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HEAVY ION PHYSICS

Prompt dipole γ-ray emission: a new cooling mechanism in fusion heavy-ion reactions

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Abstract. We investigated the prompt dipole γ-ray emission, related with entrance channel charge asymmetry effects, in the ^{40}Ar + ^{92}Zr and ^{36}Ar + ^{96}Zr fusion-evaporation reactions at E_{lab}= 15.1 and 16 MeV/nucleon, respectively, with the aim to probe its evolution with incident energy. These reactions populate, through entrance channels having different charge asymmetries, the same compound nucleus at an average excitation energy of 304 MeV with identical spin distribution. It was shown that the dipole γ-ray intensity in the bremsstrahlung subtracted linearized spectra increases by $\sim$14% for the more charge asymmetric system. This result, associated with those reported for the ^{32,36}S + ^{100,96}Mo reaction pair at lower beam energies, implies a "*rise and fall*" trend of the prompt dipole γ-ray emission with beam energy with a maximum value at E_{lab}= 9 MeV/nucleon.

Keywords: Measured γ-ray multiplicity spectra; Pre-equilibrium Giant Dipole Resonance; Evolution with beam energy
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1. Introduction

By studying the γ-ray multiplicity spectra related to heavy-ion reactions where the same composite system is formed from entrance channels having different charge asymmetry, it was observed an excess of dipole γ-rays emitted from the more charge asymmetric system for deep inelastic [1, 2] and fusionlike [2–5] events. This excess was ascribed to the prompt dipole γ-ray emission, associated with the excitation of a pre-equilibrium Giant Dipole Resonance (GDR) in the dinuclear system during the charge equilibration process. Then, the prompt dipole γ-ray emission appears in charge asymmetric collisions in addition to the statistical one originating in the thermal excitation of the hot compound nucleus dipole vibration.

Recently, it was suggested [6] that this kind of pre-equilibrium emission depends on the incident energy. A systematic study of such a dependence is of great interest mainly for two reasons. It could provide us information on the GDR spreading width evolution with temperature and it could be of aid in the formation of superheavy elements. In fact, the emission of pre-equilibrium dipole photons could represent an efficient new cooling mechanism of the composite system in charge asymmetric "hot" fusion reactions, increasing thus its survival probability.

Motivated by the above points, we started in [5, 7] a study of the prompt dipole radiation evolution with beam energy in fusion reactions by forming the ^{132}Ce compound nucleus at an excitation energy of 117 MeV ($E_{lab} = 6$ MeV/nucleon) and 173.5 MeV ($E_{lab} = 9$ MeV/nucleon) through the reaction pair: ^{32,36}S + ^{100,96}Mo. In each experiment, all the parameters were kept identical between these two reactions except from the entrance channel charge asymmetry and thus, from the initial dipole moment.

Using the same technique in the experiment presented herewith, a compound nucleus in the vicinity of ^{132}Ce was formed at an average excitation energy of 304 MeV (by taking into account the energy lost due to pre-equilibrium particle emission) through the reaction pair: ^{36}Ar + ^{96}Zr and ^{40}Ar + ^{92}Zr at E_{lab} =16 and 15.1 MeV/nucleon, respectively. The entrance channel dipole moment changed by 16.6 fm from the ^{40}Ar + ^{92}Zr system to the more N/Z asymmetric one, ^{36}Ar + ^{96}Zr, while the entrance channel mass asymmetry changed by a small amount, namely 0.2 (for a definition of the dipole moment and mass asymmetry see [7]). Furthermore, both systems were located above the critical curve in the fissility-mass asymmetry plane [9] which ensures us that dynamical effects influencing the compound nucleus statistical dipole γ-ray emission and associated with the initial mass asymmetry are negligible [10]. The fusion critical angular momentum for both reactions was $L_{max} = 83\hbar$ according to PACE2 [8] calculations. Therefore, since all the above parameters were kept identical also in this experiment, any difference in the γ-ray emission between the two reactions can be safely ascribed to the difference in the entrance channel charge asymmetry. Moreover, the results from the study of the two reaction pairs, namely ^{32,36}S + ^{100,96}Mo and ^{36,40}Ar + ^{96,92}Zr, can be directly compared with each other since they are associated with the same entrance channel dipole moment difference and the same entrance channel mass asymmetry difference.

2. The Experiment

The reactions ^{36,40}Ar + ^{96,92}Zr were performed by using the ^{36}Ar and ^{40}Ar pulsed beams provided by the Superconducting Cyclotron of the Laboratori Nazionali del Sud (Italy), impinging on a 450 μg/cm^2 thick $^{96}ZrO_2$ target (enriched to 95.63% in ^{96}Zr) and on a 600 μg/cm^2 thick $^{92}ZrO_2$ target (enriched to 95.36% in ^{92}Zr). The targets were evaporated on carbon layers 90 and 60 μg/cm^2 thick, respectively. The beam consisted of $\sim$1 ns wide bunches with a 150 ns separation. Beam current was about 2 nA.

