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Symmetry Energy Effects on Low Energy Dissipative Heavy Ion Collisions

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Abstract.

We investigate the reaction path followed by Heavy Ion Collisions with exotic nuclear beams at low energies. We focus on the interplay between reaction mechanisms, fusion vs. break-up (fast-fission, deep-inelastic), that in exotic systems is expected to be influenced by the symmetry energy term at densities around the normal value. The method described here, based on the event by event evolution of phase space quadrupole collective modes, will nicely allow to extract the fusion probability at relatively early times, when the transport results are reliable. Fusion probabilities for reactions for the more n-rich composite system, and, for a given reaction, with a soft symmetry term above saturation. A collective charge equilibration mechanism (the Dynamical Dipole Resonance, DDR) is revealed in both fusion and break-up events, depending on the stiffness of the symmetry term just below saturation. Finally we investigate the effect of the mass asymmetry in the entrance channel for systems with the same overall isospin content and similar initial charge asymmetry. As expected we find reduced fusion probabilities for the more mass symmetric case, while the DDR strength appears not much affected. This is a nice confirmation of the prompt nature of such collective isovector mode.

1. Introduction

Production of exotic nuclei has opened the way to explore, in laboratory conditions, new aspects of nuclear structure and dynamics up to extreme ratios of neutron (N) to proton numbers (Z). An important issue addressed is the density dependence of the symmetry energy term in the nuclear Equation of State (EOS), of interest also for the properties of astrophysical objects [1, 2, 3, 4]. By employing Heavy Ion Collisions (HIC), at appropriate beam energy and centrality, the isospin dynamics at different densities of nuclear matter can be investigated [3, 4].

We focus the attention on the interplay of fusion vs. deep-inelastic mechanisms for dissipative HIC with exotic nuclear beams at low energies, just above the Coulomb Barrier (between 5 and 20 AMeV), where unstable ion beams with large asymmetry will be soon available.

We show that the reaction dynamics undergoes a fusion/break-up path bifurcation at very early times due to coulomb and angular momentum effects. In such critical transition stage the final outcome is essentially ruled by dynamical fluctuations and it will be rather sensitive to differences in the neutron-repulsive symmetry term. Moreover, it is now well established that in the same energy range, for fusion reactions between nuclei with different N/Z ratios, the charge equilibration process has a collective character, the prompt Dynamical Dipole Resonance (DDR), a kind of large amplitude Giant Dipole Resonance (GDR), which is thermally excited in the final equilibrated residues, see the recent [5] and refs. therein. The gamma yield resulting from the decay of such pre-equilibrium isovector mode can encode information about the early stage of the reaction [6, 7, 8, 9]. This collective response is appearing in the intermediate neck region, while the system is still in a highly deformed dinuclear configuration with large surface contributions, and so it will be sensitive to the density dependence of symmetry energy below saturation [5]. Here we will show that this mode is present also in break-up events, provided that a large dissipation is involved. In fact we see that the strength of such fast dipole emission is not much reduced passing from fusion to very deep-inelastic mechanisms. This can be expected from the fact that such excitation is related to an entrance channel collective oscillation. Thus we suggest the interest of a study of the prompt gamma radiation, with its characteristic angular anisotropy [5], even in deep-inelastic collisions with radioactive beams.

2. Reaction Dynamics

The reaction dynamics is described by a Stochastic Mean-Field (SMF) approach, extension of the microscopic Boltzmann-Nordheim-Vlasov transport equation [3], where the time evolution of the semi-classical one-body distribution function $f(\mathbf{r}, \mathbf{p}, t)$ is following a Boltzmann-Langevin evolution dynamics (see [10] and refs. therein).

In the SMF model the fluctuating term $\delta I[f]$ is implemented in an approximate way, through stochastic spatial density fluctuations [11]. Stochasticity is essential to get distributions, as well as to allow the growth of dynamical instabilities. In order to map the particle occupation at each time step, gaussian phase space wave packets (test particles) are considered. In the simulations 100 test particles per nucleon have been employed for an accurate description of the mean field dynamics. In the collision integral, I_{coll} , an in-medium depending nucleon-nucleon cross section, via the local density, is employed [12, 13].

