Sensitivity of N/Z ratio to dynamical fission of projectile in isobaric systems: a new probe for symmetry energy?

Physics case: competition between dynamical and statistical IMFs production

Influence of the N/Z ratio of the entrance channel in the dynamical fission of the quasi-projectile: enhanced cross-section for dynamical emission for the system with higher N/Z

The new data of InKiIsSy experiment (Inverse Kinematics Isobaric Systems), $^{124}\text{Xe}+^{64}\text{Zn},^{64}\text{Ni}$ at 35 A.MeV complements the previous ones: TimeScale $^{64,58}\text{Ni} + ^{124,112}\text{Sn}$ (direct) and $^{124,112}\text{Sn}+^{64,58}\text{Ni}$ (inverse) kinematics.

First “Inkiissy” experiment results

Constrained Molecular Dynamics (CoMD-3) simulations (preliminary)

Perspectives with radioactive beams below Fermi energies ($E/A<15$ A.MeV).
In “Timescale” and “Inkiissy” experiments we mainly look at:

1) The “neck” emission where light IMFs (Z<≈9) are produced at midrapidity due to the rupture of a piece of nuclear matter a low density (“neck”). This is generally a FAST process (<100 fm/c).

2) Excitation of a primary Projectile-like PLF* (TLF*) followed by its dynamical (non-equilibrated) asymmetrical splitting (dynamical fission). In this case emission of the lighter IMF is preferentially backwards in the PLF reference system.

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Role of N/Z of entrance channel in the reaction mechanisms
The quasi-projectile break-up

$^{124}$Sn+$^{64}$Ni 35 AMeV Neutron rich

The lighter fragments are emitted preferentially backwards in the PLF reference system, i.e., towards the target nucleus:

Dynamical Fission $\rightarrow$ fast and non-equilibrated fission

Collision violence

E.De Filippo et al., PRC 71 064604 (2005)
P. Russotto et al., PRC 81, 064605 (2010)

Coulomb ring $5 \approx V_{\text{beam}} = 8.$ cm/ns $\rightarrow$ Well defined PLF source: scattering of PLF followed by its splitting in H&L fragments $\rightarrow$ sequential mechanism
The quasi-projectile break-up

A_H/A_L Mass asymmetry

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E.De Filippo et al., PRC 71 064604 (2005)
P. Russotto et al., PRC 81, 064605 (2010)
METHOD: disentangling dynamical vs. statistical emission: Angular Distributions

See also P. Russotto et al. PRC 91, 014619 (2015)
S. Hudan et al., PRC 86 021603(R) (2012)
The analysis is done for $M_{\text{IMF}}=1$ events (ternary splitting). $b/b_{\text{max}}>0.4$
Comparison of IMFs cross sections for $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$


**Cross-sections**

- **Dynamical component:** enhanced for the neutron rich
- **Statistical component:** almost equal (A ratio: $\sim 1.1$ close to the mass ratio between the systems)

see also A.B. McIntosh et al. PRC 81 034603 (2010)
Comparison of IMFs cross sections for $^{124}\text{Sn}+^{64}\text{Ni}$ and $^{112}\text{Sn}+^{58}\text{Ni}$


Ratio of $\frac{\sigma_{\text{dyn}}}{(\sigma_{\text{dyn}}+\sigma_{\text{stat}})}$ as a function of IMFs charge $Z$ for the two systems.

- **Dynamical component:** enhanced for the neutron rich
- **Statistical component:** almost equal (A ratio: $\sim 1.1$ close to the mass ratio between the systems)

see also A.B. McIntosh et al. PRC 81 034603 (2010)
Main experimental result: the dynamical component is enhanced for the neutron rich system.

Is it a size (mass) effect or isospin effect?

The idea is to use a projectile/target combination having the same mass of the neutron rich $^{124}\text{Sn}+^{64}\text{Ni}$ system and a N/Z $^{124}\text{Xe}+^{64}\text{Zn}$ as the neutron poor one $^{112}\text{Sn}+^{58}\text{Ni}$ at the same bombarding energy of 35 A.MeV using the 4π detector CHIMERA and the Farcos module prototype.

<table>
<thead>
<tr>
<th>System</th>
<th>N/Z Projectile</th>
<th>N/Z Target</th>
<th>N/Z Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{124}\text{Sn}+^{64}\text{Ni}$</td>
<td>1.48</td>
<td>1.29</td>
<td>1.41</td>
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<tr>
<td>$^{124}\text{Xe}+^{64}\text{Ni}$</td>
<td>1.30</td>
<td>1.29</td>
<td>1.29</td>
</tr>
<tr>
<td>$^{124}\text{Xe}+^{64}\text{Zn}$</td>
<td>1.30</td>
<td>1.13</td>
<td>1.24</td>
</tr>
<tr>
<td>$^{112}\text{Sn}+^{58}\text{Ni}$</td>
<td>1.24</td>
<td>1.07</td>
<td>1.18</td>
</tr>
</tbody>
</table>
A new setup: the $4\pi$ CHIMERA + a module of FARCOS prototype

FARCOS: Femtoscope Array for Correlations and Spectroscopy (INFN, Ganil, Huelva . . . )

- Based on (62x64x64 mm$^3$) clusters
- 1 square (0.3x62x62 mm$^3$) DSSSD 32+32 strips
- 1 square (1.5x62x62 mm$^3$) DSSSD 32+32 strips
- 4 60x32x32 mm$^3$ CsI(Tl) crystals

132 channels by each cluster

See: E.V. Pagano talk for FARCOS design presentation and results.
InKilsSy: data analysis: first results

Data analysis (particle’s calibration, identification) almost completed for particles punching through the 300 μm silicon detectors in the forward rings.
Analysis of the two largest fragments $Z_1, Z_2$ with $V_{\text{par}} > 4 \text{ cm/ns}$ and $M_{\text{IMF}} \leq 3$, $Z_1 + Z_2 > 35$.

