# Stiff Symmetry Energy from Isovector Aura in Charge-Exchange Reactions

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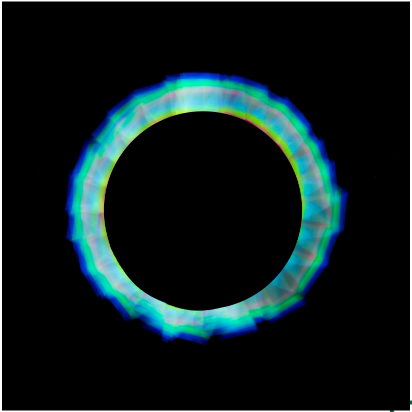
# Aura

Historically Kirlian Photography

Living Being



Nucleus

# 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 $n$-$p$ space. Isospin $\vec{T} = \sum_{i=1}^{A} \vec{\tau}_i$ SU(2)

# Charge Symmetry & Charge Invariance

Charge symmetry:
$n \leftrightarrow p$ invariance

Isobars: Nuclei with the same $A$

Charge invariance:
symmetry under
*rotations* in
$n$-$p$ space

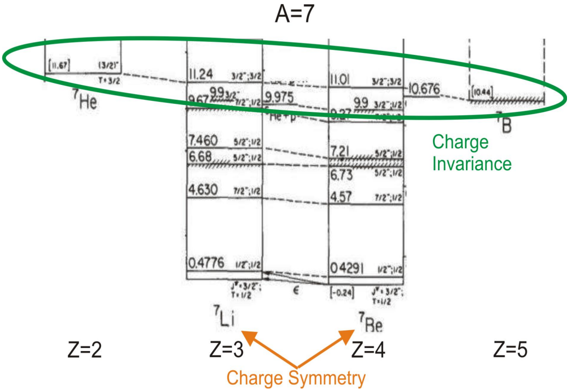
Isospin doublets

$p : (\tau, \tau_z) \quad = (\frac{1}{2}, \frac{1}{2})$

$n : (\tau, \tau_z) \quad = (\frac{1}{2}, -\frac{1}{2})$

Net isospin

$$\vec{T} = \sum_{i=1}^{A} \vec{\tau}_i$$




$T = \frac{3}{2}, \ldots$ $\quad T = \frac{1}{2}, \frac{3}{2}, \ldots$ $\quad T = \frac{3}{2}, \ldots$

Nuclear states: $\quad (T, T_z), \quad T \geq |T_z| = \frac{1}{2}|N - Z|$

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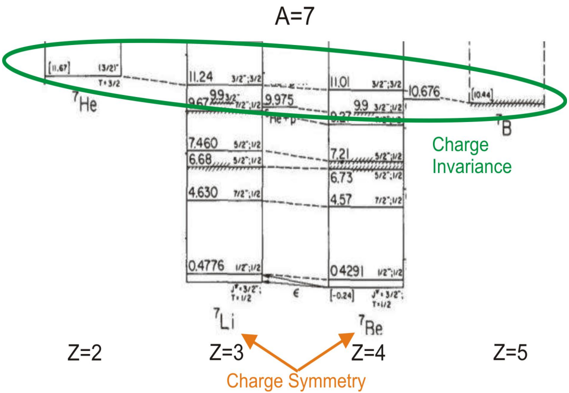
Isobars: Nuclei with the same *A*

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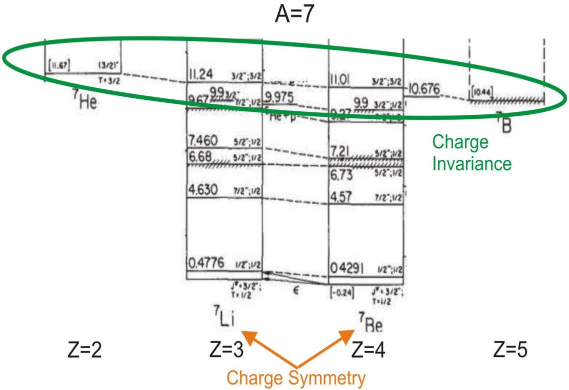


