# Symmetry Energy Effects on Fusion Cross Sections

C.Rizzo [a,b],V.Baran[c], M. Colonna[a], A. Corsi[d], M.Di Toro[a,b,*]
[a] LNS-INFN, I-95123, Catania, Italy
[b] Physics and Astronomy Dept. University of Catania, Italy
[c] NIPNE-HH, Bucharest and Bucharest University, Romania
[d] Physics. Dept., University of Milano and INFN Sez. Milano
[*] email: ditoro@lns.infn.it

We investigate the reaction path followed by Heavy Ion Collisions with exotic nuclear beams at low energies. We will 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 evolution of the system is described by a Stochastic Mean Field transport equation (SMF), where two parametrizations for the density dependence of symmetry energy (Asysoft and Asystiff) are implemented, allowing one to explore the sensitivity of the results to this ingredient of the nuclear interaction. 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 induced by $^{132}$Sn on $^{64,58}$Ni targets at 10 AMeV are evaluated. We obtain larger fusion cross sections for the more n-rich composite system, and, for a given reaction, in the Asysoft choice. Finally a collective charge equilibration mechanism (the Dynamical Dipole) is revealed in both fusion and break-up events, depending on the stiffness of the symmetry term just below saturation.

PACS numbers: 25.60.Pj;25.70.Jj;21.65.Ef;21.30.Fe

## I. 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 [1–4]. By employing Heavy Ion Collisions (HIC), at appropriate beam energy and centrality, the isospin dynamics at different densities of nuclear matter can be investigated [3–9].

In this work we will 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 will show that the competition between reaction mechanisms can be used to study properties of the symmetry energy term in a density range around the normal value. Dissipative collisions at low energy are characterized by interaction times that are quite long and by a large coupling among various mean field modes that may eventually lead to the break-up of the system. Hence the idea is to probe how the symmetry energy will influence such couplings in neutron-rich systems with direct consequences on the fusion probability. We will show that, within our approach, the reaction path is fully characterized by the fluctuations, at suitable time instants, of phase space quadrupole collective modes that lead the composite system either to fusion or to break-up.

Moreover, it is now well established that in the same energy range, for dissipative reactions between nuclei with different $N/Z$ ratios, the charge equilibration process has a collective character resembling a large amplitude Giant Dipole Resonance (GDR), see the recent [10] 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 [11–15]. 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 [10]. 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 [10], even in deep-inelastic collisions with radioactive beams.

The paper is organized as follows. In Sect.II we present our transport approach to the low energy HIC dynamics with description of the used symmetry effective potentials. Sect.III is devoted to the analysis of $^{132}Sn$ induced reactions with details about the procedure to select fusion vs. break-up events. In Sect.IV we discuss symmetry energy effects on the competition between fusion and break-up (Fast-fission, Deep-inelastic, Ternary/Quaternary-fragmentation) mechanisms. The dependence on symmetry energy of the yield and angular distribution of the Prompt Dipole Radiation, expected for entrance channels with large charge asymmetries, is presented in Sect.V. Finally in Sect.VI we summarize the main results and we suggest some experiments to be performed at the new high intensity Radioactive Ion Beam (RIB) facilities in this low energy range.

## II. 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 [16] and refs. therein):

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m}\frac{\partial f}{\partial \mathbf{r}} + \frac{\partial U}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{p}} = I_{coll}[f] + \delta I[f]. \quad (1)$$

In the SMF model the fluctuating term $\delta I[f]$ is implemented in an approximate way, through stochastic spatial density fluctuations [17]. 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 [18]. The cross section is set equal to zero for nucleon-nucleon collisions below 50 MeV of relative energy. In this way we avoid spurious effects, that may dominate in this energy range when the calculation time becomes too large. In spite of that, for low energy collisions, the simulations cannot be trusted on the time scale of a compound nucleus formation, mainly for the increasing numerical noise. As it will be explained in Section III.B, the nice feature of the procedure described here to evaluate the fusion probability is that, on the basis of a shape analysis in phase space, we can separate fusion and break-up trajectories at rather early times, of the order of 200-300 fm/c, when the calculation can still be fully reliable.

