N/Z Equilibration in Binary Nuclear Systems

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Using isospin transport to learn about the
symmetry energy

Neutron star merger

Heavy-ion collisions

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**Isospin Transport: Drift and Diffusion**

\[
\dot{j}_{p/n} = D^\rho_{p/n} \nabla \rho - D^I_{p/n} \nabla I
\]

- **Drift**
  - Due to density gradients
  - Migration of neutrons to low-density region
  - Slope of the symmetry energy

\[
D^\rho_n - D^\rho_p \propto 4I \frac{\partial E_{sym}}{\partial \rho}
\]

- **Diffusion**
  - Due to N/Z gradients
  - Migration of neutron from high N/Z region to low N/Z region
  - Absolute value of the symmetry energy

\[
D^I_n - D^I_p \propto 4\rho E_{sym}
\]

- **Isospin Drift**: due to density gradients
  - Migration of neutrons to low-density region
  - Slope of the symmetry energy

- **Isospin Diffusion**: due to N/Z gradients
  - Migration of neutron from high N/Z region to low N/Z region
  - Absolute value of the symmetry energy

Baran, PRC72, 064620 (2005)
Rizzo, NPA806, 79 (2008)
N/Z Asymmetric Collisions

- Overlapping Fermi tails / low density neck → drift
- Initial N/Z asymmetry → diffusion
- Probe: Isotopic composition of emitted clusters

Liu, PRC 76, 034603 (2007)
Kohley, PRC 85, 064605 (2012)
Barlini, PRC 87, 054607 (2013)
...

Ratios ($R_X$): Use cross-bombardment of n-rich and n-poor nuclei to reduce common characteristics (e.g. drift) to first order

± 1: no equilibration
0: equilibration

- Observed degree of equilibration limited by the short contact time between the target and the projectile (~100 fm/c).
 Experimental Setup

**Forward Indiana Ring Silicon Telescope**

**Large Area Silicon Strip Array**


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Si-CsI stack detectors & Si-Si-CsI stack detectors

→ ΔE-E technique

High Segmentation → High Angular Resolution

(592 Si channels)

Angular coverage: $3^\circ \leq \theta_{\text{Lab}} \leq 51^\circ$ (FIRST+LASSA)
Studied Systems

• Systems:
  - $^{124}$Xe + $^{112,124}$Sn @ 49 MeV/A (GANIL)
  - $^{64}$Zn + $^{64}$Zn, $^{209}$Bi, $^{27}$Al @ 45 MeV/A (TAMU)

• Experimental Setup:
  - Angular coverage: $3^\circ \leq \theta_{\text{Lab}} \leq 28^\circ$ (FIRST)
  - Z and A identification by $\Delta E$-$E$
  - A identification up to Z = 14

Paduszynski, NIMA547, 464 (2005)
Energy calibration of FIRST (T1)

Silicon detectors

13C Beam Calibration

→ Silicon Detector Thickness

Charge Pulser Calibration

→ Establish Linearity of Electronics

Isotope lines of known Z,A & Energy Loss Calculations

→ Silicon Detector Energy Calibration

CsI detector calibration

Isotopic lines of known Z,A & Silicon detector calibration & Energy Loss Calculations

→ CsI Energy Calibration

Deviation: ~ 0.5 %

Deviation: ~ 2 % most of range
As $Z$ decreases from $Z_{beam}$, velocity initially decreases (damping).

As $Z$ continues to decrease, velocity remains about constant (apparent saturation of damping).

Heaviest particle detected in FIRST ($3^\circ$ - $14^\circ$).
As $Z_{PLF}$ decreases:

- Mean velocity decreases monotonically.
- Peak velocity decreases down to $\approx 8.9$ cm/ns then rises slightly.

→ Something more than a dissipative PLF-TLF interaction (e.g. dynamic breakup of PLF)
- Two fragments in $3^\circ \leq \theta_{\text{lab}} \leq 7^\circ$
- $Z_H \geq 21$
- $Z_L \geq 4$
- $Z_H + Z_L$ at least $Z = 25$ ($\sim \frac{1}{2} Z_{\text{projectile}}$)

- For $Z_L \leq 8$, $V_{\text{parallel}}$ distribution for $Z_H$ is single peaked
- Associated distribution of $V_{\text{parallel}}$ for $Z_L$ has two peaks located at larger and smaller velocities
- For $Z_L = 14$ the $V_{\text{parallel}}$ distribution for $Z_H$ shows two peaks

Velocity of $Z_L$ is not peaked at the center-of-mass, particularly for heavy $Z_L$

Consistent with binary decay of a PLF*:

$$Z_{\text{PLF}^*} = Z_H + Z_L$$
$$V_{\text{PLF}^*} = V_{\text{cm}}$$
• $V_{cm}$ distributions for $V_H > V_L$ ("backward emission") and $V_L > V_H$ ("forward emission") are similar, exhibiting damping from beam velocity.
• **Backward emission** has a slightly larger damping on average than **forward emission**.
• **Backward emission** has an additional component of higher relative velocities not observed for **forward emission** (not just mid-rapidity emission).
Angular distribution of the binary decay is preferentially peaked for \( \cos(\alpha) > 0 \), “backward emission”

- Although asymmetry of forward and backward emission decreases with increasing \( Z_L \), it is still evident for \( Z_L = 18 \).

