Lead \(^{208}\text{Pb}\) Radius Experiment: PREX

Elastic Scattering Parity Violating Asymmetry

E = 1 GeV, \(\theta = 5^0\) electrons on lead

Spokespersons
• Krishna Kumar
• Robert Michaels
• Kent Pascke
• Paul Souder
• Guido Maria Urciuoli

Hall A Collaboration Experiment

G.M. Urciuoli
Electron - Nucleus Potential

\[ \hat{V}(r) = V(r) + \gamma_5 A(r) \]

electromagnetic

\[ V(r) = \int d^3r' Z \rho(r') / | \vec{r} - \vec{r}' | \]

Axial

\[ d\sigma / d\Omega = d\sigma / d\Omega_{Mott} | F_p(Q^2) |^2 \]

Proton form factor

\[ F_p(Q^2) = \frac{1}{4\pi} \int d^3r j_0(qr) \rho_p(r) \]

Parity Violating Asymmetry

\[ A = \frac{\left( d\sigma / d\Omega \right)_R - \left( d\sigma / d\Omega \right)_L}{\left( d\sigma / d\Omega \right)_R + \left( d\sigma / d\Omega \right)_L} = \frac{G_F^2 Q^2}{2\pi\alpha\sqrt{2}} \left[ 1 - 4\sin^2 \theta_w - \frac{F_N(Q^2)}{F_p(Q^2)} \right] \approx 0 \]

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A(r) is small, best observed by parity violation

1 - 4\sin^2 \theta_w \ll 1 \quad \text{neutron weak charge} \gg \text{proton weak charge}
Z$^0$ of weak interaction: sees the neutrons

Analysis is clean, like electromagnetic scattering:

1. Probes the entire nuclear volume
2. Perturbation theory applies

<table>
<thead>
<tr>
<th></th>
<th>proton</th>
<th>neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric charge</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Weak charge</td>
<td>0.08</td>
<td>1</td>
</tr>
</tbody>
</table>

Reminder: Electromagnetic Scattering determines $\rho(r)$ (charge distribution)
Nuclear Structure: *Neutron density is a fundamental observable that remains elusive.*

Reflects poor understanding of symmetry energy of nuclear matter = the energy cost of $N \neq Z$

$$E(n, x) = E(n, x = 1/2) + (S_v(n)) (1 - 2x^2)$$

$n = \text{n.m. density} \quad x = \text{ratio proton/neutrons}$

- Slope unconstrained by data
- Adding $R_N$ from $^{208}\text{Pb}$ will eliminate the dispersion in plot.

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$^3$. 

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Measurement at one $Q^2$ is sufficient to measure $R_{N}$

Pins down the symmetry energy (1 parameter)

( R.J. Furnstahl )

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PREX & Neutron Stars

( C.J. Horowitz, J. Piekarewicz )

R_N calibrates EOS of Neutron Rich Matter
Crust Thickness
Explain Glitches in Pulsar Frequency?

Combine PREX R_N with Obs. Neutron Star Radii
Phase Transition to “Exotic” Core?
Strange star? Quark Star?

Some Neutron Stars seem too Cold
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- Thicker neutron skin in Pb means energy rises rapidly with density → Quickly favors uniform phase.
- Thick skin in Pb → low transition density in star.

- The ²⁰⁸Pb radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above..
- If Pb radius is relatively large: EOS at low density is stiff with high P. If NS radius is small than high density EOS soft.
- This softening of EOS with density could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, color superconductor, kaon condensate…

- Proton fraction Y_p for matter in beta equilibrium depends on symmetry energy S(n).
- R_n in Pb determines density dependence of S(n).
- The larger R_n in Pb the lower the threshold mass for direct URCA cooling.
- If R_n-R_p<0.2 fm all EOS models do not have direct URCA in 1.4 M_ stars.
- If R_n-R_p>0.25 fm all models do have URCA in 1.4 M_ stars.
Atomic Parity Violation

- Low $Q^2$ test of Standard Model
- Needs $R_N$ to make further progress.