The mean field is built from Skyrme forces:

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

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

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

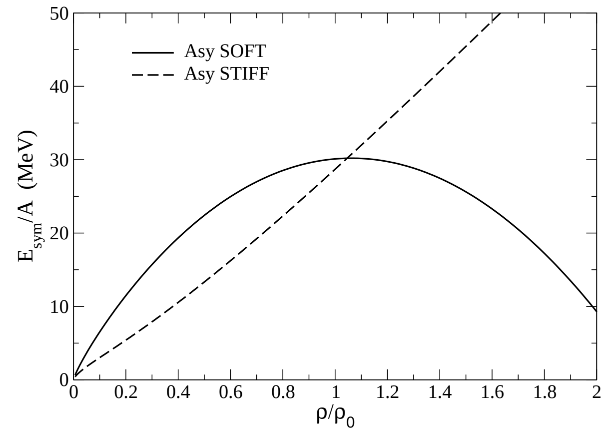


FIG. 1: Density dependence of the symmetry energy for the two parametrizations. Solid line: Asysoft. Dashed line: Asystiff

For the density dependence of the symmetry energy, we have considered two different parametrizations [19, 20], 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 $\rho_0$. For the Asystiff case, $\frac{C(\rho)}{\rho_0} = \frac{32}{\rho_0}\frac{2\rho}{\rho+\rho_0}$, the symmetry energy is quickly decreasing for densities below 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.

## III. 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 semi-peripheral impact parameters (from b =4.5 fm to b = 8.0 fm, with $\Delta$b= 0.5 fm), to explore the region of the transition from fusion to break-up dominance. The transport equations clearly give fusion events at central impact parameters and break-up events for peripheral collisions, but there are some problems when we consider semi-peripheral impact parameters at such low energies, since the time scales for break-up are not compatible with the transport treatment, as already noted. It is then not trivial to extract the fusion probability from the early dynamics of the system and test the sensitivity to the asy-EOS. Therefore we have tried to find a reliable criterion that can indicate when the reaction mechanism is changing, from fusion to deep-inelastic dominance. This will also allow to evaluate the corresponding absolute cross sections.

The new 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 metastabity and/or instability may take place. At later times, when the SMF dynamics is not reliable, the evolution of the most relevant degrees of freedom could be followed within a more macroscopic description, where the system is characterized in terms of global observables, for which the full treatment of fluctuations in phase space is numerically affordable [21]. However, we will show that a consistent picture of the fusion vs. break-up probabilities can be obtained already from a simpler analysis of phase space fluctuations in the time interval indicated above.

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

$$Q(t) =< 2z^2(t) - x^2(t) - y^2(t) >,$$

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 projectile-like/target-like direction, the x-axis is on the reaction plane.

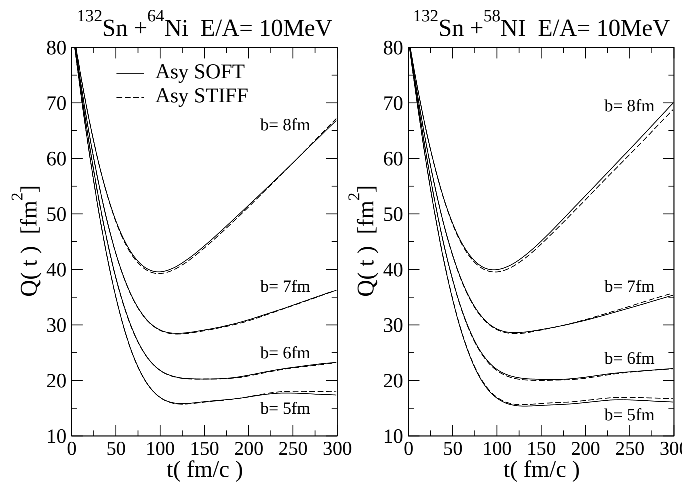


FIG. 2: Time evolution of the space quadrupole moments for different centralities and for the two systems. Solid line: Asysoft. Dashed line: Asystiff.

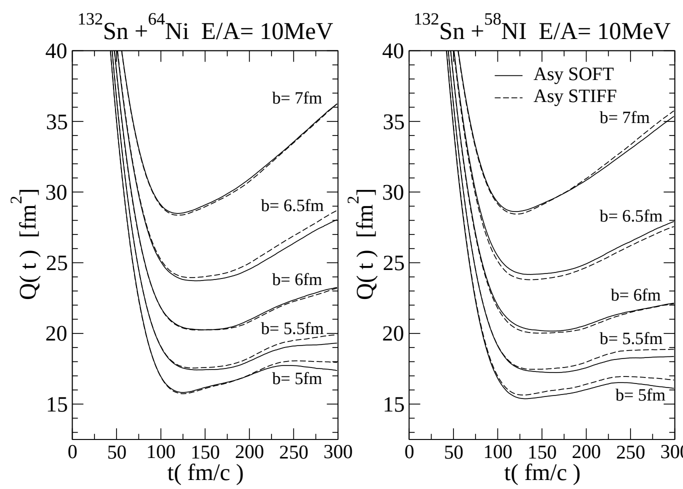


FIG. 3: Like Fig.2 but more detailed in the angular momentum transition region, between b=5.0 and 7.0 fm. Solid line: Asysoft. Dashed line: Asystiff.

