Asymmetry Effects on Nuclear Fragmentation

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We show the possibility of extracting important information on the symmetry term of the Equation of State (EOS) directly from multifragmentation reactions using stable isotopes with different charge asymmetries. We study n-rich and n-poor \textit{Sn} + \textit{Sn} collisions at 50\textit{AMeV} using a new stochastic transport approach with all isospin effects suitably accounted for. For central collisions a chemical component in the spinodal instabilities is clearly seen. This effect is reduced in the neck fragmentation observed for semiperipheral collisions, pointing to a different nature of the instability. In spite of the low asymmetry tested with stable isotopes the results are showing an interesting and promising dependence on the stiffness of the symmetry term, with an indication towards an increase of the repulsion above normal density.

1. Introduction

Our starting point is that the key question in the physics of unstable nuclei is the knowledge of the EOS for asymmetric nuclear matter away from normal conditions. We remark the effect of the symmetry term at low densities on the neutron skin structure, while the knowledge in high densities region is crucial for supernovae dynamics and neutron star cooling\textsuperscript{[1–5]}.

Effective interactions are obviously tuned to symmetry properties around normal conditions and any extrapolation can be quite dangerous. Microscopic approaches based on realistic \textit{NN} interactions, Brueckner or variational schemes, or on effective field theories show a quite large variety of predictions, see Fig.\textsuperscript{1}.

In the reaction dynamics with intermediate energy radioactive beams we can probe highly asymmetric nuclear matter in compressed as well as dilute phases: the aim of this paper is to show that fragmentation events have new features due to isospin effects and that some observables are particularly sensitive to the symmetry term of the EOS.

For fragmentation mechanisms a new qualitative feature is expected: the onset of chemical effects on spinodal instabilities\textsuperscript{[8–10]}, due to the intrinsic coupling between isoscalar
and isovector modes. The formation of a very neutron rich gas vs. an almost symmetric liquid phase is expected for neutron excess systems, in a dynamical non-equilibrium mechanism on short time scales [10–12]. This effect, which appears very much reduced in a statistical multifragmentation calculation [13], will show up in a production of more stable primary intermediate mass fragments and in enhanced yields for neutron rich light isobars.

All these predictions were actually based on linear response approaches [10,11], nuclear matter dynamics in a box [11,12] or on the evolution of a suitably prepared excited source [13]. In this paper we will present the first results of a fully "ab initio" calculation of fragmentation reactions for systems with different charge asymmetry.

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 [14,15]. A density dependent symmetry term is used also in the ground state construction of the initial conditions. Isospin effects on nucleon cross section [16] and Pauli blocking are consistently evaluated. In order to simplify the analysis of the most sensitive observables to isospin effects we have chosen a Skyrme force with the same soft EOS for symmetric Nuclear Matter (NM) ($K = 201\text{MeV}$) and with two different choices for the density dependence of the symmetry term, see Fig.1(bottom), asy-stiff (like in BPAL32, see also [17]) and asy-soft (like in $SKM^*$). In this way we force the symmetric part of the EOS to be exactly the same in order to disentangle dynamical symmetry term effects. We will show that the reaction mechanism is sensitive to the

Fig.1 - EOS for various effective forces, $SKM^*$ (dashed), $SLy230b$ (squares) and $BPAL32$ (crosses). Top: neutron matter (up), symmetric matter (down); Bottom: potential symmetry term.
different behaviours, although with stable nuclei we will limit the possible asymmetries and moreover we will certainly not reach high compression regions.

We have studied the 50 AMeV collisions of the systems $^{124}\text{Sn} + ^{124}\text{Sn}$ and $^{112}\text{Sn} + ^{112}\text{Sn}$, where new data are under analysis at NSCL – MSU \[19\]. We will comment 100 events generated in semi-central ($b = 2\,\text{fm}$) and semi-peripheral ($b = 6\,\text{fm}$) reactions. In Fig.2 we show a typical impact parameter evolution of the density plot (projected on the reaction plane) for one event (neutron rich case, asy-stiff EOS).

![Fig.2](image)

**Fig.2** - $^{124}\text{Sn} + ^{124}\text{Sn}$ 50 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 column: $b = 4\,\text{fm}$, fourth column: $b = 6\,\text{fm}$, separation phase up to the freeze-out.

