 25\%$ is found for the more N/Z asymmetric reaction.

An overview of the existing experimental results concerning the dependence of the GDR γ-ray emission on the entrance channel charge asymmetry for fusion reactions is presented in table 1. The first column of the table shows the different reaction pairs, the second column presents the percent increase of the γ-ray intensity in the compound nucleus GDR energy region for the more charge asymmetric system, E^* corresponds to the compound nucleus excitation energy, $D(t=0)$ is the initial dipole moment for each reaction given by the relation:

Table 1. The percent increase of the intensity in the linearized γ-ray spectra at the compound nucleus GDR energy region, 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	Ref.
$^{40}Ca + {}^{100}Mo$	16	71	22.1	0.15	[13]
$^{36}S + {}^{104}Pd$		71	0.5	0.17	
$^{16}O + {}^{98}Mo$	36	110	8.4	0.29	[14]
$^{48}Ti + {}^{64}Ni$		110	5.2	0.05	
$^{32}S + {}^{100}Mo$	25	173.5	18.2	0.19	present
$^{36}S + {}^{96}Mo$		173.5	1.7	0.16	work

$$D(t=0) = \frac{NZ}{A}\left|\overrightarrow{R_Z}(t=0) - \overrightarrow{R_N}(t=0)\right| = \frac{R_p + R_t}{A} Z_p Z_t \left|\left(\frac{N}{Z}\right)_t - \left(\frac{N}{Z}\right)_p\right|,$$

being $\overrightarrow{R_Z}$ and $\overrightarrow{R_N}$ the center of mass of protons and of neutrons, respectively, while R_p and R_t are the projectile and target radii.

The fifth column of table 1 shows the initial mass asymmetry Δ of the corresponding reaction:

$$\Delta = \frac{R_t - R_p}{R_t + R_p}.$$

By looking at the outcome of the three experiments presented in table 1, one can see that in all of the cases a larger amount of dipole γ-rays is emitted during the more charge asymmetric reaction. Moreover, by comparing the first and the third reaction pair with each other, it can be seen that the obtained percent increase in the linearized γ-ray spectra at the compound nucleus GDR energy region is clearly larger for the reaction pair with the larger compound nucleus excitation energy, although corresponding to a smaller initial dipole moment difference. These two cases can be compared with each other, as systems with very similar initial mass asymmetries are concerned. A direct comparison with the second reaction pair [14] of table 1 is not straightforward, as here, the initial mass asymmetry difference becomes much larger than in the other two reaction pairs.

Therefore, from the existing experimental results one can deduce that the prompt dipole γ-ray emission depends on the incident energy; however, in order to draw definite conclusions on this dependence, a systematic study of the prompt dipole γ-ray emission with the incident energy for the same reaction pair should be performed.

From a theoretical point of view [4], the prompt dipole γ-ray emission depends on the incident energy through its dependence on the initial isospin asymmetry, on the compound nucleus formation time t_{CN} and on the GDR spreading width. According to these calculations, there should be an appropriate region where the prompt dipole γ-ray emission becomes stronger, situated between the low incident energies near the Coulomb barrier and the higher ones near the Fermi energy domain, where the dipole emission diminishes. In [4] it is shown that the t_{CN} becomes shorter with increasing incident energy, while the GDR spreading width, which governs the damping of the initial dipole phonons, increases with the nuclear excitation energy. For the latter point, other works (see, for example, [25]) claim that the GDR spreading width remains constant with the nuclear temperature and, therefore, with the incident energy. Furthermore, at high incident energies the initial dipole moment decreases because of a large pre-equilibrium light particle emission. The initial mass asymmetry Δ also influences the prompt dipole γ-ray emission through its influence on t_{CN}. In order to maximize this kind of dipole emission, systems with large entrance channel mass asymmetries should be considered.

From the above predictions, it is clear that the systematic study of the prompt dipole γ-ray emission with the incident energy could be an interesting tool for investigating aspects which are not yet well understood, like the GDR spreading width evolution with the nuclear temperature. Moreover, since this kind of dipole emission is a cooling mechanism in fusion reactions, its systematic study with the incident energy could help in the superheavy element formation. The use of exotic beams could help in that direction allowing us to attain large entrance channel charge asymmetries and consequently large dipole γ-ray emission.

5 Conclusions

In summary, in this paper the dependence of the dipole γ-ray emission on the entrance channel charge asymmetry has been probed by studying the fusionlike reactions ^{32}S + ^{100}Mo and ^{36}S + ^{96}Mo at incident energy of E_{lab} = 298 MeV and 320 MeV, respectively. These reactions differed only in the entrance channel charge asymmetry, all of the other reaction parameters being kept constant. The excitation energy of the formed compound nucleus was 173.5 MeV, if pre-equilibrium light particle emission is taken into account. By comparing the differential γ-ray multiplicity spectra associated with the two reactions with each other, after subtraction of the Bremsstrahlung component, a clear difference was observed in the energy range of the compound nucleus GDR, the larger γ-ray multiplicity being related with the more N/Z asymmetric reaction. From the linearized γ-ray spectra, the increase of the GDR γ-ray intensity is found to be $\sim 25\%$. Then, in this work it is shown that the dipole γ-ray emission in fusionlike reactions shows an increasing behaviour with the entrance channel charge asymmetry also at compound nucleus excitation energy higher than those considered in previous experiments.

By comparing the outcome of the present work with the experimental result of [13] at compound nucleus excitation energy of 71 MeV, it can be seen that the prompt dipole γ-ray emission depends not only on the N/Z ratios of the colliding ions but also on the incident energy. However, a study of the prompt dipole γ-ray emission with incident energy for the same reaction pair is needed in order to draw definite conclusions on the details of this dependence. Such a study could shed light on the GDR spreading width evolution with the nuclear temperature and could investigate the existence of some energy range where the prompt dipole γ-ray emission becomes stronger, as theoretical papers predict. The use of exotic beams will offer the opportunity of very large entrance channel charge asymmetries, thus, maximizing the prompt dipole γ-ray emission. The findings of such an investigation could be of importance for the superheavy element formation.

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