Probing nucleon transport with nuclear reactions

Sylvie Hudan
Indiana University
Binary Mergers

- Recent observation of black hole merger
  Ligo/Virgo, PRL116, 061120 (2016)

- Binary mergers are dynamical in nature
- Tidal effects on large scale
- Dynamical stage followed by equilibration

Hanford, Washington (H1)  Livingston, Louisiana (L1)

McIntosh, PRL99, 132701 (2007)
Mergers and Nucleosynthesis

Neutron star - neutron star / black hole mergers

- Potential source of heavy Z production via the r-process
- Influence of the EOS of asymmetric matter, e.g. neutron rich
  - Soft EOS will give more r-process material in the ejecta


A.P. Ji et al.,
Nature 531, 610 (2016)
From Big to Small Scale

• On the macroscopic scale, EOS: P, T, ρ, I degrees of freedom
  • Long history for N=Z matter
  • Investigating the isospin degrees of freedom
From Big to Small Scale

- On the macroscopic scale, EOS: P, T, ρ, I degrees of freedom
  - Long history for N=Z matter
  - Investigating the isospin degrees of freedom
- Governed by the microscopic nature of the system
- In the laboratory, exchange between two systems used as a tool
Isospin Transport: Drift and Diffusion

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

\[ \rho = \rho_n + \rho_p \]

\[ I = \frac{\rho_n - \rho_p}{\rho} \]

Baran, PRC72, 064620 (2005)
Rizzo, NPA806, 79 (2008)
Isospin Transport: Drift and Diffusion

\[
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\]

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

- **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

\[
\rho = \rho_n + \rho_p \\
I = \frac{\rho_n - \rho_p}{\rho}
\]

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

\[
D^{I}_n - D^{I}_p \propto 4\rho E_{sym}
\]

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N/Z Symmetric Collisions

- Overlapping Fermi tails / low density neck $\rightarrow$ drift
- No initial N/Z asymmetry $\rightarrow$ minimal diffusion

Thériault, PRC74, 051602(R) (2006)
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Isotopic composition, N/Z, of mid-velocity region (“MRM”)

- From studying emitted clusters, similar N/Z than the initial system is observed for all impact parameters.
- When accounting for free nucleons, free neutrons and free protons, a neutron enrichment of the low density region is observed.

⇒ ISOSPIN DRIFT

Thériault, PRC74, 051602(R) (2006)
N/Z Asymmetric Collisions

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Liu, PRC76, 034603 (2007); Kohley, PRC 85, 064605 (2012)
Barlini, PRC87, 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
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Tsang, PRL92, 062701 (2004)

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

Detection of charged particles with high angular resolution

**Forward Indiana Ring Silicon Telescope**

**Large Area Silicon Strip Array**

- Angular coverage: $3^\circ \leq \theta_{\text{Lab}} \leq 28^\circ$
- Z and A identification by $\Delta E-E$ with Si-CsI and Si-Si-CsI stacks

FIRST: Padusznyski, NIMA547, 464 (2005)
LASSA: Davin, NIMA473, 302 (2001)
Wagner, NIMA456, 209 (2001)

672 channels of Si
80 channels of CsI
Calibration

- A identification up to $Z = 14$
- Resolution of multiple particles
- Energy calibration:
  - Si: $^{13}$C beam, Charge pulser, isotopes of know $Z,A$, energy loss calculations
  - CsI: isotopes of known $Z,A$, Si calibration, energy loss calculations

$3^\circ \leq \theta_{\text{Lab}} \leq 28^\circ$

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

PLF: Heaviest particle detected at forward angles

- As $Z_{PLF}$ decreases from $Z_{BEAM}$, the velocity initially decreases (damping)
- As $Z_{PLF}$ continues to decreases, the velocity remains quasi constant (apparent saturation of damping)

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

$\varepsilon/A = 50$ MeV

$\theta_{LAB} = 3-14^\circ$

McIntosh, PRC81, 034603 (2010)
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As $Z_{\text{PLF}}$ decreases:

- Mean velocity decreases monotonically
- Peak velocity decreases down to $\sim 8.9$ cm/ns then rises slightly:
  - Something more than a dissipative binary interaction (e.g. dynamic breakup of PLF)

McIntosh, PRC81, 034603 (2010)
Binary Breakup

• Selection:
  - Two fragments in $\theta_{\text{LAB}} = 3-14^\circ$
  - $Z_H \geq 21$ and $Z_L \geq 4$
    ▸ $Z_H + Z_L$ at least $Z = 25$ ($\sim \frac{1}{2} Z_{\text{Projectile}}$)
• For $Z_L \leq 8$
  ▩ Single peak for $V_{//}$ for $Z_H$
  ▩ Double peak for $V_{//}$ for $Z_L$ at larger and smaller velocities
• For larger $Z_L$, e.g. $Z_L = 14$, $V_{//}$ distribution for $Z_H$ shows two peaks

![Graphs showing velocity distributions for different atomic numbers](image)

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The velocity of $Z_L$ is **NOT** peaked at the initial system center-of-mass.

