Overview of Experimental Data on the Neutron-Matter Equation of State and the Neutron Skins of ^{48}Ca and ^{208}Pb

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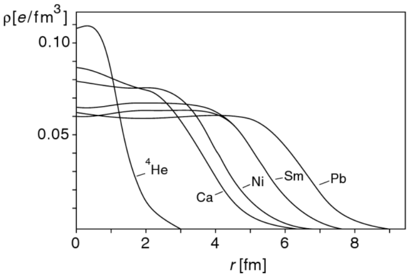
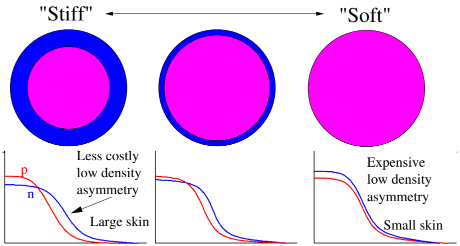
Neutron Skins and Density Dependence



- Symmetry energy 10% of E_b for heavy nuclei
- Nuclear surfaces aren't sharp - lower density at larger radii
- Size depends on competing terms: Surface energy, Coulomb repulsion, density dependence of symmetry energy



$$R_{\rm skin} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

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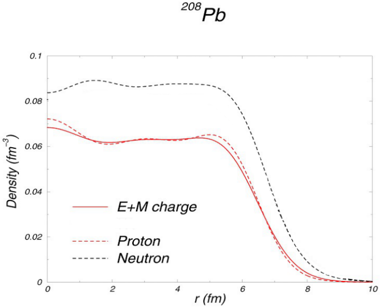
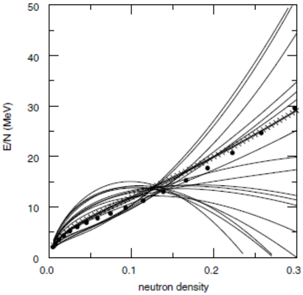
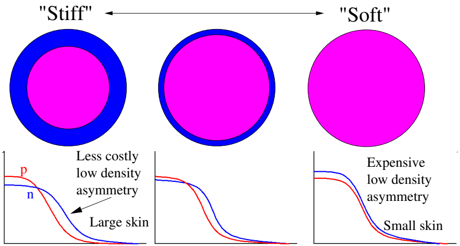




B. Alex Brown, PRL 85, 5296 (2000)



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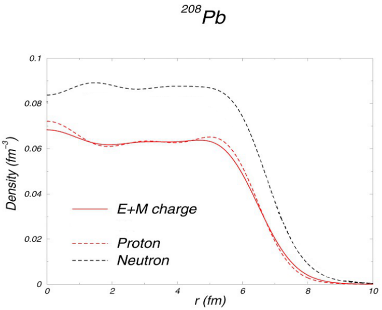
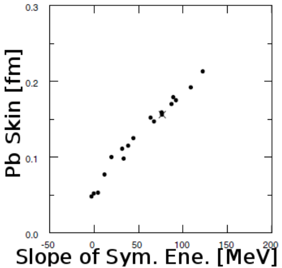
Neutron Skins and Density Dependence





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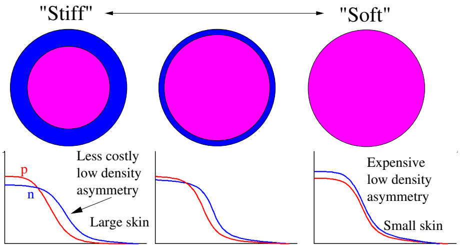
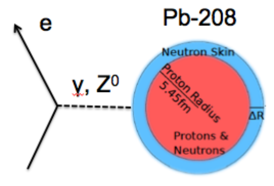


$$R_{\mathrm{skin}} \equiv \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$$

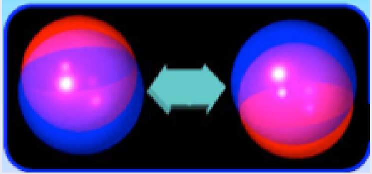
Where else does this come into play?

Lots of nuclear phenomena depend on this information!

