The PREX and CREX neutron density experiments and neutron stars
PREX measures how much neutrons stick out past protons (neutron skin).
PREX uses Parity V. to Isolate Neutrons

- Standard Model $Z^0$ couples to weak charge.
- Proton weak charge is small:
  \[ Q^p_W = 1 - 4\sin^2\Theta_W \approx 0.05 \]
- Neutron weak charge is big:
  \[ Q^n_W = -1 \]
- Weak interactions, at low $Q^2$, probe neutrons.
- Parity violating asymmetry $A_{pv}$ is cross section difference for positive and negative helicity electrons
  \[ A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-} \approx \frac{G_F Q^2 |Q_W|}{4\pi \alpha \sqrt{2Z}} \frac{F_W(Q^2)}{F_{ch}(Q^2)} \]
- $A_{pv}$ from interference of photon $Z^0$ exchange.
- Determines weak form factor
  \[ F_W(q) = \frac{1}{Q_W} \int d^3r j_0(qr) \rho_W(r) \]
- Model independently map out distribution of weak charge in a nucleus.
- Electroweak reaction free from most strong interaction uncertainties.

- PREX-2 $^{208}$Pb results $R_W=5.800+/-0.075$ fm ($R_{ch}=5.503$) and $R_n-R_p=0.283+/-0.071$ fm
• 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 and \(^{48}\)Ca constrains nuclear theory for \( R_n \) in other atomic PNC nuclei.

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

Neutrino nucleus scattering involves same weak form factor as PV electron scattering

\[
\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \frac{Q_W^2}{4} F^2(Q^2) \\
\times \left[ 2 - \frac{2T}{E} + \left( \frac{T}{E} \right)^2 - \frac{MT}{E^2} \right]
\]

Coherent at SNS probed CsI average \( R_n \) to ~15%

PREX measured \( R_w(208\text{Pb}) \) to 1.3%

CREX probed \( R_w(48\text{Ca}) \) to 0.7%

Qweak measured \( R_n(27\text{Al}) \) to 3.8%

Use PV to constrain nuclear structure. This allows coherent neutrino scattering to probe non-standard neutrino interactions.
Radii of $^{208}$Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension $\Rightarrow R_n - R_p$ of $^{208}$Pb correlated with $P$ of neutron matter.
- Radius of a neutron star also depends on $P$ of neutron matter.
- Measurement of $R_n$ ($^{208}$Pb) in laboratory has important implications for the structure of neutron stars.

Neutron star is 18 orders of magnitude larger than Pb nucleus but both involve neutron rich matter at similar densities with the same strong interactions and equation of state.
LIGO and deformability of NS

- Gravitational tidal field distorts shapes of neutron stars just before they merge.
- Dipole polarizability of an atom $\sim R^3$.
  \[ \kappa = \sum_f \frac{|\langle f | r Y_{10} | i \rangle|^2}{E_f - E_i} \propto R^3 \]
- Tidal deformability (or quadrupole polarizability) of a neutron star scales as $R^5$.
  \[ \Lambda \propto \sum_f \frac{|\langle f | r^2 Y_{20} | i \rangle|^2}{E_f - E_i} \propto R^5 \]
- GW170817 observations set upper limit on $\Lambda$.
- For NS sum over excited states = sum over osc. modes. Most important is $f_2$ mode.
- Response to static tidal or electric field -> static polarizability or deformability.
- Response to time dependent fields -> dynamical polarizability or dynamical tides.
Radii favored by LIGO

\[ \Lambda^{1.4} \]

\[ R^{208}_{\text{skin}} \text{(fm)} \]

**Phys. Rev. Let.** \textbf{120}, 172702

Farrukh Fattoyev
Radii favored by LIGO

PSR J0030+0451

NICER

LIGO upper bound

$R_{\text{skin}}^{208}$ (fm)

$\Lambda^{1.4}$

$R_{\star}^{1.4}$ (km)
CREX on $^{48}\text{Ca}$ and Chiral EFT

- Chiral EFT expands 2, 3, … nucleon interactions in powers of momentum transfer over chiral scale.

- **Three neutron forces** are hard to directly observe. They increase the pressure of neutron matter and the neutron skin thickness of both $^{208}\text{Pb}$ and $^{48}\text{Ca}$.

- Only stable, neutron rich, closed shell nuclei are $^{48}\text{Ca}$ and $^{208}\text{Pb}$.

- PREX for $^{208}\text{Pb}$ better for inferring pressure of neutron matter and structure of neutron stars.

- CREX measures neutron skin in $^{48}\text{Ca}$. Smaller system allows direct comparison to Chiral EFT calculations and very sensitive to 3 neutron forces.
CREX

- 2.182 GeV electrons scattering with $q=0.8733$ fm$^{-1}$ from $^{48}$Ca.
- Target 8% $^{40}$Ca, 0.6%, 0.6%, 0.2% of rate from first three excited states ($2^+, 3^-, 3^-$).
- $A_{PV}=2668 \pm 106 \pm 40$ ppb
- We thank J. Piekarewicz, P. G. Reinhard and X. Rocca-Maza for RPA calculations of $^{48}$Ca excited states and J. Erler and M. Gorshteyn for calculations of $\gamma - Z$ box radiative corrections.

