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

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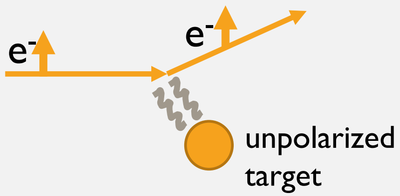
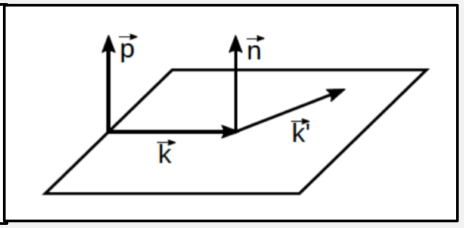
Jefferson Laboratory Hall A/C Meeting 07/16/2020

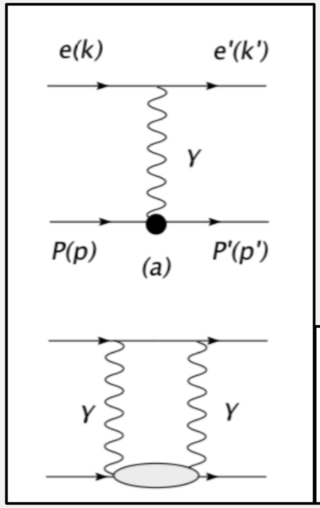
A_N MEASUREMENTS PURPOSE

A_n is a direct probe of higher-order photon exchange



$$A_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$





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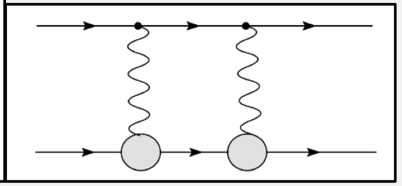


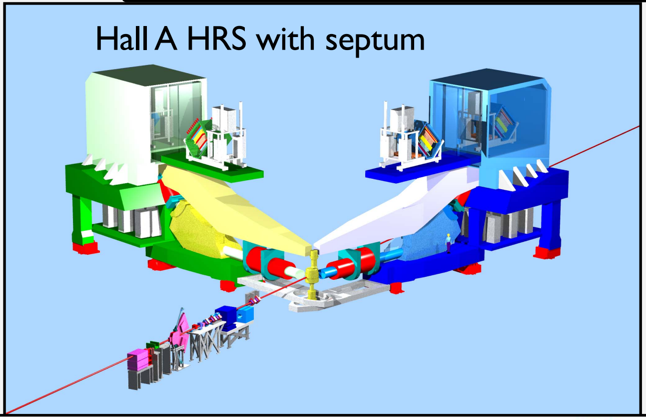
- *Incident beam is vertically polarized*
- *Change sign of vertical polarization*
- *Measure fractional rate difference*

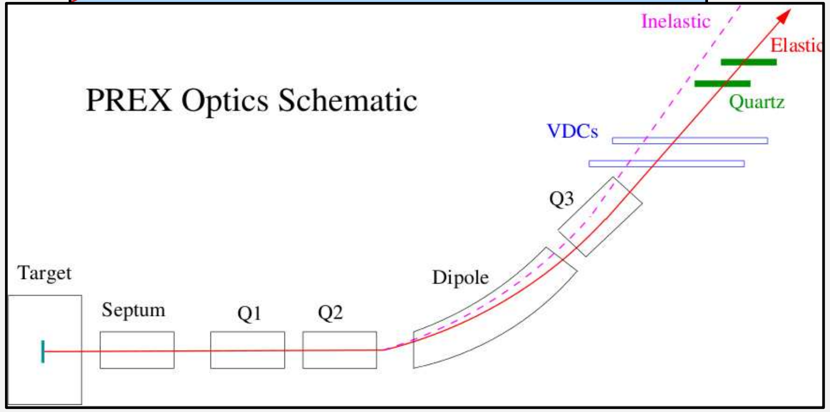
$\sigma\uparrow(\downarrow)$ elastic scattering xsec for e-'s with spin P_e parallel (or antiparallel) to the normal vector defined by the scattering plane

$$A_n^m = A_n \vec{P}_e \cdot \hat{n}$$

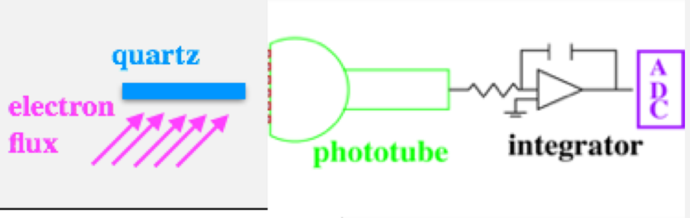
- A_n: beam-normal single spin asymmetry in elastic scattering of electrons polarized perpendicular to the scattering plane off unpolarized nucleons
- A_n is a direct probe of higher-order photon exchange, the inclusion of which is necessary for interpretation of A_{PV} data
- At higher energies, excited 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

