Flow and Correlations
Recent Experimental Results on the Symmetry Energy and Reaction Dynamics

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Recent Experimental Results on the Symmetry Energy and Reaction Dynamics

"Stiff" and "Soft" are relative, and have meaning within a particular model.

- Extraction of information on $E_{\text{sym}}(\rho)$
  - Experimental Data ↔ Theoretical Transport Model Calculations
- Reaction dynamics are critical
  - Mid-rapidity or neck emission
  - Emission from transiently deformed shapes.
**Directed Flow** of Light Charged Particles and Intermediate-Mass Fragments
Sensitive to $E_{\text{sym}}(\rho)$ – Model Dependent
- Dependence of Flow on Fragment N/Z
- Differential Flow ($^3\text{He}:^3\text{H}$)
- Dependence of Flow on impact parameter

**Statistical Decay**
Careful reconstruction of equilibrated source is needed. Info on $E_{\text{sym}}(\rho)$ from:
- Caloric Curves (asymmetry, coulomb)
- Isoscaling

**Correlations** Between Observables for Dynamically Produced Fragments
→ May provide useful new constrains for models
- Alignment
- Fragment Size
- Fragment Composition
- Yield
- Velocity Damping
- Breakup Timescale
Experimental Descriptions

70Zn + 70Zn, 64Zn + 64Zn, 64Ni + 64Ni
@ E/A = 35 MeV

124,136Xe + 112,124Sn
@ E/A = 50 MeV

TAMU NIMROD-ISiS Array
• Nearly 4π coverage
• Isotopic Resolution for Z ≤ 17
• Free Neutron Multiplicity

Indiana University FIRST-LASSA Array
• Selection of 2.8° ≤ θ_{lab} ≤ 6.6° (for this analysis)
• High Angular Resolution (0.1°)
• Isotopic Resolution for Z ≤ 14

S. Wuenschel et al., NIMA 604, 578 (2009).
T. Paduszynski et al., NIMA 547, 464 (2005)
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Zach Kohley, Ph.D. Thesis, 2010
Texas A&M University
Defining Transverse Flow

Attractive Mean Field
- Isospin-dependent part

Repulsive NN-collisions
Repulsive Coulomb

\[ F = \frac{\partial \langle P_x / A \rangle}{\partial Y_r} \]

\[ Y_r = \frac{Y_{cm}}{Y_{cm,proj}} \]
Flow of Light Charge Particles

Experimental Details
- TAMU Cyclotron Institute
- NIMROD-ISiS Detector
- 35 MeV/u (Fermi Energy)

Strong Isotopic Trends

Flow Parameter \((\text{MeV/c}/\text{nucl.})\)

Particle \(Z^*A\)

\(p\) \(d\) \(t\) \(^3\)He \(\alpha\) \(^6\)He

**Flow of Light Charge Particles**

Experimental Details
- TAMU Cyclotron Institute
- NIMROD-ISiS Detector
- 35 MeV/u (Fermi Energy)

- Strong Isotopic Trends
- Flow with n-rich
- Isobaric Effects (A=3)

Fragments are moving differently in HICs depending on their N/Z. (It’s not just a mass or charge effect)

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### $^3$H-$^3$He Flow

**Motivation:** $t/3$He flow as surrogate for $n/p$ flow

**BNV Simulation**

- **Tritons**
- **3He**

**Figure:**

- Stiff symmetry potential drives neutrons into the low density neck.
- This motion is counter to the net nucleon flow.
- "Stiff" → Larger flow of 3He than tritons for "stiff"

**References:**


**Graph:**

- Stiff $E_{\text{sym}}(\rho)$: $^3$He > $^3$H
- Soft $E_{\text{sym}}(\rho)$: $^3$He = $^3$H
Transverse flow is movement of particles following the PLF and TLF. Stiff symmetry energy propels neutrons away from the PLF and TLF into the neck, decreasing the flow for neutron-rich species.
**IMF Flow**

**Violent Collisions**

The heavier systems have more NN collisions (repulsive) → Lower $E_{bal}$ and lower flow than the lighter system

**Peripheral Collisions**

Smaller interaction volume → Less mean-field component, but same Coulomb

**Charge-dependent flow**

Mean-field is isospin dependent, so the competition between mass-dependent and charge dependent flow is sensitive to $E_{sym}(\rho)$

**AMD+GEMINI**

Molecular dynamics model coupled with statistical decay.

