PREX and CREX: Measurements of the Neutron Radius of ^{208}Pb and ^{48}Ca

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Outline

- Motivation
- Setup and Experiment
- Expected Results and Uncertainties

Theoretical Overview

- Both proton and neutron distributions are important to understanding nuclear matter
- Calculations are difficult due to non-pQCD regime complicated by many-body physics
- Interesting for
  - Fundamental nuclear structure
  - Isospin dependence and nuclear symmetry aspects
  - Dense nuclear matter and neutron stars
- Isovector properties not well constrained by binding energies - must look at distributions within nuclei
- Proton radius is relatively easy - electromagnetic probes
- Neutron radius is difficult
  - Weakly couples to electroweak probes
  - Hadronic probes have considerable uncertainty
  - Theory has range of $R_n - R_p$ for various nuclei

CREX New Developments

- Successful theory workshop with over 20 presentations

http://www.jlab.org/conferences/crex/

J. Piekarewicz: *A three-legged "isovector" stool:* $R_n[^{48}Ca]; R_n[^{208}Pb]; \alpha_D[^{208}Pb]$

Organizing Committee: C. Horowitz (Indiana), K. Kumar (UMass), R. Michaels (JLab), W. Nazarewicz (UTK/ORNL), J. Piekarewicz (FSU)

New Developments since PAC39 (2)

- Neutron skin measurements on ^{208}Pb *and* ^{48}Ca highlighted as important program

NSAC Subcommittee Report

Jefferson Lab uses a faint signal arising from parity violation induced by the weak interaction to measure the radius of the neutron distribution of stable lead and calcium nuclei. Studies of neutron skins in heavy nuclei at both FRIB and Jefferson Lab, and investigations of high-frequency nuclear oscillations and intermediate energy nuclear reactions with a range of proton and neutron-rich nuclei will help pin down the behavior of nuclear matter at densities below twice typical nuclear density

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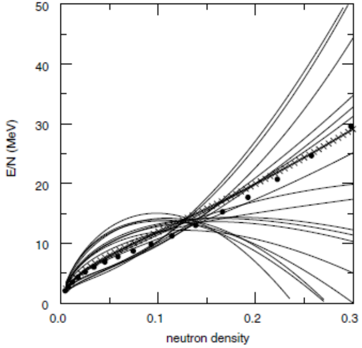
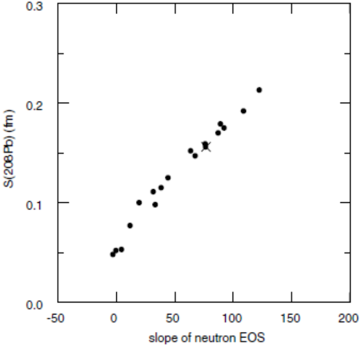
- Refined systematic errors and simulations with deeper analysis
- Updated projected uncertainty from 0.03 $\rightarrow$ 0.02 fm

Importance of Neutron Densities

- Constraints on neutron EOS





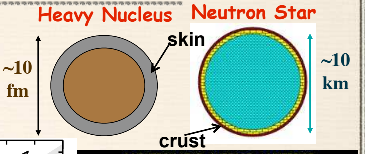
B. Alex Brown, PRL 85, 5296 (2000)

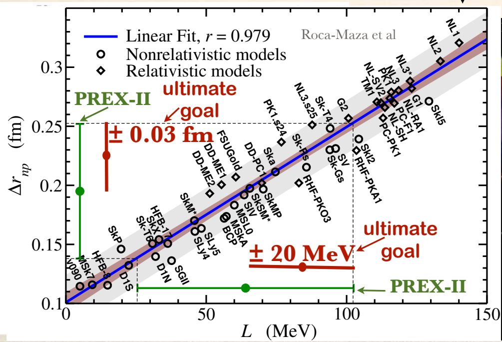
- Slope of EOS can be used to constrain DFTs
- Correlated to ρ dependence of symmetry energy

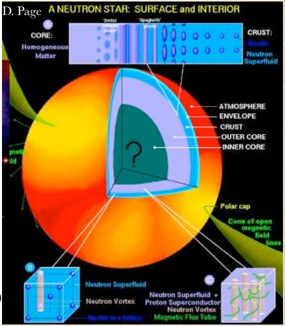
Neutron Skins and Neutron Stars

- Heavy nucleus has neutron skin
- Neutron star has solid crust over liquid core

$$L = 3\rho_0 \frac{\partial E_{\rm sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$