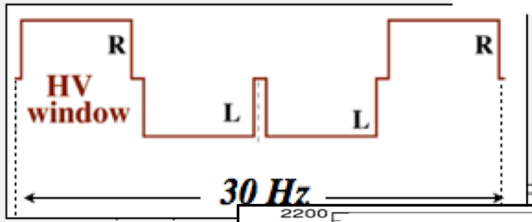
PREX / CREX An Measurement in Hall A





Flux integration Technique





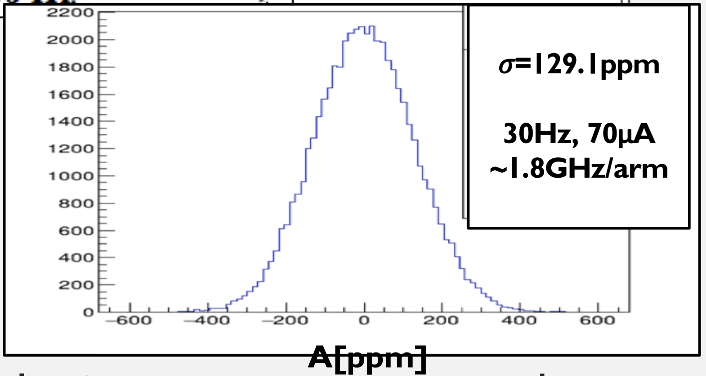
Integration detection for each helicity state in a helicity window.

Q^2 ~ 0.0062 GeV^2

5^o scattering angle

A_{PV} ~ 0.6 ppm +-0.02ppm

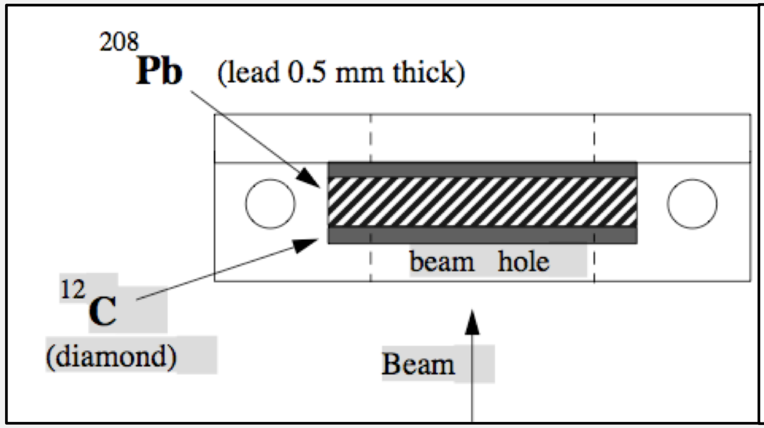
Rate ~2 GHz

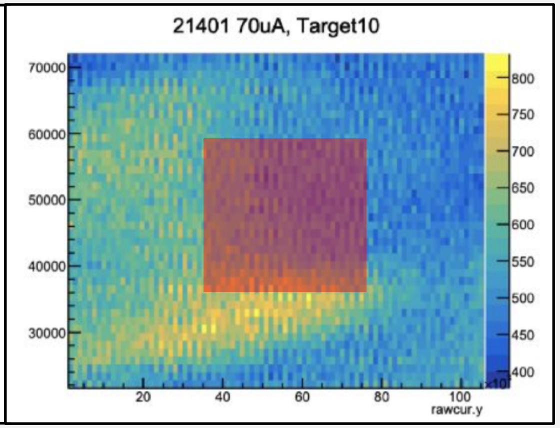


- The momentum resolution of the spectrometers ensured that essentially only elastic events were accepted.
- Analog integration of everything that hits the detector
- electron polarization was set vertical: A_n modulated by sine of the azimuthal scattering angle
- ensured acceptance of the two spectrometers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

