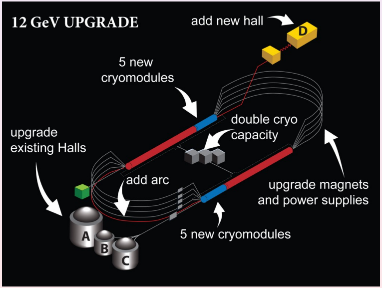
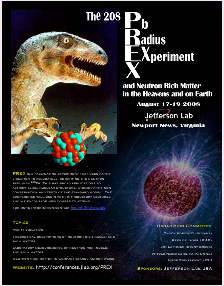
Symmetry Energy and Neutron Skins: Where do the extra neutrons go? $R_{\text{skin}} \equiv R_n - R_p$

International Workshop on
Nuclear Dynamics and Thermodynamics
in Honor of Professor Joe Natowitz




The 208 Pb Radius EXperiment

and Neutron Rich Matter in the Heavens and on Earth

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For more information contact horowit@indiana.edu

Topics

Parity Violation

Theoretical descriptions of neutron-rich nuclei and bulk matter

Laboratory measurements of neutron-rich nuclei and bulk matter

Neutron-rich matter in Compact Stars / Astrophysics

Website: http://conferences.jlab.org/PREX

Organizing Committee

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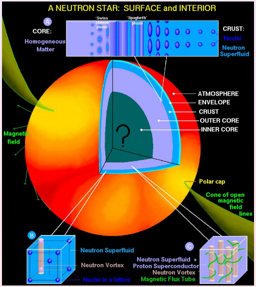


Texas A&M – August 19-21, 2013

My FSU Collaborators

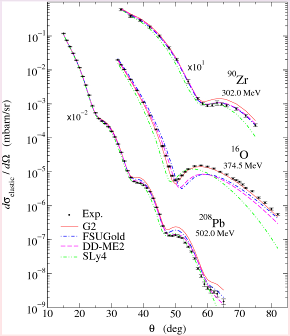
- Genaro Toledo-Sanchez
- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- Farrukh Fattoyev
- Wei-Chia Chen

My Outside Collaborators

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (U. Tennessee)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)

Neutron Skins and Density Dependence of the Symmetry Energy

- Proton (charge) densities known with enormous precision
  Started with Hofstadter in the late 1950's and continues to this day
- Neutron densities are as fundamental as proton densities
  Yet still elusive after more than 80 years of nuclear physics
- Hinders our understanding of density dependence symmetry energy
  Penalty for breaking $N = Z$ symmetry $[B(Z,N) = -a_{\rm a}(N-Z)^2/A + \ldots]$
- Neutron skin strongly correlated to the symmetry pressure $L \propto P_{\rm PNM}$
  Slope (pressure) of pure neutron matter poorly constrained



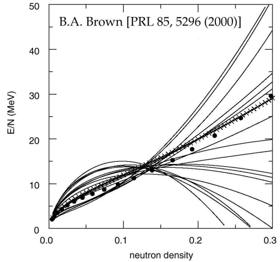


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

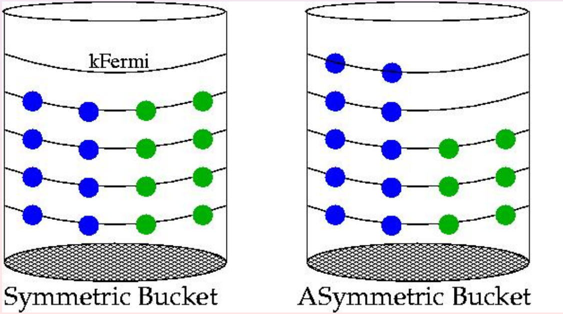
Density Dependence of the Symmetry Energy: Nuts and Bolts

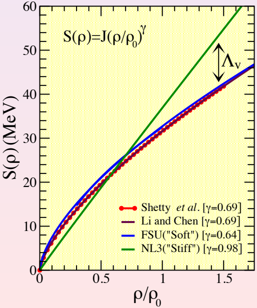
- The EOS of asymmetric matter $\left[\alpha \equiv (N-Z)/A\right]$

$$\mathcal{E}(\rho,\alpha) \approx \mathcal{E}_0(\rho)+\alpha^2\mathcal{S}(\rho)+\ldots = \mathcal{E}_0(\rho)+\alpha^2\left(\frac{k_F^2}{6E_F^*}+\frac{g_\rho^2}{12\pi^2}\frac{k_F^3}{m_\rho^{*2}}\right)$$

$$E_F^* = \sqrt{k_{\rm F}^2+M^{*2}} \quad \text{and} \quad m_\rho^{*2} = m_\rho^2 + 2\Lambda_{\rm v} g_\rho^2 W_0(\rho)^2$$

$$\mathcal{S}(\rho) \underset{k_F\to\infty}{\longrightarrow} \begin{cases} k_{\rm F}^3 \propto \rho, & \text{if } \Lambda_{\rm v} = 0; \\ k_{\rm F} \propto \rho^{1/3}, & \text{if } \Lambda_{\rm v} \neq 0. \end{cases}$$



