New results on central collisions: \(^{124,136}Xe + ^{124,112}Sn\) at 32 and 45 MeV/u

F.Gagnon-Moisan\(^1,2\) \hspace{1em} M.-F.Rivet\(^2\) \hspace{1em} B.Borderie\(^2\) \hspace{1em} R.Roy\(^1\)

and INDRA collaboration

\(^1\)Département de physique, génie physique et d’optique
Université Laval
Québec,CANADA

\(^2\)Institut de Physique Nucléaire
Université Paris-Sud 11
Orsay, FRANCE

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Introduction

Exploration of the phase diagram

- Nuclear matter description around the saturation density \( \rho \leq \rho_0 \)
  - INDRA: a very versatile multidetector array.
  - Effect of the isospin term on multifragmentation.
    1. Effects of the \( N/Z_{sys} \) on multiplicity.
    2. Spinodal decomposition.
    3. Isospin distillation.
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Identification de Noyaux et Détection avec Résolutions Accrues.

Since 1993, INDRA have been around. With more than 6 campaigns up to date, mostly at GANIL, there are experiments still planned for the future.
90% of the sphere (4π)
336 modules, more than 600 detectors.
Conceived for a large energy range analysis (1-4000 MeV).
Large Z detection capacity (1-82) : it can identify the heaviest fragment in multifragmentation events.
We have many systems with the same N/Z (1.38) but different entrance channel.

<table>
<thead>
<tr>
<th>System</th>
<th>N/Z</th>
<th>Energy</th>
<th>events</th>
</tr>
</thead>
<tbody>
<tr>
<td>First campaign</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe + $^{nat}$Sn</td>
<td>1.38</td>
<td>32</td>
<td>8 561 556</td>
</tr>
<tr>
<td></td>
<td>1.38</td>
<td>39</td>
<td>9 578 277</td>
</tr>
<tr>
<td></td>
<td>1.38</td>
<td>45</td>
<td>10 798 234</td>
</tr>
<tr>
<td>$^{136}$Xe + $^{124}$Sn</td>
<td>1.5</td>
<td>32</td>
<td>90 651 990</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>45</td>
<td>119 321 549</td>
</tr>
<tr>
<td>$^{136}$Xe + $^{112}$Sn</td>
<td>1.38</td>
<td>32</td>
<td>33 531 821</td>
</tr>
<tr>
<td></td>
<td>1.38</td>
<td>45</td>
<td>23 764 627</td>
</tr>
<tr>
<td>$^{124}$Xe + $^{124}$Sn</td>
<td>1.38</td>
<td>32</td>
<td>35 443 613</td>
</tr>
<tr>
<td>$^{124}$Xe + $^{112}$Sn</td>
<td>1.27</td>
<td>32</td>
<td>77 361 626</td>
</tr>
<tr>
<td></td>
<td>1.27</td>
<td>45</td>
<td>67 481 731</td>
</tr>
</tbody>
</table>

The number of events available for Xe+Sn reactions in the $V^{th}$ campaign (2001) is $10 \times$ the one obtain in the first campaign (1993).

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150μm silicon-CsI(Tl) telescopes are used for isotopic resolution, with higher gain, we can obtain lower identification threshold.

They replace the 300μm silicon.

With this configuration, we have isotopic resolution up to oxygen (Z = 8).

Selection of central events.

For Xe+Sn reaction:

\[ Z_{tot} = \sum_i Z_i \geq 80 \] \hspace{1cm} (1)

\[ Z_{tot}^{sys} = 104 \]

And

\[ \theta_{flow} \geq 60^\circ \]

2. J.D. Frankland et al. / Nuclear Physics A 689 (2001) 905939
The 150 μm silicon detectors are located on ring 2 to 9. For a simple analysis, in $^{124}$Xe + $^{112}$Sn @ 32A.MeV, Fragments identified:

- for 150μm are 14% and
- for 300μm are 86% of total fragments identified in Si-CsI telescopes.
Fragments selected

$V^{th}$ INDRA campaign

**124^{Xe}+^{112}Sn 32 A.MeV**

- Introduction
- INDRA
- Central events selection
- Effects of the N/Z
- Phase transition in nuclei
- Charge correlation
- Isospin distillation
- Conclusion
Effects of the N/Z : multiplicities
Xe+Sn systems, central events

Fragments (fra) $Z \geq 5$; Light Charged Particles (lcp) $Z \leq 2$

With N/Z ↑, $M_{fra}$ ↑.
With N/Z ↑, $M_{lcp}$ and $M_{tot}$ ↓.

