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Excitation of the dynamical dipole in the charge asymmetric reaction $^{16}O + ^{116}Sn$

A. Corsi [a,b], O. Wieland [b], V.L. Kravchuk [c], A. Bracco [a,b], F. Camera [a,b,*], G. Benzoni [b], N. Blasi [b], S. Brambilla [b], F.C.L. Crespi [a,b], A. Giussani [a,b], S. Leoni [a,b], B. Million [b], D. Montanari [a,b], A. Moroni [a,b], F. Gramegna [c], A. Lanchais [c], P. Mastinu [c], M. Brekiesz [d], M. Kmiecik [d], A. Maj [d], M. Bruno [e,f], M. D'Agostino [e,f], E. Geraci [i,j], G. Vannini [e,f], S. Barlini [g], G. Casini [g], M. Chiari [g], A. Nannini [g], A. Ordine [h], M. Di Toro [i,j], C. Rizzo [i,j], M. Colonna [i,j], V. Baran [k]

[a] Dipartimento di Fisica, Università di Milano, Milano, Italy
[b] INFN Sezione di Milano, Milano, Italy
[c] Laboratori Nazionali INFN di Legnaro, Legnaro, Italy
[d] The Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[e] Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[f] INFN Sezione di Bologna, Italy
[g] INFN Sezione di Firenze, Italy
[h] INFN Sezione di Napoli, Italy
[i] Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy
[j] INFN, Laboratori Nazionali del Sud, Catania, Italy
[k] NIPNE-HH, Bucharest, Romania

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A B S T R A C T

The γ-ray emission from the dynamical dipole formed in heavy-ion collisions during the process leading to fusion was measured for the N/Z asymmetric reaction $^{16}O + ^{116}Sn$ at beam energies of 8.1 and 15.6 MeV/nucleon. High-energy γ-rays and charged particles were measured in coincidence with the heavy recoiling residual nuclei. The data are compared with those from the N/Z symmetric reaction $^{64}Ni + ^{68}Zn$ at bombarding energies of 4.7 and 7.8 MeV/nucleon, leading to the same CN with the same excitation energies as calculated from kinematics. The measured yield of the high-energy γ-rays from the ^{16}O-induced reaction is found to exceed that of the thermalized CN and the excess yield increases with bombarding energy. The data are in rather good agreement with the predictions for the dynamical dipole emission based on the Boltzmann–Nordheim–Vlasov model. In addition, a comparison with existing data in the same mass region is performed to extract information on the dipole moment dependence.

Investigation of the photon emission from the dynamical electric dipole formed during the process leading to fusion in N/Z asymmetric heavy-ion reactions is of special interest because it can provide information on isospin dynamics in the fusion process and, in particular, on the symmetry term of the equation of state. Presently, a particular effort is made to study the symmetry term of the equation of state (see e.g. [1,2]) also because of its implications in nuclear astrophysics problems such as neutron stars and the elements burning in supernovae [3]. The origin of the dynamical dipole is related to the fact that, in dissipative collisions, energy and angular momentum are quickly distributed among all single particle degrees of freedom while charge equilibration takes place on a larger timescale through a collective motion of nucleons generating an oscillating electric dipole which is damped after 3–5 vibrations [4]. Consequently, for charge asymmetric entrance channels, at the time of compound nucleus (CN) formation, one expects pre-equilibrium photon emission from the dipole oscillation in the isospin transfer dynamics.

The dynamical dipole (called also prompt dipole) was predicted some years ago for heavy-ion collisions as a collective mode in the initial phase of the reaction [5,6] and it was observed in fusion and deep-inelastic reactions [7–11]. Although the data are still rather scarce, the existing experimental information shows that, in gen-

* Corresponding author at: Dipartimento di Fisica, Università di Milano, Milano, Italy.
E-mail address: franco.camera@mi.infn.it (F. Camera).

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eral, there is a dependence of the dynamical dipole strength on the beam energy and on the dipole moment, which is related to the N/Z asymmetry between the projectile and the target. Particularly interesting are the results of a recent work [11] concerning the mass region A $\sim$ 132 in which the observed angular anisotropy is consistent with an oscillation along a preferential axis and supports the picture of prompt dipole emission at an early stage of the fusion dynamics.

