Isoscalar and Isovector Densities and Symmetry Energy

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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

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n ↔ *p* invariance

Charge invariance:
symmetry under
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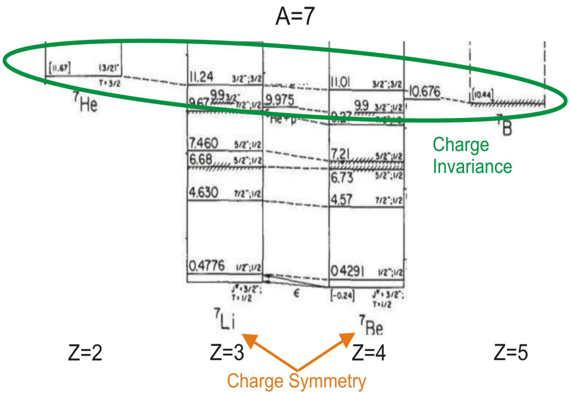
Isobars: Nuclei with the same A



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

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

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

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

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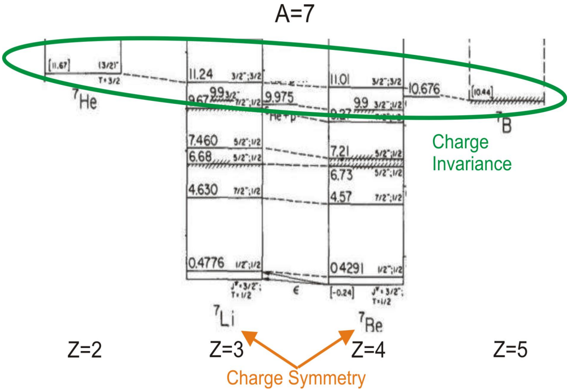

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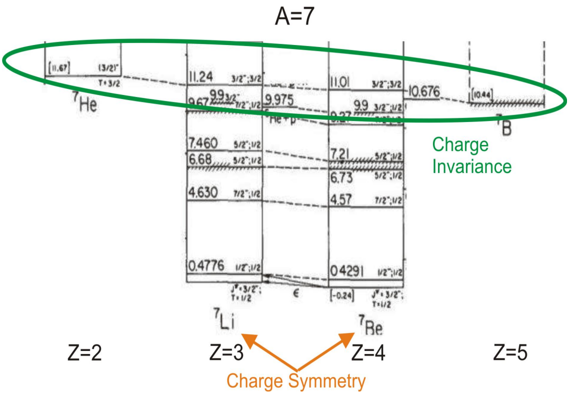

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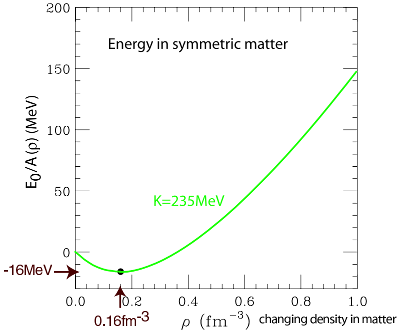
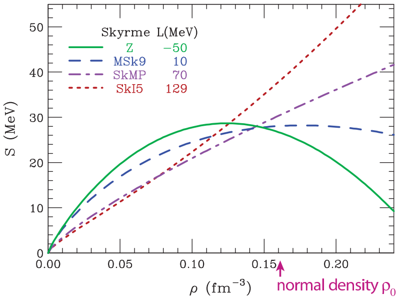
Energy in Uniform Matter

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

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

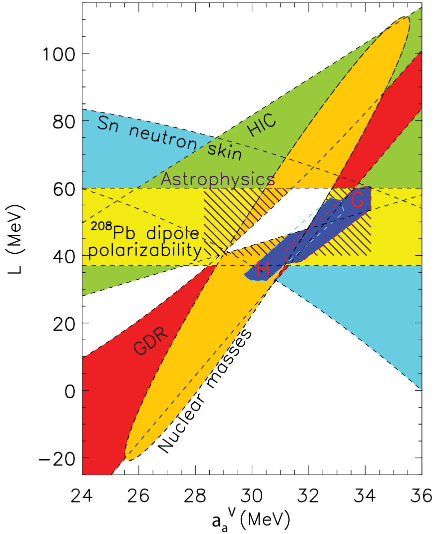




$$\frac{E_0}{A}(\rho) = -a_V + \frac{K}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots \qquad S(\rho) = a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \ldots$$

Known: $a_a \approx 16$ MeV $K \sim 235$ MeV Unknown: a_a^V ? L ?

