Measurements of Dynamical Dipole in isospin asymmetric fusion reactions

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Abstract. In heavy ion nuclear reactions the process leading to complete fusion is expected to produce pre-equilibrium $\gamma$-ray emission, if particular conditions are met. Indeed, when there is an N/Z asymmetry between projectile and target, charge equilibration takes place with a collective dipole oscillation, called Dynamical Dipole (DD), associated to a $\gamma$-ray emission. The existing experimental data concerning this pre-equilibrium $\gamma$-ray emission are still rather scarce and mainly concentrated in the A$^{132}$ mass region. The very preliminary results concerning the measurement of the DD $\gamma$-ray emission in the fusion reaction $^{16}$O ($E_{lab}$=192 MeV) + $^{116}$Sn at 12 MeV/u will be presented and compared with the $\gamma$ yield measured for the same reaction at 8.1 and 15.6 MeV/u. The present experiment aims at the measurement of the total emission yield of the DD at 12 MeV/u where the predicted theoretical yield does not completely reproduce the experimental data. The experiment has been performed at the INFN Legnaro Laboratories using the GARFIELD-HECTOR array.

1. Introduction
The study of the collective properties of a nuclear system is a powerful tool to understand the structure which lies inside the nucleus. A successful technique which has been used in this field
is the measurement of the decay of the highly collective Giant Dipole Resonance (GDR). In fact, GDR can be used as a probe for the internal structure of hot nuclei and, in addition, constitutes a clock for the thermalization process. Using the fusion-evaporation reaction, it has been recently possible to study i) the yield of the high-energy gamma-ray emission of the Dynamical Dipole which takes place during the fusion process if there is an N/Z asymmetry and ii) the degree of isospin mixing at T=0 in the decay of $^{80}\text{Zr}$ [1].

In heavy ion nuclear reactions the process leading to complete fusion is expected to produce pre-equilibrium gamma-ray emission. If there is isospin asymmetry between the projectile and the target, it is possible to form a time dependent dipole moment which is associated with gamma radiation emission, called dynamical dipole (DD). This phenomenon is expected to depend on the energy of the projectile and on the size of the dipole moment calculated as

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

The existing experimental data are still rather scarce and, although some systematic exists in the A\lessgtr 132 mass region, the data do not seem to follow the theoretical predictions concerning the dependence of the DD yield emission with beam energy. Experimentally, it was observed that Dynamical Dipole emission increases with beam energy up to \approx 10 MeV/u, then the yield significantly decreases [2], [3], [4]. Qualitatively, an increase of the DD yield with beam energy is expected as the dynamics in the neck region between projectile and target, where the DD oscillation develops, become faster. A decreasing yield for higher beam energies is similarly expected due to the damping related to fast processes like pre-equilibrium neutron emission and proton-neutron direct collisions that reduces the isospin asymmetry and damps the isovector oscillation [5]. The DD yield dependence with beam energy is the result of the interplay between these two phenomena.

The model which better describes the Dynamical Dipole uses the dynamical evolution of the dipole in the framework of BNV prescription and employs the bremsstrahlung expression for the calculation of the photon yield. It is important to point out that the model critically depends on the nuclear equation of state with its symmetry term and on its density dependence. In $^{16}\text{O} + ^{116}\text{Sn}$ the dependence on the nuclear EOS with its symmetry term is not so strong, instead this dependence become significantly in neutron rich nuclei such as $^{132}\text{Sn}$. The theoretical model predict that the dependence on the symmetry term of EOS is clear visible for $^{132}\text{Sn} + ^{58}\text{Ni}$ [6]; so it is necessary to study this phenomena in neutron rich nuclei. Consequently, the dynamical dipole emission, being related to the isospin asymmetry in the entrance channel, is also affected by the value of the symmetry energy and in the future could be used to estimate a value for it.

The understanding of this mechanism is relevant in the study of exotic nuclear matter especially in view of the future availability of intense radioactive beams that are expected to give a boost to this kind of measurements especially if $^{132}\text{Sn}$ beams will be available with high intensity.

An experimental campaign on the DD yield has been performed at LNL [14] (Laboratori Nazionali di Legnaro), using GARFILED-HECTOR arrays [7]. During this campaign the DD emission in the fusion reaction $^{16}\text{O} (E_{lab}=192 \text{ MeV}) + ^{116}\text{Sn}$ has been measured in function of beam energy (in particular at 8.1MeV/u, at 12MeV/u and at 15.6MeV/u); data at 8.0 and 15.6 MeV/u have been already discussed in [8]. Some preliminary results of an experiment which has measured the DD emission in the fusion reaction $^{16}\text{O} (E_{lab}=192 \text{ MeV}) + ^{116}\text{Sn}$ will be presented. The experiment aims at the measurement of the total emission yield of the DD at an intermediate value of beam energy (12 MeV/u). The experiment set up is composed by the GARFIELD array (for the measurement of light charged particles), by an array of phoswich detectors (for the measurement of fusion residues) and by the HECTOR+HELENA arrays of BaF$_2$ detectors.
2. Experimental set up

The experimental setup was composed by different detection systems in order to provide correlated information on γ rays and particle emission in coincidence with the evaporation residue. The setup is illustrated in figure 1. In particular, the forward chamber of the GARFIELD apparatus is dedicated to the measurement of light charged particles (LCP) emitted during the different steps of the fusion-evaporation process.