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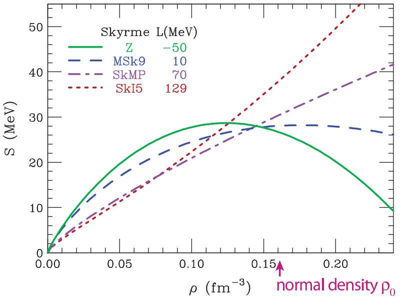
# Examples: Nuclear Energy, Densities

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

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




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

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

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

Difference $\rho_n - \rho_p$ isovector

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

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

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

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

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

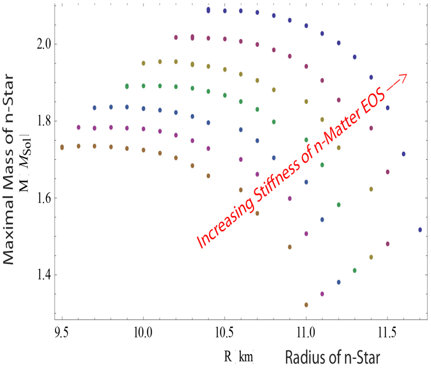
In neutron matter:

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

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

Pressure:

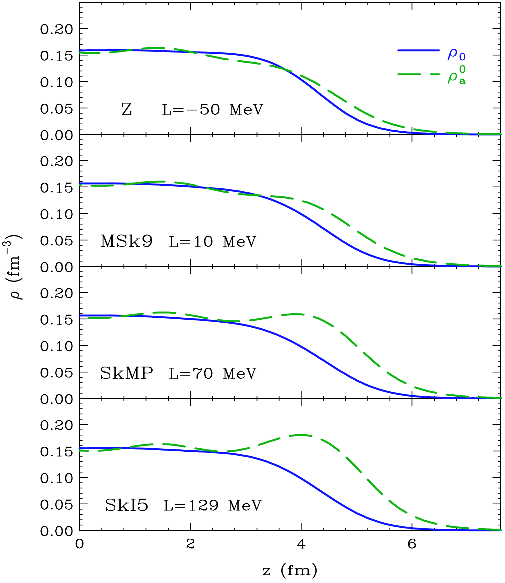
$$P = \rho^2 \frac{d}{d\rho}\frac{E}{A} \simeq \rho^2 \frac{dS}{d\rho} \simeq \frac{L}{3\rho_0}\rho^2$$




Schematic Calculation by Stephen Portillo (Harvard U)

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

# Relation between $\rho$, $\rho_a$ & $S(\rho)$

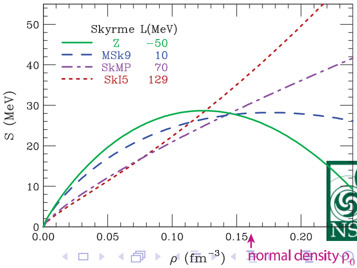



Results f/different Skyrme ints in half-∞ matter

PD&Lee NPA818(09)36

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.

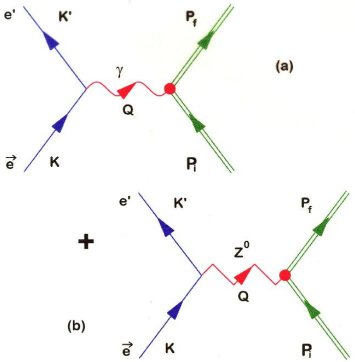


# Probing Independently 2 Densities

Jefferson Lab

Direct: $\sim p$

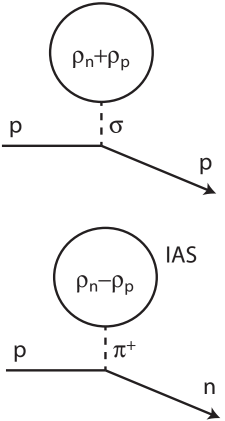
Interference: $\sim n$



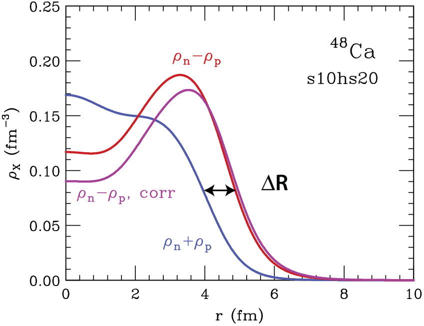

PD, Singh, Lee NPA958(17)147 [after Dao Tien Kho]

elastic: $\sim p + n$

charge exchange: $\sim n - p$



# Expectations on Isovector Aura?




Much Larger Than Neutron Skin!