Importance of Slope



Lattimer&Lim ApJ771(2013)51

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

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

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:

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

$43 \lesssim L \lesssim 60$ MeV ??

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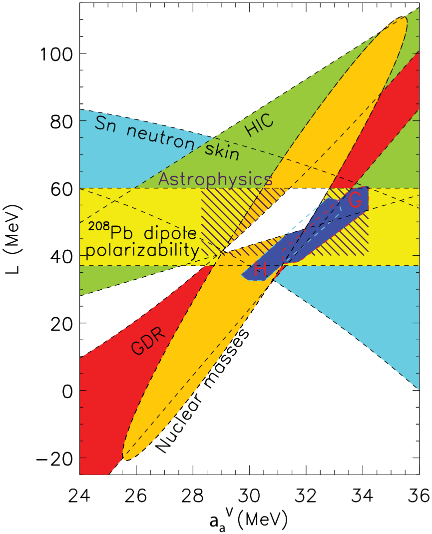

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Isoscalar and Isovector Densities

Net density $\rho(r) = \rho_n(r) + \rho_p(r)$ is isoscalar $\Rightarrow$ weakly depends on $(N-Z)$ for given A. [Coulomb suppressed. . .]

$\rho_{np}(r) = \rho_n(r) - \rho_p(r)$ isovector but $A\,\rho_{np}(r)/(N-Z)$ isoscalar!

$A/(N-Z)$ normalizing factor global. . . Similar local normalizing factor, in terms of intense quantities, $2a_a^V/\mu_a$, where $a_a^V \equiv S(\rho_0)$

Isoscalar formfactor for isovector density:

$$\rho_a(r) = \frac{2a_a^V}{\mu_a}\left[\rho_n(r) - \rho_p(r)\right]$$

Normal matter: $\rho_a = \rho_0$. Both $\rho(r)$ & $\rho_a(r)$ weakly depend on η!

In any nucleus:

$$\rho_{n,p}(r) = \frac{1}{2}\left[\rho(r) \pm \frac{\mu_a}{2a_a^V}\rho_a(r)\right]$$

where $\rho(r)$ & $\rho_a(r)$ have universal features! (subject to shell effects)

No shell-effects, ρ's as dynamic vbles: Hohenberg-Kohn functional

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Net density ρ usually parameterized w/Fermi function

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{d}\right)} \qquad \text{with} \quad R = r_0\, A^{1/3}$$

Isovector density ρ_a?? Related to $S(\rho)$!

In uniform matter

$$\mu_a = \frac{\partial E}{\partial(N-Z)} = \frac{\partial[S(\rho)\,\rho_{np}^2/\rho]}{\partial\rho_{np}} = \frac{2\,S(\rho)}{\rho}\,\rho_{np}$$

$$\Rightarrow \quad \rho_a = \frac{2a_a^V}{\mu_a}\,\rho_{np} = \frac{a_a^V\,\rho}{S(\rho)}$$

$\Longrightarrow$ Hartree-Fock study of surface

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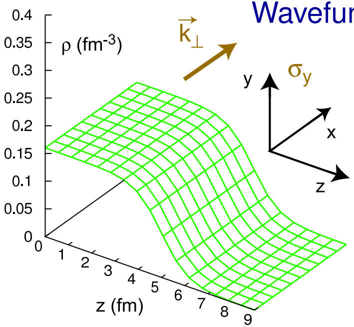
Half-Infinite Matter in Skyrme-Hartree-Fock

