Probing the symmetry energy with Exotic Proton-Rich Beams

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Abstract

We present here some physics points to support the development of Fragmentation Radioactive Ion Beams (FRIBS) at LNS, in particular on the Proton-Rich side, more suitable for the SC-Cyclotron. We discuss the possibility of getting independent new information on the poorly known symmetry term of the nuclear EOS at densities below saturation [1, 2]. Based on mean-field transport simulations we suggest some experiments on isospin effects in dissipative collisions with unstable beams, in particular on the properties of reaction products (deformations and isotopic content) and on the microscopic mechanisms responsible for charge equilibration in fusion and deep-inelastic collisions. Due to required high beam intensities, in particular for the photon exps., it would be extremely important to realize the planned development of a new, more performant, transmission line as well as of new ion sources.

A. Isospin Effects on Dissipative Heavy Ion Collisions

Dissipative mid-peripheral collisions, including binary and three-body breakings, offer a unique opportunity to study phenomena occurring in nuclear matter under extreme conditions with respect to shape, intrinsic excitation energy, spin, N/Z ratio (isospin), etc., together with the possibility to control these conditions by choosing appropriate entrance and exit channels. Thus, it is possible to probe the mechanims of nuclear excitation, how intrinsic degrees of freedom are converted into collective modes, how these modes decay and how relaxation processes occur within a small quantal system that is initially far from equilibrium. The velocity and the angular distribution of the reaction products furnish natural clocks from which it is possible to determine the equilibration times of the various degrees of freedom (e.g. N/Z ratio, mass, excitation energy) and discuss whether non-equilibrium features in light particle and IMF emissions are present.

For dissipative collisions at low energy, interaction times are quite long and therefore a large coupling among various mean-field modes is expected. In some cases, due to a combined Coulomb and angular momentum (deformation) effect, some instabilities can show up, like in fission decays [3]. This can lead to three-body breakings, where a light cluster is emitted from the neck region. Three-body process, in heavy-ion reactions with exotic systems, can certainly provide a new access to the dynamics of nuclear scission in new conditions, allowing to investigate the role of the isovector part of the nuclear interaction. In particular, one can investigate whether the development of surface (neck-like) instabilities, that would help ternary breaking, is sensitive to the structure of the symmetry term.

The reaction theory developed at the LNS, based on a Stochastic Mean Field Transport Approach, is particularly suitable for these studies. The mean field dynamics, essential at these low energies, is very accurately treated but fluctuations are also consistently accounted for, in order to reproduce the stochastic effects of dynamical instabilities. The simulations are performed with two choices of the isovector part of the nuclear interaction in the medium, "asystiff", corresponding to a symmetry term passing through the saturation point with a positive slope, and "asysoft", for the case of a flat behavior and eventually a decrease above saturation, see [1, 2].

We have already very promising results for the case of neutron rich beams, which represent part of a Letter of Intent for SPIRAL2 experiments [4], also shown at the last Nucleus-

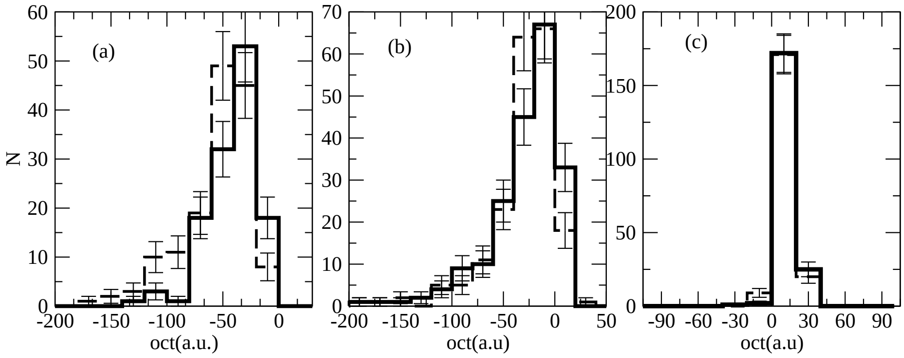

FIG. 1: Distribution of the octupole moment of primary fragments for the $^{132}Sn +^{64} Ni$ reaction at 10 $AMeV$ (impact parameters (a):$b = 6fm$, (b):$7fm$, (c):$8fm$). Solid lines: asysoft. Dashed lines: asystiff

Nucleus Collisions Conference of Rio de Janeiro, [5]. The possibility of exploring events with proton-rich beams looks then very appealing.

