Electrons and Mirror Symmetry

Parity-violating Electron Scattering and the Search for Strange Seas, New Physics and Quark Stars

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The present and future program of parity-violating electron scattering

- Framing the question: electron scattering, mirror symmetry, and the electroweak interaction
- Experimental Techniques
- An important question about VERY big nuclei
- Using parity-violation to fish in the nucleon sea
- Indirect searches for new physics
### Matter and Interactions

<table>
<thead>
<tr>
<th>Gravity</th>
<th>Weak</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>mediator</td>
<td>(not found)</td>
<td>$W^+, W^-, Z^0$</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>acts on</td>
<td>all</td>
<td>quarks and leptons</td>
<td>Electrically charged</td>
</tr>
<tr>
<td>Strength at $3 \times 10^{-17}$ m</td>
<td>$10^{-41}$</td>
<td>$10^{-4}$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

**Electromagnetic**

- Weak: $W^+, W^-, Z^0$
- Electromagnetic: $\gamma$
- Strong: gluons

One unified framework for weak and electromagnetic interactions.

**Elementary Particles**

- Electron: $< 10^{-19}$ m
- Nucleon: $10^{-15}$ m
- Quark: $< 10^{-18}$ m
- Atom: $10^{-10}$ m
- Nucleus: $10^{-14}$ m

**Force Carriers**

I, II, III: Three Generations of Matter

*Image*: Diagram showing the scale of different particle sizes and their interactions.
Introduction to electron scattering

Electron scattering: electromagnetic interaction, described as an exchange of a virtual photon.

If photon carries low momentum
-\rightarrow long wavelength
-\rightarrow low resolution

Q^2: 4-momentum of the virtual photon

point-like target

Increasing momentum transfer
-\rightarrow shorter wavelength
-\rightarrow higher resolution to observe smaller structures
Parity Symmetry

**Parity transformation**
\[ x, y, z \rightarrow -x, -y, -z \]
\[ \vec{p} \rightarrow -\vec{p}, \quad \vec{L} \rightarrow \vec{L}, \quad \vec{S} \rightarrow \vec{S} \]

**Parity transformation**
Parity transformation is analogous to reflection in a mirror:

- ... reverses momentum but preserves angular momentum
- ... takes right-handed (helicity = +1) to left-handed (helicity = -1).

**Helicity**: spin in direction of motion
\[ h = \vec{S} \cdot \vec{p} = \pm 1 \]

**Parity symmetry**: interaction must be the same after parity transformation

1957 – Parity Violation observed
Weak decay of $^{60}\text{Co}$ Nucleus

$^{60}\text{Ni}$
$e^{-}$
$^{60}\text{Co}$
$\bar{\nu}_{e}$

$e^{-}$
$\bar{\nu}$
$\nu$
$e^{-}$

Observed
Not observed
Charge and Handedness

Electric charge determines strength of electric force

Neutrinos are “charge neutral”: do not feel the electric force

Weak charge determines strength of weak force

Left-handed particles (Right-handed antiparticles) have weak charge

Right-handed particles (left-handed antiparticles) are “weak charge neutral”

Observed

\[ ^{60}\text{Co} \rightarrow W^- e^- L \]

\[ ^{60}\text{Ni} \rightarrow V_{eR} \]

Not observed

\[ ^{60}\text{Co} \rightarrow W^- e^- R \]

\[ ^{60}\text{Ni} \rightarrow V_{eL} \]
Neutral Weak Force

Electroweak unification implied a pattern of neutral weak charges with only one free parameter: $\theta_W$

Neutral weak interaction first measured in the early ‘70s

Z bosons produced in electron-positron collisions: precise measurements of Z charge of most fermions

<table>
<thead>
<tr>
<th></th>
<th>Left-</th>
<th>Right-</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ Charge</td>
<td>$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$</td>
<td>$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$</td>
</tr>
<tr>
<td>$W$ Charge</td>
<td>$T = \pm \frac{1}{2}$</td>
<td>0</td>
</tr>
<tr>
<td>$Z$ Charge</td>
<td>$T - q \sin^2 \theta_W$</td>
<td>$-q \sin^2 \theta_W$</td>
</tr>
</tbody>
</table>

Measurements of Z mass, Z charges validated the electroweak theory
Electron scattering, weakly

Electron scattering is (mostly) electromagnetic scattering.

The weak amplitude is $\sim 10^{-6}$ smaller.

The weak quark charges are different than the EM charge. The weak interaction can be a valuable probe of nuclear matter, complementary to the extensive electromagnetic data set.

Fundamental Weak and EM interactions are predicted with very high precision, but with an apparently incomplete model. Can we find a crack in the Standard Model in precision measurements at low energy?

