An overview of neutron skin physics from nuclear structure and reaction: method and implications

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RBRC Workshop:
Physics Opportunities from the RHIC Isobar Run
Brookhaven National Laboratory

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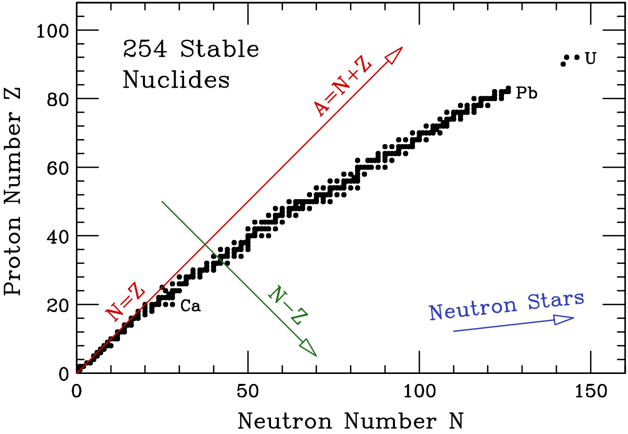
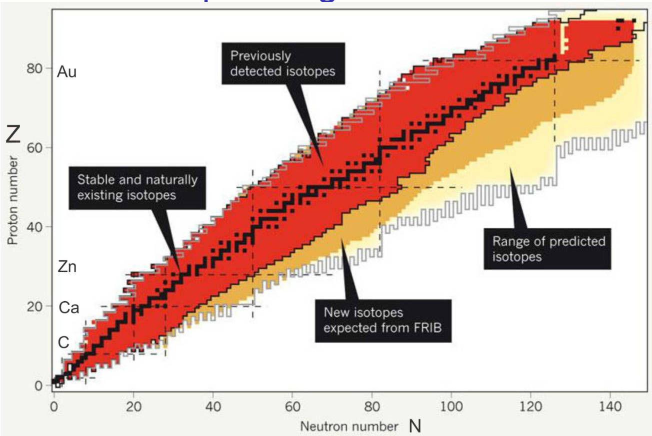
Nuclei as Binary Systems



Preference for $N \sim Z$

Extrapolation to neutron stars with $N \gg Z$?

Expanding Chart of Nuclides



Accelerator tech progress pushes chart boundaries out. . .

Thoennessen IJMP E24(15)1530002:

over 3000 nuclides (over 10$\times$ than stable!) known by now

Up to 1000 new nuclides expected in next decade!

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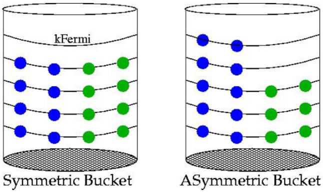
Protons & Neutrons

$N \approx Z$ favored when strong interactions dominate

Pauli principle + interactions more attractive for np pairs than pp or nn (also Pauli, but at quark level)



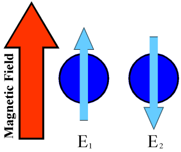
Mass formula:

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

symmetry energy term $a_a(A)$?

Relative spatial distribution of the species?

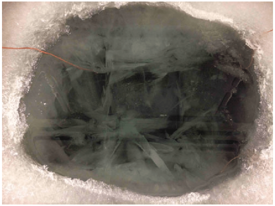
Relative Distribution of Species?



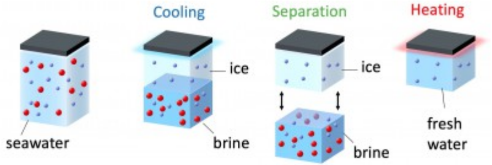
Statistical considerations: entropy vs energy

Example: $H_2O + NaCl$

Above freezing & below saturation, salinity (relative concentration of *NaCl*) is uniform, entropy & energy go along but, when water freezes, *NaCl* gets expelled from ice, as energy wins



Industrial desalination:



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Energy in Uniform Matter

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

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

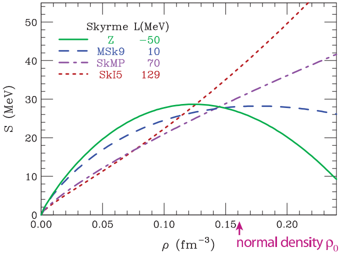
Net $\rho = \rho_n + \rho_p$ isoscalar

Difference $\rho_n - \rho_p$ isovector

$\rho_a = \frac{A}{N-Z}(\rho_n - \rho_p)$ isoscalar

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

ρ & ρ_a universal in isobaric chain!



$$S(\rho) = S(\rho_0) + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \dots$$

Unknown: $S(\rho_0)$? L ?

