$B = a_v A - a_s A^{2/3} + \delta - a_c \frac{Z(Z-1)}{A^{1/3}} - a_{sym} \frac{(A-2Z)^2}{A}$

$a_{sym} = 30-42$ MeV for infinite NM
Symmetry Energy in Liquid Drop Model

disagreement with known masses is large

Inclusion of surface terms in symmetry

\[ a_{\text{sym}} \left( \frac{(A - 2Z)^2}{A^2} \right) \]

\[ (a_{\text{sym}}^V A + a_{\text{sym}}^S A^{2/3}) \left( \frac{(A - 2Z)^2}{A^2} \right) \]
Symmetry Energy Determination in Heavy Ion Collisions

Betty Tsang
Halong Bay, Vietnam
Nov 20-25, 2005

- $E(\rho, \delta) = E(\rho, 0) + S_{\text{sym}}(\rho) \delta^2$
- Isospin asymmetry: $\delta = (\rho_n - \rho_p) / (\rho_n + \rho_p)$
• Both the elliptical and transverse flow reflect the pressure created in the collisions
What is known about the EOS of symmetric matter

Danielewicz, Lacey, Lynch (2002)

Prospects are good for improving constraints further. Relevant for supernovae - what about neutron stars?
The density dependence of asymmetry term is largely unconstrained.
Studies of Isospin Effects in Heavy Ion Reactions

Central Collisions
• Isospin fractionation

Peripheral Collisions
• Isospin mixing and isospin diffusion
Are you still awake?
Inhomogeneous Distributions of isospin -- Fractionation

asy-stiff (F1)
neutron-rich dense region
more symmetric emitted particles

asy-soft (F3)
more symmetric dense region
neutron-rich emitted particles
Varying the neutron contents

<table>
<thead>
<tr>
<th>System</th>
<th>$^{112}\text{Sn}+^{112}\text{Sn}$</th>
<th>$^{124}\text{Sn}+^{124}\text{Sn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(N/Z)_0$</td>
<td>1.24</td>
<td>1.48</td>
</tr>
<tr>
<td>$A_0$</td>
<td>224</td>
<td>248</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$N_0$</td>
<td>124</td>
<td>148</td>
</tr>
</tbody>
</table>

$^{112}\text{Sn}+^{112}\text{Sn} \quad \overset{\text{Gain = 24 Neutrons}}{\longrightarrow} \quad ^{124}\text{Sn}+^{124}\text{Sn}$

$\hat{\rho}_{n}^{112} = 1$

$\hat{\rho}_{p}^{112} = 1$

$\hat{\rho}_{n}^{124} \approx 1.078$

$\hat{\rho}_{p}^{124} \approx 0.903$
Measured Isotopic yields

\[
\frac{dM}{d\Omega_{cm}} \text{ (sr}^{-1})
\]

\begin{align*}
\text{E/A} = 50 \text{MeV} \\
\text{Li} & \text{ (pink solid line)} \\
\text{B} & \text{ (pink dashed line) x0.1} \\
\text{N} & \text{ (pink dotted line) x0.01} \\
\text{Be} & \text{ (blue solid line)} \\
\text{C} & \text{ (blue dashed line)} \\
\text{O} & \text{ (blue dotted line)}
\end{align*}
Isoscaling from Relative Isotope Ratios

$$R_{21} = \frac{Y_2}{Y_1} \propto e^{N\Delta \mu_n + Z\Delta \mu_p} \propto (\hat{\rho}_n)^N (\hat{\rho}_p)^Z$$

Factorization of yields into $p$ & $n$ densities

Cancellation of effects from sequential feedings

Robust observables to study isospin effects
Isospin Fractionation

Enrichment of $n$ in the gas

$\rho_n \propto e^{\Delta \alpha}$

Depletion of $p$ in the gas

$\rho_p \propto e^{\Delta \beta}$
Sensitivity to the isospin terms in the EOS

Isotope Ratios

Asy-stiff
$\gamma \sim 2$

Asy-soft
$\gamma \sim 0.5$

Data

Asy-stiff term agrees with data better

$\gamma \sim 0.5$

$\gamma \sim 2$

Isotone Ratios

$\langle \rho_n \rangle$

$\langle \rho_p \rangle$

$(N/Z)_0$

BUU
F1, F3

Freeze-out source

SMM

Y(N,Z)

$R_{21}(N,Z)$

PRC, C64, 051901R (2001).
Density dependence of asymmetry energy

\[ S(\rho) = 23.4 (\rho/\rho_0)^\gamma \]

Results are model dependent

\( \alpha = 0.36 \Rightarrow \gamma = 2/3 \)

Strong influence of symmetry term on isoscaling

Consistent with many body calculations with nn interactions
New observable: isospin diffusion in peripheral collisions

- Vary isospin driving forces by changing the isospin of projectile and target.
- Examine asymmetry by measuring the scaling parameter for projectile decay.

Asymmetric systems:
- Proton rich system
- Neutron rich system

Symmetric system: no diffusion
Peripheral Collisions

\[ \frac{Y(N,Z)}{Y^{112+112}(N,Z)} = C \cdot \exp(\alpha N + \beta Z) \]
The neck is consistent with complete mixing.

Isospin flow from n-rich projectile (target) to n-deficient target (projectile) – dynamical flow

Isospin flow is affected by the symmetry terms of the EoS – studied with BUU model
Data: $\alpha$ from 4 Sn+Sn reactions; 0.0, 0.35, 0.42, 0.57

BUU predictions $E(\rho, \beta) = E(\rho, 0) + S_{\text{sym}}(\rho) \beta^2$

N/Z $\rightarrow \delta$ from the PLF

- Data indicates a smooth transition
- The calculations with the asy-soft EOS’s predict faster diffusion and more abrupt transition, inconsistent with the data.
Challenge: Can we constrain the density dependence of symmetry term?

Density dependence of symmetry energy can be examined experimentally with heavy ion collisions. → Existence of isoscaling relations

Isospin fractionation: Conclusions from multi-fragmentation work are model dependent:
- Transport models favor $\rho^2$ dependence of $S(\rho)$.
- EES favors $\rho^{2/3}$ dependence of $S(\rho)$.

Isospin diffusion from projectile fragmentation data provides another observable to study the symmetry energy
Acknowledgements

Bill Friedman

Future Perspectives

- Equation of State of Asymmetric Matter
  - Saturation density
  - Incompressibility
Symmetry Terms

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

- \[ K(F_1) = +61 \text{ MeV} \]
- \[ K(F_3) = -69 \text{ MeV} \]

Affect neutron star radii, moments of inertia, central densities.