Neutron Skins and Charge Radii:Relevance of Short-Ranged Correlations

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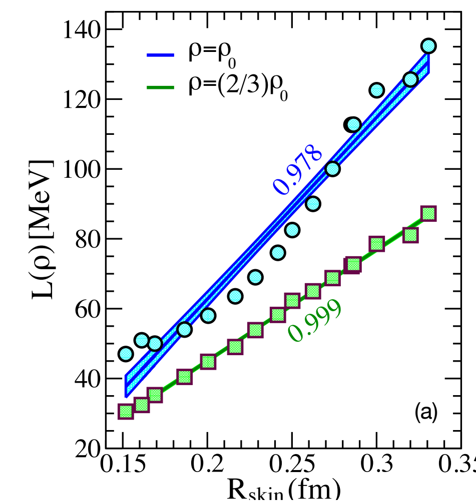
- PREX arXiv:2102.10767. parity violating electron scattering ^{208}Pb- $R_n - R_p = 0.283 \pm 0.071$ fm



$$\frac{E}{A} = \mathscr{E}_{\rm SNM}(\rho) + \left(\frac{\rho_n - \rho_p}{\rho}\right)^2 S(\rho) + \cdots$$

$$S(\rho) = J + L\frac{\rho - \rho_0}{3\rho_0}$$ L is important in neutron star physics and related to neutron skin

Sanjay will give us a brown bag talk on **Wednesday, March 24th at 12:30**, titled: "Resuscitating pion condensation to alleviate the tension between large neutron skins and small neutron stars."

References:

https://arxiv.org/pdf/2101.03193.pdf. PREX-> $L = 106 \pm 37$ MeV Large compared to expts& astrophysical measurements

https://arxiv.org/pdf/2102.10074.pdf

astorphysical data + PREXII : $L = 58 \pm 19$ MeV, $R_{\rm skin}(^{208}{\rm Pb}) = 0.19^{+0.03}_{-0.04}$ fm

Why PV electron scattering?
It's the best way

- Neutral weak interaction mainly with neutrons: protons $\propto (1/4 - \sin^2\theta_W)$
- Strongly interacting probes very model dependent
- Example $\gamma +^{208}\mathrm{Pb} \rightarrow \pi^0 +^{208}\mathrm{Pb}$ gives $R_n - R_p = 0.15 \pm 0.03\,(\mathrm{stat}) \pm 0.025(\mathrm{sys})$
- But omitted charge exchange fsi changes skin by about 50 %, and there are many other effects G A Miller PRC100,044608
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Why study SRC effect on neutron density?

- Extraction of $R_n - R_p$ depends on models
- Density functional theory is used -not sure if all effects of tensor-force driven SRC included for Pb
- SRC strong in np interaction

Can Long-Range Nuclear Properties Be Influenced by Short Range Interactions? A chiral dynamics estimate

Miller, G. A., Beck, S. M-T Beck, L.B. Weinstein, E.Piasetzky and O. Hen
PLB793 (2019) 30

- Short range correlations (SRC) are important -this meeting
- protons get more momentum as neutrons added
- protons get larger extent in space- because of np attraction
- Higher momentum usually means smaller extent in space- so which wins?
- Can have higher momentum AND larger spatial extent? YES -Wigner Distribution for non-Gaussian wave functions
- ~20 % of nucleons in SRC primarily np
- Protons more influenced by correlations
- Do SRC influence computations of nuclear charge radius ?- YES

Aims of calculation

- Estimate influence of SRC on computed charge radii- motivated by Garcia-Ruiz Nat.Phys. 12, 294('16) Ca isotopes, measured radii larger than theory -adding neutrons changes charge radius

- Study relevance of SRC: Need simple model that accounts for np src

- np dominance comes from iterated one pion exchange Hen et al RMP 1611.09748,*Phys.Rev.C* 92 (2015) 4, 045205

- Chiral dynamics of Kaiser Fritsch Weise nucl-th/0105057, Kaiser, Blockmann, Weise nucl-th/9706045 uses same mechanism

Chiral dynamics Kaiser et al

Chiral expansion in powers of Fermi momentum:

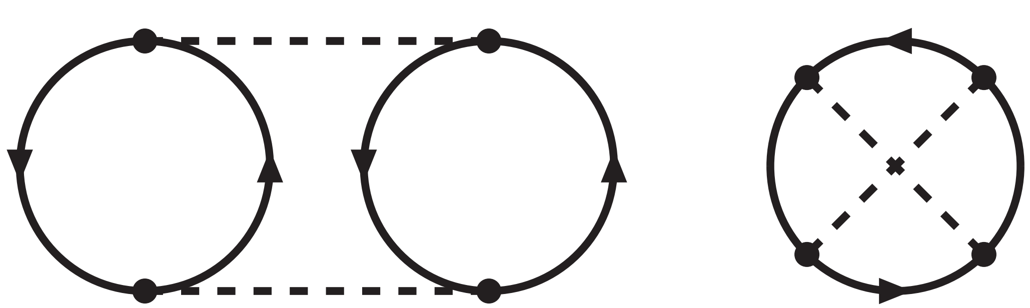
$$E/A = \frac{3}{10}\frac{k_F^2}{M} - \alpha\frac{k_F^3}{M^2} + \beta\frac{k_F^4}{M^3}$$

