Parity Violation at Jefferson Lab

Report to the NSAC Subcommittee

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Neutral Currents Beyond the Standard Model

Many new physics models require new, heavy, neutral current interactions

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{new}} \]

Heavy Z’s and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

**Low energy WNC interactions** \((Q^2 << M_Z^2)\)

Consider \( f_1 f_1 \rightarrow f_2 f_2 \) or \( f_1 f_2 \rightarrow f_1 f_2 \)

\[ \mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda^2_{ij}} \bar{f}_1 i \gamma \mu f_1 \bar{f}_2 j \gamma \mu f_2 j \]

mass scale \( \Lambda \), coupling \( g \) for each \textit{fermion} and \textit{handedness} combination

Sensitivity to TeV-scale contact interactions if:

- \( \delta(\sin^2\theta_W) \leq 0.5\% \)
- away from the Z resonance

- Precision neutrino scattering
- PV couplings through interference with EM
- opposite-parity transitions in heavy atoms
- parity-violating electron scattering

Kent Paschke  JLab Parity Violation  NSAC Subcommittee, September 2012
Parity Violation in Electron Scattering

Electromagnetic amplitude interferes with Z-exchange as well as any new physics

\[ \sigma \propto |A_\gamma + A_{\text{weak}}|^2 \]

\[ A_{\text{PV}} = \frac{\sigma - \sigma}{\sigma + \sigma} \]

\[ \sim A_{\text{EM}}^2 + 2A_{\text{EM}} A_{\text{weak}}^* + \ldots \]

\[ \sim \frac{A_{\text{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4 \pi \alpha} (g_A e g_V T + B g_V e g_A T) \]

\[ |A_\gamma + A_Z + A_{\text{new}}|^2 \rightarrow A_\gamma^2 \left[ 1 + 2 \left( \frac{A_Z}{A_\gamma} \right) + 2 \left( \frac{A_{\text{new}}}{A_\gamma} \right) \right] \]

PV in Deep Inelastic Scattering from \(^2\)H
\( A_{\text{PV}} \sim 100 \pm 10 \text{ ppm} \)

- *Parity Violation in Weak Neutral Current Interactions*
- *\( \sin^2 \theta_W = 0.224 \pm 0.020 \): same as in neutrino scattering*

improved by **PV-DIS-6** (JLab, 2012)

**Proton Weak Form Factors (2000-2011)**
Elastic e-p and e-N scattering
SAMPLE (Bates), A4 (MAMI),
G0 and HAPPEX (JLab)
Probing over a range of low-\(Q^2\), strange quark contributions to the form-factors are small (<3%) and consistent with zero.

**E158 (2004)**
*Electron weak vector charge*
48 GeV Møller Scattering
\( A_{\text{PV}} = (-131 \pm 14 \pm 10) \text{ ppb} \)
\( \delta (\sin^2 \theta_W) = 0.0014 \ (0.6\%) \)
*Phys. Rev. Lett. 95 081601 (2005)*

**QWeak (Jlab, 2010-2012)**
*Proton weak vector charge*
1 GeV elastic e-p scattering
\( \delta (\sin^2 \theta_W) = 0.0007 \ (0.3\%) \)
3 Decades of Technical Progress

Parity-violating electron scattering has become a precision tool

Interplay between probing hadron structure and electroweak physics

- Beyond Standard Model Searches
- Strange quark form factors
- Neutron skin of a heavy nucleus
- QCD structure of the nucleon

For future program:

- sub-part per billion statistical reach and systematic control
- sub-1% normalization control

photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors
Running Weak Charge

Improvement in SM prediction

- Petriello (2002)
- Sirlin et. al. (2004)

Deviation from this SM curve would indicate observation of a new interaction, beyond the SM $Z^0$

**E158**: First confirmation of SM running Constraints on new physics into 15 TeV (lepton compositeness) 0.5-2 TeV ($Z'$, extra dimensions)

Future Program of Precision Weak Charge Measurements

- Elastic Electron-Proton Scattering
- Moller Scattering
- Deep Inelastic Scattering off Deuterium

Each tests different couplings and plays a role in constraining/detailing possible BSM physics
Proton Weak Charge, $Q_{W}^{p}$

Program to study strange quark contribution to the nucleon form-factors

Strange Quark FF: shape of curve

Proton weak vector charge: projection to $Q^{2} = 0$

The strange quark program has led to significant improvement measurement of quark weak vector couplings

**Qweak**

$\delta Q_{W}^{p} = \pm 4\%$

$\Rightarrow \delta (\sin^{2} \theta_{W}) = \pm 0.3\%$

$C_{1i} \equiv 2g^{e}_{A}g^{i}_{V}$

$\Lambda \sim \frac{1}{g} \sim 4.6 \text{ TeV}$

Non-perturbative theory $g \sim 2\pi$, $\Lambda \sim 29 \text{ TeV}$

Extra $Z'$ $g \sim 0.45$, $m_{Z'} \sim 2.1 \text{ TeV}$

R. Young et al., PRL 99 122003 (2007)
QWeak at JLab

World’s highest power cryotarget

2300 Watts

Designed with CFD simulation

Boiling <40 ppm at 180 μA (about 3% excess noise)