Energy min in Thomas-Fermi:

$$\rho_a(r) \propto \frac{\rho(r)}{S(\rho(r))}$$

low $S \Leftrightarrow$ high ρ_a

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Symmetry-Energy Stiffness: *M* & *R* of *n*-Star

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

$$S \simeq a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0}$$

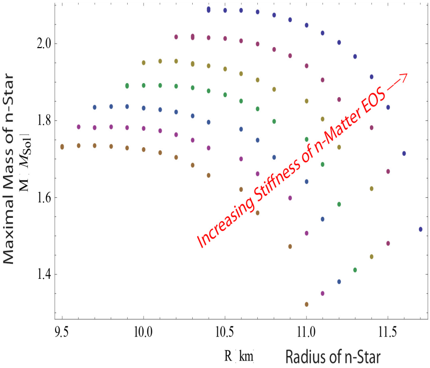
In neutron matter:

$\rho_p \approx 0$ & $\rho_n \approx \rho$.

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

Pressure:

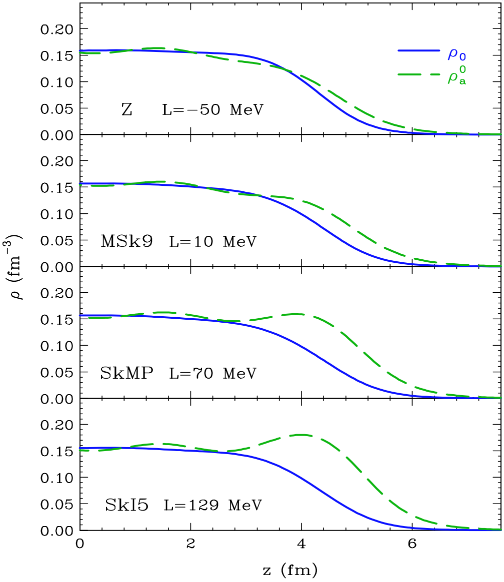
$$P = \rho^2 \frac{d}{d\rho}\frac{E}{A} \simeq \rho^2 \frac{dS}{d\rho} \simeq \frac{L}{3\rho_0}\rho^2$$



Schematic Calculation by Stephen Portillo (Harvard U)

Stiffer symmetry energy correlates with
larger max mass of neutron star & larger radii

Relation between ρ, ρ_a & $S(\rho)$

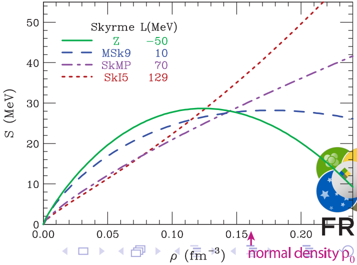


Results f/different Skyrme ints in half-∞ matter

PD&Lee NPA818(09)36

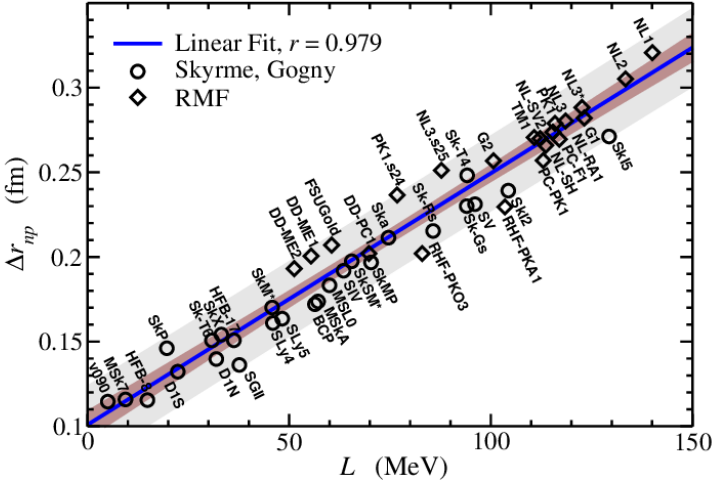
Isoscalar (ρ=ρ_n+ρ_p; blue) & isovector ($\rho_a \propto \rho_n$-ρ_p; green) densities displaced relative to each other.

