Results from

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

Elastic Scattering
Parity Violating Asymmetry

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

Spokespersons
Paul Souder, Krishna Kumar
Guido Urciuoli, Robert Michaels
(speaker)

Graduate Students
Ahmed Zafar, Chun Min Jen,
Abdurahim Rakham (Syracuse)
Jon Wexler (UMass)
Kiadtisak Saenboonruang (UVa)

Ran March – June 2010
in Hall A at Jefferson Lab
**Standard Electroweak Model**

The **Glashow-Weinberg-Salam Theory** unifies the electromagnetic and weak interactions.

Left-handed fermion fields (quarks & leptons) = doublets under SU(2)

Right-handed fields = singlets under SU(2)

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**Parity Violation**

- **β decay**
- **Weak charge of $^{208}$Pb**
A piece of the weak interaction violates parity (mirror symmetry) which allows to isolate it.
Parity Violating Asymmetry

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-4} \times Q^2 \sim 10^{-6} \]

\[ \sigma \approx \left| e^{-} \gamma _{208Pb} e^{-} Z_{0} ^{208Pb} \right|^2 \]

Applications of \( A_{PV} \) at Jefferson Lab

- **Nucleon Structure**
  - Strangeness \( s \bar{s} \) in proton (HAPPEX, G0 expts)

- **Test of Standard Model of Electroweak** \( \sin^2 \theta_W \)
  - \( e-e \) (MOLLER) or \( e-q \) (PVDIS)
  - Elastic \( e-p \) at low \( Q^2 \) (QWEAK)

*This talk*

- **Nuclear Structure (neutron density)**: **PREX**
Idea behind PREX

$Z^0$ of Weak Interaction:
Clean Probe Couples Mainly to Neutrons

In PWIA (to illustrate):

$$A = \frac{\frac{d\sigma}{d\Omega}}{R} - \frac{\frac{d\sigma}{d\Omega}}{L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[ 1 - 4\sin^2 \theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

w/ Coulomb distortions (C. J. Horowitz):

$$\frac{dA}{A} = 3\% \rightarrow \frac{dR^n}{R_n} = 1\%$$
Hall A at Jefferson Lab
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)

$R_n$

PREX Physics Output

Atomic Parity Violation

Mean Field & Other Models

Neutron Stars

Slide adapted from C. Horowitz
Fundamental Nuclear Physics:

What is the size of a nucleus?

Neutrons are thought to determine the size of heavy nuclei like $^{208}\text{Pb}$.

Can theory predict it?
Reminder: Electromagnetic Scattering determines $\rho(r)$ (charge distribution)
**$Z^0$ of weak interaction:** sees the neutrons

<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>

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r \ j_0(qr) \ \rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[ 1 - 4\sin^2 \theta_W - \frac{F_N(Q^2)}{F_P(Q^2)} \right] \approx 0$$

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T.W. Donnelly, J. Dubach, I. Sick  

C. J. Horowitz, S. J. Pollock, P. A. Souder, R. Michaels  

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R. Michaels, Jlab Seminar @ UVa  
Feb 10, 2012
How to Measure
Neutron Distributions, Symmetry Energy

- Proton-Nucleus Elastic
- Pion, alpha, d Scattering
- Pion Photoproduction
- Heavy ion collisions
- Rare Isotopes (dripline)

\[
\begin{align*}
\text{Involve strong probes} \\
\text{Most spins couple to zero.}
\end{align*}
\]

- Magnetic scattering
- PREX (weak interaction)
- Theory

\[
\begin{align*}
\text{MFT fit mostly by data other than neutron densities}
\end{align*}
\]
Example: **Heavy Ions**
(adapted from Betty Tsang, PREX Workshop, 2008)

Isospin Diffusion (NSCL)
Probe the symmetry energy in $^{124}$Sn + $^{112}$Sn

Constraining the EOS at high densities by laboratory collisions

- Experiment: measure collective flow (emission patterns) of particles emitted in Au+Au collisions from (E/A=1-8 GeV).
- Transport model (BUU) relates the measurements to pressure and density.