The existing theoretical predictions describing the dynamical dipole are based on two different approaches. The first, namely the phonon model [4,5,7,12], applies the formalism valid for an equilibrated system to a system in which the isospin degree of freedom is not yet equilibrated. The model predicts an increase of the photon yield related to the increase of the size of the dipole moment. The limit of this model is that it does not include a dependence on the bombarding energy and it does not take into account the radiation emitted in the pre-equilibrium phase, before the CN is formed and when also particle emission takes place. In the alternative approach, the photon yield is calculated using the Bremsstrahlung formula once the evolution of the dipole moment is known from its onset up to its complete damping. The dynamics is computed by numerical solution of the microscopic transport equations such as time-dependent Hartree–Fock [12,13] or Boltzmann–Nordheim–Vlasov (BNV) [14,15] with, as important input parameters, the N–N collision cross section and the nuclear equation of state with its symmetry term. In fact, being the dynamical dipole emission related to an isospin oscillation in the neck region between projectile and target, it is affected by the value of symmetry energy at densities lower than the saturation one.

The aim of this Letter is to investigate three different aspects of the dynamical dipole emission which are expected to provide a test to theory and consequently to shed light on the underlying physical mechanisms. The first aim is to clearly show the presence of γ-ray emission from a dynamical dipole. The second is to determine the dependence on bombarding energy of the strength of the dynamical dipole and the third is to deduce the dependence on the initial dipole moment at a fixed bombarding energy (in MeV/nucleon) by comparing the present data with those of Ref. [11]. The chosen reaction is the $^{16}O + ^{116}Sn$ ($E_{lab} = 8.1$ and 15.6 MeV/nucleon), leading to a CN ^{132}Ce. The initial value of the dipole moment of the fusing system $D(0)$, proportional to the distance between neutron and proton centre of mass, is approximately 8.6 e fm as obtained using the expression [9]:

$$D(0) = \frac{r_0(A_p^{1/3} + A_t^{1/3})}{A} Z_p Z_t \left| \frac{N_t}{Z_t} - \frac{N_p}{Z_p} \right| \quad (1)$$

where $r_0 = 1.2$ fm, $e = 1$ and the indexes p and t refer respectively to the projectile and the target of the reaction. Both γ-rays and charged particles were measured in order to deduce the excitation energy of the equilibrated compound, which is the reference to extract the dynamical dipole yield. In fact, the measured γ-ray spectra contain both the contribution of the equilibrated system and, in presence of a dipole moment, of the pre-equilibrium phase. Both statistical and pre-equilibrium photons have a dipole nature and energy centred in the interval 10–15 MeV. Consequently, to extract the dynamical dipole yield one needs: (i) to measure the excitation energy independently from γ-rays (e.g. from charged particle spectra); (ii) to measure the γ-ray spectrum for a reference fusion-evaporation reaction producing the same CN but without dynamical dipole emission; (iii) to understand and reproduce with statistical model the γ-ray spectrum of the symmetric reaction to test the model parameters. In the present case the reference reaction is $^{64}Ni + ^{68}Zn$ [16] and the excitation energy is inferred from the measurements of the charged particles [19].

The experiment was performed at LNL using the beams from the Tandem-Alpi accelerator complex. The experimental setup consisted of the combination of three detector systems: the GARFIELD array [17] for the measurement of light charged particles (LCP), the HECTOR setup made of large volume BaF_2 detectors [18] and a set of two Position Sensitive Parallel Plate Avalanche Counter telescopes (PSPPAC). A comprehensive description of the experimental apparatus can be found in Refs. [16–19].

The particle and γ data discussed in this Letter were obtained by setting appropriate gates on both time of flight and energy loss measured with the PSPPAC in order to select compound-residues events. This double gating is expected to eliminate in the best possible way contaminations from other reaction types such as fission. The time resolution of both the pulsed beam and the PSPPAC was around 1 ns. The time resolution of BaF_2 (less than 1 ns) allowed a good neutron rejection by TOF measurement. An electronic threshold of approximately 3 MeV was set on the γ-rays energies in order to reduce the acquisition dead time. The calibration of the GARFIELD detectors was performed using elastically scattered ^{12}C and ^{16}O ions from a ^{181}Ta target at different bombarding energies ranging from 6 to 20 MeV/nucleon, while the BaF_2 detectors were calibrated using standard γ-ray sources and the 15.1 MeV γ-rays from the reaction $d(^{11}B, n\gamma)^{12}C$ at beam energy of 19.1 MeV. Trigger conditions required a coincidence of signals from PSPPACs and an OR between charged particle in the GARFIELD array and a signal in the BaF_2 detectors. In addition, scaled down counts from the PSPPACs, GARFIELD and BaF_2 detectors in single mode were registered.

