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

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Abstract

We propose to measure the gamma decay of the Dynamical Dipole produced during fusion process in reactions with a charge asymmetric entrance channel.
The aim of this experiment is to explore the Dynamical Dipole dependence on beam energy and on entrance channel dipole moment in a region intermediate between the ones of existing data in the mass region A≈130 [1-6]. Therefore, we propose to measure Dynamical Dipole emission in the following reactions:
^{16}O (E_{lab}=12 MeV/u) + ^{116}Sn (with ^{64}Ni (E_{lab}=5.7 MeV/u) + ^{68}Zn as reference reaction)
^{24}Mg (E_{lab}=15 MeV/u) + ^{110}Pd
The experimental setup we plan to use is the already successfully used combination of GARFIELD and HECTOR arrays. The evaporation residues will be detected via a wall of phoswich scintillators whose signals are processed by digital electronics. In addition, we will measure the neutron multiplicity in forward and backward directions (using time of flight information in additional BaF_2 detectors).

The request is for 17 days of beam time divided as follows:
5 days for ^{16}O + ^{116}Sn with E_{beam} = 192 MeV
5 days for ^{64}Ni + ^{68}Zn with E_{beam} = 365 MeV
5 days for ^{24}Mg + ^{110}Pd with E_{beam} = 360 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.

The comment on this proposal of the PAC Meeting held in July 2008 was the following:

Decisions of the PAC meeting held at LNL, 14-15 July, concerning the experiment:
COMMENT:
The committee found the science motivation for the proposal worthwhile. Unfortunately, however, the PAC could not recommend approval at this time because of the limited beam time available and the fact that other proposals were given a higher priority.

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, before compound nucleus formation, a preequilibrium 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 with respect to the one of the Giant Dipole Resonance decay [7-14].

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):

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

The evolution of the dipole oscillation during the fusion process can be described in the framework of dynamic models (as BNV [9,10,14], TDHF [11] or Molecular Dynamics [12]) and the preequilibrium photon yield can be calculated with Bremsstrahlung formula [10]. The BNV model critically depends on the nuclear equation of state with its symmetry term and on its density dependence [13, 14]. 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 astrophysics topics such as neutron stars properties and the dynamics of nuclear reaction chains during a supernovae explosion [15].

In recent experimental campaigns performed in LNL and LNS [1-6], the properties of the Dynamical Dipole in A≈130 mass region were studied with different beam energies and with different initial dipole moments. Fig. 1 shows the experimental results compared with the theoretical predictions obtained using the BNV model. In figures 1a and 1b data relative to the intensity of the Dynamical Dipole measured with N/Z asymmetric reactions producing ^{132}Ce compound nucleus are shown [2-6]. In Fig. 1c the predictions of the BNV model calculated for the measured systems are shown [3,16]. 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 effect, the position of this maximum is not correctly predicted. An additional experimental value at 12 MeV/u (objective of this proposal) will be extremely important to clarify this open question. Moreover, BNV calculations predict a strong increase of Dynamical Dipole multiplicity with entrance channel dipole moment, while comparing existing data at 15-16 MeV/u beam energy a rather flat dependence is found (Fig. 1d). For this reason an intermediate case at D=14.8 fm would improve the understanding of the role of N/Z asymmetry in heavy-ions fusion reactions.

