WHAT CAN WE LEARN FROM NUCLEAR MATTER INSTABILITIES?

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We discuss the features of instabilities in binary systems, in particular, for asymmetric nuclear matter. We show its relevance for the interpretation of results obtained in experiments and in "ab initio" simulations of the reaction between $^{124}\text{Sn} + ^{124}\text{Sn}$ at 50AMeV.

1 Instabilities in asymmetric nuclear matter

The process of multifragmentation following the collision of heavy nuclei in the region of medium energies displays several features analogous to usual liquid-gas phase transitions of water. However in this analogy one should be aware of differences due to Coulomb, finite size and quantum effects as well as to the binary, i.e. two-component, character of nuclear matter. Moreover, the time scales of the process are of the order of, or shorter than, the relaxation times of the relevant degrees of freedom. Therefore we have to consider not only equilibrium phase-transition in binary systems, but in an equally important way the dynamical evolution driving such phase transition and its dependence on the symmetry term of the equation-of-state. Indeed after a fast compression and expansion we expect the nuclear system to be quenched into an unstable state either inside the coexistence curve in the metastability region (where the phase is unstable against short wave length but large amplitude fluctuations) or in the instability (spinodal) region (were the system becomes unstable against long wave length but small amplitude fluctuations). Then the system will evolve toward a stable thermodynamical state of two coexisting phases either through nucleation (in former case) or through spinodal decomposition (in the latter case). These aspects were discussed repeatedly in the past, but the binary character will induce new features for both scenarios that are absent in one-component systems. Therefore studying the nature of instabilities which

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develop in nuclear systems, their relaxation times and the influence of the isospin degree of freedom will provide information on the mechanisms involved in the fragment formation processes and will set limits for the applicability of fully equilibrium approaches.

In the framework of Landau theory for two component Fermi liquids the spinodal border was determined by studying the stability of collective modes described by two coupled Landau-Vlasov equations for protons and neutrons. In terms of the appropriate Landau parameters the stability condition can be expressed as:

\[(1 + F_{nn}^0)(1 + F_{pp}^0) - F_{np}^0 F_{pn}^0 > 0 .\] (1)

It is possible to show that this condition is equivalent to the following thermodynamical condition:

\[\left( \frac{\partial P}{\partial \rho} \right)_{T,y} \left( \frac{\partial \mu_p}{\partial \rho} \right)_{T,P} > 0 .\] (2)

discussed in\(^8\),\(^9\), where \(y\) is the proton fraction. In Fig. 1 we show the spinodal lines obtained from eq. (1) (continuous line with dots) which for asymmetric nuclear matter is seen to contain the lines corresponding to "mechanical instability", \(\left( \frac{\partial P}{\partial \rho} \right)_{T,y} < 0\) (crosses). Therefore eqs. (1,2) describe the "chemical instability" of nuclear matter.

![Figure 1: Spinodal lines corresponding to chemical (joined points) and mechanical (crosses) instability for three asymmetries, \(I=(N-Z)/(N+Z)=0.0,0.5,0.8\) of nuclear matter.](image)

We want to stress, however, that by just looking at the above stability conditions we cannot determine the nature of the fluctuations against which a binary system becomes chemically unstable. Indeed, the thermodynamical condition in eq. (2) cannot distinguish between two very different situations.
which can be encountered in nature: an attractive interaction between the two
components of the mixture \( F_{\text{np}}^{0}, F_{\text{pn}}^{0} < 0 \), as is the case of nuclear matter, or
a repulsive interaction between the two species. We define as isoscalar-like den-
sity fluctuations the case when proton and neutron Fermi spheres (or equiva-
ently the proton and neutron densities) fluctuate in phase and as isovector-like
density fluctuations when the two Fermi sphere fluctuate out of phase. Then
it is possible to prove, based on a thermodynamical approach of asymmetric
Fermi liquid mixture, that chemical instabilities are triggered by isoscalar
fluctuations in the first, i.e. attractive, situation and by isovector fluctuations
in the second one. For the asymmetric nuclear matter case because of the
attractive interaction between protons and neutrons the phase transition is
thus due to isoscalar fluctuations that induce chemical instabilities while the
system is never unstable against isovector fluctuations. Of course the same
attractive interaction is also at the origin of phase transitions in symmetric
nuclear matter. However, in the asymmetric case isoscalar fluctuations lead
to a more symmetric high density phase everywhere under the instability line
defined by eq. (1).