The γ-rays and the light charged particles were detected by using the 180 BaF_2 modules of the MEDEA experimental apparatus [11] that covers the polar angular range between θ=30° and θ=170° and the full range in the azimuthal angle ϕ. The total solid angle covered by the MEDEA apparatus was 3.7π sr.

The fusion-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. The total solid angle covered by the PPAC's was 0.089 sr. They provided the time of flight (TOF) with respect to the radiofrequency signal of the accelerator, the energy loss (ΔE) and the position of the reaction products.

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 detector was greater than $\sim$ 6 MeV. The coincidence request eliminated any cosmic ray contamination of the γ-ray spectra.

The energy calibration of the γ-ray detectors was obtained by using the sources ^{60}Co, ^{88}Y, the composite sources of ^{241}Am+^{9}Be and ^{238}Pu+^{13}C and the 15.1 MeV γ-rays from the p+^{12}C reaction while the calibration of the charged particles was performed as described elsewhere [12].

The discrimination between γ-rays, light charged particles and high-energy neutrons (E>20 MeV) was performed by means of a shape analysis of the BaF_2 signal; the discrimination between γ-rays and low energy neutrons was achieved with a TOF measurement with respect to the radiofrequency signal of the Cyclotron.

3. Results and discussion

The fusionlike events were selected off-line in the bidimensional plot of the ΔE versus the TOF of the reaction products detected in each PPAC. At the present incident energies, the incomplete fusion cross section represents approximately the 90% of the total fusion cross section [13]. The average excitation energy lost due to pre-equilibrium particle emission for the considered fusionlike events was evaluated by means of the empirical relation given by Kelly et al. [14] and was taken into account when calculating the appropriate beam energy for each reaction to form the compound nucleus at the same excitation energy. It was found to be approximately

81 and 76 MeV for the ^{36}Ar + ^{96}Zr and ^{40}Ar + ^{92}Zr reaction, respectively. Subsequently, the quality of such an evaluation was checked by looking at the proton energy spectra obtained with the BaF_2 scintillators in coincidence with evaporation residues for the two systems. At very backward angles, $\theta = 160°$, we can reasonably assume that the protons originate mainly from the compound nucleus and we can perform a moving source fit by using a surface-type Maxwell distribution for the emitted protons in the source rest frame (see for example [16]).

During the fitting procedure, the average source velocity for the considered residues was fixed at $v_s = 1.46$ e 1.36 cm/ns (corresponding to 90% of the compound nucleus velocity) for the reaction ^{40}Ar + ^{92}Zr and ^{36}Ar + ^{96}Zr, respectively. The source parameters extracted from the fit (multiplicity and apparent temperature) for the two systems are the following: M = (1.60 ± 0.07), T = (4.78 ± 0.05) MeV for ^{40}Ar + ^{92}Zr and M = (1.52 ± 0.03), T = (4.79 ± 0.03) MeV for ^{36}Ar + ^{96}Zr. Since the M and T values for the two reactions are found to be equal to one another within the errors, we can conclude that the compound nucleus was formed at the same average excitation energy and with the same average mass (A$\sim$ 125) and thus, we can safely compare the corresponding γ-ray spectra with each other.

The γ-ray multiplicity spectra in coincidence with evaporation residues for the ^{40}Ar + ^{92}Zr (triangles) and the ^{36}Ar + ^{96}Zr (circles) reactions at θ= 90° are plotted in Fig.1. ϵ_{det} appearing in the Oy axis is the energy dependent efficiency of the experimental apparatus. The spectra were integrated in 4π by assuming isotropic emission in the center of mass reference frame. From this figure it is clear that the data present a definite difference (squares) in the compound nucleus GDR energy region. Notice that the difference between the data was displayed up to E_γ= 28 MeV for clarity reasons. Before drawing any conclusion about the origin of this difference the bremsstrahlung component must be subtracted from the spectra. To evaluate it, the γ-ray multiplicity spectrum of the ^{40}Ar + ^{92}Zr (^{36}Ar + ^{96}Zr) reaction was fitted by means of an exponential function [15] for $E_\gamma \geq 32$ (35) MeV. The inverse slopes extracted from the fitting procedure are: (8.25 ± 1.36) MeV and (8.6 ± 1.4) MeV for the ^{40}Ar + ^{92}Zr and ^{36}Ar + ^{96}Zr system, respectively. In the left hand side of Fig. 1 the solid (dotted) line represents the bremsstrahlung component of the ^{40}Ar + ^{92}Zr (^{36}Ar + ^{96}Zr) spectrum.

By assuming that the bremsstrahlung γ-ray emission follows the same exponential function down to low energies, we subtracted it from the data in the whole energy range and the resulting γ-ray spectra associated with the two reactions were linearized. This linearization was performed by dividing them by the same theoretical γ-ray spectrum, calculated with the CASCADE code [17] where a constant dipole strength and a level density parameter a=A/10 MeV^{-1} were considered. Moreover, the constant strength theoretical γ-ray spectrum was folded by the response function of the MEDEA experimental apparatus [18]. The bremsstrahlung subtracted linearized γ-ray spectrum of the ^{40}Ar + ^{92}Zr (^{36}Ar + ^{96}Zr) reaction is displayed by the triangles (circles) in the right hand side of Fig. 1. The error bars in the bremsstrahlung subtracted linearized spectra include both statistical uncertainties and errors on the slope and normalization of the bremsstrahlung component. If these spectra are integrated between 8 and 21 MeV, an increase of the GDR γ-ray intensity of (13.8 $\pm$ 3.5)% is found by going towards the more charge asymmetric system. We conclude that such an increase is related to entrance channel charge asymmetry effects.