Integrating Main Detector
5 GHz total rate

1 ppm precision in 4 minutes

Width 236 ppm at 240 Hz

New Hall C Compton Polarimeter

Preliminary “internal consumption only” Polarization, measured through Compton and Moller

Precision Collimator

Secondary Collimator

Inelastics

35 cm Liquid Hydrogen Target

35 cm Liquid Hydrogen Target

35 cm Liquid Hydrogen Target

Toroidal Magnet

Shielding

Elastic ep

Ring of Integrating Quartz Cherenkov detectors

Integrated Main Detector
5 GHz total rate

5 GHz total rate

Boiling <40 ppm at 180 μA (about 3% excess noise)
Proton Weak Charge

Run II Beam Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$\Delta x$</td>
<td>-0.95 nm</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>-0.24 nm</td>
</tr>
<tr>
<td>$\Delta x'$</td>
<td>-0.07 nrad</td>
</tr>
<tr>
<td>$\Delta y'$</td>
<td>-0.06 nrad</td>
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<tr>
<td>$A_{\text{Energy}}$</td>
<td>0.23 ppb</td>
</tr>
</tbody>
</table>

Main detector asymmetry in “prompt” monitoring plots

JLab QWeak Completed run (2010-2012)
First results (~5% of data) to be released at DNP

Future: MESA/P2 at Mainz

New ERL complex will also support a high-current extracted beam suitable for a PV measurement of proton weak charge

- $A_{PV} = -20$ ppb to 2.1% (0.4 ppb)
- $\delta(sin^2\theta_W) = 0.2\%$
- Funding approved from DFG
- Development starting now
- Planned running 2017-2020
12 GeV Upgrade at JLab

Unique Facility for PVeS
- High intensity
- High polarization
- Low noise (cold CW RF)
- Energy range

12 GeV for Hall D
Upgrade magnets and power supplies

Two 1.1 GV linacs

Enhanced capabilities in existing Halls

Lower pass beam energies still available
2-11 GeV
MOLLER at 11GeV JLab

An ultra-precise measurement of the weak mixing angle using Møller scattering

\[ A_{PV} \propto E_{lab}^2 Q_W, \quad \sigma \propto \frac{1}{E_{lab}} \]

Figure of Merit proportional to beam power

At 11 GeV, JLab luminosity and stability makes large improvement possible

\[ \delta(A_{PV}) = 0.73 \text{ parts per billion} \]
\[ \delta(Q_W^e) = \pm 2.1 \% \text{ (stat.)} \pm 1.0 \% \text{ (syst.)} \]
\[ \delta(sin^2\theta_W) = \pm 0.00026 \text{ (stat.)} \pm 0.00012 \text{ (syst.)} \]

\[ \sim 0.1\% \]

Matches best collider (Z-pole) measurement!

Luminosity: 3x10^{39} cm^2/s
75 \mu A 80\% polarized

MOLLER

A_{PV} = 35.6 \text{ ppb}
Precision Measurement of $\sin^2 \theta_W$

Direct measurement of SM weak mixing angle is average of two measurements that disagree by $3\sigma$... ...yet the naive statistical average agrees to a very high level with the LHC Higgs candidate

We failed to nail $\sin^2 \theta_W$ when we had the colliders! -B. Marciano

The consistency of the SM prediction, between directly measured $m_H$, $m_W$, $m_t$, $\sin^2 \theta_W$ bears testing

- $\sin^2 \theta_W$ improvements at hadron colliders very challenging
- “Giga-Z” option of ILC or neutrino factory: powerful but far future
MOLLER Sensitivity to BSM Physics

$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma^\mu e_j \bar{e}_j \gamma^\mu e_j$$

$$\frac{\Lambda}{\sqrt{g_{RR}^2 - g_{LL}^2}} = 7.5 \text{ TeV}$$

best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider

Heavy Photons: (Z):
The Dark Sector

Hypothesis could explain \((g-2)_\mu\) discrepancy as well as several intriguing astrophysical anomalies related to dark matter

Beyond kinetic mixing:
introduce mass mixing with Z

Davoudiasl, Lee, Marciano  arXiv:1203.2947v2

Complementary to direct heavy photon searches:
Lifetime/branching ratio model dependence vs mass mixing assumption

MOLLER reach: red dashed lines
Meeting the Challenges of MOLLER

Unprecedented Precision

- ~ 150 GHz scattered electron rate (80ppm at 2kHz)
- 100% Azimuthal acceptance, with $\theta_{\text{lab}} \sim 5$-15 mrad
- Robust and redundant 0.4% beam polarimetry
- 1 nm control of beam centroid on target
- > 10 gm/cm$^2$ target needed

