Measurement of the Dynamical Dipole gamma decay in N/Z asymmetric reactions

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ABSTRACT

We propose to measure the gamma decay of the Dynamic Dipole (DD) produced in the early phase of the fusion process in reactions with charge asymmetric entrance channel. The measurement of this pre-equilibrium emission is obtained by comparing the high energy gamma ray spectra measured in two fusion reactions (one symmetric and one asymmetric in N/Z) associated to the same compound nucleus in identical conditions.

The existing experimental data concerning this topic are still rather scarce, and although some systematic exists in the A≈132 mass region the data seem not to follow the theoretical predictions concerning the energy of the emission and its intensity dependence on the beam energy.

The proposed experiment is a follow up of a very successful experimental campaign performed in 2003 [1-3] where, in addition to the temperature dependence of the GDR width, the intensity of the Dynamical Dipole in the reaction ^{16}O + ^{116}Sn at beam energies of 130 and 250 MeV was measured.

This measurement intends to measure the Dynamic Dipole emission in the region between the data points previously taken, where disagreement is found between very recent measurements and calculations in literature [3-8]. Moreover a good excitation function of the Dynamical Dipole Effect appears even important in order to extract independent information on the symmetry energy below saturation [8].

We propose to use the N/Z asymmetric ^{16}O (E_{lab}=192 MeV) + ^{116}Sn fusion evaporation reaction to excite the Dynamical Dipole. The high energy gamma ray spectra relative to the N/Z symmetric reaction (necessary to isolate the pre-equilibrium emission) will be obtained with the additional reaction ^{64}Ni (E_{lab}=367.5

MeV) + ^{68}Zn. Both reactions will produce, after pre-equilibrium emission, ^{132}Ce at E*=135 MeV.

The experimental setup we plan to use is the combined setup of the GARFIELD and HECTOR arrays. As compared with the setup of the 2003 campaign the array has been improved. In fact, the evaporation residues will be detected via a wall of phoswich scintillators and fast sampling digital electronics will be used instead of analogue one. Such changes in the setup have already shown, in the measurement of February 2008, an evident improvement in the quality of the data. In addition, we will measure the neutron multiplicity in forward and backward directions (using TOF information in additional BaF_2 detectors) and low energy gamma rays (using $LaBr_3$ detectors).

The request is for 14 days of beam time divided as follows:
6 days for ^{16}O + ^{116}Sn with E_{beam} = 192 MeV
6 days for ^{64}Ni + ^{68}Zn with E_{beam} = 367.5 MeV
1 day for calibration of BaF_2 with 45 MeV ^{11}B + ^{2}D
1 day for calibration of Garfield set-up.

We ask a current on target of 1-2 pnA of Tandem-Alpi beam.

Following the PAC request the GARFIELD-HECTOR proposal on the measurement of the temperature evolution of the GDR width and Jacobi shape transition in hot rotating ^{88}Mo nuclei will be resubmitted. Consequently the proposed experiment on the measurement of the Dynamic Dipole is planned by the collaboration to come after the ^{88}Mo measurement. In fact, the experimental setup for this measurement requires additional work not necessary for ^{88}Mo proposal. For the same reason it should come before the experiments discussed in the LOI submitted to the PAC by the GARFIELD collaboration.

1. The physics case:

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 larger timescale.
In the case of charge asymmetric entrance channels, one expects, at the time of the CN formation, a pre-equilibrium photon emission from the dipole oscillation due to the isospin transfer dynamics. The energy of this photon emission ranges between 8 to 15 MeV and its centroid energy is predicted to be at a lower energy relatively to that of the GDR state.
The Dynamical Dipole was firstly measured in 1996 [9]. The presence of this pre-equilibrium dipole strength was already predicted [10] and, in recent papers, is described as a pre-equilibrium collective dipole mode [7,11,12]. Experimental data are rather scarce and complete and more systematic studies are still missing. It has

been shown that, in general, the strength of the Dynamical Dipole depends on the beam energy and on the asymmetry of the N/Z value between projectile and target, namely on the value of the initial dipole moment D(0) of the fusing system (see eq. 1, where the indices *p* and *t* refer to the projectile and target of the reaction):

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

In recent experimental campaigns performed in LNL and LNS, the properties of the Dynamic Dipole in A ~ 130 mass region have been studied with different beam energies and with different initial dipole moments. Figure 1 shows the experimental results compared with the theoretical prediction obtained using the BNV model [11]. In fig. 1a and 1b data relative to the intensity of the Dynamical Dipole measured with N/Z asymmetric reactions, all producing ^{132}Ce compound nucleus, are shown [2-3,4-6]. In the bottom panel of figure 1 the predictions of the BNV model calculated for the measured systems are shown in comparison [7,8,11,13]. It is evident that, even though both theory and experiment show that the prompt dipole radiation intensity as a function of beam energy presents a maximum or a saturation, the position of the maximum is not correctly predicted. A data point in fig 1b at 12 MeV/u (objective of this proposal) will be extremely important to clarify this open question.

