MEASUREMENTS OF TRANSVERSE BEAM ASYMMETRY FOR ELASTIC ELECTRON SCATTERING OFF VARIOUS NUCLEI FROM PREX-II AND CREX

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**AN MEASUREMENTS PURPOSE**

\( A_n \) is a direct probe of higher-order photon exchange

- Incident beam is vertically polarized
- Change sign of vertical polarization
- Measure fractional rate difference

\[ A_n = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]

\( \sigma^\uparrow(\downarrow) \) elastic scattering xsec for e’s with spin \( P_e \) parallel (or antiparallel) to the normal vector defined by the scattering plane

\[ A_n^m = A_n \hat{P}_e \cdot \hat{n} \]

- \( A_n \): beam-normal single spin asymmetry in elastic scattering of electrons polarized perpendicular to the scattering plane off unpolarized nucleons
- \( A_n \) is a direct probe of higher-order photon exchange, the inclusion of which is necessary for interpretation of \( A_{PV} \) data
- At higher energies, excited intermediate nuclear states become important for determining \( A_n \) in dispersive calculations, which neglect Coulomb distortions, and have most success in forward angle scattering
- Measured via fractional rate difference between incident electron beam vertical polarization states on unpolarized target
- \( A_n \) can contribute systematic uncertainty to the extracted \( A_{PV} \) (in elastic electron scattering experiments like PREX and CREX) if the beam polarization has a transverse component and the apparatus lacks perfect symmetry

PREX / CREX An Measurement in Hall A

- The momentum resolution of the spectrometers ensured that essentially only elastic events were accepted.
- Analog integration of everything that hits the detector
- Electron polarization was set vertical: A_n modulated by sine of the azimuthal scattering angle
- Ensured acceptance of the two spectrometers (symmetrically placed to accept horizontally scattered events) contained the maximum and minimum of the asymmetry

**Integration detection for each helicity state in a helicity window.**

\( Q^2 \sim 0.0062 \text{ GeV}^2 \)

5° scattering angle

\( A_{PV} \sim 0.6 \text{ ppm } \pm 0.02 \text{ ppm} \)

Rate \( \sim 2 \text{ GHz} \)
Targets

- Diamond foils - excellent thermal conductivity
- $^{12}$C is isoscaler, spin-0, $A_{pv}$ is well-measured, so benign background! (dilution, not false asymmetry)
- 70uA limited in PREX because of target thermal properties

0.5mm lead, 0.25mm diamond, 1 sqin
Use synchronized 4x4mm raster to handle non-uniform lead thickness

- Target has good thermal conductivity, so can run at higher 150uA current
- New Target sandwiched 3 pucks together: ~92% 48Ca
• Data obtained in Su 2019, Sp 2020 during PREX-II and CREX runs where the goal was to determine the radius of the distribution of neutrons.

• Data obtained to study systematic uncertainties for these measurements in elastic electron scattering, since $A_n$ can contribute to the extracted $A_{PV}$ if the beam polarization has a transverse component and the apparatus lacks perfect symmetry.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target</th>
<th>$\theta_{\text{lab}}$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$E_b$ (GeV)</th>
<th>$&lt;\cos \phi&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREX-II</td>
<td>Carbon-12</td>
<td>5°</td>
<td>0.0066</td>
<td>0.95</td>
<td>0.966</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>5°</td>
<td>0.0062</td>
<td>0.95</td>
<td>0.969</td>
</tr>
<tr>
<td></td>
<td>Ca40</td>
<td>5°</td>
<td>0.0066</td>
<td>0.95</td>
<td>0.974</td>
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<tr>
<td>CREX</td>
<td>Carbon-12</td>
<td>5°</td>
<td>0.033</td>
<td>2.183</td>
<td>0.963</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>5°</td>
<td>0.032</td>
<td>2.183</td>
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</tr>
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<tr>
<td></td>
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<td>5°</td>
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<td>2.183</td>
<td>0.964</td>
</tr>
</tbody>
</table>
Beam from source to target

**Laser Beam**
- Circularly polarized light
- Pockels Cell
- +/- HV
- Randomized Helicity Signal

**GaAs photocathode**
- Laser beam
- e-beam

**Electron Beam**
- e- : Right handed
- e- : Left handed
- Experimental Hall
- +/− HV

Ref: Silwal Thesis, Fig 6.7.2
**Beam from source to target**

**Laser Beam**
- Circularly polarized light
- Randomized Helicity Signal
- Pockels Cell
- +/- HV

**Electron Beam**
- e- : Vertical
- Spin
- e- : Vertical
- Spin
- Injector spin manipulation:
  - ExB for $\pi$ precession

Ref: Silwal Thesis, Fig 6.7.2

*Both fast and slow reversals*
- 4 reversal combinations
- Helicity: HV +/-, IHW out/in
Fast Reversals: Statistical Uncertainty & Helicity Flipping

- Helicity switching: Time “windows” are generated in the electron bunch train at a selected flip rate, with the sign of the beam’s polarization in each window assigned on a pseudo-random basis.