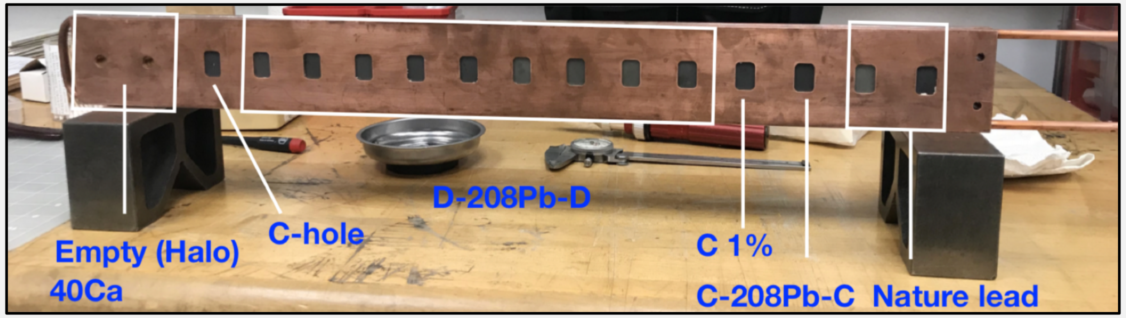
Targets

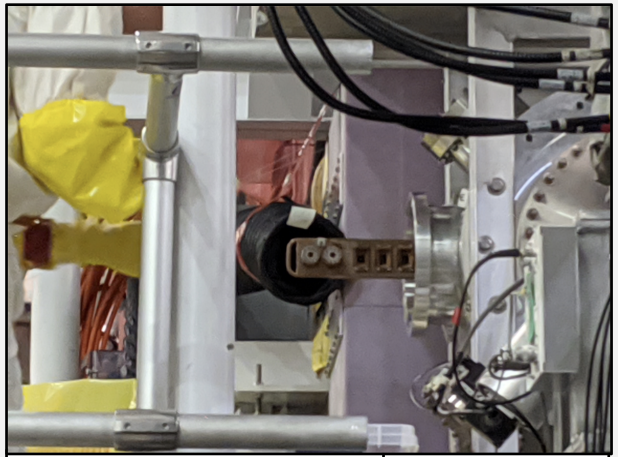
- Diamond foils - excellent thermal conductivity
- ^{12}C is isoscaler, spin-0, A_{pv} is well-measured, so benign background! (dilution, not false asymmetry)
- 70uA limited in PREX because of target thermal properties

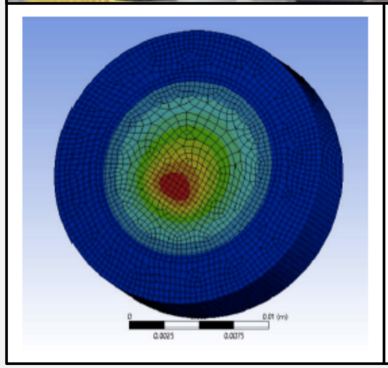


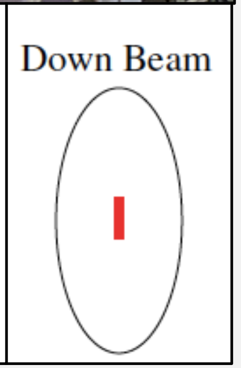


0.5mm lead,
0.25mm diamond, 1 sqin
Use synchronized 4x4mm raster to handle non-uniform lead thickness









1.1g/cm2
~2x2mm raster

- Target has good thermal conductivity, so can run at higher 150uA current
- New Target sandwiched 3 pucks together:
  ~92% 48Ca

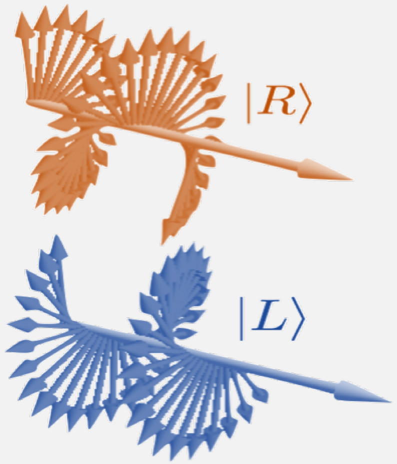
Kinematics

- 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

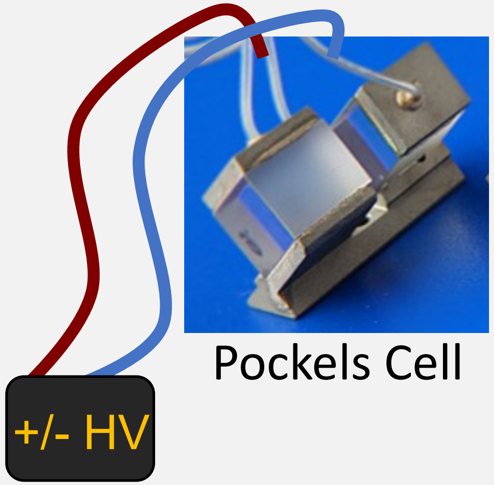
Experiment	Target	θ_{lab}	Q^2 (GeV^2)	E_b (GeV)	<cosϕ>
PREX-II	Carbon-12	5°	0.0066	0.95	0.966
	Pb	5°	0.0062	0.95	0.969
	Ca40	5°	0.0066	0.95	0.974
CREX	Carbon-12	5°	0.033	2.183	0.963
	Pb	5°	0.032	2.183	0.963
	Ca40	5°	0.030	2.183	0.964
	Ca48	5°	0.030	2.183	0.964