Figure 2: \(^{124}\text{Sn} + ^{124}\text{Sn} 50\text{AMeV}\): time evolution of the nucleon density projected on
the reaction plane. First two columns: \( b = 2\text{fm} \) collision, approaching, compression and
separation phases. Third and fourth columns: \( b = 4\text{fm} \) and \( b = 6\text{fm} \), separation phase up
to the freeze-out.
2 "Ab initio" simulations of Sn + Sn reactions

A new code for the solution of microscopic transport equations, the *Stochastic Iso-BNV*, has been written where asymmetry effects are suitably accounted for and the dynamics of fluctuations is included.

We have studied the 50AMeV collisions of the systems $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{112}\text{Sn} + ^{112}\text{Sn}$, where new data have been measured at NSCL – MSU. We will discuss averages over 100 events generated in semi-central ($b = 2\text{ fm}$) and semi-peripheral ($b = 6\text{ fm}$) reactions. In Fig.2 we show the evolution with impact parameter of the density plot (projected on the reaction plane) for one event each (neutron rich case $^{124}\text{Sn} + ^{124}\text{Sn}$, EOS with stiff asymmetry term).

We remark: i) In the cluster formation we see a quite clear transition with impact parameter from bulk to neck instabilities. ii) The "freeze-out times", i.e. when the nuclear interaction among clusters disappears, are decreasing with impact parameter. These two dynamical effects will influence the isospin content of the produced primary fragments, as shown below.

![Figure 3: $^{124}\text{Sn} + ^{124}\text{Sn}$ 50AMeV $b = 2\text{ fm}$ collisions: time evolution and freeze-out properties. See text.](image)

A detailed analysis of the results for the same system is shown in Fig.3 (central, $b = 2\text{ fm}$) and Fig.4 (peripheral, $b = 6\text{ fm}$). Each figure is organized in the following way: Top row, time evolution of: (a) **Mass** in the liquid (clusters with $Z \geq 3$, upper curve) and the gas (lower curve) phase; (b) **Asymmetry** $I = (N - Z)/(N + Z)$ in gas "central" (solid line with squares), gas total (dashed+squares), liquid "central" (solid+circles) and IMF’s ($3 \leq Z \leq 12$, stars). "Central" means in a cubic box of side 20fm around the c.m.. The horizontal line shows the initial average asymmetry; (c) **Mean Fragment Multi-**
Figure 4: $^{124}Sn + ^{124}Sn$ 50AMeV $b = 6fm$ collisions: time evolution and freeze-out properties. See text.

Multiplicity $Z \geq 3$. The saturation of this curve defines the freeze-out configuration, as we can also check from the density plots in Fig.2. Bottom row, properties of the "primary" fragments in the freeze-out configuration: (d) Charge Distribution, (e) Asymmetry Distribution and (f) Fragment Multiplicity Distribution (normalized to 1).

We see a neutron dominated prompt particle emission and a second neutron burst at the time of fragment formation in the "central region". The latter is consistent with the dynamical spinodal mechanism in dilute asymmetric nuclear matter, as discussed before. The effect is quite reduced for semi-peripheral collisions (compare Figs. 3b and 4b) and the IMF’s produced in the neck are more neutron rich (Figs. 3e and 4e). This seems to indicate a different nature of the fragmentation mechanism in central and neck regions, i.e. a transition from volume to shape instabilities with different isospin dynamics. In more peripheral collisions the interaction time scale is also very reduced (Fig.4c) and this will quench the isospin migration.

3 Conclusions

Starting from the thermodynamical features of instabilities and the dynamics of phase-transitions in binary systems we obtain a consistent description of the multifragmentation process in heavy ion collisions and, in particular, of isospin effects. Isospin proves to be a useful probe in signaling a change in the fragment formation mechanism passing from central to semiperipheral collisions. Moreover this "isospin dynamics" is found to be quite sensitive to the symmetry term of the EOS, opening new stimulating perspectives on such
studies, which are of great astrophysical interest, under laboratory controlled conditions.

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