Exploring the nuclear matter phase diagram with heavy ion reactions

M Colonna\textsuperscript{1}, V Baran\textsuperscript{2}, M Di Toro\textsuperscript{1,3}, C Rizzo\textsuperscript{1}
\textsuperscript{1}Laboratori Nazionali del Sud, INFN, via Santa Sofia 62, I-95123, Catania, Italy
\textsuperscript{2}Physics Faculty, University of Bucharest, Romania
\textsuperscript{3}Physics-Astronomy Dept., University of Catania, Italy
E-mail: colonna@lns.infn.it

Abstract. We review recent results concerning heavy ion reactions between charge asymmetric systems from low up to intermediate energies. Solving numerically self-consistent transport equations for neutrons and protons, we focus on isospin sensitive observables, aiming at extracting information on the density dependence of the nuclear symmetry energy. For reactions close to the Coulomb barrier, we explore the structure of pre-equilibrium dipole oscillations, rather sensitive to the low-density behavior of the isovector component of the nuclear effective interaction. In the Fermi energy regime, we investigate the interplay between dissipation mechanisms, fragmentation and isospin effects. At intermediate energies, where regions with higher density and momentum are reached, we discuss collective flows and their sensitive to neutron and proton effective masses.

1. Introduction
The Equation of State (EOS) of nuclear matter is of crucial importance for the understanding of a large variety of phenomena in nuclear physics and astrophysics. Transient states of nuclear matter far from normal conditions can be created in terrestrial laboratories and many experimental and theoretical efforts have been devoted to the study of nuclear reactions, from low to intermediate energies, as a possible tool to learn about the behavior of nuclear matter and its EOS. In particular, the availability of exotic beams 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 (Z) numbers. Over the past years, measurements of isoscalar collective vibrations, collective flows and meson production have contributed to constrain the EOS for symmetric matter for densities up to five time the saturation value \cite{1}. However, the EOS of asymmetric matter has comparatively few experimental constraints: The isovector part of the nuclear effective interaction (Asy-EOS) and the corresponding symmetry energy are largely unknown far from normal density.

This information is essential also in the astrophysical context, for the understanding of the properties of compact objects such as neutron stars, whose crust behaves as low-density asymmetric nuclear matter \cite{2} and whose core may touch extreme values of density and asymmetry. Moreover, the low-density behavior of the symmetry energy also affects the structure of exotic nuclei and the appearance of new features involving the neutron skin \cite{3}.

Over the past years, several observables which are sensitive to the Asy-EOS and testable experimentally, have been suggested \cite{4, 5, 6, 7}.
In this article we will discuss dissipative collisions in a wide range of beam energies, from just above the Coulomb barrier up to the $AGeV$ range. Low to Fermi energies will bring information on the symmetry term around (below) normal density, while intermediate energies will probe high density regions.

2. Transport theories and symmetry energy

Nuclear reactions are modeled by solving transport equations based on mean field theories, with correlations included via hard nucleon-nucleon elastic collisions and via stochastic forces, selfconsistently evaluated from the mean phase-space trajectory, see [8, 5]. Stochasticity is essential in order to get distributions as well as to allow for the growth of dynamical instabilities.

In the energy range up to a few hundred $AMeV$, the appropriate tool is the so-called Boltzmann-Langevin equation (BLE) [8]:

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \{f, H\} = I_{\text{coll}}[f] + \delta I[f],$$

where $f(r, p, t)$ is the one-body distribution function, or Wigner transform of the one-body density, $H(r, p, t)$ the mean field Hamiltonian, $I_{\text{coll}}$ the two-body collision term incorporating the Fermi statistics of the particles, and $\delta I[f]$ the fluctuating part of the collision integral. Here we follow the approximate treatment of the BLE introduced in Ref.[9], the Stochastic Mean Field (SMF) model. Effective interactions and the nuclear matter EOS can be considered as ingredients of the transport codes and from the comparison with experimental data one can finally get some hints on nuclear matter properties.