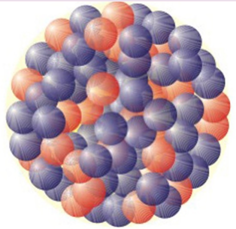


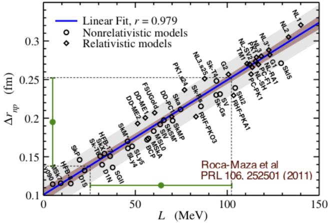
Where do the extra neutrons go?

- The EOS of asymmetric matter $\left[\alpha \equiv (N-Z)/A,\ x \equiv (\rho-\rho_0)/3\rho_0\right]$

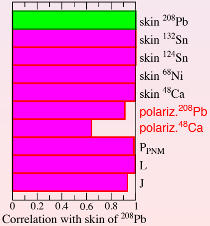
  $$\mathcal{E}(\rho,\alpha) \approx \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \approx \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + \boxed{L}\, x + \frac{1}{2}K_{\rm sym} x^2\right)\alpha^2$$

- Neutron-skin thickness of heavy nuclei sensitive to ***L* not *J***
- In ^{208}Pb, 82 protons/neutrons form an isospin symmetric spherical core
  Where do the extra 44 neutrons go?
- Competition between surface tension and **density dependence** of $\mathcal{S}(\rho)$
  Surface tension favors placing them in the core where $\mathcal{S}(\rho_0)$ is large
  Symm. energy favors pushing them to the surface where $\mathcal{S}(\rho_{\rm surf})$ is small
- If difference $\mathcal{S}(\rho_0)-\mathcal{S}(\rho_{\rm surf}) \propto L$ is large, then neutrons move to the surface
  The larger the value of *L* the thicker the neutron skin of ^{208}Pb





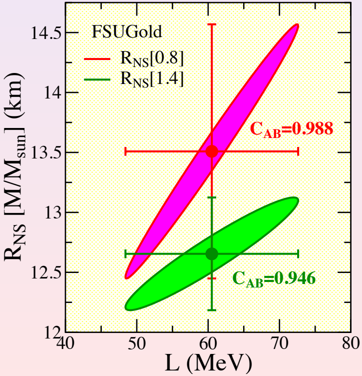
Roca-Maza et al
PRL 106, 252501 (2011)

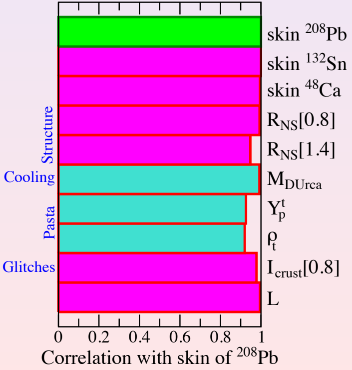


The Enormous Reach of the Neutron Skin

Reinhard-Nazarewicz, PRC 81 (2010) 051303; Fattoyev-Piekarewicz, PRC 86 (2012) 015802; PRC 84 (2011) 064302

- Neutron skin as proxy for neutron-star radii . . . and more!
- Calibration of nuclear functional from optimization of a quality measure
- Predictions accompanied by meaningful theoretical errors
- Covariance analysis least biased approach to uncover correlations
- Neutron skin strongly correlated to a myriad of neutron star properties:
  Radii, Enhanced Cooling, Moment of Inertia, . . .





The Traditional Approach: Elastic Proton-Nucleus Scattering

Piekarewicz-Weppner, NPA 778, (2006) 10

- Long tradition of pA experiments (IUCF, LAMPF, TRIUMF, RCNP, etc.)
- Unfortunately, they suffer from large and uncontrolled uncertainties
  reaction mechanism, in-medium NN interaction, optical potential, etc.
- Enormous ambiguities yield an **energy dependent** neutron skin
- Medium energy protons mostly sensitive to isoscalar density $\rho_p+\rho_n$
  … insensitive to isovector density $\rho_p-\rho_n$ and thus to the neutron skin

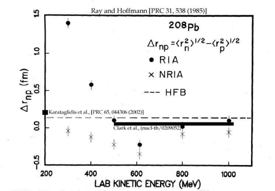
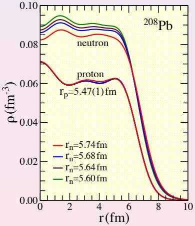
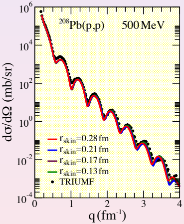
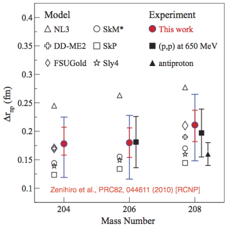


FIG. 10. Same as Fig. 8 except that the ^{208}Pb results are shown. The theoretical value of 0.13 fm (Ref. 39) is indicated by the dashed line.