The mean field is built from Skyrme forces:

$$U_{n,p} = A \frac{\rho}{\rho_0} + B(\frac{\rho}{\rho_0})^{\alpha+1} + C(\rho) \frac{\rho_n - \rho_p}{\rho_0} \tau_q + \frac{1}{2} \frac{\partial C}{\partial \rho} \frac{(\rho_n - \rho_p)^2}{\rho_0}$$
(1)

where q = n, p and $\tau_n = 1, \tau_p = -1$. The coefficients A, B and the exponent α , characterizing the isoscalar part of the mean-field, are fixed requiring that the saturation properties of symmetric nuclear matter ($\rho_0 = .145 fm^{-3}, E/A = -16 MeV$), with a compressibility modulus around 200 MeV, are reproduced. The function $C(\rho)$ will give the potential part of the symmetry energy:

$$\frac{E_{sym}}{A}(\rho, T=0) = \frac{E_{sym}}{A}(kin) + \frac{E_{sym}}{A}(pot) \equiv \frac{\epsilon_F}{3} + \frac{C(\rho)}{2\rho_0}\rho$$
(2)

For the density dependence of the symmetry energy, we have considered two different parametrizations [14, 15], that are presented in Fig.1. In the Asysoft EOS choice, $\frac{C(\rho)}{\rho_0} = 482 - 1638\rho$, the symmetry energy has a weak density dependence close to the saturation, being almost flat around ρ_0 . For the Asystiff case, $\frac{C(\rho)}{\rho_0} = \frac{32}{\rho_0} \frac{2\rho}{\rho + \rho_0}$, the symmetry energy has a clear increasing slope at normal density. Aim of this work is to show that fusion probabilities, fragment properties in break-up events, as well as properties of prompt collective modes, in collisions induced by neutron-rich exotic beams, are sensitive to the different slopes of the symmetry term around saturation.



Figure 1. Density dependence of the symmetry energy for the two parametrizations. Solid line: Asysoft. Dashed line: Asystiff

3. Fusion dynamics for ^{132}Sn induced reactions

In order to study isospin and symmetry energy effects on the competition between fusion and break-up (deep-inelastic) we consider the reactions ${}^{132}Sn + {}^{64,58}Ni$ at 10 AMeV, having in mind that ${}^{132}Sn$ beams with good intensities in this energy range will be soon available in future Radioactive Ion Beam facilities. In particular, we have performed collision simulations for semiperipheral impact parameters (from b =4.5 fm to b = 8.0 fm, with Δb = 0.5 fm), to explore the region of the transition from fusion to break-up dominance. We have found a reliable criterion that can indicate when the reaction mechanism is changing. This will also allow to evaluate the corresponding absolute cross sections and the symmetry energy effects..

The method is based on a phase space analysis of quadrupole collective modes. The information on the final reaction path is deduced investigating the fluctuations of the system at early times (200-300 fm/c), when the formation of composite elongated configurations is observed and phenomena associated with surface metastabily and/or instability may take place, [16].

We start considering the time evolution, in each event, of the quadrupole moment in coordinate space which is given by:

$$Q(t) = \langle 2z^2(t) - x^2(t) - y^2(t) \rangle,$$

averaged over the space distribution in the composite system. At the same time-steps we construct also the quadrupole moment in momentum space:

$$QK(t) = <2p_z^2(t) - p_x^2(t) - p_y^2(t) >,$$

in a spatial region around the center of mass. The z-axis is along the rotating projectilelike/target-like direction, the x-axis is on the reaction plane.

We run 200 events for each set of macroscopic initial conditions and we take the average over this ensemble.

