Symmetry Energy: in Structure and in Central and Direct Reactions

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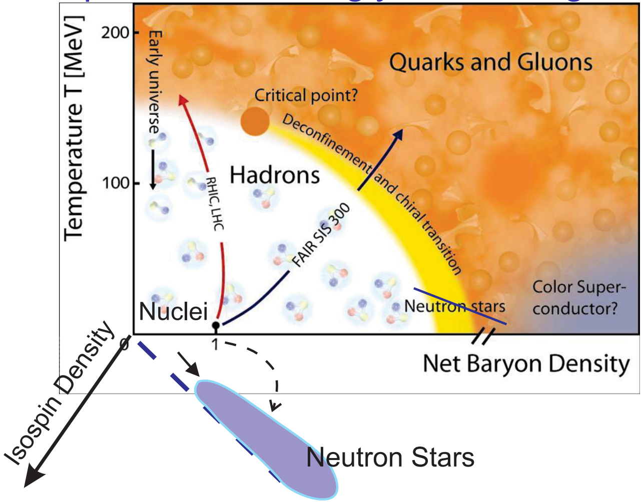
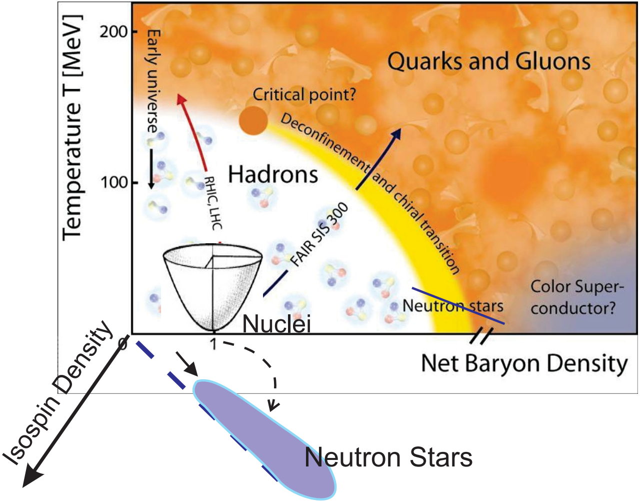
Bulk Properties of Strongly-Interacting Matter



Equation of State

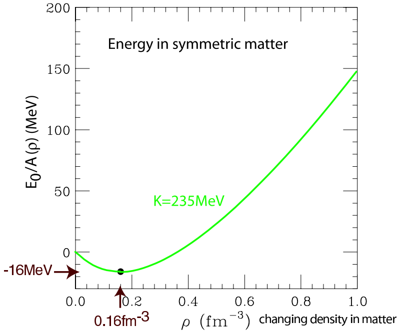


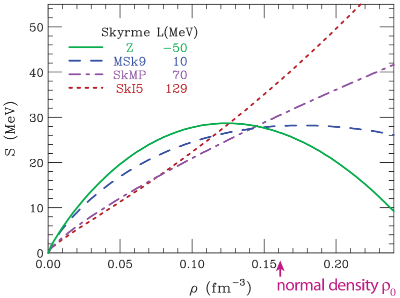
Reactions - coarse. Structure - detailed, but competition of macroscopic & microscopic effects

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 ?

Symmetry Energy in Nuclear Mass Formula

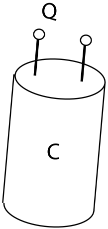
Textbook Bethe-Weizsäcker formula:

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

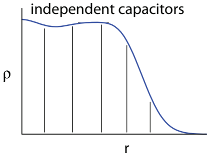
Symmetry energy: charge $n \leftrightarrow p$ symmetry of interactions

Analogy with capacitor:

$$E_a = a_a\, \frac{(N-Z)^2}{A} \equiv \frac{(N-Z)^2}{\frac{A}{a_a}} \Leftrightarrow E = \frac{Q^2}{2C}$$



?Volume Capacitance? $E_a = \frac{(N-Z)^2}{\frac{A}{a_a}} \rightarrow \frac{(N-Z)^2}{\frac{A}{a_a^V} + \frac{A^{2/3}}{a_a^S}}$