Preparations on Track

- Strong Collaboration being formed with international participation
- JLab Director’s Review (chair: C. Prescott) gave strong endorsement
- Conceptual design and cost range being developed (~20M$)
- Funding proposal has been submitted to DoE
- ~3 years construction, aim to complete data collection in 2020
**SOLID: \( C_{1q}, \ C_{2q} \) in Deep Inelastic Scattering**

\[
A^{PV}_{D} = -\left( \frac{3G_{F}Q^{2}}{\pi\alpha 10\sqrt{2}} \right) \left[ 2C_{1u} - C_{1d} \right] + Y \left[ 2C_{2u} - C_{2d} \right]
\]

**PV-DIS with \(^2\text{H}^\text{H}\)**

**11 GeV PVDIS**

**Qweak**

**PV-DIS**

Red ellipses are PDG fits.

Blue bands represent expected data:
- Qweak (left)
- PV-DIS-6GeV (right)

Green bands are the proposed measurement of PV-DIS (SOLID)

\[
\begin{align*}
C_{1u} & = -\frac{1}{2} + \frac{4}{3} \sin W = -0.10 \\
C_{1d} & = \frac{1}{2} - \frac{2}{3} \sin W \approx 0.35 \\
C_{2u} & = -\frac{1}{2} + 2 \sin \theta_W \\
C_{2d} & = \frac{1}{2} - 2 \sin \theta_W
\end{align*}
\]
QCD and Hadronic Structure in PV-DIS

Charge Symmetry Violation
- Direct sensitivity of parton-level CSV
- Important implications for PDF's
- Could be partial explanation of the NuTeV anomaly

Higher Twist
- cancellations isolate effects to coherent operator: Diquarks!
- HT thumbprint (increase with $x, Q^2$) should be clear if it is significant

Strategy: requires precise kinematics and broad range

Variations over $x, Q^2$ can discriminate QCD effects and new physics

SOLID
- Large acceptance spectrometer based on large solenoid (e.g. CLEO)
- High luminosity
- Tracking, calorimetry, Cerenkov detectors
- Precision polarimetry

Measure $A_d$ in **narrow** bins of $x, Q^2$ with 0.5% precision

Statistical error bar $\sigma_{A}/A(\%)$ shown at center of bins in $Q^2, x$
SoLID would fill a unique corner of parameter space

No other technique can provide comparable precision on axial hadronic weak neutral currents

**Leptophobic Z’**

Since electron vertex must be vector, the Z’ cannot couple to the $C_{1q}$’s if there is no electron coupling: can only affect $C_{2q}$’s

- **Leptophobic Z’ as light as 120 GeV could have escaped detection**

Deuterium PV-DIS drives the need for SoLID, but it also supports a **broad program of hadronic studies**

Transverse Spin Structure
semi-inclusive DIS from polarized targets

$J/\Psi$ Production

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arXiv:1203.1102v1
Buckley and Ramsey-Musolf

{$Q^2 = 10 \text{ GeV}^2$}

QCD fit
cTEQ4M
cTEQ4M (modified)
This proposal, 90 days (follows MRST-2004)
**Fundamental Symmetries at an EIC**

Hadronic physics: Novel $\gamma Z$ structure functions

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**polarized electron, unpolarized hadron**

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[ g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2} \frac{F_3^{\gamma Z}}{F_1^{\gamma}} \right]$$

**unpolarized electron, polarized hadron**

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[ g_V \frac{F_5^{\gamma Z}}{F_1^{\gamma}} + g_A f(y) \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \right]$$

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There are 15 different structure function combinations that can be measured (EM, $\gamma Z$, W)

**proton**

$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$

$$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$$

**deuteron**

$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$

$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

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**BSM: Search for Lepton Flavor Violation $e \rightarrow \tau$**

$$e^- + p \rightarrow \tau^- + X$$

$$e^- + p \rightarrow \tau^+ + X$$

EIC can go beyond HERA limits on search for neutrinoless $\tau$ production and competes with super-B factory

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Inclusive cross-check of semi-inclusive $\Delta s$ extraction

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BaBar limits tau decay (quark flavor diagonal)
Summary: Compelling new opportunities in PVeS

Since 2007:

- New constraint on quark vector weak charges
- (Completion of Strange quark program)
- (First electroweak observation of neutron skin in a heavy nucleus)
- Successfully completed PV-DIS-6 running (results soon!)
- Successfully completed QWeak running

MOLLER at JLab

- Ultra-precise weak-mixing angle comparable to the best collider measurements, needed and unavailable anywhere else!
- TeV-scale BSM sensitivity to complement LHC

SOLID at JLab

- Unique access to axial weak hadronic coupling tests un-illuminated corner of BSM parameter space
- Broad program of hadronic studies: high-\(x\) partonic structure, transverse spin structure, nuclear modification, QCD studies

P2 at Mainz

- Factor of two and low \(Q^2\) available on \(Q_w^p\)
- Extend precision and improved interpretation

JLab provides unique capabilities that enable a compelling program of high precision studies of parity violation in electron scattering