In Fig.2 we present the time evolution of the mean space quadrupole moment at various centralities in the fusion-break-up transition region for the two reactions and for the two choices of the symmetry term. We notice the difference in Q(t) between the behavior corresponding to more peripheral impact parameters and that obtained for b=5-6 fm, where we have still a little oscillation in the time interval between 100 and 300 fm/c, good indication of a fusion contribution.

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Figure 2. Time evolution of the space quadrupole moments in the angular momentum transition region, between b=5.0 and 7.0 fm. Solid line: Asysoft. Dashed line: Asystiff.



Figure 3. Time evolution of the space density distributions for the reaction ${}^{132}Sn + {}^{64}Ni$ (n-rich systems), 10 AMeV beam energy, for semicentral collisions, b=6.5 fm impact parameter (average over 20 events). Upper Panel: Asystiff. Lower Panel: Asysoft.

We can interpret these observations assuming that starting from about b = 5 fm, we have a transition from fusion to a break-up mechanism, like deep-inelastic. Positive values of the Q(t)-slope should be associated with a quadrupole deformation velocity of the dinuclear system that is going to a break-up exit channel. We notice a slight systematic difference, especially in the most neutron-rich system, with a larger deformation velocity in the Asystiff case. Hence, just from this simple analysis of the average space quadrupole "trajectories" we can already appreciate that the Asysoft choice seems to lead to larger fusion cross sections.

The latter point can also be qualitatively seen from the time evolution of the space density distributions projected on the reaction plane, as shown in Fig.3. The formation of a more compact configuration in the Asysoft case can be related to a larger fusion probability.

It is very instructive to look also at the time evolution of the quadrupole deformations in momentum space. In Fig.4 we present the time evolution of the average p-quadrupole moments at various centralities for the two systems and the two choices of the symmetry term. We notice



Figure 4. Time evolution of the momentum quadrupole moments, in a sphere of radius 3 fm around the c.o.m., for different centralities and for the two systems. Solid line: Asysoft. Dashed line: Asystiff.



Figure 5. ${}^{132}Sn + {}^{64}Ni$ system. Mean value and variance of QK vs Q', averaged over the 100-300 fm/c time interval, at various centralities in the transition region. The box limited by dotted lines represents the break-up region. Upper panel: Asystiff. Bottom Panel: Asysoft.

a difference between the plots corresponding to peripheral or central collisions. With increasing impact parameter the quadrupole QK(t) becomes more negative in the time interval between 100 and 300 fm/c: the components perpendicular to the symmetry axis, that is rotating in reaction plane, are clearly increasing eventually leading to a separation of the deformed dinuclear system. Thus the break-up probability will be larger if the quadrupole moment in p-space is more negative.

From Fig.s 2, 4 one can see that there is a region of impact parameter (b = 5-6.5 fm) where the derivative of the quadupole moment in coordinate space, Q', and the quadrupole moment in momentum space, QK, are both rather close to zero. This is the region where we expect that fluctuations of these quantities should play an important role in determining the fate of the reaction and an event-by-event analysis is essential to estimate fusion vs. break-up probabilities.

The Q'-QK correlation plots for the two systems and the two asy-EOS are presented in



Figure 6. Like in Fig.5 but for the ${}^{132}Sn + {}^{58}Ni$ system.

Figs.5 and 6, respectively. The displayed quantities are mean value and variance of the two extracted properties of the phase space moment evolution in the "bifurcation" time interval $t = 200 - 300 \ fm/c$. We can evaluate the normal curves and the relative areas for each impact parameter in order to select the events: break-up events will be located in the regions with both positive slope of Q(t) and negative QK. In this way, for each impact parameter we can evaluate the fusion events by the difference between the total number of events and the number of break-up cases. Finally the fusion cross section is obtained (in absolute value) by

$$\frac{d\sigma}{dl} = \frac{2\pi}{k^2} l \frac{N_f}{N_{tot}},\tag{3}$$

where l is the angular momentum calculated in the semiclassical approximation, k is the relative momentum of the collision, N_f the number of fusion events and N_{tot} the total events in the angular momentum bin.

