Short-lived binary splits of an excited projectile-like fragment induced by transient deformation

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Outline

• Motivation
• Experimental Setup and Calibration
• Aligned Binary Break-up
• Size-Symmetric Ternary Break-up
Nuclear Symmetry Energy

\[ E(\rho, \delta) = E(\rho, \delta = 0) + S(\rho)\delta^2 \]

\[ \delta = \frac{N - Z}{N + Z} \]

• Impacts:
  • Properties of neutron stars
  • Characteristics of supernovae → r-process nucleosynthesis
  • Nucleon transport in heavy-ion collisions

• How does the symmetry energy vary with density?

Liu et al., PRC 69, 014603 (2004)

Low-density:
  • Correlations in dilute systems
  • Clustering phenomena
  • Behavior of materials at the surface
Nucleon Transport in a Dynamically Evolving System

$^{114}$Cd + $^{92}$Mo @ 50 MeV/A

$b_{\text{max}} = 11.24$ fm

- Antisymmetrized Molecular Dynamics calculations
- Transiently deformed nuclei
- Early cluster production

S. Hudan et al., PRC71, 05402 (2006)
Velocity Ordering and Alignment

Ordering fragments by size sorts them on average by their velocity

(TIMF: Z ≥ 3)

Ta + Au at E/A = 33MeV

Hierarchy observed for several systems at several energies

Neutron Enrichment

$^{64}\text{Zn} + ^{64}\text{Zn}$ at $E/A = 45\text{MeV}$:
Mass-Symmetric and Isospin-Symmetric Reactions

- “Mid-velocity material” neutron-rich at the expense of the projectile-like fragment
- Much of the enhancement is due to free nucleons
- Importance of measuring free nucleons

D. Thériault et al., PRC 74, 051602 (2006)
The Next Step

• Measure both N/Z symmetric and N/Z asymmetric reactions
  - $^{124,136}\text{Xe} + ^{112,124}\text{Sn}$

• Measurement of free neutrons
  - DEMON neutron detectors

<table>
<thead>
<tr>
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<th>N/Z</th>
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<tbody>
<tr>
<td>$^{124}\text{Xe}$</td>
<td>1.30</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>1.52</td>
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<tr>
<td>$^{112}\text{Sn}$</td>
<td>1.24</td>
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<tr>
<td>$^{124}\text{Sn}$</td>
<td>1.48</td>
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Goals

• Overarching Goal: Nuclear Equation of State, particularly $E_{\text{sym}}(\rho)$

  …but first…

• Understanding the impact of collision dynamics

• Collision dynamics are interesting in their own right!
GANIL: Experiment E432

- June/July and October 2007
- Equipment brought from the US (including scattering chamber)
- DEMON provided by LPC
**Experimental Setup**

**FIRST**
- T1: \(2.8^\circ \leq \theta_{\text{lab}} \leq 6.6^\circ\)
- T2: \(7.3^\circ \leq \theta_{\text{lab}} \leq 14.3^\circ\)
- LASSA: \(36.4^\circ \leq \theta_{\text{lab}} \leq 51.5^\circ\)

**FIRST:**

**LASSA:**
- B. Davin *et al.*, NIMA **473**, 301 (2001)
DEMON Neutron Detectors
Electronics: Between two worlds

- ASIC ("HiRA": WashU – IU – MSU)
- MASE (IU)
- Pico-Systems
- VME Readout
- NSCL-MSU Data Acquisition

656 channels

J. Engel et al.,
NIMA 573, 418 (2007)

C. Metelko et al.,
NIMA 569, 801 (2006)
Charged Particle Identification

ΔE-E technique

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

carbon neon silicon

\( ^{13}\text{C} \)

\( ^{22}\text{Ne} \)

\( ^{30}\text{Si} \)

carbon neon silicon

\( ^{13}\text{C} \)

\( ^{22}\text{Ne} \)

\( ^{30}\text{Si} \)
Energy Calibration

- Precision Charge Pulser
  - Linearity of Electronics
- Knowledge of Detector Thicknesses
  - Calibration Beams (C, N, Ne, Ar, S)
- Observed Isotopic Bands
- Energy-Loss Calculations

Energy resolution: $\Delta E/E \approx 0.5\%$

$\uparrow$ M. Parlog et al., NIM A 482, 693 (2002)

MAKE USE OF SILICON-DETECTOR CALIBRATION

FIRST - T1

Parlog$^\dagger$ Parameterization
(Z and A dependence)

$\uparrow$ M. Parlog et al., NIM A 482, 693 (2002)
Decay of excited projectile-like fragments

$^{124}\text{Xe} + ^{124}\text{Sn}$ at $E/A = 50\text{MeV}$

$3^\circ \leq \theta_{\text{lab}} \leq 7^\circ$

- Dissipative binary collision
- For events with $M_{Z \geq 4} \geq 2$, suppression of elastic and quasi-elastic.
Parallel velocity of $Z_{\text{Heavy}}$ and $Z_{\text{Light}}$

- Select events with at least 2 fragments ($Z_H \geq 21$, $Z_L \geq 4$)
- $3^\circ \leq \theta_{\text{lab}} \leq 7^\circ$ selects only “forward” and “backward” break-up
- Light fragment ($Z_L$) is peaked forward of mid-velocity
- Recoil effects indicate a common parent
Velocity Damping

- Larger damping associated with smaller heavy residue
- Events with $M_{Z\geq4} \geq 2$ are more damped by 0.4
- “Backward” decays are slightly more damped than “forward” decays

Low energy (E/A~30 MeV):
G. Souliotis et al., PRC 68, 024605 (2003)