The projectile have no effect on $M$. 
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The nuclear EOS links the different thermodynamic variables \((P, \rho, T, V)\) which describe an infinite nuclear matter. Ex: Van der Waal’s liquid \((\infty \text{ system})\)

\[
P + \frac{n^2 a}{V^2} (V - nb) = nRT \tag{3}
\]

Within this regime, there a region of mechanical instabilities, called spinodal region.

\[
\frac{\partial P}{\partial \rho} |_{T \leq 0} < 0 \tag{4}
\]
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The spinodal region

$\infty$ systems

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The system will break up in fragments of equal charge ($Z \sim 10 - 15$ for Xe+Sn).

Fluctuations are amplified by the mean-field.
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Spinodal decomposition consequences

The system will break up in fragments of equal charge ($Z \sim 10 – 15$ for Xe+Sn).
The spinodal region
Actual nuclear systems

Phase transition signal perturbed
- beating of different modes
- coalescence of nascent fragments
- secondary decay of the excited fragments
- finite-size effects
Higher order charge correlations\textsuperscript{a}

\[ 1 + R(\sigma_Z, \langle Z \rangle) = \frac{Y(\sigma_Z, \langle Z \rangle)}{Y'(\sigma_Z, \langle Z \rangle)} \left|_M \right., \quad (5) \]

\[ \langle Z \rangle = \frac{\sum_{i=1}^{M} Z_i}{M}, \quad (6) \]

\[ \sigma_Z = \sqrt{\frac{\sum_{i=1}^{M} (Z_i - \langle Z \rangle)^2}{M}} \quad (7) \]

Where \( M \) is the IMF multiplicity \( M_{\text{IMF}} \).

For the denominator, the intrinsic probabilities method\textsuperscript{b} is used.

\textsuperscript{a} L.G. Moretto \textit{et al}. Phys.Rev.Lett. 7 (1996) 2634

\textsuperscript{b} P.Désesquelles Phys. Rev. C65 (2001) 034604
There is less *extra* events for the neutron-rich system.
BNV calculation
Central Sn+Sn collisions @ 50 A.MeV

dashed = soft
full line = stiff

- Soft parametrization demonstrate greater difference.
- For both parametrizations, differences between liquid and gas increase with (N/Z).
- Inversion for Stiff for low (N/Z) (Coulomb effects).
Isospin distillation with radial flow *M. Colonna et al. PRC78 (2008) 064618*

**dashed = soft**

**full line = stiff**

Slopes are characteristic of \((N/Z)_{sys}\) and stiffness for \(E_{sym}\) parametrization.
Experimental results

**PRELIMINARY RESULTS**

There is a difference between the slopes for n-rich and n-poor systems.

The effect seems linked to flow (0.5MeV for 32A.MeV and 1.5MeV for 45A.MeV).

More statistic available.

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Conclusion

- INDRA is a powerful tool for analysis of nuclear reactions.
- Effects observed on multiplicities confirms previous observations.
- Spinodal decomposition signal (charge correlations)
  - The spinodal signal seems to be greater at 32 A.MeV than 45 A.MeV.
  - The number of extra events is lower for neutron-rich system.
- The results obtain with the variable elaborate by M.Colonna seems to corroborate simulations.
- Details and final conclusions to be published in my thesis (2010).

The correlation function is given by:

\[
P(\langle Z \rangle, \sigma | M_f) \]

\[
= P_{nc}(\langle Z \rangle, \sigma | M_f) = 1 + R(\langle Z \rangle, \sigma | M_f). \tag{8}
\]

With the experimental distribution, we can calculate the probability by convolution:

\[
P_{nc}(\langle Z \rangle | M_f) = \sum_{z_1} \cdots \sum_{z(M_f-1)} P_z(z_1 | M_f) \cdots P_z(z(M_f-1) | M_f)P_z(M_f \langle Z \rangle - (M_f - 1) \langle Z \rangle' | M_f), \tag{9}
\]

and obtain the expression for a denominator without correlated events:

\[
P_{nc}(\langle Z \rangle \cap \sigma | M_f) = M_f! \sum_{\{nz\}} \prod_z \frac{P_{nz}(Z | M_f)}{nz!}. \tag{10}
\]

Finally, the statistical significance is given by:

\[
\alpha \leq \frac{n(M_f P_{nc}^3(\langle Z \rangle, \sigma | M_f))}{(P(\langle Z \rangle, \sigma | M_f)P_{nc}(\langle Z \rangle, \sigma | M_f))^2}. \tag{11}
\]