Neutron stars at JLAB and the Pb Radius Experiment

**PREX** uses parity violating electron scattering to accurately measure the neutron radius of $^{208}\text{Pb}$.

This has many implications for nuclear structure, astrophysics, atomic parity non-conservation, and low energy tests of the Standard Model.

JLAB Users Group Meeting, June 2009
C. J. Horowitz, Indiana University
PREX and Related Physics

- Introduction: PREX exp.
- PREX and:
  - Atomic PNC.
  - Nuclear structure.
  - Neutron stars.
- Radiative corrections to PREX and Qweak.
Parity Violation Isolates Neutrons

- In Standard Model $Z^0$ boson couples to the weak charge.
- Proton weak charge is small:
  \[ Q_{W}^p = 1 - 4\sin^2\Theta_W \approx 0.05 \]
- Neutron weak charge is big:
  \[ Q_{W}^n = -1 \]
- Weak interactions, at low $Q^2$, probe neutrons.
- Parity violating asymmetry $A_{pv}$ from interference of photon and $Z^0$ exchange. In Born approximation
  \[ A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{ch}(Q^2)} \]
  \[ F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r) \]
- PREX will measure $A_{pv}$ for 1.05 GeV electrons scattering from $^{208}$Pb at 5 degrees to 3%. This gives neutron radius to 1% ($\pm 0.05$ fm).
  - Donnelly, Dubach, Sick first suggested using PV to measure neutrons.

\[ A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-} \]
Weak and E+M charge densities

Relativistic mean field calculation showing point proton and neutron densities (dashed) and weak and electromagnetic charge densities (solid).

\[
\rho_W(r) = \int d^3 r' \left[ G_W^m (r' - r) \rho_n(r') + \frac{Q_W^p}{Q_W^n} G_W^p (r' - r) \rho_p(r') \right]
\]

Total weak charge of nucleus

\[
Q_W = \int d^3 r \rho_W(r) = N - (1 - 4 \sin^2 \Theta_W) Z
\]
New $5^0$ Septum being developed

Increases the Figure of Merit
High Resolution Spectrometers

Spectrometer Concept:
Resolve Elastic

1st excited state Pb 2.6 MeV

Left-Right symmetry to control transverse polarization systematic

R. Michaels
Systematic Error Challenges

- Small asymmetry: \(500 \pm 15 \text{ ppb}\)
- High precision: \(\delta A_{pv}/A_{pv} \pm 3\%\)
- No backgrounds (not what you might think ---\> spectrometers)
- 1\% normalization (polarimetry).
- Analyzing power \(\sim 10 A_{pv}\). Need to measure and control transverse components of polarization.
- Need excellent control of helicity correlated beam properties.
- Hall A parity collaboration has completed a number of successful parity experiments.
PREX and Atomic Parity Nonconservation

$^{208}\text{Pb}$
Atomic Parity Nonconservation

• Atomic PNC depends on overlap of electrons with neutrons in nucleus.

• Cs experiment good to 0.3%. Not limited by $R_n$ but future 0.1% exp would need $R_n$ to 1%

• Measurement of $R_n$ in $^{208}$Pb constrains nuclear theory for $R_n$ in other atomic PNC nuclei.

• Combine neutron radius from PV e scattering with an atomic PNC exp for best low energy test of standard model.

• Recent Atomic PNC Progress:
  • Improved atomic theory for Cs.
  • First PNC results from Berkeley Yb experiment.
  • Start of TRIUMF program for laser trapped radioactive Fr.
  • KVI program on PNC in Ra+.
Density Functional Theory (DFT)

Hohenberg-Kohn: There exists an energy functional $E_{\text{vext}}[\rho]$. 

$$
E_{\text{vext}}[\rho] = F_{\text{HK}}[\rho] + \int d^3 x v_{\text{ext}}(x) \rho(x)
$$

$F_{\text{HK}}$ is universal (same for any external $v_{\text{ext}}$) $\Rightarrow H_{2\text{toDNA}}$

Introduce orbitals and minimize energy functional $= \Rightarrow E_{\text{gs}}, \rho_{\text{gs}}$

Useful if you can approximate the energy functional

Construct microscopically or fit a "general" form

---

PREX and Nuclear Structure

Experimental charge densities from electron scattering
Neutron Skin and Symmetry E

- $^{208}$Pb has $Z=82$ protons and $N=126$ neutrons.
- **Where do the $N-Z=44$ extra neutrons go?** In the center of the nucleus? At the surface?
- Relevant microphysics: A $pn$ pair in bound $^3S_1$ state has more attractive interaction than $pp$ or $nn$ pair in unbound $^1S_0$ state.

The symmetry energy $S(n)$ describes how $E$ of nuclear matter rises when one goes away from $N=Z$.

$$E(n, \delta) \approx E(n, \delta = 0) + \delta^2 S(n)$$

$$\delta = (N - Z)/A$$

PREX will constrain density dependance of sym. $E$, $dS/dn$.