- Frequency selection for helicity flipping – noise, widths, statistical errors
  - PREXII – 240Hz octets +--+-+-- -+-++-+-+
  - CREX – 120Hz quartets +-- +---

\[ \text{Octet Asymmetry} \]

\[ \text{~90ppm at 30Hz} \]

\[ 1\text{ppm precision in 5min} \]
Any change in the polarized beam, correlated to helicity reversal, can be a potential source for a false asymmetry.

Means: Charge asymmetry, Position differences, Spot-size Asymmetry
- Small as possible
- Minimize helicity correlated \( A_Q \)
- Minimize helicity correlated position differences

Widths: Beam noise, Monitor Noise
- Smaller widths help statistically
- Larger widths help establish correlations with monitors (ie slopes), which are then used to correct contributions from helicity correlated beam differences (ie. means)
- Help get corrections (ie shifts)

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

MONITOR: I,E,X,Y

Slope x Mean = Shift

\[
\begin{align*}
\text{Raw asymmetry} & = \text{Slope x Mean} = \text{Shift} \\
340\text{ppm RMS} & \rightarrow 95\text{ppm RMS}
\end{align*}
\]
• Left and Right arms symmetrically probe $A_n$ with opposite sign and are combined via $A_{\text{raw}} = (A_{\text{Larm}} - A_{\text{Rarm}})/2$
• Sign corrected for IHWP state, several hours were spent at each IHWP state on each target, ~8 hours of data shown above
• Beam corrections made via charge normalization
• $\beta_i$ calculated via beam noise regression and measured several times per hour by dithering steering coils. Both methods results are shown above

$A_{\text{raw}} = A_{\text{det}} - A_Q + \alpha \Delta_E + \sum \beta_i \Delta x_i$
Uncertainties

- Nonlinearity in the PMT response was limited to 0.3% in bench tests that mimicked running conditions.
- Total relative nonlinearity between the calibration of the PMT response and those of the beam intensity monitors was limited to 2%.
- Beam polarization was inferred from longitudinal polarization measurements taken before and after the transverse polarization data taking.
- \( P_e \) (CREX): 86.9% obtained by averaging both Compton and Moller measurements. \( P_e \) (PREX): 89.5% obtained by averaging only Moller measurements for in/out states [and while detailed polarimetry analysis completes, we are assigning a relative uncertainty of 2%].
- Target impurities in \(^{208}\text{Pb}\) (sandwiched between diamond \(^{12}\text{C}\) foils) and \(^{48}\text{Ca}\) (partly \(^{40}\text{Ca}\)) were accounted for via rate ratio calculation and subtraction of measured asymmetries in \(^{12}\text{C}\) and \(^{40}\text{Ca}\). \(^{12}\text{C}\) contributes \(\sim 7\%\) rate (at 1\,GeV) and \(\sim 47\%\) rate (at 2\,GeV, due to FF) in Pb target measurements and \(^{40}\text{Ca}\) contributes \(< 1\%\) rate in \(^{48}\text{Ca}\) target measurement.
- Beam asymmetry uncertainties contributed approximately 1-4\% in \(^{12}\text{C}\), \(^{40}\text{Ca}\) (and 0.06\,ppm for \(^{208}\text{Pb}\)) at 1\,GeV and 1-2\% in \(^{12}\text{C}\), \(^{40}\text{Ca}\), \(^{48}\text{Ca}\) (and 0.09\,ppm for \(^{208}\text{Pb}\)) at 2\,GeV.
- Statistical uncertainties for the \(^{40}\text{Ca}\), \(^{48}\text{Ca}\) and \(^{12}\text{C}\) measurements were approximately 6\% (and 0.35\,ppm for \(^{208}\text{Pb}\)) at 1\,GeV and 11\% (and 1.9\,ppm for \(^{208}\text{Pb}\)) at 2\,GeV.
- (Note: And small residual longitudinal component of the electron spin will only introduce a negligible parity-violating contribution to the measured asymmetry.)
Old Model:
• Gorchstein & Horowitz 2008
• $A_n \sim Q/A/Z$
• not strongly $Z$-dependent
• 2-photon exchange calculation
• includes a dispersion integral over intermediate excited states
• neglects Coulomb distortions
• Await new calculations

