Demands on polarized electron sources by future parity violating experiments

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**Parity Violating Asymmetry**

**Measurement:** asymmetry in electron scattering rate (dependent on longitudinal polarization of the beam)

\[ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\gamma}{Z^0} \sim \frac{10^{-4} Q^2}{\text{GeV}^2} \]

Very small effect! part-per-million (ppm) to part-per-billion (ppb)

- High precision obtained by repeated measurements at moderate precision.
- Precision tests of the Standard Model of particle physics
- Flavor separation of nucleon form-factors
- Neutron distribution in neutron rich nuclei
### PVES Experiments

#### PVeS Experiment Summary

![Graph showing PVeS Experiment Summary]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Uncertainty</th>
<th>Reversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAPPEX</td>
<td>$\delta A \sim 1000$ ppb</td>
<td>30 Hz</td>
</tr>
<tr>
<td>A4</td>
<td>$\delta A \sim 300$ ppb</td>
<td>30 Hz</td>
</tr>
<tr>
<td>G0</td>
<td>$\delta A \sim 300$ ppb</td>
<td>30 Hz</td>
</tr>
<tr>
<td>HAPPEX-II He</td>
<td>$\delta A \sim 250$ ppb</td>
<td>30 Hz</td>
</tr>
<tr>
<td>HAPPEX-II H</td>
<td>$\delta A \sim 100$ ppb</td>
<td>30 Hz</td>
</tr>
<tr>
<td>SLAC E158</td>
<td>$\delta A \sim 15$ ppb</td>
<td>30 Hz</td>
</tr>
<tr>
<td>PREx II</td>
<td>$\delta A \sim 15$ ppb</td>
<td>240 Hz</td>
</tr>
<tr>
<td>Qweak</td>
<td>$\delta A \sim 5$ ppb</td>
<td>960 Hz</td>
</tr>
<tr>
<td>MOLLER</td>
<td>$\delta A \sim 0.5$ ppb</td>
<td>1920 Hz</td>
</tr>
<tr>
<td>P2</td>
<td>$\delta A \sim 0.3$ ppb</td>
<td>?</td>
</tr>
</tbody>
</table>

*Asymmetry size: absolute uncertainty*
Beam False Asymmetries

The beam must look the same (intensity, position, shape, background) between the two polarization states. Any differences can lead to a false asymmetry.

\[ A_{\text{false}} = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i \]

compare to size of physics asymmetry

\[ x_i = x, y, x', y', E \]

Polarization dependent beam differences:

\[ \Delta x_i \]

Originate in the procedure used to change the polarization.

\[ \frac{\partial A}{\partial x_i} \]

Sensitivity:

Depends on scattering angle, target nucleus and detector geometry.
MOLLER Experiment

Flagship JLab experiment
important and powerful precision standard model test
tiny asymmetry, precision
open geometry, faster flip

\[ Q^2 = 0.0056 \text{ (GeV/c)}^2 \]
\[ E_{\text{beam}} = 11 \text{ GeV} \]
\[ 0.29^\circ < \theta_{\text{lab}} < 0.97^\circ \]

\~85 \mu A, 
1.5 m LH2 target

\[ A_{PV} \approx 35 \pm 0.73 \text{ ppb} \]

MOLLER limits
cumulative helicity-correlated :
position difference < 0.5 nm,
angle differences < 0.05 nrad,
laser spot size difference < 0.01 %
Changing Electron Polarization

Electrons produced by photoemission from laser light.

Laser polarization determines electron polarization

Laser helicity changed using a Pockels Cell (electro-optic birefringent element) acting as a variable-wave plate. Rotate initial linear light into right-circular or left-circular

Electrons produced by photoemission from laser light.

Pockels cell

Specialized optics

Laser

HV pulse

Polarized source

GaAs

100 kV

Accelerator

Polarized electrons

Half-wave plate

10 cm

10 cm
### Table Layout

<table>
<thead>
<tr>
<th>Insertable Half Wave Plate (IHWP)</th>
<th>Rotatable Half Wave Plate (RHWP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverses the polarization of the linear photon beam</td>
<td>Rotates the polarization ellipse</td>
</tr>
<tr>
<td>Pockels Cell</td>
<td>Vacuum window birefringence</td>
</tr>
</tbody>
</table>
Pockels Cell Steering

Crystal nature of Pockels medium leads to steering effects and vibrations after high voltage shocks which damp slowly.
Cathode has ~4% analyzing power acting on residual linear polarization.