In the case of an unstable n-rich projectile, Sn132+64Ni semi-peripheral reactions at 10AMeV have been considered, for which we observe mostly binary exit channels. The two different behaviours of the symmetry energy have been tested. The Wilczynski plots, kinetic energy loss vs. deflection angle, show slightly more dissipative events in the $asystiff$ case, consistent with the point that in the interaction at lower densities in very neutron-rich matter (the neck region of the dinuclear system) we have a less repulsive symmetry term.

In fact the neck dynamics is rather different in the two cases, as it can be well evidenced looking at the deformation of the PLF/TLF residues. The distribution of the octupole moment over the considered ensemble of events is shown in Fig.1 for the three considered impact parameters.

Except for the most peripheral events, larger deformations, strongly suggesting a final 3-body outcome, are seen in the $asystiff$ case. In fact now, due to the lower value of the symmetry energy, the neutron-rich neck connecting the two systems survives a longer time leading to very deformed primary fragments, from which eventually small clusters will be dynamically emitted. Finally we expect to see effects of the different interaction times on the charge equilibration mechanism, probed starting from entrance channels with large N/Z asymmetries, like $^{132}Sn(N/Z = 1.64) +^{58} Ni(N/Z = 1.07)$. Moreover the equilibration mechanism is also directly driven by the strenght of the symmetry term. For more central collisions this has been studied via the direct measurement of the prompt Dynami-

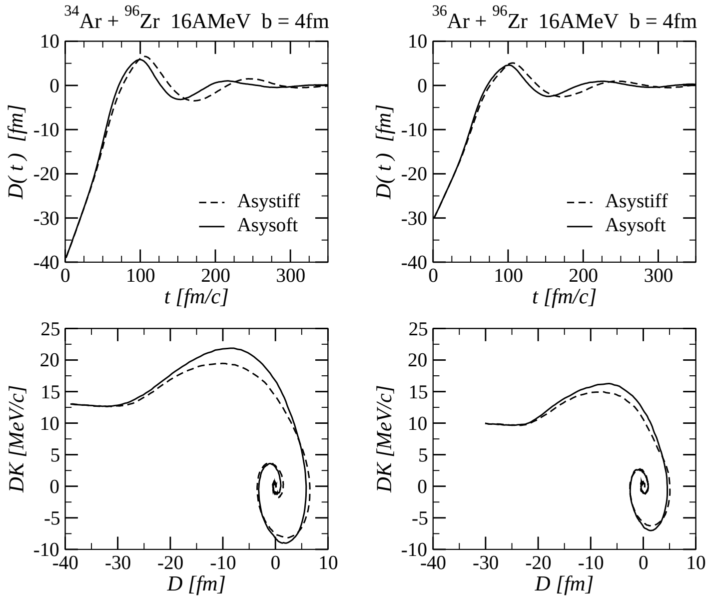

FIG. 2: Entrance channel Dipole Dynamics at 16AMeV, $b = 4fm$ centrality. Left panels: Proton-rich unstable ^{34}Ar beam. Right panels: Stable ^{36}Ar beam. Top figures: Time evolution of dipole moment D(t) in real space. Bottom figures: Dipole phase-space correlation (see text). Solid lines correspond to Asysoft EoS, the dashed to Asystiff EoS.

cal Dipole Emission, nucleus-nucleus collective bremsstrahlung radiation during the charge equilibration path, see the recent [6]. More details for this kind of experiments in the case of proton-rich beams will be shown in the next section.

B. The Prompt Dipole Radiation in Fusion Reactions with Proton-Rich Beams

We discuss an important entrance channel effect in Fusion reactions. If we collide ions with different isospin content, the charge equilibration process proceeds via a damped large amplitude collective Dipole Oscillation which gives rise to a prompt γ-ray emission. This radiation can be easily separated from the statistical compound nucleus GDR emission for the different energy and angular distributions, due to the dynamical character (large deformation of the source, oscillation along the dinuclear symmetry axis), see [7] and the recent results in [6, 8]. Due to the possibility of larger entrance channel charge asymmetries, the effect will be enhanced with the use of exotic proton-rich projectiles. Moreover we will have the chance to form the same compound nucleus with a more charge symmetric entrance