As $S(\rho)$ changes, $\rho_a(r) \propto \frac{\rho(r)}{S(\rho(r))}$, so does displacement or aura



Correlation Between Stiffness & ^{208}Pb n-Skin

Vinas *et al.*, EPJA50(14)1



From skin to n-star...

Experimental Efforts

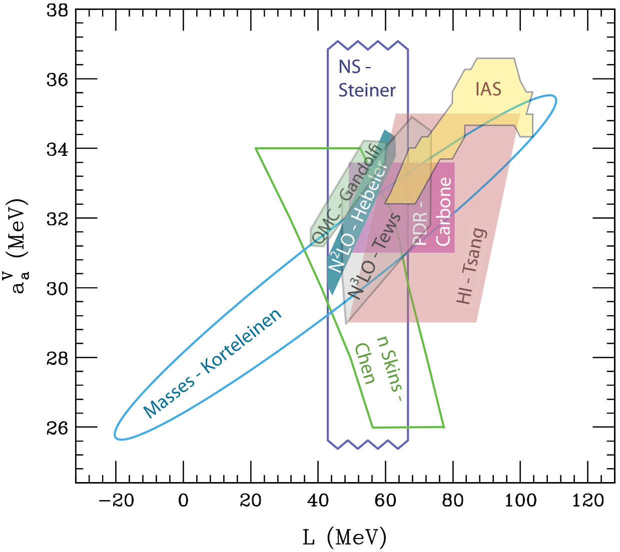
Experiments directly probing ground-state geometry:

- Elastic scattering
- Parity-violation in electron scattering
- Quasielastic charge exchange reactions
- Charge radii of mirror nuclei
- Charge-changing reactions

Other data testing symmetry energy:

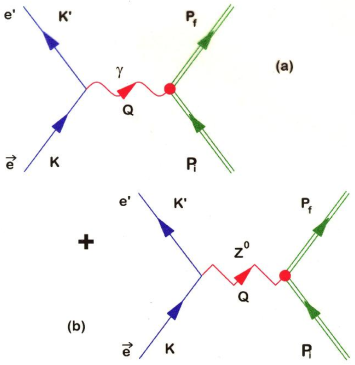
- Dipole polarizability
- Masses
- Heavy ions: diffusion, π^-/π^+ ratio, ...
- Neutron star: maximal *M*, *M*-*R* relation, deformability
- ...

Sample Symmetry-Energy Constraints



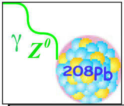
Parity Violation in *e*-Scattering: PREX & CREX

Parity violation in interference: $\sim n$



$$\sigma \propto |M_\gamma + M_{Z^0}|^2 = |M_\gamma|^2 + M_\gamma \times M^*_{Z^0} + \dots$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-6}$$