To one side infinite uniform matter & vacuum to the other



Wavefunctions: $\Phi(\boldsymbol{r}) = \phi(z)\, e^{i\boldsymbol{k}_\perp \cdot \boldsymbol{r}_\perp}$

matter interior/exterior:

$$\phi(z) \propto \sin\left(k_z\, z + \delta(\boldsymbol{k})\right)$$

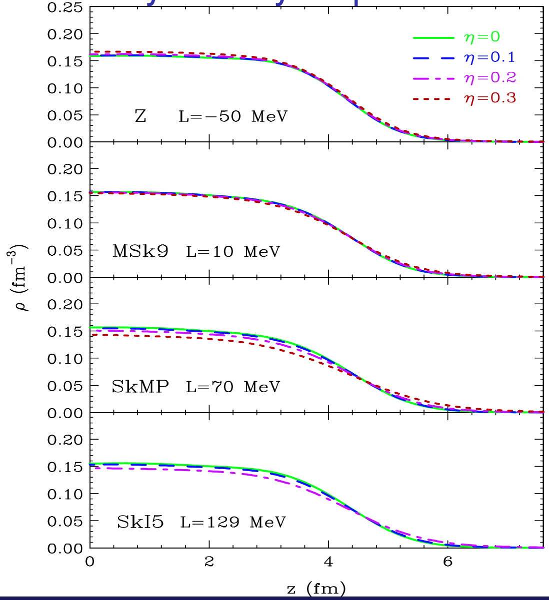
$$\phi(z) \propto e^{-\kappa(\boldsymbol{k}) z}$$

Discretization in ***k***-space. Set of 1D HF eqs solved using Numerov's method until self-consistency:

$$-\frac{d}{dz}\frac{\hbar^2}{2m^*(z)}\frac{d}{dz}\,\phi(z) + \left(\frac{\hbar^2\, k_\perp^2}{2m^*(z)} + U(z)\right)\phi(z) = \epsilon(\boldsymbol{k})\,\phi(z)$$

PD&Lee, NPA818(09)36. Before: Farine *et al*, NPA338(80)86

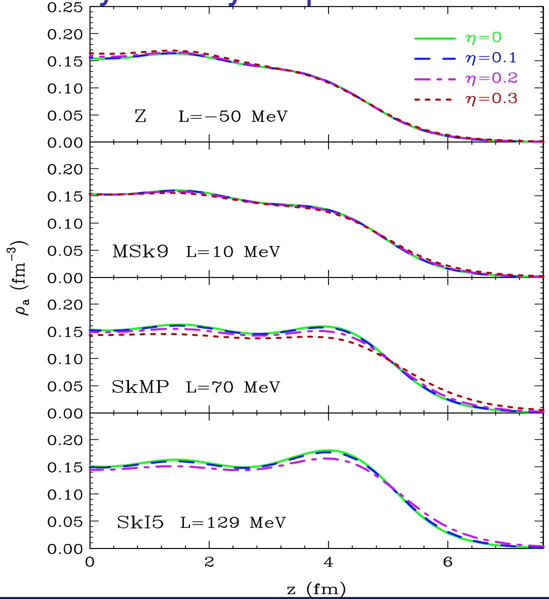
Asymmetry Dependence of Net Density



Half-∞ matter results for different Skyrme interactions and asymmetries

$$\eta = \frac{N-Z}{A}$$

Asymmetry Dependence of Isovector Density



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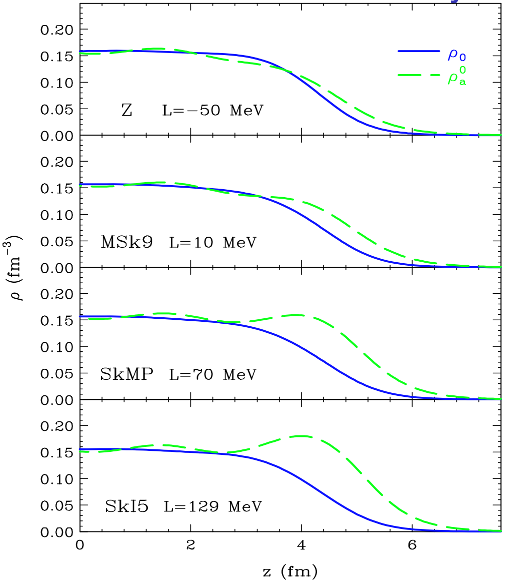
PD&Lee NP818(09)36

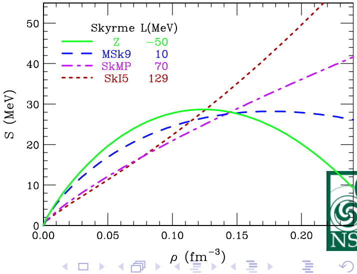
Sensitivity to $S(\rho)$



Results f/different Skyrme ints in half-∞ matter.

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

As $S(\rho)$ changes, so does displacement.