Thomas-Fermi (local density) approximation:

$$'C' = \frac{A}{a_a(A)} = \int \frac{\rho\, d\mathbf{r}}{S(\rho)} = \frac{A}{a_a^V}, \quad \text{for } S(\rho) = a_a^V$$

TF breaks in nuclear surface at $\rho < \rho_0/4$ PD&Lee NPA818(2009)36

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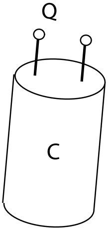

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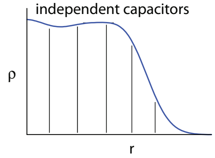

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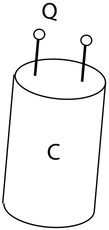

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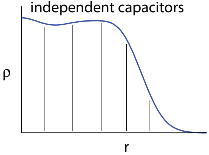

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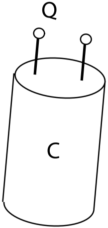

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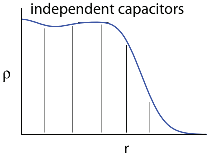

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PD&Lee NPA818(2009)36

Mass Formula & Isospin Symmetry

Symmetry-energy details in a mass-formula are intertwined with details of other terms: Coulomb, Wigner & pairing + even those asymmetry-independent, due to $(N-Z)/A$ - A correlations along stability line (PD)!

Best would be to study the symmetry energy in isolation from the rest of mass-formula! Absurd?!

Charge invariance to rescue: lowest nuclear states characterized by different isospin values (T, T_z), $T_z = (Z-N)/2$. Nuclear energy scalar in isospin space:

sym energy $$E_a = a_a(A)\,\frac{(N-Z)^2}{A} = 4\,a_a(A)\,\frac{T_z^2}{A}$$

$$\rightarrow E_a = 4\,a_a(A)\,\frac{T^2}{A} = 4\,a_a(A)\,\frac{T(T+1)}{A}$$

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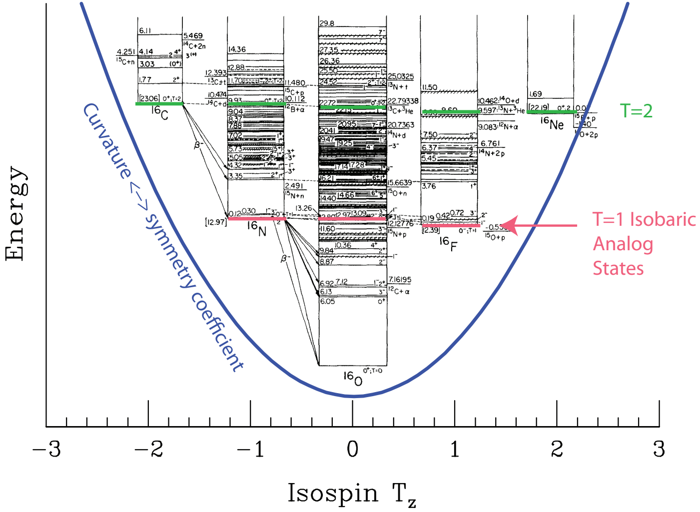
Isobaric Chains and Symmetry Coefficients

Energy Levels of A=16 Isobaric Chain



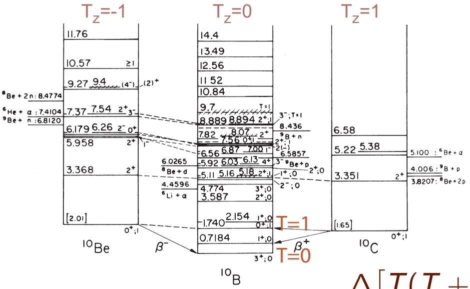
Symmetry Coefficient Nucleus-by-Nucleus

Mass formula generalized to the lowest state of a given T:

$$E(A, T, T_z) = E_0(A) + 4a_a(A)\,\frac{T(T+1)}{A} + E_{\rm mic} + E_{\rm Coul}$$

In the ground state T takes on the lowest possible value $T = |T_z| = |N - Z|/2$. Through '+1' most of the Wigner term absorbed.

