Symmetry Tests in Nuclear Physics

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Editorial Board:
Low Energy QCD: B. Bernstein, A. Gasparian, J. Goity

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Opportunities for Symmetry Tests at 12 GeV

• **Strong Interaction**
  - Chiral symmetry breaking
  - Charge symmetry violation
  - Spin-Flavor symmetry breaking

• **Electroweak Interaction**
  - TeV scale physics
Outline

• **Parity-Violating Electron Scattering**
  - Brief Overview
  - Weak Neutral Current Interactions at $Q^2 \ll M_Z^2$

• **Parity-Violating Deep Inelastic Scattering**
  - New Physics at 10 TeV in Semileptonic Sector
  - Charge Symmetry Violation
  - $d/u$ at High $x$
  - Higher Twist Effects

• **Parity-Violating Möller Scattering**
  - Ultimate Precision at $Q^2 \ll M_Z^2$: 25 TeV reach
PV Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 \ll M_Z^2$

Longitudinally Polarized Electron Scattering off Unpolarized Fixed Targets

\[
\begin{align*}
\sigma &\propto |A_\gamma + A_{\text{weak}}|^2 \\
-A_{LR} = A_{PV} &\approx \frac{\sigma^- - \sigma^+}{\sigma^+ + \sigma^-} \\
&\approx \frac{A_{\text{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4 \pi \alpha} \left( g_A e g_V^T + \beta g_V e g_A^T \right)
\end{align*}
\]

- The couplings $g$ depend on electroweak physics as well as on the weak vector and axial-vector hadronic current
- With specific choice of kinematics and targets, one can probe new physics at high energy scales
- With other choices, one can probe novel aspects of hadron structure

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Symmetries Tests in Nuclear Physics
$A_{PV}$ Measurements

$A_{PV} \sim 10^{-5} \cdot Q^2$ to $10^{-4} \cdot Q^2 \quad \Rightarrow \quad 0.1$ to $100 \ \text{ppm}$

SLAC E122: parity-violating deep inelastic scattering

20 GeV longitudinally polarized electrons

precision monitors

liquid Deuterium

asymmetry $\sim 10^{-4}$

error $\sim 10^{-5}$

C.Y. Prescott et al. 1978

• Steady progress in technology
• part per billion systematic control
• 1% normalization control
• JLab now takes the lead
  - New results from HAPPEX
  - Photocathodes
  - Polarimetry
  - Targets
  - Diagnostics
  - Counting Electronics
The Annoying Standard Model

(it just wont break!)

Nuclear Physics Long Range Plan:
What is the new standard model?

Low $Q^2$ offers unique and complementary probes of new physics

- Rare or Forbidden Processes
- Symmetry Violations
- Electroweak One-Loop Effects

- Double beta decay..
- neutrinos, EDMs..
- Muon g-2, beta decay..

Low energy experiments are again players in the neutral current sector
World Electroweak Data

16 precision electroweak measurements:

\[ \chi^2/\text{dof} \sim 25.4/15 \]

*Probability* < 5%

Leptonic and hadronic

Z couplings seem inconsistent

Perhaps there are bigger deviations lurking elsewhere
**Electroweak Physics at Low $Q^2$**

$Q^2 \ll$ scale of EW symmetry breaking

Consider

\[
\begin{align*}
X & \rightarrow A_X \propto \frac{1}{Q^2 - M_X^2} \\
& \sim \frac{4\pi}{\Lambda^2}
\end{align*}
\]

$Q^2 \sim M_Z^2$

on resonance: $A_Z$ imaginary

\[A_Z^2 \left[ 1 + \frac{A_X^2}{A_Z^2} \right]
\]

no interference!