NSCL

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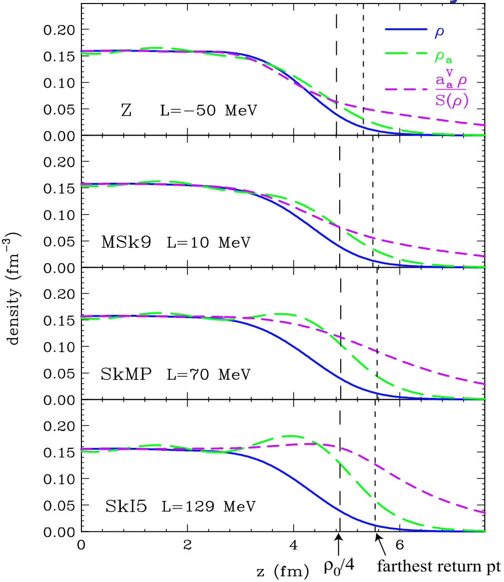

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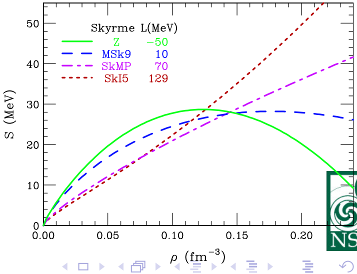
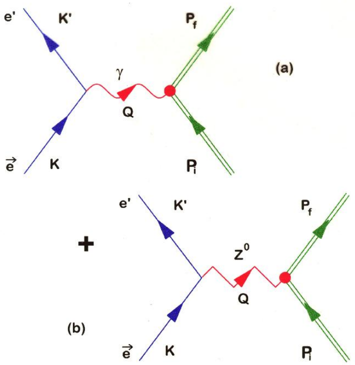


Strategies for Independent Densities

Jefferson Lab

Direct: $\sim p$

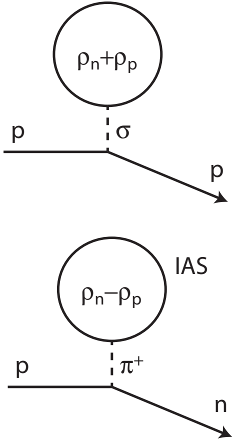
Interference: $\sim n$



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 (Lane) 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

Quasielastic governed by U_1

Geometry usually assumed the same for U_0 and U_1

e.g. Koning & Delaroche NPA713(03)231

?Isovector skin ΔR from comparison of elastic and quasielastic (p,n)-to-IAS scattering?

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Not suppressed by low $(N-Z)/A$!

Nucleon (Lane) 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

Quasielastic governed by U_1

Geometry usually assumed the same for U_0 and U_1

e.g. Koning & Delaroche NPA713(03)231

?Isovector skin ΔR from comparison of elastic and quasielastic (p,n)-to-IAS scattering?

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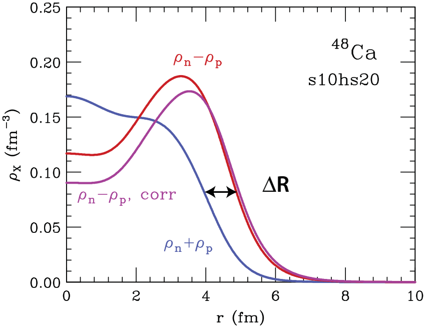
Expectations on Isovector Skin?



Much Larger Than Neutron!

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

rms neutron skin

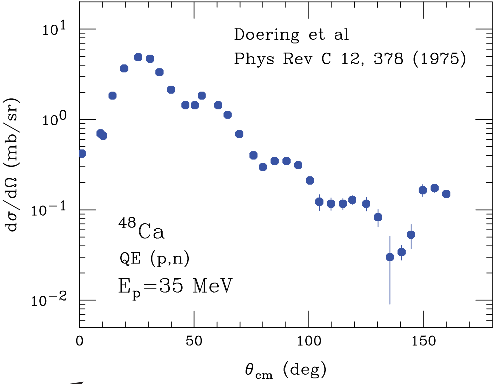
$$\langle r^2 \rangle_{\rho_n}^{1/2} - \langle r^2 \rangle_{\rho_p}^{1/2} \simeq 2 \frac{N-Z}{A} \left[\langle r^2 \rangle_{\rho_n - \rho_p}^{1/2} - \langle r^2 \rangle_{\rho_n + \rho_p}^{1/2} \right]$$

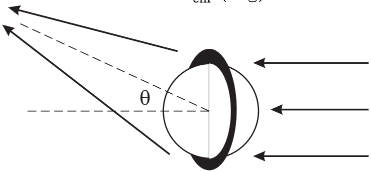
rms isovector skin

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

Even before consideration of Coulomb effects that further enhances difference!