Beam from source to target

Laser Beam



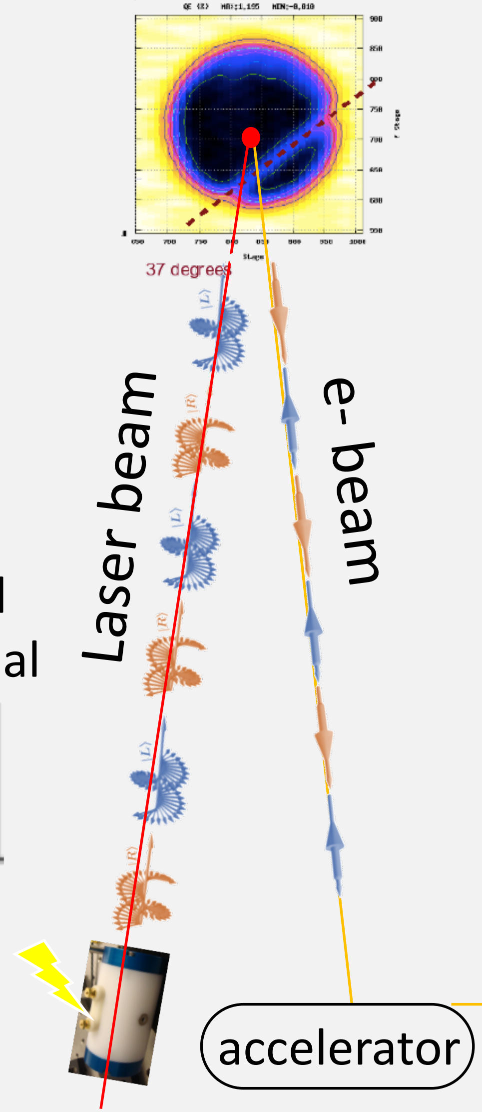
Circularly polarized light



Pockels Cell

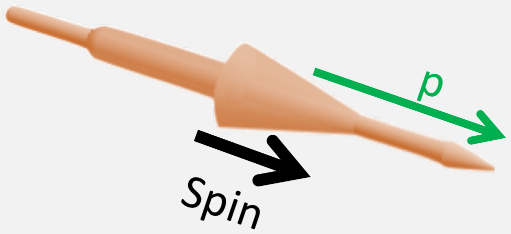
Randomized Helicity Signal

GaAs photocathode

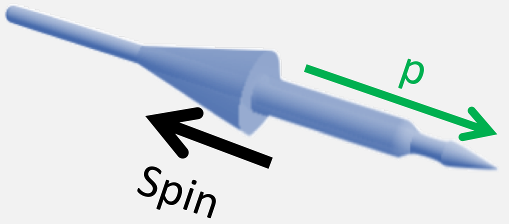


Electron Beam

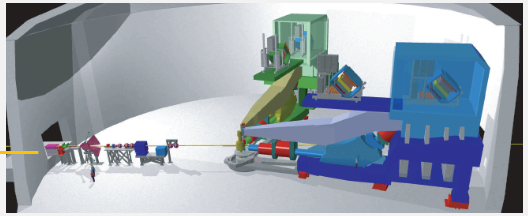
e- : Right handed



e- : Left handed



Experimental Hall

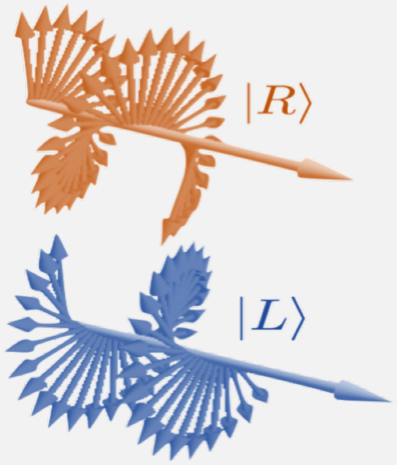


Ref: Silwal Thesis, Fig 6.7.2

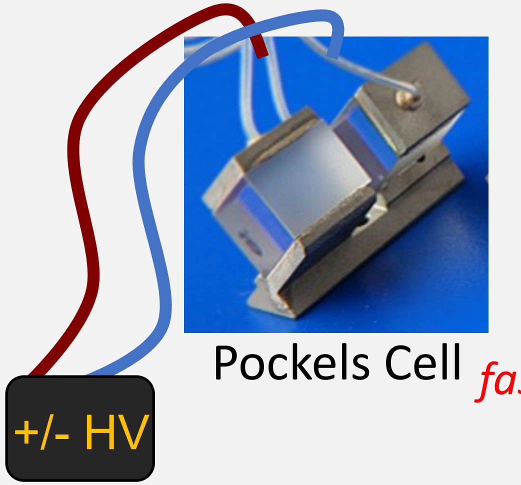
Beam from source to target

Both fast and slow reversals
4 reversal combinations
Helicity: HV +/-, IHWP out/in