### A. Average dynamics of shape observables

We run 200 events for each set of macroscopic initial conditions and we take the average over this ensemble. In Figs.2, 3 we present the time evolution of the mean space quadrupole moment at various centralities 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.

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, see the more detailed picture of Fig.3. 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, at least for less peripheral impact parameters, between b=5.0 fm and b=6.5 fm. 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.4. 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. For

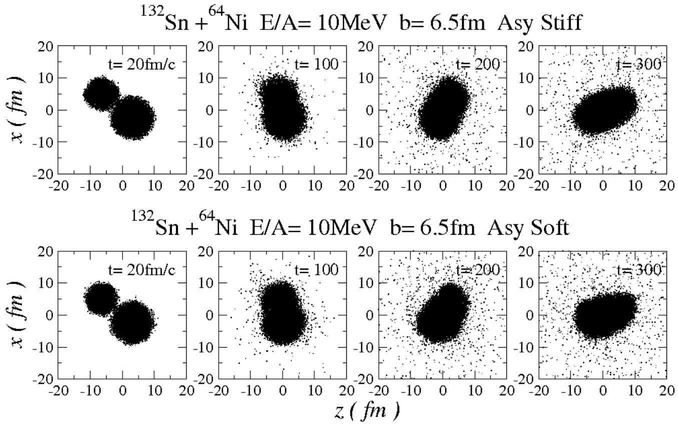


FIG. 4: Time evolution of the space density distributions for the reaction $^{132}Sn +^{64}Ni$ (n-rich systems), 10 AMeV beam energy, for semicentral collisions, b=6.5 fm impact parameter (average over 20 events). Upper Panel: Asystiff. Lower Panel: Asysoft.

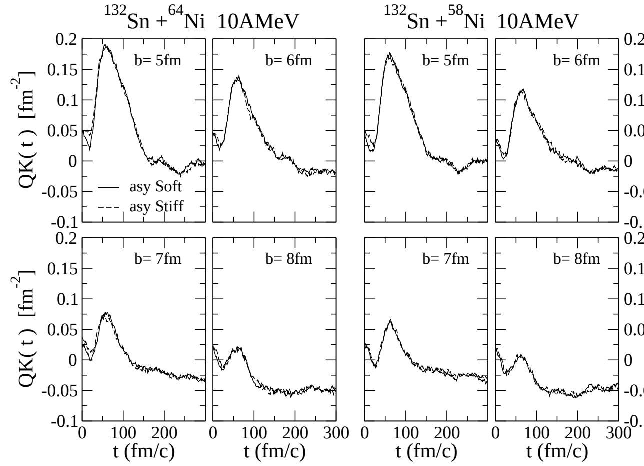


FIG. 5: Time evolution of the momentum quadrupole moments, in a sphere of radius 3 fm around the c.o.m., for different centralities and for the two systems. Solid line: Asysoft. Dashed line: Asystiff.

each event we perform the calculation in a spherical cell of radius 3 fm around the system center of mass. In Fig.5 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 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. We can interpret this effect as due to the presence, in the considered region, of Coriolis forces that are enhanced when the angular momentum is larger. These forces help to break the deformed dinuclear system. Then the break-up probability will be larger if the quadrupole moment in p-space is more negative. From Fig.s 3,5 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 event-by-event analysis is essential to estimate fusion vs. break-up probabilities.

### B. Analysis of fluctuations and fusion probabilities for $^{132}Sn$ induced reactions

To define a quantitative procedure to fix the event by event fusion vs break-up probabilities, we undertake an analysis of the correlation between the two quadrupole moments introduced in the previous Section, in the time interval defined before (100-300 fm/c). Another important suggestion to look at correlations comes from the

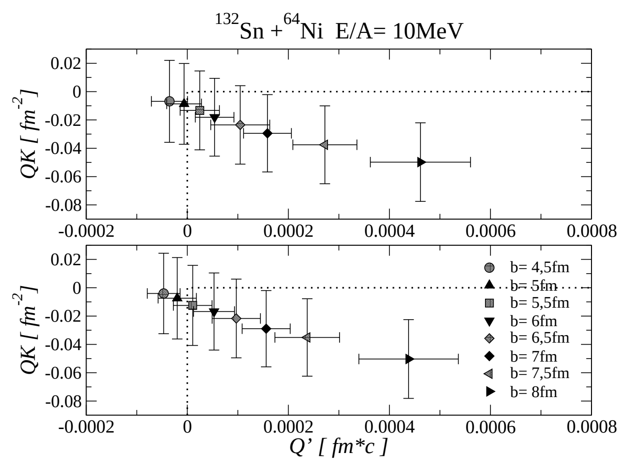


FIG. 6: $^{132}Sn$ + $^{64}Ni$ system. Mean value and variance of QK vs Q', averaged over the 100-300 fm/c time interval, at various centralities in the transition region. The box limited by dotted lines represents the break-up region. Upper panel: Asystiff. Bottom Panel: Asysoft.

very weak presence of isospin as well as symmetry energy effects in the separate time evolution of the two quadrupole moments, as we can see from Figs.2,3 and Fig.5.