Direct Reaction Primer





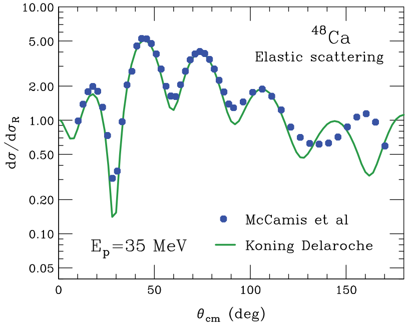
DWBA:

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

- Oscillations: 2-side interference/source size
- Fall-off: softness of source
- Filling of minimae: imaginary/real contributions, spin-orbit

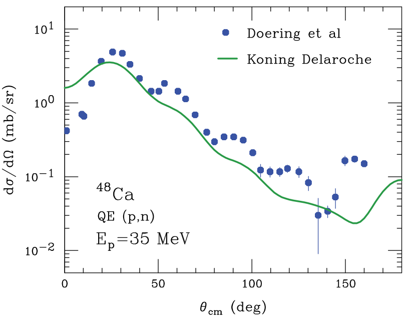
Potentials Fit to Elastic in Quasielastic

E.g. Koning-Delaroche NPA713(03)231 same radii for neutrons/protons, isoscalar/isovector, focus on p elastic



p Elastic Scattering

$$U_0 + \frac{N-Z}{A} U_1$$



QuasiElastic (p,n)

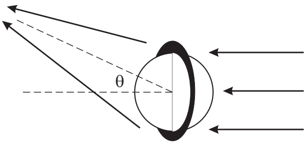
U_1 only?

Effect of Changing Isovector Radius

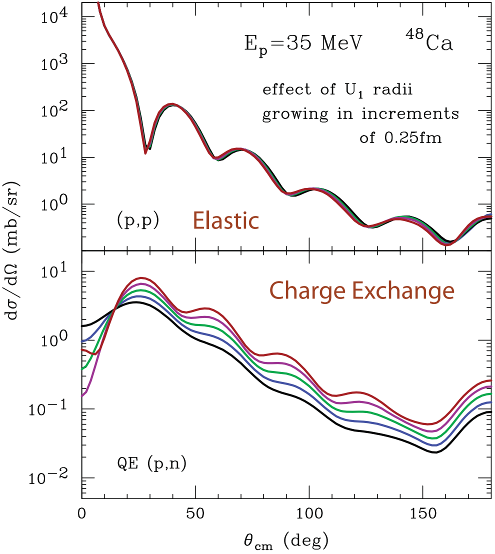
Koning-Delaroche
NPA713(03)231
same radii R for U_0 & U_1!

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

$R \rightarrow R + \Delta R_1$



charge-exchange cs
oscillations grow

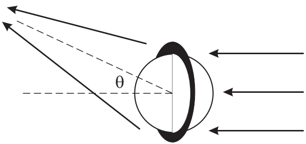


Effect of Changing Isoscalar Radius

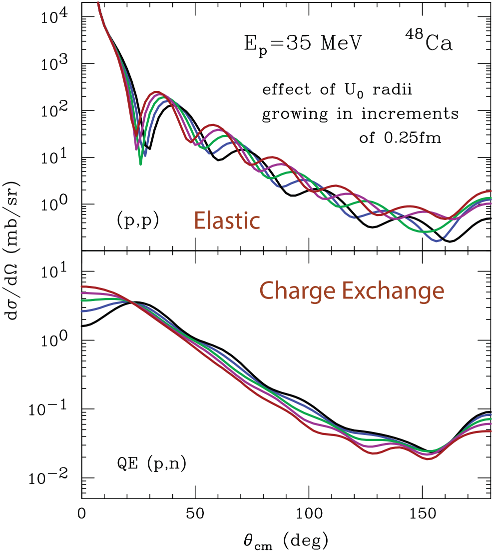
Koning-Delaroche
NPA713(03)231
same radii R for U_0 & U_1!