We recall that the symmetry energy $E_{\text{sym}}$ appears in the energy density $\epsilon(\rho, \rho_3) \equiv \epsilon(\rho) + \rho E_{\text{sym}}/A(\rho_3/\rho)^3 + O(\rho_3/\rho)^4 + ...$, expressed in terms of total ($\rho = \rho_p + \rho_n$) and isospin ($\rho_3 = \rho_p - \rho_n$) densities. $E_{\text{sym}}$ gets a kinetic contribution directly from basic Pauli correlations and a potential part, $C(\rho)$, from the highly controversial isospin dependence of the effective interactions:

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

The sensitivity of the simulation results is tested against different choices of the density and momentum dependence of the isovector part of the Equation of State. We will consider for the potential part of the symmetry energy, $C(\rho)$, two opposite density parametrizations (Asy-EOS) of the mean field [5, 10]: i) $\frac{C(\rho)}{\rho_0} = 482 - 1638\rho$ ($MeV f m^3$) for Asysoft EOS: $E_{\text{sym}}/A(\text{pot})$ has a weak density dependence close to the saturation, with an almost flat behavior below the saturation density $\rho_0$ and even decreasing at suprasaturation; ii) a constant coefficient, $C = 32 MeV$, for the Asystiff EOS choice, see figure 1. The isoscalar section of the EOS is the same in both cases, fixed requiring that the saturation properties of symmetric nuclear matter with a compressibility around $220MeV$ are reproduced.

The role of the isospin degree of freedom on the dynamics of a nuclear reaction can be discussed in a compact way by means of the chemical potentials for protons and neutrons as a function of density $\rho$ and asymmetry $I = (N - Z)/A$ [11]. The $p/n$ currents can be expressed as

$$\mathbf{j}_{p/n} = D_{p/n}^\rho \nabla \rho - D_{p/n}^I \nabla I,$$

with $D_{p/n}^\rho$ the drift, and $D_{p/n}^I$ the diffusion coefficients for transport, which are given explicitly in Ref. [11]. Of interest for the study of isospin effects are the differences of currents between protons and neutrons which have a simple relation to the density dependence of the symmetry energy

$$D_{n}^\rho - D_{p}^\rho \propto 4I \frac{\partial E_{\text{sym}}}{\partial \rho},$$

$$D_{n}^I - D_{p}^I \propto 4\rho E_{\text{sym}}.$$  

(4)
Thus the isospin transport due to density gradients (isospin migration) depends on the slope of the symmetry energy, or the symmetry pressure, while the transport due to isospin concentration gradients (isospin diffusion) depends on the absolute value of the symmetry energy. Hence transport phenomena in nuclear reactions are directly linked to the EOS properties.

3. The prompt dipole $\gamma$-ray emission in dissipative collisions

The low-density behavior of the symmetry energy can be explored looking at dipole excitations in dissipative charge asymmetric reactions around $10$ $A$MeV. The possibility of an entrance channel bremsstrahlung dipole radiation due to an initial different N/Z distribution was suggested at the beginning of the nineties [12]. After several experimental evidences, in fusion as well as in deep-inelastic reactions, [13, 14, 15] and references therein, the process is now well understood and stimulating new perspectives are coming from the use of radioactive beams.

During the charge equilibration process taking place in the first stage of dissipative reactions between colliding ions with different N/Z ratios, a large amplitude dipole collective motion develops in the composite dinuclear system, the so-called Dynamical Dipole mode. This collective dipole gives rise to a prompt $\gamma$-ray emission which depends on the absolute value of the initial amplitude, $D(t = 0)$, on the fusion/deep-inelastic dynamics and on the symmetry term, below saturation, that is acting as a restoring force. Indeed this oscillation develops in the low density interface between the two colliding ions (neck region).

A detailed description is obtained in mean field transport approaches [16]. One can follow the time evolution of the dipole moment in the $r$-space, $D(t) = \frac{N Z}{A} (R_Z - R_N)$ and in $p$--space, $DK(t) = (P_p - P_n)$, being $R_p$, $P_p$ ($R_n$, $P_n$) the centers of mass in coordinate and momentum space for protons (neutrons). A nice “spiral-correlation” clearly denotes the collective nature of the mode, see figure 2. The “prompt” photon emission probability, with energy $E_\gamma = \hbar \omega$, can be estimated applying a bremsstrahlung approach to the dipole evolution given from the BLE approach [16]:

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

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.

We must add a couple of comments of interest for the experimental selection of the Dynamical Dipole: i) The centroid is always shifted to lower energies (large deformation of the dinucleus);
ii) A clear angular anisotropy should be present since the prompt mode has a definite axis of oscillation (on the reaction plane) at variance with the statistical giant dipole resonance (GDR). These features have been observed in recent experiments [14].

The use of unstable neutron rich projectiles would largely increase the effect, due to the possibility of larger entrance channel asymmetries.