Laser Beam



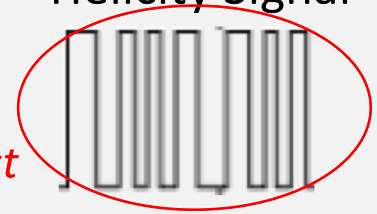
Circularly polarized light



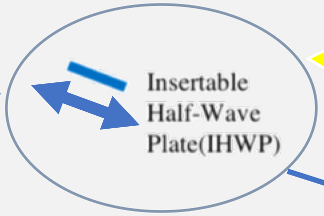
Pockels Cell

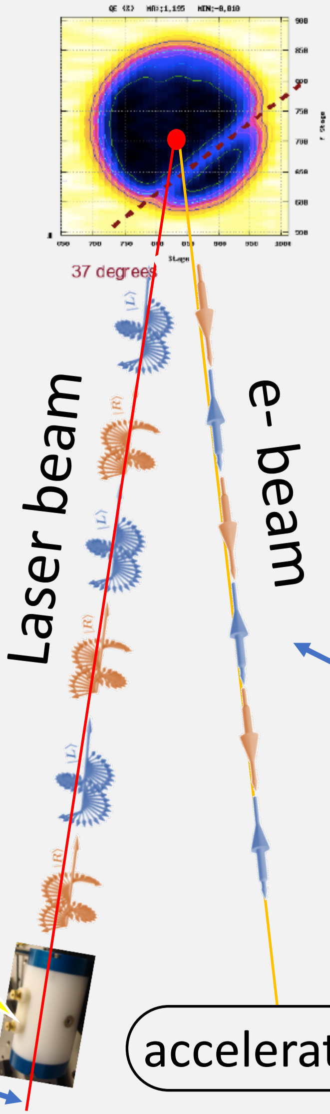
fast

Randomized Helicity Signal



slow





accelerator

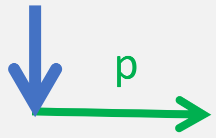
Electron Beam

e- : Vertical ↑

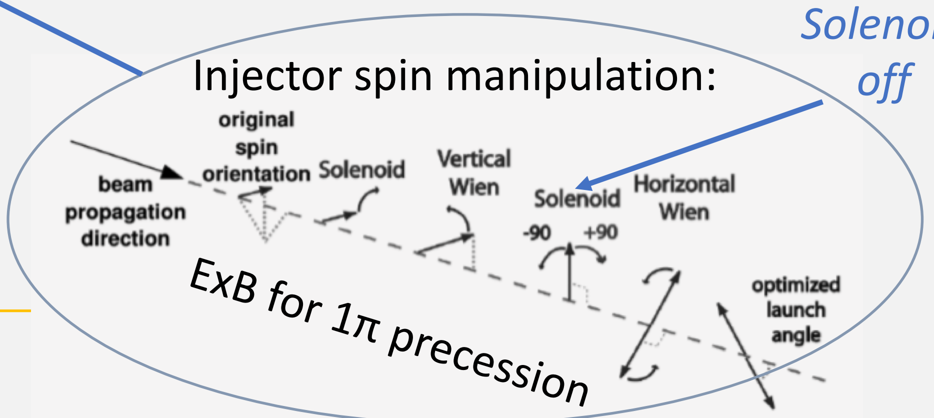
Spin

e- : Vertical ↓

Spin

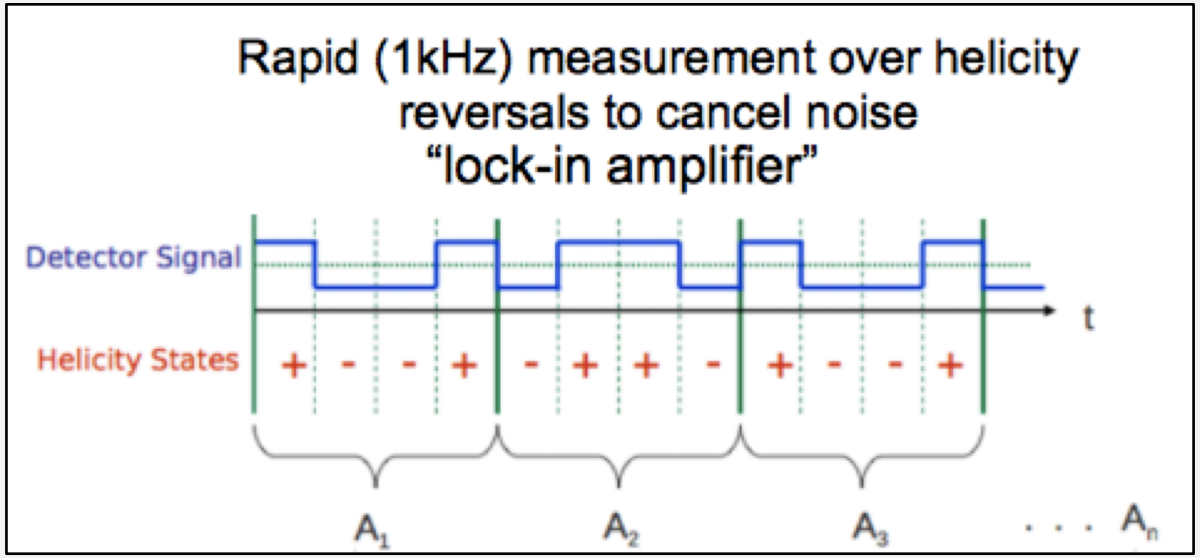


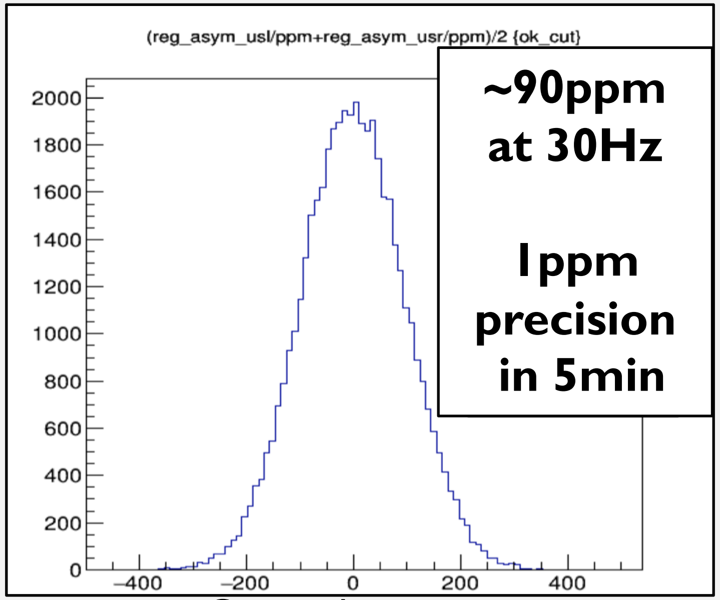
Solenoid off



Ref: Silwal Thesis, Fig 6.7.2

Fast Reversals: Statistical Uncertainty & Helicity Flipping





Octet Asymmetry

- *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 +--+ -++-

Widths and Means

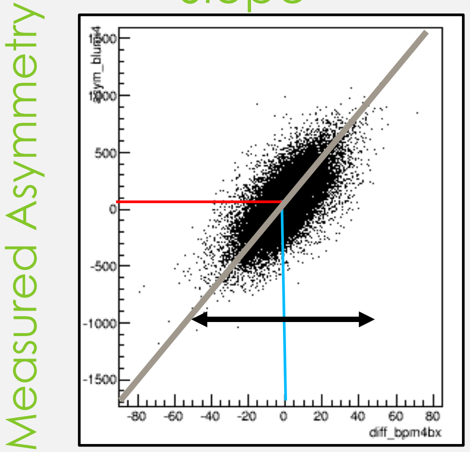
$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

MONITOR: I,E,X,Y

- ***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 Aq