$$U_0(r) \propto \frac{U_{00}}{1 + \exp\frac{r-R}{a}}$$

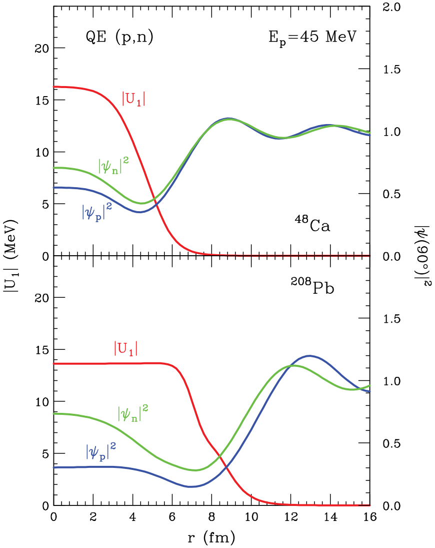
$R \to R + \Delta R_0$



charge-exchange cs
oscillations shrink



Impact of *U*-Radii on (p,n) Cross Section



DWBA

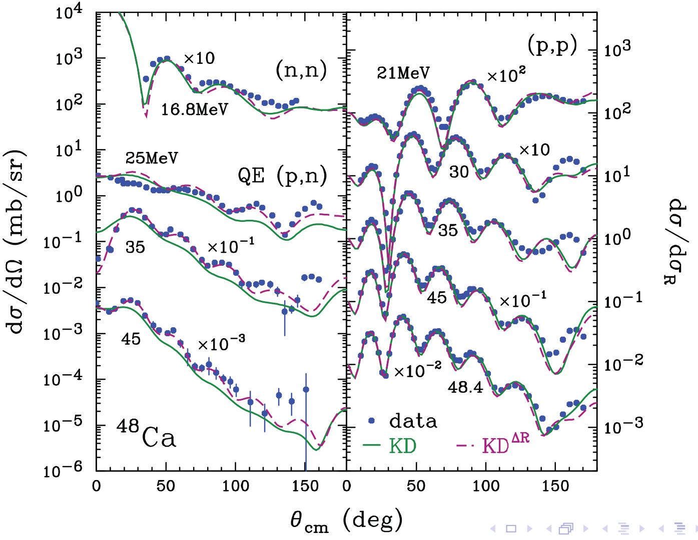
$$\frac{d\sigma}{d\Omega} \propto \left| \int dr\, \Psi_p^*(r)\, U_1(r)\, \Psi_n(i) \right|^2$$

Isoscalar radius responsible for holes in wavefunctions Ψ

Isovector radius responsible for region where (p,n) conversion can occur

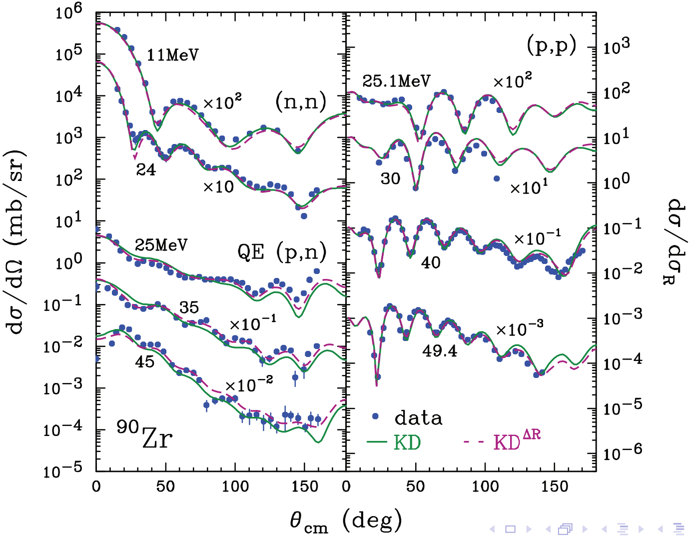
Modified Koning-Delaroche Fits: ^{48}Ca

In Koning-Delaroche: $R_{0,1} = R + \Delta R_{0,1}$ $\quad a_{0,1} = a + \Delta a_{0,1}$



