New developments in beam properties for future Parity Violating Electron Scattering (PVES) experiments

Mark Dalton
Acknowledgements to the QWeak and MOLLER collaborations.
Outline

The Electroweak Physics available from PVES

The role of the beam properties

Current state of the art ➔ QWeak experiment

Requirements for future experiments, particularly MOLLER

Possible technical improvements to realize these requirements
Electroweak parameters

To describe electroweak interactions, there are three parameters needed:

1. Scale of electromagnetism i.e. the fine structure constant
2. Scale of the weak interaction i.e. the $W$ boson mass
3. Weak mixing angle i.e. the ratio of $W$ and $Z$ boson masses

The actual parameters are chosen from the three most precise EW experimental measurements:

1. electron $g$-2
2. The muon lifetime
3. The Z line shape

4th and 5th measurements: $M_W$ and $\sin^2\theta_W$ can then act as tests of the structure.
If measured values differ from tree level predictions: indirect access to “heavy” physics
Parity Violating Asymmetry

\[ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \left(\frac{\gamma}{2}\right) \sim 10^{-4}Q^2 \text{GeV}^2 \]

sensitive to $1 - 4 \sin^2 \theta_W$

Asymmetry distribution

HAPPE\text{Ex III} example

Entries $2.694749 \times 10^7$
RMS $3733$

$30 \text{ Hz flip rate}$
Testing of the Standard Model

Precision measurements at low energy can probe TeV scale physics through deviations from Standard Model predictions
PVES access to New Physics

Including global fit constraints

⇒ νs are Majorana

⇒ Lightest Supersymmetric Particle can’t be Dark Matter

Figure: Ramsey-Musolf

Tension between E158 and (g-2)μ (if interpreted in SS, favors large loop effects)
PVES Evolution

2nd generation: complete
Strange quarks in the nucleon, weak charge on electron.

3rd generation: in progress
Strange quarks swansong, neutron self interaction energy, weak charge on proton.

4th generation: beginning 2016?
Fundamental Standard Model parameters.
Source of Polarized electrons

Goal: Provide **high current, high polarization** electrons in two helicity states.

- Increase ‘statistics’
- Identical in all other respects to: Decrease systematic uncertainty

**Step 1a:** produce circularly polarized light

**Step 1b:** change helicity of light

**Step 2:** shine light on **strained** GaAs photocathode

---

**Diagram:**

- HV pulse
- Laser
- Specialized optics
- Polarized source
- GaAs
- Pockels cell
- Half-wave plate
- Accelerator
- 100 kV
- 780 - 850 nm
- Circularly polarized
- Conduction band
- Valence band
- GaAs
- $E_g = 1.43 \text{ eV}$
- $E_{strain} = 0.05 \text{ eV}$
Helicity Correlated Differences

**charge asymmetry**
Measure and feedback

**beam-position** differences, **angle** differences and **energy** differences
Diminish as far as possible, measure and correct

**beam spot size** differences, **beam** "shape" differences
Can’t be directly measured, must be bounded

--

zeroth moment

1st moment

2nd moment
\[ Q^2 = 0.027 \text{ (GeV/c)}^2 \]
\[ E_{\text{beam}} = 1.16 \text{ GeV} \]
\[ \theta_{\text{lab}} = 8^\circ \]

\(~165 \mu\text{A, 35 cm LH2 target}\)

\[ \text{APV} \approx 200 \pm 5 \text{ ppb} \]
Azimuthally symmetric detectors decrease sensitivity to 1st moment HC beam motions.
Helicity Correlated beam sensitivities

Despite the highly symmetrical detector QWeak is still sensitive to 1st moment HC beam properties.
Target density fluctuations

High currents cause density fluctuations in target liquid which adds low frequency noise to the measurement.

Target noise kept to ~ 50 ppm at high current through sophisticated target design AND fast flipping.
Noise and Width: QWeak

**Width calculation**

Total detected rate = 5.83 GHz
Pure counting statistics = 215 ppm + detector energy resolution + beam current normalization + target fluctuations

![Asymmetry distribution graph](image)

Figure: 6.5 minutes of data @ 165 μA (93K quartets)
0.8 ppm statistical error

σ = 236 ppm
Fast Flip Causes 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.
Limitation of Pockels Cell

Crystal nature of Pockels medium leads to steering effects and vibrations after high voltage shocks which damp slowly.
MOLLER Experiment

$Q^2 = 0.0056 \text{ (GeV/c)}^2$

$E_{\text{beam}} = 11 \text{ GeV}$

$0.29^\circ < \theta_{\text{lab}} < 0.97^\circ$

$\sim 85 \mu\text{A}, 1.5 \text{ m LH2 target}$

$A_{PV} \approx 35 \pm 0.73 \text{ ppb}$
Accuracy goals for MOLLER are factors of 2 to 10 beyond those of E158 & Qweak.