?Lowest state of a given T: isobaric analogue state (IAS) of some neighboring nucleus ground-state.

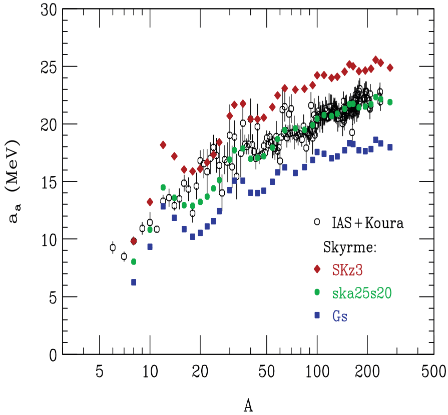


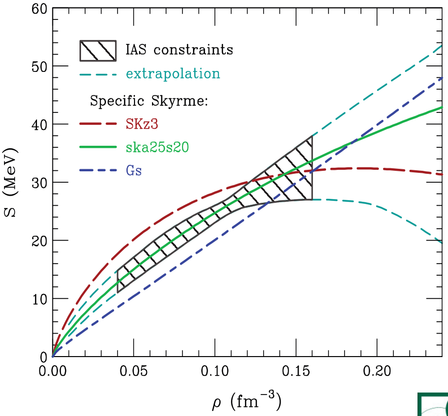
Study of changes in the symmetry term possible nucleus by nucleus

$$E^*_{\rm IAS} = \Delta E = a_a\,\frac{\Delta\left[T(T+1)\right]}{A} + \Delta E_{\rm mic}$$

From $a_a(A)$ to $S(\rho)$

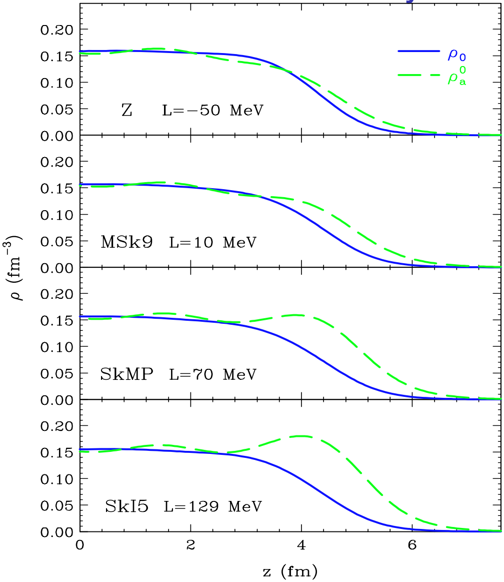
Strong $a_a(A)$ dependence [PD & Lee NPA922(14)1]:
lower $A \Rightarrow$ more surface $\Rightarrow$ lower $\rho \Rightarrow$ lower S





$a_a(A)$ from IAS give rise to constraints on $S(\rho)$ in Skyrme-Hartree-Fock calculations

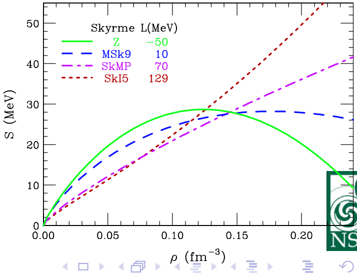
Auxiliary Info: Skins



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.

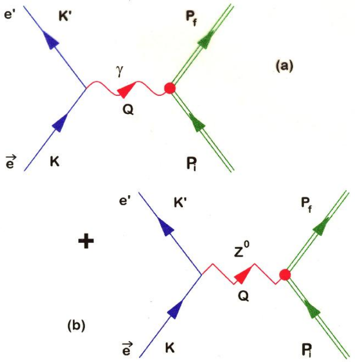


Strategies for n and p Densities

Jefferson Lab

Direct: $\sim p$

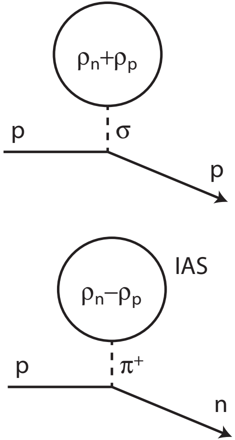
Interference: $\sim n$



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 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