For the reaction $^{16}O + ^{116}Sn$ the charged particle spectra, measured in coincidence with heavy recoiling nuclei, show the presence of pre-equilibrium particle emission. In Fig. 1 proton and α particles at the two bombarding energies are displayed (dots) together with the predicted yields from two emitting sources (continuous and dashed lines). In fact, a unique evaporative source fit is, in general, not sufficient to describe the experimental spectra. A second pre-equilibrium source with a velocity intermediate between the recoiling CN and the beam has to be added. The emission from the fast moving source is particularly evident in both protons and α-particles spectra at $E_{beam} = 15.6$ MeV/nucleon (right panels) and this gives a clear indication of pre-equilibrium emission removing excitation energy before the system thermalizes.

It is important to stress that such LCP pre-equilibrium emission is not related to the dynamical dipole mechanism discussed in the introduction. Its origin, in fact, is not related to isospin effects in the entrance channel of the reaction but simply to the high projectile velocity as was already reported and discussed in several papers [20–23]. Its relevance in this analysis is due to the fact that when pre-equilibrium LCP emission is present, the excitation energy of the thermally equilibrated CN is lower than the one calculated by the reaction kinematics. Therefore, to obtain the prompt dipole yield one cannot simply subtract the yield of two reactions with different dipole moments and the same excitation energy as deduced from kinematics. For the analysis of the charged particles spectra the description of the pre-equilibrium contribution was based on the Watt distribution [24], successfully applied in previous works (see e.g. [20–22]). The pre-equilibrium neutron multiplicity was estimated from the systematic work of Cabrera et al. [20]. The excitation energies after the correction of pre-equilibrium energy loss resulted in $E^* = 94 \pm 3$ MeV (100 MeV is the excitation energy if there were no pre-equilibrium) at $E_{beam} = 8.1$ MeV/nucleon and $E^* = 165 \pm 7$ MeV (206 MeV is the excitation energy if there were no pre-equilibrium) at $E_{beam} = 15.6$ MeV/nucleon [16,19]. The corresponding loss in velocity of the CN was calculated to be approximately 7% at the highest bom-