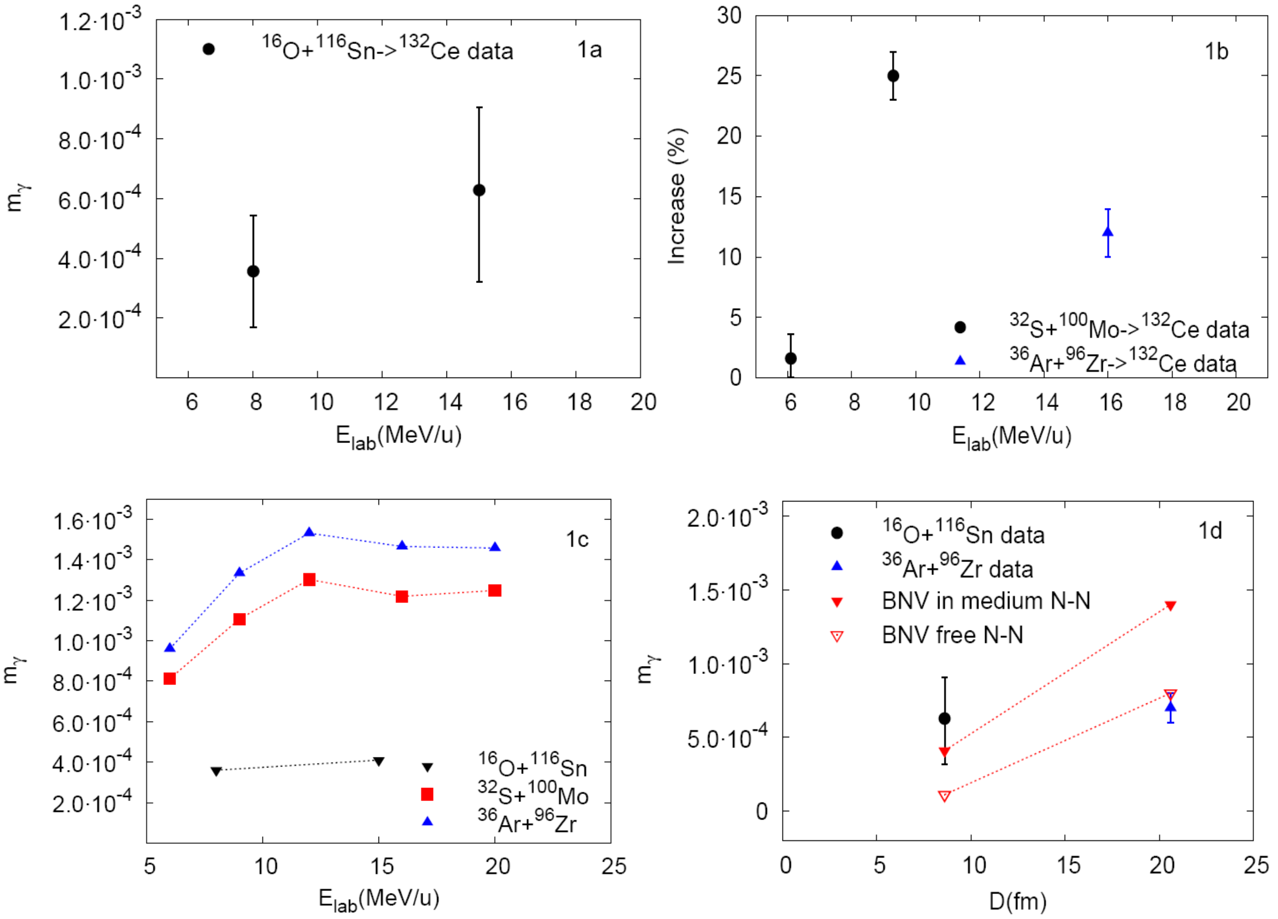

Fig 1a: *Multiplicity of the Dynamical Dipole measured in the 2003 campaign at LNL and discussed in ref [2,3] for the N/Z asymmetric reaction* ^{16}*O +* ^{116} *Sn at 8.1 and 15.6 MeV/u.* **1b**: *Excess yield of the Dynamical Dipole (measured relatively to the statistical emission) reported in ref [4-6] obtained using the N/Z asymmetric reactions* ^{32}*S (*E_{lab} *= 6 and 9 MeV/u) +* ^{100}*Mo and* ^{36}*Ar (*E_{lab} *= 16 MeV/u) +* ^{96}*Zr.* **1c:** *Theoretical predictions of the multiplicity of the Dynamical Dipole obtained with BNV model, for the N/Z asymmetric reactions shown in 1a and 1b* [3,16]. **1d**: *Measured and BNV calculated Dynamical Dipole multiplicity of* ^{16}*O+*^{116}*Sn reaction at 15.6 MeV/u together with the data and calculations reported in reference [5,6] for the reaction* ^{36}*Ar +* ^{96}*Zr at 16 MeV/u. In all plots the lines are intended to guide the eye.*

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

A further complication might occur if particle preequilibrium emission is present. In fact such kind of emission, which normally depends on the energy of the projectile, cools down the compound nucleus. To assess this issue, the preequilibrium energy loss will be deduced from the measurement of light charged particles as was done in 2003 campaign (see Fig. 2).

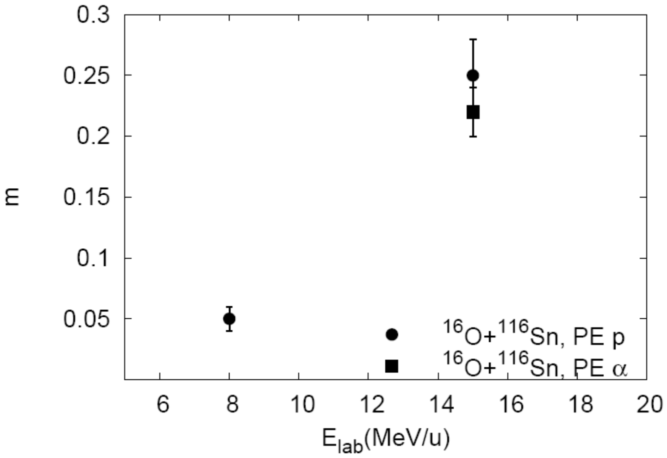

Fig 2: *Preequilibrium light charged particle multiplicity measured in the reaction* $^{16}O+^{116}Sn$ *at 8.1 an 15.6 MeV/u in the 2003 experimental campaign [2,3,17].*

