Dipolar Degree of Freedom and Isospin Equilibration Phenomena in Heavy Ions Collisions
(the Equilibration experiment)

M. Papa

I.N.F.N. Catania Italy


INPC2019

27th International Nuclear Physics Conference
29 July – 2 August 2019 Glasgow UK
Introduction

- Isospin equilibration phenomenon has been studied for long time because it is strictly linked with symmetry energy and then with the isovectorial part of the effective interaction.
- These investigations have been performed mainly looking to the relative productions of particle and fragment as function of their charge and mass.
- As it is well known the study of heavy collisions aimed to get Information on the effective interaction in the dynamical stage can be strongly affected by the statistical decay process.
- In particular in a two/three works it has been also shown in some detail how the peculiarity of the statistical mechanisms can affect the relative production of particles and the related effects on some key parameters concerning the effective interaction.

M.B.Tzang et al PRL 86 5023(2001)  
T.G.Ma et al, PRC72,064602 (2005)  
M.Brondi et al; EPJ Web of Conferences 2, 04002 (2010)  
P.Zhou et al; Phys Rev C 84 037605 (2011)  
D.Cussol et al; PRC 65 044604
Search for Isospin effects on nuclear level density

Fig. 3. Ratio between 1n and 2n channel cross sections predicted by the statistical model for different isospin dependences of the level density.

Fig. 5. Light particle multiplicities and neutron energy spectra predicted by the statistical model including temperature-dependent symmetry energy $E_{sym}(T)$ and level density parameter $\alpha(T)$ according to Ref. [16],[17], respectively. The results of the standard calculation are also shown for comparison.
Isoscaling parameters and multistep statistical decay

M.B. Tsang  PRC 84 036705
A.Ono  PRC 68 051601; Y.G.Ma PRC 69 064610

\[ R_{21}(N, Z) = \frac{Y_2(N, Z)}{Y_1(N, Z)} = C \exp(\alpha N + \beta Z), \]

**FIG. 2.** (Color online) Comparisons of isoscaling parameters \( \alpha \) (left) and \( \beta \) (right) as a function of the source excitation energy from source pairs of \( Z_s = 30 \). All solid symbols represent the first-step-only secondary decay products; open symbols represent the entire-steps secondary decay products. Symbols in the figure correspond to \( Y_{A_t=69}/Y_{A_t=60} \) (downward triangles), \( Y_{A_t=69}/Y_{A_t=63} \) (diamonds), and \( Y_{A_t=69}/Y_{A_t=66} \) (left-pointing triangles).

P.Zhou et al; Phys Rev C 84 037605 (2011)
FIG. 6. Schematic explanation of the two possible contributions to the flow parameter. The uppermost picture corresponds to the beginning of the reaction when the projectile $P$ and the target $T$ are touching each other. Arrows correspond to the velocity of “direct” (promptly emitted) particles. Middle pictures correspond to the time at which the QP and QT are leaving each other. The lowermost pictures correspond to the expected variation of $(P_{\pi}/A)$ with $Y_{r}$ for “evaporated” particles (dashed line) and “direct” particles (dashed and dotted line) in case of attraction (left column) and bounce-off (right column).
Time Derivative of the total dipole

("Coherent Cluster production")

\[ < \hat{D} > = < \sum_{i=1}^{m} \hat{Z}_i (\hat{V}_i - \hat{V}_{cm}) >_K \]

A) because of the symmetries of the statistical decay mode, \( < \hat{D} > \) is not affected by the statistical emission of all the produced sources in the later stages [1].

B) as shown in [2], this quantity is closely linked to the charge/mass equilibration process.

\[ < m_{Z,A} > < \hat{P}_{Z,A} > \neq 0 \]

\[ < \hat{D} > \propto \sum_{Z,A} Z < m_{Z,A} \hat{P}_{cm} > = \sum_{Z,A} Z < m_{Z,A} > < \hat{P}_{cm} > C_{\hat{P}_{cm}}^{Z,A} = \frac{< m_{Z,A} \hat{P}_{Z,A}^c >}{< m_{Z,A} > < \hat{P}_{Z,A}^c >} \]

Isospin Equilibration according to the Rami definition \[ \langle \hat{P} \rangle = 0 \]

On the contrary if \[ \langle \hat{D} \rangle \neq 0 \]

\[ < \hat{D} > = < \hat{D}_m > = \frac{1}{2} \mu (\beta_T - \beta_P) (\hat{V}_p - \hat{V}_T) \]

