Measurement of Lepton-Lepton Electroweak Reaction
MOLLER

Introduction

Agenda Overview
& MOLLER Goals

Krishna Kumar
Stony Brook U.

DOE Nuclear Physics MOLLER Science Review, UMass, Amherst, September 10, 2014
Outline

✦ Comments on the Agenda
✦ Introduction to Møller Scattering
✦ SLAC E158 Result
✦ Introduction to MOLLER
  ★ Precision and Accuracy Goals
  ★ The Collaboration
Thanks

✧ Thanks to the panel members for taking the time and agreeing to participate in this review
✧ Thanks to the DOE Office of Nuclear Physics for scheduling this review and providing the opportunity to present the physics case for MOLLER
✧ Thanks to Michael Ramsey-Musolf and the Amherst Center for Fundamental Interactions (ACFI) for hosting this review at UMass, Amherst
Talk Titles and Speakers

✧ Parity-Violating Møller Scattering: Global Context (45): Michael Ramsey-Musolf

✧ Weak Mixing Angle, Radiative Corrections and New Vector Bosons (45): Bill Marciano

✧ Experimental Context and Overview of Technique (45): Krishna Kumar

✧ Overview of MOLLER Subsystems (45): Mark Pitt

✧ Statistics, Systematics and Run Phases (30): Kent Paschke

✧ Impact on JLab Science Program (20): Cynthia Keppel
Flow of Talks

✧ Morning Talks:

★ **M. Ramsey-Musolf:** Context for ultra-precise low $Q^2$ measurements

★ **W. Marciano:** robust theoretical prediction and unique discovery reach of low $Q^2$ weak neutral current measurements

✧ Afternoon Talks:

★ **K. Kumar:** Phenomenological perspective and experimental technique overview

★ **M. Pitt:** Description of Main MOLLER Subsystems

★ **K. Paschke:** Systematic Control and Progressive Run Phases

★ **C. Keppel:** The JLab Hall A Program Science Impact
Charge Elements

✧ Scientific Significance
  ★ Morning talks + first part of K.Kumar talk

✧ Impact on Advancement of Nuclear Physics
  ★ Morning talks + K.Kumar talk

✧ Research Effort Needed
  ★ W. Marciano talk (theory), K.Kumar and JLab talks (experiment)

✧ Feasibility and First Three Year Impact
  ★ Afternoon talks, especially K. Paschke talk

✧ Impact of Implementation on JLab Program
  ★ Afternoon talk by C. Keppel
Fixed Target Electron Scattering

**A_PV in Møller Scattering**

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

11 GeV Beam

\( e^- \quad Z^0 \quad e^- \quad Z^0 \quad e^- \quad Z^0 \quad e^- \)

10-20 mrad
**Fixed Target Electron Scattering**

**$A_{PV}$ in Møller Scattering**

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

\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2mE} \frac{(3 + \cos^2 \Theta)^2}{\sin^4 \Theta} \]

$11$ GeV Beam

$10-20$ mrad

LH2

Cross-section (mb)
Fixed Target Electron Scattering

**A_{PV} in Møller Scattering**

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2mE} \frac{(3 + \cos^2 \Theta)^2}{\sin^4 \Theta}
\]

\[
Q_{W}^{e} = 1 - 4 \sin^2 \theta_{W} \sim 0.075
\]

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

\[
A_{PV} = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q_{W}^{e}
\]
**Fixed Target Electron Scattering**

**ApV in Møller Scattering**

**11 GeV Beam**

\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2mE} \frac{(3 + \cos^2 \Theta)^2}{\sin^4 \Theta} \]

\[ Q_W^e = 1 - 4 \sin^2 \theta_W \sim 0.075 \]

**Asymmetry**

\[ A_{PV} = -mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q_W^e \]

**ApV varies from roughly 68 to 45 ppb**

Figure of merit slowly decreases as COM scattering angle moves away from 90 degrees.
Radiative Corrections

\[ A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha} \frac{1 - y}{1 + y^4 + (1 - y)^4} \left\{ 1 - 4\kappa(0) \sin^2 \theta_W (m_Z)_{\overline{MS}} \right\} \]

\[ + \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2} (1 - 4\hat{s}^2)[1 + (1 - 4\hat{s}^2)^2] \]

\[ + F_1(y, Q^2) + F_2(y, Q^2) \right\} \]

\[ Q^e_W = 1 - 4\sin^2 \theta_W \sim 0.075 \Rightarrow 0.045 \]

The small size of the coupling, further reduced by radiative corrections, will be a recurring theme: it eases the pressure on “normalization” errors.
The Standard Model Prediction: Remarkably Well-Known

Radiative Corrections

\[ A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha} \frac{1 - y}{1 + y^4 + (1 - y)^4} \left\{ 1 - 4\kappa(0) \sin^2 \theta_W (m_Z)_{\overline{MS}} \right\} \]

\[ + \frac{\alpha(m_Z)}{4\pi \hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi \hat{s}^2 \hat{c}^2} (1 - 4\hat{s}^2)[1 + (1 - 4\hat{s}^2)^2] \]

\[ + F_1(y, Q^2) + F_2(y, Q^2) \right\} \]

Czarnecki and Marciano (1995)

\[ Q_e^W = 1 - 4 \sin^2 \theta_W \sim 0.075 \implies 0.045 \]

The small size of the coupling, further reduced by radiative corrections, will be a recurring theme: it eases the pressure on “normalization” errors.
Radiative Corrections

\[ A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2\pi\alpha}} \frac{1 - y}{1 + y^4 + (1 - y)^4} \left\{ 1 - 4\kappa(0) \sin^2 \theta_W (m_Z)_{\overline{MS}} \right. \]

\[ + \frac{\alpha(m_Z)}{4\pi \hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi \hat{s}^2 \hat{c}^2} (1 - 4\hat{s}^2) [1 + (1 - 4\hat{s}^2)^2] \]

\[ + \left. F_1(y, Q^2) + F_2(y, Q^2) \right\} \]