In Fig.7 we present the fusion spin distribution plots. We note that just in the centrality transition region there is a difference between the σ -fusion corresponding to the two different asy-EOS, with larger values for Asysoft.

In fact, the total cross sections are very similar: the difference in the area is about 4-5 % in the neutron rich system, 1128 mb (Asysoft) vs. 1078 mb (Asystiff), and even smaller, 1020 mb vs. 1009 mb, for the ⁵⁸Ni target. However, through a selection in angular momentum, $130 \leq l \leq 180$ (\hbar), we find that the Asysoft curve is significantly above the Asystiff one, and so in this centrality bin the fusion cross section difference can reach a 10% in the case of the more neutron-rich system. Then it can be compared to experimental data as an evidence of sensitivity to the density dependence of the symmetry energy.

From the comparison of the total areas for the two systems we can also estimate isospin effects on the total fusion cross section, with a larger value in the more neutron-rich case, as also recently observed in fusion reactions with Ar + Ni [17] and Ca + Ca isotopes [18].

Finally we like to note that for the neutron-rich case, ${}^{132}Sn + {}^{64}Ni$, our absolute value of the total fusion cross section presents a good agreement with recent data, at lower energy (around 5 AMeV), taken at the ORNL [19].

In Fig.7 for the same system (left panel) we show also the results obtained with the macroscopic fusion probability evaluation code *PACE4*, [20, 21] obtained with different l-diffuseness parameters, fixing, as input parameters, our total fusion cross section and maximum angular momentum. We see that in order to have a shape similar to our $\sigma(l)$ distribution we



Figure 7. Angular momentum distributions of the fusion cross sections (mb) for the two reactions and the two choices of the symmetry term. For the ${}^{132}Sn + {}^{64}Ni$ system (left panel), the results of PACE4 calculations are also reported, for different l-diffuseness.



Figure 8. Reaction ${}^{132}Sn + {}^{64}Ni$ semiperipheral. Time evolution of the total density in the "neck" region

have to choose rather large diffuseness values, while the suggested standard choice for stable systems is around $\Delta l = 4 \hbar$. This seems to be a nice evidence of the neutron skin effect.

4. Analysis of symmetry energy effects

The larger fusion probability obtained with the Asysoft choice, especially in the more n-rich system, seems to indicate that the reaction mechanism is regulated by the symmetry term at suprasaturation density, where the Asysoft choice is less repulsive for the neutrons [3, 14]. In order to check this point we have performed a detailed study of the density evolution in the region of overlap of the two nuclei, named *neck* in the following. We present results obtained for the system ${}^{132}Sn + {}^{64}Ni$ at impact parameter b = 6.5 fm.

The time evolution of the total density in this "neck" region is reported in Fig.8 for the two choices of the symmetry energy . We note that in the time interval of interest we have densities



Figure 9. Reaction ${}^{132}Sn + {}^{58}Ni$ semiperipheral. Prompt Dipole oscillations in the composite system for break-up (solid lines) and fusion (dashed lines) events. Left Panel: Asystiff. Right Panel: Asysoft.

above or around the normal density and so a less repulsive symmetry term within the Asysoft choice, corresponding to larger fusion probabilities.

This also explains why larger fusion cross sections are seen for the neutron rich system, mainly in the Asysoft case. In fact, the neutron excess pushes the formed hot compound nucleus closer to the stability valley, especially when the symmetry energy is smaller.

Other nice features are: i) the density values found in the Asysoft case are always above the Asystiff ones, to confirm the expectation of a smaller equilibrium density for a stiffer symmetry term [3]; ii) collective monopole oscillations are present after 100 fm/c, showing that also at these low energies we can have some compression energy.