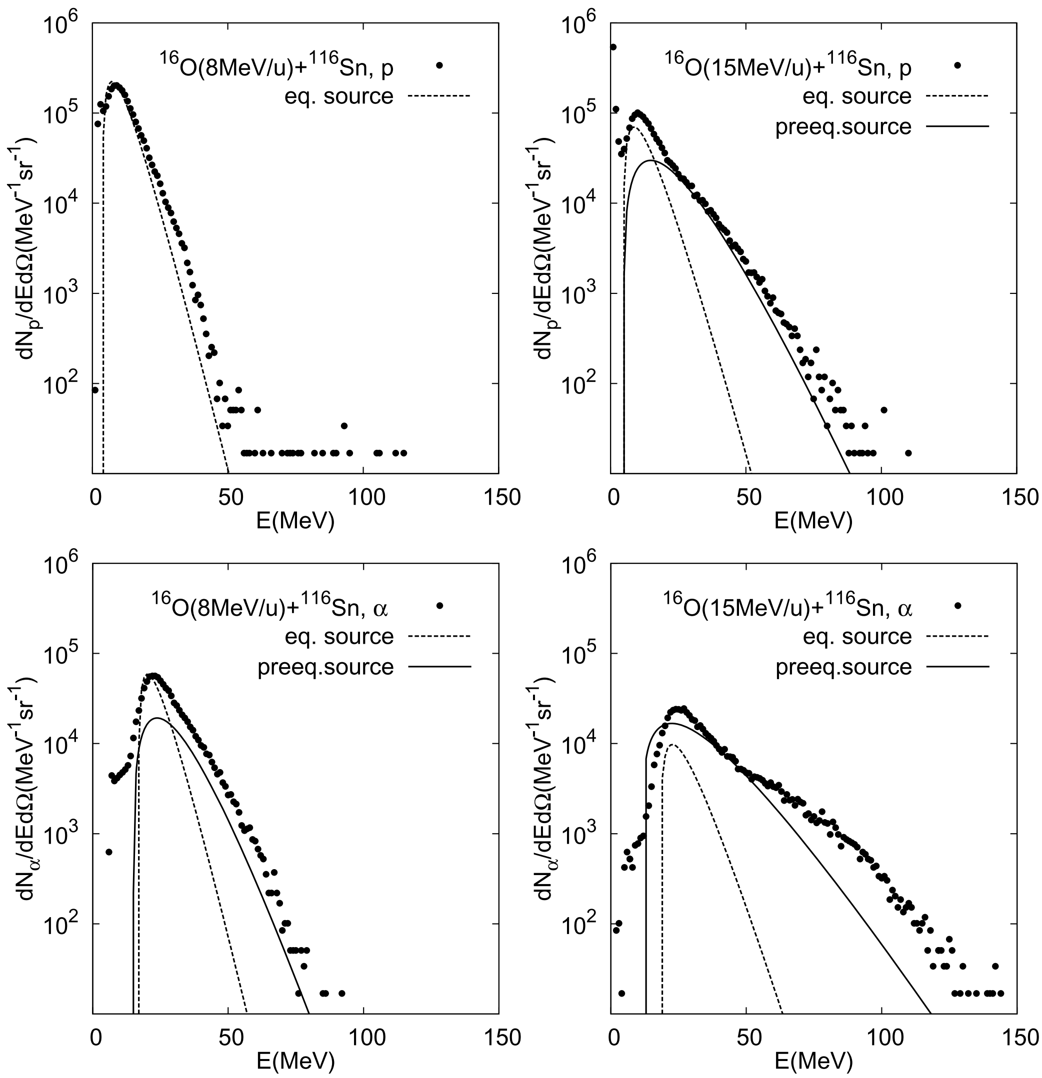

Fig. 1. Spectra of protons (top panels) and α particles (bottom panels) in the laboratory system measured at 29°–41° degrees in coincidence with evaporation residues for the N/Z asymmetric reaction $^{16}O + {}^{116}Sn$ at the two bombarding energies of 8.1 MeV/nucleon (left panels) and 15.6 MeV/nucleon (right panels). The dashed line represents the emission from the evaporative source while the continuous line the emission from the pre-equilibrium source.

barding energy. This is in good agreement with the results of Ref. [21] and with the systematic measurements of the linear momentum transfer that for $\Delta p < 100\%$ was interpreted in terms of incomplete fusion [25].

The measured γ-ray spectra for the ^{16}O induced reactions in coincidence with the heavy recoiling residual nucleus are shown together with the statistical model calculations in Fig. 2. All the quantities entering in the statistical model calculations (with the exception of the excitation energy E^* and of the Giant Dipole Resonance (GDR) width, whose value depends on E^*) are those providing the best fit in the high energy γ-ray spectra measured with the reaction $^{64}Ni + {}^{68}Zn$ ($E_{lab} = 4.7$, 6.2 and 7.8 MeV/nucleon) [16]. For the charge and mass symmetric reaction induced by the ^{64}Ni beam, no sizable pre-equilibrium particle emission was found and no dynamical dipole contribution is expected since the initial dipole moment is very small, 1.2 e fm. The GDR parameters for the statistical calculations were not fitted to the data but were taken from Ref. [16] and scaled down to the estimated excitation energy. In particular the calculations in the top-left panel of Fig. 2 corresponds to $E_{GDR} = 14.0$ MeV, $\Gamma_{GDR} = 7.3$ MeV, while that in the top-right panel to $E_{GDR} = 14.0$ MeV, $\Gamma_{GDR} = 12.9$ MeV, as deduced from the systematics of the temperature dependence ([16] and references therein). For the two reactions the same distribution of the angular momentum with $l_{max} = 70\hbar$ was used. The assumption of using the same maximum angular momentum at the two bombarding energies is based on the work of Ref. [26] in which a similar reaction $^{18}O + {}^{100}Mo$ was studied in almost the same energy range. An additional calculation with $l_{max} = 58\hbar$ (as given by the Bass model) was made and used as a reference for the experimental data and this gives an excess yield which is 25% lower. This difference is however smaller than the uncertainty on the excitation energy removal of the pre-equilibrium emission (the latter shown with the shaded area in the bottom panels of Fig. 2). The angular momentum removed by pre-equilibrium particle emission was estimated to be 5–6$\hbar$, using the approach of [20]. Being the excitation energy high as compared to the yrast line, such changes in angular momentum do not affect the statistical γ yield (e.g. a change of 15$\hbar$ corresponds to a change in γ yield smaller than 10%). The response function of the HECTOR array, calculated with the GEANT libraries, was also folded into the calculations. The comparison of the statistical model with the data (see top panels of Fig. 2) shows an experimental excess yield increasing with bombarding energy. An attempt to fit the data with the statistical model was made. The best statistical model fit to