One can notice in figure 2 the large amplitude of the first oscillation for the “132” system, but also the delayed dynamics for the Asystiff EOS related to a weaker isovector restoring force. In figure 3 (left panel) we report the power spectrum, $|D''(\omega)|^2$ in semicentral “132” reactions, for different Asy-EOS choices. The gamma multiplicity is simply related to it, see Eq.(5). The corresponding results for the stable “124” system are drawn in the right panel. As expected from the larger initial charge asymmetry, we clearly see an increase of the Prompt Dipole Emission for the exotic n-rich beam. Such entrance channel effect allows also for a better observation of the Asy-EOS dependence. We remind that in the Asystiff case we have a weaker restoring force for the dynamical dipole in the dilute “neck” region, where the symmetry energy is smaller [17]. This is reflected in the lower value of the centroid, $\omega_0$, as well as in the reduced total yield, as shown in figure 3. The sensitivity of $\omega_0$ to the stiffness of the symmetry energy is more
easily identified increasing $D(t_0)$, i.e. using exotic, more asymmetric beams. Moreover, a good sensitivity to the symmetry energy is also observed for dipole oscillations in more peripheral collisions [18], where low-density surface contributions become more important.

The prompt dipole radiation angular distribution is the result of the interplay between the collective oscillation life-time and the dinuclear rotation. In this sense one expects also a sensitivity to the Asy-EOS of the anisotropy, in particular for high spin event selections [17].

4. Isospin equilibration and fragmentation mechanisms at Fermi energies

In this energy range (30-60 AMeV), reactions between charge asymmetric systems are characterized by a direct isospin transport in binary events. This process also involves the low density neck region and is sensitive to the low density behavior of $E_{sym}$, see Refs.[19, 20] and references therein. Moreover, it is now quite well established that the largest part of the reaction cross section for dissipative collisions at Fermi energies goes through the Neck Fragmentation channel, with intermediate mass fragments (IMF) directly produced in the interacting zone in semiperipheral collisions on short time scales [21]. It is possible to predict interesting isospin transport effects also for this fragmentation mechanism since clusters are formed still in a dilute asymmetric matter but always in contact with the regions of the projectile-like and target-like remnants almost at normal densities.

Results on these mechanisms, obtained with the SMF model, are discussed below.

4.1. The isospin transport ratio

In peripheral and semi-peripheral reactions, it is interesting to look at the asymmetries of the various parts of the interacting system in the exit channel: emitted particles, projectile-like (PLF) and target-like fragments (TLF), and in the case of ternary (or higher multiplicity) events, IMF’s. In particular, one can study the so-called isospin transport ratio, which is defined as

\[
R_{\beta}^x = \frac{2(x^M - x^{eq})}{(x^H - x^L)},
\]

with $x^{eq} = \frac{1}{2}(x^H + x^L)$. Here, $x$ is an isospin sensitive quantity that has to be investigated with respect to equilibration. We consider primarily the asymmetry $\beta = I = (N - Z)/A$, but also other quantities, such as isoscaling coefficients, ratios of production of light fragments, etc, can be of interest [6]. The indices $H$ and $L$ refer to the symmetric reaction between the heavy ($n$-rich) and the light ($n$-poor) systems, while $M$ refers to the mixed reaction. $P, T$ denote the rapidity region, in which this quantity is measured, in particular the PLF and TLF rapidity regions. Clearly, this ratio is $\pm 1$ in the projectile and target regions, respectively, for complete transparency, and oppositely for complete rebound, while it is zero for complete equilibration.

In a simple model one can show that the isospin transport ratio mainly depends on two quantities: the strength of the symmetry energy and the interaction time between the two reaction partners. Let us take, for instance, the asymmetry $\beta$ of the PLF (or TLF) as the quantity $x$. At a first order approximation, in the mixed reaction this quantity relaxes towards its complete equilibration value, $\beta^{eq} = (\beta_H + \beta_L)/2$, as

\[
\beta^{eq}_{P,T} = \beta^{eq} + (\beta^{H,L} - \beta^{eq}) e^{-t/\tau},
\]

where $t$ is the time elapsed while the reaction partners stay in contact (interaction time) and the damping $\tau$ is mainly connected to the strength of the symmetry energy [20]. Inserting this expression into Eq.6, one obtains $R_{\beta}^x = \pm e^{-t/\tau}$ for the PLF and TLF regions, respectively. Hence the isospin transport ratio can be considered as a good observable to trace back the strength of the symmetry energy from the reaction dynamics provided a suitable selection of
the interaction time is performed. The centrality dependence of the isospin ratio, for Sn + Sn collisions at 35 and 50 AMeV, has been investigated in experiments as well as in theory [19, 20, 22], and information about the stiffness of the symmetry energy has been extracted from the analysis presented in [22], based on other transport models.

