Dynamics of Phase Transitions in Asymmetric Nuclear Matter

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We present several possibilities offered by the reaction dynamics of dissipative heavy ion collisions to study in detail the symmetry term of the nuclear equation of state, \textit{EOS}. In particular we discuss isospin effects on the nuclear liquid-gas phase transition, \textit{Isospin Distillation}, and on collective flows. We stress the importance of a microscopic relativistic structure of the effective interaction in the isovector channel. The possibility of an \textit{early} transition to deconfined matter in high isospin density regions is also suggested. We finally select \textit{Eleven} observables, in different beam energy regions, that appear rather sensitive to the isovector part of the nuclear \textit{EOS}, in particular in more exclusive experiments.

\section*{Introduction}

There are quite stimulating predictions on new phases of Asymmetric Nuclear Matter, \textit{ANM}, that eventually could be reached during heavy ion reaction dynamics with radioactive beams \cite{1,2,3,4,5,6}. More symmetric and narrower isotopic distribution of primary fragments are predicted, \textit{and sensitive to the symmetry term of the EOS}. For semi-central collisions the dynamics of the participant zone appears also to be quite affected by the symmetry term \cite{7,8,9,10,11}.

Collective flows are particularly interesting since we can probe different density regions of the \textit{EOS}. A very stimulating result shown here is the sensitivity to the microscopic covariant structure of the isovector channel in the \textit{in medium} interaction. A related \textit{earlier} possible transition to a mixed phase with deconfined matter is finally presented.

\textit{The EOS symmetry term}

The behaviour of the symmetry term of the nuclear \textit{EOS} is poorly known in regions

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far from normal density. In the following we will compare results obtained with forces that have the same saturation properties for symmetric NM. We will refer to a "asy-stiff/superstiff" EOS when we are considering a potential symmetry term with a linear/parabolic increase with nuclear density and to a "asy-soft" EOS when it shows a saturation and eventually a decrease above normal density [8].

In Figs. [1,2] we report, for a $^{124}\text{Sn}$ asymmetry $(N-Z)/A = 0.2$, the density dependence of the symmetry contribution to the mean-field potential (left) and of the chemical potentials (right) for neutrons (top curves) and protons (bottom curves), for the different effective interactions in the isovector channel. From the behavior in the low densities region we expect that when the inhomogenities develop both neutrons and protons have the tendency to move from lower to higher density regions, in phase: the system is unstable against isoscalar-like fluctuations and not isovector, see later. Since the variations of the two chemical potentials are different (larger for protons) we expect a lower asymmetry in the liquid phase. In the case of a contact between more dilute and "normal" density regions, we see from Fig. [2] that in this range the neutrons have the tendency to move towards the dilute part producing a $n$-enrichment while the protons will migrate to the higher density regions. This mechanism is present in the "neck fragmentation", [9,10,11]: the neck IMF's will be always more $n$-rich compared to the fragments produced in the case of bulk fragmentation.

Stochastic transport simulations [7,12,13,14] of fragment production collisions at medium energies are confirming these predictions, see refs. [10,11] where a comparison with recent data [15,16] is also performed.

Isospin Distillation in Dilute Nuclear Matter

For charge asymmetric systems we expect a qualitative new feature in the liquid-gas phase transition, the onset of chemical instabilities that will show up in a novel structure of the unstable modes [5,6]. Experimentally this will be revealed through the
Isospin Fractionation or Distillation effect in multifragmentation events. We have now a new degree of freedom, the concentration, and in the spinodal region the fluctuations against which a binary system becomes unstable depend on the nature of the interaction between the two components of the mixture. We define density fluctuations as isoscalar-like in the case when proton and neutron densities fluctuate in phase and as isovector-like when the oscillations are out of phase. For the dilute asymmetric nuclear matter because of the attractive force between protons and neutrons at low density the phase transition is uniquely driven by isoscalar-like instabilities [6, 17].

An intuitive picture is presented in Fig. 3. With increasing asymmetry the direction of the unstable modes (arrows) in the \((\delta \rho_n, \delta \rho_p)\) plane is more and more diverging from the constant concentration value (thick lines), towards a less asymmetric liquid phase. The angle between the two directions, i.e. the amount of isospin distillation, will be proportional to the repulsion of the symmetry term at sub-saturation densities.

Symmetry effects at high baryon density: collective flows

It is quite desirable to get information on the symmetry energy at higher density, where furthermore we cannot have complementary investigations from nuclear structure like in the case of the low density behaviour. Heavy Ion Collisions (HIC) provide a unique way to create asymmetric matter at high density in terrestrial laboratories.

The isospin dependence of collective flows has been already discussed in a non-relativistic framework [13, 18]. The main new result shown here, in a Relativistic Mean Field (RMF) scheme [19], is the importance at higher energies of the microscopic covariant structure of the effective interaction in the isovector channel: effective forces with very similar symmetry terms can give rise to very different flows in relativistic heavy ion collisions [20].