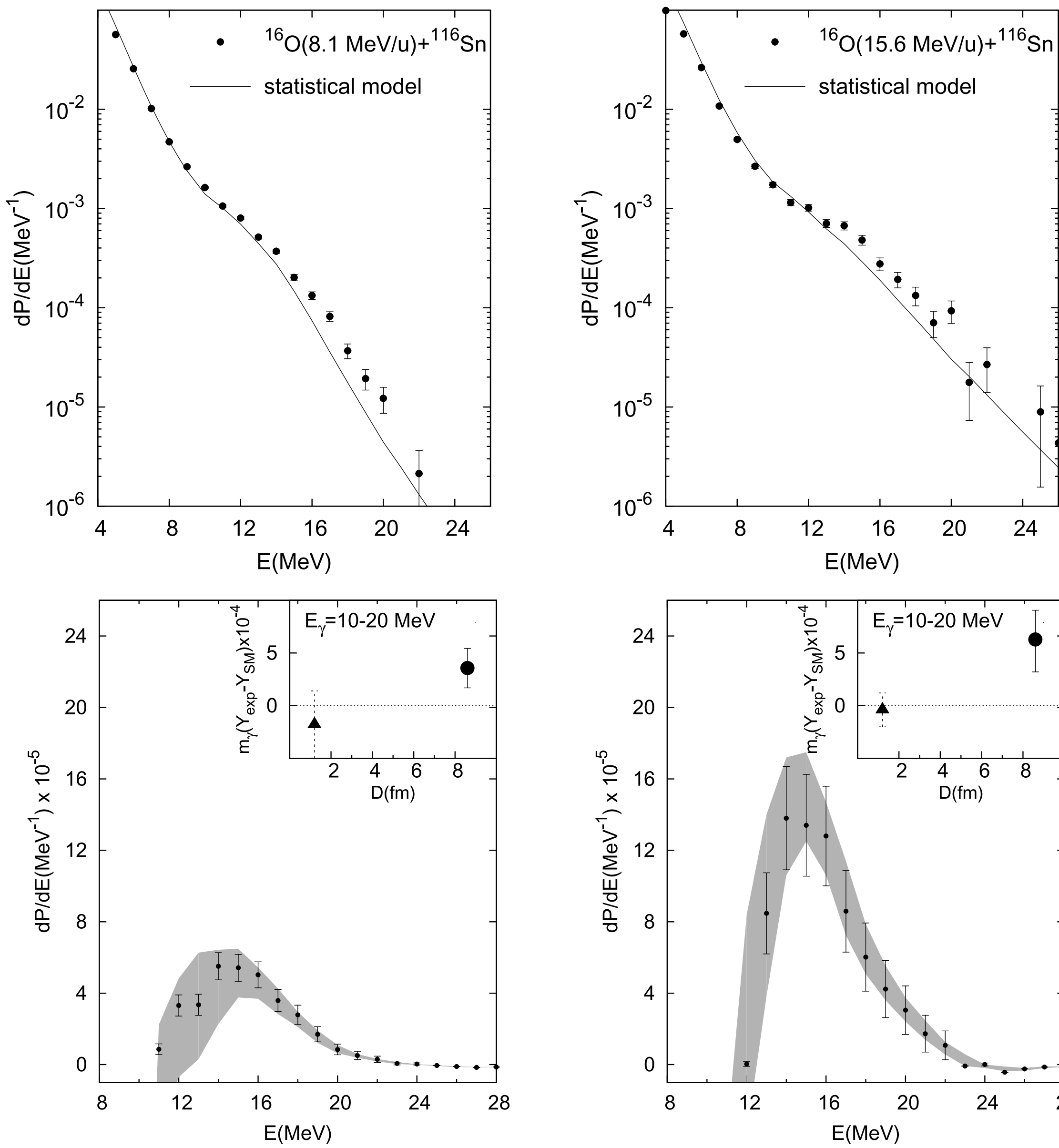

Fig. 2. The measured γ-ray spectra of $^{16}O + ^{116}Sn$ at the two bombarding energies of 8.1 MeV/nucleon (left panel) and 15.6 MeV/nucleon (right panel). The continuous line is the statistical model prediction at $E^* = 94$ MeV and $E^* = 165$ MeV (see text), respectively. The bottom panels show the difference between the measured spectra and the statistical model of the top figures providing the γ-ray yield of the dynamical dipole. The uncertainty in the determination of the pre-equilibrium contribution is shown with the shaded area. In the inset of these figures the integrated yield in the region 10-20 MeV obtained as difference between the experiment and the statistical model prediction is shown for $^{16}O + ^{116}Sn$ (filled points) and $^{64}Ni + ^{68}Zn$ (filled triangles) at beam energies 4.7 and 7.8 MeV/nucleon, respectively.

the data at $E_{\mathrm{Beam}} = 250$ MeV corresponds to the GDR parameters $E_{\mathrm{GDR}} = 16$ MeV, $\Gamma_{\mathrm{GDR}} = 9$ MeV and 125% of the EWSR strength. These values differ considerably from those deduced from Ref. [16] and are also far from the systematics in this mass and excitation region (see Ref. [27]). This finding indicates the presence of an additional non statistical mechanism.

In the lower panels of Fig. 2 the excess yields with respect to statistical model predictions (calculated at $E^* = 94$ MeV for $E_{\mathrm{beam}} = 8.1$ MeV/nucleon and at $E^* = 165$ MeV for $E_{\mathrm{beam}} = 15.6$ MeV/nucleon, respectively) are displayed on a linear scale. The shaded areas correspond to the uncertainty in the excitation energy