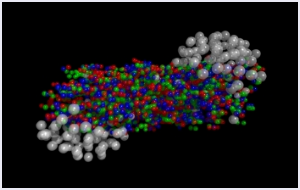
Neutron Skins



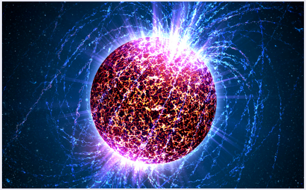
Dipole Polarizability



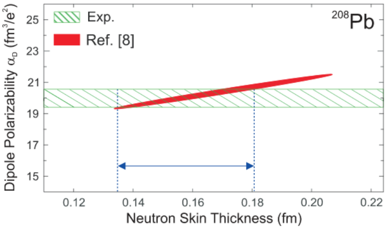
Heavy Ion Collisions

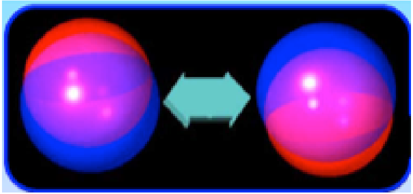


Neutron Stars



Isovector Dipole Polarizability

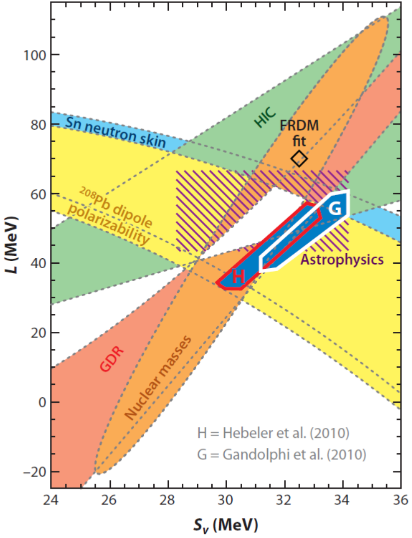




Tamii et al, PRL 107 062502 (2011)

- Isovector dipole polarizability contains similar information
- Density dependence of symmetry energy provides restoring force
- Highly correlated with neutron skin
  - Measurements together build coherent picture
- Precision measurements done on several nuclei including ^{48}Ca and ^{208}Pb

L vs. S_v

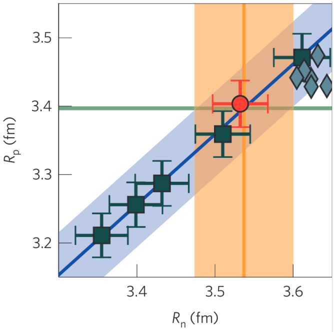


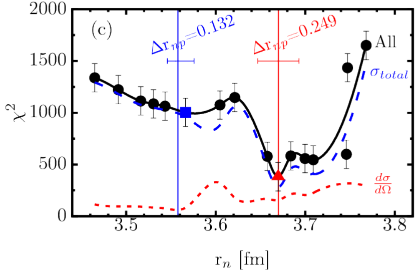
J.M. Lattimer

Annu. Rev. Nucl. Part. Sci. 2012. 62:485

- L parameter is slope for EOS density dependence
- Different measurement techniques should combine to coherent picture
- Model dependent uncertainties *very hard to constrain* - unknown model dependence problem
- Cleanly interpretable signals critical for any data set

Medium Nuclei Skins Advantage: ^{48}Ca



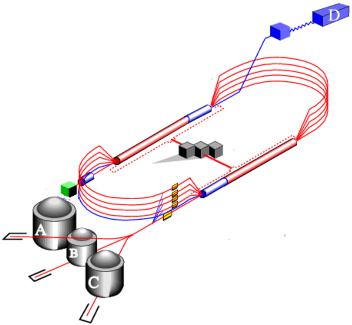


Mahzoon et al. PRL 119 (2017) 222503

Hagen et al. Nature 12 (2016) 186

- New state of the art predictions from microscopic models
- Significant disagreement between coupled cluster and optical model can be tested

Continuous **E**lectron **B**eam **A**ccelerator **F**acility
at Jefferson Lab, Newport News, VA
"World's most powerful microscope"



