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

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Xiamen-CUSTIPEN Workshop on the EOS of Dense Matter in the Era of Gravitational Wave Astronomy

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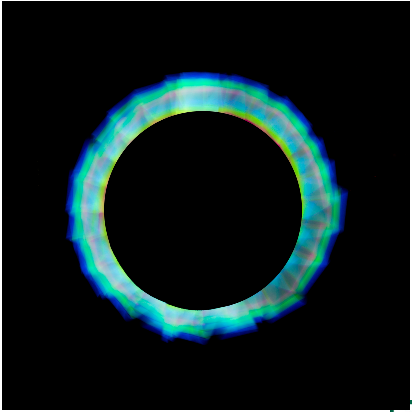
Aura

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

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

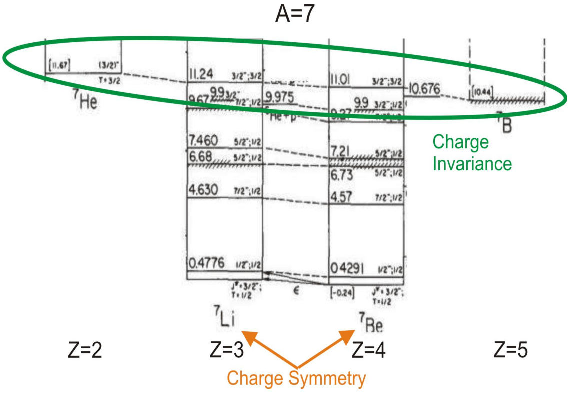
Isospin doublets

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

Net isospin

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

Isobars: Nuclei with the same *A*



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

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

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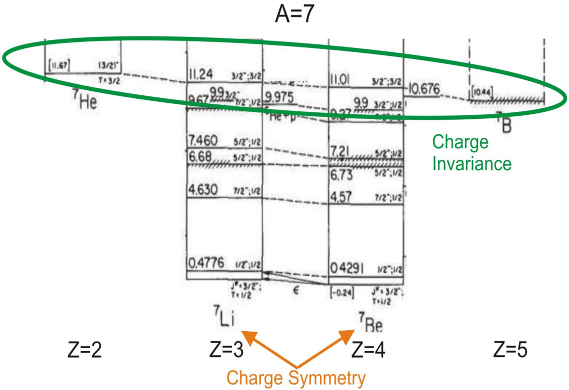

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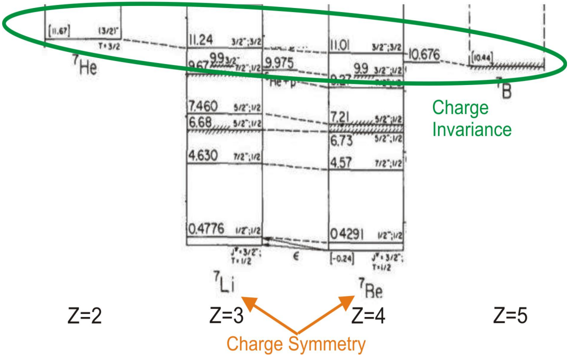
Isobars: Nuclei with the same *A*

A=7



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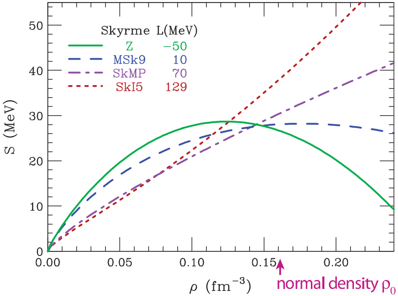
Examples: Nuclear Energy, Densities