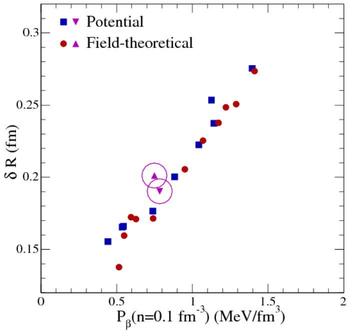
Stolen from Krishna Kumar

Neutron Stars

A. W. Steiner *et al.*,

Phys Rep 411, 325 (2005)

- Neutron star structure is also better understood with measurements on R_n
- Larger R_n correlates with larger pressure
- X-ray observations from neutron stars predict $\delta R_{Pb} = 0.15 \pm 0.02\ \mathrm{fm}$
- Structure can influence properties such as gravity waves



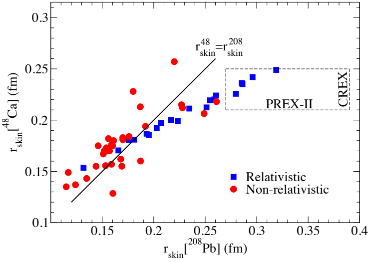
- Additionally, symmetry energy governs proton fraction (∼4%)
  - Direct Urca cooling depends on processes

$$\begin{aligned} n &\rightarrow p + e^- + \bar{\nu} \\ e^- + p &\rightarrow n + \nu \end{aligned}$$

  - Larger symmetry energy gives larger proton fraction

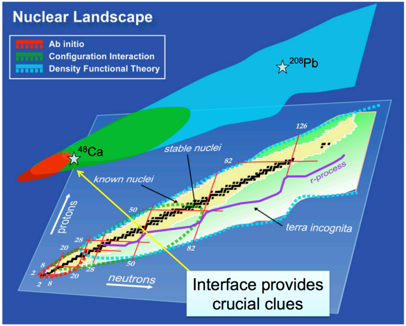
Density Functional Theory

- PREX constrains slope of symmetry energy
- A correlation is predicted between ^{48}Ca and ^{208}Pb, but needs to be tested in DFT framework



- Model spans suggest values between Ca and Pb, need to be tested, correlation isn't good, may have systematic assumptions across all models
- A successful test would build confidence in extending isovector observables across the periodic table
- Disagreement means something is missing - isovector and surface energy contribution strengths not well understood? models incomplete?

Intermediate Mass Nuclei as a Bridge

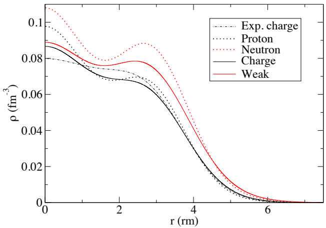


Theory TAC Review

...this and the complementary one in ^{208}Pb are important measurements for constraining, on the one hand, inputs to nuclear DFT phenomenologies and, on the other, inputs to nuclear dynamics–the modeling of three-neutron forces–in microscopic approaches.

- Data from medium-sized nuclei can act as a bridge between light-nuclei ab initio calculations and heavy nuclei DFT
- Iso*vector* observables are not easily accessible and typically poorly constrained
- Facilities like FRIB will study nuclei with very large neutron skins and halos, need CREX and PREX to reliably anchor those measurements

Coupled Cluster Models



G. Hagen *et al.*,

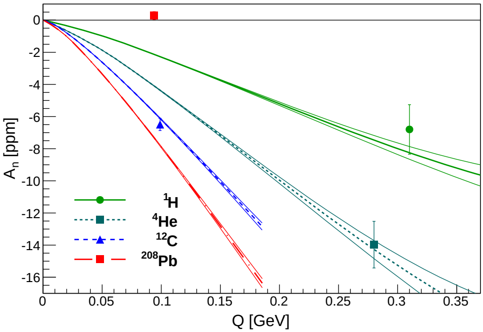
Phys. Rev. Lett 109 032502 (2012)

- Coupled cluster models just becoming computationally feasible, but are still preliminary
- G. Hagen of ORNL awarded early-carreer award to do these calculations
- 3-neutron forces have an effect on isovector properties, such as the neutron skin

- Agreement with calculations increases confidence in such calculations to be applied to other nuclei and is a test of such models
- Disagreement means something is missing, such as important terms in the expansion and models need to be refined

Transverse Asymmetries

- Vertically transverse beam asymmetries sensitive to two photon effects
- Asymmetries are highly suppressed, few ppm for $Q^2 \sim 10^{-2}\ \mathrm{GeV}^2$



- Dispersion calculations: agreement with low Z nuclei
- ^{208}Pb is significantly off - Coulomb distortions?