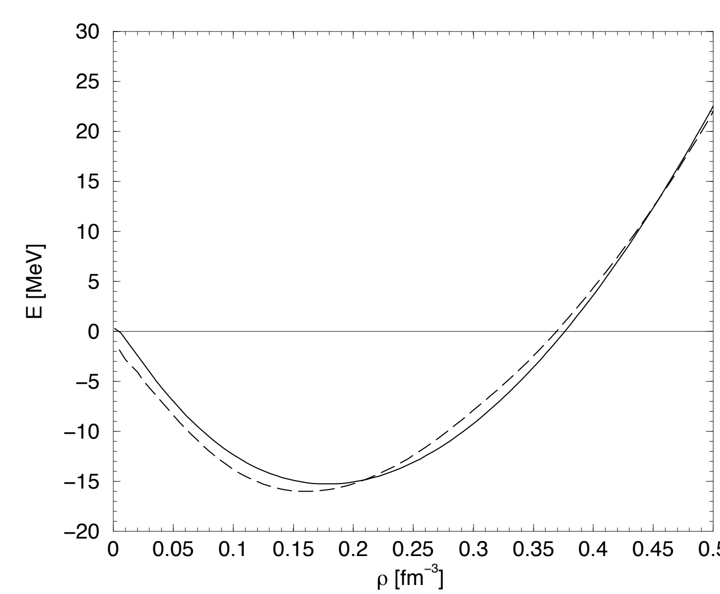
Effects: kinetic energy, Iterated One Pion Exchange,
Irreducible two pion exchange, uses cutoff regularization $\Lambda = 650$ MeV

Chiral limit used to analytically demonstrate feasibility

N=Z infinite nuclear matter:
binding energy, density, compressibility ≈ agrees with measurements

Also get symmetry energy





Our calculation I- SRC Probability

Effect of correlations on neutron (orbital n), proton (orbital α)

$$|n,\alpha\rangle = C_{n,\alpha}^{-1/2}\left[|n,\alpha) + \frac{1}{\Delta E} QG|n,\alpha)\right],$$

G is Bruckner G-matrix, here well-approximated by iterated OPEP

G is a short-ranged, attractive operator

$S=1, T=0$ operator 9 times $S=0, T=1$ operator

Calculation for Ca isotopes, $\alpha = 0s, 0p, 1s, 0d \;\; n = 0f_{5/2}, 1p_{3/2}$

Starts with 40Ca add neutrons

SRC Probability $\mathcal{P}_{n\alpha}^{SRC} \approx 0.2 \pm 0.02$

Our Calculation II- Change in charge radius

- add neutron to the $1f_{5/2} - 2p_{3/2}$ shell around a ^{48}Ca core.
- consider effect of short-ranged potential V np product wave function $|n,\alpha)$, $n =$ neutron α =proton
- The effect of V: $|n,\alpha\rangle = C_{n\alpha}^{-1/2}\left[|n,\alpha) + \frac{1}{\Delta E} QG|n,\alpha)\right]$, $G =$ Bruckner G-matrix, $C_{n\alpha}$ =normalization constant $C_{n\alpha} = 1 + \langle n,\alpha|G\frac{Q}{(\Delta E)^2}G|n,\alpha\rangle \equiv 1 + I_{n\alpha}$, $P_{n\alpha}^{\rm SRC} = \frac{I_{n\alpha}}{1+I_{n\alpha}} \approx 0.2$
- $\langle n,\alpha|R_p^2|n,\alpha\rangle = C_{n\alpha}^{-1}[(n,\alpha|R_p^2|n,\alpha) + (n,\alpha|GQ\frac{1}{\Delta E}R_p^2\frac{1}{\Delta E}QG|n,\alpha)]$

$$\langle n,\alpha|R_p^2|n,\alpha\rangle = (\alpha|R_p^2|\alpha) + \mathcal{P}_{n\alpha}^{SRC}[(n,\alpha|GQ\frac{1}{\Delta E}R_p^2\frac{1}{\Delta E}QG|n,\alpha) - (\alpha|R_p^2\alpha)]$$

SRC causes changed charge radius of protons with excess neutron in orbital n:

$$\Delta R^2(n) = \sum_{\alpha=\rm occ}\mathcal{P}_{n\alpha}^{SRC}[(n,\alpha|GQ\frac{1}{\Delta E}R_p^2\frac{1}{\Delta E}QG|n,\alpha) - (\alpha|R_p^2\alpha)]$$

$$\Delta R^2(0f_{5/2}) = 0.17 \pm 0.12\,{\rm fm}^2,\ \Delta {\rm R}^2(1{\rm p}_{3/2}) = -0.8\,{\rm fm}^2$$

SRC is important for precision calculations

Crude calculation

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Application to neutron radius in Pb

- neutron skin important for neutron star physics & cooling
- difficulties in determining neutron skin from coherent photo production of pions discussed in Miller arXiv:1907.11764, PRC 100,044608
- Apply previous formalism to the neutron excess
- Preliminary Estimate SRC produces about 1/2 % decrease in neutron radius approx. 30 % effect on skin!

SRC is important for precision calculations