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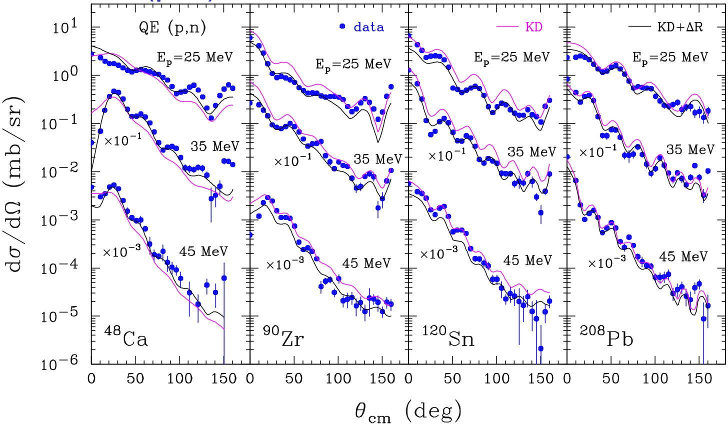
Quasielastic (p,n) Reaction to IAS: Skin or No-Skin?

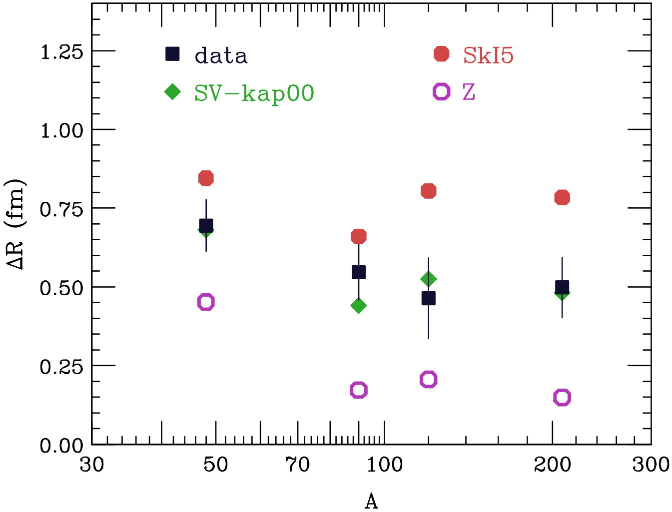


Data: Patterson *et al.* NPA263(76)261

Calculations: PD & Singh (preliminary) with and without change ΔR in radius of U_1 compared to elastic