Break-up Events

Within the same transport approach, a first analysis of symmetry energy effects on break-up events in semiperipheral collisions of ${}^{132}Sn + {}^{64}Ni$ at 10 AMeV has been reported in ref.[22]. Consistently with the more accurate study presented here, smaller break-up probabilities have been seen in the Asysoft choice. Moreover the neck dynamics on the way to separation is found also influenced by the symmetry energy below saturation. This can be observed in the different deformation pattern of the Projectile-Like and Target-Like Fragments (PLF/TLF), as shown in Fig.1 of [22]. Except for the most peripheral selections, larger deformations are seen in the Asystiff case, corresponding to a smaller symmetry repulsion at the low densities probed in the separation region. The neutron-rich neck connecting the two partners can then survive a longer time producing very deformed primary PLF/TLF. Even small clusters can be eventually dynamically emitted leading to ternary/quaternary fragmentation events [23, 24].

In conclusion not only the break-up probability but also a detailed study of fragment deformations in deep-inelastic (and fast-fission) processes, as well as of the yield of 3-4 body events, will give independent information on the symmetry term around saturation.

5. The Prompt Dipole Mode in Fusion and Break-up Events

From the time evolution of the nucleon phase space occupation, see Eq.(1), it is possible to extract at each time step the isovector dipole moment of the composite system. This is given





Figure 10. Reaction ${}^{132}Sn + {}^{58}Ni$ semiperipheral. Prompt Dipole strengths (in c^2 units), see text, for break-up (solid lines) and fusion (dashed lines) events. Left Panel: Asystiff. Right Panel: Asysoft.

by $D(t) = \frac{NZ}{A}X(t)$, where A = N + Z, and $N = N_1 + N_2$, $Z = Z_1 + Z_2$, are the total number of participating nucleons, while X(t) is the distance between the centers of mass of protons and neutrons. It has been clearly shown, in theory as well as in experiments, that at these beam energies the charge equilibration in fusion reactions proceeds through such prompt collective mode. In our study we have focused the attention on the system with larger initial charge asymmetry, the 132 Sn on 58 Ni case,

In Fig.9 we present the prompt dipole oscillations obtained for semicentral impact parameters, in the transition zone. We nicely see that in both classes of events, ending in fusion or deepinelastic channels, the dipole mode is present almost with the same strength. We note that such fast dipole radiation was actually observed even in the most dissipative deep-inelastic events in stable ion collisions [25, 26, 28].

The corresponding emission rates can be evaluated, through a "bremsstrahlung" mechanism, in a consistent transport approach to the rection dynamics, which can account for the whole contribution along the dissipative non-equilibrium path, in fusion or deep-inelastic processes [27].

In fact from the dipole evolution D(t) we can directly estimate the photon emission probability $(E_{\gamma} = \hbar \omega)$:

$$\frac{dP}{dE_{\gamma}} = \frac{2e^2}{3\pi\hbar c^3 E_{\gamma}} |D''(\omega)|^2,\tag{4}$$

where $D''(\omega)$ is the Fourier transform of the dipole acceleration D''(t). We remark that in this way it is possible to evaluate, in *absolute* values, the corresponding pre-equilibrium photon emission yields. In Fig.10 we report the prompt dipole strengths $|D''(\omega)|^2$ for the same event selections of Fig.9.

The dipole strength distributions are very similar in the fusion and break-up selections in this centrality region where we have a strong competition between the two mechanisms. In any case there is a smaller strength in the less central collisions (b=6.0fm), with a centroid slightly shifted to lower values, corresponding to more deformed shapes of the dinuclear composite system.

In the Asysoft choice we have a systematic increase of the yields, roughly given by the area of the strength distribution, of about 40% more than in the Asystiff case, for both centralities and

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selections. In fact from Eq.(4) we can directly evaluate the total γ -multiplicities, integrated over the dynamical dipole region. For centrality b=5.5fm we get 2.3 10^{-3} (1.6 10^{-3}) in the Asysoft (Asystiff) choice, and for b=6.0fm respectively 1.9 10^{-3} (1.3 10^{-3}), with almost no difference betwen fusion and break-up events.