• **Previously published 2012**
• $^{208}\text{Pb} A_n \equiv 0$ for $Q=1\text{GeV}$
• $^1\text{H}, ^4\text{He}, ^{12}\text{C}$ consistent with 2008 Gorchstein theoretical calculation
OLD Model:

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• not strongly $Z$-dependent

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PREX-II and CREX $A_n$ Results

Observe features:

- New $A_n$ measurements (PREXII,CREX) consistent with old measurements (PREXI)
  - $^{208}$Pb $A_n$ nearly 0 for multiple $Q$ [from 0.08-0.17GeV] (after $^{12}$C diamond subtraction)
  - $^{12}$C and $^{40}$Ca $A_n$ nearly overlap one another for 2 different $Q$ [from 0.08-0.17GeV]
  - $^{48}$Ca and $^{40}$Ca $A_n$ overlap one another for these kinematics (despite differing $A/Z$)

All points here:

- forward angle scattering 5°, 6°
- Clean separation of elastics from inelastics in acceptance

<table>
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<tr>
<td>H</td>
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Phenomenological Model

Global phenomenological fit presuming linear Q dependent model:

- Observe: $^4$He, $^{12}$C, $^{48}$Ca, $^{40}$Ca (measured at $5^\circ$ and $6^\circ$) points appear to lie along this linear fit
- Observe: offset is non-zero
- Forcing a fit through (0,0) fails, indicating $A_n$ is not strictly proportionate to $Q$ in this kinematic region
Considering A/Z scaling

Model:
- Gorchstein & Horowitz 2008

\[ A_n = \hat{A}_n \frac{QA}{Z} \]

- Plot with \( A_n \) normalized to A/Z to remove A,Z dependence

- For the light and A/Z=2 nuclei \((^1\text{H}, ^4\text{He}, ^{12}\text{C}, ^{40}\text{Ca})\), \( A_n \) does appear to satisfy A/Z scaling

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All points here HRS data forward angle scattering 5°, 6°
Considering A/Z scaling

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- Gorchstein & Horowitz 2008

\[ A_n = \hat{A}_n \frac{Q A}{Z} \]

- Plot with \( A_n \) normalized to A/Z to remove A,Z dependence

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All points here HRS data forward angle scattering 5°, 6°

- For the light and A/Z=2 nuclei (\(^1\)H, \(^4\)He, \(^{12}\)C, \(^{40}\)Ca), \( A_n \) does appear to satisfy A/Z scaling

- However there exist other measurements at other angles (i.e. not 5°) such as a new \(^1\)H Qweak point (~8°) which deviates from this rough A/Z scaling
• Newer dispersive calculations (by Gorchtein) exist which were extended to address larger scattering angle measurements.

• Larger angle scattering measurements require model corrections and may not follow the same trends with Q as small angle scattering, new calculations are awaited

• Gorchtein working on new curve closer to the kinematics of our measurements region
Other Measurements

- Beginning to develop a landscape of $A_n$ measurements for a range of $A$ and $Z$ at various kinematics
- HAPPEX, PREX and CREX measurements all small angle elastic scattering ($5^\circ, 6^\circ$)
- (Note: larger angle scattering measurements exist but require model corrections and may not be useful for comparison on the same diagram)
Summary

- Achieved: a systematic set of $A_n$ measurements for a range of $Z$ at various beam energies [for the purpose of constraining transverse spin component systematic contributions in $A_{P_{\nu}}$ measurements of PREX and CREX]

- Observed (for forward elastic electron scattering at 50°) features:
  - New $A_n$ measurements (PREXII, CREX) consistent with old measurements (HAPPEX, PREXI)
  - $^{208}\text{Pb} A_n$ nearly 0 for multiple $Q$ [from 0.08-0.17GeV]
  - $^{12}\text{C}$ and $^{40}\text{Ca}$ $A_n$ nearly overlap one another for 2 different $Q$ [from 0.08-0.17GeV]
  - $^{48}\text{Ca}$ and $^{40}\text{Ca}$ $A_n$ overlap one another for these kinematics (despite differing $A/Z$)
  - $A_n$ for $^4\text{He}, ^{12}\text{C}, ^{48}\text{Ca}, ^{40}\text{Ca}$ (while appearing linear with $Q$) does not appear strictly proportionate to $Q$ in the kinematic range
  - For the light and $A/Z$=2 nuclei ($^1\text{H}, ^4\text{He}, ^{12}\text{C}, ^{40}\text{Ca}$), $A_n$ does appear to satisfy $A/Z$ scaling.

- Wish: new theoretical calculations that treat dispersion corrections and Coulomb distortions simultaneously

- Hope: might lead to new insights into the structure of heavy nuclei [or just help guide and constrain theoretical calculations]