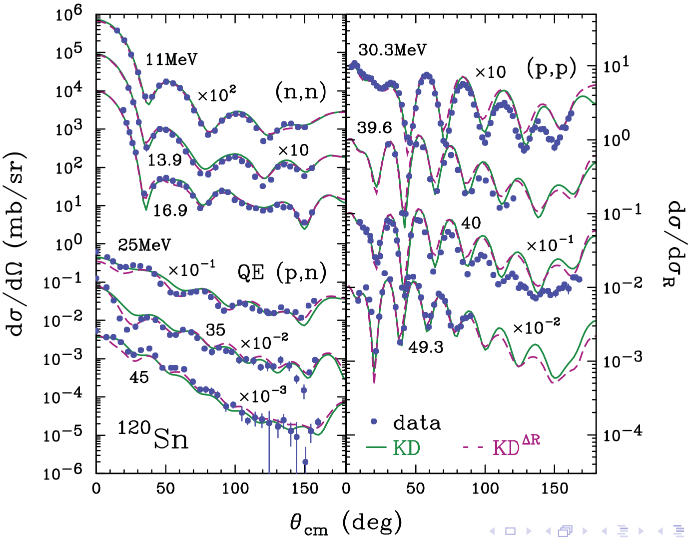
Modified Koning-Delaroche Fits: ^{90}Zr

In Koning-Delaroche: $R_{0,1} = R + \Delta R_{0,1}$ $\quad a_{0,1} = a + \Delta a_{0,1}$



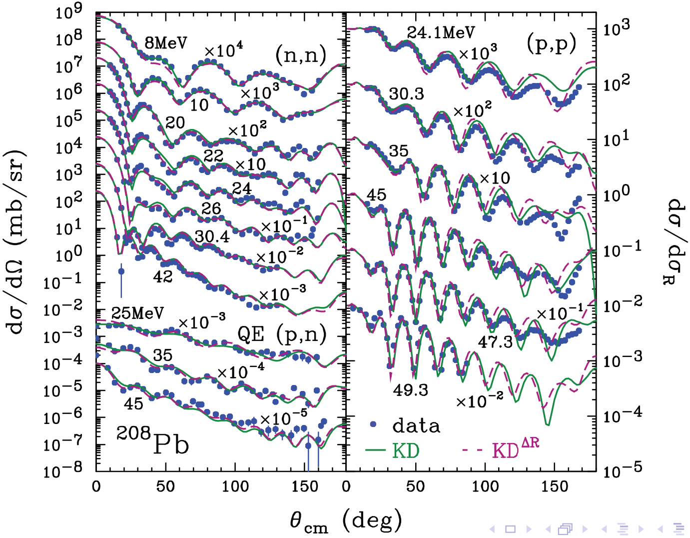
Modified Koning-Delaroche Fits: ^{120}Sn

In Koning-Delaroche: $R_{0,1} = R + \Delta R_{0,1}$ $a_{0,1} = a + \Delta a_{0,1}$

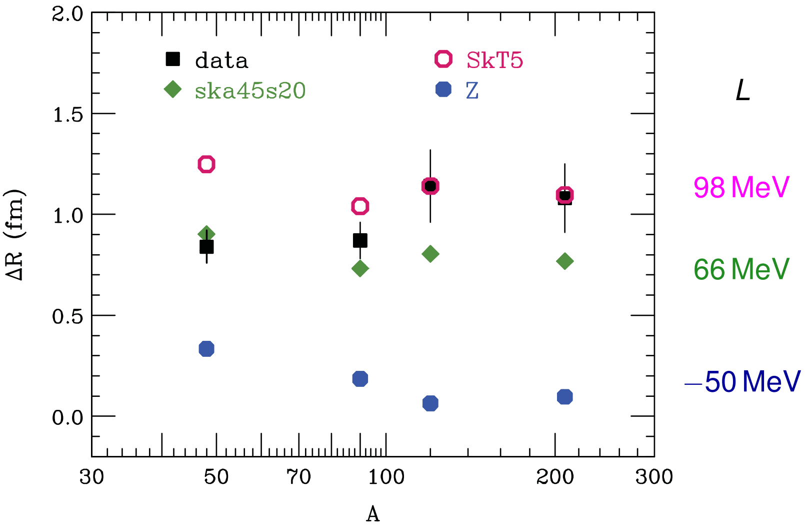


Modified Koning-Delaroche Fits: ^{208}Pb

In Koning-Delaroche: $R_{0,1} = R + \Delta R_{0,1}$ $a_{0,1} = a + \Delta a_{0,1}$