GaAs crystal

Most sensitive

Least sensitive

Ellipses resulting from phase adjust

Rotate by 22.5 degrees (90 degree full cycle)

Birefringence gradients cause beam differences

Right-helicity intensity

Left-helicity intensity

Horizontal Position (mm)
General RHWP scan

Separate out mechanical and polarization effects and help to determine sources.

Careful alignment on the table to minimize as much as possible.

\[ A_q = -7.98 + -1211.75 \sin (2\theta + 75.52) + -3151.04 \sin (4\theta + 158.47) \]

- \(2\theta\) term measures RHWP phase error and axis
- \(4\theta\) term measures analyzing power*DoLP (from Pockels cell)
General RHWP scan

RHWP scan, Run 15630, IHWP (1,2) = (IN,OUT), PITA=0

Aq = +31.0 +124.6 sin (2θ +2.8) -205.6 sin (4θ -38.2) +71.2 sin (θ +61.0) +85.5 sin (θ -17.0) sin (4θ +38.2)

dx = -149.3 +53.1 sin (θ +53.8) -11.0 sin (2θ +151.4) -55.6 sin (4θ +135.9) +53.1 sin (θ +53.8) -36.9 sin (θ +64.1) sin (4θ +302.1)

RHWP angle

Careful alignment on the table to minimize as much as possible

Separate out mechanical and polarization effects

Balance birefringence of vacuum window and cathode analyzing power
Measure Position Differences

As a function of monitor in the injector

Charge asymmetry slope depends on RHWP

PITA effect depends on RHWP
Optimization

Optimize some figure of merit using a lot of data

Physically motivated functions used to project

- Position difference
- RHWP angle
- Figure of merit X
- Figure of merit Y
- Figure of merit both

FOM

Physically motivated functions used to project
Qweak Experiment: Position differences start out at ~ 100 nm off the cathode. As-good or better than previously achieved.

**Position Differences**

**X position differences**

**Y position differences**

**Propagation through injector monitors**
Try to obtain additional suppression due to Lorentz boost (so call ‘kinematic’ or ‘adiabatic’ damping.) Area of beam distribution in phase space (emittance) is inversely proportional to momentum. Requires commitment from the collaboration to allow careful (time consuming) setup of accelerator optics. For Qweak this was not done and position differences do not decrease from the injector values. Position differences do not change sign with passive polarization.

**Kinematic Damping**

**HWP2**

\[
\langle \text{inL} \rangle = -81.846 \pm 1.743, \text{Chi}^2/\text{NDF}=24.080
\]

\[
\langle \text{outL} \rangle = 39.532 \pm 1.766, \text{Chi}^2/\text{NDF}=77.570
\]

**Target X**
This works, but these are heavy hammers for a subtle problem. Does nothing to fix higher-moment problems, may even create them. Preferred strategy: configure system with care to minimize effects. If you do it right, all problems get small together*! If you do your best there, you can use feedback to go the last mile (or nanometer).
Higher Moment Effects

Beam spot size asymmetries

Simple breathing.
Same $<x>$, $<l>$,
Different $<x^2>$

Interaction between scraping and intensity feedback.
Same $<x>$, $<l>$,
Different $<x^2>$

Differential intensity bounce.
Same $<x>$, $<l>$,
Different $<l^2>$
Spot Size Asymmetry

Linear Photodiode Array

Profile laser beam in 1 dimension at high differential rate

Measure helicity correlated spot size asymmetry
higher moment spot “shape” asymmetry

Using this technique, bounded spot size asymmetry for
PREx to < $10^{-4}$
and QWeak to < $10^{-3}$
Clipping on Apertures

Qweak was clipping or close to clipping on the injector apertures most of the time.
Occurs after the table (can’t measure)
Blows up charge asymmetry width
Potentially causes higher moment beam moments
Potentially couple various otherwise-independent effects (charge asymmetry, position differences, higher moments)

Effective Charge Variation (0 < Aq < 0 ppm) Across Injector in run 2365

Chopper

PITA feedback makes it all look good
Qweak Background Asymmetry

Qweak is an open geometry experiment. Background detectors measure asymmetries at positions away from the main scattered flux.

Hypothesis is that background signal is halo scattering from the beamline, particularly a small tungsten collimator. Asymmetry is presumed to be from a charge asymmetry on the halo. Needs to be studied with simulation.
Asymmetry is large (50 ppm) in background detectors, normal running. Asymmetry show qualitative agreement between all background detectors.
Chopper Phase Study

The chopper is an RF device which allows the beam pulses to be chopped in the longitudinal direction at front or back to set the pulse length.

Sharply narrowing the aperture (master slit) and varying the chopper phase allows the longitudinal profile of the beam to be measured.