The theoretical predictions describing the Dynamical Dipole are based on two different models. The first, the phonon model [10], 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 the increase of the yield related to the increase of the size of the dipole moment but not so well the behaviour as a function of the bombarding energy. A weak point of this phonon model is that it does not take into account the radiation emitted in the pre-equilibrium phase, before the CN formation, when also particle emission takes place.

The second model uses a dynamical approach, which describes the dynamical evolution of the dipole in the framework of BNV model and employs the bremsstrahlung expression for the calculation of the photon yield [7]. The BNV model critically depends on the nuclear equation of state with its symmetry term and on its density dependence [13]. 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. Presently, a particular effort is made to study the symmetry term of the equation of state due to its impact in nuclear astrophysical problems such as that of the dynamics of nuclear reaction chains during a supernovae.

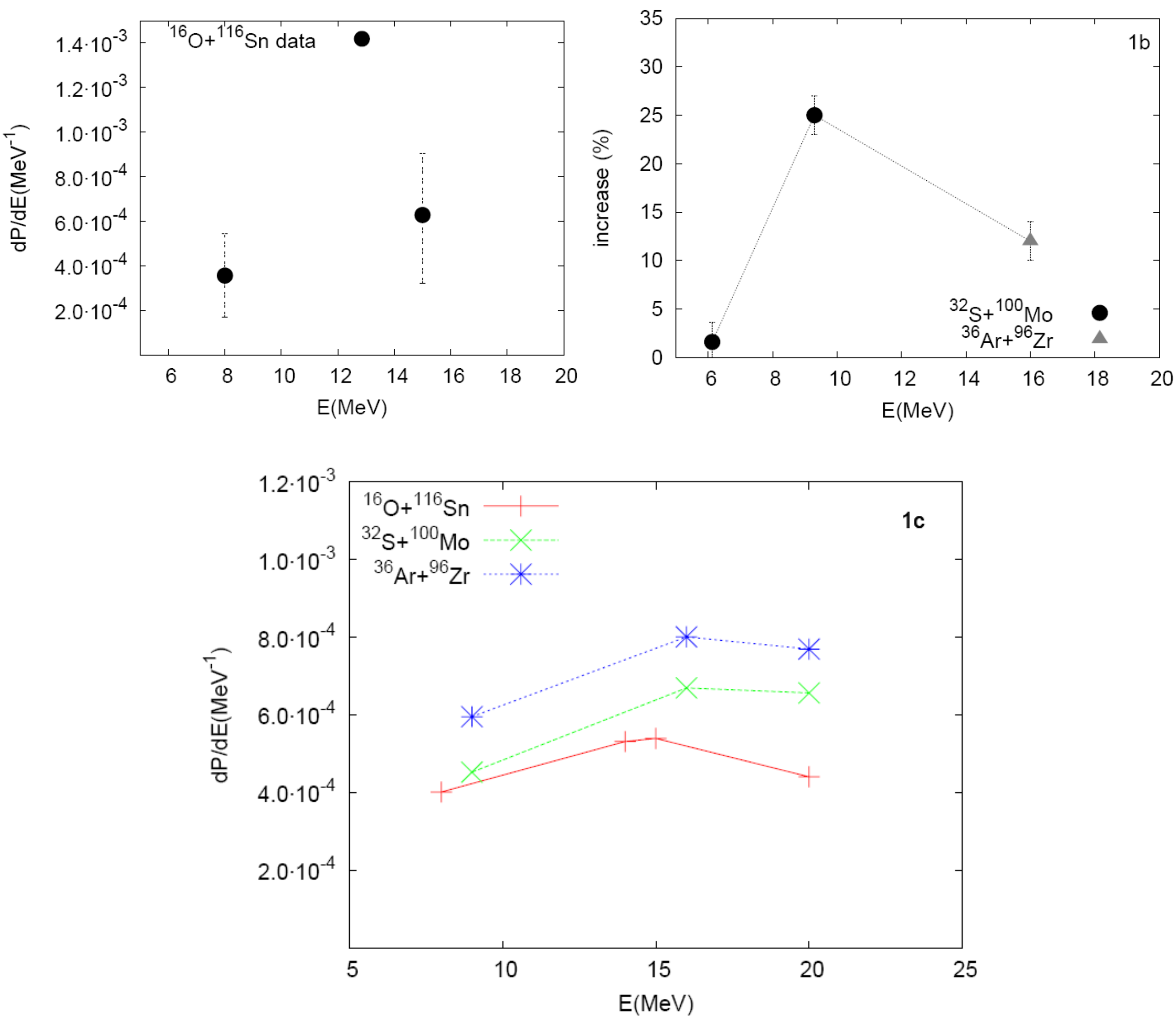

Figure 1a: *the absolute intensity of the Dynamic Dipole as was measured in the 2003 campaign and discussed in ref [2,3] for the asymmetric N/Z reaction ^{16}O + ^{116} Sn at 8.1 and 15.6 MeV/u.* **1b**: *the excess yield of the Dynamical Dipole (measured relatively to the statistical emission) reported in ref [4-6] obtained using the N/Z asymmetric reactions ^{32}S + ^{100}Mo at 6 and 9 MeV/u and ^{36}Ar (E_{lab} = 16 MeV/u) + ^{96}Zr.* **1c:** *Theoretical prediction of the intensity of the Dynamical Dipole, using the BNV model (see text), for the pre-equilibrium emission for the N/Z asymmetric reactions shown in 1a and 1b* [7,8]. *In all plots the lines are intended to guide the eyes.*

Experimentally, it is practically impossible to isolate the DD emission from the statistical decay of the Giant Dipole Resonance. In fact, both statistical and pre-equilibrium photons have a dipole nature and an energy centred between 10-20 MeV. A good way to isolate and measure the intensity and spectral shape of the gamma decay of the Dynamical Dipole emission is to measure the high energy gamma rays spectra from the decay of a compound nucleus produced using two different heavy ion fusion reactions. One reaction uses a projectile and target combination which is symmetric in N/Z, the second one uses a projectile and target combination which is

N/Z asymmetric. If the fused compound nucleus produced in the two reactions is exactly the same, the difference between the two gamma rays spectra will display the pre-equilibrium emission only, namely the Dynamical Dipole emission.
