Investigating the Fragmentation of Excited Nuclear Systems

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Equation of State (EoS)

EoS for isospin asymmetric nuclear matter:

\[ E(\rho, \delta) = E(\rho, \delta = 0) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4) \]

- **baryon density** \( \rho = \rho_n + \rho_p \)
- **isospin asymmetry** \( \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) \)
  - \( \delta = (N-Z)/(N+Z) \)
- **energy per nucleon in symmetric nuclear matter** \( E(\rho, \delta = 0) \)
- **nuclear symmetry energy** \( E_{\text{sym}}(\rho) \)

Symmetry Energy

- Symmetry Energy related to Isospin
Heavy Ion Collisions

- Nuclear collision reactions...
<table>
<thead>
<tr>
<th>Time ($fm/c$) = 1</th>
<th>Heavy Ion Collisions</th>
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<tbody>
<tr>
<td>11</td>
<td>10</td>
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<td>3</td>
<td>2</td>
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<td>1</td>
<td>0</td>
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</table>
Detect the Z and A of most fragments with NIMROD, and free neutrons with the Neutron Ball.
Comparing Identified Fragments

\[ R_{21}(N, Z) = \frac{Y_2(N, Z)}{Y_1(N, Z)} = C \exp(N\alpha + Z\beta) \]

- **Neutron-rich source**
- **Neutron-poor source**
Comparing Identified Fragments

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Comparing Identified Fragments

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- \( \alpha \) is the slope
- \( \beta \) is the distance between

\[ \alpha = \frac{4C_{\text{sym}}}{T} \left[ \left( \frac{Z}{A} \right)_1 - \left( \frac{Z}{A} \right)_2 \right] = \frac{4C_{\text{sym}}}{T} \Delta. \]

Tsang, Phys. Rev. C 64, 041603(R) (2001)

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Neutron-rich \hspace{1cm} Neutron-poor

Tsang. Phys. Rev. C 64, 041603(R) (2001)
Evolution of Isoscaling

- System-to-System Isoscaling
  - Tsang at MSU, etc.
  - Sources are compound nuclei
  - Isoscaling with global alpha and global beta
  - Lines are parallel and evenly spaced, but do not align perfectly with points

Tsang. Phys. Rev. C 64, 041603(R) (2001)
Isostopic Scaling... It can get us to the symmetry energy

- Ratio of isotopic yields

\[ R_{21}(N, Z) = \frac{Y_2(N, Z)}{Y_1(N, Z)} = C \exp(N\alpha + Z\beta) \]

- Relation of \( \alpha \) to \( E_{\text{sym}} \) \( (C_{\text{sym}}) \)

\[ \alpha = \frac{4C_{\text{sym}}}{T} \left[ \left( \frac{Z}{A} \right)_1^2 - \left( \frac{Z}{A} \right)_2^2 \right] = \frac{4C_{\text{sym}}}{T} \Delta. \]

Source Definition

- $^{86}\text{Kr}$ projectile + $^{64}\text{Ni}$ target = $^{150}$Compound Nucleus
- $^{78}\text{Kr}$ projectile + $^{58}\text{Ni}$ target = $^{136}$Compound Nucleus
Source Reconstruction

- Peripheral collisions → Quasiprojectile (QP) & Quasitarget (QT)
- Reconstructed QP as source
- Distribution of QP sources (in N/Z of source)
- Better defines source

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Transition in Isoscaling

System-to-System Isoscaling

WHY?

Bin-to-Bin Isoscaling

Evolution of Isoscaling

- Bin-to-Bin Isoscaling
  - Combine systems and divide into bins
  - Isoscaling with individual alphas and betas for each Z
  - Better resolution from better definition of the delta

- Better defined $\alpha$ and $\Delta$ should mean better defined $C_{sym}$

Wuenschel used bins in N/Z, of width 0.06, and always compared bins 2 and 4.

But what if you changed the width, or range, in N/Z, or changed the bins that were being compared?

- Bin widths: 0.02 – 0.28 in increments of 0.02, and 0.28-0.60 in increments of 0.04
- All comparisons of Bins 1-5
Fragment Yield

N/Z of source

NZdist

Entries 158829
Mean 1.173
RMS 0.1105
\[ \alpha = \frac{4C_{\text{sym}}}{T} \left[ \left( \frac{Z}{A} \right)_{1}^{2} - \left( \frac{Z}{A} \right)_{2}^{2} \right] = \frac{4C_{\text{sym}}}{T} \Delta. \]

**Alpha vs. Bin Width for all combinations**

**Delta vs. Bin Width for all combinations**

Bin comparisons trend by bin separation
Convergence of \( \alpha \) and \( \Delta \) for large bin widths
$\frac{\alpha}{\Delta} = \frac{4}{T} C_{\text{sym}}$

Roughly around the $C_{\text{sym}}$

Convergence around 0.3
Minimum of the relative error in alpha is with a bin width of 0.18 (in N/Z) using the 5/2 comparison.
Theoretically, $\alpha$ should equal $-\beta$. Ours is pretty close.
Some outliers, but groups are the smallest three bin width.
Consistent $\alpha/\Delta$ means consistent $C_{\text{sym}}$. All the offset groups involve Bin 1 and the 3 smallest bin widths!
The excitation energies of bin 1 are quite a bit higher than the other bins!

$E^*$ is proportional to $T^2$ and a higher temperature would mean lower $\alpha$
Bin 1 combinations are obviously off the line.
What We’ve Learned So Far

° Varying the source selection (bin width) changes the isoscaling
° Using a bin width of 0.18 (in N/Z) when comparing bins 5 and 2 will give the optimum results
° Some characteristic of bin 1 is causing a systematic difference in the $\alpha$, shown on the $\alpha$ vs. $\Delta$ plot
Evolution of Isoscaling

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Where we went next…

- Examine Bin 1
  - Is the excitation energy of bin 1 different from the other bins?

- N/Z to N/A
  - N/Z has been used by convention
  - Technically, isoscaling should be in terms of concentration (N/A)
These are the N/Z bins used by Wuenschel in her isoscaling.
These are the corresponding N/A bins. Variations in the N/A bins can also be studied.
N/Z bins of 0.10 width

N/A bins of 0.020 width
Conclusions

- Source definition affects quality of isoscaling, alpha, $C_{sym}$
- Bin width of 0.18, comparison of bins 5/2 are optimal
- Bin 1 has significantly higher excitation energy than the other bins, which affects $\alpha$
Where do we go from here?

- Further exploration into excitation energy effects
- Possibly looking into the effect of free neutrons in the reconstruction
Acknowledgements

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- YOU!
Questions?
References