Upstream of chopper

Downstream of chopper
There exists a non-zero beam charge asymmetry for some portions of the beam in the longitudinal profile.

This is at least a proof of principle that small portions of the beam phase space can carry large charge asymmetries.
Fast Flip Pockels Cell ‘Ringing’

70 μs switching time
For 960 Hz flip frequency ⇒ ~ 7 % dead time

QWeak experience

Potentially troublesome ‘ringing’ if coupled to other effects

Better Pockels Cells and high voltage switches exist but the setup is notoriously tricky.
Kerr Effect and Kerr Cell

\[ n(E) \approx n + a_1 E + \frac{1}{2} a_2 E^2 \]

very small

Kerr Material: centrosymmetric materials (gases, liquids, and certain crystals)

\[ n(E) \approx n + \frac{1}{2} a_2 E^2 \]

\[ \Delta n = \lambda KE^2 \]

A Kerr Cell is cell containing a Kerr Material with an applied electric field through which a laser beam propagates.
Problems with Kerr Cells

**Weakness of effect**
- Difficulty designing cell
  - High voltages
  - Close electrode spacing

**Non-linearity of effect**
- Field uniformity very important
  - Symmetry provided by field not by a crystal

**Transverse E**
- Self interaction
  - Optic Kerr (AC) Effect
  - Laser field causes self focussing
  - Spot size depends on beam power.
  - Mitigate by shortening the cell and increasing the high voltage.

**Sign Independent**
- Reversing the laser circular-polarization more difficult
Weakness of Kerr effect

Requires some combination of:
1) long cell
2) close electrodes
3) high voltages
4) difficult materials

Kerr cell as $\lambda/4$ plate, 10 cm long electrodes

- 4'-n-heptyl-4-cyanobiphenyl (HBN)
- nitrobenzene
- Acetone

Kerr cell as $\lambda/4$ plate, 3 cm electrode gap

- cell voltage vs. electrode gap for $\lambda/4$ (cm)
- cell length vs. cell voltage for $\lambda/4$ (cm)
Kerr Cell: no “crossed” plates

Presence of passive plates leads to field non-uniformities.

Thus two Kerr Cells would be required, in series, one for each state. However, this introduces a natural source of asymmetry between the states.
Sign Independent

Changing sign of electric field does not reverse birefringence

\[ \Delta n = \lambda B E^2 \]

"plate number"

\[ N = \frac{L \Delta n}{\lambda} \]

Two ways to reverse the birefringence

need to either:
"rotate" the electric field

use the 3/4 wave voltage

\[ N = \frac{1}{4} \]

\[ E_{\frac{1}{4}} \]

\[ N = \frac{3}{4} \]

\[ E_{\frac{3}{4}} = \sqrt{3} E_{\frac{1}{4}} \]
Previous Kerr cells may have seen a non-uniform electric field between the plates (apparently due to charge screening effects.)
### Kerr vs Pockels Effects

\[ \Delta n = \lambda KE^2 \]

Birefringence that depends on the square of a transverse electric field

<table>
<thead>
<tr>
<th>Pockels Cell</th>
<th>Kerr Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>Liquid or gas</td>
</tr>
<tr>
<td>Longitudinal Field</td>
<td>Transverse Field</td>
</tr>
<tr>
<td>Commercially available</td>
<td>Development required</td>
</tr>
<tr>
<td>Strong Effect ( \sim 3 \text{ kV} ) (KD*P) Deuterated Potassium Dihydrogen Phosphate</td>
<td>Weak Effect ( \sim 30 \text{ kV} ) (nitrobenzene, acetone)</td>
</tr>
</tbody>
</table>

Mitigate steering effects, or physical oscillations following large potential changes.

Self focussing, since laser is transverse E.

Even higher voltage
Kerr Cell Summary

Kerr cells could offer advantages over Pockels cells for future measurements in Parity Violating Electron Scattering

1) No ringing
2) Birefringence gradients should only come from electric field gradients
3) helicity reversed quicker, less dead time
4) reduced helicity correlated effects?

Potential Issues

1) More than a simple sign change is required to reverse the polarization
2) A charge asymmetry on the incoming beam would become a spot size asymmetry on the exiting beam.
3) Obtaining uniform high electric fields is both difficult and important for these purposes.
Future Parity Violating Electron Scattering experiment will still have to worry about the classic false asymmetries.

In addition, higher moment effects, which generally cannot be measured will be serious issues for future experiments.

Open geometry experiments will need to worry about asymmetric background scattering.

Kerr Cells could be useful but there are significant potential issues and development is required.