Fragment Isospin as a Probe of Heavy-Ion Collisions

- Symmetry term of EOS
- Equilibration
- “Fractionation” – inhomogeneous distribution of isospin
- Source composition
- Energy spectra
- Dynamics: preequilibrium emission / PLF composition
- Statistical breakup: composition of fragments
- Recent work at TAMU and IU
  - Peripheral / mid peripheral events: PLF and MR
Isospin Equilibration

Johnston, 1995

B.A. Li, 1996

Rami, 2000

\[ R_z = \frac{2(Z_{\text{det}} - Z_{\text{Ru}}^Z) - Z_{\text{Zr}}^Z - Z_{\text{Ru}}^Z}{Z_{\text{det}}^Z - Z_{\text{Ru}}^Z} \]
Isotopic composition of fragments as a signature of parent system

FIG. 1. Ratios of energy-integrated isotope yields, measured at $\theta_{\text{lab}} = 40^\circ$, as functions of the $N/Z$ ratio of the combined system of projectile and target. Closed and open symbols denote $^{12}$C and $^{18}$O projectiles, respectively; circles, squares, triangles, and lozenges stand for $^{58}$Ni, $^{64}$Ni, natAg, and $^{197}$Au targets, respectively. The dashed lines are meant to guide the eye.


FIG. 2. Ratios of triton to proton yields (top) and triton to deuteron yields (bottom), measured at $\theta_{\text{lab}} = 40^\circ$, and plotted as functions of the $N/Z$ ratios of the combined system (left-hand side) and of a source consisting of equal numbers of nucleons from the projectile and from the target (right-hand side). The symbols are chosen as in Fig. 1, the dashed lines are meant to guide the eye.
30 MeV/nucleon $^{58}\text{Fe}, ^{58}\text{Ni} + ^{58}\text{Fe}, ^{58}\text{Ni}$

Carbon fragments

Ramakrishnan et al, PRC 57, 1803 (1998)
$^{124,136}$Xe + $^{112,124}$Sn
55MeV/nucleon

Dempsey et al, PRC 54, 1710(1996)

$^{58}$Fe, $^{58}$Ni + $^{58}$Fe, $^{58}$Ni
30 MeV/nucleon

Ramakrishnan et al, PRC 57, 1803 (1998)

$\left< \frac{N}{Z} \right> = \frac{3He + 2(4He) + 4(6He)}{2(3He + 4He + 6He)}$.

Projectile fragmentation (with isotopically reconstructed QP)

- Isospin effects the dynamics
- QP with a diversity in isospin
- Possible route to neutron-rich RNB
  - > G.Souliotis clip
$^{28}\text{Si} + ^{112}\text{Sn}, ^{124}\text{Sn} @ 30,50\text{MeV/nucleon}$

$^{20}\text{F}, ^{20}\text{Ne}, ^{20}\text{Na} + \text{Au} @ 32\text{ MeV/nucleon}$
$^20\text{F}, ^{20}\text{Ne}, ^{20}\text{Na} + \text{Au} @ 32 \text{ MeV/nucleon}$

<table>
<thead>
<tr>
<th>Beam</th>
<th>$&lt;N/Z&gt;$ proj</th>
<th>$&lt;N/Z&gt;$ DIT</th>
<th>$&lt;N/Z&gt;$ DIT+evap</th>
<th>$&lt;N/Z&gt;$ exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{Na}$</td>
<td>.818</td>
<td>.926</td>
<td>.876</td>
<td>.912</td>
</tr>
<tr>
<td>$^{20}\text{Ne}$</td>
<td>1</td>
<td>1.06</td>
<td>.953</td>
<td>1</td>
</tr>
<tr>
<td>$^{20}\text{F}$</td>
<td>1.22</td>
<td>1.23</td>
<td>1.02</td>
<td>1.07</td>
</tr>
</tbody>
</table>

D. Rowland
Distillation of a neutron-rich gas?

Projectile fragmentation of $^{20}\text{Na},^{20}\text{Ne},^{20}\text{F}$ at 35 Mev/nucleon
<table>
<thead>
<tr>
<th></th>
<th>30 MeV</th>
<th>50 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{28}\text{Si} + ^{112}\text{Sn}$</td>
<td>$^{28}\text{Si} + ^{124}\text{Sn}$</td>
</tr>
<tr>
<td>exp</td>
<td>$4.0 \pm .4$</td>
<td>$4.1 \pm .1$</td>
</tr>
<tr>
<td>DIC + SMM</td>
<td>$3.9 \pm .2$</td>
<td>$4.6 \pm .2$</td>
</tr>
</tbody>
</table>

Both the multiplicity and neutron content of the fragmentation products are dependent on the N/Z of the fragmenting system.