Isotope Chain Experiments
  e.g. Berkeley Yb

\[
H_{PNC} \approx \frac{G_F}{2\sqrt{2}} \int \left[ -N \rho_N(\vec{r}) + Z (1-4\sin^2 \theta_W) \rho_P(\vec{r}) \right] \psi_e^+ \gamma^5 \psi_e \, d^3r
\]

$\approx 0$

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Neutron Skin and Heavy–Ion Collisions (Alex Brown)

Skx-s15

Skx-s20

Skx-s25

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Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one $Q^2$

Small Corrections for $G^n_E$, $G^s_E$, MEC

Neutron Density at one $Q^2$

Assume Surface Thickness Good to 25% (MFT)

Mean Field & Other Models

Atomic Parity Violation

PREX Physics Impact

Heavy Ions

Neutron Stars

$R_n$
Hall A at Jefferson Lab
PREX in Hall A at JLab

Lead Foil Target

Spectrometers

Pol. Source

Hall A

CEBAF

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High Resolution Spectrometers

Spectrometer Concept:
Resolve Elastic

Left-Right symmetry to control transverse polarization systematic

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Experimental Method

Flux Integration Technique:
HAPPEX: 2 MHz
PREX: 850 MHz

Rapid, Random Helicity Flips
Measure flux $F$ for each window

$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

Signal Average $N$ Windows Pairs:

$$A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$$

Calorimeter Raw Window Pair Asymmetry

23 Million Window Pairs
$\sigma = 3.8 \times 10^{-3}$
$\sim 90$ microamps
0.8 ppm

No non-gaussian tails to $\pm 5\sigma$
Consolidated techniques from the previous Hall A parity violating electron scattering experiments (HAPPEX)

**Polarized Source**

- Optical pumping of solid-state photocathode
- High Polarization
- Pockels cell allows rapid helicity flip
- Careful configuration to reduce beam asymmetries.
- Slow helicity reversal to further cancel beam asymmetries

**Intensity Feedback**

- Adjustments for small phase shifts to make close to circular polarization

**PITA Effect**

(Polarization Induced Transport Asymmetry)

\[ A_i = \epsilon \Delta \sin(\theta) \]

Intensity Asymmetry

where \( \epsilon = \frac{\Delta I}{I_0 + I_0/2} \)

Transport Asymmetry

\( \Delta \) drifts, but slope is stable.

Feedback on \( \Delta \)

**Beam Asymmetries**

\[ A_{\text{raw}} = A_{\text{det}} - A_Q + \alpha \Delta E + \Sigma \beta_i \Delta x_i \]

Slopes from:
- natural beam jitter (regression)
- beam modulation (dithering)

**Intensity Feedback**

- Low jitter and high accuracy allows sub-ppm Cumulative charge asymmetry in \( \sim 1 \) hour

In practice, aim for 0.1 ppm over duration of data-taking.
New for PREX

(to achieve a 2% systematic error)
Double Wien Filter

Crossed E & B fields to rotate the spin

- Two Wien Spin Manipulators in series
- Solenoid rotates spin +/-90 degrees (spin rotation as B but focus as B²).
  Flips spin without moving the beam!

Electron Beam

Joe Grames, et. al.

G.M. Urciuoli
Parity Quality Beam!

Helicity – Correlated Position Differences

< ~ 3 nm

Wien Flips helped!

Points: Not sign corrected

Average with signs = what exp’t feels

$< X_R - X_L >$ for helicity $L, R$

Units: microns

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Upgraded Polarimetry
(Sirish Nanda et al.)

Compton Polarimeter (1 % Polarimetry)

Upgrades:

Laser → Green Laser

Moller Polarimeter (< 1 % Polarimetry)

Upgrades:

Magnet → Superconducting Magnet from Hall C
Target → Saturated Iron Foil Targets
DAQ → FADC
Lead Target

• Three bays
• Lead (0.5 mm) sandwiched by diamond (0.15 mm)
• Liquid He cooling (30 Watts)
$5^0$ Septum magnet
(augments the High Resolution Spectrometers)
(Increased Figure of Merit)
Integrating Detection

Deadtime free, 18 bit ADC with \(< 10^{-4}\) nonlinearity.

The x, y dimensions of the quartz determined from beam test data and MC (HAMC) simulations. Quartz thickness optimized with MC.

New HRS optics tune focuses elastic events both in x & y at the PREx detector location.