The FIASCO [11] array consists of four boxes placed in the very forward direction (5° - 13°) to be used as an evaporation residue trigger and as a proton/alpha multiplicity counter. Each box contains eight phoswich detectors made of three layer scintillators. GARFIELD and FIASCO detectors use fully digitized electronics [12], [13] that allows on-line pulse shape analysis of both GARFIELD CsI(Tl) and FIASCO multilayer scintillators. This allows to perform LCP pulse shape identification in GARFIELD and evaporation residue accurate selection in FIASCO.

Eight large volume BaF$_2$ scintillators from HECTOR array are used for the measurement of the high-energy γ rays [7] [14].

Two additional groups of small (3”x3”) BaF$_2$ scintillators from the HELENA array have been used. The first group was placed close to the target to provide a time reference to be compared with the one obtained from the pulsed beam radiofrequency (RF), while the second one was mounted in the forward direction for the measurement of pre-equilibrium neutrons.

3. Preliminary results

The analysis of the data has been focused to produce the high energy γ ray spectrum emitted in the fusion evaporation process (see the data in figure 3). From the data analysis we have estimated ≈50000 coincidence events between high energy γ rays (10-20 MeV) and one evaporation residue. A preliminary comparison with Statistical Model shows evidence of an excess yield between 10-20MeV (see figure 3) which is attributed to Dynamical Dipole emission. The extra yield has been compared with the previous results obtained at 8 MeV/u and 15.6 MeV/u (see [8]). The measured data shows an increasing behavior (see figure 3) similar to that of [3].

The measured pre-equilibrium contribution has been compared to the theoretical predictions from BNV-model calculations [5]. The BNV model has as input of the simulation i) the nuclei and parameters of the reaction; ii) the nuclear Equation of State (EOS) as function of his density (The model uses two different parametization of EOS: Asy-Stiff and Asy-Soft) [5]; iii) the Nucleon-Nucleon (N-N) in medium cross section. The output of the model is the nucleon dynamics from BNV equation during fusion reaction for an isovector oscillation on isolated
Figure 2. The comparison between the BaF$_2$ energy spectrum (blue points) with prediction by the statistical model (straight line). An excess of counts between 10-20MeV is visible. The two spectra have been normalized at 7 MeV.

Figure 3. The DD $\gamma$-emission yield measured in mass region A=132 for beam energy ranging from 6 to 15 MeV/u. Left panel: data reported in reference [3]. Right panel: data points at 8 and 15.6 MeV/u are from [8], in green the experimental point (indicate with data), in red the point from the BNV model of asy-soft parametrization (indicated with a2), in blue the point of asy-stiff parametrization (indicated with a1). For the point at 12 MeV/u, as the analysis is not completed yet, we report the region where we expect to have the measured total gamma yield.

nucleus (GDR-like). This model has been used to estimate the DD $\gamma$ multiplicity for different impact parameters at the three beam energies (8.1 - 12 - 15.6 MeV/u). In the reaction $^{16}$O (Elab=192 MeV) + $^{116}$Sn there is not enough sensitivity to different EOS parametrizations. The DD $\gamma$ multiplicity has been calculated with the BNV model, for the three different beam energies and for different impact parameter (b=0, 2, 4, 5, 5.5, 6 and 6.5 fm). From this calculation we obtain that the DD contribution decreases when the impact parameter increase; for impact parameter $b = 7$ there is not fusion and at high impact parameter (bigger than 4)
the DD contribute became smaller and seems to be constant untill $b = 6.5$. For this reason it is very important to choose the right weight of each impact parameter. The DD $\gamma$ multiplicity increases, with the beam energy, but this increase is rather small, namely of the order of 8%. Furthermore, the different nuclear equation of state parametrizations used in calculation do not seem to produce a good agreement with measured data [8], [2], [3]. This difference between the expected and measured DD total $\gamma$-ray yield calls for further investigation, e.g. performing new theoretical calculations with different parameterization of N-N cross section and a more detailed description of the pre-equilibrium particle emission. For this reason, it is necessary to well understand the DD emission yield in function of the beam energy to be prepared for radioactive beams with extreme N/Z Ratios.

The Angular distribution of $\gamma$-rays measured in the backward hemisphere (covered by HECTOR detectors) will be extracted from data at 12 MeV/u and the comparison with the one obtained within theoretical model will provide a much deeper detailed check of the model.

4. Conclusion
The measured $\gamma$-ray spectra has been compared with the statistical $\gamma$ decay of $^{132}$Ce$^+$ and the measured pre-equilibrium Dynamical Dipole emission yield has been compared with that given by the BNV-model. The theoretical model displays an almost constant trend in function of the beam energy for the DD $\gamma$ multiplicity instead for the experimental data there is a different trend. More detailed theoretical BNV calculation (in collaboration with Catania) are in progress. The general trend of the calculations shows a small increase of DD multiplicity with the beam energy (at a fixed impact parameter) and a decrease of the DD contribute as the of impact parameter increases (at a fixed beam energy). For the future the angular distribution (at 12MeV/u) will be extrated from the experimental data and the pre-equilibrium neutron multiplicity (in collaboration with Bologna and Firenze) will be calculated.

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