A further complication might occur if particle pre-equilibrium emission is present. In fact, such kind of emission, which normally depends on the energy of the projectile, cools down the compound nucleus. The straightforward consequence is that it would not be possible to isolate the DD emission simply by the difference of the measured gamma rays spectra. This phenomenon has been accurately studied and quantified (see figure 2) in our 2003 campaign. Consequently we can predict the energy lost by pre-equilibrium and calculate the kinetic energy of the projectile in order to obtain the correct excitation energy of the fused compound.

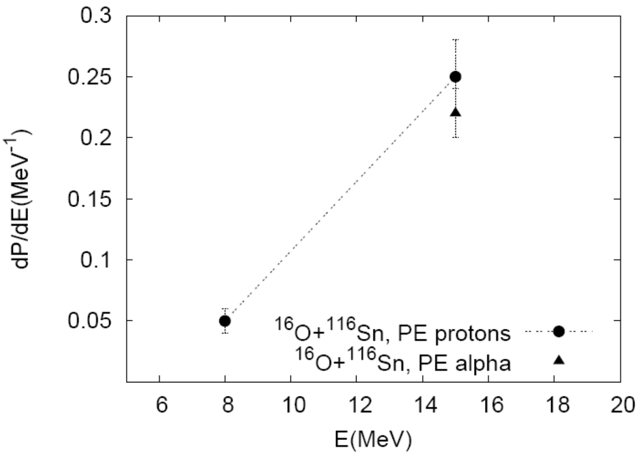

Figure 2: *Charged particle pre-equilibrium emission probability measured in the reactions $^{16}O+^{116}Sn$ at 8.1 an 15.6 MeV/u in the 2003 experimental campaign[2-3].*

In summary, we propose to study the Dynamical Dipole emission during the fusion process in N/Z asymmetric reactions. This study could solve an open problem consisting in a disagreement between theoretical and experimental data concerning the intensity dependence of this emission on the projectile energy. The nuclear equation of state, the symmetry energy and the nucleon-nucleon cross section in nuclear matter are critical input parameters of the BNV model which is used to describe this phenomenon. Consequently, experimental data are very useful to correctly pin down or check their values. An additional reason which makes this kind of studies interesting is related to the fact that, with the future availability of intense radioactive beams, it will be possible to produce the same compound nucleus in a large variety of projectile-target combinations. In the case of DD studies this means to have the possibility to better study the intensity of the Dynamical Dipole as a function of the initial dipole moment (see eq. 1). It is therefore important to understand now, before the radioactive beams will become available, the dependence of this emission with the beam energy.

2. Experiment

The proposed study of the Dynamic Dipole emission needs the measurement of the pre-equilibrium and statistical γ emission produced in two reactions leading to the same compound nucleus. The reactions are ^{16}O (192 MeV) + ^{116}Sn and ^{64}Ni (377 MeV) + ^{68}Zn both leading to a hot compound nucleus at the same excitation energy (E*) and similar angular momentum distribution. The beam energy of ^{16}O has been appropriately corrected to produce a compound nucleus exactly at the same excitation energies as that produced by ^{64}Ni using the results of the detailed pre-equilibrium charged particle emission study performed in 2003.