removal by pre-equilibrium. One can see that the excess yield (obtained as difference between the measured and statistical model γ-ray multiplicities) is peaked at around 14 MeV. It should be noticed that, at variance from other measurements, in this case the reference spectrum was not normalized to the data, having deduced the multiplicity values directly from the experiments. As discussed in Ref. [13], the choice of the region of normalization to the measured spectra strongly affects the yield of the difference spectrum, possibly leading to spurious effects. The integrated value of the measured dynamical dipole yield is reported in the insets of the lower panels of Fig. 2. The same quantity is also shown for the reactions induced by the ^{64}Ni beam [16] that is consistent with zero (see triangles in the insets of Fig. 2). This confirms the fact that the nature of the γ-ray emission of the ^{64}Ni-induced reaction is fully statistical and consequently it provides a test to the statistical model calculation used as reference to deduce the prompt dipole yield.

Fusion dynamics for $^{16}O + ^{116}Sn$ reaction at the beam energies of 8, 15 MeV/nucleon was calculated in the framework of BNV

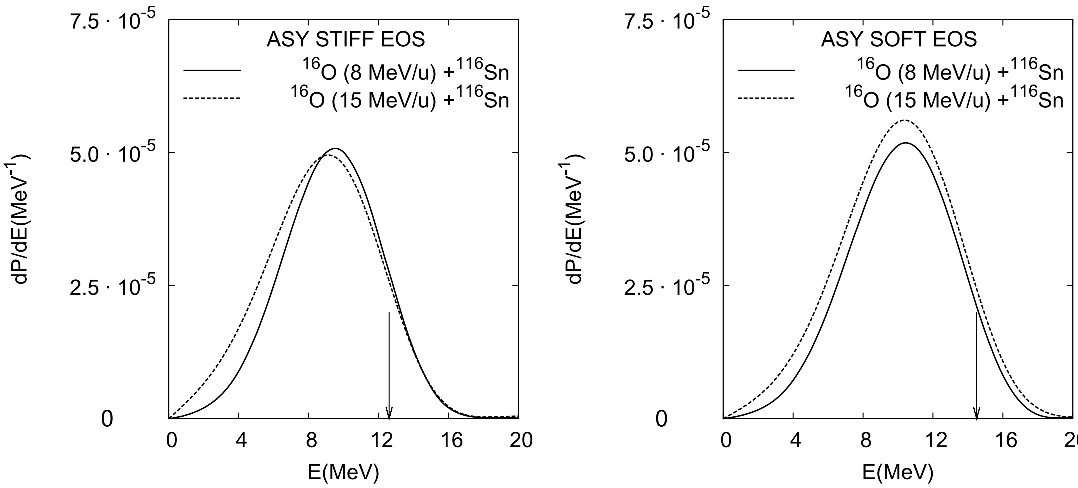

Fig. 3. Bremsstrahlung spectra averaged on the impact parameters 0, 2, 4 and 6 fm, for 8 MeV/nucleon (full line) and for 15 MeV/nucleon beam energy (dashed line). The arrows point at the centroid position of the Bremsstrahlung spectrum obtained for a GDR-like oscillation, as described in the text. Left panel displays the results obtained with asy-stiff EOS, right panel with asy-soft EOS [1,2].