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R. Michaels, Jlab
Seminar @ UVa
Feb 10, 2012
Using Parity Violation

Electron - Nucleus Potential \[ \hat{V}(r) = V(r) + \gamma_5 A(r) \]

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

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

Neutron form factor \[ F_N(Q^2) = \frac{1}{4\pi} \int d^3 r \ j_0(qr) \ \rho_N(r) \]

Parity Violating Asymmetry
\[ A = \frac{\left( \frac{d\sigma}{d\Omega} \right)_R - \left( \frac{d\sigma}{d\Omega} \right)_L}{\left( \frac{d\sigma}{d\Omega} \right)_R + \left( \frac{d\sigma}{d\Omega} \right)_L} = \frac{G_F Q^2}{2\pi \alpha \sqrt{2}} \left[ 1 - 4\sin^2 \theta_w - \frac{F_N(Q^2)}{F_p(Q^2)} \right] \approx 0 \]
Why only one parameter?

(next slide...)
Nuclear Structure: *Neutron density is a fundamental observable that remains elusive.*

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

\[
E(n,x) = E(n,x = 1/2) + \left( S_v (n) \right) (1 - 2x^2)
\]

\[
n = \text{n.m. density} \quad x = \frac{\text{proton/neutrons}}{\text{ratio}}
\]

- Slope unconstrained by data
- Adding \( R_N \) from \(^{208}\text{Pb} \) will significantly reduce 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\(^3\).
Thanks, Alex Brown
PREX Workshop 2008

\[ \Delta R_{np} \text{ (fm)} \]

\[ \rho_N \]

\[ ^{100}\text{Sn} \quad ^{132}\text{Sn} \quad ^{208}\text{Pb} \]

Neutron Number
Thanks, Alex Brown
PREX Workshop 2008

\[ \Delta R_{np} \text{ (fm)} \]

Neutron Number

\[ \rho_N \]

\[ {^{100}}\text{Sn} \quad {^{132}}\text{Sn} \quad {^{208}}\text{Pb} \]
Thanks, Alex Brown
PREX Workshop 2008

\[ \Delta R_{np} \text{ (fm)} \]

\[ \rho_N \]

\[ E/N \]

\[ ^{100}_{\text{Sn}} \]
\[ ^{132}_{\text{Sn}} \]
\[ ^{208}_{\text{Pb}} \]

Neutron Number

R. Michaels, Jlab
Seminar @ UVa
Feb 10, 2012
Application: Atomic Parity Violation

- Low $Q^2$ test of Standard Model
- Needs $R_N$ (or APV measures $R_N$)

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

Isotope Chain Experiments e.g. Berkeley Yb
Neutron Stars

What is the nature of extremely dense matter?

Do collapsed stars form "exotic" phases of matter? (strange stars, quark stars)

Crab Nebula (X-ray, visible, radio, infrared)
Inputs:

- Eq. of state (EOS) \( P(\rho) \)

PREX helps here

- Hydrostatics (Gen. Rel.)

- Astrophysics Observations
  
  Luminosity \( L \)
  Temp. \( T \)
  Mass \( M \) from pulsar timing

\[
L = 4\pi\sigma_B R^2 T^4
\]  
(with corrections ...)

Mass - Radius relationship
PREX & Neutron Stars

C.J. Horowitz, J. Piekarewicz

- $R_N$ calibrates equation of state (pressure vs density) of Neutron Rich Matter

- Combine PREX $R_N$ with Observed Neutron Star Radii

  Phase Transition to “Exotic” Core ?
  Strange star ? Quark Star ?

- Some Neutron Stars seem too cold

  Explained by Cooling by neutrino emission (URCA process) ?

  $R_n - R_p > 0.2$ fm $\rightarrow$ URCA probable, else not
PREX Setup

Parity: “The entire lab is the experiment”

Hall A JLAB

CEBAF

Lead Foil Target

Spectrometers

- Position Monitors
- Intensity Monitors
- Luminosity Monitors
- Detectors
- Modulation Coils
How to do a Parity Experiment
(integrating method)

 Flux Integration Technique:
HAPPEX: 2 MHz
PREX: 500 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:
\[
A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}
\]

Example: HAPPEX

Calorimeter Raw Window Pair Asymmetry

23 Million Window Pairs
\( \sigma = 3.8 \times 10^{-3} \)

~ 90 microamps
0.8 ppm

No non-gaussian tails to +/- 5\( \sigma \)
Polarized Electron Source

- Based on Photoemission from GaAs Crystal
- Polarized electrons from polarized laser

Need:
- Rapid, random helicity reversal
- Electrical isolation from the rest of the lab
- Feedback on Intensity Asymmetry
Important Systematic: **PITA Effect** (Gordon Cates)