- For the least damped cases, no forward backward asymmetry is evident.

- With increasing damping, the preference for backward emission increases.

McIntosh, PRC81, 034603 (2010)
We associate the forward emission with the long-lived statistical emission of a hot, rotating PLF*.
Using the observed yield in the forward direction as a reference and assuming isotropic emission, we calculate the backward emission, correcting for the detector acceptance.

The difference distributions reflect the short-lived decays of the PLF*. The angular distributions associated with these decays become broader with increasing $Z_L$.

McIntosh, PRC81, 034603 (2010)
• The yield of the short-lived/dynamical component first increases with increasing $Z_L$, is peaked at $Z_L = 6$ and then decreases smoothly.

• The distribution of $V_{cm}$ associated with this process is significantly damped from beam velocity.

All major trends observed for the extracted yield (difference) are also observed for the total yield observed backward.
Projectile-Like Dynamical Breakup

- Decay mode characterized by:
  - Strong alignment
  - Large charge asymmetry
  - Preferential emission at velocities intermediate between the projectile and the target
  - Larger relative velocity than standard fission
  - Angular momentum results in rotation

- Relatively long lifetime
  - Much larger than 100 fm/c, the projectile-target contact time

Dynamical fission with multi-neck ruptures

Davin, PRC65, 064614 (2002)
Piantelli, PRL88, 052701 (2002)
McIntosh, PRC81, 034603 (2010)
De Filippo, PRC86, 044605 (2012)
Summary on Binary decay

- Since Rotation angle represents time it is a fundamental observable:

  Angle between the relative velocity and the fragment “parent” velocity

  \[ \cos(\alpha) = 1: Z_L \text{ “backward” of } Z_H \]
  \[ \cos(\alpha) = -1: Z_L \text{ “forward” of } Z_H \]

Light fragment **not** emitted at mid-rapidity.

Now examine isotopic composition of $Z_L$ as a function of rotation angle

Event Selection:
1) 2 fragments detected at forward angles: $Z_L$ and $Z_H$
2) Large fraction of projectile: $Z_H \geq 0.4*Z_{\text{Projectile}}$

McIntosh, PRC81, 034603 (2010)
Hudan, PRC86, 021603(R) (2012)
Brown, PRC87, 061601(R) (2013)
Isotopic Composition vs Rotation Angle

- Backward emission neutron-rich relative to forward emission
- Fragment neutron content enhanced for larger alignment
- Small target effect on the relative neutron composition
- Similar $\langle N \rangle / Z$ observed in $^{124}\text{Sn}$ fragmentation @ 600 MeV/A*

<table>
<thead>
<tr>
<th></th>
<th>$^{124}\text{Xe}$</th>
<th>$^{124}\text{Sn}$</th>
<th>$^{112}\text{Sn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N/Z$</td>
<td>1.30</td>
<td>1.48</td>
<td>1.24</td>
</tr>
</tbody>
</table>
Isotopic Composition vs Rotation Angle

\( ^{64}\text{Zn} + ^{64}\text{Zn}, ^{209}\text{Bi}, ^{27}\text{Al} \)

- \( \langle N \rangle/Z \) dependence on decay angle for a given \( Z_L \)
  - Backward decay neutron-rich relative to forward decay
  - Fragment neutron content enhanced for larger alignment
  - Larger \( \langle N \rangle/Z \) values for the Bi target
  - Stronger effect observed for Be fragments
  
  → “Amplification” of the extremes by the “missing \( ^{8}\text{Be} \)”

Brown, PRC87, 061601(R) (2013)

Isotopic Composition vs Rotation Angle
Relating Decay Angle to Time

- The rotation angle can be related to time via the rotational frequency $\omega$:
  \[ t = \frac{\alpha}{\omega} \quad \text{with} \quad \omega = \frac{J\hbar}{I_{\text{eff}}} \]

- The angular momentum, $J$, is determined by the use of a standard statistical emission code to mimic the case of “forward” decay $\Rightarrow J = 6 \pm 1 \ \hbar$
  - The value of $J$ is *independently* confirmed by $\alpha$ particle’s out-of-plane distribution.