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

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 ρ_a

Stiffness of EOS & Mass & Radius of *n*-Star

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

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

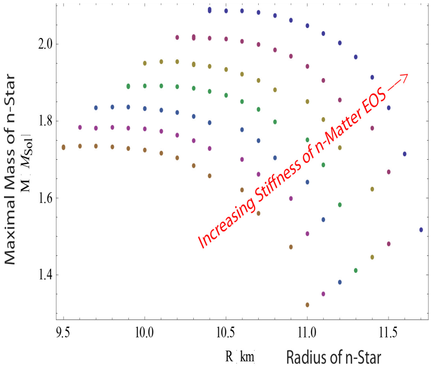
In neutron matter:

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

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

Pressure:

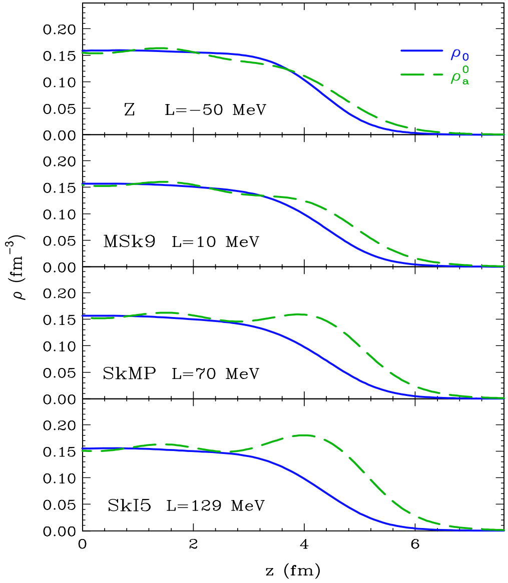
$$P = \rho^2 \frac{d}{d\rho}\frac{E}{A} \simeq \rho^2 \frac{dS}{d\rho} \simeq \frac{L}{3\rho_0}\rho^2$$



Schematic Calculation by Stephen Portillo (Harvard U)

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

Relation between ρ, ρ_a & $S(\rho)$

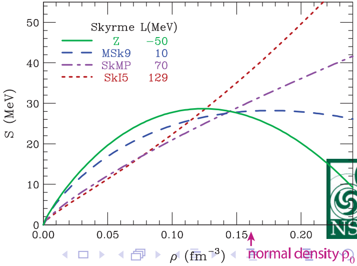


Results f/different Skyrme ints in half-∞ matter

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.



Probing Independently 2 Densities

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[after Dao Tien Kho]