Usefulness/Importance of Flow Measurements

HIC Dynamics

J. Lukasik et al., PLB (2005)

EoS Symmetric Nuclear Matter


In-medium NN cross sections

D.J. Magestro et al., (2000)

Probe of EoS for asymmetric nuclear matter.

IMF flows

LCP flows (Ex. 3H-3He)

Balance energy

π+/π- flows

N/P flows
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Careful **reconstruction** of equilibrated source is needed. Info on $E_{sym}(\rho)$ from:
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- Isoscaling
Source Selection

S. Wuenschel et al., PRC79, 061602 (2009)
J.C. Steckmeyer et al., NPA686, 537 (2001)

Remove particles that clearly do not belong (on average) to a statistically emitting projectile-like source

\[ Z = 1: \quad 0.35 \leq \frac{v_z}{v_{z,PLF}} \leq 1.65 \]
\[ Z = 2: \quad 0.40 \leq \frac{v_z}{v_{z,PLF}} \leq 1.60 \]
\[ Z \geq 3: \quad 0.55 \leq \frac{v_z}{v_{z,PLF}} \leq 1.45 \]

Select events with a well-measured QP:

\[ 25 \leq \sum Z \leq 30 \]

Select events with near-zero average momentum quadrupole.

\[ -1 \leq \log Q \leq 1 \]

\[ Q = \frac{\sum p_{z,i}^2}{\frac{1}{2} \sum p_{T,i}^2} \]
Fluctuation Temperature

\[ T_{\text{Fluc}} \text{(MeV)} \]

\[ E^*_{\text{T}/A} \text{(MeV)} \]

- **p-rich**
- **N=Z**
- **n-rich**

Classical:
\[ \sigma_{xy}^2 = 4m^2T_{\text{cl}}^2 \]

Fermionic:
\[ \sigma_{xy}^2 = \frac{16m^2\epsilon_f^2}{35}\left(1 + \frac{7}{6}\pi^2\left(\frac{T}{\epsilon_f}\right)^2\right) \]
\[ \sigma_M^2 = \frac{3}{2} \frac{T}{\epsilon_f} \]
Isoscaling of Fragments from Reconstructed Quasi-Projectiles

\[ ^{78,86}\text{Kr} + ^{58,64}\text{Ni} \text{ @ E/A = 35 MeV} \]

Isoscaling over a very wide range of nuclides:
\[ 1 \leq Z \leq 17 \]

\[ Y(N, Z) \propto \exp\left(\left(-G(N, Z) + \mu_n N + \mu_p Z\right)/T\right) \]

\[ R_{12}(N, Z) = \frac{Y_1(N, Z)}{Y_2(N, Z)} \propto \exp\left(\frac{\mu_{n,2} - \mu_{n,1}}{T} N - \frac{\mu_{p,2} - \mu_{p,1}}{T} Z\right) \]

\[ R_{12}(N, Z) \propto \exp(\alpha N - \beta Z) \]

\[ \frac{C_{sym}}{T} = \frac{\alpha}{\Delta} \]

Careful source characterization is an integral part of this analysis!

S. Wuenschel et al., PRC 79, 061602 (2009)
see also P. Marini et al., submitted to PRC

M.B. Tsang et al., PRC 64, 054615 (2001)
• Challenge: to form a description of the heavy ion collisions that respects the dynamical and statistical evolution of the system
Correlations Between Observables for Dynamically Produced Fragments

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  - Fragment Size
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Alan McIntosh, Ph.D. Thesis, 2010
Indiana University

Out-of-equilibrium fragment production
Recoil Effects Between $Z_{\text{Heavy}}$ and $Z_{\text{Light}}$