model and the γ-ray yield from the dynamical dipole emission mechanism was extracted. All the calculations were performed at the impact parameters $b = 0$, 2, 4 and 6 fm which are relevant for fusion process. The results obtained for each impact parameter have been summed with a weight extracted according to the fusion cross section provided by PACE4 code. Very similar results are obtained using weights extracted from the fusion probability evaluated from the behaviour of the time dependent quadrupole moment calculated in the same BNV approach. In the calculations two different parametrizations of the symmetry term of the equation of state (EOS) have been used. The first one, denoted as asy-stiff, has a rapid decrease of the symmetry energy towards low nuclear densities while the second one (asy-soft) has a more smooth behaviour. A more detailed discussions on the EOS used in the calculation can be found in Refs. [1,2].

The corresponding spectra of the Bremsstrahlung emission, derived as a Fourier transform of the dipole acceleration, are shown in Fig. 3. One can note that, in contrast with the experiment for which the dynamical dipole yield is centred at γ-ray energy of approximately 14 MeV (see Fig. 2), the calculated Bremsstrahlung emission is located around 10–11 MeV. As the energy of the dynamical dipole yield centroid is related to the restoring force of the isovector oscillation, a BNV calculation with the same parametrizations of the symmetry term of the EOS was performed applying a 0.3 fm separation between the centre of mass of protons and neutrons of ^{132}Ce nucleus to mimic the GDR oscillation and to extract its centroid. As expected, the GDR centroid energy was found to be higher than the dynamical dipole one. In Fig. 3 the calculated GDR centroid is displayed with arrows.

Possible explanations of the discrepancy between measured and calculated dynamical dipole centroid could be related to the fact that, experimentally, it is very difficult to extract the strength in the region below 12 MeV because of the very steep exponential yield dominated by statistical emission.

The total multiplicity of the prompt dipole radiation was obtained integrating the measured γ-ray excess over energy and over solid angle by taking into account a flat angular distribution and the experimental set up efficiency. If, instead, we take into account the angular distribution given by the BNV calculation, the values of the total multiplicity changes for less than 10%. The error bars in the measurements are mainly related to the uncertainty in the determination of the energy lost in the pre-equilibrium phase.

The predicted total multiplicities are compared with the measured ones in the left panel of Fig. 4. The BNV calculations (filled triangles) reproduce the measured data and consequently their beam energy dependence. From Figs. 3 and 4 (left panel) one can see that, in our case, the density dependence of the symmetry energy below saturation is essentially affecting only the centroid of the prompt dipole photon spectrum. Another quantity probing the dynamical dipole picture is the angular distribution of the γ-ray yield. For the present experiment, with the BaF_2 mounted in the angular interval 120°–160°, the angular distribution of the γ yield from the prompt dipole in the region $E_\gamma = 10$–20 MeV at $E_{beam} = 15.6$ MeV/nucleon is presented in the inset of Fig. 4 (left panel). The angular distribution of the measured excess yield is compared to calculations ($W(\theta) = W_0[1 + a_2 P_2(\cos\theta)]$) with 3 values of a_2 ($a_2 = -1$ corresponding to a dipole aligned to beam axis, $a_2 = -0.24$ giving the best fit to the data and $a_2 = -0.12$ given by the BNV calculation with asy-stiff parametrization of the EOS [2]). Although restricted to a rather narrow interval the data are in agreement with the BNV prediction.

It is interesting to compare the measured yield of the dynamical dipole emission of the $^{16}O + ^{116}Sn$ reaction ($D(0) = 8.6\ e\,\mathrm{fm}$) at the bombarding energy of 15.6 MeV/nucleon with the one in Ref. [11] concerning the reaction of $^{36}Ar + ^{96}Zr$ ($D(0) = 20.6\ e\,\mathrm{fm}$) at the bombarding energy 16 MeV/nucleon. This comparison is shown in the right panel of Fig. 4 together with the predicted yields. The dependence on the value of the initial dipole moment at ~ 15 MeV/nucleon is measured to be less pronounced than in the BNV predictions. If one uses values of the in medium N–N cross section [28] the calculation is able to reproduce the datum at $D(0) = 8.6\ e\,\mathrm{fm}$ but not the one at $D(0) = 20.6\ e\,\mathrm{fm}$, and the opposite is true when one uses the N–N cross section in vacuum. This fact could be related to the lower nuclear density in the case of the point at larger dipole moment.