Kinematics consistent with binary decay of a PLF*:

$$Z_{\text{PLF}^*} = Z_H + Z_L \quad v_{\text{PLF}^*} = v_{\text{c.m.}}$$

McIntosh, PRC81, 034603 (2010)
Angular distribution

Asymmetric angular distributions with preferential emission for $\cos(\alpha) > 0$, "backward emission"

- Larger asymmetry for lighter $Z_L$
- Asymmetry persists up to $Z_L = 18$

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

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• Similar distribution for different targets

McIntosh, PRC81, 034603 (2010)
Brown, PRC87, 061601(R) (2013)
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.
Non Standard Statistical Emission

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)
Projectile-Like Dynamical Breakup

- Decay mode well established and characterized
  - 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

Davin, PRC65, 064614 (2002)
Piantelli, PRL88, 052701 (2002)
McIntosh, PRC81, 034603 (2010)
De Filippo, PRC86, 044605 (2012)
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Dynamical fission with multi-neck ruptures

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

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Binary Decay: Isotopic Effects and Target Dependence

What have we learnt so far?

- The light fragment is not emitted at mid-rapidity.
- A preferential emission for backward emission is observed.
- The associated lifetime is relatively long.

The rotation angle represents time and therefore is a fundamental observable.
Binary Decay: Isotopic Effects and Target Dependence

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

Can the isotopic composition of the emitted fragments as function of rotation angle teach us something about isospin transport?

McIntosh, PRC81, 034603 (2010); Hudan, PRC86, 021603(R) (2012); Brown, PRC87, 061601 (2013); Barlini, PRC87, 054607 (2013)
Isotopic Composition

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

- $\langle N \rangle/Z$ 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

$\Rightarrow$ “Amplification” of the extremes by the “missing $^8\text{Be}$”
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 $\alpha$ particles 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 $T = 3-5$ MeV

$$ \Rightarrow \omega = 0.4-0.5 \times 10^{21} \text{ rad/s} $$

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Consistent with previous data

Casini, PRL71, 2567 (1993)
Piantelli, PRL88, 052701 (2002)

Brown, PRC87, 061601 (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

Brown, PRC 87, 061601 (2013)
CoMD: $^{64}$Zn + $^{64}$Zn

- Predictions from CoMD-II
- Calculations up to 1000 fm/c
- Isospin-dependent part of the interaction with $L = 51, 78, 105$

- Excellent description of the experimental angular distribution
- Fundamental dynamics reproduced
- Dynamics of the dinuclear breakup not sensitive to the symmetry energy

Stiefel, PRC 90, 061605(R) (2014)
Predicted Angular Dependence

- Underprediction of N/Z for $Z_L$
- Trend well reproduced
- Corresponding increase of N/Z for $Z_H$
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- Underprediction of N/Z for $Z_L$
- Trend well reproduced
- Corresponding increase of N/Z for $Z_H$

- Loss of neutron for $Z_L$ similar to gain for $Z_H$
- Isospin transport dominates N/Z evolution
Isospin drift acts to make low density region neutron rich.
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

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

- Isospin diffusion occurs on the timescale of up to $\sim 1000\text{ fm/c}$
- The impact of isospin drift has been observed as neutron enrichment of low density region.
- Isospin drift occurs on a faster timescale, $\leq 100\text{ fm/c}$
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*Thériault, PRC74, 051602 (2006)*

**Physical picture**

- Drift
- Diffusion
- Low density region
Conclusions

• Dynamical binary breakup provides an effective means to access isospin equilibration out to long time, \( t \sim 1000 \text{ fm/c} \).

• Within CoMD, N/Z angular/time evolution depends on the slope of the symmetry energy.

• For symmetric projectile-target combinations, in a first stage isospin drift (density term) precedes isospin diffusion (N/Z term) establishing an isospin disequilibrium.

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

• Studying damped reactions might provide more insights into isospin transport, therefore the symmetry energy.
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