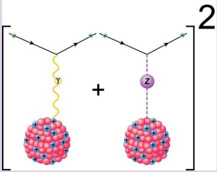


Must learn how to deal with the uncertainties; proton scattering in inverse kinematics will remain the only option for exotic nuclei

The Modern Approach: PV in Elastic Electron-Nucleus Scattering

Donnelly, Dubach, Sick, NPA 503, 589 (1989); Abrahamyan et al., PRL 108, (2012) 112502

- Charge (proton) densities known with enormous precision
  charge density probed via parity-conserving eA scattering
- Weak-charge (neutron) densities very poorly known
  weak-charge density probed via parity-violating eA scattering



$$A_{\rm PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

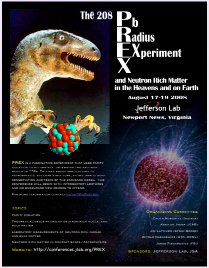
- Use parity violation as Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (and r_n)

	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

PREX: The Lead Radius EXperiment Abrahamyan et al., PRL 108, (2012) 112502

- **Ran for 2 months: April-June 2010**
- First electroweak observation of the neutron-rich skin in ^{208}Pb
- Promised a 0.06 fm measurement of r_n^{208}; error 3 times as large!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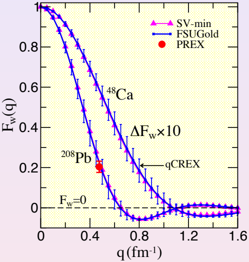

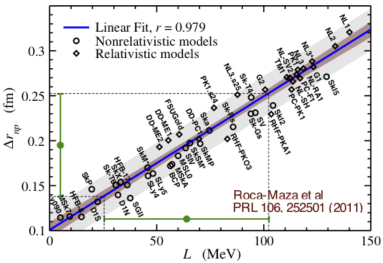

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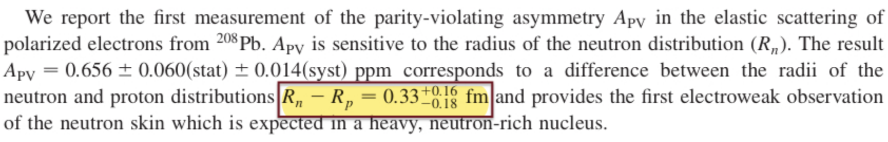
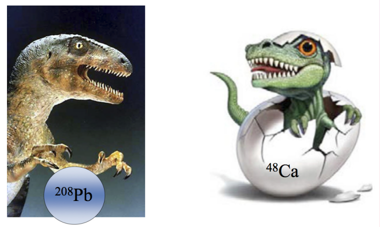

We report the first measurement of the parity-violating asymmetry A_{PV} in the elastic scattering of polarized electrons from ^{208}Pb. A_{PV} is sensitive to the radius of the neutron distribution (R_n). The result $A_{\mathrm{PV}} = 0.656 \pm 0.060(\mathrm{stat}) \pm 0.014(\mathrm{syst})$ ppm corresponds to a difference between the radii of the neutron and proton distributions $\boxed{R_n - R_p = 0.33^{+0.16}_{-0.18}\ \mathrm{fm}}$ and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

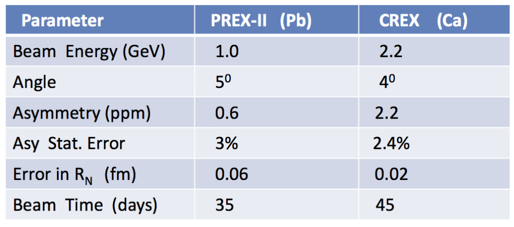
A Physics case for PREX-II and beyond!