Surface radius $R \simeq \sqrt{\frac{5}{3}}\,\langle r^2\rangle^{1/2}$

rms neutron skin

$$\langle r^2\rangle^{1/2}_{\rho_n} - \langle r^2\rangle^{1/2}_{\rho_p}$$

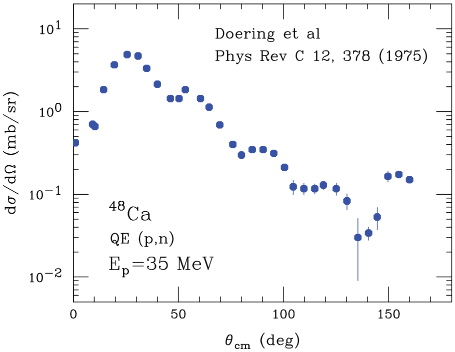
$$\simeq 2\,\frac{N-Z}{A}\left[\langle r^2\rangle^{1/2}_{\rho_n-\rho_p} - \langle r^2\rangle^{1/2}_{\rho_n+\rho_p}\right]$$

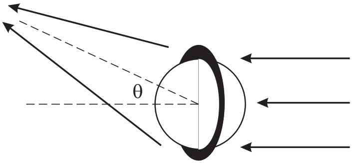
rms isovector aura

Estimated $\Delta R \sim 3\left(\langle r^2\rangle^{1/2}_{\rho_n} - \langle r^2\rangle^{1/2}_{\rho_p}\right)$ for $^{48}$Ca/$^{208}$Pb!

Even before consideration of Coulomb effects that further enhances difference!

# Direct Reaction Primer




DWBA:

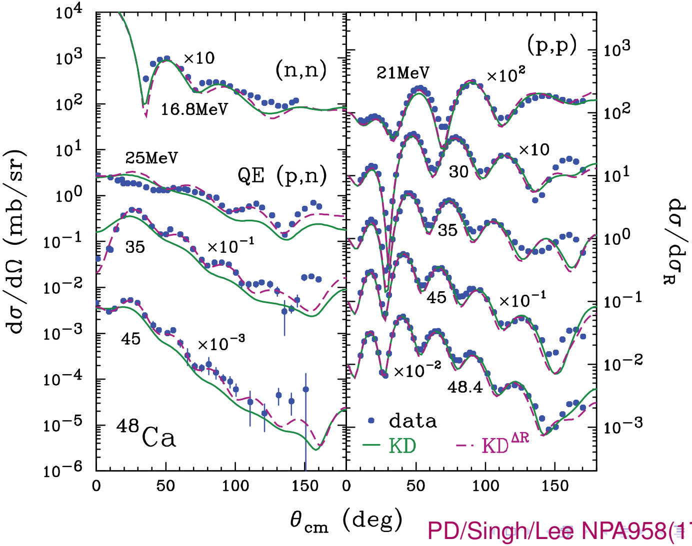
$$\frac{d\sigma}{d\Omega} \propto \left| \int dr\, \Psi_f^*\, U_1\, \Psi_i \right|^2$$

Lane Potential
$$U = U_0 + \frac{4\tau T}{A} U_1$$
$$U_0 \propto \rho \qquad U_1 \propto \rho_n - \rho_p$$

It is common to assume the same geometry for $U_0$ & $U_1$, implicitly $\rho$ & $\rho_a$, e.g. Koning&Delaroche NPA713(03)231