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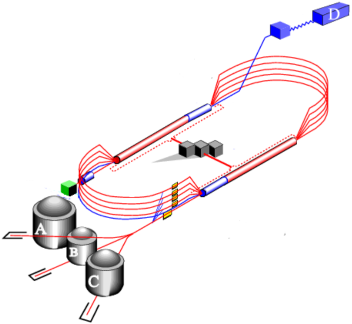
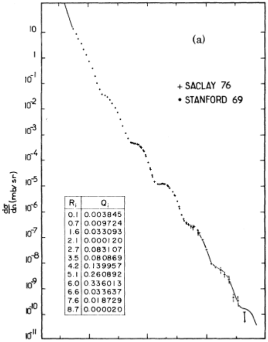


- Electron accelerator by superconducting RF cavities
- 4 experimental halls
- E up to 11 GeV ($\lambda \sim r_p/50$)
- $I_{\mathrm{max}} = 200\ \mu\mathrm{A}$
- $P_e =\sim 90\%$
- Ideal for studying insides of nucleons and nuclei!

What's new that we can do?
Look at weak-force interactions!
Primarily couples to neutron and (mostly) not proton!

$$Q_{\rm weak}^{\rm proton} \propto 1 - 4\sin^2\theta_{\rm W} \approx 0.076, \qquad Q_{\rm weak}^{\rm neutron} \propto -1$$



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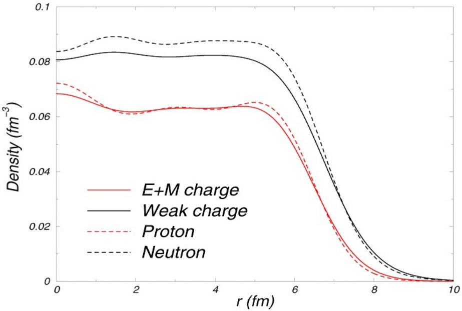
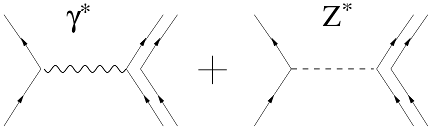
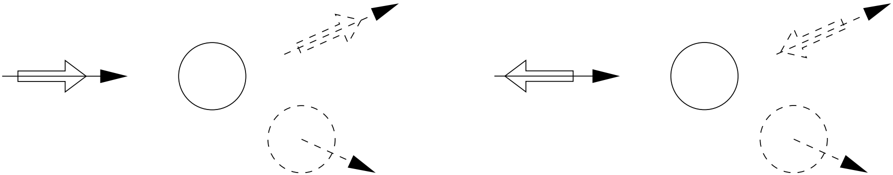


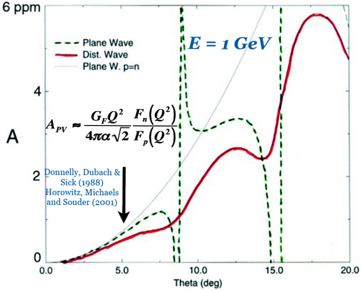
- We can use parity violation to pick out the weak interaction component over the electromagnetic