120 Hz pair windows asymmetry distribution.

No Gaussian tails up to 5 standard deviations.
Beam-Normal Asymmetry in elastic electron scattering

\[ A_T \equiv \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \vec{S}_e \cdot (k_e \times k'_e) \]

i.e. spin transverse to scattering plane

Possible systematic if small transverse spin component

New results PREX

Preliminary! Publication in preparation

\[ ^{208}Pb: \quad A_T = +0.13 \pm 0.19 \pm 0.36 \text{ ppm} \]

\[ ^{12}C: \quad A_T = -6.52 \pm 0.36 \pm 0.35 \text{ ppm} \]

- Small \( A_T \) for \(^{208}\text{Pb}\) is a big (but pleasant) surprise.

- \( A_T \) for \(^{12}\text{C}\) qualitatively consistent with \(^4\text{He}\) and available calculations (1) Afanasev ; (2) Gorchtein & Horowitz

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PREX Result
### Systematic Errors

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Absolute (ppm)</th>
<th>Relative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization (1)</td>
<td>0.0071</td>
<td>1.1</td>
</tr>
<tr>
<td>Beam Asymmetries (2)</td>
<td>0.0072</td>
<td>1.1</td>
</tr>
<tr>
<td>Detector Linearity</td>
<td>0.0071</td>
<td>1.1</td>
</tr>
<tr>
<td>BCM Linearity</td>
<td>0.0010</td>
<td>0.2</td>
</tr>
<tr>
<td>Rescattering</td>
<td>0.0001</td>
<td>0</td>
</tr>
<tr>
<td>Transverse Polarization</td>
<td>0.0012</td>
<td>0.2</td>
</tr>
<tr>
<td>$Q^2$ (1)</td>
<td>0.0028</td>
<td>0.4</td>
</tr>
<tr>
<td>Target Thickness</td>
<td>0.0005</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{12}$C Asymmetry (2)</td>
<td>0.0025</td>
<td>0.4</td>
</tr>
<tr>
<td>Inelastic States</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.0130</strong></td>
<td><strong>2.0</strong></td>
</tr>
</tbody>
</table>

(1) Normalization Correction applied
(2) Nonzero correction (the rest assumed zero)

$$A = 0.656 \text{ ppm} \pm 0.060 \text{(stat)} \pm 0.0140 \text{(syst)}$$

$\Rightarrow$ Statistics limited (9%)

$\Rightarrow$ Systematic error goal achieved! (2%)
PREX Asymmetry \((P_e \times A)\)

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Asymmetry leads to $R_N$

\[ R_N \approx 6.156 + 1.675 \langle A \rangle - 3.420 \langle A \rangle^2 \]
**PREX Result, cont.**

\[ A = 0.656 \pm 0.060 \text{(stat)} \pm 0.014 \text{(syst)} \text{ ppm} \]

\[ R_N = 5.78 \pm 0.16 - 0.18 \text{ fm} \]

Neutron Skin = \( R_N - R_P = 0.33 \pm 0.16 - 0.18 \text{ fm} \)

Establishing a neutron skin at \( \sim 92\% \text{ CL} \)
$^{208}$Pb Radius from the Weak Charge Form Factor
Measured Asymmetry

A = 0.656 ± 0.060 (stat) ± 0.014 (syst) ppm

\[ \rho_w = \frac{\rho_0}{1 + e^{-\frac{r-R}{a}}} \]

\[ F_w(q) = \frac{1}{Q_w} \int d^3r \frac{\sin(qr)}{qr} \rho_w(r) \]

\[ F_w(\bar{q}) = 0.204 ± 0.028 (exp) ± 0.001 (mod) \]

Helm Model

\[ R_w = 5.826 ± 0.181 (exp) ± 0.027 (mod) \text{ fm} \]

Small Corrections for
\[ G^n_{\text{Fe}} \quad G^s_{\text{Fe}} \quad \text{MEC} \]

Assume Surface Thickness Good to 25% (MFT)

\[ R^2_n = \frac{Q_w}{q_n N} R^2_w - \frac{q_p Z}{q_n N} R^2_{ch} - \left< r^2_p \right> - \frac{Z}{N} \left< r^2_n \right> + \frac{Z + N}{q_n N} \left< r^2_s \right> \]

\[ R^2_n = 0.9525 \bullet R^2_w - 1.671 \bullet \left< r^2_s \right> + 0.7450 \text{ fm}^2 \]

\[ R_n = 5.751 ± 0.175 (exp) ± 0.026 (mod) ± 0.005 (str) \text{ fm} \]