Why ^{48}Ca and ^{208}Pb?

- Why ^{48}Ca and ^{208}Pb and not something else?
- What further measurements could be done?

These are the *only* choices available for such a program

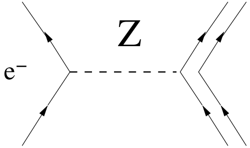
- Require neutron excess
- Require large inelastic state separation, doubly-magic (3.8 MeV for ^{48}Ca)
- Must have very long lifetime

No other nuclei meet these criteria

- Both nuclei will provide two points over a broad mass range and provide powerful tests when done together

Parity Violating Electron Scattering

- e^- also exchange Z, which is parity violating
- Primarily couples to neutron:



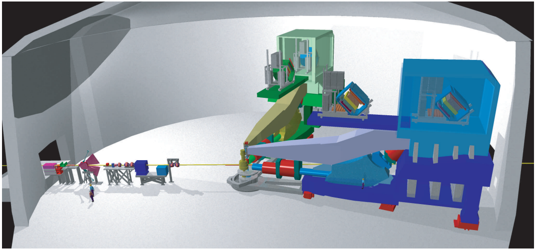
$$Q_{\text{weak}}^{\text{proton}} \propto 1 - 4\sin^2\theta_{\text{W}} \approx 0.076, \quad Q_{\text{weak}}^{\text{neutron}} \propto -1$$

- Detectable in parity violating asymmetry of electrons with different helicity
- In Born approximation, $Q^2 \ll M_Z^2$, from $\gamma - Z$ interference:

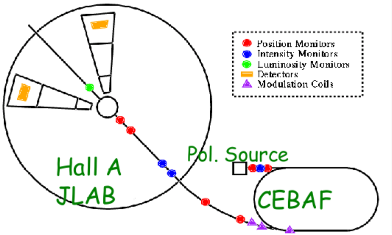
$$A_{\text{PV}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

- For fixed target exp., typical $A_{\text{PV}} \sim 10^{-7} - 10^{-4}$

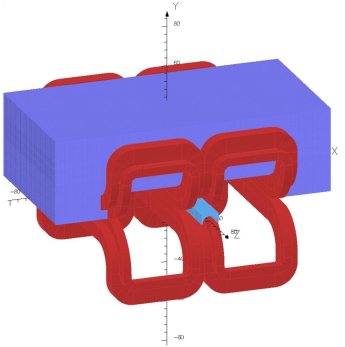
Experimental Configuration

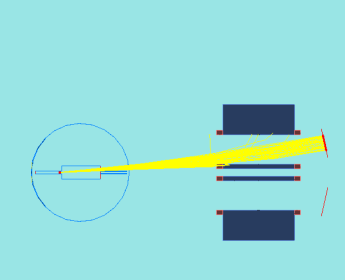


- HRS's run simultaneously and symmetrically
- PREx needs 5°, $E = 1.1\ \mathrm{GeV}$
- CREx needs 4°, $E = 2.2\ \mathrm{GeV}$
- CREx much less challenging - 2ppm vs 0.5ppm



Septum Magnet



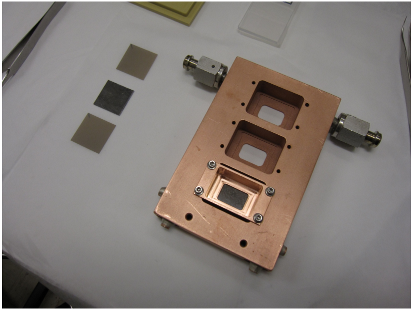


Septum Magnet Requirements

- HRS only go to 12.5°, require septum to reach 4°
- Sufficient hardware resolution must be maintained, need pure dipole
- Need to reach 1350 $\mathrm{A/cm^2}$ with 2-coil configuration
- Require new power supply, LCW pumps
- Target must be moved back for 4° acceptance, room is available without major reworking