A full description of the isovector channel in a relativistic framework in principle should rely on the balance between a scalar \((\delta - \text{like}, \text{attractive})\) and a vector \((\delta - \text{repulsive})\) [21].
Figure 4. Proton-neutron differential collective flow in the $^{132}\text{Sn} + ^{132}\text{Sn}$ reaction at 1.5 AGeV $b=6$ fm for the three different model for the isovector mean fields. Full circles and solid line: $RMF - (\rho + \delta)$. Open circles and dashed line: $RMF - \rho$. Stars and short dashed line: $RMF - D\rho$.

Figure 5. Difference between neutron and proton elliptic flow as a function of the transverse momentum in the $^{132}\text{Sn} + ^{132}\text{Sn}$ reaction at 1.5 AGeV $b=6$ fm in the rapidity range $-0.3 \leq y/y_{proj} \leq 0.3$. Full circles and solid line: $RMF - (\rho + \delta)$. Open circles and dashed line: $RMF - \rho$. Stars and short dashed line: $RMF - D\rho$.

21, 23, 24, 25 contributions. This is a quite controversial point. In relativistic HIC’s, due to the large counterstreaming nuclear currents, one may directly exploit the different Lorentz nature of a scalar and a vector field [20].

For the description of heavy ion collisions we solve the covariant transport equation of the Boltzmann type within the Relativistic Landau Vlasov (RLV) method [26] (for the Vlasov part) and applying a Monte-Carlo procedure for the collision term, including inelastic processes involving the production/absorption of nucleon resonances, [27]. Typical results for the $^{132}\text{Sn} + ^{132}\text{Sn}$ reaction at 1.5 AGeV (semicentral collisions) are shown in Figs. 4, 5. In Fig 4 we report the differential flow $F^{pn}(y) \equiv 1/N(y) \sum_i p_{x_i} \tau_i$ where $N(y)$ is the total number of free nucleons at the rapidity $y$, $p_{x_i}$ is the transverse momentum of particle $i$ in the reaction plane, and $\tau_i$ is +1 and -1 for protons and neutrons, respectively. The $RMF - (\rho + \delta)$ case (full circles and solid line) presents a stiffer behaviour relative to the $RMF - \rho$ (open circles) model, as expected from the more repulsive symmetry energy $E_{sym}(\rho_B)$ at high baryon densities [23, 20]. We have however repeated the calculation using the $RMF - D\rho$ interaction, i.e. with only a $\rho$ contribution but tuned to reproduce the same EOS of the $RMF - (\rho + \delta)$ case. The results, short-dashed curve of Fig 4 are very similar to the ones of the $RMF - \rho$ interaction. Therefore we can explain the large flow effect as mainly due to the different strengths of the vector-isovector field between $RMF - (\rho + \delta)$ and $RMF - \rho, D\rho$ in the relativistic dynamics. In fact if a source is moving the vector field is enhanced (essentially by the local $\gamma$ Lorentz factor) relative to the scalar one. Keeping in mind that $RMF - (\rho + \delta)$ has a three times larger $\rho$ field it is clear that dynamically the vector-isovector mean field acting during the HIC is much greater than the one of the $RMF - \rho, D\rho$ cases.

In Fig 5 we report the elliptic flow $v_2(y, p_t)$, $v_2 = (p_x^2 - p_y^2)/p_t^2 > 0$. $p_t = \sqrt{p_x^2 + p_y^2}$ is the transverse momentum [28]. A negative value of $v_2$ corresponds to the emission
Figure 6. Central Au + Au collisions at 0.6AGeV (upper) and 1.0AGeV (bottom). Time evolution of $n/p$ ratio and $\Delta$ resonance production in high density regions ($\rho/\rho_0 \geq 2.0$) (first two columns) and of the total $\pi^-/\pi^+$ ratio (right). Solid lines: $RMF - \rho$. Dashed lines: $RMF - (\rho + \delta)$.

of matter perpendicular to the reaction plane, $s\text{queeze} - out$ flow. The $p_t$-dependence of $\nu_2$ is very sensitive to the high density behavior of the EOS since highly energetic particles ($p_t \geq 0.5$) originate from the initial compressed and out-of-equilibrium phase of the collision. We focus on the proton-neutron difference of the elliptic flow. From Fig.5 we see that in the $(\rho + \delta)$ dynamics the high-$p_t$ neutrons show a much larger $s\text{queeze} - out$. This is fully consistent with an early emission (more spectator shadowing) due to the larger repulsive $\rho$-field. The $\nu_2$ observable, which is a good $chronometer$ of the reaction dynamics, appears to be particularly sensitive to the Lorentz structure of the effective interaction.

$\pi^-/\pi^+$ ratios

Using the same relativistic transport code we have evaluated the $\pi^-$ vs. $\pi^+$ production for central Au + Au collisions at different energies, see Fig.4. As expected the larger repulsion seen by neutrons at high densities in the $RMF - (\rho + \delta)$ will show up in a reduced $n/p$ ratio, smaller $\Delta^{0-}$ density and finally a reduced $\pi^-$ production. However now reabsorption effects are important and actually the effect appears to be decreasing at higher energies.