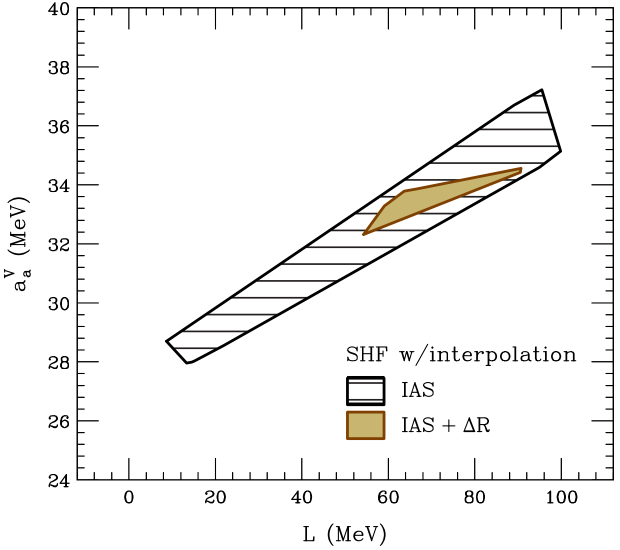
Before *n*-skin: Stephen Schery

Size of Isovector Skin

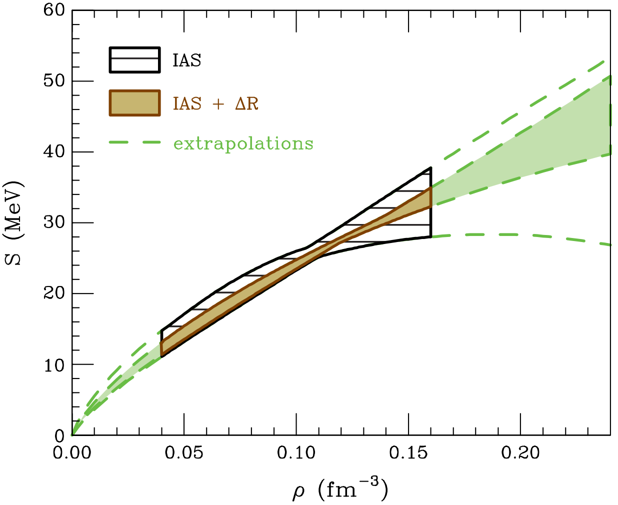


Large ~ 0.5 fm skins!

Constraints on Symmetry-Energy Parameters

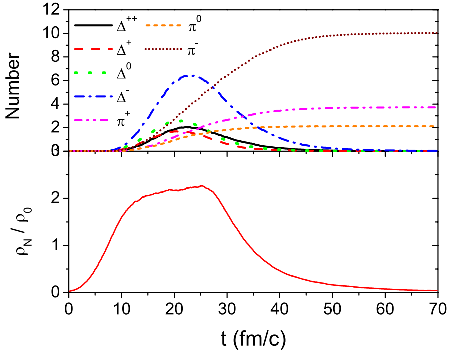


Constraints on $S(\rho)$

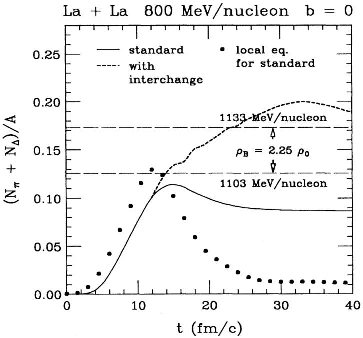


Pions Probe System at High-ρ!

Elementary processes: $N + N \leftrightarrow N + \Delta, \quad \Delta \longleftrightarrow N + \pi$



Song&Ko PRC91(15)014901

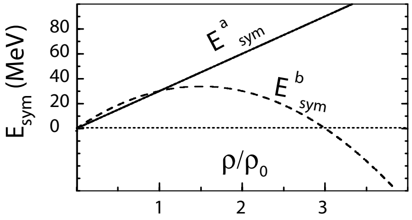


PD PRC51(95)716

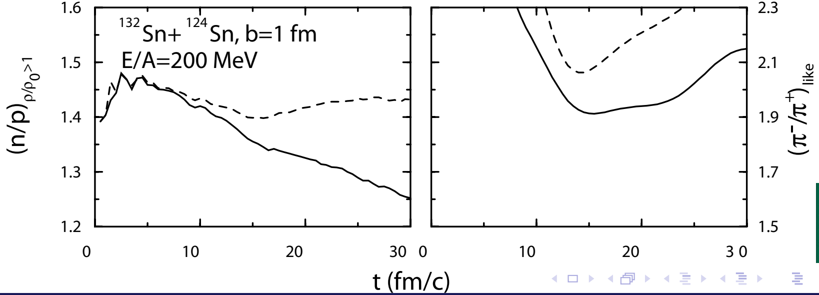
π test the maximal densities reached and collective motion then

Pions as Probe of High-ρ Symmetry Energy

B-A Li: $S(\rho > \rho_0) \Rightarrow n/p_{\rho>\rho_0} \Rightarrow \pi^-/\pi^+$



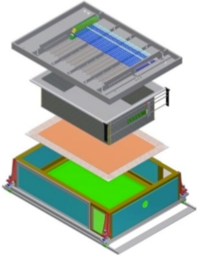
Pions originate from high ρ



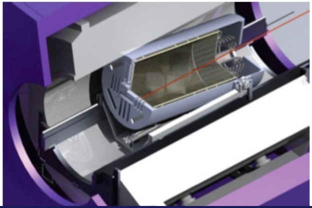
Dedicated Experimental Efforts

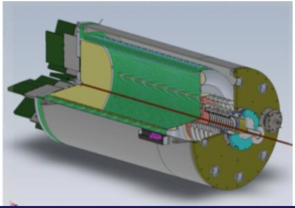
SAMURAI-TPC Collaboration (8 countries and 43 researchers): comparisons of near-threshold π^- and π^+ and also *n*-*p* spectra and flows at RIKEN, Japan.