In summary, we propose to study the Dynamical Dipole emission during the fusion process in N/Z asymmetric reactions. This study could help solving an open problem consisting in a disagreement between theoretical and experimental data concerning the dependence of the intensity of this emission on the projectile energy and on the entrance channel dipole moment.
A stringent test to theory is important and needed for future investigations with radioactive beams that will allow to populate systems with larger values of entrance channel dipole moment.

2. Experiment

The proposed experiment is intended to measure Dynamical Dipole emission for the N/Z asymmetric systems ^{16}O + ^{116}Sn at E_{beam}=12 MeV/u (intermediate between the ^{16}O beam energies used in the 2003 campaign [1-3], see Fig. 1a) and ^{24}Mg +^{110}Pd at E_{beam}=15 MeV/u, with an entrance channel dipole moment D=14.8 fm (intermediate between the ones of ^{16}O +^{116}Sn and ^{36}Ar+^{96}Zr, see Fig. 1d).
In order to isolate Dynamical Dipole emission a N/Z symmetric reference reaction is needed. As in the 2003 campaign [1-3], the chosen reaction is ^{64}Ni (E_{lab}=5.7 MeV/u) + ^{68}Zn, leading to the compound nucleus ^{132}Ce at the same excitation energy E*=135 MeV as reaction ^{16}O (E_{lab}=12 MeV/u) + ^{116}Sn. In the case of the ^{24}Mg (E_{lab}=15 MeV/u) + ^{110}Pd reaction we plan to use as a reference the reaction ^{64}Ni+^{68}Zn that we have measured in the past.

The proposed set up will consist of three main parts:

Gamma-ray detectors:

- 8 large volume BaF_2 crystals of the HECTOR set up are used for high-energy gamma-ray detection.
- Two clusters of hexagonal BaF_2 detectors for the time reference and the measurement of the neutron multiplicity

Evaporation residues detector:

The evaporation residues detector is made up by a group of phoswich detectors positioned at about 160 cm from the target. The phoswich set up consists of 4 boxes each containing up to 9 detectors 6.4 cm x 6.4 cm each. The angular coverage ranges from about 4^o to 13^o in the laboratory reference frame. 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 particles and light fragments detection:

The GARFIELD array will detect Light Charged Particles and fragments in the angular range between 30° and 90° using ΔE-E signals obtained with gaseous microstrip plus CsI(Tl) scintillator inside the drift chamber. The LCP identification capability is now extended to the most weakly ionizing particles thanks to Pulse Shape Analysis for the CsI(Tl) crystals performed by means of entirely digitized electronics.

Beam time request

For the N/Z asymmetric 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 kinematic conditions).
We expect a count rate of ≈ 45-50 cts/day in 0.5 MeV bin at E_γ =12 MeV for the ^{16}O (E_{lab}=12 MeV/u) + ^{116}Sn, slightly higher for the ^{24}Mg (E_{lab}=15 MeV/u) + ^{110}Pd due to the higher fusion cross section. In order to measure the Dynamical 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 250 counts at E_γ= 12 MeV per 0.5 MeV bin, in order to obtain the Dynamical Dipole intensity with an error of 10-20%.
Therefore we need 5 days of ^{16}O and 5 days of ^{24}Mg beam. For the reference reaction ^{64}Ni + ^{68}Zn at E_{lab} = 365 MeV the requirements are identical. In addition, we need 1 day of ^{11}B calibration beam to produce high energy γ rays of 15.1 MeV and 1 more day for GARFIELD calibration.
The total request of Beam time is 17 days (not including tuning of ALPI) divided as follows:

5 days for ^{16}O + ^{116}Sn with E_{beam} = 192 MeV
5 days for ^{64}Ni + ^{68}Zn with E_{beam} = 365 MeV
5 days for ^{24}Mg + ^{110}Pd with E_{beam} = 360 MeV
1 day for calibration of BaF_2 with 45 MeV ^{11}B + ^2D
1 day for calibration of Garfield set-up

Possibly, in this experiment no beam time structure will be required as we plan to use a suitable gamma-based start array (HELENA-BaF_2) to produce a time reference signal.

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