**Polarization Induced Transport Asymmetry**

**Intensity Asymmetry**

\[ A_I = \varepsilon \Delta \sin(\theta) \]

where \( \varepsilon = \frac{T_x - T_y}{T_x + T_y} \)

**Transport Asymmetry**

\[ \Delta \text{ drifts, but slope is } \sim \text{ stable. Feedback on } \Delta \]

\[ (Gordon \ Cates) \]
Methods to Reduce Systematics

(Gordon Cates, Kent Paschke, Mark Dalton, Rupesh Silwal)

A rotatable $\lambda/2$ waveplate downstream of the P.C. allows arbitrary orientation of the ellipse from DoLP

Scanning the Pockels Cell voltage = scanning the residual linear polarization (DoLP)

A simplified picture: asymmetry=0 corresponds to minimized DoLP at analyzer

Intensity Asymmetry (ppm)

Pockels cell voltage $\Delta$ offset (V)

$Aq = -947.06 + 16.39 \times x$

A rotatable $\lambda/2$ waveplate downstream of the P.C. allows arbitrary orientation of the ellipse from DoLP

GaAs crystal

Most sensitive

Least sensitive

Ellipses resulting from phase adjust

Rotate by 22.5 degrees

(90 degree full cycle)
Intensity Feedback

Adjustments for small phase shifts to make close to circular polarization

Low jitter and high accuracy allows sub-ppm cumulative charge asymmetry in ~ 1 hour
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 $B^2$).
  Flips spin without moving the beam!
Beam Asymmetries

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

Slopes from

- natural beam jitter (regression)
- beam modulation (dithering)
Parity Quality Beam! (why we love Jlab!)

Helicity – Correlated Position Differences

\[ < X_R - X_L > \] for helicity \( L, R \)

Units: microns

\( \chi^2 \): 0.97, \( P = 0.54 \)
\( \chi^2 \): 0.92, \( P = 0.94 \)
\( \chi^2 \): 0.95, \( P = 0.97 \)

\( \chi^2 \): 0.97, \( P = 0.54 \)
\( \chi^2 \): 0.92, \( P = 0.94 \)
\( \chi^2 \): 0.95, \( P = 0.97 \)

Points: Not sign corrected

Average with signs = what exp’t feels

\(< \sim 3 \text{ nm}\)
Compton Polarimeter

$e - \gamma$ scattering

to measure electron beam’s **polarization**
(needed to normalize asymmetry)

- **Green Laser** (increased sensitivity at low E)
- **Integrating Method** (removes some systematics of analyzing power)
- **New Photon & Electron Detectors**

Upgrade for 1% accuracy at 1 GeV

R. Michaels, Jlab Seminar @ UVa
Feb 10, 2012
Compton Polarimeter Results

the grand average of laser cycle wise beam polarization V.S. slug number

\[ P_0 = 87.41014 \pm 0.11617, \quad \frac{\chi^2}{\text{N.D.F.}} = 1.09 \]
Upgraded for PREX

**Moller Polarimeter**

\[ e - e \] scattering

Superconducting Magnet from Hall C

Saturated Iron Foil Targets

1% Accuracy in Polarization

Magnet and Target

Electronics/DAQ Upgrade (FADC)
Hall A  High Resolution Spectrometers

- Resolve Elastic Scattering
- Discriminate Excited States

Elastic

Inelastic

detector

target

Dipole

Quads

Pure, Thin $^{208}$Pb Target

Scattered Electron’s Momentum (GeV/c)
Measure $\theta$ from Nuclear Recoil

( Nilanga Liyanage, Kiadtisak Saenboonruang)

$\delta E =$ Energy loss  
$E =$ Beam energy  
$M_A =$ Nuclear mass  
$\theta =$ Scattering angle

Recoil is large for H, small for nuclei  
(3X better accuracy than survey)
Backgrounds that might re-scatter into the detector?

Run magnets down: measure inelastic region

Run magnets up: measure probability to rescatter

No inelastics observed on top of radiative tail. Small systematic for tail.
Detector Package in HRS
PREX Integrating Detectors
UMass / Smith

DETECTORS

TOP of VDC BOX

Transport z = 0

Transport z at det1 location

45° Nominal Central Ray

VDC2

VDC1

PMT

PMT

s0
Lead / Diamond Target

- Three bays
- Lead (0.5 mm) sandwiched by diamond (0.15 mm)
- Liquid He cooling (30 Watts)
Performance of Lead / Diamond Targets

Targets with \textit{thin} diamond backing (4.5 \% background) degraded fastest.