The Case for PREX-II, CREX, TREX, and beyond

"One of the main science drivers of FRIB is the study of nuclei with neutron skins 3-4 times thicker than is currently possible. FRIB will provide rare isotopes to explore the properties of halos and skins. JLab uses parity violation to measure the neutron radius of stable lead and calcium nuclei. Studies of neutron skins at JLab and FRIB will help pin down the behavior of nuclear matter at densities below twice typical nuclear density" 2013 Subcommittee Report to NSAC

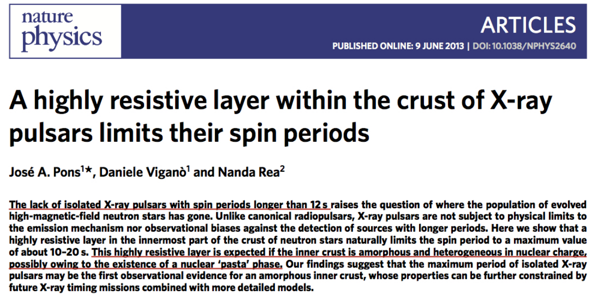
- PREX-II has been approved and will run in 2016
- CREX has been approved (unscheduled)
- ^{48}Ca a doubly magic, neutron-rich nucleus within ab-initio reach
  Critical insights for DFT, role of three-body force, . . .
- PREX-II and CREX as powerful calibrating anchors for skins at FRIB





Parameter	PREX-II (Pb)	CREX (Ca)
Beam Energy (GeV)	1.0	2.2
Angle	5^0	4^0
Asymmetry (ppm)	0.6	2.2
Asy Stat. Error	3%	2.4%
Error in R_N (fm)	0.06	0.02
Beam Time (days)	35	45

Evidence for Nuclear Pasta and Strange Quark Matter?



nature physics

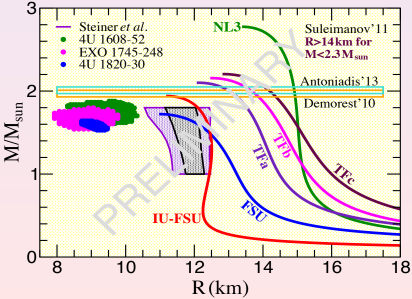
ARTICLES

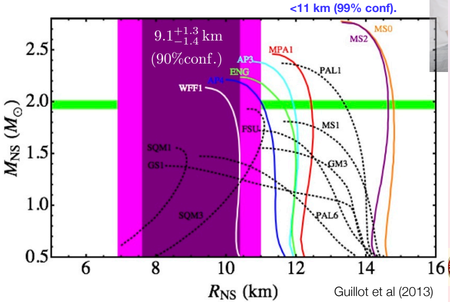
PUBLISHED ONLINE: 9 JUNE 2013 | DOI: 10.1038/NPHYS2640

A highly resistive layer within the crust of X-ray pulsars limits their spin periods

José A. Pons[1]*, Daniele Viganò[1] and Nanda Rea[2]

The lack of isolated X-ray pulsars with spin periods longer than 12 s raises the question of where the population of evolved high-magnetic-field neutron stars has gone. Unlike canonical radiopulsars, X-ray pulsars are not subject to physical limits to the emission mechanism nor observational biases against the detection of sources with longer periods. Here we show that a highly resistive layer in the innermost part of the crust of neutron stars naturally limits the spin period to a maximum value of about 10–20 s. This highly resistive layer is expected if the inner crust is amorphous and heterogeneous in nuclear charge, possibly owing to the existence of a nuclear 'pasta' phase. Our findings suggest that the maximum period of isolated X-ray pulsars may be the first observational evidence for an amorphous inner crust, whose properties can be further constrained by future X-ray timing missions combined with more detailed models.



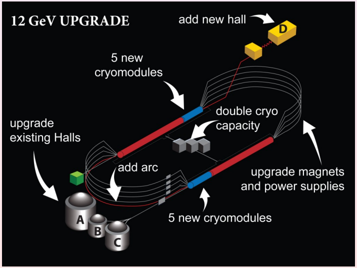


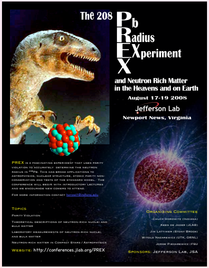
Guillot et al (2013)

Conclusions and Outlook

- Symmetry energy $\mathcal{S}(\rho)$ fundamental for our understanding of both heaven and earth
  From the limits of nuclear existence to the structure of neutron stars
- Neutron skins at low and stellar radii at intermediate densities critical inputs for $\mathcal{S}(\rho)$
  Same neutrons push against surface tension and gravity
- Large skins and small stellar radii best evidence in favor of a phase transition
- Electroweak measurements of neutron skins as calibrating anchors
  Science driver of FRIB are nuclei with skins 3-4 times thicker than is currently possible
- Theoretical Pillar: Search for an accurately-calibrated microscopic theory that both predicts and provides well-quantified theoretical uncertainties from finite nuclei to neutron stars
- **Accurate measurements of neutron rskins will continue to play a fundamental role in elucidating the physics of neutron-rich systems in both heaven and earth!**

All observables (and theories) are created equal but some are more equal than others!





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