Impinging nuclei with different charge/mass asymmetries: during the pre-equilibrium stage the \( Z/A \) are redistributed in momentum-space and \[ | < \hat{D} > | \rightarrow 0 \]


Time dependence of the Dipolar signals

\[ ^{48}\text{Ca} + ^{27}\text{Al} \text{ 40 MeV/A} \]

\[ ^{124}\text{Sn} + ^{64}\text{Zn} \text{ 400 MeV/A} b = 1\text{fm} \]

G. Giuliani and M. Papa PHYSICAL REVIEW C 73, 031601(R) (2006)
M. Papa et al PHYSICAL REVIEW C 72, 064608 (2005)
M. Papa et al; PHYSICAL REVIEW C 68, 034606 (2003)
$^{48}\text{Ca} + ^{27}\text{Al}$ 40 MeV/Nucleon investigated at LNS with the multi-detector CHIMERA

First stage of investigation on Dissipative Binary Processes

$$U_{\text{sym}}(\rho) = U_{\text{sym}}(\rho_0)(\frac{\rho}{\rho_0})^\gamma \quad \gamma \approx 1 \quad E_{\text{sym}} \approx 30 \text{ MeV}$$

M. Papa et al; PHYSICAL REVIEW C 91, 041609 (2015)

Recent preliminary analysis on IMF production In the Mid-rapidity region
We will focus on the beam axis component of \( <D> \)

\[
< D^c_z > = \sum_{i=1}^{m} Z_i (V^i_z - V^{cm,d}_z) \\
< \vec{D} > = \sum_{i=1}^{m} Z_i (\vec{V}^i - \vec{V}^{cm})
\]

We correct for possible systematic errors on the velocity by using \( V^{cm,d}_z \) instead of \( V^{cm}_z \)

\( <D^c_z> \) represents a partial dipolar signal related to the intrinsic motion of the subsystem formed by all the charged particles.
Summary and Outlook

A new campaign of measurements has been performed in 2018 on the same main system $^{48}$Ca+$^{27}$Al 40 MeV/A and the auxiliary ones $^{40}$Ca+$^{27}$Al and $^{40}$Ca+$^{40}$Ca. The long work related to calibration and identification is in progress.

- Selection of central processes
- Estimation of possible systematic uncertainty through the analysis of the reference systems
- More detailed comparison with microscopic calculations
48Ca+27Al 40 MeV/Nucleon investigated with the multi-detector CHIMERA at LNS

\[ \langle D \rangle = \langle \sum_{i=1}^{m} Z_i (V_i - V_{i,\text{cm}}) \rangle_K \]

Good reconstruction of events:
- \( m \geq 2 \)
- \( Z_{\text{tot}}^d = 33 \)
- \( P_{\text{tot}}^d \geq 0.7 P_{\text{tot}} \)
- \( 62 \leq m_{\text{tot}}^d \leq 78 \)

the main system and the auxiliary one

\[ K \equiv Z_b, \text{TKEL} \]

Evaluation/correction of errors

a) Random uncertainty (zero average) can be very small \( \delta < D > \approx 1 / \sqrt{N} \)

b) Eventual systematic uncertainty on charges and velocities \( \Delta Z < D >, \Delta V < D > \)

\( \Delta Z < D > \leq 0.2 \text{ cm/nsec} \)

TKEL \leq 350 \text{ MeV}
Experimental Data and CoMD-III calculations

\[ \gamma = 0.8(L \approx 79\text{MeV}), \gamma = 1(L \approx 90\text{MeV}), \gamma = 1.2(L \approx 100\text{MeV}), \gamma = 1.5(L \approx 114\text{MeV}) \text{ and } E_{\text{sym}} \approx 32 \text{ MeV} \]

\[ < D_Z > \approx < D_Z^c > + Z_{\text{tot}}^d \left( V_{Z_{\text{cm}}}^{c,e} - V_{\text{cm}}^{e} \right) \]

We observe:

For \( \gamma \neq 0.8 \) and \( Z_b \neq Z_P \) \( |\bar{D}_Z^c| < |\bar{D}_Z^c(Z_P)| \)
we obtain that \( V_{Z_{\text{cm}}^{c,e}} < V_{\text{cm}} \)
therefore \( V_{Z_{\text{cm}}^{c,N}} > V_{\text{cm}} \) and more neutron emission from PLF region more charge/mass symmetric fragments.