<table>
<thead>
<tr>
<th>parameter</th>
<th>E158</th>
<th>Qweak</th>
<th>MOLLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>3 GHz</td>
<td>6 GHz</td>
<td>135 GHz</td>
</tr>
<tr>
<td>reversal rate</td>
<td>120 Hz</td>
<td>960 Hz</td>
<td>1920 Hz</td>
</tr>
<tr>
<td>pair stat. width</td>
<td>200 ppm</td>
<td>400 ppm</td>
<td>82.9 ppm</td>
</tr>
<tr>
<td>$\delta(A_{raw})$</td>
<td>11 ppb</td>
<td>4 ppb</td>
<td>0.544 ppb</td>
</tr>
<tr>
<td>$\delta(A_{stat})/A$</td>
<td>10%</td>
<td>3%</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\delta(sin2\theta W)_{stat}$</td>
<td>0.001</td>
<td>0.0007</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

Extremely narrow width increases sensitivity to noise sources e.g. electronics noise.
MOLLER apparatus

Enormous technical challenges: MOLLER is a IV Generation Expt at JLab

**Polarized Beam**
- unprecedented polarized luminosity
- unprecedented beam stability

**Liquid Hydrogen Target**
- 5 kW dissipated power (2 X QWeak)
- computational fluid dynamics

**Toroidal Spectrometer**
- Novel 7 “hybrid coil” design
- warm magnets, aggressive cooling

**Integrating Detectors**
- build on QWeak and PREX
- intricate support & shielding
- radiation hardness and low noise
MOLLER error budget

<table>
<thead>
<tr>
<th>source of error</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>absolute value of Q2</td>
<td>0.5</td>
</tr>
<tr>
<td>beam second order</td>
<td>0.4</td>
</tr>
<tr>
<td>longitudinal beam polarization</td>
<td>0.4</td>
</tr>
<tr>
<td>inelastic e-p scattering</td>
<td>0.4</td>
</tr>
<tr>
<td>elastic e-p scattering</td>
<td>0.3</td>
</tr>
<tr>
<td>beam first order</td>
<td>0.3</td>
</tr>
<tr>
<td>pions and muons</td>
<td>0.3</td>
</tr>
<tr>
<td>transverse polarization</td>
<td>0.2</td>
</tr>
<tr>
<td>photons and neutrons</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.0</strong></td>
</tr>
</tbody>
</table>

Very little room for uncertainties from HC beam properties.
Demands from the beam

Small helicity correlated differences

Faster differential measurements

Decreased “dead” time

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

Flip rate: 960 Hz → 1920 kHz
Transition time: 70 μs → 10 μs

Can be achieved through:

significant improvements to existing technology:
- KD*P Pockels cell → RTP Pockels cell
- further improvements in alignment and setup methods

use of new technologies:
- Using a “Kerr” cell rather than a Pockels cell to reverse the helicity of the laser beam.

Speculative, R&D required
## Kerr vs Pockels Effects

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

- **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} \quad (KDP))</td>
<td>Weak Effect (\sim 30 \text{ kV} \quad \text{nitrobenzene, acetone})</td>
</tr>
</tbody>
</table>

- **Kerr Cell**
  - Mitigate steering effects, or physical oscillations following large potential changes.
  - **Self focussing, since laser is transverse E**
  - **Even higher voltage**
Self interaction: transverse electric field of the laser beam will itself cause a Kerr Effect.

Can results in a “wave guide” or graded index focusing lens.

Mitigate by shortening the cell and increasing the high voltage.

Geometry of a Kerr cell

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

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

- Electrode
  - Electric field $> 1$ MV/m
  - Laser $100$ mW

- Kerr medium

- Cell voltage

- Cell length for $\lambda/4$ (cm)

- Electrode gap for $\lambda/4$ (cm)

- Nitrobenzene

- $4'$-n-heptyl-$4$-cyanobiphenyl (HBN)

- Acetone

- Cell voltage (V)
Spot Size Asymmetry Measurement

Linear Photodiode Array

Already used in PREx and QWeak to bound spot size differences to < 10e-4

Profile laser beam at high differential rate

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

Future parity experiments provide indirect access to new physics at the multi-TeV energy scale.