Here we investigate more in detail the relation between charge equilibration, interaction times and thermal equilibrium. Longer interaction times should be correlated to a larger dissipation. It is then natural to look at the correlation between the isospin transport ratio and the total kinetic energy loss. In this way one can also better disentangle dynamical effects of the isoscalar and isovector part of the EOS, see [20].

It is seen in figure 4 (top) that the curves for the asysoft EOS (dashed) are generally lower in the projectile region (and oppositely for the target region), i.e. show more equilibration, than those for the asystiff EOS, due to the higher value of the symmetry energy at low density. To emphasize this trend, all the values for the stiff (circles) and the soft (squares) Asy-EOS, corresponding to different impact parameters, beam energies and also to two possible parametrizations of the isoscalar part of the nuclear interaction (with and without momentum dependence, MD and MI), are collected together in the bottom part of the figure. One can see that all the points essentially follow a given line, depending only on the symmetry energy parameterization adopted. It is seen, that there is a systematic effect of the symmetry energy of the order of about 20 percent, which should be measurable. Moreover, we notice that the quantity $R$ is a rapidly decreasing function of the degree of dissipation, $E_{\text{loss}}$, reached in the collision. This can be explained in terms of dissipation mechanisms mainly due to mean-field effects, as predicted by the SMF model. Indeed, according to a mean-field picture, a significant degree of thermal equilibrium (i.e. a considerable $E_{\text{loss}}$) would imply a rather long contact time between the two reaction partners, thus certainly leading to isospin equilibration, that needs a shorter time scale to be reached. The correlation suggested in figure 4 should represent a general feature of isospin diffusion, as expected on the basis of dominant mean-field mechanisms, and it would be of great interest to verify it experimentally.
4.2. Isospin dynamics in neck fragmentation at Fermi energies

In presence of density gradients, as the ones occurring when a low-density neck region is formed between the two reaction partners in semi-peripheral collisions, the isospin transport is mainly ruled by the density derivative of the symmetry energy and so we expect a larger neutron flow to the neck clusters for a stiffer symmetry energy around saturation [5]. This mechanism leads to the neutron enrichment of the neck region (isospin migration). This is shown in figure 5 (left), where the asymmetry of the neck and PLF-TLF regions, obtained in neutron-rich reactions at 50 AMeV, are plotted for two Asy-EOS choices.

From the experimental point of view, a new analysis has been recently published on Sn+Ni data at 35 AMeV by the Chimera Collab.[23]. A strong correlation between neutron enrichment and fragment alignment (when the short emission time selection is enforced) is seen, that points to a stiff behavior of the symmetry energy ($L \approx 70$ MeV), for which a large neutron enrichment of neck fragments is seen (left).

![Figure 5](image)

**Figure 5.** Left panel: asymmetry of IMF’s (circles) and PLF-TLF (squares), as a function of the system initial asymmetry, for two Asy-EOS choices: asystiff (full lines) and asysoft (dashed lines). Right panel: Ratio between the neck IMF and the PLF asymmetries, as a function of the system initial asymmetry. The bands indicate the uncertainty in the calculations.

In order to build observables less affected by secondary decay effects, in figure 5 (right) we consider the ratio of the asymmetries of the IMF’s to those of the residues ($\beta_{res}$) for stiff and soft Asy-EOS. This quantity can be estimated on the basis of simple energy balance considerations. By imposing to get a maximum (negative) variation of $E_{sym}$ when transferring the neutron richness from PLF and TLF towards the neck region, one obtains:

$$\frac{\beta_{IMF}}{\beta_{res}} = \frac{E_{sym}(\rho_R)}{E_{sym}(\rho_I)}$$

(8)

From this simple argument the ratio between the IMF and residue asymmetries should depend only on symmetry energy properties and, in particular, on the difference of the symmetry energy corresponding to the residue and neck densities ($\rho_R$ and $\rho_I$), as appropriate for isospin migration. It should also be larger than one, more so for the asystiff than for the asysoft EOS. It is seen indeed in figure 5 (right part), that this ratio is nicely dependent on the Asy-EOS only (being larger in the asystiff case) and not on the system considered. If final asymmetries were affected
in the same way by secondary evaporation in the case of neck and PLF fragments, then one could directly compare the results of figure 5 (right) to data. However, due to the different size and temperature of the neck region with respect to PLF or TLF sources, de-excitation effects should be carefully checked with the help of suitable decay codes.