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

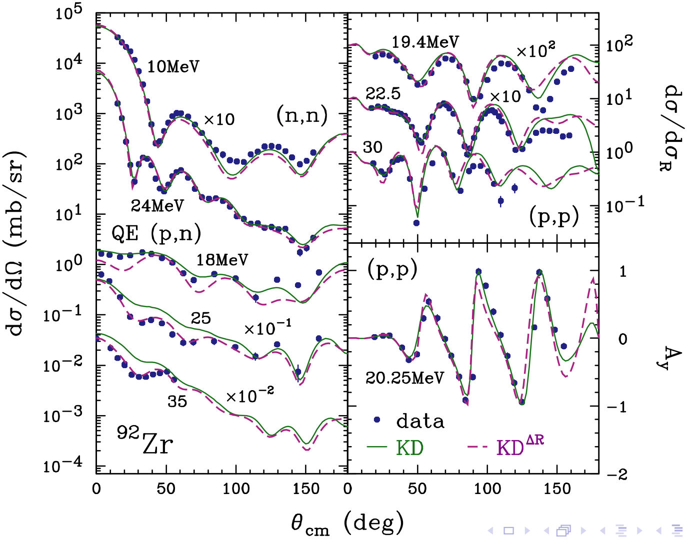
## Different radii for densities/potentials: $R_a = R + \Delta R$




PD/Singh/Lee NPA958(17)147

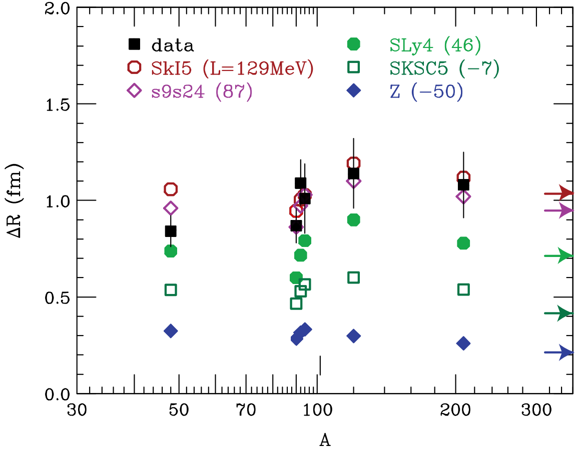
# Simultaneous Fits to Elastic & Charge-Change: $^{92}$Zr

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



# Thickness of Isovector Aura

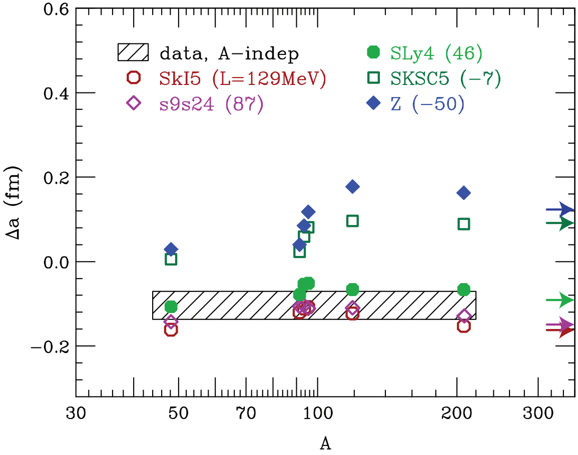
## 6 targets analyzed, differential cross section + analyzing power




Colored: Skyrme predictions. Arrows: half-infinite matter

Thick ∼ 0.9 fm isovector aura! ∼Independent of $A$...

# Difference in Surface Diffuseness

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Sharper isovector surface than isoscalar!

# Bayesian Inference

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

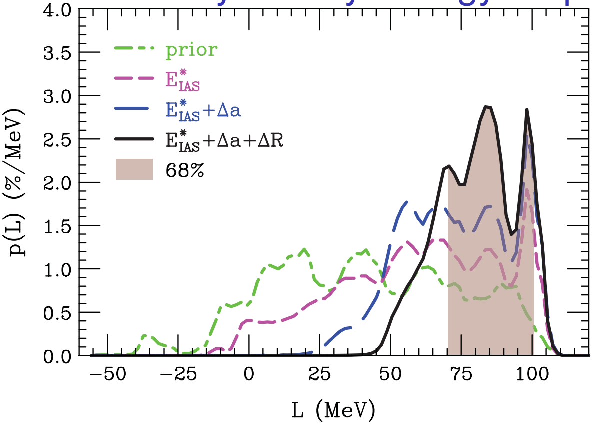
Probability $p$ is updated iteratively, starting with prior $p_{\text{prior}}$
$p(a|b)$ - conditional probability

$$p(x|\overline{E}) \propto p_{\text{prior}}(x) \int \mathrm{d}E \, \mathrm{e}^{-\frac{(E-\overline{E})^2}{2\sigma_E^2}} \, p(E|x)$$