for spin-0 nucleus

	proton	neutron
Electric charge	**1**	**0**
Weak charge	**~0.08**	**1**

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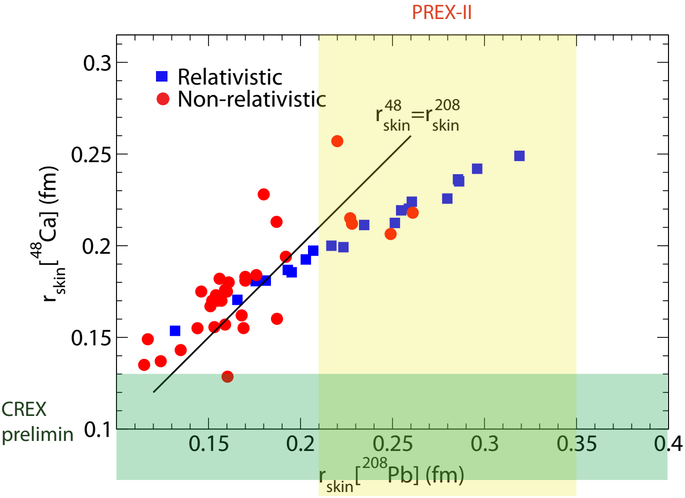
Parity Violation in *e*-Scattering: PREX & CREX

Adhikari *et al.*, PRL126(21)172502 + Palatchi@DNP'21

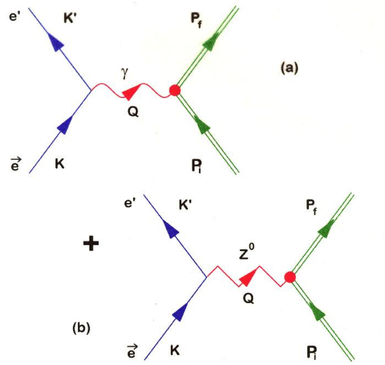


Differently Probing 2 Densities??

Jefferson Lab

Direct: $\sim p$

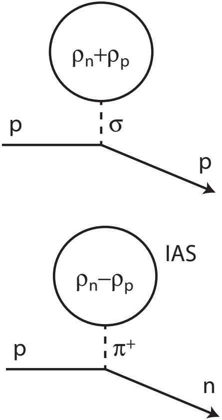
Interference: $\sim n$



PD, Singh, Lee NPA958(17)147
[after Dao Tien Khoa]

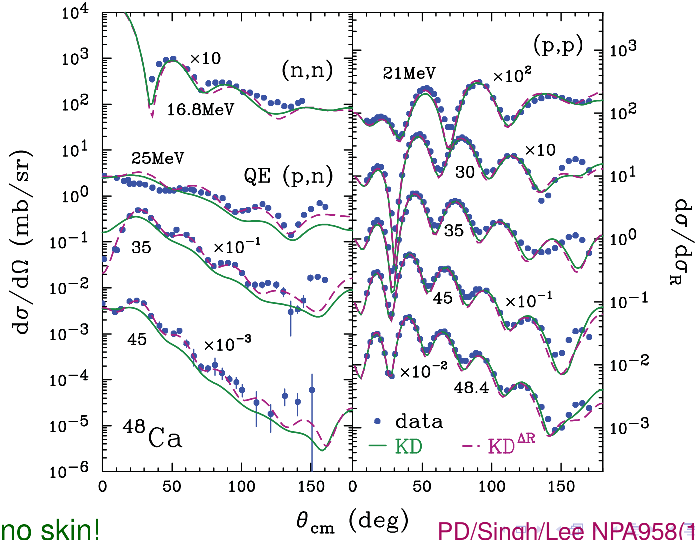
elastic: $\sim p + n$

charge exchange: $\sim n - p$



Simultaneous Fits to Elastic & Charge-Change: ^{48}Ca

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



KD: no skin!

PD/Singh/Lee NPA958(17)147

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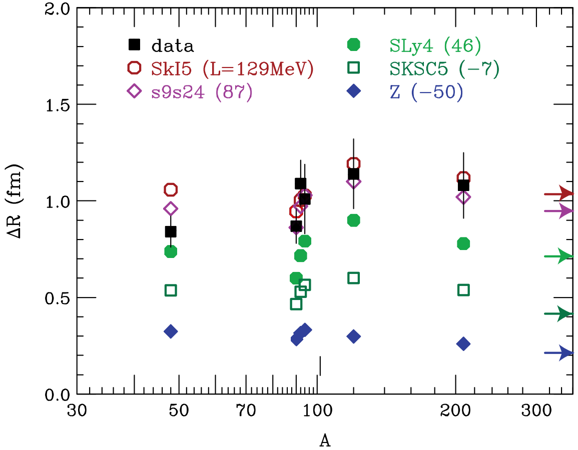
Thickness of Isovector Aura