For \( \gamma = 0.8 \) and \( Z_b > Z_P \) \( |\bar{D}_Z^c| > |\bar{D}_Z^c(Z_P)| \)
we obtain that \( V_{Z_{\text{cm}}^{c,e}} > V_{\text{cm}} \)
therefore \( V_{Z_{\text{cm}}^{c,N}} < V_{\text{cm}} \), more neutron emission from TLF and mid-rapidity region.

In this case, a closer look to the fragments shows an almost complete disassembly of the light partner (TLF).
Dipolar Signal decomposition - transversal component differential flow

\[ \langle \mathbf{V} \rangle = \left\langle \frac{A_G(1 - \beta_G^2)}{4} \mathbf{u}_r^{PN} \right\rangle + \left\langle \frac{\mu_G L (\beta_L - \beta_G)}{2} \mathbf{u}_{cm, LG}^{\prime} \right\rangle + \langle \mathbf{V}_{r,L} \rangle \]

Figure 2. In panel (a) the neutron-proton differential flow $F_{np}$ is shown as a function of the c.m. reduced rapidity $y$. In panel (b), $F_{np}$ is plotted after the correction for the relative c.m. velocity of the neutron and proton "gases" $\mathbf{u}_r^{PN}$. Different symbols refer to different options. In the panel (c) the average value of $\mathbf{u}_r^{PN}$ contributing to the isospin equilibration process are represented for the Stiff1 and Soft options.
Measured transversal component 
\( E_{\text{diss}} \leq 350 \text{ MeV} \)

Parallel component more dissipative processes 
\( E_{\text{diss}} \approx 350-500 \text{ MeV} \)

Calculations in progress
TABLE I. For different windows of $Zb$ and for TKEL $< 350$ MeV, the values (cm/nsec) of $\langle Dz \rangle$ and the corresponding values of $\langle Dz^D \rangle$ are shown for the $^{48}Ca + ^{27}Al$ system, for $\gamma = 1$

<table>
<thead>
<tr>
<th>$Zb$</th>
<th>$\langle Dz \rangle$ (cm/nsec)</th>
<th>$\langle Dz^D \rangle$ (cm/nsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-15</td>
<td>-5.73</td>
<td>-5.9</td>
</tr>
<tr>
<td>15-17</td>
<td>-8.36</td>
<td>-8.34</td>
</tr>
<tr>
<td>17-19</td>
<td>-8.86</td>
<td>-8.87</td>
</tr>
<tr>
<td>20</td>
<td>-9.79</td>
<td>-9.78</td>
</tr>
<tr>
<td>21-22</td>
<td>-5.36</td>
<td>-5.30</td>
</tr>
</tbody>
</table>

Conclusive remarks

- Further experimental investigation should involve different systems and different reaction mechanisms ($\gamma < 1$).

- In particular, a next step forward in these kind of measurements would require a more detailed investigation, including a reliable estimation or minimization of systematic uncertainty on the velocity of the charged particles. This would permit a direct experimental estimation of $\langle D_z \rangle$, allowing for a corresponding experimental estimation of the global effect associated with the dynamically-emitted neutrons. For this purpose, longer measurements involving targets and projectiles with same charge/mass and mass asymmetry. (vanishing values of $\langle D_z \rangle$ independently from the reaction mechanism) could be helpful.
Introduction

• The experimental evidences on Heavy Ion Collisions highlight, in different ways, processes which evolve on different time scales. At Fermi energies, semi-classical dynamical models can not describe the system during its overall time evolution ($\Upsilon_{n} \approx 2500 \text{ fm/c } T=2\text{MeV}$)

• The observed data should be described phenomenological through a fast pre-equilibrium stage described using dynamical models, and later-stage processes described by statistical decay models (different explored densities).

• In particular, in the last stage the Isospin and excitation energy dependencies of the level density formula play a key role and have been subjects of investigation.

• A phenomenon closely linked to the Iso-vectorial-forces is the well-known process leading to the redistribution in momentum-space of the charge/mass excess $\beta = (N-Z)/A$ of the emitted particles and fragments (complex phenomenon)

• Taking full advantage (as much as possible) of the today’s high efficiency multi-detectors, the attempt to measure observables in principle closely linked to only one of the two regimes is therefore highly desirable.