  - 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)

Slope x Mean = Shift

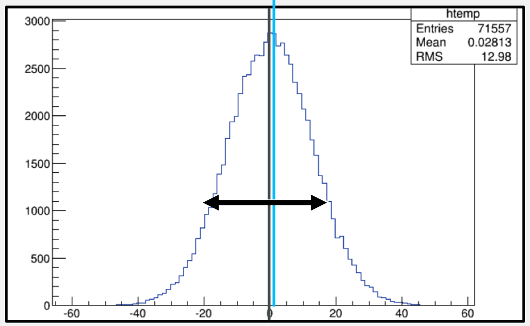
Slope



Position difference

x

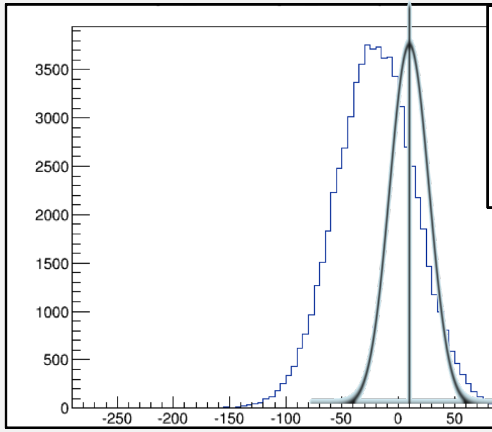
Mean



Position difference

Shift+narrowing

=



RMS
340ppm
95ppm

Raw asymmetry
Corrected asymmetry

340ppm RMS -> 95ppm RMS

Raw Data: Ca48 2GeV

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

regression

dithering

- Left and Right arms symmetrically probe A_n with opposite sign and are combined via $A_{raw} = (A_{Larm} - A_{Rarm})/2$
- Sign corrected for IHWP state, several hours were spent at each IHWP state on each target, ~8hours of data shown above
- Beam corrections made via charge normalization
- β_i calculated via beam noise regression and measured several times per hour by dithering steering coils. Both methods results are shown above