Lead/Diamond Targets

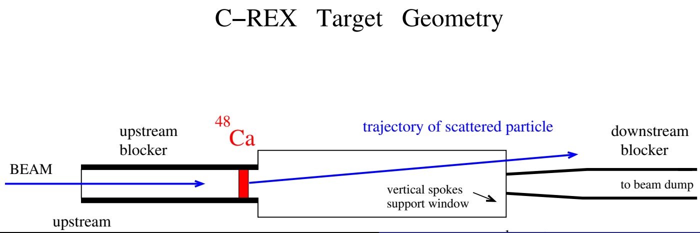
- $\sim$ 0.25 mm thick diamond, 0.5 mm thick Pb, 9% radiator
- Cryogenically cooled frame (30 W)
- Beam is rastered 4×4 mm to diffuse beam on surface



- Suffered damage in PREx-I running with high current
- Target diamond will be thicker for PREX-II to avoid damage, have $\sim$ 10 targets available

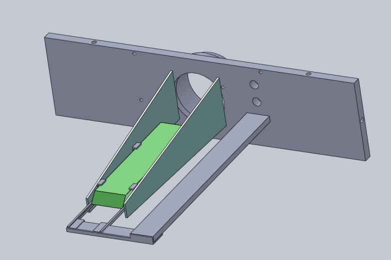
^{48}Ca Target

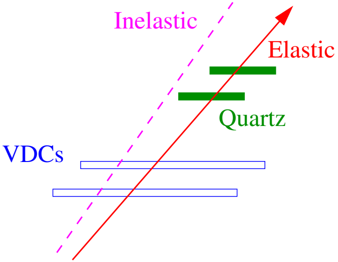
- 1 $\mathrm{g/cm^2}$, 5% radiator (much less than PREX!)
- Factor 20 safety margin in beam current to avoid target melting due to higher conductance, smaller dE/dx, and higher melting point
- Oxidizes when exposed to air, must remain isolated
- End windows (Al or steel) contribute background, must remove from acceptance
- Collimators degrade e^- energy by > 20 MeV
- Test with ^{40}Ca target during PREx-II



HRS and Quartz Detectors

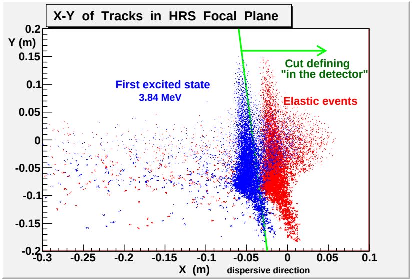
- Quartz Cerenkov detectors will be used as in PREx
- Integrate signal from PMT over helicity windows
- Need longer design for CREx





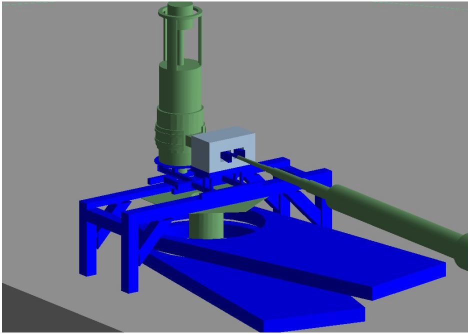
HRS and Quartz Detectors

- HRS has hardware resolution 10^{-3}, use to separate inelastic states



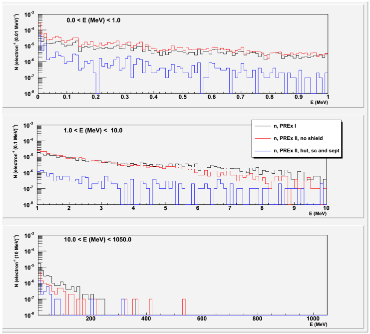
- Place quartz Cerenkov detectors to minimize inelastics
- Several states, but kept to $< 0.5\%$. Asymmetries calculable to some level and are expected to be benign