We remark: i) In the cluster formation we see a quite clear transition from bulk \[20–22\] to neck \[23–25\] instabilities. ii) The "Freeze-Out times", 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 later.

A detailed analysis of the results from 100 events for the same system (asy-stiff calculation) is shown in Fig.3 (central, $b = 2\,\text{fm}$) and Fig.4 (peripheral, $b = 6\,\text{fm}$). Each figure is organized in this way:

Top row, time evolution of: (a) Mass in the liquid (up) and gas (down) phase; (b) Asymmetry $I = (N - Z)/(N + Z)$ in the gas "central" (solid line and squares), gas total (dashed+squares), liquid "central" (solid+circles) and clusters (stars). "Central" means in a cubic box of side 20 fm around the c.m.. The horizontal line shows the initial average asymmetry; (c) Mean Fragment Multiplicity $Z \geq 3$. The saturation of this curve defines...
\begin{figure}[h!]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{$^{124}Sn + ^{124}Sn$ 50 AMeV $b = 2\, fm$ collisions: time evolution and freeze-out properties. See text. \textit{ASY-STIFF EOS}.}
\end{figure}

\begin{figure}[h!]
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Like Fig.3 for $b = 6\, fm$.}
\end{figure}

the freeze-out configuration, as we can also check from the density plots like in Fig.2.

Bottom row, properties of the "primary" fragments in the \textit{Freeze-Out Configuration}: (d) \textit{Charge Distribution}, (e) \textit{Asymmetry Distribution} and (f) \textit{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 Fig.s 3b and 4b) and the IMF’s ($3 \leq Z \leq 12$) produced in the neck are more neutron rich (Fig.s 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.

In Fig.s 5,6 we have the corresponding results for the *asy-soft EOS*. The main qualitative difference is a larger prompt neutron emission (compare the gas asymmetry in
Fig. 7 - Correlation between mean IMF multiplicity and charge of the heaviest fragment: 
squares n-rich "asy-stiff"; diamonds n-poor "asy-stiff"; circles n-rich "asy-soft"; stars n-poor "asy-soft".

Fig.s 3b,4b with the corresponding Fig.s 5b,6b) joined to a "slower" dynamics (see the (c)-plots), as expected from the more attractive nature of the asymmetric EOS [12].

The interesting point is that the effect on fragment production is different for central and peripheral events. With respect to the asy-stiff case we have a smaller mean IMF multiplicity for central collisions (Fig.s 3f vs. 5f) and more fragments produced in the neck region (Fig.s 4f vs. 6f).

Neck instabilities have also the feature of forming clusters on the "spectator" side [23] leading to a "fission-like" splitting of the Projectile-/Target-like fragment. This mechanism has been clearly observed in accurate kinematical selections [26]. In our study of n-rich systems the rate of such dynamical fission processes is systematically larger for the asy-soft EOS, as expected from the previous discussion. This seems to be an quite sensitive observable to look at.

The most important qualitative difference of the neutron poor case, $^{112}Sn + ^{112}Sn$, is a larger prompt proton emission, in particular for central collisions. The number of protons available to produce clusters is then reduced with a related smaller mean IMF multiplicity. Moreover the reduction of the overall asymmetry is acting in the same direction. In Fig. 7 we show the average IMF multiplicity vs. the average charge of the heaviest produced fragment, which measures the centrality of the collision, for the two symmetry terms and for the two systems. The effect, in agreement with recent data [27], is more evident with the asy-stiff choice, in particular for central collisions (low $< Z >_{\text{heavy}}$).

3. Outlook

Starting from simulations of reaction dynamics performed with a new transport code where isospin and fluctuation effects are suitably accounted for, we have shown that dissipative heavy ion collisions, and in particular fragment production reactions, at medium energies are rather sensitive to the density dependence of the symmetry contribution to the nuclear Equation of State.

Interesting differences appear between isospin effects on central and neck fragmentation.
An indication for a "stiff" symmetry term is emerging, consistent with transverse flow calculations in the same energy range \[28\].

The effects are not large but quite encouraging for similar studies with radioactive beams. A possibility is emerging of obtaining in terrestrial accelerator laboratories important information on the symmetry term of large astrophysical interest. It appears essential to have good charge asymmetric beams available at intermediate energies and to perform more exclusive experiments.

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