Negative $QK$ values denote the presence of velocity components orthogonal to the symmetry axis, due to angular momentum effects, that help the system to separate in two pieces. At the same time, the observation of a velocity component along the symmetry axis indicates that the Coulomb repulsion is dominating over surface effects (that would try to recompact the system), also pushing the system in the direction of the break-up. Hence, in order to get the fusion probability from the early evolution

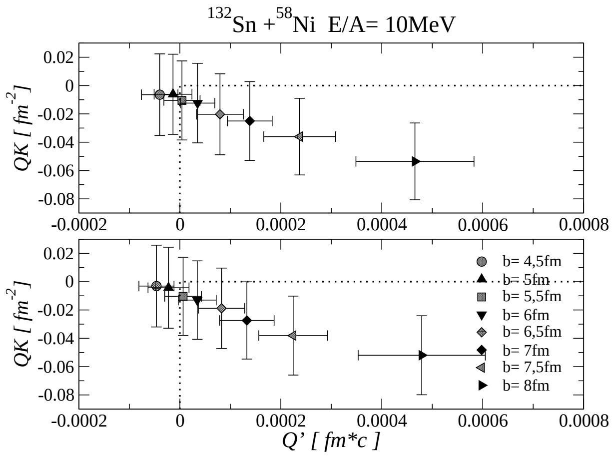


FIG. 7: Like in Fig.6 but for the $^{132}Sn + {}^{58}Ni$ system.

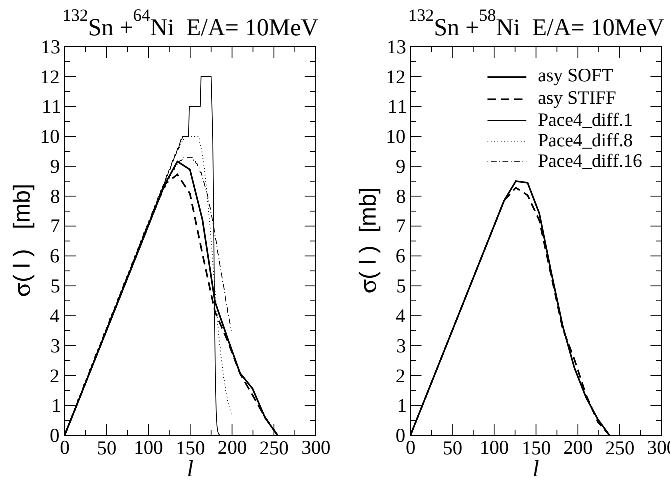


FIG. 8: Angular momentum distributions of the fusion cross sections (mb) for the two reactions and the two choices of the symmetry term. For the $^{132}Sn + {}^{64}Ni$ system (left panel), the results of PACE4 calculations are also reported, for different l-diffuseness.

of the system we assume positive Q' and negative $QK$ for break-up events. In other words, we suppose that, in the impact parameter range where the average value of the two quantities is close to zero, the system evolution is decided just by the amplitude of shape fluctuations, taken at the moment when the formation of a deformed composite system is observed along the SMF dynamics (t = 200-300 fm/c, see the contour plots of Fig.4). Within our prescription, the fusion probability is automatically equal to one for central impact parameters, where the system goes back to the spherical shape and Q' is negative, while it is zero for peripheral reactions, where Q' is always positive and $QK$ always negative.

The correlation plots for the two systems studied and the two asy-EOS are represented in Figs.6 and 7, respectively. Through the quantities displayed in the Figures, mean value and variance of the two extracted properties of the phase space moment evolution, 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 events. Finally the fusion cross section is obtained (in absolute value) by

$$\frac{d\sigma}{dl} = \frac{2\pi}{k^2} l \frac{N_f}{N_{tot}}, \tag{4}$$

where $l$ is the angular momentum calculated in the semi-classical 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.8 we present the fusion spin distribution plots. We note that just in the centrality transition region there is a difference between the $\sigma$-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 $^{58}$Ni target. However, through a selection in angular momentum, $130 \le l \le 180$ ($\hbar$), 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 [22] and Ca + Ca isotopes [23]. We note that this effect is also, slightly, dependent on the symmetry term: The total fusion cross section for the more neutron rich system is 10% larger in the Asysoft calculation and about 7% in the Asystiff case.