(To be compared with \( R_N = 5.78 + 0.16 - 0.18 \) fm)

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TRANSVERSE ASIMMETRY
Two photon exchange

$R = \frac{\mathcal{G}_E}{\mathcal{G}_M}$ discrepancy → $2\gamma$ exchange amplitude $A_{2\gamma}$

Observable: Beam normal spin asymmetry BNSA

BNSA sensitive to $\text{Im}(A_{2\gamma})$. 
Asymmetry dependency on azimuthal angle

\[ A_\perp^m = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = A_\perp(\theta) \vec{P}_e \cdot \hat{s} = A_\perp \cos \phi \]

\[ \hat{s}_\perp = \frac{\vec{k} \times \vec{p}}{|\vec{k} \times \vec{p}|} \]
PREX measured $A_n$ with $^{12}\text{C}$ and $^{208}\text{Pb}$ targets.
HAPPEX and HAPPEX-II measured $A_n$ with $^1\text{H}$ and $^4\text{He}$ targets.

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FUTURE: PREX-II
PREX-II Approved by PAC (Aug 2011)
“A” Rating 35 days run in 2013 / 2014

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PREX Region After Target

Tungsten Collimator & Shielding

Septum Magnet

Former O-Ring location which failed & caused time loss during PREX-I

→ PREX-II to use all-metal seals
Strategy

- Tungsten (W) plug
  \[ 0.7^0 < \theta < 3^0 \]

- Shield the W

- x 10 reduction in
  0.2 to 10 MeV neutrons
Parity Violating Electron Scattering Measurements of Neutron Densities
Shufang Ban, C.J. Horowitz, R. Michaels

arXiv:1010.3246 [nucl-th]
Summary

• Fundamental Nuclear Physics with many applications
• Because of significant time-losses due to O-Ring problem and radiation damage PREX achieved a 9% stat. error in Asymmetry (original goal was 3 %).
• PREX measurement of Rn is nevertheless the cleanest performed so far
• Several experimental goals (Wien filters, 1% polarimetry at 1 GeV, etc.) were all achieved.
• Systematic error goal was consequently achieved too.
• PREX-II approved (runs in 2013 or 2014) ➔ 3% statistical error

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Spare

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Corrections to the Asymmetry are Mostly Negligible

- Coulomb Distortions \( \sim 20\% = \text{the biggest correction.} \)
- Transverse Asymmetry
- Strangeness
- Electric Form Factor of Neutron
- Parity Admixtures
- Dispersion Corrections
- Meson Exchange Currents
- Shape Dependence
- Isospin Corrections
- Radiative Corrections
- Excited States
- Target Impurities

Horowitz, \textit{et.al.} PRC 63 025501
Polarized Electron Source

- Rapid, random helicity reversal
- Electrical isolation from rest of lab
- Feedback on Intensity Asymmetry

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Future in Hall A at JLab

- **Early Experiments**
  - g2p/GEp
  - 12 mo. Shutdown
  - no promised beam

- **Commissioning**
  - Beam 1st to Hall A

- **SuperBigbite**
  - $$

- **Moller**
  - $$$

- **PREX – II ?**

- **SOLID $$$**

Timeline:
- 2011
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018
Possible
Future PREX
Program?

Each point 30 days  stat. error only

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>E (GeV)</th>
<th>(dR_N / R_N)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{208}\text{Pb})</td>
<td>1</td>
<td>1 %</td>
<td>PREX-II (approved)</td>
</tr>
<tr>
<td>(^{48}\text{Ca})</td>
<td>2.2 (1-pass)</td>
<td>0.4 %</td>
<td>natural 12 GeV exp’t</td>
</tr>
<tr>
<td>(^{48}\text{Ca})</td>
<td>2.6</td>
<td>2 %</td>
<td>surface thickness</td>
</tr>
<tr>
<td>(^{40}\text{Ca})</td>
<td>2.2 (1-pass)</td>
<td>0.6 %</td>
<td>basic check of theory</td>
</tr>
<tr>
<td>tin isotope</td>
<td>1.8</td>
<td>0.6 %</td>
<td>apply to heavy ion</td>
</tr>
<tr>
<td>tin isotope</td>
<td>2.6</td>
<td>1.6 %</td>
<td>surface thickness</td>
</tr>
</tbody>
</table>

Not yet proposed. Just a “what if ?”