Parity-violating electron scattering measurements at Jefferson Lab

David S. Armstrong
William & Mary

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“New Physics” parallel session
Overview

1. Parity-Violating electron scattering
   Physics context: Standard Model tests

2. Qweak at JLab (completed)

3. MOLLER at JLab (under development)
   
   **MOLLER**: Measurement of a Lepton Lepton Elastic Reaction
Physics Context – Precision Low-energy physics

- Received Wisdom: Standard Model is incomplete: low-energy effective theory of more fundamental physics
- Low energy ($Q^2 << M^2$): Precision Frontier
  complementary to Energy Frontier measurements (LHC)

Any LHC new physics signals likely will need additional indirect measurements to pin down their nature

- **Neutrons**: Lifetime, $P$- & $T$-Violating Asymmetries  [LANSCE, Grenoble, NIST, SNS...]
- **Muons**: Lifetime, Michel parameters, $g$-2, Mu2e  [PSI, TRIUMF, FNAL, J-PARC...]
- **Atoms**: atomic parity violation

- **PVES**: Low-energy weak neutral current couplings, precision weak mixing angle  [SLAC, Jefferson Lab, Mainz]

**Ideal** - select observables that:

1) are zero, or significantly suppressed, in Standard Model
2) Have robust predictions within Standard Model
Parity-violating electron scattering (PVES)

- Search for new flavor-diagonal neutral current couplings
- Tiny yet measurable deviations from precise standard model predictions
- Probe via electroweak interference in elastic electron scattering

- Analyze in context of Standard Model Effective Field Theory (SMEFT):

  - Desired sensitivity: $\Lambda \sim 10$ TeV
MOLLER: Parity-violating asymmetry in Møller scattering

- Scatter longitudinally-polarized electrons from unpolarized target
- Probe neutral current via *Electroweak interference*
- Originally proposed by Ya. B. Zeldovich JETP 36 (1959)

Rapid reversal of electron helicity to measure Asymmetry

\[ A_{\text{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M_Z|}{|M_\gamma|} \]

\[ = -mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q^e_W \]

\[ \Theta : \text{center of mass scattering angle} \]

Weak charge of electron: \( Q^e_W = 1 - 4\sin^2 \theta_W \sim 0.075 \)

(weak charge suppressed in Standard Model)
Qweak: Parity-violating asymmetry in ep scattering

\[ A \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \xrightarrow{Q^2 \to 0, \theta \to 0} \left[ \frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \left[ Q^2 Q_{weak}^p + Q^4 B\left(Q^2\right) \right] \]

For forward angle scattering at low \(Q^2\):
\[ A_{PV} \text{ accesses } Q_{W}^p \text{.} \]

“Form factor” term due to finite proton size – hadron structure – determined well by existing PVES high-\(Q^2\) data

Weak charge of proton:
\[ Q_{W}^p = 1 - 4 \sin^2 \theta_W \sim 0.075 \]
(weak charge suppressed in Standard Model)

Note: sensitivity to various New Physic models differs for \(Q_{W}^e\) and \(Q_{W}^p\)
→ Complementary probes

Can parameterize New Physics sensitivity via deviations from Standard Model value of \(\sin^2 \theta_W\)
**PVES: Brief History**

Pioneering (1978) early SM tests
SLAC E122 PVDIS – Prescott et al.  A = -152 ppm
Bates $^{12}\text{C}$, Mainz Be

Strange Form Factors (1998 –2009)
SAMPLE, HAPPEX, G0, A4
A $\sim 1 – 50$ ppm

SLAC E158 Moller: A = - 131 ppb
(13% precision on electron’s weak charge)
JLAB Qweak: A = -230 ppb

Neutron radii: (2012-2022)
JLab: PREX-I, PREX-II, CREX, QWeak

Future: Standard Model, hadron structure studies:
**MOLLER**: A = - 35 ppb
Goal: 2.5% precision on electron’s weak charge

P2@MESA, SOLID, 12C@MESA

Figure courtesy of Kent Paschke
Qweak experiment

- Hall C at Jefferson Lab (Newport News, Virginia)

• Custom designed apparatus

• Data-taking: 2010 – 2012 (~ 1 year total beam time)
• Jefferson Lab record beam current: 180 μA
• Last experiment in Hall C in “6 GeV era” CEBAF
• First results on proton’s weak charge (based on first 4% of the dataset)

• Final result: Nature 557, 207 (2018)

\[ A_{PV} = -226.5 \pm 9.3 \text{ ppb} \]
Global fit of world PVES data to extract proton’s weak charge:

\[ A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta), \quad A_0 = \left[ -\frac{G_F Q^2}{4 \pi \alpha \sqrt{2}} \right]. \]

**Qweak: Extracting Weak Charge from Asymmetry Result**

\[ A_{ep} = -226.5 \pm 7.3 \text{(stat)} \pm 5.8 \text{(syst)} \text{ ppb at } \left< Q^2 \right> = 0.0249 \text{ (GeV }/\text{c})^2 \]
Low-energy Weak Mixing Angle measurements