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 [24].

In Fig.8 for the same system (left panel) we show also the results obtained with the macroscopic fusion probability evaluation code $PACE4$, [25, 26] 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 more similar to our $\sigma(l)$ distribution we have to choose rather large diffuseness values, while the suggested standard choice for stable systems is around $\Delta l$=4. This seems to be a nice evidence of the neutron skin effect.

Our main conclusion is that we can extract significant

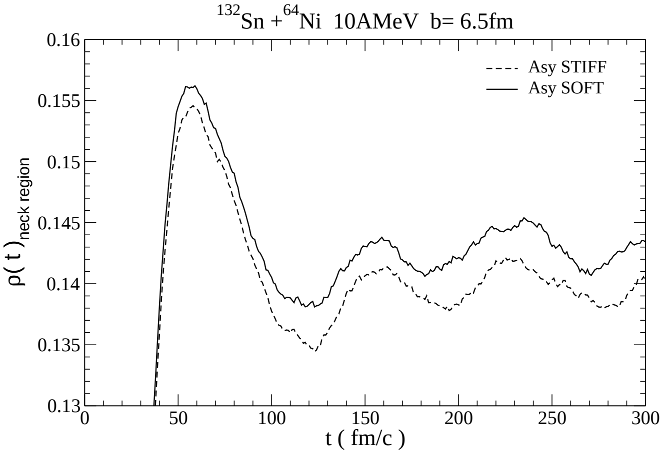


FIG. 9: Reaction $^{132}Sn +^{64} Ni$ semiperipheral. Time evolution of the total density in the "neck" region

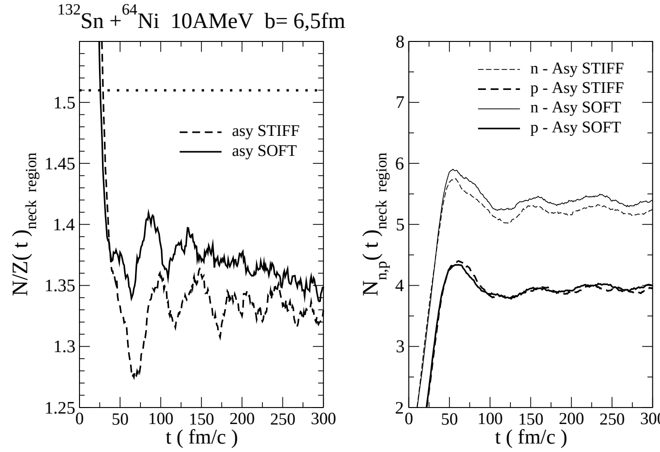


FIG. 10: Reaction $^{132}Sn +^{64} Ni$ semiperipheral.Left panel: time evolution of the neutron/proton ratio in the "neck" region. The dotted line corresponds to the initial isospin asymmetry of the composite system. Right panel: time evolution of the neutron and proton densities.

signals on the event by event reaction mechanism by the fluctuations of the quadrupole moments in phase space evaluated in a time region well compatible with the interval where the transport results are reliable.

## IV. 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, 19]. 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. To account for the system mass asymmetry, this "neck" region is identified by a sphere of radius 3 fm centered on the symmetry axis, at a distance from the projectile center of mass equal to $d(t) * R_1/(R_1 + R_2)$, where $R_1$ and $R_2$ are the radii of projectile and target, and $d(t)$ is the distance between the centers of mass of the two colliding nuclei. In fact, in the time interval of interest for the fusion/break-up dynamics it will almost coincide with the system center of mass, see also the contour plots of Fig.4.

The time evolution of the total density in this "neck" region is reported in Fig.9 for the two choices of the symmetry energy . We note that in the time interval of interest we have densities 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.

It is also instructive to look at the evolution of the isospin content, the N/Z ratio, in this "neck" region, plotted in Fig.10. As reference we show with a dotted line the initial average isospin asymmetry. We see that in the Asysoft choice a systematic larger isospin content is appearing (Left Panel). This is consistent with the presence of a less repulsive neutron potential at densities just above saturation probed in the first $100 fm/c$, when the fast nucleon emission takes place (Figs.9 and 10, Left Panel). All that is confirmed by the separate behavior of the neutron and proton densities shown in the Right Panel of Fig.10.

It is finally very interesting the appearance of N/Z oscillations after 100 fm/c. This can be related to the excitation of isovector density modes in the composite system during the path to fusion or break-up. Since initially a charge asymmetry is present in the system (N/Z=1.64 for $^{132}$Sn and 1.28 for $^{64}$Ni) we expect the presence of collective isovector oscillations during the charge equilibration dynamics for *ALL* dissipative collisions, regardless of the final exit channel. The features of this isovector mode, the Dynamical Dipole already observed in fusion reactions with stable beams [10], will be further discussed in Section V.