The challenge: Isolate the tiny effect of the weak interaction.
Mirror Asymmetry

- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference

\[ \sigma = |\mathcal{M}_\gamma + \mathcal{M}_Z|^2 \]

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|} A_{PV} \text{ ranges from } 10^{-4}-10^{-7} \text{ (0.1-100 ppm)} \]
Experimental Technique
Experimental Technique

Goal: small asymmetry measured at the few percent level

\[ A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx 10^{-6} \]

\[ \frac{\sigma_A}{A} = \frac{1}{A \sqrt{N}} = 10\% \]

\[ N \sim 10^{14} !!! \]

How do you pick a tiny signal out of a noisy environment?

Beam helicity pairs with fixed time intervals are ordered pseudo-randomly

helicity reversal is rapid (30 Hz - 1 kHz)

\[ \delta(A_{PV}) = \frac{540 \text{ ppm}}{\sqrt{25.3 \times 10^6}} = 0.11 \text{ ppm} \]

25 million trials
0.05% precision

15 Hz, 540 ppm implies 50 MHz rate
JLab: Continuous Electron Beam Accelerator Facility

Superconducting, continuous wave, recirculating linac
- 1500 MHz RF, with 3 interleaved 500 MHz beams

“Cold” RF is makes a clean, “quiet” beam... perfect for precision experiments

5x1.2 GeV = 6 GeV Maximum Energy

Bending magnets in arc

Linac tunnel
Polarized Electrons for Measuring $A_{PV}$

Photoemission from semiconductor cathode

- High luminosity (200 μA, 80+C lifetime)
- High polarization (~90%)
- High stability / uptime
- Electro-optic Pockels cell enables rapid helicity flip

Strain gives high polarization (~85%) but also introduces anisotropy
Measuring $A_{PV}$

High rates to get statistical precision, but also:

- Control Noise - quiet electronics, luminosity stability
- Low backgrounds - must be known PV asymmetry
- Polarimetry - Can’t do better on $A_{PV}$ than on $P_{beam}$
- Kinematics - Interpretation requires $Q^2$ precision
- False Asymmetries - electronics, beam motion... ?

Beam must look the same for the two helicity states!
- More beam = more signal: so intensity change $\rightarrow A_{false}$
- Cross-section vs angle is very steep: position change $\rightarrow A_{false}$

Major effort toward reducing beam asymmetries at the polarized source

Corrections use measured sensitivities

$$A_{cor} = A_{det} - A_Q + \sum_{i=1}^{5} \beta_i \Delta x_i$$
Beam Asymmetries from the Source

Uniformity of circular polarization: components, alignment techniques, diagnostics

PITA: Polarization Induced Transport Asymmetry

Intensity Asymmetry

\[ A_I = \varepsilon \Delta \sin(\theta) \]

where \( \varepsilon = \frac{T_x - T_y}{T_x + T_y} \)

Quantum Efficiency Asymmetry

If on average linear polarization = 0, that doesn’t mean that it is everywhere zero

A non-zero 1st moment creates a position difference

A non-zero 2nd moment creates a spot-size difference

Laser at Polarized Source
Helicity Correlated Position Differences

Over the ~20 million pairs measured in HAPPEX-II, the average position was not different between the two helicity states by more than 2 nanometers.

**X position difference**

$0.56 \pm 0.53 \text{ nm}$

$\text{RMS} = 2.77 \mu \text{m}$

**Y position difference**

$1.69 \pm 1.83 \text{ nm}$

$\text{RMS} = 9.50 \mu \text{m}$

This was still the leading source of systematic uncertainty in the asymmetry.
Precision Electroweak Physics

Steady progress in technology:
- part per billion systematic control
- 1% systematic control
- Major developments in
  - photocathodes (I & P)
  - polarimetry
  - high power cryotargets
  - nanometer beam stability
  - precision beam diagnostics
  - low noise electronics
  - radiation hard detectors
Just how big are the really big nuclei?
Form Factors and Extended Targets

The point-like scattering probability is modified to account for Finite Target Extent by introducing the “form factor”

\[ \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} |F(q)|^2 \]

\[ F(q) = \int e^{iqr} \rho(r) d^3r \]

Form factor is the Fourier transform of charge distribution.

Figure from Particles and Nuclei, Povh et al.
Weak Charge Distribution of Heavy Nuclei

Nuclear theory predicts a neutron "skin" on heavy nuclei

$\text{Density (fm}^{-3}\text{)}$

208Pb

Uncertainty in $R_n$ reflects poor understanding of symmetry energy of nuclear matter = the energy cost of $N \neq Z$

$E(n, x) = E(n, x = 1/2) + S_v(n)(1 - 2x^2)$

$n = \text{n.m. density}$

$x = \text{ratio proton/neutrons}$

$R_n$ calibrates the Equation of State of neutron rich matter

$P(\rho)$
From $^{208}$Pb to a Neutron Star

Crust Thickness
Explain Glitches in Pulsar Frequency?

A NEUTRON STAR: SURFACE and INTERIOR

Combine PREX $R_n$ with observed neutron star radii

Phase Transition to “Exotic” Core?
Strange star? Quark Star?