Symmetry E very important to extrapolate to neutron rich systems in astrophysics.
Pb Radius Measurement

- Pressure forces neutrons out against surface tension. Large pressure gives large neutron radius.
- Pressure depends on derivative of energy with respect to density.
- Energy of neutron matter is $E_{\text{nuc}}$ of nuc. matter plus symmetry energy.

\[ E_{\text{neutron}} = E_{\text{nuclear}} + S(\rho) \]

\[ P \rightarrow dE/d\rho \rightarrow dS/d\rho \]

- Neutron radius determines $P$ of neutron matter at $\approx 0.1 \text{ fm}^{-3}$ and the density dependence of the symmetry energy $dS/d\rho$.

Neutron minus proton rms radius of Pb versus pressure of pure neutron matter at $\rho=0.1 \text{ fm}^{-3}$. 
PREX and Neutron Stars
Neutron Star Crust vs $^{208}\text{Pb}$ Neutron Skin

- Neutron star has solid crust (yellow) over liquid core (blue).
- Nucleus has neutron skin.
- Both neutron skin and NS crust are made out of neutron rich matter at similar densities.
- Common unknown is EOS at subnuclear densities.

Liquid/Solid Transition Density

- Thicker neutron skin in Pb means energy rises rapidly with density $\rightarrow$ quickly favors uniform phase.
- Thick skin in Pb $\rightarrow$ low transition density in star.

J Piekarewicz, CJH
Neutron Star Quadrupole Moment and Gravitational Waves

- A solid crust can support an off axis mass quadrupole moment.
- Rapidly rotating NS quad. moment efficiently radiates gravitational waves.
- Very active ongoing/ future searches for continuous GW at LIGO, Virgo, Advanced LIGO...
- How big can the quad. moment be? This depends on the thickness and strength of the crust (before any mountain collapses under the extreme gravity of a NS).
- We have performed large scale molecular dynamics simulations of the crust breaking stress, including effects of defects, impurities, and grain boundaries...
- We find: neutron star crust is the strongest material known. It is 10 billion times stronger than steel. Very promising for GW searches.
Pb Radius vs Neutron Star Radius

- The \(^{208}\text{Pb}\) radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above. Central density of NS few to 10 x nuclear density.
- Important to have both low density and high density measurements to constrain density dependence of EOS from a possible phase transition.
  - 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…

J Piekarewicz, CJH
Measuring Neutron Star Radii

- Deduce surface area from luminosity, temperature from X-ray spectrum.

- Complications:
  - Need distance (from parallax for nearby isolated NS...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.

- Proposed International X-ray Observatory (larger collecting area) can measure both R and mass.

\[ L_\gamma = 4\pi R^2 \sigma_{SB} T^4 \]

IXO could be an important machine to study dense QCD.
Radiative Corrections
γ-Z Box Diagrams

• Elastic intermediate states are coherent, order $Z\alpha$. Important for PREX (Pb has $Z=82$).

• Inelastic is order $\alpha/Q_w$ compared to tree level. Possibly important for Qweak exp on proton. Note inelastic involves weak transition form factor and not weak charge $Q_w$!
Coulomb Distortions for PREX

- We sum elastic intermediate states to all orders in $Z\alpha$ by solving Dirac equ for $e$ moving in coulomb $V$ and weak axial $A$ potentials.

\[ A \propto G_F \rho_W(r) \approx 10 \text{ eV} \quad V(r) \approx 25\text{MeV} \]

- Right handed $e$ sees $V+A$, left handed $V-A$

\[ A_{pv} = \frac{[d\sigma/d\Omega|_{V+A} - d\sigma/d\Omega|_{V-A}]}{2d\sigma/d\Omega} \]

- Coulomb distortions reduce $A_{pv}$ by $\sim30\%$, but they are accurately calculated.

--- With E.D. Cooper!
Inelastic $\gamma Z$ box correc. for Qweak

- Not obviously big for PREX, but important for the Qweak experiment because of the small weak charge of the proton.

- We sum over excited nucleon states with a dispersion integral using a model that fits photo-absorption data.

- Two main contributions: Resonances $\sim 2\%$, dominated by Delta.

- High E non resonant contribution that we evaluate using a generalized vector meson dominance model $\sim 4\%$.

- For 1.16 GeV kinematics of Qweak we find a total correction of 5.7\% to the parity violating asym. compared to the exp error goal of 2\% (statistical).

with M. Gorchtein, Phys. Rev. Let. 102, 091806
We don’t want Qweak to be another NuTeV

- NuTeV is a beautiful Fermi Lab neutrino experiment that has proved difficult to interpret as a Standard Model test.

- Important to have more work on radiative corrections to Qweak involving excited nucleon intermediate states. This should be done soon.
Pb Radius Experiment

- PREX uses parity violating electron scattering to accurately measure the neutron radius of $^{208}\text{Pb}$. This has implications for nuclear structure, astrophysics, and atomic parity nonconservation.

- People:
  - Coulomb distortions with E.D. Cooper.
  - Correlations with J. Piekarewicz.
  - Radiative corrections with M. Gorshtein.


- Supported in part by DOE and State of Indiana.