\textbf{Thick} diamond (8\%) ran well and did not melt at 70 \textmu A.

Solution: Run with 10 targets.
Beam-Normal Asymmetry in elastic electron scattering i.e. spin transverse to scattering plane

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

Possible systematic if small transverse spin component

New results PREX

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

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

- 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
PREX-I 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>0.0083</td>
<td>1.3</td>
</tr>
<tr>
<td>Beam Asymmetries (2)</td>
<td>0.0072</td>
<td>1.1</td>
</tr>
<tr>
<td>Detector Linearity</td>
<td>0.0076</td>
<td>1.2</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>0.0</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>0.0005</td>
<td>0.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.0140</td>
<td>2.1</td>
</tr>
</tbody>
</table>

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

Physics Asymmetry

$A = 0.656 \text{ ppm}$

$\pm 0.060 (\text{stat}) \pm 0.014 (\text{syst})$

→ Statistics limited ( 9% )

→ Systematic error goal achieved! (2%)

A physics letter was recently accepted by PRL.

arXiv 1201.2568 [nucl-ex]
PREX Asymmetry \((P_e \times A)\)

R. Michaels, Jlab Seminar @ UVa
Feb 10, 2012
Asymmetry leads to $R_N$ Establishing a neutron skin at ~95% CL

Neutron Skin = $R_N - R_P = 0.33 \pm 0.16 - 0.18$ fm

Interpretation requires the acceptance function for spectrometer: $\mathcal{E}(\theta)$
PREX-I Result, cont.

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

A physics letter was recently accepted by PRL.

arXiv 1201.2568 [nucl-ex]
PREX-II Approved by PAC (Aug 2011)

“A” Rating 35 days to run in 2013 or 2014

PREX-II: Kent Paschke, Krishna Kumar, Paul Souder, Guido Urciuoli, Robert Michaels
Recent $R_n$ predictions can be tested by PREX at full precision

PREX could provide an electroweak complement to $R_n$ predictions from a wide range of physical situations and model dependencies.

**Recent $R_n$ predictions:**

- **Hebeler et al.** Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

- **Steiner et al.** X-Ray $n$-star mass and radii observation + Brown correlation. (Ozel et al. finds softer EOS, would suggest smaller $R_n$).

- **Tamii et al.** Measurement of electric dipole polarizability of $^{208}\text{Pb}$ + model correlation with neutron skin.

- **Tsang et al.** Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.

These can be tested with:

\[ \delta(A_{PV})/A_{PV} \sim 3\% \]

\[ \delta(R_n)/R_n \sim 1\% \]
Improvements for PREX-II

Tungsten Collimator & Shielding

Location of ill-fated O-Ring which failed & caused significant time loss during PREX-I

→ PREX-II to use all-metal seals

Region downstream of target
Parity Violating Electron Scattering Measurements of Neutron Densities
Shufang Ban, C.J. Horowitz, R. Michaels

Possible Future PREX Program?

Each point 30 days  stat. error only

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>E (GeV)</th>
<th>dRₙ / Rₙ</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>²⁰⁸Pb</td>
<td>1</td>
<td>1 %</td>
<td>PREX-II (approved by Jlab PAC, A rating)</td>
</tr>
<tr>
<td>⁴⁸Ca</td>
<td>2.2 (1-pass)</td>
<td>0.4 %</td>
<td>natural 12 GeV exp’t will propose @ next PAC</td>
</tr>
<tr>
<td>⁴⁸Ca</td>
<td>2.6</td>
<td>2 %</td>
<td>surface thickness</td>
</tr>
<tr>
<td>⁴⁰Ca</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 proposed
UVa Participants in Jlab Parity-Violation & PREX

Gordon Cates  Kent Paschke  Nilanga Liyanage  Xiaochao Zheng

PREX-II spokesperson

Mark Dalton  Diancheng Wang  Rupesh Silwal  Kiadtisak Saenboonruang

Thesis on PREX-I

Also: Chao Gu, Xiaoyan Deng, Ge Jin, Richard Lindgren, Vladimir Nelyubin, Seamus Riordan, Ramesh Subedi, Al Tobias
PREX : Summary

• Fundamental Nuclear Physics with many applications

• PREX-I achieved a 9% stat. error in Asymmetry
  (original goal : 3 %)

• Systematic Error Goals Achieved !!