The proposed set up will consist of three main parts:

Detector for gamma-rays:

- Eight large volume BaF_2 crystals of the HECTOR set up are used for high energy γ-ray detection.
- One or more $LaBr_3$ detectors for low energy gamma rays detection
- Two clusters of hexagonal BaF_2 detectors for the time reference and the measurement of the neutron multiplicity

Evaporation residues trigger:

The evaporation residues trigger is made up by a group of phoswich detectors positioned at about 150 cm from the target. The phoswich set up consists of 4 boxes each containing up to 9 detectors 6.4cm X 6.4 cm each. The angular coverage ranges from about 4 to 13 degrees in the laboratory reference system. The evaporation residues are stopped in the plastic foil and identified through Time of Flight, while the phoswich second stage is used for forward light charged particle detection.

Light charged particle detection and light fragments detection:

The GARFIELD array will detect Light Charged Particle (LCP) and fragments from 30 to 90 ° through ΔE-E signals obtained by gaseous microstrip plus CsI(Tl) scintillator inside the drift chamber. The LCP identification capability is now extended to the most weakly ionizing particles due to Pulse Shape Analysis (PSA) for the CsI(Tl) crystals done by means of entirely digitalized electronics.
We have calculated the γ-ray yield of the proposed reaction with the statistical model including pre-equilibrium effects. In order to measure the Dynamic Dipole emission with good precisions it is crucial to have sufficient statistics to compare the experimental spectra which could differ by small amount (up to 10-20%) of events in the high energy part of the energy spectrum.

We need approximately 300 counts at E_γ= 14 MeV per 0.5 MeV bin, in order to obtain the DD intensity with an error of 10% - 20%

Beam time request

For the asymmetric N/Z reaction, $^{16}O+^{116}Sn$, we plan to use a beam current of 1-2 pnA on a target 0.5 mg/cm^2 thick. The expected absolute efficiencies are ≈ 1% for the BaF_2 detection system at 12 MeV and 11% for the fast Phoswich scintillators (these numbers have been verified in previous experimental campaigns with the Garfield+Hector setup under similar kinematical conditions).
At E_{lab} = 192 MeV (corresponding to a pre-equilibrium emission of ≈ 20 MeV) we expect in 0.5 MeV bin at E_γ =12 MeV a count rate of ≈ 45-50 cts / day.
In this experiment no beam time structure is requested as we plan to use a suitable gamma-based start array (HELENA-BaF_2) to produce a time reference signal.
To obtain the necessary minimum of statistics to be able to observe DD effects we need ≈ 300 cts at 12 MeV, this means 6 days of 24/24h beam on Target. In addition, we need 1 day of calibration beam to produce high energy γ rays of 15.1 MeV. For the second reaction ^{64}Ni + ^{68}Zn at E_{lab} = 367.5 MeV as the produced compound nucleus is the same at the same excitation energy the requirements are identical..
The total request of Beam time is 14 days (not including tuning of ALPI) divided as follows:

6 days for ^{16}O + ^{116}Sn with E_{beam} = 192 MeV
6 days for ^{64}Ni + ^{68}Zn with E_{beam} = 367.5 MeV
1 day for calibration of BaF_2 with 45 MeV ^{11}B + ^{2}D (with a gold foil).
1 day for calibration of Garfield set-up

[1] O.Wieland et al. Phys. Rev. Lett. 97, 012501 (2006)
[2] G.Benzoni *et al*., ISPUN07 Proceedings, World Scientific Singapore (2007)
[3] A. Corsi, Master Thesis, Università degli Studi di Milano (2007)
[4] D.Pierroutsakou *et al*., Phys.Rev C 71, 056405 (2005)
[5] B.Martin *et al.,* Phys. Lett. B-664, 47 (2008)
[6] B.Martin *et al.,* Acta Physica Polonica B, 38 (2007)
[7] V.Baran *et al*., Phys.Rev.Lett 87, 182501 (2001);
[8] M.Di Toro et al., Int.Jou.Modern Physics E17 (2008) 110-119, and M.Di Toro, private communication
[9] S.Flibotte *et al*., Phys.Rev.Lett. 77, 1448 (1996)
[10] Ph.Chomaz *et al*., Nucl.Phys. A 563, 509 (1993); C.Simenel, Ph. Chomaz *et al*., Phys.Rev.Lett 86, 2971 (2001)
[11] V.Baran *et al*., Nucl.Phys. A 600, 111 (1996)
[12] C.Simenel, Ph. Chomaz and G. de France, Phys. Rev. C **76**, 024609 (2007)
[13] V.Baran *et al*., Phys.Rep. 410, 335 (2005)