Symmetry Energy:
in Structure
and in Central and Direct Reactions

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Bulk Properties of Strongly-Interacting Matter

Temperature $T$ [MeV]

Isospin Density

Net Baryon Density

Hadamron Deconfinement and chiral transition
Color Superconductor?

Early universe

Critical point?

Deconfinement

Quarks and Gluons

Neutron Stars

Symmetry Energy

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Reactions - coarse. Structure - detailed, but competition of macroscopic & microscopic effects
Energy in Uniform Matter

\[ \frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + S(\rho) \left( \frac{\rho_n - \rho_p}{\rho} \right)^2 + \mathcal{O}(\ldots^4) \]

symmetric matter \quad (a)symmetry energy \quad \rho = \rho_n + \rho_p

\[ E_0/A(\rho) = -a_V + \frac{K}{18} \left( \frac{\rho - \rho_0}{\rho_0} \right)^2 + \ldots \]

Known: \quad a_a \approx 16 \text{ MeV} \quad K \sim 235 \text{ MeV}

\[ S(\rho) = a_a^V + \frac{L}{3} \frac{\rho - \rho_0}{\rho_0} + \ldots \]

Unknown: \quad a_a^V \quad L \quad ?
Symmetry Energy in Nuclear Mass Formula

Textbook Bethe-Weizsäcker formula:

\[ E = -a_V A + a_S A^{2/3} + a_C \frac{Z^2}{A^{1/3}} + a_a \frac{(N - Z)^2}{A} + E_{\text{mic}} \]

Symmetry energy: charge \( n \leftrightarrow p \) symmetry of interactions

Analogy with capacitor:

\[ E_a = a_a \frac{(N - Z)^2}{A} \equiv \frac{(N - Z)^2}{\frac{A}{a_a}} \iff E = \frac{Q^2}{2C} \]

?Volume Capacitance?

\[ E_a = \frac{(N - Z)^2}{\frac{A}{a_a}} \rightarrow \frac{(N - Z)^2}{\frac{A}{a_a} + \frac{A^{2/3}}{a_a^{2/3}}} \]

Thomas-Fermi (local density) approximation:

\[ 'C' \equiv \frac{A}{a_a(A)} = \int \frac{\rho \, dr}{S(\rho)} = \frac{A}{a_a^V}, \text{ for } S(\rho) \equiv a_a^V \]

TF breaks in nuclear surface at \( \rho < \rho_0/4 \)
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PD&Lee NPA818(2009)36

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Mass Formula & Isospin Symmetry

Symmetry-energy details in a mass-formula are intertwined with details of other terms: Coulomb, Wigner & pairing + even those asymmetry-independent, due to \((N - Z)/A - A\) correlations along stability line (PD)!

Best would be to study the symmetry energy in isolation from the rest of mass-formula! Absurd?!

Charge invariance to rescue: lowest nuclear states characterized by different isospin values \((T, T_z)\), \(T_z = (Z - N)/2\). Nuclear energy scalar in isospin space:

\[
\text{sym energy } E_a = a_a(A) \frac{(N - Z)^2}{A} = 4 a_a(A) \frac{T_z^2}{A}
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\rightarrow E_a = 4 a_a(A) \frac{T^2}{A} = 4 a_a(A) \frac{T(T + 1)}{A}
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Isobaric Chains and Symmetry Coefficients

Energy Levels of A=16 Isobaric Chain

Symmetry Energy Danielewicz
Symmetry Coefficient Nucleus-by-Nucleus

Mass formula generalized to the lowest state of a given $T$:

$$E(A, T, T_z) = E_0(A) + 4a_a(A) \frac{T(T+1)}{A} + E_{mic} + E_{Coul}$$

In the ground state $T$ takes on the lowest possible value $T = |T_z| = |N - Z|/2$. Through ’+1’ most of the Wigner term absorbed.

Lowest state of a given $T$: isobaric analogue state (IAS) of some neighboring nucleus ground-state.

$E_{IAS} = \Delta E = a_a \frac{\Delta[T(T+1)]}{A} + \Delta E_{mic}$

Study of changes in the symmetry term possible nucleus by nucleus
From $a_a(A)$ to $S(\rho)$

Strong $a_a(A)$ dependence [PD & Lee NPA922(14)1]:
lower $A \Rightarrow$ more surface $\Rightarrow$ lower $\rho \Rightarrow$ lower $S$

$a_a(A)$ from IAS give rise to constraints on $S(\rho)$ in Skyrme-Hartree-Fock calculations
Auxiliary Info: Skins

Results for different Skyrme interactions in half-$\infty$ matter.

Isoscalar ($\rho = \rho_n + \rho_p$; blue) and isovector ($\rho_n - \rho_p$; green) densities displaced relative to each other.