 Particularly the MOLLER experiment, will require significant improvements in helicity correlated differences and helicity state transition time, while also increasing the helicity reversal rate.

 Kerr cells should offer significant advantages over Pockels cells: helicity reversed quicker, less dead time; reduced helicity correlated effects reduced
Bonus Slides
Liquid Crystals?

4'-n-pentyl-4-cyanobiphenyl (PBN)  
**55 times** the Kerr constant of nitrobenzene

4'-n-heptyl-4-cyanobiphenyl (HBN)  
**30 times**

Chemically and photochemically stable. Temperature must be carefully controlled.
Position Differences in Hall

Over the ~20 million pairs measured in HAPPEX-II, the average position was not different between the two helicity states by more than 1 nanometer.

- **X position difference**
  - $0.56 \pm 0.53$ nm
  - $RMS = 2.77$ $\mu$m

- **Y position difference**
  - $1.69 \pm 1.83$ nm
  - $RMS = 9.50$ $\mu$m

- **X angle difference**
  - $-0.26 \pm 0.24$ nrad
  - $RMS = 1.23$ $\mu$rad

- **Y angle difference**
  - $0.21 \pm 0.25$ nrad
  - $RMS = 1.29$ $\mu$rad
Laser Table View

- High voltage switch
- Rotating Half-Wave plate
- Pockels Cell
Sources of Helicity Differences

Steering effects – Pockels cell
Imperfect circularly polarized light
   Intrinsic birefringence of the Pockels cell
   Other birefringent beamline elements (vacuum window)
   Phase gradient in beam before Pockels Cell
   Laser divergence in the Pockels cell
   Quantum Efficiency Anisotropy Gradient
Beam element/helicity electronics pickup
Quantum Efficiency Variation (“QE holes”)
Cross-talk between different beams: cathode effects or cross-talk in electron-beam transport
Steering

The piezoelectric Pockels Cell acts as “active” lens

- High voltage positive
- High voltage negative

Translation (inches)

Red, IHWP Out
Blue, IHWP IN

X position diff. (um)

Y position diff. (um)
Cathode Analyzing Power
Cathode Analyzing Power

GaAs crystal

Most sensitive

Least sensitive

Ellipses resulting from phase adjust

Rotate by 22.5 degrees
(90 degree full cycle)
Solutions
Differences must be minimised and corrected for:

Some cannot be measured

Experience suggests that the error on the correction cannot be determined much better than about 10% of itself.

Understand their origins and make them as SMALL as possible. Measure them and make appropriate corrections. Be prepared to judiciously apply feedback.

- Sometimes this is essential, particularly if you cannot measure them with small enough errors to correct for them quickly. If detector is sufficiently symmetric, higher order effects will be dominant!

One needs to be careful to focus on the largest problems and develop systems for measuring, removing, and/or estimating corrections for higher order helicity-correlated beam parameters. (Not in this talk.)
PREx Source Summary

Source Setup
- didn’t start by checking transitions -
  best Pockels cell died, the current PC is not as good as Sam (or Arwen) -
  rotating HWP has few percent phase offset. (physical limit or imperfect element?) -
  new vacuum window has large birefringence -
  cathode showed significant analyzing power gradient (Aq -> Δx)

What was GREAT:
- the ability to rotate the photocathode limits the effect of the vacuum window
- For the first +me, the ability to measure spot size asymmetry with the production laser. Results: spot size asymmetry bound at few x 10^-5 due to laser effects. (PREX required bound of 10^-4, Qweak can afford nearly 10^-3)
- Position jitter in injector, now at ~3 microns at 30Hz. Injector studies can measure to high precision, quickly!
- Acer spot move, new cathode spot had 4x less gradient in analyzing power. This should allow an excellent zeroing of position differences
PREx Experience

- Slower than expected transition (slightly over 100 μs)
- Ringing (out to very long timescales, ~18 μs period)
- Asymmetric transition

- Transition ~80 μs
- Ringing down by ~3x
- Transition more symmetric

DAQ “Ramp Delay” increased to 500 μs
Detector Time Constants (PREx)

Electron beam test:
- direct test of beam monitor (and detector) time constants
- 100 microsecond pulse - short integrate gate with flexible delay

Beam Current Monitor
\( \tau \sim 12 \mu s \)

PREx Main Detector
\( \tau \sim 65 \mu s \)

BCM \( \sim 12 \mu s \)
Detectors \( \sim 65 \mu s \) (cable capacitance)
- now about 15 \( \mu s \) (twinax cable)
Feedback

This works, but these are heavy hammers for a subtle problem. Does nothing to fix higher-order 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).