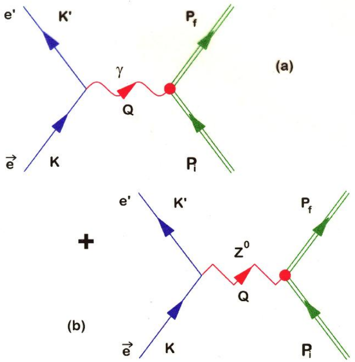
Jefferson Lab

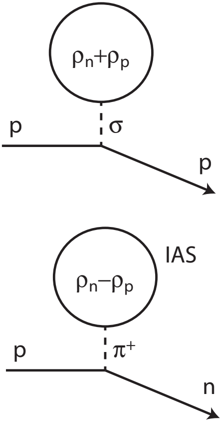
Direct: $\sim p$

Interference: $\sim n$

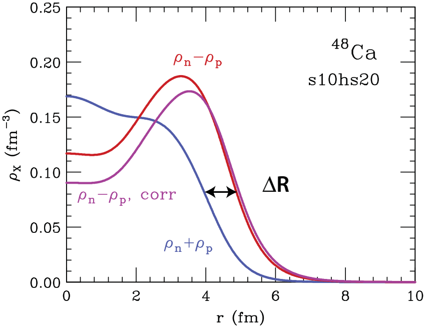
elastic: $\sim p + n$

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

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

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

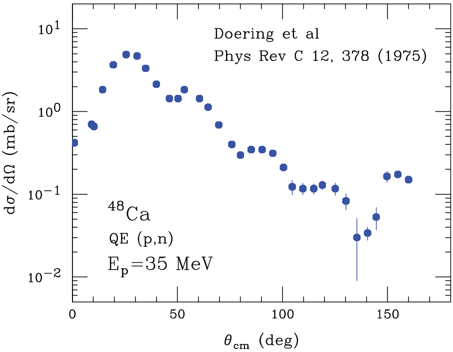
rms isovector aura

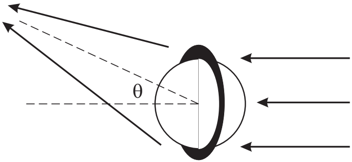
Estimated $\Delta R \sim 3 \left(\langle r^2 \rangle^{1/2}_{\rho_n} - \langle r^2 \rangle^{1/2}_{\rho_p} \right)$ for ^{48}Ca/^{208}Pb!

Even before consideration of Coulomb effects that further enhances difference!

NSCL

Direct Reaction Primer





DWBA:

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

Lane Potential
$$U = U_0 + \frac{4\tau T}{A} U_1$$

$$U_0 \propto \rho \qquad U_1 \propto \rho_n - \rho_p$$

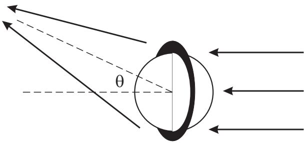
It is common to assume the same geometry for U_0 & U_1, implicitly ρ & ρ_a, e.g. Koning&Delaroche NPA713(03)231

Cross-Section Sensitivity to Isovector Surface

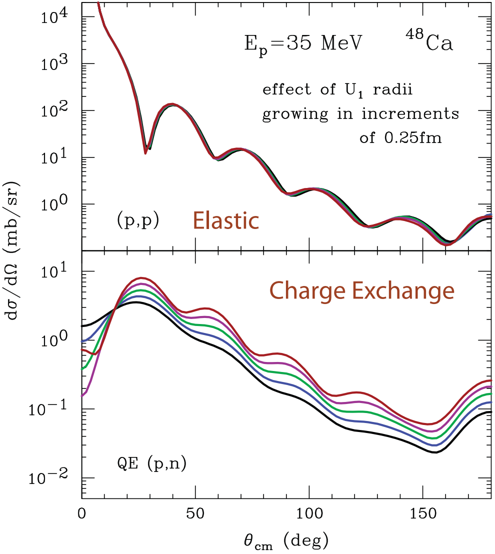
Koning-Delaroche
NPA713(03)231
same radii R for U_0 & U_1!

