Parity Radius Experiment and Neutron Densities

C. J. Horowitz
Indiana University
RIA INT Workshop, Sep. 2007
Neutron Densities

• Introduction: atomic parity.
• PREX experiment.
• Implications of the neutron density for astrophysics.
• PREX details.
• Conclusions for neutron densities.

With J. Piekarewicz, E. D. Cooper, R. Michaels, P. Souder ...
Atomic Parity Nonconservation

- Depends on overlap of electrons with neutron density.
- Cs exp. good to 0.3%.
- Not limited by $R_n$ but future 0.1% exp would need $R_n$ to 1%
- Future isotope ratio exp may need neutron radii differences.
- Possible exp with Fr isotopes

Colorado Cs Experiment

- Combine neutron radii from PV e scattering with an atomic PNC exp for best low energy test of standard model.
Coherent Weak Charge

• In standard model weak charge $Q_w$ is
  \[ Q_w = Z \left(1 - 4 \sin^2 \Theta_w \right) - N \]

• Weak charge dominated by neutrons and is large for large $N$ nucleus.

• Important in Astrophysics. Nu-A elastic scattering has a large cross section $\sim N^2$. This first traps neutrinos in core collapse supernovae. Dynamics involve sensitive balance between gravity and lepton Fermi pressure. If nu not trapped, star may collapse to black hole without SN explosion.
Neutrino-Nucleus Elastic Scattering

• One way to measure neutron density of nucleus: 0707.419 Amanik+McLaughlin

• I strongly support an experiment even if one learns no new info. on neutron density.
  – Fundamental process never observed before.
  – Important technology for future. Explore new domain of low threshold experiments.
  – Use nu-A elastic in osc. exp. sensitive to nu sterile.
  – Low E solar nu, double beta decay, dark matter ... detectors sensitive to SN nu via elastic scattering.
PREX uses parity violating elastic electron scattering to measure the neutron radius of $^{208}\text{Pb}$

Spokespersons: P. Souder, R. Michaels, and G. Urciuoli

http://hallaweb.jlab.org/parity/prex
Parity Radius Experiment

- Parity violation probes neutrons because weak charge of $n \gg p$.
- Elastic scattering of 850 MeV e from $^{208}\text{Pb}$ at $6^\circ$.

$$A = \frac{d\sigma}{d\Omega} + \frac{d\sigma}{d\Omega} - \frac{d\sigma}{d\Omega} + \frac{d\sigma}{d\Omega} -$$

- Measure $A \approx 0.6$ ppm to 3%. This gives neutron radius to 1% ($\pm 0.05$ fm).
- Purely electroweak reaction is model independent
PREX History

• **1989** Donnelly Dubach, Sick --> PV for n densities.
• **1998** CJH calculates PV asy. with coulomb distortions
• **1999** Michaels + CJH optimize PREX kinematics.
• **2000** PREX discussed at ECT* conference on PV.
• **2001-** Relation of neutron density to:
  – Pressure of neutron matter (Alex Brown),
  – Density dependence of symmetry energy,
  – Many neutron star properties, identified.
• **2000-5** HAPPEX, HAPPEX II, HAPPEX He run.
• **2008-9** PREX runs (?!)

Atomic PV was original motivation for PREX. Now nuclear structure, implications for astrophysics, important.
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 $E_{\text{neutron}} = E_{\text{nuclear}} + S(\rho)$.

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

- 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 $\rho=0.1 \text{ fm}^{-3}$. 

Alex Brown et al.
Symmetry Energy

• Describes how energy of system rises as one moves away from N=Z.

• Can think about $S(n_0)$ and $dS/dn$ or volume symmetry energy $S_v = a_4 (N-Z)^2 / A$ and surface symmetry energy $S_s$ of semi-empirical mass formula.

• Nuclear masses determine some combination of $S_v$ and $S_s$ but ratio $S_s / S_v$ is not well constrained.
Isospin Diffusion In HI Collisions

• Bring two chunks of nuclear matter with different N/Z ratios into contact. Symmetry E will drive isospin diffusion.

