Stiff Equation of State of Neutron Matter from Thick Isovector Aura

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XIIIth Quark Confinement and the Hadron Spectrum

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Bulk Properties of Strongly-Interacting Matter
Equation of State

Structure/Direct Reactions - $\rho \leq \rho_0$. HI Collisions - coarse, but all $\rho$

Isospin Density Neutron Stars
Nuclei

Neutron Stars
Charge Symmetry & Charge Invariance

Charge symmetry: invariance of nuclear interactions under $n \leftrightarrow p$ interchange

An isoscalar quantity $F$ does not change under $n \leftrightarrow p$ interchange. E.g. nuclear energy. Expansion in asymmetry $\eta = (N - Z)/A$, for smooth $F$, yields even terms only:

$$F(\eta) = F_0 + F_2 \eta^2 + F_4 \eta^4 + \ldots$$

An isovector quantity $G$ changes sign. Example:

$$\rho_{np}(r) = \rho_n(r) - \rho_p(r).$$

Expansion with odd terms only:

$$G(\eta) = G_1 \eta + G_3 \eta^3 + \ldots$$

Note: $G/\eta = G_1 + G_3 \eta^2 + \ldots$

In nuclear practice, analyticity requires shell-effect averaging!

Charge invariance: invariance of nuclear interactions under rotations in $n\cdot p$ space. Isospin $\vec{T} = \sum_{i=1}^{A} \vec{\tau}_i$ $\text{SU}(2)$
Examples: Nuclear Energy, Densities

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

symmetric matter (a)symmetry energy

\[
\rho = \rho_n + \rho_p
\]

Net \( \rho = \rho_n + \rho_p \) isoscalar

Difference \( \rho_n - \rho_p \) isovector

\[
\rho_a = \frac{A}{N-Z} (\rho_n - \rho_p) \text{ isoscalar}
\]

\[
\rho_{n,p}(r) = \frac{1}{2} \left[ \rho(r) \pm \frac{N-Z}{A} \rho_a(r) \right]
\]

Energy min in Thomas-Fermi:

\[
\rho_a(r) \propto \frac{\rho(r)}{S(\rho(r))}
\]

low \( S \Leftrightarrow \) high \( \rho_a \)
Stiffness of EOS & Mass & Radius of $n$-Star

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

\[ S \approx a_v + \frac{L}{3} \frac{\rho - \rho_0}{\rho_0} \]

In neutron matter:
\[ \rho_p \approx 0 \text{ & } \rho_n \approx \rho. \]

Then, \[ \frac{E}{A}(\rho) \approx \frac{E_0}{A}(\rho) + S(\rho) \]

Pressure:
\[ P = \rho^2 \frac{d}{d\rho} \frac{E}{A} \approx \rho^2 \frac{dS}{d\rho} \approx \frac{L}{3\rho_0} \rho^2 \]

Stiffer symmetry energy correlates with larger max mass of neutron star & larger radii
Relation between $\rho$, $\rho_a$ & $S(\rho)$

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

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

As $S(\rho)$ changes, $\rho_a(r) \propto \frac{\rho(r)}{S(\rho(r))}$, so does displacement.
Probing Independently 2 Densities

elastic scattering: $\sim \rho_p + \rho_n$

charge exchange $p \rightarrow n$: $\sim \rho_n - \rho_p$

PD, Sigh, Lee NPA958(17)147
Simultaneous Fits to Elastic & Charge-Change: $^{48}$Ca

Different radii for densities: $R_a = R + \Delta R$
Simultaneous Fits to Elastic & Charge-Change: $^{92}$Zr

Different radii for densities: $R_a = R + \Delta R$

![Graph showing data analysis for elastic and charge-change reactions](image-url)
Thickness of Isovector Aura

6 targets analyzed, differential cross section + analyzing power

Colored: Skyrme predictions. Arrows: half-infinite matter

Thick $\sim 0.9$ fm isovector aura! $\sim$ Independent of $A$. 
Bayesian Inference

Probability density in parameter space \( p(x) \) updated as experimental data on observables \( E \), value \( \bar{E} \) with error \( \sigma_E \), get incorporated.

Probability \( p \) is updated iteratively, starting with prior \( p_{\text{prior}} \)

\[
p(a|b) - \text{conditional probability}
\]

\[
p(x|\bar{E}) \propto p_{\text{prior}}(x) \int dE \exp \left( -\frac{(E-\bar{E})^2}{2\sigma_E^2} \right) p(E|x)
\]

For large number of incorporated data, \( p \) becomes independent of \( p_{\text{prior}} \)

In here, \( p_{\text{prior}} \) and \( p(E|x) \) are constructed from all Skyrme ints in literature, and their linear interpolations. \( p_{\text{prior}} \) is made uniform in plane of symmetry-energy parameters \((L, S_0)\)
Likelihood $f$/Symmetry-Energy Slope

$E_{\text{IAS}}^*$ - from excitations to isobaric analog states in PD&Lee NPA922(14)1

Oscillations in prior of no significance - represent availability of Skyrme parametrizations
Likelihood f/Energy of Neutron Matter

$E^*_{\text{IAS}}$ - from excitations to isobaric analog states in PD&Lee NPA922(14)1

Some oscillations due to prior
Isovector Aura

Isovector density

Isoscalar density

0.9fm!
Conclusions

- Symmetry-energy polarizes nuclear densities, pushing isovector density out to region of low isoscalar density
- For large $A$, displacement of isovector relative to isoscalar surface is expected to be roughly independent of nucleus and depend on slope of symmetry energy
- Surface displacement can be studied in comparative analysis of data on elastic scattering and quasielastic charge-exchange reactions
- Such an analysis produces thick isovector aura $\Delta R \sim 0.9$ fm!
- Symmetry & neutron energies are stiff! $L = (70 - 100) \text{ MeV}, S(\rho_0) = (33.5 - 36.5) \text{ MeV}$ at 68% level