Isospin and Deconfinement at High Baryon Density

It is relatively easy to show that at high baryon density and low temperature we can expect a transition from hadronic matter to deconfined quark matter. The procedure is straightforward:

(i) Start from two "reasonable" model Equations of State (EOS), one for the hadronic phase, which can reproduce saturation properties, one for the quark phase, which can
reproduce the hadron spectrum.

(ii) Construct the phase separation boundary surface from the Gibbs phase rule. For symmetric matter the baryon density \( \rho_{tr} \) corresponding to the transition to the coexistence region is relatively high, as expected, ranging from 4 to 8 times the saturation value \( \rho_0 \), depending on the stiffness of the hadronic EOS at high densities. The new feature we would like to focus on in this report is the isospin dependence of such boundary location. We can foresee an interesting asymmetry effect, in the appealing direction of a decrease of \( \rho_{tr} \), since the hadronic EOS becomes more repulsive ref.[29, 30].

The proton fraction \( Z/A \) dependence of the \( \rho_{tr} \) is reported in Fig.7 with the bag constant value \( B^{1/4} = 150 \text{ MeV} \) and \( \alpha_s = 0 \) for the quark phase and various choices for the hadronic EOS: Dotted line GM3 parametrization [31]; Dashed line RMF – \( \rho \) parametrization [28]; Solid line RMF – \( (\rho + \delta) \) parametrization [28]. GM3 and RMF – \( \rho \) have the same source of the interaction symmetry term (only the \( \rho \)-meson). The effects of the asymmetry appears now quite dramatic: we see a \( \rho_{trans} \) as low as \( 2\rho_0 \) for proton fractions between 0.3 and 0.4, conditions that with some confidence we could ”locally” reach in a heavy ion collision at intermediate energy using exotic very asymmetric beams.

Using our Relativistic Transport Code, with the RMF – \( (\rho + \delta) \) effective interaction, we have performed some simulations of the \( ^{132}Sn + ^{132}Sn \) (average \( Z/A = 0.38 \)) collision at various energies, for a semicentral impact parameter, \( b = 6\text{ fm} \), just to optimize the neutron skin effect. In Fig.7 the paths in the \( (\rho, Z/A) \) plane followed in the c.m. region during the collision are reported, at two energies 300 AMeV (crosses) and 1 AGeV (circles). We see that already at 300 AMeV we are reaching the border of the mixed phase, and we are well inside it at 1 AGeV.

In conclusion we support the possibility of observing precursor signals of the phase transition to a deconfined matter in violent collision (central and semicentral) of exotic (radioactive) heavy ions in the energy range of few hundred MeV per nucleon. A possible signature could be revealed through an earlier ”softening” of the hadronic EOS for larger asymmetries.

Figure 7. Variation of the transition density with proton fraction followed in the interaction zone during a semicentral \( ^{132}Sn + ^{132}Sn \) collision at 1 AGeV (circles) and 300 AMeV (crosses)
Outlook: The Eleven Observables

As a conclusion of our report we like to suggest a selection of Eleven Observables, from low to relativistic energies, that we expect particularly sensitive to the microscopic structure of the in medium interaction in the isovector channel, i.e. to the symmetry energy and its “fine structure”:

1. Competition of Reaction Mechanisms. Interplay of low-energy dissipative mechanisms, e.g. [7], fusion (incomplete) vs. deep-inelastic vs. neck fragmentation: a stiff symmetry term leads to a more repulsive dynamics.

2. N/Z of fast nucleon emission. Symmetry repulsion of the neutron/proton mean field in various density regions.

3. Neutron/Proton correlation functions. Time-space structure of the fast particle emission and its relation to the baryon density of the source, see the recent [32].

4. Fragment Multiplicities. A more efficient use of protons in forming primary fragments is expected in the asy-stiff case.

5. Isospin Distillation (Fractionation). Isospin content of the Intermediate Mass Fragments in central collisions. Test of the symmetry term in dilute matter.

6. Isospin content of Neck-Fragments. Test of the symmetry term around $\rho_0$.

7. Fast Fission Multiplicity. The rate of “aligned” fission events of the Projectile-Like/Target-Like Fragments reflects the symmetry repulsion in semicentral collisions.

8. Isospin Diffusion. Measure of charge equilibration in the “spectator” region in semicentral collisions, test of symmetry repulsion.

9. Neutron-Proton Collective Flows. Together with light isobar flows. Check of symmetry transport effects. Test of the momentum dependence (relativistic structure) of the interaction in the isovector channel. Measurements also for different $p_t$ selections.

10. $\pi^-/\pi^+$ Yields. Since $\pi^-$ are mostly produced in $nn$ collisions we can expect a reduction for highly repulsive symmetry terms at high baryon density, see [33, 34].

11. Deconfinement Precursors. Signals of a mixed phase formation (quark-bubbles) in high baryon density regions reached with asymmetric HIC at intermediate energies.

From the points 3, 4, 5, 8, 9 in our simulations we presently get some indications for asy-stiff behaviors, i.e. increasing repulsive density dependence of the symmetry term, but not more fundamental details. Moreover all the available data are obtained with stable beams, i.e. within low asymmetries.

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