APV: atomic parity violation $^{133}\text{Cs}$
- future measurement/theory: challenging

PV Moller scattering
- SLAC E158: statistics-limited, theory robust
- next generation: MOLLER (factor 5 better)

PV elastic e-p scattering
- $Q_{\text{weak}}$ (JLab 2018) theory robust at low energy
- next generation: P2 at Mainz (factor of 3 better)

eDIS: PV deep inelastic scattering
- JLab 2014
- theory robust for $^2\text{H}$ in valence quark region
- next generation: SOLID (factor of 5 better)
Measuring tiny asymmetries

Rapid (2kHz) helicity reversals

Place a detector where it sees the Møller scattered electron

Analog integrate detector current

Form an asymmetry over the helicity reversal

Measure to 0.01% at 1 kHz, repeat for a year straight

Specialized experimental techniques
• Precise spectrometer to separate signal
• Low noise electronics
• Precise beam control and measurement
• ...
MOLLER goal

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]

- Measure: \( A_{PV} \approx 35 \text{ ppb} \) to 0.73 ppb precision
- Yields weak charge: \( Q^e_W = 1 - 4 \sin^2 \theta_W \) with 2.1\% (stat) and 1\% (syst) precision
- Yields \( \sin^2 \theta_W \) to 0.1\% precision
- Matches precision of best measurements at the Z pole

MOLLER new physics reach: \( \Lambda_{ee}^{LL} \approx 27 \text{ TeV} \)

\textit{MOLLER will access discovery space for new lepton-lepton couplings not otherwise accessible without a next generation collider, or a neutrino factory}

\textbf{Requires:}

- 11 GeV longitudinally-polarized electron beam
- Detected flux of 135 GHz
- 8200 hrs data taking
- \( 3 \times 10^{18} \) detected electrons

Custom Apparatus in Hall A at Jefferson Lab
Experimental Overview

Highest figure of merit at $\theta_{\text{CM}} = 90^\circ$

[Graph showing asymmetry $(A_{PV})$ vs. center of mass angle with peaks at 90° and 270°]

[Diagram of experimental setup with labeled sections: Target, Upstream Torus, Lead wall, Downstream Torus, Drift Region, Tracking Chambers, SAMs, Pion Detectors, Scanners, Collimator 1 & 2, Main Detectors]
Exploiting Identical Particles

Since you only need either the forward or the backward scatter, accept forward+backward for half the azimuth

CM angles 60°-120°
11 GeV in: 2.75 to 8.25 GeV out
Lab angles ~5 mrad - 17 mrad

Unique concept allows for full azimuthal acceptance (effectively) even leaving space for coils but makes for a challenging design
Spectrometer Concept

- Bend scattered particles, separate ee from ep and photons
- Small angles and high beam power
- Large energy range (3-8 GeV)
- Long target

- Two toroidal magnets (Upstream and Downstream)
- Collimation + “shields” or “blockers”
- Vacuum pipe to take beam to dump
Focus Moller electrons from full acceptance (3 – 8 GeV) to tight radial location on detectors

long and skinny

0.5 x 2m  0.9 x 6.5m
Main Detector

- Radiation hard fused-silica Cerenkov detectors
- Highly segmented for background deconvolution
Auxiliary Detectors

- Verify flux distributions and measure kinematics
- Measure backgrounds ($\pi^-, \mu^-$)
- Alternate asymmetry measurement with energy-weighting, reduced sensitivity to hadronic and soft backgrounds.
- Monitoring potential false asymmetries in irreducible backgrounds.
MOLLER Collaboration/Schedule

~160 authors, 37 institutions, 6 countries

**Spokesperson:** K. Kumar, UMass, Amherst

**Executive Board Chair and Deputy Spokesperson:** M. Pitt, Virginia Tech

**Other Executive Board Members:** D. Armstrong (William & Mary), J. Fast (JLab), C. Keppel (JLab), F. Maas (Mainz), J. Mammei (Manitoba), K. Paschke (UVa), P. Souder (Syracuse U.)

**Major Equipment Funding:**
- U.S. Dept of Energy
- U.S. National Science Foundation
- Canada Foundation for Innovation/Research Manitoba
- NSERC

**Present Status:** Engineering, Design, Prototyping phase

DOE CD-2/3: expected 2023

Data-taking: 2025-2027

More information: arXiv/1411.4088
Summary

**Qweak:** precision measurement of $A_{PV}$ in electron-proton scattering

- $\sin^2 \theta_W$ to 0.46% – excellent agreement with Standard Model prediction

**MOLLER:** precision measurement of $A_{PV}$ in electron-electron scattering

- $\sin^2 \theta_W$ to 0.1% – will match best measurements at Z-pole
  → Precision Standard Model test

- New physics reach for flavor-diagonal lepton couplings to 27 TeV

*Thanks to the Organizers, and thanks to you for listening!*