• If S small, E independent of N/Z and isospin diffusion will be slow.

• Measure equilibration of N/Z in asymmetric HI collisions vs collision time (related to energy).

• Compare to semi-classical simulations and find

\[ S(n) = S_0 \left( \frac{n}{n_0} \right)^{\gamma}, \quad \gamma \approx 0.7 - 1 \]

For \(^{208}\text{Pb}:\) \[ < r_n^2 >^{1/2} - < r_p^2 >^{1/2} \approx 0.22\gamma + 0.06 \text{ fm}. \]

• High E HI collisions may probe S at high densities. Calibrate HI results with PREX at \(n_0\)

-- B. Tsang ...
Neutron Star Crusts

- Neutron stars are densest macroscopic objects. 
  \[ \approx 1.4 \, M_\odot, \, R \approx 12 \, \text{km} \]
- Crust is crystal lattice plus neutron gas (superfluid).
- Liquid core of neutron rich matter of \( \sim \) nuclear density and above with possible exotic interior.
- Pasta is at lower limit of inner crust \( \approx \frac{1}{2} \, \text{km} \) down.

Exotic: quark matter, color superconductor, meson condensate?
Neutron Star Crust vs 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 oscillations

- Neutron stars admit many different types of vibration.
- Theoretical calculations of magnetar starquakes suggested that the easiest modes to excite would be *toroidal* (horizontal) shear modes of the crust (Duncan 1998).
- Mode frequency depends primarily on shear speed. Models predict fundamental $\approx 30$ Hz. Higher n=0 harmonics scale in a predictable way with l.
- Magnetic field effectively boosts shear modulus – important effect if Alfven speed exceeds shear speed.
Magnetar Giant Flares

- Large release of magnetic energy starts crust oscillating.
- Observe modes with radial nodes \((n>0)\) sensitive to crust thickness.
- Suggests thick crust in low mass star??
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.
- 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…

J Piekarewicz, CJH
Measuring Neutron Star Radii

- Deduce surface area from luminosity. \( L_{\gamma} = 4\pi R^2 \sigma_{SB} T^4 \)
- Complications:
  - Need distance (from parallax for nearby isolated NS, from cluster membership for NS in globular clusters ...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
- Radii major goal of Chandra, XMM..
PREX Constrains Rapid Direct URCA Cooling of Neutron Stars

- Proton fraction $Y_p$ for matter in beta equilibrium depends on symmetry energy $S(n)$.
  \[ S \approx \mu_n - \mu_p = \mu_e \]

- $R_n$ 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 $M_\odot$ stars.

- If $R_n - R_p > 0.25$ fm all models do have URCA in 1.4 $M_\odot$ stars.

If $Y_p >$ red line NS cools quickly via direct URCA $n \rightarrow p + e + \nu$

J Piekarewicz, CJH
Comparison with Data

Mag H fits:
1) RX J0822-4247 (in Puppis A)
2) 1E 1207.4-5209 (in PKS 1209-52)
3) PSR 0538+2817
4) RX J0002+6246 (in CTB 1)
5) PSR 1706-44
6) PSR 0933-45 (in Vela)

BB fits:
7) PSR 1055-52
8) PSR 0656+14
9) PSR 0633+1748 "Geminga"
10) RX J1856.5-3754
11) RX J0720.4-3125

Upper limits:
A) CXO J232327.8+584842 (in Cas A)
B) PSR J0205+6449 (in 3C58)
C) PSR J1124-5916 (in G292.0+1.8)
D) RX J0007.0+7302 (in CTA 1)
Hadronic Probes of Neutron Density

• Anti-protons are sensitive to low density tail, not rms radius. [Model dependent to fit wood-saxon ... to tail and use it to calculate rms radius.]