NSCL/MSU, Texas A&M U
Western Michigan U, U of Notre Dame
GSI, Daresbury Lab, INFN/LNS
U of Budapest, SUBATECH, GANIL
China IAE, Brazil, RIKEN, Rikkyo U
Tohoku U, Kyoto U



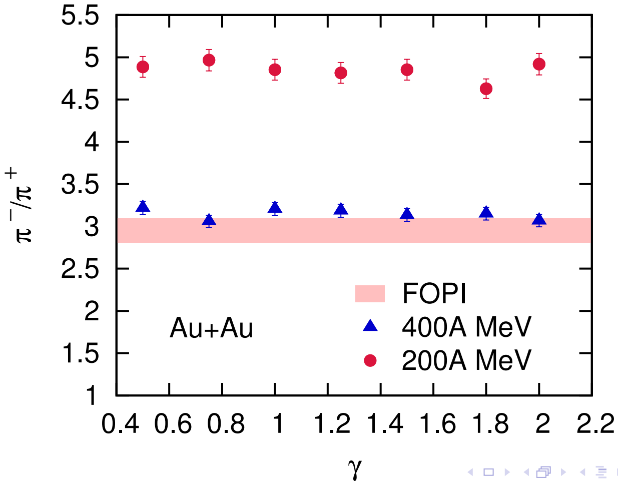
AT-TPC Collaboration (US & France)



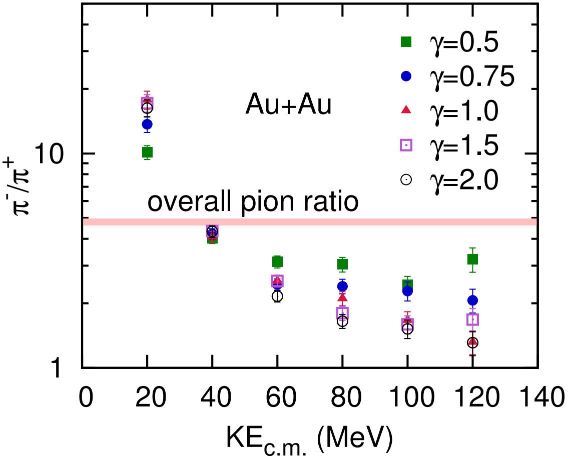


FOPI: π^-/π^+ at 400 MeV/nucl and above

Hong & PD, PRC90(14)024605: measured ratios reproduced in transport irrespectively of $S_{\text{int}}(\rho) = S_0\,(\rho/\rho_0)^\gamma$:



Original Idea Still Correct for High-E π's



$S_{int}(\rho) = S_0\,(\rho/\rho_0)^\gamma$ $\rightarrow$ charge-exchange reactions blur signal

Conclusions

- Symmetry-energy term weakens as nuclear mass number decreases: from $a_a \sim 23$ Mev to $a_a \sim 9$ MeV for $A \lesssim 8$.
- Weakening of the symmetry term can be tied to the weakening of $S(\rho)$ in uniform matter, with the fall of ρ.
- IAS energies insufficiently constrain $L \rightarrow$ skin info needed!
- Isovector skins - large and relatively weakly dependent on nucleus! Large $\Delta R \sim 0.5$ fm $\Rightarrow L \sim 70$ fm
- Comprehensive analysis of elastic/quasielastic scattering data needed!
- In the region of $\rho \gtrsim \rho_0$, $S(\rho)$ is quite uncertain. One promising observable is high-en charged-pion yield-ratio around NN threshold.

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