<table>
<thead>
<tr>
<th>Correction</th>
<th>Absolute [ppb]</th>
<th>Relative [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam polarization</td>
<td>382 ± 13</td>
<td>14.3 ± 0.5</td>
</tr>
<tr>
<td>Beam trajectory &amp; energy</td>
<td>68 ± 7</td>
<td>2.5 ± 0.3</td>
</tr>
<tr>
<td>Beam charge asymmetry</td>
<td>112 ± 1</td>
<td>4.2 ± 0.0</td>
</tr>
<tr>
<td>Isotopic purity</td>
<td>19 ± 3</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>3.831 MeV ($2^+$) inelastic</td>
<td>$-35 \pm 19$</td>
<td>$-1.3 \pm 0.7$</td>
</tr>
<tr>
<td>4.507 MeV ($3^-$) inelastic</td>
<td>0 ± 10</td>
<td>0 ± 0.4</td>
</tr>
<tr>
<td>5.370 MeV ($3^-$) inelastic</td>
<td>$-2 \pm 4$</td>
<td>$-0.1 \pm 0.1$</td>
</tr>
<tr>
<td>Transverse asymmetry</td>
<td>0 ± 13</td>
<td>0 ± 0.5</td>
</tr>
<tr>
<td>Detector non-linearity</td>
<td>0 ± 7</td>
<td>0 ± 0.3</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0 ± 24</td>
<td>0 ± 0.9</td>
</tr>
<tr>
<td>Radiative corrections ($Q_W$)</td>
<td>0 ± 10</td>
<td>0 ± 0.4</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>40 ppb</td>
<td>1.5%</td>
</tr>
<tr>
<td>Statistical Uncertainty</td>
<td>106 ppb</td>
<td>4.0%</td>
</tr>
</tbody>
</table>
Model error in extraction of $R_W - R_{ch}$ or $R_n - R_p$ from spread in model predictions for given $F_{ch} - F_W$.

Exp. error in $R_n$ $\pm 0.026$ fm (0.7%)
Total error in $R_n$ $\pm 0.035$ fm (1%)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value ± (exp) ± (model) [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_W - R_{ch}$</td>
<td>$0.159 \pm 0.026 \pm 0.023$</td>
</tr>
<tr>
<td>$R_n - R_p$</td>
<td>$0.121 \pm 0.026 \pm 0.024$</td>
</tr>
</tbody>
</table>

No model error in $F_{ch} - F_W$

$F_{ch}(q) - F_W(q) = 0.0277 \pm 0.0055$ (exp)
CREX Experiment

• New and precise measurement of $A_{PV}$ from $^{48}\text{Ca}$ at $q=0.8733$ fm$^{-1}$

• Main result (model independent):

$$F_{\text{ch}}(q) - F_{\text{W}}(q) = 0.0277 \pm 0.0055 \text{ (exp)}$$

• Extract with small model dependence from shape of $\rho_w(r)$

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value ± (exp) ± (model) [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_W - R_{\text{ch}}$</td>
<td>$0.159 \pm 0.026 \pm 0.023$</td>
</tr>
<tr>
<td>$R_n - R_p$</td>
<td>$0.121 \pm 0.026 \pm 0.024$</td>
</tr>
</tbody>
</table>

• Compared to many density functional models, neutron skin of $^{48}\text{Ca}$ is somewhat thin and $^{208}\text{Pb}$ somewhat thick. However, a number of models are consistent (at 90%) with both PREX and CREX.
PREX and CREX Collaborations

**Students:** Devi Adhikari, Devaki Bhatta Pathak, Quinn Campagna, Yufan Chen, Cameron Clarke, Catherine Feldman, Iris Halilovic, Siyu Jian, Eric King, Carrington Metts, Marisa Petrusky, Amali Premathilake, Victoria Owen, Robert Radloff, Sakib Rahman, Ryan Richards, Ezekiel Wertz, Tao Ye, Adam Zec, Weibin Zhang

**Post-docs and Run Coordinators:** Rakitha Beminiwattha, Juan Carlos Cornejo, Mark-Macrae Dalton, Ciprian Gal, Chandan Ghosh, Donald Jones, Tyler Kutz, Hanjie Liu, Juliette Mammei, Dustin McNulty, Caryn Palatchi, Sanghwa Park, Ye Tian, Jinlong Zhang

**Spokespeople:** Kent Paschke ([contact](mailto:kent.paschke@iu.edu)), Krishna Kumar, Robert Michaels, Paul A. Souder, Guido M. Urciuoli

Thanks to the Hall A techs, Machine Control, Yves Roblin, Jay Benesch and other Jefferson Lab staff

Student **Brenden Reed** made important contributions!

C. Horowitz (horowit@iu.edu)