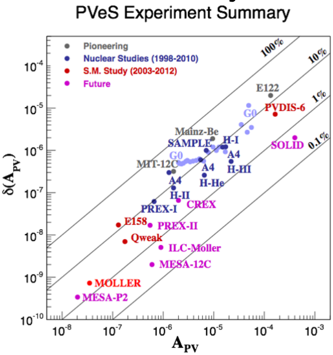
A ~ 



↑ Rates are different if parity is violated ↑

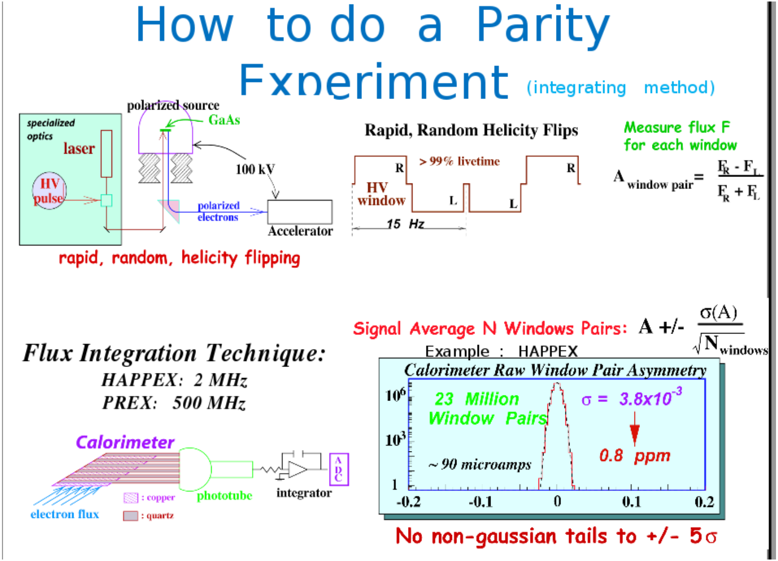
Measure *relative* rates in form of an asymmetry





$$A_{\mathrm{PV}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

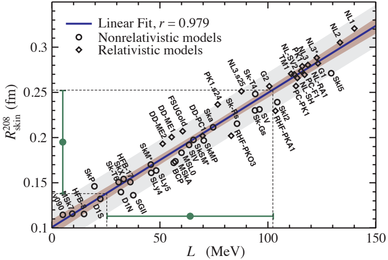
- Higher order effects (Coulomb distortions) wash things out
- Optimized for running with 1.1 GeV, 5° $A \sim 0.5\ \mathrm{ppm}$



Stolen from R. Michaels

PREX - Neutron Radius of ^{208}Pb

- Ultimate goal to measure R_n to 0.06 fm (1%), $R_n - R_p \sim 0.2$ fm
- Ran Spring 2010 in Hall A at JLab
- Approved for ~35 days
- ~ 50μA, 1.1 GeV at 5°
- ^{208}Pb because
  - Large neutron excess
  - Doubly-magic nucleus
  - Spin 0
  - First inelastic state 2.6 MeV



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

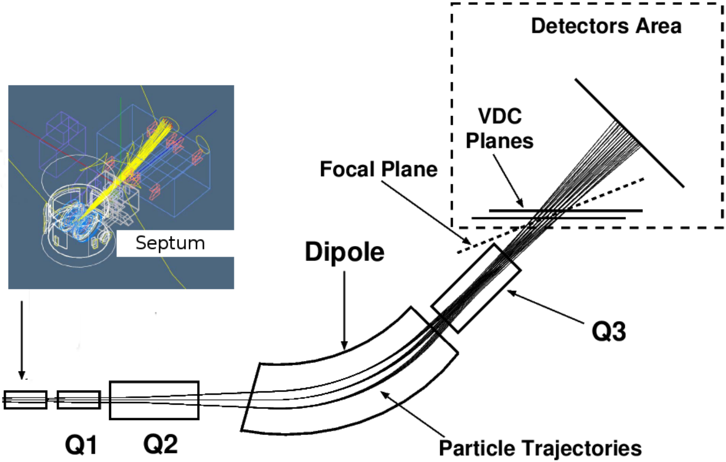
PREX Experimental Configuration - HRS

Pair of High Resolution Spectrometers (HRS) magnetically separate elastic scattering events

10^{-3} *hardware* momentum resolution, $\Omega \sim 5$ msr

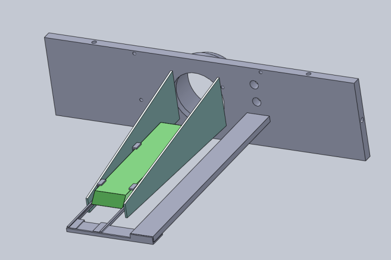
PREX Experimental Configuration - HRS

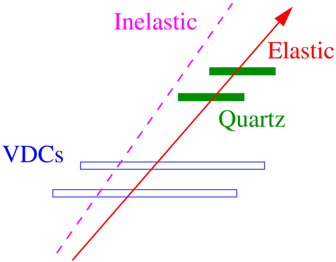
- HRS minimum 12.5°, for 5° insert $\sim$ 0.5 T·m dipole