• Significant time-losses due to O-Ring problem and radiation damage

• PREX-II approved (runs in 2013 or 2014 )
Geant 4 Radiation Calculations
PREX-II shielding strategies

**Strategy**

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

- **Shield the W**

- **x 10 reduction in 0.2 to 10 MeV neutrons**

---

**Number of Neutrons per incident Electron**

- **0 - 1 MeV**
  
  ![Graph for 0 - 1 MeV neutrons]

- **1 - 10 MeV**
  
  ![Graph for 1 - 10 MeV neutrons]

- **10 - 1200 MeV**
  
  ![Graph for 10 - 1200 MeV neutrons]
Pull Plot (example)

PREX Data

$\left( A - \overline{A} \right) / \sigma$
Corrections to the Asymmetry are Mostly Negligible

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

Horowitz, *et.al.* PRC 63 025501
Optimum Kinematics for Lead Parity: $E = 1$ GeV if $\theta = 5^\circ$

$<A> = 0.5$ ppm. Accuracy in Asy 3%

Figure of merit

$$FOM = \frac{d\sigma}{d\Omega} \times A^2$$

Min. error in $R_n$

$\rightarrow FOM \times \varepsilon^2$

1 month run

$\rightarrow 1\%$ in $R_n$

(2 months x 100 uA

$\rightarrow 0.5\%$ if no systematics)
Source Studies
Kent Paschke, Gordon Cates, Mark Dalton, Rupesh Silwal
Optimizing laser optics to minimize helicity-correlated systematics.

Charge Asymmetry

\[ A_q = 70.25 + 1919.41 \sin(2\theta + 53.75) - 244.94 \sin(4\theta + 168.86) \]

\[ \Delta X \approx 0.5 \text{ um} \]

\[ \Delta Y \approx 0.5 \text{ um} \]

Transmission of Helicity-Correlated Position DIffs

BPMs in Injector Region

R. Michaels, Jlab Seminar @ UVa
Feb 10, 2012
Water Cell : Measure $\langle \theta \rangle$ (agrees with survey)

Nilanga Liyanage, Seamus Riordan, Kiadtisak Saenboonruang,

- $^{16}$O

Scattered Energy Difference from Beam Energy for H$_2$O (P$_0$=1.05843GeV)

Scattered Energy Difference from Beam Energy for Oxygen (P$_0$=1.05843GeV)

Scattered Energy Difference from Beam Energy for Hydrogen (P$_0$=1.05843GeV)

dp for Oxygen: -1.678925 MeV

dp for Hydrogen: -5.762643 MeV

dp separation: 4.083718 MeV
An instability in Pockel Cell “bleeds” into the integration gate. It depends on helicity.

**Beam Current**

**Detector (1 of 4)**

Want small time constants, and same for detectors and bcm
PREX: pins down the symmetry energy (1 parameter)

\[
\frac{E}{A} \approx -a_v + a_4 \left( \frac{N-Z}{A} \right)^2 + a_s / A^{1/3} + \ldots
\]

energy cost for unequal # protons & neutrons

( R.J. Furnstahl )

Actually, it's the density dependence of \(a_4\) that we pin down.

\[208\text{Pb}\]
Pb Radius vs Neutron Star Radius

- The $^{208}$Pb radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above.
- Most interested in density dependence of equation of state (EOS) from a possible phase transition.
- Important to have both low density and high density measurements to constrain density dependence of EOS.
  - 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...
PREX Constrains Rapid Direct URCA Cooling of Neutron Stars

- 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.

If $Y_p > \text{red line}$ NS cools quickly via direct URCA reaction $\nu\nu\nu
\rightarrow n + p + e$.
Thicker neutron skin in Pb means energy rises rapidly with density → Quickly favors uniform phase.
Thick skin in Pb → low transition density in star.
Weak Interaction

1930’s - The weak nuclear interaction was needed to explain nuclear beta decay
Contact interaction with charge exchanged
or, mediated by a heavy, charged boson

1950’s - Discovery of parity-violation by the weak interaction

V-A theory described W’s as only interacting with left-handed particles!

<table>
<thead>
<tr>
<th>W Charge</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T = \pm \frac{1}{2}$</td>
<td>$\text{zero}$</td>
<td></td>
</tr>
</tbody>
</table>