Logical to push to higher energies, away from the $Z$ resonance

**LEPII, Tevatron, LHC access scales greater than $\Lambda \sim 10$ TeV**

\[
\frac{\delta A_Z}{A_Z} \propto \frac{\pi}{\Lambda^2} \frac{g}{G_F}
\]

$\delta(g)/g \sim 0.1$

$\Lambda \sim 10$ TeV

$\frac{\delta (\sin \theta_W)}{\sin^2 \theta_W} \lesssim 0.01$

**Complementary:** Parity **Violating** vs Parity **Conserving**
WNC Low $Q^2$ Processes

**Atomic Parity Violation (APV)** $\rightarrow$ series of isotopes

- Limited by theory: Atomic structure; Neutron Halo

**Semi-Leptonic** $\rightarrow$ **PV Elastic electron-proton scattering at JLab**
  - PV DIS experiment feasible within scope of HMS/SHMS upgrade
  - Unique, complementary probes of New Physics
  - Theoretical issues are interesting in themselves:

**NuTeV**

**Leptonic**

- $\nu$-e scattering in reactor
- Møller scattering at upgraded JLab

- Reactor experiment cannot do better than SLAC E158
- Dedicated new apparatus at upgraded JLab can do significantly better:

Best low energy measurement until Linear Collider or $\nu$-Factory

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Electron-Quark Phenomenology

\[ C_{1i} = 2g_A^e g_V^i \]

\[ C_{2i} = 2g_V^e g_A^i \]

\[ C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 (\theta_W) \approx -0.19 \]

\[ C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 (\theta_W) \approx 0.35 \]

\[ C_{2u} = -\frac{1}{2} + 2 \sin^2 (\theta_W) \approx -0.04 \]

\[ C_{2d} = \frac{1}{2} - 2 \sin^2 (\theta_W) \approx 0.04 \]

\[ C_{1u} \text{ and } C_{1d} \text{ will be determined to high precision by other experiments} \]

\[ C_{2u} \text{ and } C_{2d} \text{ are small and poorly known: can be accessed in PV DIS} \]

\[ \text{New physics such as compositeness, new gauge bosons:} \]

\[ \text{Deviations to } C_{2u} \text{ and } C_{2d} \text{ might be fractionally large} \]

\[ \text{Proposed JLab upgrade experiment will improve knowledge of } 2C_{2u} - C_{2d} \text{ by more than a factor of 20} \]

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SymmetriesTests in Nuclear Physics
Parity Violating Electron DIS

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \left[ a(x) + f(y)b(x) \right] \]

\[ x \equiv x_{Bjorken} \]

\[ a(x) = \frac{\sum C_{1i} Q_i f_i(x)}{\sum Q_i^2 f_i(x)} \]

\[ b(x) = \frac{\sum C_{2i} Q_i f_i(x)}{\sum Q_i^2 f_i(x)} \]

\[ y \equiv 1 - E'/E \]

\[ f_i(x) \text{ are quark distribution functions} \]

For an isoscalar target like \(^2\text{H}\), structure functions largely cancel in the ratio:

Provided \(Q^2 >> 1 \text{ GeV}^2\) and \(W^2 >> 4 \text{ GeV}^2\) and \(x \sim 0.2 - 0.4\)

\[ a(x) = \frac{3}{10} \left[ (2C_{1u} - C_{1d}) \right] + \cdots \]

\[ b(x) = \frac{3}{10} \left[ (2C_{2u} - C_{2d}) \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \right] + \cdots \]

Must measure \(A_{PV}\) to fractional accuracy better than 1%

- 11 GeV at high luminosity makes very high precision feasible
- JLab is uniquely capable of providing beam of extraordinary stability
- Systematic control of normalization errors being developed at 6 GeV

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**2H Experiment at 11 GeV**

\[ E' : 5.0 \text{ GeV} \pm 10\% \]

\[ I_{beam} = 90 \mu \text{A} \]

\[ \theta_{lab} = 12.5^\circ \]

\[ 60 \text{ cm LD}_2 \text{ target} \]

- Use both HMS and SHMS to increase solid angle
- \(~2 \text{ MHz DIS rate}, \pi/e \sim 2-3\)

\[ A_{PV} = 217 \text{ ppm} \]

\[ x_{Bj} \sim 0.235, \ Q^2 \sim 2.6 \text{ GeV}^2, \ W^2 \sim 9.5 \text{ GeV}^2 \]