$$U_1(r) \propto \frac{U_{01}}{1 + \exp \frac{r-R}{a}}$$

$$R \to R + \Delta R_1$$

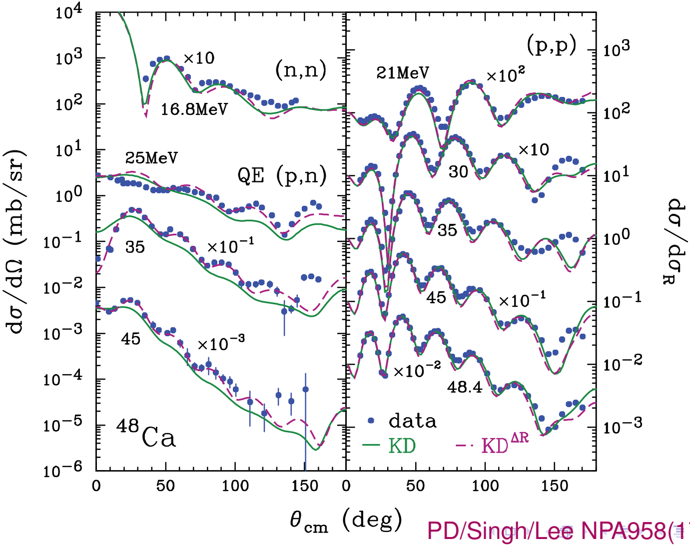


charge-exchange cs
oscillations grow



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

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



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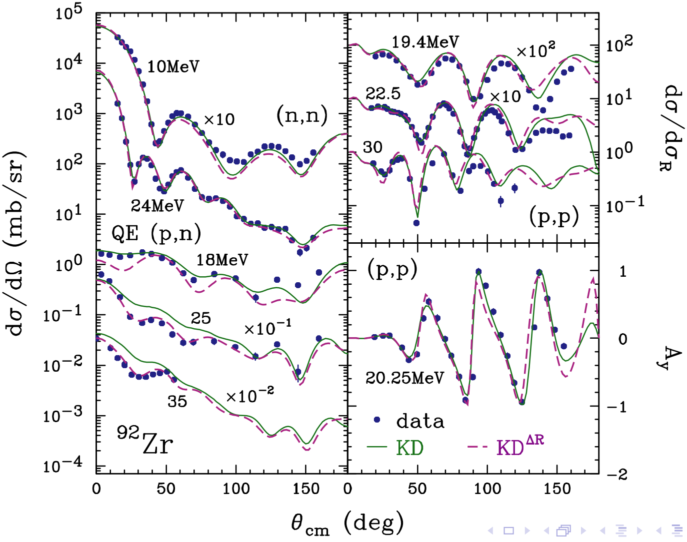
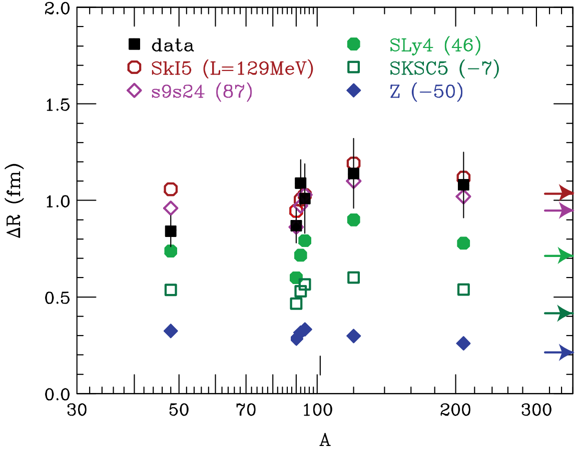
Simultaneous Fits to Elastic & Charge-Change: ^{92}Zr

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



Thickness of Isovector Aura

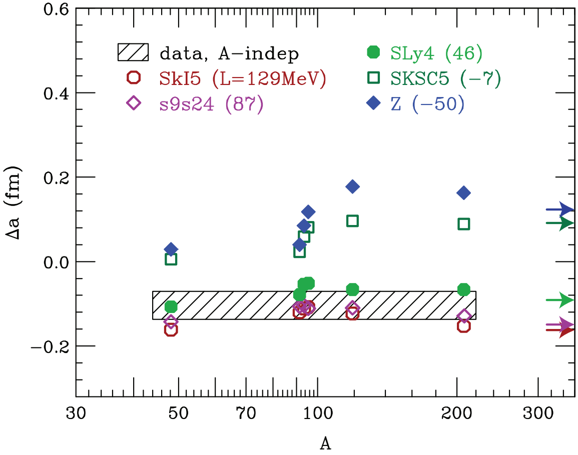
6 targets analyzed, differential cross section + analyzing power