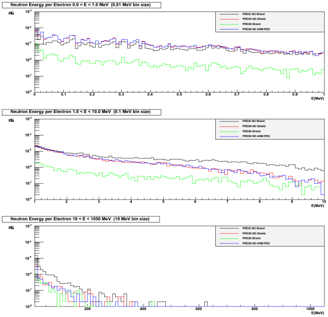
Radiation Impact



- CREX is at higher beam energy (more forward peaked), target is half rad. thickness
- Radiation simulations show PREx-II order of magnitude lower than PREX-I, CREX order of magnitude lower the PREx-II
- Continuing further simulations will be performed to optimize any shielding

Radiation Impact





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- Continuing further simulations will be performed to optimize any shielding

Results

With 30 days for PREX: 3% stat, 35 days for CREX 2% stat

PREX, $E = 1.1$ GeV, $A = 0.6$ ppb

Charge Normalization	0.1%
Beam Asymmetries	1.1%
Detector Non-linearity	1.0%
Transverse	0.2%
Polarization	1.1%
Inelastic Contribution	$< 0.1\%$
Effective Q^2	0.4%
Total	2%

CREX, $E = 2.2$ GeV, $A = 2$ ppm

Charge Normalization	0.1%
Beam Asymmetries	0.3%
Detector Non-linearity	0.3%
Transverse	0.1%
Polarization	0.8%
Inelastic Contribution	0.2%
Effective Q^2	0.8%
Total	1.2%

- Polarimetry errors could improve with planned advances for Moller and SoLID
- CREX more sensitive to Q^2 uncertainty than PREX, angular resolution demonstrated using elastic *ep*

Conclusion

- Neutron radius densities are challenging to measure, but provide important information for nuclear structure and astrophysics
- Parity-violating electron scattering provides a clean method to measure such a distribution
- The PREX and CREX measurements aim to measure δR_n to a precision of 0.02 fm and 0.06 fm with 35 and 30 production days respectively

BACKUP

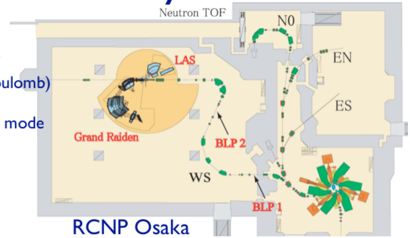
Dipole Polarizability

Dipole Polarizability α_D

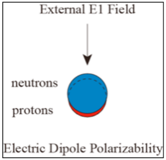
Polarized proton inelastic scattering

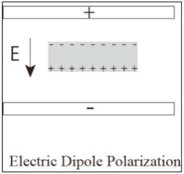
Integrate the electric dipole (E1) response of Pb-208 at very small angles < 2.5° (purely Coulomb)

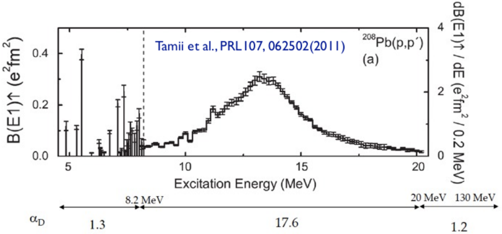
Electromagnetic probe, independent of decay mode



RCNP Osaka



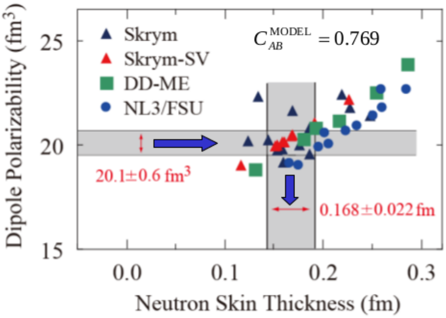




Dipole Polarizability

CREX WS, March 17-19, 2013

Correlation Between Dipole Polarizability and Neutron Skin Thickness



(0.168 ± 0.022) fm in ^{208}Pb

J. Piekarewicz, W. Nazarewicz, et al., PRC85, 041302(2012)

Precision given Beam Time/Current

Current [μA]	Beam Time [days]	δA_{PV} [%]	dR [fm]
150	35	2.4	0.020
100	35	2.8	0.023
100	30	3.0	0.024

- 1 MW power limit to A and C
- RF power on the R100 cavity at injector has maximum 200 μA
- RF power to linacs limit the total beam current in any linac to 465 μA

For 150 $\mu\mathrm{A}$ 1-pass 2.2 GeV to Hall A, that leaves up to 50 $\mu\mathrm{A}$ 5-pass for the remaining halls