$V_{\text{par}}$ of Light fragment $Z_2$: two velocity components

\[ \eta = \frac{Z_1 - Z_2}{Z_1 + Z_2} \]
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$V_{\text{PAR of Light fragment Z}_2}$: two velocity components

$\eta = \frac{Z_1 - Z_2}{Z_1 + Z_2}$
Analysis of new data with conditions as similar as possible to the previous Sn + Ni experiment as described in detail in Phys. Rev. C91, 014610 (2015).

Same experimental conditions and analysis methods for the two targets.
Constrained Molecular Dynamics simulation on Sn+Ni

CoMD-II time steps of one event leading to PLF fission in $^{124}\text{Sn}+^{64}\text{Ni}@35\text{ A.MeV}$

M. Papa et al. (CHIMERA coll.), PRC 75, 054616 (2007).
Constrained Molecular Dynamics simulation (CoMD-3)

- 124Xe + 64 Zn @ 35 A.MeV
- Preliminary test at 650 fm/c and stiffness parameter on $E_{\text{sym}}(\rho)$, $\gamma=1$
- Checking for projectile break-up events

Model → see M. Papa, Phys. Rev. C87, 014001 (2013) and refs therein

Selection: Three biggest fragments in events with $M_{\text{IMF}}\geq3$
Constrained Molecular Dynamics simulation (CoMD-3)

\[ Z_{2F} = Z_1 + Z_2 \]

InKiIsSy

Exp. data

See also: CoMD-2 simulations in \( ^{64}\text{Zn} + ^{64}\text{Zn} @ 45 \text{ A. MeV} \)

K. Stiefel, Z. Kohley et al., 
PRC90, 061605 (2014).
Dynamical fission: interest to extend these studies at lower energies

Study of $^{84}\text{Kr} + ^{166}\text{Er}$ and $^{129}\text{Xe} + ^{122}\text{Sn}$ at 12.5 AMeV. Strong Coulomb proximity effects observed for not fully equilibrated PLF fission.

A. Stefanini et al., $^{100}\text{Mo} + ^{100}\text{Mo}$, $^{120}\text{Sn} + ^{120}\text{Sn}$ at 20 A.MeV, Z. Phys. A351,167 (1995)

Skwira et al. (CHIMERA collaboration)
J. Wilczynski et al., PRC 81, 024605 (2010)
C. Rizzo et al., PRC 90, 054618 (2014).

$^{197}\text{Au} + ^{197}\text{Au}$ collisions have been studied at 15 AMeV and more recently at 23 A.MeV. A new process of fast reseparation of this heavy system into three or four fragments of comparable size is observed.

P. Cammarata et al., Texas A&M IWM-2014, EPJ-WebOfConf vol. 88
Study of three-body break-up mechanism in $^{136}\text{Xe} + ^{64}\text{Ni}$, $^{124}\text{Xe} + ^{58}\text{Ni}$, $^{124}\text{Sn} + ^{64}\text{Ni}$ at 15 A.MeV with FAUST array.
1) The study of the isospin dependence on compound nucleus formation and decay (ISODEC scientific program, see B. Gnoffo talk FF session).

2) The study of the influence of the isospin on the competition between Statistical and Dynamical Fission processes.

Interest in the intermediate mass region: Kr, Sr, Sn beams on Ca, Ni - 88-94Kr with 10^5 - 10^7 pps @ E/A = 10 - 12 MeV/A - Sn or Cs exotic beams on target of Ca, Ni and Sn isotopes
The evaluation of cross-sections for dynamical and statistical IMFs emission has shown that the dynamical emission is enhanced for a neutron rich system while the statistical emission is equally probable for the two systems.

The dynamical IMF emission can be a good probe in order to constraint the density dependence of the symmetry energy but this need calculations following the full range of time-scales and IMF mass emission involved in PLF binary splitting. Still a challenge for dynamical models (SMF, CoMD...).

We have shown first results of the Inkissy experiment, \(^{124}\text{Xe}+^{64}\text{Zn},^{64}\text{Ni}\) at 35 A.MeV using a system that is isobaric with the \(^{124}\text{Sn}+^{64}\text{Ni}\) one. In this experiment a first prototype of a Farcos block (4 telescopes) was used coupled to the Chimera 4π detector. IMF-IMF correlations in Farcos will improve our capability to analyse events with \(M_{\text{IMF}}<1\). As well Farcos will permit to study p-p correlations in more central collisions.

Sensitivity of N/Z ratio to dynamical fission: this effect could be new signature or probe of Isospin effect in reaction mechanisms.

Inkilssy data analysis ...... continue
The INKIISSY experiment at LNS:

**Spokes:** P. Russotto, E. De Filippo, A. Pagano