High Energy (E/A~1 GeV):
V. Henzl, Ph.D. Thesis, Czech Tech. Institute
• Excess yield of IMF emitted toward Target-Like Fragment
• Strong alignment
• Degree of alignment decreases with $Z_L$
• Persists up to near-symmetric splits
Modeling the Isotropic Component

- Isotropic emission from a rotating source
- Sample parameters from data $Z_H$, $Z_L$, $V_{CM}$, $\theta_{CM}$, $V_{rel}$
- Adjust out-of-plane distribution (spin) to reproduce forward angular distribution
- Account for detector acceptance, granularity

→ Isotropic emission cannot account for backward yield
Velocity Damping and Alignment

- Alignment increases with damping
- Isotropic emission describes forward emission, but not backward emission
- Detector acceptance accounted for
• Smooth evolution in the yield and width
  • Asymmetric $\leftrightarrow$ Symmetric
  • Small damping $\leftrightarrow$ Large damping

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

- Abrupt change in average neutron excess at $Z_L=9$
- Less aligned fragments have larger neutron excess
→ Isospin equilibration may not reached between regions of the decaying PLF*
Langevin Model

\[ V(x) = -(x - c)(x + c) \left( \frac{x}{d} \right)^2 + \sum_{i=1}^{2} e^2 \frac{Z_{TLF^*}Z_i}{R_i} \]

x: reaction coordinate in one dimension
Backward barrier higher due to TLF*
Barrier changes in time (spin & TLF* distance)
No inertial terms – high-friction limit
\( \beta \): friction coefficient
T: temperature
k: fluctuating term – random thermal motion

\[ \Delta x = \frac{F \Delta t}{\beta} + k \sqrt{\frac{2T \Delta t}{\beta}} \]

Langevin model courtesy of R. Charity
Langevin Model

Account for detector acceptance & granularity. Vary the initial deformation (x) to reproduce the experimental angular distributions. → Sensitivity <1.0fm

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

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

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

\[ Z_L = 4: \]
\[ \langle \tau \rangle = 0.90 - 1.5 \times 10^{-21} \text{s} \]
(270-450fm/c)

A.B. McIntosh et al.,
PRC 81, 034603 (2010)

[7]: G. Casini et al., PRL 71, 2567 (1993)
Ternary break-up of excited projectile-like fragments

\[ ^{124}\text{Xe} + ^{112,124}\text{Sn} \]

\[ 3^\circ \leq \theta_{\text{lab}} \leq 14^\circ \]

- One large, two very small
  \[ Z_L \geq 2 \]
  \[ Z_1/Z_{\text{tot}} \]
  \[ Z_2/Z_{\text{tot}} \]
  \[ Z_3/Z_{\text{tot}} \]
  \[ Z_{\text{tot}} = Z_1 + Z_2 + Z_3 \]

- Significant yield of three equal-sized fragments
  \[ Z_L \geq 5 \]

Three-fragment charge-correlation ("Dalitz diagram")

S. Hudan, GANIL-LPC, July 9 2010
Symmetric Ternary break-up: size and velocity distributions

To select decay channel which minimizes the role of dynamics:

→ Select events with $V_H < V_{CM}$ (of the 3-fragment system)

(à la Davin2002, Colin2003, and McIntosh2010)

- Fragments not produced around mid-velocity.
- Centered around projectile velocity

Ternary break-up of PLF* following dissipative binary collision with target

- Slight velocity ordering

Memory of entrance channel
Statistical Multifragmentation Model

\[ F_{AZ} = F_{AZ}^B + F_{AZ}^S + E_{AZ}^C + E_{AZ}^{\text{sym}} \]

Z=45, A=103
E*/A=4,5,6MeV, J=0\hbar, 42\hbar, 83\hbar

Data indicates E*/A\approx 5.5\text{MeV} for low to modest spin (0\hbar and 42\hbar):
Model reproduces average \( Z_{\text{tot}} \), \( Z_H \), \( Z_M \), and \( Z_L \).
Average Fragment Composition

J: small effect
E*: small effect
γ: significant effect!

\[ E_{sym} = \gamma \frac{(N - Z)^2}{A} \]

Reduction in \( \gamma \) gives better agreement with measured composition for \( Z > 6 \)

Composition of heavier fragments is more sensitive to the symmetry energy

Reduction in symmetry energy at low density:
see also, for example,
M. Famiano et al., PRC 97, 052701 (2006)
J. Iglio et al., PRC 74, 024605 (2006)
G. Souliotis et al., PRC 75, 011601(R) (2007)
M. B. Tsang et al., PRC 102, 122701 (2009)
Isotopic Distributions

- Smaller symmetry energy provides better description: broader, with more heavy isotopes
- High sensitivity
- Same composition for ternary and size-symmetric ternary events
- Target composition: no significant effect

S. Hudan et al., PRC 80, 064611 (2009)
Conclusions

A.B. McIntosh et al., PRC 81, 034603 (2010)

- Decay of an excited PLF exhibits a short-lived (dynamical) component (time≈10^{-21}s) which persists even for near symmetric splits. Moreover, this timescale increases smoothly with increasing $Z_L$ (decreasing $\eta$)
- Transition around $Z_L=9$ observed in three independent quantities: composition, relative yield, distance from the barrier (angular distribution)
- Dependence of composition on decay orientation: suggests sensitivity to N/Z transport as the excited transiently deformed nucleus decays

S. Hudan et al., PRC 80, 064611 (2009)

- Decreasing the symmetry energy coefficient is necessary to describe the measured fragment composition (within SMM)
- The isotopic distributions for heavy fragments ($Z\geq7$) are a particularly sensitive probe of the symmetry energy
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