Uncertainties

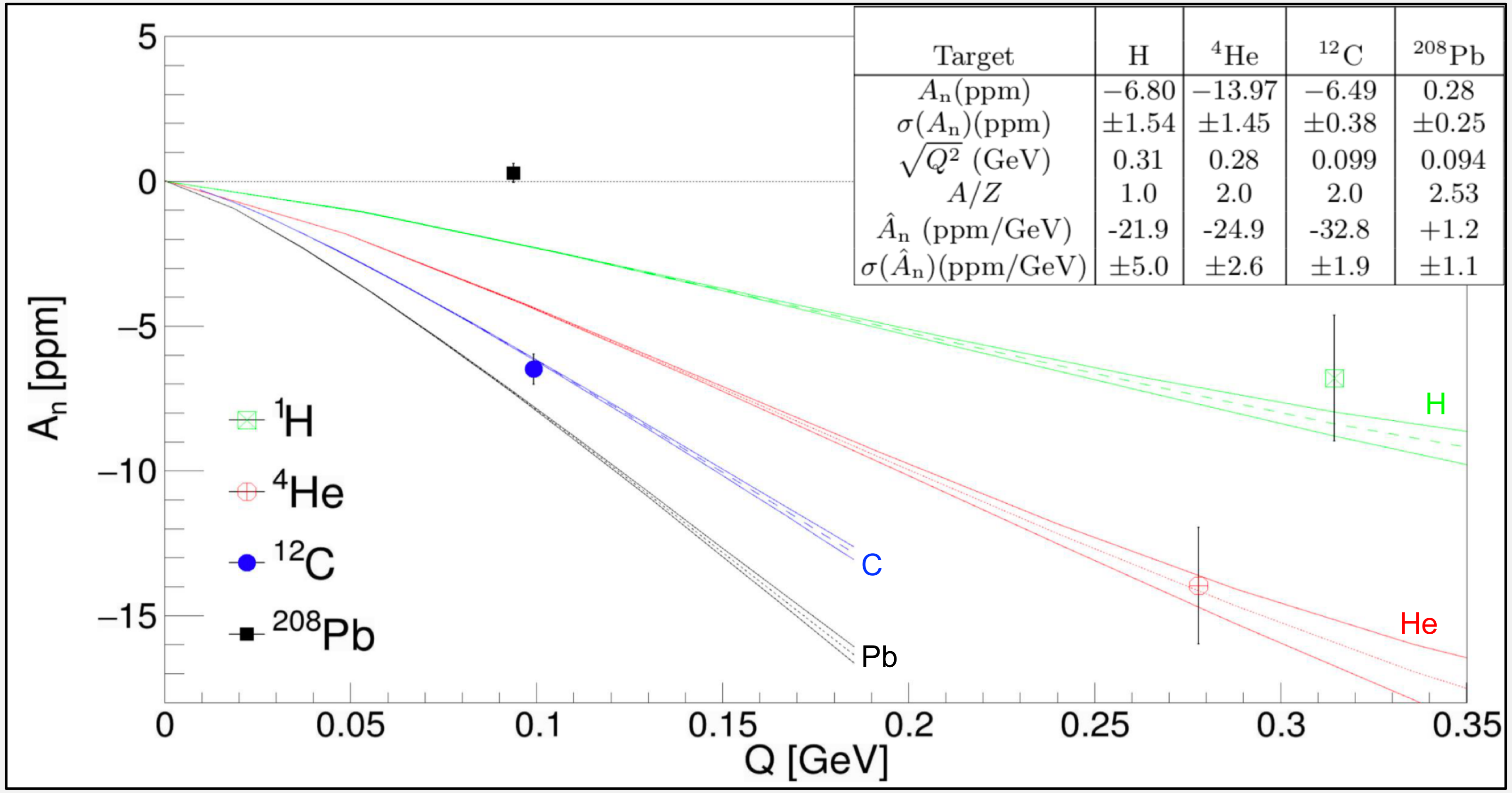
- Nonlinearity in the PMT response was limited to 0.3% in bench tests that mimicked running conditions
- Total relative nonlinearity between the calibration of the PMT response and those of the beam intensity monitors was limited to 2%
- Beam polarization was inferred from longitudinal polarization measurements 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}Pb (sandwiched between diamond ^{12}C foils) and ^{48}Ca (partly ^{40}Ca) were accounted for via rate ratio calculation and subtraction of measured asymmetries in ^{12}C and ^{40}Ca. ^{12}C contributes ~7% rate(at 1GeV) and ~47% rate(at 2GeV, due to FF) in Pb target measurements and ^{40}Ca contributes <1% rate in ^{48}Ca target measurement.
- Beam asymmetry uncertainties contributed approximately 1-4% in ^{12}C, ^{40}Ca (and 0.06ppm for ^{208}Pb) at 1GeV and 1-2% in ^{12}C, ^{40}Ca, ^{48}Ca (and 0.09ppm for ^{208}Pb) at 2GeV
- Statistical uncertainties for the ^{40}Ca,^{48}Ca and ^{12}C measurements were approximately 6% (and 0.35ppm for ^{208}Pb) at 1GeV and 11% (and 1.9ppm for ^{208}Pb) at 2GeV
- *(Note: And small residual longitudinal component of the electron spin will only introduce a negligible parity-violating contribution to the measured asymmetry)*

PREX-I and HAPPEX A_n Measurements

PREVIOUSLY PUBLISHED

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



Target	H	^{4}He	^{12}C	^{208}Pb
A_n(ppm)	−6.80	−13.97	−6.49	0.28
$\sigma(A_n)$(ppm)	±1.54	±1.45	±0.38	±0.25
$\sqrt{Q^2}$ (GeV)	0.31	0.28	0.099	0.094
A/Z	1.0	2.0	2.0	2.53
$\hat{A}_n$ (ppm/GeV)	-21.9	-24.9	-32.8	+1.2
$\sigma(\hat{A}_n)$(ppm/GeV)	±5.0	±2.6	±1.9	±1.1

Phys. Rev. Lett. 109, (2012) 192501

- **Previously published 2012**
- ^{208}Pb $A_n \cong 0$ for Q=1GeV
- ^{1}H,^{4}He,^{12}C consistent with 2008 Gorchstein theoretical calculation

PREX-II and CREX A_n Results

PRELIMINARY

OLD Model:

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- 2-photon exchange calculation
- includes a dispersion integral over intermediate excited states
- neglects Coulomb distortions
- Await new calculations

PREX-II and CREX A_n Results

PRELIMINARY

All points here:

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

Target	A/Z
H	1.0
^{4}He	2.0
^{12}C	2.0
^{208}Pb	2.53
^{40}Ca	2.0
^{48}Ca	2.4

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)

Phenomenological Model

PRELIMINARY

Model:

- Gorchstein & Horowitz 08
- $A_n = \hat{A}_n \frac{QA}{Z}$

- Forcing fit through (0,0) fails

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

Global phenomenological fit presuming linear Q dependent model:

- Observe: ^{4}He, ^{12}C , ^{48}Ca, ^{40}Ca (measured at 5° and 6°) 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

PRELIMINARY

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

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

Target	A/Z
H	1.0
^{4}He	2.0
^{12}C	2.0
^{208}Pb	2.53
^{40}Ca	2.0
^{48}Ca	2.4

- 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

Considering A/Z scaling

PRELIMINARY

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- $A_n = \hat{A}_n \frac{QA}{Z}$
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H	1.0
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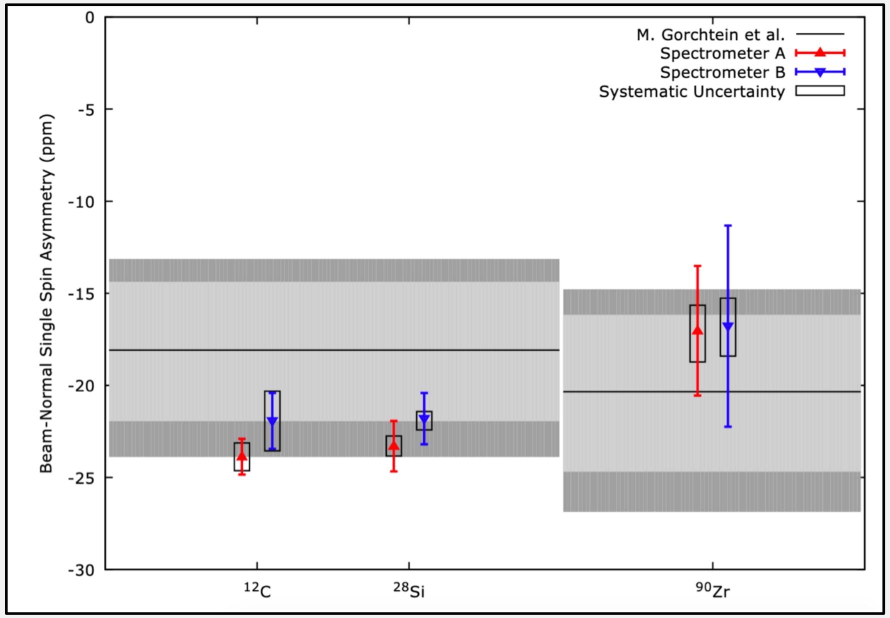
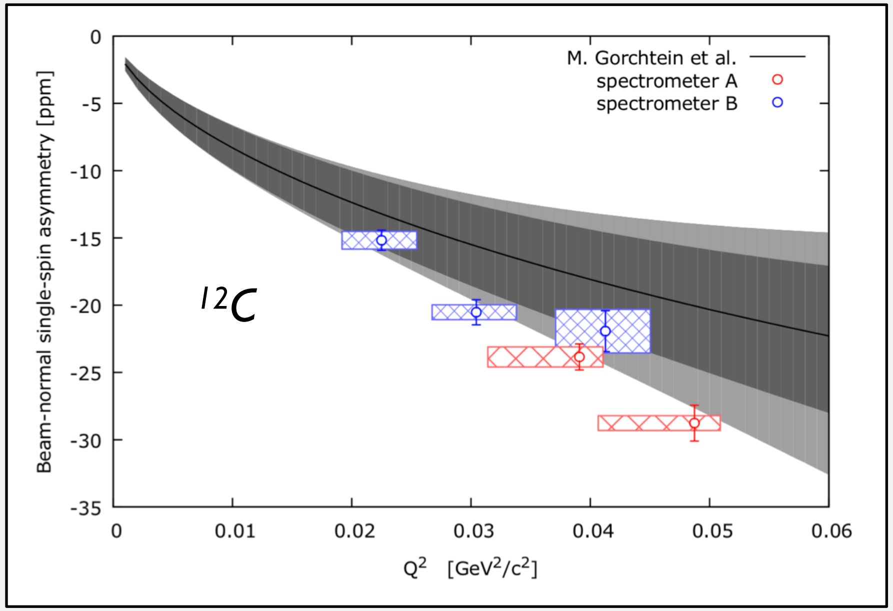
^{48}Ca	2.4

- 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 Calculations for Other Measurements



https://arxiv.org/pdf/2004.14682.pdf



Mainz ^{12}C Phys.Rev.Lett. 121 (2018) 2, 022503

- 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

(smaller angle scattering)

(larger angle scattering included)

- 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^o,6^o)
- (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_{PV} measurements of PREX and CREX]*
- Observed (for forward elastic electron scattering at 5°) features:
  - **New A_n measurements (PREXII,CREX) consistent with old measurements (HAPPEX, PREXI)**
  - **^{208}Pb A_n nearly 0 for multiple Q** [from 0.08-0.17GeV]
  - ^{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)
  - A_n for ^{4}He, ^{12}C, ^{48}Ca, ^{40}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}H, ^{4}He, ^{12}C, ^{40}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]*