Colored: Skyrme predictions. Arrows: half-infinite matter

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

Difference in Surface Diffuseness



Colored: Skyrme predictions. Arrows: half-infinite matter

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 σ_E, get incorporated

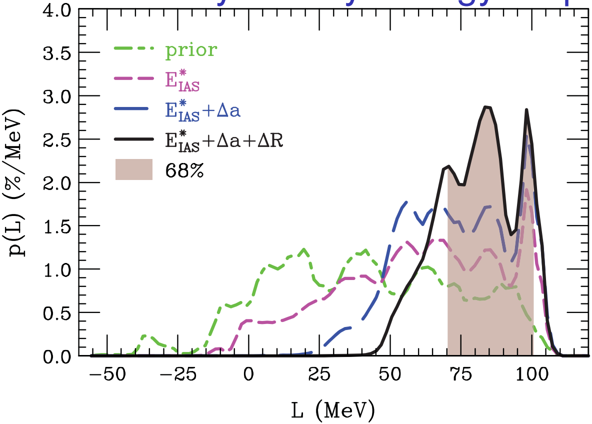
Probability p is updated iteratively, starting with prior $p_{\rm prior}$
$p(a|b)$ - conditional probability

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

For large number of incorporated data, p becomes independent of $p_{\rm prior}$

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

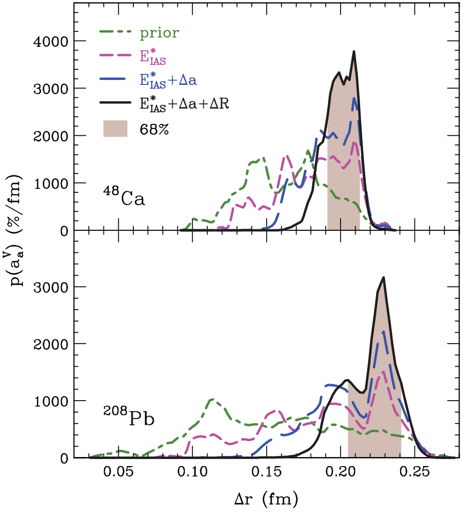
Likelihood f/Symmetry-Energy Slope



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

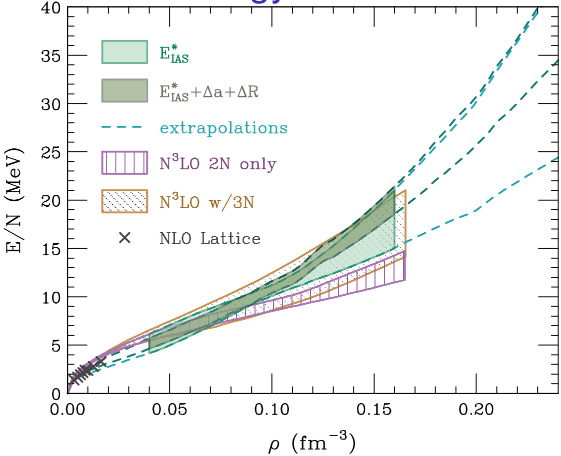
Oscillations in prior of no significance
- represent availability of Skyrme parametrizations

Likelihood f/Neutron-Skin Values



Sizeable *n*-Skins

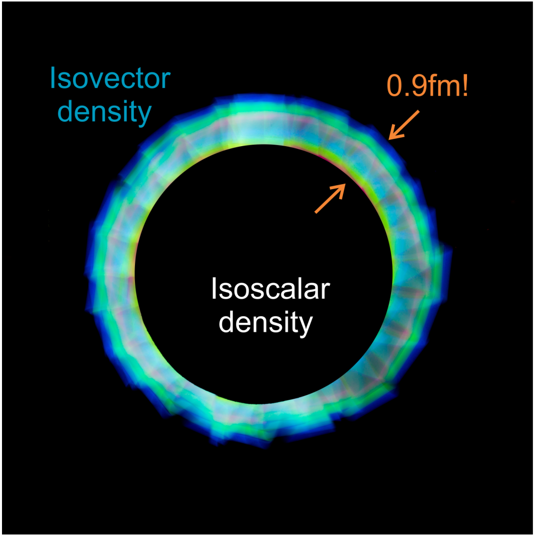
Likelihood f/Energy of Neutron Matter



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
- Now: Novel error analysis

PD, Lee & Singh NPA818(09)36, 922(14)1, 958(17)147 + in progress
DOE DE-SC0019209 + CUSTIPEN

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