- Select events with at least 2 fragments ($Z_{\text{H}} \geq 21$, $Z_{\text{L}} \geq 4$)
- $3^\circ \leq \theta_{\text{lab}} \leq 7^\circ$ selects only “forward” and “backward” break-up
- Light fragment ($Z_{\text{L}}$) is peaked forward of mid-velocity
- Recoil effects indicate a common parent
• Excess yield of IMF emitted toward Target-Like Fragment
• Isotropic emission cannot account for backward yield
• Strong alignment
• Alignment decreases with $Z_L$
• Persists to near-symmetric splits
• Mechanism...
Velocity Damping and Alignment

- Detector acceptance accounted for
- Isotropic emission describes forward emission, but not backward emission
- Correlation: Alignment increases with damping

\( V_{\text{beam}} = 9.4 \text{cm/ns} \)
- Smooth evolution in both the yield and width
- Asymmetric $\leftrightarrow$ Symmetric
- Small damping $\leftrightarrow$ Large damping

Relative yield is peaked at $Z_L=9$
Composition of Aligned Fragments

- \( \cos(\alpha) > 0.97 \) (More Aligned)
- \( 0.88 < \cos(\alpha) < 0.95 \) (Less Aligned)

- Abrupt change in average neutron excess at \( Z_L = 9 \)
- Less aligned fragments have larger neutron excess

\( 124 \text{Xe} + 124 \text{Sn} \) @ \( E/A = 50 \text{ MeV} \)

McIntosh et al., PRC 81, 034603 (2010)
Langevin Model

- Separation of PLF* into $Z_L$ and $Z_H$ evolves on a potential energy surface
- Nuclear between $Z_H$ and $Z_L$
- Coulomb between $Z_H$, $Z_L$ and the target-like fragment
- High-fraction Limit: Motion is over-damped
- Motion along the potential energy surface is stochastic (thermal)

Langevin model courtesy of R. Charity
Account for detector acceptance & granularity. Vary the initial deformation \((x)\) to reproduce the experimental angular distributions.

\[ Z_L = 13 \]

\[ \beta = 0.4 \quad J = 40 \hbar \quad T = 4 \text{MeV} \]

Within the context of the model, the lightest fragments are produced from systems already deformed beyond the barrier

\[ \text{Sensitivity} < 1.0 \text{fm} \]
Timescale of Aligned Decay

\[ \langle \tau \rangle = 0.25 - 0.35 \times 10^{-21} \text{s} \]
(75-100fm/c)

\[ \langle \tau \rangle = 0.90 - 1.5 \times 10^{-21} \text{s} \]
(270-450fm/c)

For \( J = 30 \hbar \) \( \rightarrow \) increase \( \tau \) by 25%

\[ \eta = \frac{Z_H - Z_L}{Z_H + Z_L} \]

\( \dagger \) Mo + Mo at E/A = 20MeV
Casini et al., PRL 71, 2567 (1993)

\( \ddagger \) \( ^{116}\text{Sn} + ^{93}\text{Nb} \) at E/A = 29MeV
Piantelli et al., PRL 88, 052701 (2002)
Correlations Summary

- Smooth evolution of aligned component with size ($Z_L$)
  - Stronger alignment for small $Z_L$
  - Alignment persists for near-symmetric splits
- Smooth evolution of aligned component with damping
  - Alignment increases with damping
- Decay time-scale ($0.25-1.5 \times 10^{-21}$s) evolves with $Z_L$ (or $\eta$)
- Transition around $Z_L=9$ observed in:
  - Composition ($N/Z$), Relative Yield, Distance from the Barrier
- Observed dependence of composition on decay orientation
  - Suggests sensitivity to $N/Z$ transport within an excited transiently-deformed nucleus – further investigation is needed.

McIntosh et al., PRC 81, 034603 (2010)
Final Remarks

- Dynamical transport models and molecular dynamics models are used to extract information on $E_{\text{sym}}(\rho)$.
- These models are successful in describing some aspects of fragment production – but a more complete description of the reaction is necessary to constrain $E_{\text{sym}}(\rho)$
- Single description of the reaction needed – respect both dynamical & statistical nature
- Cluster production in the dynamical evolution
- Correlations between observables for dynamically produced fragments $\Rightarrow$ Further constraints for models