HRS and Quartz Detectors

- Quartz detectors used as integrating detectors
- Electrons emit Cherenkov radiation - few hundred photons, $\sim$30 pe's/$e-$
- Integrate signal from PMT over helicity windows
- PMTs should be quiet (low gain) and linear (better than few %)





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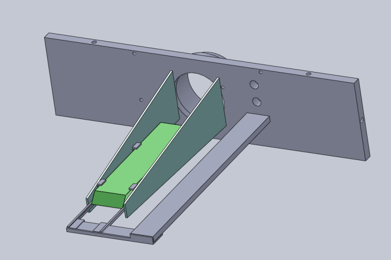
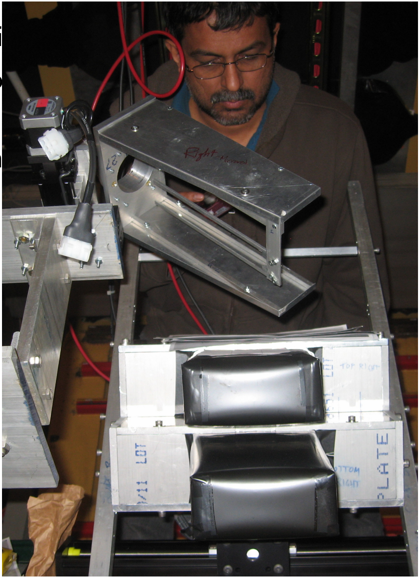
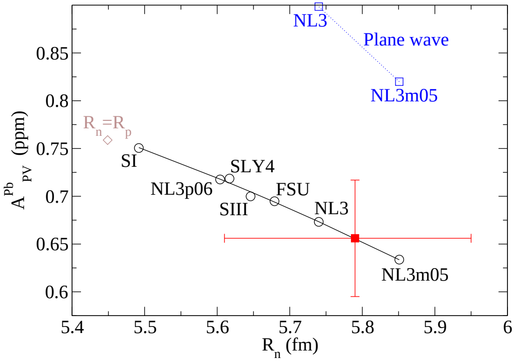




Results



- Set 95% CL on existence of neutron skin
- $R_n - R_p = 0.34 + 0.15 - 0.17$ fm
- Goal of 2% systematics (polarimetry, detector linearity, beam asymmetries each $\sim 1\%$) reached!
  - S. Abrahamyan *et al.* Phys. Rev. Lett. 108, 112502 (2012)
  - C.J Horowitz *et al.* Phys. Rev. C 85, 032501(R) (2012)

Near Future!

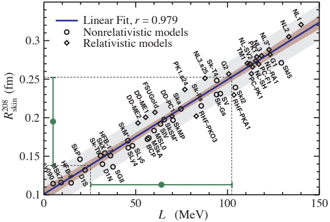
Next round of experiments for summer of 2019!

PREX-II - ^{208}Pb

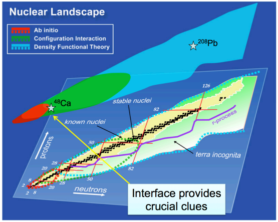
- Aims to each goal of $\delta R_n \sim 0.06$ fm
- Improved shielding and more advanced targets allow for full running
- Will provide reliable constraints on slope of symmetry energy

CREX - ^{48}Ca

- Measurements on ^{48}Ca to 0.02 fm
- Gives broader reach over periodic table
- Contributing systematics slightly different
- $A \sim 40$ now within reach of microscopic calculations



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



Summary

- Neutron skins contain information on asymmetric nuclear matter
- Interpreting neutron star observables requires good models for asymmetric matter
- Parity violating electron scattering gives neutron distributions using weak force
- The PREX-II and CREX programs aim to measure δR_n to a precision of 0.06 fm and 0.02 fm respectively next year

PREX and CREX Collaborations

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Paul Souder	Syracuse University
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Juliette Mammei	Manitoba
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Robert Michaels	Jefferson Lab
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