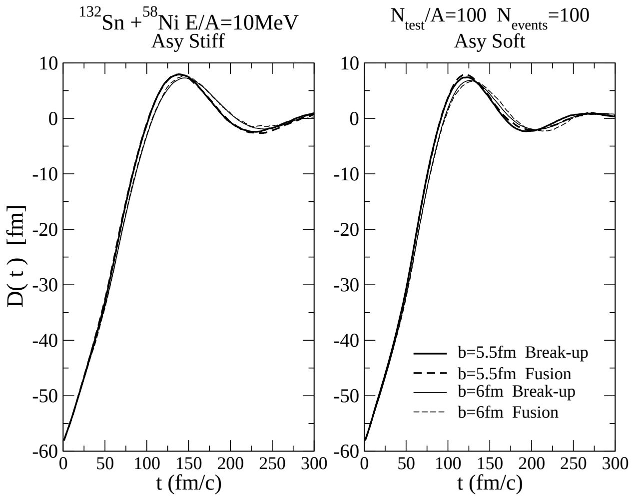


FIG. 11: Reaction $^{132}Sn + ^{58}Ni$ semiperipheral. Prompt Dipole oscillations in the composite system for break-up (solid lines) and fusion (dashed lines) events. Left Panel: Asystiff. Right Panel: Asysoft.

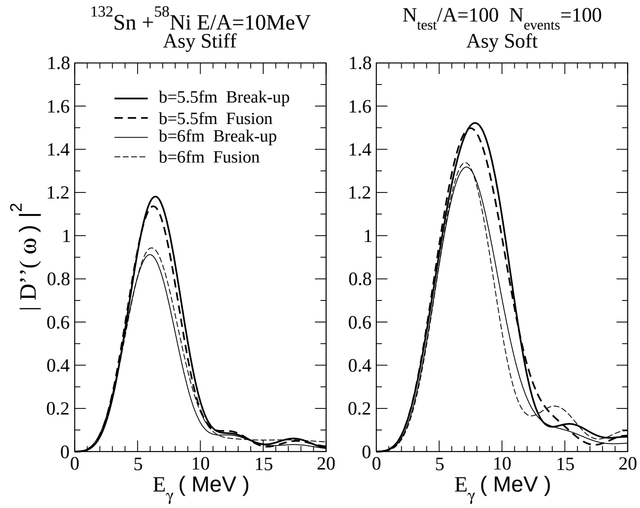


FIG. 12: Reaction $^{132}Sn + ^{58}Ni$ semiperipheral. Prompt Dipole strengths (in $c^2$ units), see text, for break-up (solid lines) and fusion (dashed lines) events. Left Panel: Asystiff. Right Panel: Asysoft.

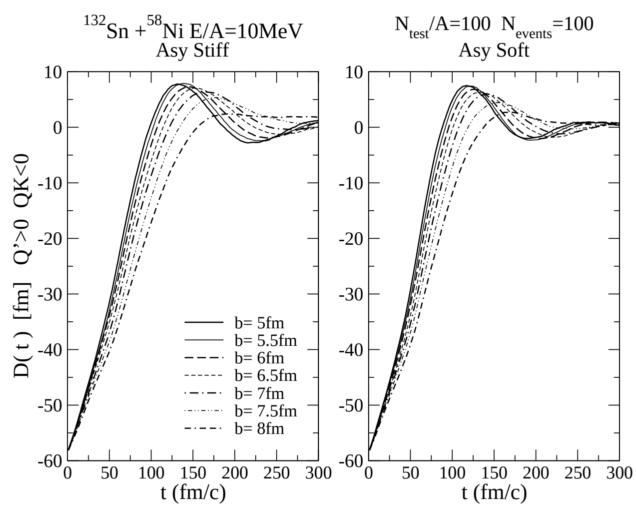


FIG. 13: Reaction $^{132}Sn + ^{58}Ni$ semiperipheral to peripheral.Prompt Dipole oscillations in the composite system for break-up event selections at each impact parameter. Left Panel: Asystiff. Right Panel: Asysoft.

### 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.[27]. 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 [27]. 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 [28, 29].

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.

## V. 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 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.11 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 deep-inelastic 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 [30–32].

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 [15].

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

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}|D''(\omega)|^2, \tag{5}$$

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.12 we report the prompt dipole strengths $|D''(\omega)|^2$ for the same event selections of Fig.11.

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 selections. In fact from Eq.(5) we can directly evaluate the total $\gamma$-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.[10].