- The moment of inertia, $I_{\text{eff}}$, is calculated for a non-spherical dinuclear shape [Carjan, PRC45, 2185 (1992)] and a temperature $T = 3-5 \ \text{MeV}$
  \[ \Rightarrow \omega = 0.4-0.5 \times 10^{21} \ \text{rad/s} \]

Consistent with previous data
Casini, PRL71, 2567 (1993)
Piantelli, PRL88, 052701 (2002)

Brown, PRC87, 061601(R) (2013)
N/Z Equilibration Timescale

\[ \Delta \langle N \rangle = \langle N(t) \rangle - N(t = 0) \]

- Neutron number of $Z_L$ changes for times as long as 1000 fm/c
- Stronger dependence for $Z_L = 4$
- Target dependence with the strongest slope for the most neutron-rich target
  - Equilibration rate of $\langle N \rangle$ governed by the initial N/Z gradient in the dinuclear system

No rotation $\Leftrightarrow$ $t = 0$

Brown, PRC87, 061601(R) (2013)
In N/Z symmetric collisions, isospin diffusion would NOT occur without prior isospin drift.

Isospin drift acts to make low density region neutron rich.

Isospin diffusion acts to make the system homogeneous in isospin.
Isospin Drift and Diffusion Timescales

$^{64}\text{Zn}+^{64}\text{Zn} \text{ @ } 45 \text{ MeV/A}$

- Isospin diffusion occurs on the timescale of up to $\sim 1000 \text{ fm/c}$
- The impact of isospin drift has independently been observed as neutron enrichment of low density region.
- Isospin drift occurs on a faster timescale, $\leq 100 \text{ fm/c}$

Physical picture

Thériault, PRC74, 051602 (2006)
Conclusions

- Dynamical binary decay provides an effective means to access isospin equilibration out to long times $t \sim 1000 \text{ fm/c}$

- For symmetric projectile-target combinations, in a first stage drift precedes diffusion establishing an isospin disequilibrium.

- In a second stage, both drift and diffusion contribute in an attempt to return the system to isospin equilibrium with a net flow of neutrons out of the light fragment observed.

- Need microscopic calculations (TDHF ?) to better understand this process and relate these observations to

$$\frac{\partial E_{\text{sym}}}{\partial \rho} \quad \text{and} \quad E_{\text{sym}}$$
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  • The support of the Cyclotron Institute at Texas A&M U.
  • The DEMON collaboration

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Decay Angle to Time

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- The angular momentum, $J$, is determined by the use of a standard statistical emission code to mimic the case of "forward" decay $\Rightarrow J = 6 \pm 1 \hbar$

- The moment of inertia, $I_{\text{eff}}$, is calculated for a non-spherical dinuclear shape and a temperature $T = 3-5$ MeV:

$$J = l\hbar = I_{\text{eff}}\omega \quad I_{\text{eff}} = \frac{2}{5}MR^2F_I$$

$M = m_0c^2A$ with $m_0c^2 = 931.5$ MeV

$R = r_0A^{\frac{1}{3}}$ with $r_0 = 1.2$ fm

$A_{PLF^*} = \left(\frac{N}{Z}\right)_{\text{projectile}}Z_{PLF^*}$

$\Rightarrow \omega = 0.4-0.5\times10^{21}$ rad/s

Carjan, PRC45, 2185 (1992)
N/Z Equilibration Timescale

\[ \Delta \langle N \rangle = \langle N(t) \rangle - N(t = 0) \]

No rotation \( \Leftrightarrow t = 0 \)

- Parametrization performed with a first degree polynom resulting in the following slope (\( \Delta N / 1000 \) fm/c):

<table>
<thead>
<tr>
<th>Z</th>
<th>Bi</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z=4</td>
<td>1.135</td>
<td>0.845</td>
<td>0.668</td>
</tr>
<tr>
<td>Z=6</td>
<td>0.247</td>
<td>0.178</td>
<td>0.156</td>
</tr>
</tbody>
</table>

Brown, PRC87, 061601(R) (2013)
Particle Identification in T1 Telescope

Si-Si

\[ \frac{dE}{dx} \propto \frac{Z^2 A}{E} \]

Z=54 elastic

Si-Si

Si-CsI

T1 Si-Si Pie 2

T1 Si-CsI Pie 2

Z=54

Z=20

T1 Si-CsI Pie 2

Carbon

E-Silicon (ch)

E-Silicon (ch)

Counts

E-Silicon (ch)

E-Silicon (ch)

Yield

Yield

Yield

INdiana University
LASSA

Si-E 0.5 mm
Si-dE 65 μm
4x CsI(Tl) 6cm
Pixel
16 strips h. (back)
16 strips v. (front)

36° ≤ θ_{lab} ≤ 51°

Carbon
Si-Csl
p, d, t
N/Z Time Dependence

$^{124}\text{Xe} + ^{112}\text{Sn}$

- $Z_L = 4$
  - Strong time dependence
  - Two components
- $Z_L = 5, 6$
  - Time dependence not as pronounced as for $Z_L = 4$
- $Z_L = 8$
  - Similar dependence for both short and long times

$1 \text{zs} = 10^{-21} \text{s} = 300 \text{ fm/c}$

$\Rightarrow$ Persistence of N/Z equilibration over long times