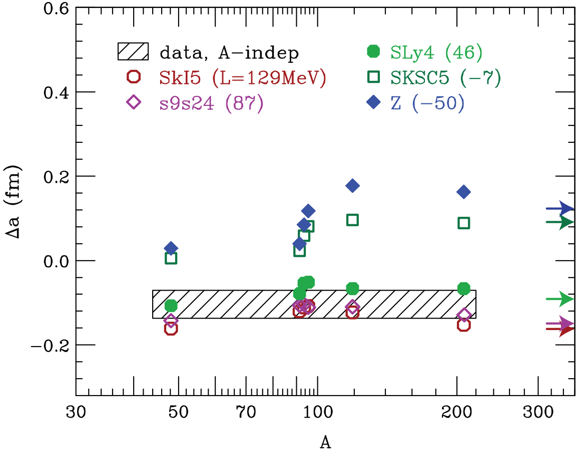
6 targets analyzed, differential cross section + analyzing power



Colored: Skyrme predictions. Arrows: half-infinite matter

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

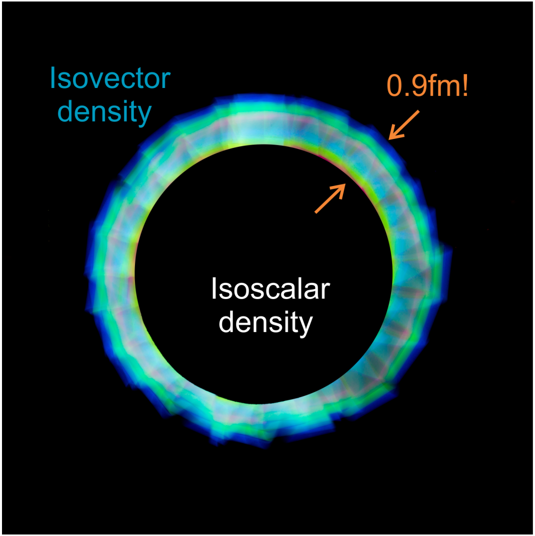
Diffuseness: Isovector-Isoscalar Difference



Colored: Skyrme predictions. Arrows: half-infinite matter

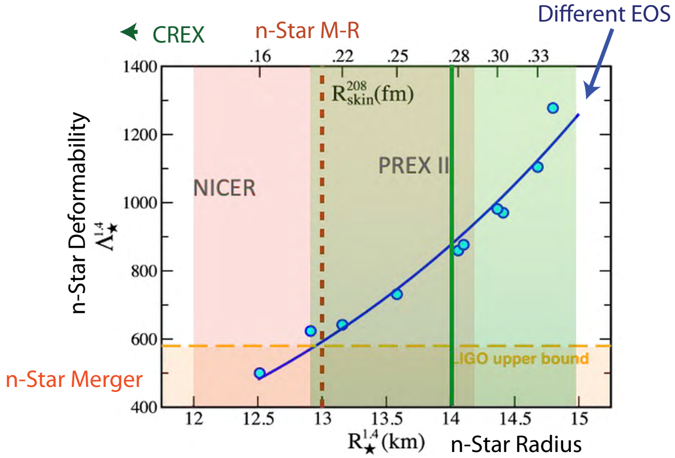
Sharper isovector surface than isoscalar!

Isovector Aura



Heaven vs Earth

after Chuck Horowitz



Tensions. . .

Conclusions

- In nuclear surface, isovector density leaks out of isoscalar density. In effect of isovector aura, rms radius for majority nucleons is greater than for minority, or majority-nucleon skin appears
- Size of aura or skin size is a direct consequence of dependence of symmetry energy on ρ, at $\rho \lesssim \rho_0$, and diffuseness for isoscalar density
- Constraints on skins emerge from data that directly reflect nuclear geometry and from data that in other ways probe ρ-dependence of symmetry energy
- As uncertainties in skin constraints or in ρ-dependence of symmetry energy become more seriously determined, clear tensions emerge that need to be taken seriously

DOE DE-SC0019209

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