5. Asy-EOS at supra-saturation density: collective flows

The problem of Momentum Dependence in the Isovector channel \((\text{Iso} - \text{MD})\) of the nuclear interaction is still very controversial and it would be extremely important to get more definite experimental information, see the recent Refs. [24, 25]. Momentum dependent effective interactions essentially lead to the concept of effective masses. If also the isovector component of the interaction is momentum dependent, one observes different effective masses (i.e. effective mass splitting) for neutrons and protons. Exotic Beams at intermediate energies (100-500 \(\text{AMeV}\)) are of interest in order to have high momentum particles and to test regions of high baryon (isoscalar) and isospin (isovector) density during the reaction dynamics. Transport codes are usually implemented with different \((n,p)\) momentum dependences, see [24, 25]. This allows one to follow the dynamical effect of opposite n/p effective mass \(m^*\) splitting while keeping the same density dependence of the symmetry energy [20].

For central collisions in the interacting zone baryon densities about \(1.7-1.8\rho_0\) can be reached in a transient time of the order of 15-20 fm/c. The system is quickly expanding and the Freeze-Out time is around 50 fm/c. Here it is very interesting to study again the collective response of the system. Collective flows are very good candidates since they are expected to be rather sensitive to the momentum dependence of the mean field, see [26, 5].

The transverse flow, \(V_1(y,p_t) = \frac{\langle p_x \rangle}{p_t}\), where \(p_t = \sqrt{p_x^2 + p_y^2}\) is the transverse momentum and \(y\) the rapidity along the beam direction, provides information on the anisotropy of the nucleon emission on the reaction plane. Very important for the reaction dynamics is the elliptic flow, \(V_2(y,p_t) = \frac{\langle p_x^2 - p_y^2 \rangle}{p_t^2}\). The sign of \(V_2\) indicates the azimuthal anisotropy of emission: on the reaction plane \((V_2 > 0)\) or out-of-plane \((\text{squeeze-out}, V_2 < 0)\) [26].

Let us consider semicentral \((b/b_{\text{max}} = 0.5)\) collisions of \(^{197}\text{Au} + ^{197}\text{Au}\) at 400 \(\text{AMeV}\). As seen from figure 6, the neutron squeeze-out is larger (i.e. more negative) in the \(m^*_n < m^*_p\) case, independently of the stiffness of the symmetry term. In particular, in the Asysoft case we see an inversion of the neutron/proton squeeze-out at mid-rapidity for the two effective mass-splittings. Good data seem to be suitable to disentangle \(\text{Iso} - \text{MD}\) potentials [27, 28]. The results are also
slightly depending on the Asy-stiffness, with large neutron squeeze-out effects in the Asystiff case. Due to the difficulties in measuring neutrons, one could investigate the difference between light isobar flows, like $^3$H vs. $^3$He. We still expect to see effective mass splitting effects [29].

6. Conclusions

We have reviewed some aspects of the rich phenomenology associated with nuclear reactions, from which interesting hints are emerging to constrain the nuclear EOS and, in particular, the largely debated density behavior of the symmetry energy.

Information on the low density region can be accessed in reactions from low to Fermi energies, where collective excitations and fragmentation mechanisms are dominant. Results on isospin sensitive observables have been presented. In particular, we have concentrated our analysis on the charge equilibration mechanism (and its relation to energy dissipation) and on the neutron-enrichment of the neck region in semi-peripheral reactions. From the study of the latter mechanism, for which new experimental evidences have recently appeared [23], hints are emerging towards a stiff behavior of the symmetry energy around normal density. This is compatible with recent results from structure data, see for instance the review article [30].

The greatest theoretical uncertainties concerns the high density domain, that has the largest impact on the understanding of the properties of neutron stars. This regime can be explored in terrestrial laboratories by using intermediate energy and relativistic heavy ion collisions of charge asymmetric nuclei. Collective flows and meson production are promising observables.

A considerable amount of work has already been done in the symmetry energy domain. In the near future, thanks to the availability of both stable and rare isotope beams, more selective analyses, also based on new exclusive observables, are expected to provide further stringent constraints.

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