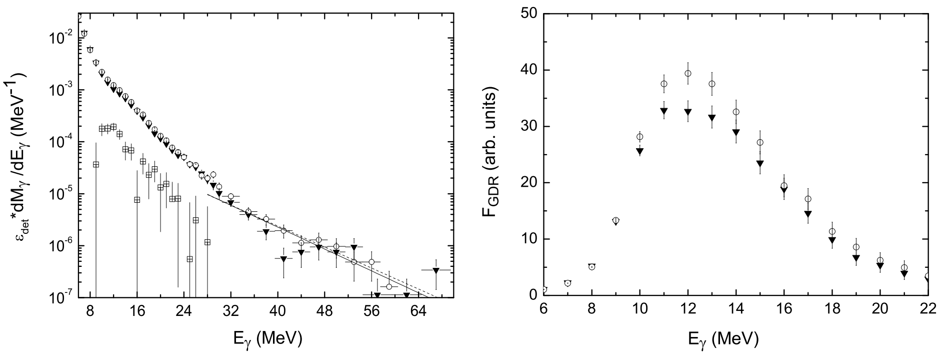

Fig. 1. Left hand side: γ-ray multiplicity spectrum of the ^{40}Ar + ^{92}Zr (triangles) and ^{36}Ar + ^{96}Zr (circles) reaction for fusionlike events at θ=90°. The difference between the data (squares) is displayed up to E$_\gamma$=28 MeV for clarity reasons. The solid (dotted) line represents the bremsstrahlung component of the ^{40}Ar + ^{92}Zr (^{36}Ar + ^{96}Zr) spectrum evaluated as described in the text. Right hand side: Bremsstrahlung subtracted linearized γ-ray spectrum of the ^{40}Ar + ^{92}Zr (triangles) and ^{36}Ar + ^{96}Zr (circles) reaction for fusionlike events at θ= 90°.

As mentioned previously, the present results can be compared directly with those related to the ^{32,36}S + ^{100,96}Mo reactions performed at E$_{lab}$= 6 and 9 MeV/nucleon [5,7]. In those works, the increase of the GDR γ-ray intensity in the linearized spectra for the more charge asymmetric system was found to be zero within the error bars for the lower beam energy and ~25% for the higher one. From all these experimental findings one can see that the prompt dipole γ-ray emission presents a maximum at incident energy of 9 MeV/nucleon decreasing towards lower and higher incident energies. As discussed in [5], the shape of the pre-equilibrium GDR in the dinuclear system cannot be deduced from the linearized spectra. Results concerning the parameters of the pre-equilibrium GDR (centroid energy and width) at E$_{lab}$= 9 and ~16 MeV/nucleon will be presented in a forthcoming paper.

Calculations performed within the BNV transport model framework and based on a collective bremsstrahlung approach at beam energy of 6 and 9 MeV/nucleon predict a lower dynamical dipole yield at the lower incident energy related to a slower neck dynamics which obstructs a full collective response [7]. Within the same model, at high beam energies, above (15-20) MeV/nucleon, the extra dipole radiation is expected to be hindered by a larger pre-equilibrium particle emission that will reduce the initial dipole moment amplitude [6].

4. Conclusions

In the present work we investigated the evolution of the prompt dipole γ-ray emission with beam energy by studying the ^{36}Ar + ^{96}Zr and ^{40}Ar + ^{92}Zr fusion reactions at E_{lab}=16 and 15.1 MeV/nucleon, respectively, in order to form the same compound nucleus in the vicinity of ^{132}Ce at an average excitation energy of 304 MeV with identical spin distribution. The only difference between the two systems concerns the entrance channel dipole moment.

From the bremsstrahlung subtracted linearized γ-ray spectra, associated with the ^{36,40}Ar + ^{96,92}Zr reactions, a GDR γ-ray intensity increase of $\sim$14% was evidenced for the more charge asymmetric system. The present result can be directly compared with those reported for the ^{32,36}S + ^{100,96}Mo fusion reactions performed at 6 and 9 MeV/nucleon. It can be seen that the prompt dipole γ-ray emission presents a "*rise and fall*" trend with beam energy taking its maximum value at E_{lab}= 9 MeV/nucleon. These results are in good agreement with the theoretical predictions of [6].

In future, the investigation of the prompt dipole γ-ray emission should be pursued in association with the use of radioactive beams which allow the maximization of this kind of emission. Such studies could be of aid to form superheavy elements by taking advantage of the prompt dipole γ-ray emission taking place in "hot" fusion reactions between charge asymmetric colliding ions.

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