Advantages over 6 GeV:
- Higher \( Q^2, W^2, f(y) \)
- Lower rate, better \( \pi/e \)
- Better systematics: 0.7%

\[ \delta(A_{PV}) = 0.65 \text{ ppm} \]

\[ \delta(2C_{2u}-C_{2d}) = \pm 0.0086 \pm 0.0080 \]

Theory: +0.0986

PDG (2004): -0.08 \pm 0.24
Physics Implications

Unique, unmatched constraints on axial-vector quark couplings:
Complementary to LHC direct searches

Examples:
- 1 TeV extra gauge bosons (model dependent)
- TeV scale leptoquarks with specific chiral couplings

\[ \delta(2C_{2u} - C_{2d}) = 0.012 \]
\[ \delta(\sin^2\theta_W) = 0.0009 \]
PV DIS and Nucleon Structure

- Analysis assumed control of QCD uncertainties
  - Higher twist effects
  - Charge Symmetry Violation (CSV)
  - d/u at high x

- NuTeV provides perspective
  - Result is 3σ from theory prediction
  - Generated a lively theoretical debate
  - Raised very interesting nucleon structure issues: cannot be addressed by NuTeV

- JLab at 11 GeV offers new opportunities
  - PV DIS can address issues directly
    - Luminosity and kinematic coverage
    - Outstanding opportunities for new discoveries
    - Provide confidence in electroweak measurement
Search for CSV in PV DIS

\[ u^p(x) = d^n(x)? \quad \cdot \text{u-d mass difference} \]
\[ d^p(x) = u^n(x)? \quad \cdot \text{electromagnetic effects} \]

- Direct observation of parton-level CSV would be very exciting!
- Important implications for high energy collider pdfs
- Could explain significant portion of the NuTeV anomaly

For \( A_{PV} \) in electron-\(^2\)H DIS:

\[
\frac{\delta A_{PV}}{A_{PV}} = 0.28 \frac{\delta u - \delta d}{u + d}
\]

Sensitivity will be further enhanced if \( u+d \) falls off more rapidly than \( \delta u-\delta d \) as \( x \to 1 \)

Strategy:

- Measure or constrain higher twist effects at \( x \sim 0.5-0.6 \)
- Precision measurement of \( A_{PV} \) at \( x \sim 0.7 \) to search for CSV
Higher Twist Effects

\[ F_2(x, Q^2) = F_2(x)(1 + D(x)/Q^2) \]

\[ A_{PV}(x, Q^2) = A_{PV}(x)(1 + C(x)/Q^2) \]

- \( A_{PV} \) sensitive to diquarks: ratio of weak to electromagnetic charge depends on amount of coherence
- If Spin 0 diquarks dominate, likely only \( 1/Q^4 \) effects.
- Novel interference terms might contribute
- On the other hand, higher twist effects may cancel, so \( A_{PV} \) may have little dependence on \( Q^2 \).
\[ A_{PV} \text{ in DIS on } ^1\text{H} \]

\[
A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi \alpha} \left[ a(x) + f(y)b(x) \right]
\]

\[
a(x) = \frac{3}{2} \left[ \frac{2C_{1u}u(x) - C_{1d}(d(x) + s(x))}{4u(x) + d(x) + s(x)} \right]
\]

\[
b(x) = \frac{3}{2} \left[ \frac{2C_{2u}u_v(x) - C_{2d}d_v(x)}{4u(x) + d(x) + s(x)} \right]
\]

\[
a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)} + \text{small corrections}
\]

- Allows d/u measurement on a single proton!
- Vector quark current! (electron is axial-vector)

- **Determine that higher twist is under control**
- **Determine standard model agreement at low x**
- **Obtain high precision at high x**
d/u at High x

Deuterons analysis has nuclear corrections

$A_{PV}$ for the proton has no such corrections

Must simultaneously constrain higher twist effects

The challenge is to get statistical and systematic errors $\sim 2\%$
PV DIS Program