In the previous Sections 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.9 and 11. 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

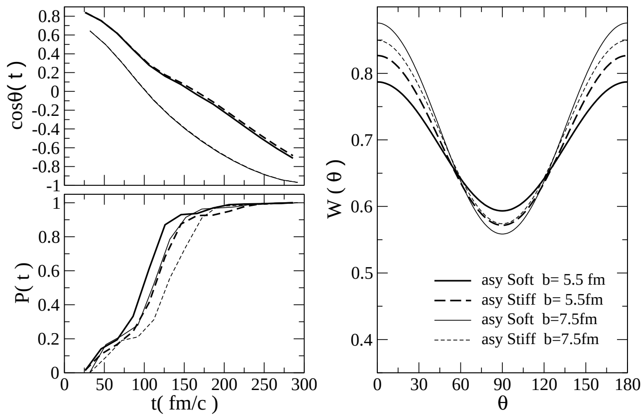


FIG. 14: reaction $^{132}Sn +^{58} Ni$ semiperipheral.Upper Left panel: Rotation angle. Bottom Left Panel: emission probabilities. Right panel: Weighted angular distribution.

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.

Another interesting information is derived from Fig.13 where we show the prompt dipole oscillations only for break-up events at centralities covering the range from semicentral to peripheral. We nicely see that the collective mode for charge equilibration, due to the action of the mean field of the dinuclear system, is disappearing for the faster, less dissipative break-up collisions.

**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 [33]. 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 $\theta$ 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.

Let us denote by $\phi_i$ and $\phi_f$ the initial and final angles of the symmetry axis (which is also oscillation axis) with respect to the beam axis, associated respectively to excitation and complete damping of the dipole mode. Then $\Delta\phi = \phi_f - \phi_i$ is the rotation angle during the collective oscillations. We can get the angular distribution in this case by averaging only over the angle $\Delta\phi$ obtaining

$$W(\theta) \sim 1 - (\frac{1}{4} + \frac{3}{4}x)P_2(cos\theta) \tag{6}$$

where $x = cos(\phi_f + \phi_i)\frac{sin(\phi_f - \phi_i)}{\phi_f - \phi_i}$ .

The point is that meanwhile the emission is damped.

Within the bremsstrahlung approach we can perform an accurate evaluation of the prompt dipole angular distribution using a weighted form where the time variation of the radiation emission probability is accounted for

$$W(\theta) = \sum_{i=1}^{t_{max}} \beta_i W(\theta, \Phi_i) \tag{7}$$

We divide the dipole emission time in $\Delta t_i$ intervals with the corresponding $\Phi_i$ mean rotation angles and the related radiation emission probabilities $\beta_i = P(t_i) - P(t_{i-1})$, where $P(t) = \int_{t_0}^{t} \mid D''(t) \mid^2 dt/P_{tot}$ with $P_{tot}$ given by $P(t_{max})$, total emission probability at the final dynamical dipole damped time.

In Fig.14, upper left panel, we plot the time dependence of the rotation angle, for the $^{132}$Sn + $^{58}$Ni system, extracted from all the events, fusion and break-up, at two semiperipheral impact parameters, for the two symmetry terms. We note that essentially the same curves are obtained with the two Iso-EoS choices: the overall rotation is mostly ruled by the dominant isoscalar interaction.

Symmetry energy effects will be induced by the different time evolution of the emission probabilities, as shown in the bottom left panel.

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. Another interesting point is the dependence on the symmetry energy. With a weaker symmetry term at low densities (Asystiff case), the $P(t)$ is a little delayed and presents a smoother behavior. As a consequence, according to Eq.(7), we can expect possible symmetry energy effects even on the angular distributions.

This is shown in the right panel of Fig.14, where we have the weighted distributions (Eq.(7)), for the two impact parameters and the two choices of the symmetry energies. We see some sensitivity to the stiffness of the symmetry term. Hence, from accurate measurements of the angular distribution of the emitted $\gamma$'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.

## VI. 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. In reactions with exotic systems, these mechanisms are expected to be sensitive to the isovector part of the nuclear interaction, yielding information on the density dependence of the symmetry energy. 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 just 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. It should be noticed that the fluctuations discussed here are essentially of thermal nature. It would be interesting to include also the contribution of quantal (zero-point) fluctuations of surface modes and angular momentum. Indeed the frequencies of the associated collective motions are comparable to the temperature ($T \approx 4\, MeV$) reached in our reactions [34]. This would increase the overall amplitude of surface oscillations, inducing larger fluctuations in the system configuration and a larger break-up probability. Such quantum effect has been recently shown to be rather important for fusion probabilities at near and sub-barrier energies [35]. The agreement of our semiclassical procedure with present data above the barrier could be an indication of a dominance of thermal fluctuations at higher excitation energy. In any case this point should be more carefully studied.