As $S(\rho)$ changes, so does displacement.
Strategies for $n$ and $p$ Densities

**Jefferson Lab**

**Direct:** $\sim p$

**Interference:** $\sim n$

**PD**

- Elastic: $\sim p + n$
- Charge exchange: $\sim n - p$
Why Isovector Rather than Neutron Skins

Isovector skin: in no-curvature, no-shell-effect, no-Coulomb limit, the same for every nucleus!
Not suppressed by low \((N - Z)/A\)!

Nucleon optical potential in isospin space:

\[ U = U_0 + \frac{4\tau T}{A} U_1 \]

isoscalar potential \(U_0 \propto \rho\), isovector potential \(U_1 \propto (\rho_n - \rho_p)\)

In elastic scattering \(U = U_0 \pm \frac{N-Z}{A} U_1\)
In quasielastic charge-exchange \((p,n)\) to IAS: \(U = \frac{4\tau T}{A} U_1\)
Elastic scattering dominated by \(U_0\)
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Geometry usually assumed the same for \(U_0\) and \(U_1\)
e.g. Koning & Delaroche NPA713(03)231

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Quasielastic \((p,n)\) Reaction to IAS: Skin or No-Skin?

Data: Patterson \textit{et al.} NPA263(76)261
Calculations: PD & Singh (preliminary) with and without change \(\Delta R\) in radius of \(U_1\) compared to elastic
Before \(n\)-skin: Stephen Schery
Size of Isovector Skin

![Graph showing the size of isovector skin](image)

Large \( \sim 0.5 \text{ fm skins!} \)
Constraints on Symmetry-Energy Parameters
Constraints on $S(\rho)$

![Graph showing constraints on symmetry energy $S(\rho)$ for different density values. The graph compares IAS and IAS + $\Delta R$ models with extrapolations.]
Pions Probe System at High-$\rho$!

Elementary processes: $N + N \leftrightarrow N + \Delta, \quad \Delta \leftrightarrow N + \pi$

$\pi$ test the maximal densities reached and collective motion then

Song&Ko PRC91(15)014901

PD PRC51(95)716
Pions as Probe of High-$\rho$ Symmetry Energy

B-A Li: $S(\rho > \rho_0) \Rightarrow n/p_{\rho>\rho_0} \Rightarrow \pi^-/\pi^+$

Pions originate from high $\rho$

Symmetry Energy

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Dedicated Experimental Efforts

**SAMURAI-TPC Collaboration** (8 countries and 43 researchers): comparisons of near-threshold $\pi^-$ and $\pi^+$ and also $n$-$p$ spectra and flows at RIKEN, Japan.
- NSCL/MSU, Texas A&M U
- Western Michigan U, U of Notre Dame
- GSI, Daresbury Lab, INFN/LNS
- U of Budapest, SUBATECH, GANIL
- China IAE, Brazil, RIKEN, Rikkyo U
- Tohoku U, Kyoto U

**AT-TPC Collaboration** (US & France)
**FOPI: \( \pi^-/\pi^+ \) at 400 MeV/nucl and above**

Hong & PD, PRC90(14)024605: measured ratios reproduced in transport irrespectively of \( S_{\text{int}}(\rho) = S_0 \left( \rho/\rho_0 \right)^\gamma \):

\[
\begin{array}{cccccccc}
\pi^-/\pi^+ & 0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 & 1.6 & 1.8 & 2 & 2.2 \\
\hline
Au+Au & \text{FOPI} & 400A MeV & \text{200A MeV} \\
\end{array}
\]
Original Idea Still Correct for High-\(E\) \(\pi\)'s

\[
S_{\text{int}}(\rho) = S_0 \left(\frac{\rho}{\rho_0}\right)^\gamma 
\]

\(\rightarrow\) charge-exchange reactions blur signal
Conclusions

- Symmetry-energy term weakens as nuclear mass number decreases: from $a_a \sim 23$ MeV to $a_a \sim 9$ MeV for $A \lesssim 8$.

- Weakening of the symmetry term can be tied to the weakening of $S(\rho)$ in uniform matter, with the fall of $\rho$.

- IAS energies insufficiently constrain $L \rightarrow$ skin info needed!

- Isovector skins - large and relatively weakly dependent on nucleus! Large $\Delta R \sim 0.5$ fm $\Rightarrow L \sim 70$ fm

- Comprehensive analysis of elastic/quasielastic scattering data needed!

- In the region of $\rho \gtrsim \rho_0$, $S(\rho)$ is quite uncertain. One promising observable is high-en charged-pion yield-ratio around NN threshold.

PD&Lee NPA922(14)1; Hong&PD PRC90(14)024605; PD&Singh US NSF PHY-1068571 & PHY-1403906 + Indo-US Grant
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