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 $(L, S_0)$

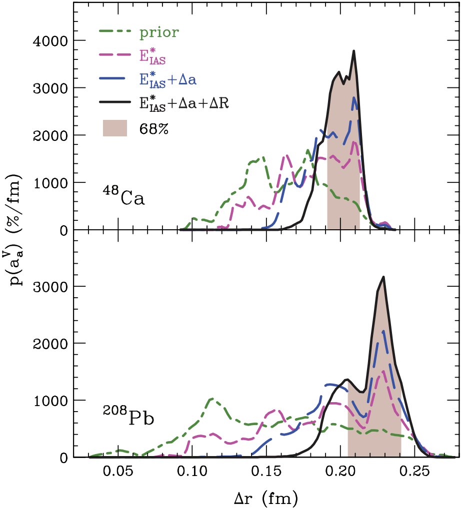
# Likelihood f/Symmetry-Energy Slope




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

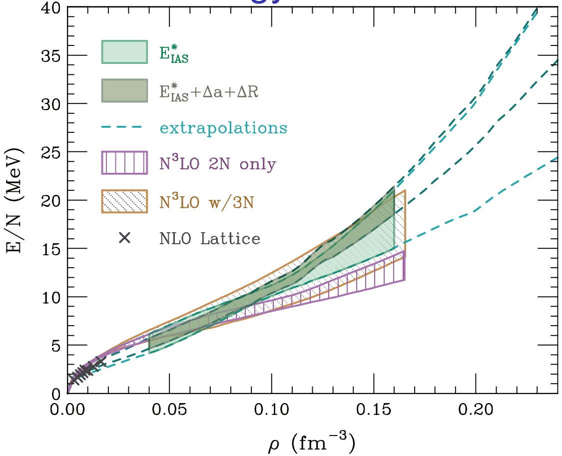
Oscillations in prior of no significance
- represent availability of Skyrme parametrizations

# Likelihood f/Neutron-Skin Values




Sizeable *n*-Skins

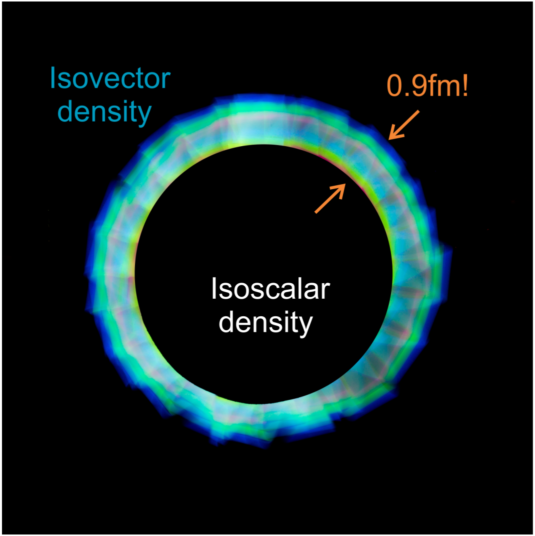
# Likelihood f/Energy of Neutron Matter




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

Some oscillations due to prior

# Isovector Aura



# 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
  $\Delta R \sim 0.9\,\mathrm{fm}$!
- Symmetry & neutron energies are stiff!
  $L = (70 - 100)\,\mathrm{MeV}$, $S(\rho_0) = (33.5 - 36.5)\,\mathrm{MeV}$ at 68% level

PD, Lee & Singh NPA818(09)36, 922(14)1, 958(17)147 + in progress

NSF PHY-1403906 & DOE DE-SC0019209

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