Finally, we would like to stress that, according to our analysis, 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) $\gamma$-multiplicity and anisotropy of the Prompt Dipole Radiation, for dissipative collisions in charge asymmetric entrance channels.

**Aknowledgements**

We warmly thank Alessia Di Pietro for the discussions about the the use of Pace4 fusion simulations. One of authors, V. B. thanks for hospitality at the Laboratori Nazionali del Sud, INFN. This work was supported in part by the Romanian Ministery for Education and Research under the contracts PNII, No. ID-946/2007 and ID-1038/2008.

[1] Isospin Physics in Heavy Heavy Ion Collisions at Intermediate Energies, Eds. Bao-An Li and W. Udo Schroder, Nova Science Publishers, Inc, New York, 2001.
[2] A.W. Steiner,M. Prakash,J.M. Lattimer, P.J. Ellis, Phys. Rep. 411, 325 (2005)
[3] V. Baran, M. Colonna, V.Greco, M. Di Toro, Phys. Rep. 410, 335 (2005)
[4] Bao-An Li, Lie-Wen Chen, Che Ming Ko Phys. Rep. 464, 113 (2008)
[5] M. Colonna and M.B. Tsang, Eur. Phys. Jou. A30, 165 (2006)
[6] M.B. Tsang et al., Phys. Rev. Lett. 102, 122701 (2009)
[7] A.L. Kelsis et al., Phys. Rev. C81, 054602 (2010)
[8] V. Baran, M. Colonna, M. Di Toro, Nucl. Phys. A730, 329 (2004)
[9] E. De Filippo et al., Phys. Rev. C71, 044602 (2005)
[10] V.Baran, C.Rizzo, M.Colonna, M.Di Toro, D.Pierroutsakou, Phys.Rev. C79, 021603(R) (2009)
[11] P. Chomaz, M. Di Toro, A. Smerzi, Nucl. Phys. A563, 509 (1993)
[12] V. Baran et al., Nucl. Phys. A600, 111 (1996)
[13] C. Simenel, P. Chomaz, G.de France, Phys. Rev.Lett. 86, 2971 (2001); Phys. Rev. C76, 024609 (2007)
[14] V. Baran et al., Nucl. Phys. A679, 373 (2001)
[15] V. Baran, D.M. Brink, M. Colonna, M. Di Toro, Phys. Rev. Lett. 87, 182501 (2001)
[16] J. Rizzo, Ph. Chomaz, M. Colonna, Nucl. Phys. A806, 40 (2008)
[17] M. Colonna et al., Nucl. Phys. A642, 449 (1998)
[18] G.Q. Li, R. Machleidt, Phys. Rev. C48, 1702 (1993); Phys. Rev. C49, 566 (1994)
[19] M. Colonna et al., Phys. Rev. C57, 1410 (1998)
[20] V. Baran et al., Nucl. Phys. A703, 603 (2002)
[21] L. Shvedov, M. Colonna, M. Di Toro, Physi. Rev. C81, 054605 (2010)
[22] P. Marini, B. Borderie, A. Chbihi, N. Le Neindre, M.-F. Rivet, J.P. Wieleczko, M. Zoric et al. (Indra-Vamos Collab.), *IWM2009 Int.Workshop*, Eds.J.D.Frankland et al., SIF Conf.Proceedings Vol.101, pp.189-196, Bologna 2010.
[23] F.Amorini et al., Phys. Rev. Lett. 102, 112701 (2009)
[24] J.F. Liang et al., Phys. Rev. C75, 054607 (2007)
[25] A. Gavron, Phys. Rev. 21, 230 (1979)
[26] O.B. Tarasov, D. Bazin, Nucl. Inst. Methods, B204, 174 (2003)
[27] M. Di Toro et al., Nucl. Phys. A787, 585c (2007)
[28] I. Skwira-Chalot et al. (Chimera Collab.), Phys. Rev. Lett. 101, 262701 (2008)
[29] J. Wilczynski et al. (Chimera Collab.), Phys. Rev. C81, 024605 (2010)
[30] D. Pierroutsakou et al., Eur. Phys. Jour. A 16 (2003) 423, Nucl. Phys. A687, 245c (2003)
[31] D. Pierroutsakou et al., Phys. Rev. C71, 054605 (2005)
[32] F. Amorini et al., Phys. Rev. C69, 014608 (2004)
[33] B. Martin, D. Pierroutsakou et al. (Medea Collab.), Phys. Lett. B664, 47 (2008)
[34] L.D. Landau, E.M. Lifshitz, *Statistical Physics* Part.1, Vol.5 (3rd ed.), Butterworth-Heinemann, 1980
[35] S. Ayik, B. Yilmaz, D. Lecroix, Phys. Rev. C81, 034605 (2010)