TABLE II. Yields of light charged particles from reconstructed events of $^{28}$Si + $^{112}$Sn at 50 MeV/nucleon divided by the yields from $^{28}$Si + $^{124}$Sn. The ratios were normalized for the same number of events for both targets. All LCPs were measured in the range of 1.64°–33.6° in the laboratory.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Overall</th>
<th>QP decay</th>
<th>Direct emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>1.36</td>
<td>1.24</td>
<td>2.58</td>
</tr>
<tr>
<td>$^2$H</td>
<td>1.15</td>
<td>1.11</td>
<td>1.40</td>
</tr>
<tr>
<td>$^3$H</td>
<td>0.96</td>
<td>1.01</td>
<td>0.53</td>
</tr>
<tr>
<td>$^3$He</td>
<td>1.32</td>
<td>1.23</td>
<td>1.74</td>
</tr>
<tr>
<td>$^4$He</td>
<td>1.12</td>
<td>1.10</td>
<td>1.18</td>
</tr>
</tbody>
</table>
Rare Isotope Production with MARS

Silicon Telescope:
$\Delta E_1$, $X,Y$ (Strips)
$\Delta E_2$, $Er$

MARS Acceptances:
Angular: 9 msr
Momentum: 4 %

Souliotis Clip
Fragments at mid rapidity
larger fragments from midrapidity
(Rapidity Dist. for Z = 2, 3, 4 for different Multiplicity Bins)

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

\[ 4\text{He} \quad 7\text{Li} \quad 11\text{B} \]

\[ 28\text{MeV/A} {}^{209}\text{Bi} + {}^{136}\text{Xe} <b> = 12.4 \text{ fm} \]

Toke, PRL 75, 2920 (1995)

Shetty poster
Rapidity Dist. for $^3$He, $^4$He, $^6$He for different Multiplicity Bins

$^{124}$Xe, $^{124}$Sn + $^{112,124}$Sn
3He, 4He, 6He Spectra Comparison

$^{124}$Xe, $^{124}$Sn + $^{112,124}$Sn
$^{114,106}$ Cd + $^{92,98}$ Mo at E/A = 50 MeV

LASSA: 9 telescope Si(IP)-Si(IP)-CsI(Tl)/PD array; $7^\circ \leq \theta_{\text{lab}} \leq 58^\circ$

Si-CsI(Tl)/PD; $2.5^\circ \leq \theta_{\text{lab}} \leq 4.5^\circ$

Miniball/Wall; Fast plastic/CsI(Tl); $2^\circ \leq \theta_{\text{lab}} \leq 170^\circ$
Reproducing Ramakrishnan
(neutron deficient isotopes dominate at central angles)
Perpendicular velocity spectra

LASSA, $^{114}$Cd+$^{92}$Mo @ 50 A.MeV
Mid-peripheral, $V_{\parallel} \geq V_{\parallel}^{PLF}$

$^7$Be : $\langle V_\perp \rangle = 2.59565$

$^{10}$Be : $\langle V_\perp \rangle = 2.16671$
Fractional yield as function of perpendicular velocity
Spectral Comparison for $Z = 3$ Isotopes
(change in slope trend for heaviest isotope?)

$^{124}\text{Xe}, \; ^{124}\text{Sn} + ^{112,124}\text{Sn}$
isotopic energy spectra (preequilibrium effects)

FIG. 5. Ratio of individual isotopic yields to total element yield for Li, Be, B, C, and N fragments observed at 15° as a function of IMF energy. Lines are the result of an accreting-source calculations [13], as identified in the figure. Nuclides are identified by key at upper right.


FIG. 6. Isotope ratios [fraction of given isotope to total elemental yield, $\sigma(Z,A)/\sigma(Z)$] as a function of IMF kinetic energy for Li, Be, B, and C ejectiles from $^{124}$Sn target. Left column is for data at 12°; right column for data at 154°.

Energy Spectra As a Probe Of Symmetry Potential

B.A. Li, PRL 78, 1544 (1997)

The ratio of pre-equilibrium neutrons to protons as a function of nucleon kinetic energy for central (upper panel) and peripheral (lower panel) collisions calculated with the Coulomb and symmetry potentials.
Isotope ratios as function of centrality

$^{114}$Cd + $^{98}$Mo; 50MeV/nuc

$^{124,136}$Xe + $^{112,124}$Sn 55MeV/nucleon


Dempsey et al, PRC 54, 1710(1996)
Enhanced neutron richness in central versus peripheral collisions

In the spirit of the Gordon Conf...

$^{20}\text{F}, ^{20}\text{Ne}, ^{20}\text{Na} + \text{Au}$

32 MeV/nucleon

![Graphs and diagrams](image-url)
Summary

• Fragment Isospin can tell us about
  – Equilibration
  – Source composition – distribution of isospin

• DIT mechanism can be used to create systems with a diversity of isospin

• Isotopic energy spectra are important to understanding the sources of these fragments
The following people were responsible for bringing you the unpublished data shown in this presentation...*


- DOE, NSF, Welch Foundation

*However they should not be held accountable for the actual presentation.