In summary, the energy and dipole moment dependence of the γ-ray yield emitted by the prompt dipole was obtained using the reactions $^{16}O + ^{116}Sn$, $^{64}Ni + ^{68}Zn$ and the one of Ref. [11]. While the intensity of the prompt dipole emission is found to be reproduced within the error bars by the predictions based on the BNV model at the two measured bombarding energies of 8.1 and 15.6 MeV/nucleon, the predicted centroid energy is approximately 3 MeV lower than the experimental values (obtained by subtracting a statistical model prediction free of any normalization factor).

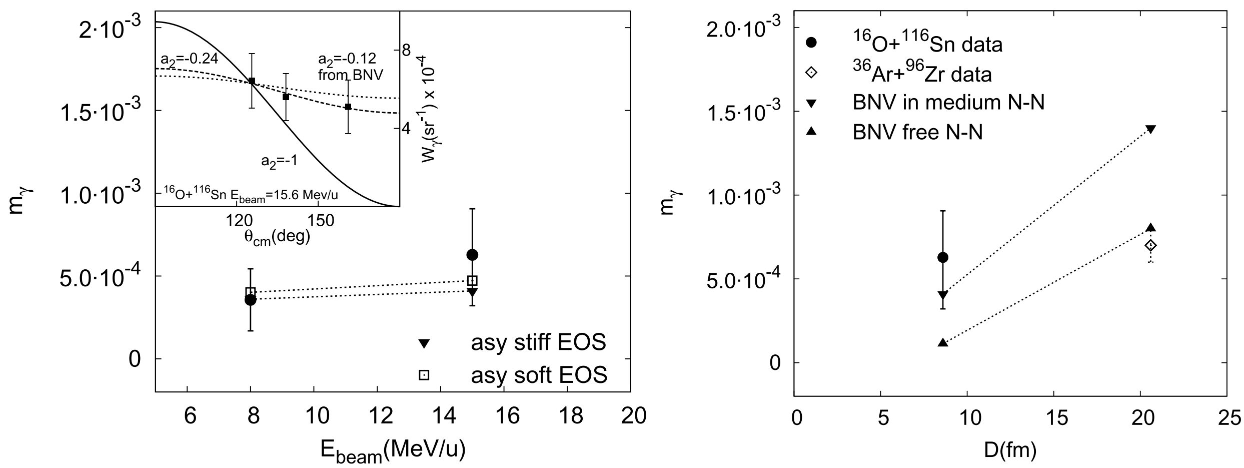

Fig. 4. The left panel shows the measured and calculated total γ multiplicity as a function of beam energy for the system $^{16}O + {}^{116}Sn$. The error bars in the measurement (filled dots) reflect mainly the uncertainty in the determination of the energy lost in the pre-equilibrium phase. The calculations performed with the BNV model correspond to two different parametrizations of the symmetry term. The inset shows the measured angular distribution of γ-ray excess yield in the region $E_\gamma = 10$–20 MeV for $E_{beam} = 15.6$ MeV/nucleon compared with 3 different parametrizations. The right panel shows the present datum at 15.6 MeV/nucleon in comparison with the datum and calculations reported in Ref. [11] for the reaction $^{36}Ar + {}^{96}Zr$ at 16 MeV/nucleon. In both panels, the lines are to guide the eyes.

The dependence of the γ-ray yield on the value of the dipole moment is found to be rather flat in the experiment, in contrast with predictions. As a final remark it should be pointed out that the absolute γ-ray multiplicity of the prompt dipole emission was measured only in very few experiments. This fact limits a comprehensive comparison with the theory. Consequently, the findings of the present work call for more data providing the multiplicity of the prompt dipole emission for reactions leading to CN in the same mass region as a function of bombarding energy and N/Z asymmetry (dipole moment). To reach very asymmetric N/Z values one will need radioactive beam facilities although a better understanding of this effect should be obtained before aiming at extreme values of N/Z. Further systematic studies with stable and radioactive beams is expected to provide, together with the multi-fragmentation studies, relevant information on the symmetry energy for very asymmetric nuclear matter.

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