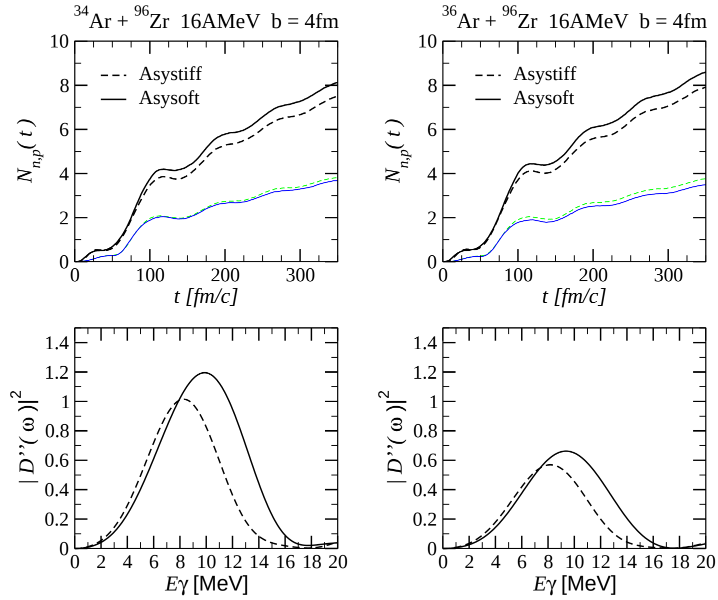

FIG. 3: Same systems as before: entrance channel emissions at 16AMeV, $b = 4fm$ centrality. Top panels: fast nucleon emission rates. Bottom panels: Strength distribution of the prompt dipole radiation (see text) Solid lines correspond to Asysoft EoS, the dashed to Asystiff EoS.

channel and so the extra γ-yield of the asymmetric case will be better revealed. All that will allow to perform detailed studies of the properties of such Dynamical Dipole, in particular for the sensitivity to the low density behavior of the symmetry term.

We present here quantitative evaluations based on transport simulations within a mean-field plus NN collision dynamics, where the radiative probability can be directly estimated as a bremsstrahlung emission during the collective dipole oscillation of the dinuclear system [7]. The simulations are again performed with two (asysoft/asystiff) choices of the isovector part of the nuclear interaction in the medium. Since the symmetry term is acting as a restoring force for the pre-equilibrium isovector dipole oscillation in the more dilute dinuclear system we expect to see a different response for the two effective interactions.

In Fig.2 we report a comparison of the dipole mode in entrance channel for the p-rich ^{34}Ar beam vs the more symmetric stable ^{36}Ar beam in fusion reactions with the same n-rich target, ^{96}Zr. The latter case has been recently studied at LNS in a Medea exp. where it has been possible to measure even the anisotropy of this prompt dipole radiation, [8]. The bottom panels show the spiral correlation between space and momentum dipole oscillation, nice indication of the collective nature of the mode.

We clearly see that in the p-rich beam case we get larger dipole oscillations, more sensitive to the different choice of the isovector interaction.

In the top panels of Fig.3 we show a comparison of the fast nucleon emission rates. In the p-rich beam case we have less pre-equilibrium neutron emissions and this will enhance the prompt collective dipole mechanism for charge equilibration.

In the bottom panels of Fig.3 we present the dynamical dipole γ-emission strength for the same reactions. In fact we can perform a quantitative estimation of the gamma yield in a bremsstrahlung approach [7]:

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma} \mid D''(\omega) \mid^2, \tag{1}$$

where $E_\gamma = \hbar\omega$ is the photon energy and $\mid D''(\omega) \mid^2$ is the Fourier transform of the dipole "acceleration" $D''(\omega) = \int_{t_0}^{t_{max}} D''(t) e^{i\omega t} dt$. (shown in Fig.3). For each event t_0 represents the onset-time of the collective dipole response (phase-space spiraling) and t_{max} the "damping time". i.e. the time step corresponding to an almost flat D(t) behavior.

We note stimulating expectations in the p-rich projectile case, in particular for the dipole radiation: larger yields and better sensitivity to the effective isovector forces. We see roughly a 70% increase of the yields and a more pronounced separation between the centroids varying the symmetry term. Moreover we remark that for the ^{34}Ar beam we can also choose the very charge symmetric $^{40}A+^{90}Zr$ as reference reaction in order to better reveal the entrance channel isospin effects

Finally some comments can be added on the use of such "Light-house" entrance channel effect to detect fusion paths for unstable beams and on the possibility to take advantage of such fast cooling process in the synthesis of heavy elements.

A last point is about the possibility of using exotic proton rich projectiles at highest energies delivered by the LNS Cyclotron. We expect a different charge equilibration dynamics, of exponential type like an overdamped mode, very sensitive to the symmetry energy as well as to the interaction time and so to the total kinetic loss in the binary events, see [9]. The Chimera detector appears to be an ideal facility to analyze these data with proton-rich Fribs beams.

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