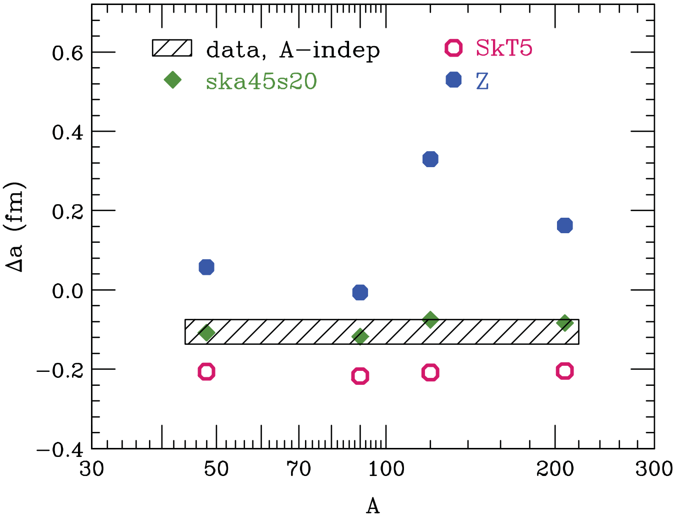


Size of Isovector Skin



Large ∼ 0.9 fm skins! ∼Independent of *A*. . .

Difference in Surface Diffuseness



L

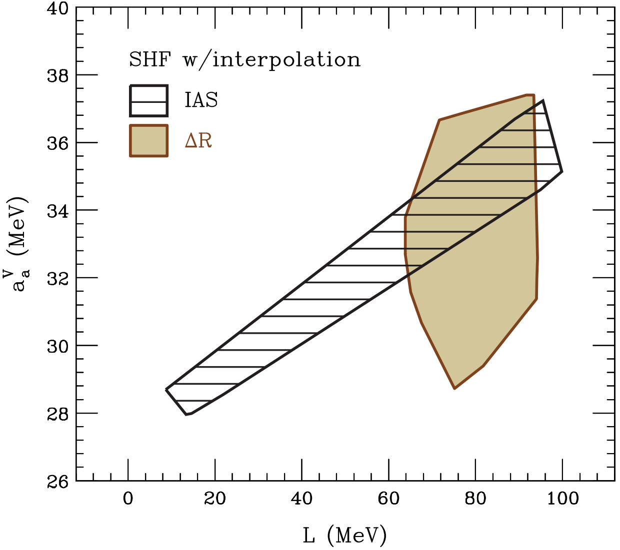
–50 MeV

66 MeV

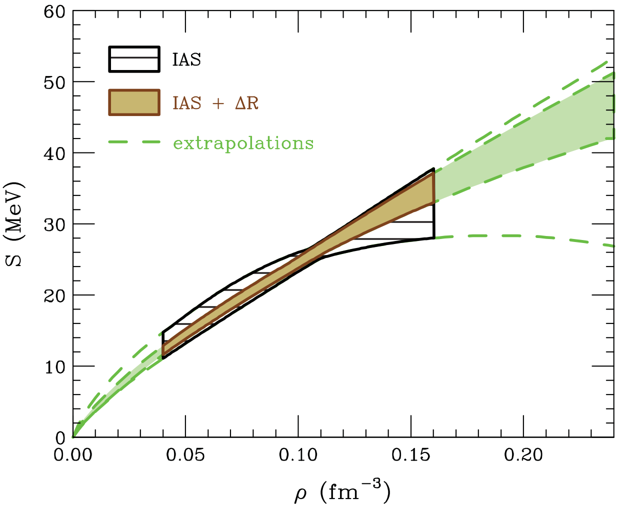
98 MeV

Sharper isovector surface!

Constraints on Symmetry-Energy Parameters



Constraints on $S(\rho)$



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 large isovector skins
  $\Delta R \sim 0.9\,\text{fm}!$
- Symmetry energy is stiff! $L = (65-90)\,\text{MeV}$, $a_a^V = (33-36)\,\text{MeV}$

PD&Lee NPA818(09)36 NPA922(14)1; PD, Singh *et al*

US PHY-1403906 + Indo-US Grant

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