From Fig.1 we see that Asysoft corresponds to a larger symmetry energy below saturation. Since the symmetry term gives the restoring force of the dipole mode, our result is a good indication that the prompt dipole oscillation is taking place in a deformed dinuclear composite system, where low density surface contributions are important, as already observed in ref.[5].

Previously we have shown that the Asysoft choice leads to a large fusion probability since it gives a smaller repulsion at the suprasaturation densities of the first stage of the reaction. Here we see that for the dipole oscillation it gives a larger restoring force corresponding to mean densities below saturation. This apparent contradictory conclusion can be easily understood comparing Figs.8 and 9. We note that the onset of the collective dipole mode is delayed with respect to the first high density stage of the neck region since the composite system needs some time to develop a collective response of the dinuclear mean field.

In this way fusion and dynamical dipole data can be directly used to probe the isovector part of the in medium effective interaction *below and above* saturation density.

Anisotropy

Aside the total gamma spectrum the corresponding angular distribution can be a sensitive probe to explore the properties of preequilibrium dipole mode and the early stages of fusion dynamics. In fact a clear anisotropy vs. the beam axis has been recently observed [29]. For a dipole oscillation just along the beam axis we expect an angular distribution of the emitted photons like $W(\theta) \sim \sin^2 \theta \sim 1 + a_2 P_2(\cos\theta)$ with $a_2 = -1$, where θ is the polar angle between the photon direction and the beam axis. Such extreme anisotropy will be never observed since in the collision the prompt dipole axis will rotate during the radiative emission. In fact the deviation from the $\sin^2 \theta$ behavior will give a measure of the time interval of the fast dipole emission. In the case of a large rotation one can even observe a minimum at 90 degrees [16].

We clearly see that the dominant emission region is the initial one, just after the onset of the collective mode between 80 and 150 fm/c, while the emitting dinuclear system has a large rotation. We can predict a dependence of the angular distribution on the symmetry energy. With a weaker symmetry term at low densities (Asystiff case), the emission probability is a little delayed and presents a smoother behavior. If meanwhile the system has a fast rotation we can expect a clear symmetry term effect on the $W(\theta)$, in particular for the large angular momenta in the transition region.

Hence, from accurate measurements of the angular distribution of the emitted γ 's, in the range of impact parameters where the system rotation is significant, one can extract independent information on the density behavior of the symmetry energy.

6. Mass symmetry effects

It is well known that the mass symmetry of the colliding partners is also affecting the fusion probability. Mass symmetric cases are expected to lead to a reduced fusion events for the combined effect of larger coulomb barrier and smaller dissipation (in a macroscopic "window" model). Since the Dynamical Dipole mode is also related to the fusion dynamics we have analysed both the fusion-break-up competition and the DDR emission for n-rich systems selecting entrance channels with roughly the same charge asymmetry but with rather different mass asymmetry.

We report here some preliminary results for the reactions ${}^{124}Sn(N/Z = 1.48) + {}^{56}Fe(N/Z = 1.15)$ vs. ${}^{90}Kr(N/Z = 1.5) + {}^{90}Zr(N/Z = 1.25)$ at 10 AMeV, i.e. with same average $\langle N/Z \rangle = 1.37$, but with close charge asymmetry and rather different mass symmetry in the entrance channel.



Figure 11. Reactions ${}^{124}Sn + {}^{56}Fe$ vs. ${}^{90}Kr + {}^{90}Zr$ at 10 AMeV. Time evolution of the space quadrupole moments in the angular momentum transition region, between b=4.0 and 7.0 fm. Solid line: Asysoft. Dashed line: Asystiff.



Figure 12. Reactions ${}^{124}Sn + {}^{56}Fe$ vs. ${}^{90}Kr + {}^{90}Zr$ at 10 AMeV. Angular momentum distributions of the fusion cross sections (mb) for the two choices of the symmetry term. The results of PACE4 calculations are also reported, l-diffuseness 12 \hbar .