Czarnecki and Marciano (1995)

\[ Q_W^e = 1 - 4\sin^2 \theta_W \sim 0.075 \Rightarrow 0.045 \]

The small size of the coupling, further reduced by radiative corrections, will be a recurring theme: it eases the pressure on “normalization” errors
Previous Result: SLAC E158

~ 10 ppb raw sensitivity at highest $E_{\text{beam}}$, ~ 0.5% error on weak mixing angle

First PVES Measurement with TeV-scale sensitivity 1997-2004

\[ A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9} \]

*Phys. Rev. Lett.* **95** 081601 (2005)
**E158 Physics Implications 2003**

Unique discovery space probed: Complementary to Colliders

**Limits on “New” Physics**

\[ A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9} \]

Tree-level prediction: \(~ -270 \text{ ppb}~

\[ LEP \text{ II } \begin{array}{c}
\begin{array}{c}
R \times R \times e^2 + L \times L \times e^2
\end{array}
\end{array}
\]

\[ 17 \text{ TeV} \]

\[ 16 \text{ TeV} \]

\[ 0.8 \text{ TeV} \]

\[ 1.0 \text{ TeV} (Z' \chi) \]

\[ 95\% \text{ C.L.} \]

\[ \text{E158} \]

\[ q \]

\[ Z' \]

\[ \text{doubly charged scalar exchange} \]

\[ 0.01 \times G_F \]

**Fermilab**

\[ e^- \]

\[ e^- \]

\[ e^- \]

\[ e^- \]
E158 Physics Implications
2003

Unique discovery space probed: Complementary to Colliders

Limits on "New" Physics

Tree-level prediction: ~ -270 ppb
SM with all corrections: -154 ppb

\[ A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9} \]
E158 Physics Implications
2003

Unique discovery space probed: Complementary to Colliders

Limits on “New” Physics

Tree-level prediction: ~ -270 ppb

SM with all corrections: -154 ppb

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

Fermilab

$0.01 \cdot G_F$

**E158**

$95\%$ C.L.

$17$ TeV

$16$ TeV

$1.0$ TeV ($Z'_{\chi}$)

$0.8$ TeV

$10^{-9}$

$\text{MS-Bar curve (Erler and Ramsey-Musolf '04) in 2012 PDG + APV update}$
An ultra-precise measurement of the weak mixing angle using Møller scattering

**MOLLER at JLab**

Measurement of Lepton Lepton Electroweak Reaction

Unique opportunity leveraging the 12 GeV Upgrade investment

Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

Special purpose installation in Hall A:
Narrow apparatus would be situated along beam line; HRS pair placed out of the way at wide angles
**Projected Uncertainty**

\( A_{PV} = 35 \text{ ppb} \)  
**Luminosity:** \( 3 \times 10^{39} \text{ cm}^2/\text{s} \)

75 \( \mu \text{A} \)  
80\% polarized

\[ \delta(A_{PV}) = 0.73 \text{ parts per billion} \]

\[ \delta(Q^e_W) = \pm 2.1 \% \text{ (stat.)} \pm 1.1 \% \text{ (syst.)} \]

\[ \delta(\sin^2\theta_W) = \pm 0.00024 \text{ (stat.)} \pm 0.00013 \text{ (syst.)} \]

\[ A_{PV} = 35 \text{ ppb} \]

\[ \sin^2\theta_W \approx 0.1\% \]

\[ Q_W = 1 - 4 \sin^2\theta_W \]

\[ \mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_i^2}{2\Lambda^2} \bar{e}_i \gamma^\mu e_i \bar{e}_j \gamma^\mu e_j \]

\[ \Lambda \sqrt{\left| g^2_{RR} - g^2_{LL} \right|} = 7.5 \text{ TeV} \]
MOLLER Collaboration
~120 Collaborators, 30 institutions, 6 countries

Expertise from several generations of successful parity experiments

Spokesperson: K. Kumar, Stony Brook U.
Executive Board Chair and Deputy Spokesperson: M. Pitt, Virginia Tech

Other Executive Board Members

Dave Armstrong (William and Mary)
Javier Gomez (JLab)
Cynthia Keppel (JLab)
Frank Maas (U. Mainz)
Juliette Mammei (U. Manitoba)
Kent Paschke (U. Virginia)
Paul Souder (Syracuse U.)

MOLLER Subsystem Leaders

Polarized Source: G. Cates (U. Virginia)
Beam Instrumentation: M. Pitt (Virginia Tech)
Hydrogen Target: S. Covrig (JLab)
Spectrometer: J. Mammei (Manitoba)
Integrating Detectors: M. Gericke (Manitoba)
Tracking Detectors, D. Armstrong (William and Mary)
Polarimetry: K. Paschke (U. Virginia)
Electronics/DAQ: R. Michaels (JLab) and P. King (Ohio)
Simulations: S. Riordan (UMass) and D. McNulty (Idaho State)

If/when MOLLER is ready to move forward as a funded project, the governance structure will be appropriately expanded.
Collaborators Present at Review

-

D. Armstrong (College of William and Mary)
-

G. Cates (U. Virginia)
-

M. Gericke (U. Manitoba)
-

E. Ihloff (MIT)
-

K. Kumar (Stony Brook)
-

K. Paschke (U. Virginia)
-

M. Pitt (Virginia Tech)
-

S. Riordan (UMass)
-

P. Souder (Syracuse U.)