- Hydrogen and Deuterium targets
- Better than 2% errors
  - It is unlikely that any effects are larger than 10%
- $x$-range 0.25-0.75
- $W^2$ well over 4 GeV$^2$
- $Q^2$ range a factor of 2 for each $x$ point
  - (Except $x \sim 0.7$)
- Moderate running times

- With HMS/SHMS: search for TeV physics
- With larger solid angle apparatus: higher twist, CSV, d/u...
Large Acceptance: Concept

**JLab Upgrade**

- CW 90 µA at 11 GeV
- 40-60 cm liquid H$_2$ and D$_2$ targets
- Luminosity > $10^{38}$/cm$^2$/s

**Need high rates at high x**

**For the first time: sufficient rates to make precision PV DIS measurements**

- solid angle > 200 msr
- Count at 100 kHz
- online pion rejection of $10^2$ to $10^3$
Fixed Target Møller Scattering

Purely leptonic reaction

Weak charge of the electron:

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

\[ A_{PV} \propto m_{e} E_{lab} (1 - 4 \sin^{2} \vartheta_{W}) \]

\[ \sigma \propto \frac{1}{E_{lab}} \]

Figure of Merit rises linearly with \( E_{lab} \)

- Maximal at 90° in COM (\( E' = E_{lab}/2 \))
- Highest possible \( E_{lab} \) with good \( P^{2}I \)
- Moderate \( E_{lab} \) with LARGE \( P^{2}I \)

Unprecedented opportunity: The best precision at \( Q^{2} \ll M_{Z}^{2} \) with the least theoretical uncertainty until the advent of a linear collider or a neutrino factory
Design for 12 GeV

- \( E' : 3-6 \text{ GeV} \)
- \( \theta_{\text{lab}} = 0.53^\circ - 0.92^\circ \)
- \( A_{\text{PV}} = 40 \text{ ppb} \)
- \( \delta(A_{\text{PV}}) = 0.58 \text{ ppb} \)

**Beam systematics:** steady progress (E158 Run III: 3 ppb)

- Focus alleviates backgrounds: \( ep \rightarrow ep(\gamma), ep \rightarrow eX(\gamma) \)
- Radiation-hard integrating detector
- Normalization requirements similar to other planned experiments
- Cryogenics, density fluctuations and electronics will push the state-of-the-art
New Physics Reach

**New Contact Interactions**

\[ \Lambda_{ee} \sim 25 \text{ TeV} \]

\[ \Lambda_{ee} \sim 15 \text{ TeV} \]

**JLab Møller**

\[ e^+ e^- \rightarrow e^- e^- \]

**LEP200**

\[ e^+ e^- \rightarrow e^+ e^- \]

Does Supersymmetry (SUSY) provide a candidate for dark matter?

- Lightest SUSY particle (neutralino) is stable if baryon (B) and lepton (L) numbers are conserved.
- However, B and L need not be conserved in SUSY, leading to neutralino decay (RPV).

Kurylov, Ramsey-Musolf, Su
Electroweak Physics

Delta (sin^2 \theta_W) \sim 0.0003
Comparable to single collider measurements

- Semileptonic processes have theoretical uncertainties
- E158 established running, probing vector boson loops
- JLab measurement would have impact on discrepancy between leptonic and hadronic Z-pole measurements
Summary

• **12 GeV Upgrade**
  - Opens unique opportunities for new PV measurements
  - Hall configuration must support dedicated apparatus
    • Large solid angle toroid/calorimeter for PV DIS
    • Superconducting solenoid for Møller scattering

• **Science in the first five years**
  - Complete TeV physics search in DIS with SHMS/HMS
    • Important complement to direct LHC searches
  - Address new questions raised:
    • Develop experimental tools for PV DIS at high $x$
    • Major potential for new discoveries in nucleon structure
  - Launch electron weak charge measurement
    • Best low energy probe of TeV scale physics for decades