In Fig.11 we show the time evolution of the mean space quadrupole moments (like Fig.2) for the two reactions and the two choices of the symmetry term. We see that for the mass asymmetric case Sn/Fe we have more definite oscillations in the centrality transition region, clear indication of a larger fusion probability. We note also that in mass symmetric Kr/Zr case the fusion process is slower and at the same 300 fm/c time step we do not see clear asymptotic trends for the space quadrupoles in the transition region (and the same is observed for the momentum quadrupoles QKs). It is then difficult to distinguish symmetry energy effects but we can clearly evaluate the impact of mass symmetry on the fusion cross sections. This is shown in Fig.12. The total cross sections are 1115 mb and 630 mb respectively for the mass asymmetric and symmetric cases (Asysoft choice). We are performing an extension of the calculation to later



Figure 13. Reactions ${}^{124}Sn + {}^{56}Fe$ vs. ${}^{90}Kr + {}^{90}Zr$ at 10 AMeV. Prompt Dipole strengths (in c^2 units) for break-up (solid lines) and fusion (dashed lines) events for impact parameters in the transition region. Left Panel: Asystiff. Right Panel: Asysoft.

times in order to evaluate the dependence on the stiffness of the symmetry terms. Even in this n-rich case we find that in order to have similar $\sigma(l)$ distributions for the PACE4 simulations we have to use a rather large l-diffuseness value.

It is interesting to look at the DDR excitation. In Fig.13 we report the dipole strength distribution $|D''(\omega)|^2$ for the fusion/break-up event selection in the impact parameter transition region. As in the previous ${}^{132}Sn + {}^{58}Ni$ system the DDR emission is larger in the Asysoft choice and not much different for the two reaction mechanism selections. An important point to remark is the larger emission probability for the mass-asymmetric Sn/Fe case. However this effects is almost exactly scaling with the square of the initial Dipole Moment D(t = 0), 26.3 fm for Sn/Fe vs. 22.4 fm for Kr/Fe. This is a clear indication that only the initial charge asymmetry really matters for the prompt dipole emission, which then is not much affected from the different fusion dynamics. All that is fully consistent with the very fast nature of the Dynamical Dipole mode.

7. Conclusions and perspectives

We have undertaken an analysis of the reaction path followed in collisions involving exotic systems at beam energies around 10 AMeV. In this energy regime, the main reaction mechanisms range from fusion to dissipative binary processes, together with the excitation of collective modes of the nuclear shape. Moreover, in charge asymmetric systems, isovector dipole oscillations can be excited at the early dynamical stage, also sensitive to the behavior of the symmetry energy. We have shown that, in neutron-rich systems, fusion vs. break-up probabilities are influenced by the neutron repulsion during the approaching phase, where densities just above the normal value are observed. Hence larger fusion cross sections are obtained in the Asysoft case, associated with a smaller value of the symmetry energy at supra-saturation densities. On the other hand, the isovector collective response, that takes place in the deformed dinuclear configuration with large surface contributions, is sensitive to the symmetry energy below saturation. The relevant point of our analysis is that it is based on the study of the fluctuations that develop during the early dynamics, when the transport calculations are reliable. Fluctuations of the quadrupole moments, in phase space, essentially determine the final reaction path.

In conclusion considerable isospin effects are revealed just selecting the impact parameter

window corresponding to semi-peripheral reactions. Interesting perspectives are opening for new experiments on low energy collisions with exotic beams focused to the study of the symmetry term below and above saturation density. We suggest some sensitive observables:

i) Fusion vs. Break-up probabilities in the centrality transition region;

ii) Fragment deformations in break-up processes and probability of ternary/quaternary events.

iii) γ -multiplicity and anisotropy of the Prompt Dipole Radiation, for dissipative collisions in charge asymmetric entrance channels.

iv) Analysis of the same observables vs. the entrance channel mass asymmetry.

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