• Proton and or alpha elastic scattering can measure neutron density.  
  – What are systematic errors of rxn mechanism? 
  – Calibrate with PREX $^{208}$Pb result. 
  – Measure n densities of rare isotopes in inverse kinematics.
PREX Details
Optimize Kinematics

- Maximize figure of merit times square of sensitivity to neutron radius.
- Minimizes run time for 1% sensitivity to neutron radius.
- 850 MeV, 6 degrees.
Pb Target Test

- A thinner version of the Pb-diamond foil target was tested recently by a different group.
- Diamond foils did not suffer radiation damage.
- Target melted near 80 micro-amps! Presumably because of poor thermal contact Pb to diamond.
- Earlier, shorter, test with grease was fine.
Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one $Q^2$

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

Neutron Density at one $Q^2$

Assume Surface Thickness Good to 25% (MFT)

$R_n$

Mean Field & Other Models

q = 0.45 fm$^{-1}$

EOS of n rich matter

PREX Physics Impact

Atomic Parity Violation

Heavy Ions

Neutron Stars
Coulomb Distortions

- In Born approx, $A$ is ratio of weak to EM form factor.
  \[ A = \frac{G_F Q^2}{4\pi\alpha 2^{1/2}} \frac{F_W(Q^2)}{F_{ch}(Q^2)} \]
- Coulomb distortions reduce $A$ by $\sim30\%$ (largest correction), but still sensitive to $n$ density.
- Analyzing power $A_n$ is, parity allowed, left right asymmetry for normal polarized beam.
  - This is potential systematic error from small normal $P$ of beam.
  - $A_n$ approx. same size as $A$
  - E.D. Cooper, CJH, PRC 72 (2005)034602.
  - Need to include excited intermediate states.
  - Dispersion calc underway

\[ 208\text{Pb at 850 MeV} \]
PREX: Measurement at one $Q^2$ is sufficient to measure $R_N$.

PREX error bar (1$\sigma$)

Skyrme

covariant meson

covariant point coupling

( R.J. Furnstahl )
Atomic Parity Overlap

Atomic PV depends on overlap of elec. axial transition matrix element with nuclear weak density.

\[ f(r) \approx \psi_p^+(r) \gamma_5 \psi_s(r) \]

For Pb, f(r) looks like \( j_0(qr) \) for \( q \sim 0.3 \text{ fm}^{-1} \)
PREX Status

• Control of helicity correlated beam parameters ok from HAPPeX.

• Target (with vacuum grease) seems fine. Radiation in hall is ok.

• Plan to build warm septum magnets (bend 6 deg. scattered electrons to 12 deg. to enter spectrometers).

• Plan to upgrade polarimetry including green laser for Compton e-gamma polarimeter.

• Full run early ’09 (?)

P. Souder, R. Michaels, G. Urciuoli
Extrapolation from one nucleus to another

- Two nuclei with “simple” nuclear structure. Strong correlation in MFT $R_n$ in $^{208}$Pb vs $^{132}$Ba. IE $R_n$ in Pb constrains density dep. of symmetry $E$ and this determines $R_n$ in other nuclei. PV on Ba is possible but may not provide much more info then Pb.

- Large SCIDAC program to calculate an improved energy density functional for nuclei. This will agree with (or be tuned to?) PREX for Pb and then may provide the best neutron densities in other systems (Fr?).
Neutron Densities

• Have many implications for nuclear structure and astrophysics including for the radius, crust transition density, and cooling of neutron stars.

• The neutron radius in Pb depends on the density dependence of the symmetry energy.

• PREX aims to measure $R_n$ in Pb to 1% using PV electron scattering.

• What n density would you like? Let’s work on it.
What one thing should atomic physicists take away from this talk?

- Through advances in nuclear theory, a parity violating measurement, and other measurements with strongly interacting probes, our knowledge of neutron densities is improving significantly.
PREX

• Implications of PREX in astrophysics done with J. Piekarewicz.

• Coulomb distortion and analyzing power calculations done with E. D. Cooper.