Some neutron stars seem too cold

Cooling by neutrino emission (URCA)

$R_n - R_p > 0.2$ fm URCA probable, else not
Weak Charge Distribution of Heavy Nuclei

Nuclear theory predicts a neutron “skin” on heavy nuclei.

The single measurement of $F_n$ translates to a measurement of $R_n$ (via mean-field nuclear models).

Neutron distribution is not accessible to the charge-sensitive photon.

<table>
<thead>
<tr>
<th></th>
<th>proton</th>
<th>neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric charge</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Weak charge</td>
<td>$\sim 0.08$</td>
<td>1</td>
</tr>
</tbody>
</table>

for the spin-0 $^{208}$Pb nucleus

$$M_{EM}^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}} \left[ (1 - 4\sin^2\theta_W) F_p(Q^2) - F_n(Q^2) \right]$$

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ 1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

$r_n$ in $^{208}$Pb (fm)
Measurements of neutron skin

- Proton-Nucleus Elastic
- Pion, alpha, d Scattering
- Pion Photoproduction
- Heavy ion collisions
- Rare Isotopes (dripline)

- Magnetic scattering

- $A_{PV}$

- Theory

Involve strong probes

Most spins couple to zero.

Electroweak probe

MFT fit mostly by data other than neutron densities
**PREX (Pb-Radius Experiment)**

- \( Q^2 \sim 0.01 \text{ GeV}^2 \)
- \( 5^\circ \) scattering angle
- \( \lambda_{PV} \sim 0.6 \text{ ppm} \)
- Rate \( \sim 1.5 \text{ GHz} \)

**Ultimate goal:**

\[
\frac{\delta(A_{PV})}{A_{PV}} \sim 3\%
\]

Stat. Error \( \sim 15 \text{ ppb (3\%)} \)

\[
\frac{\delta(R_n)}{R_n} \sim 1\%
\]

Syst. Error \( \sim 5 \text{ ppb (1\%)} \)

**First Run (early 2010)**

\[
A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = 0.6571 \pm 0.0604 \text{(stat)} \pm 0.0130 \text{(syst)} \text{ ppm}
\]

- 9.2 %
- 2.0 %

- The most precise measurement of electron-nuclear scattering asymmetry yet: 62 ppb
- Demonstrated control of random noise, to get full precision
- Demonstrated control of systematic error for full precision
High Resolution Spectrometers in JLab Hall A

Twin spectrometers built for HIGH precision

- Bending (dipole) magnet – 450 tons
- 1.6 T magnetic field
- 45° bend angle
- 3,500,000 J stored energy
- up to 3 GeV central momentum
- 12 meter dispersion
- Resolution (momentum) – 0.01%

- Total spectrometer – 1000 tons
Integrating in the High Resolution Spectrometers

Very clean separation of elastic events by HRS optics

- no PID needed; detector sees only elastic events
- Analog integration of everything that hits the detector

Polarimetry: 1%
Scattering Angle: 0.4%
Backgrounds: well known, 0.4%
Beam Asymmetries: 1%

FIGURE 1. Distribution of the asymmetries for a typical run at 70 µA. Beam-related noise has been subtracted using the standard “dither correction” method. The width of 171 ppm is consistent with counting statistics.
PREX source setup

First time at JLab: an empirical bound on possible spot-size asymmetries, <1e-4
PREX could provide an electroweak complement to $R_n$ predictions from a wide range of physical situations and model dependencies.

**Recent $R_n$ predictions:**

- **Hebeler et al.** Chiral EFT calculation of neutron matter. Correlation of pressure with neutron skin by Brown. Three-neutron forces!

- **Steiner et al.** X-Ray n-star mass and radii observation + Brown correlation. (Ozel et al finds softer EOS, would suggest smaller $R_n$).

- **Tamii et al.** Measurement of electric dipole polarizability of $^{208}$Pb + model correlation with neutron skin.

- **Tsang et al.** Isospin diffusion in heavy ion collisions, with Brown correlation and quantum molecular dynamics transport model.
Fishing the strange sea
The Simple Nucleon

The nucleon is composed of three quarks (up and down flavors) interacting via the Strong force (Quantum Chromodynamics).

The quark flavor content determines the nucleon properties.

It’s simple: the nucleon is three marbles in a bag!

Not so fast. The strong force is weird!

The nucleon contains three quarks... embedded in a teeming sea of gluons and additional quarks and anti-quarks.

It grows with distance, and is huge at “large” distances ($10^{-15}$ m).
Gluons (strong carriers) interact with themselves.

The bare mass of the three quarks ~1% of the proton mass.
99% of the mass of the proton is in the sea!

So why does the simple quark model work so well?

Sea contributions to nucleon static properties are unsettled
mass, spin, charge radius, magnetic moment

By analogy with the electron shell structure that determines the chemical properties of an atom, the three dominant quarks are referred to as “valence” quarks. The rest of the quarks and gluons are called the “sea”.
Elastic Electron-Nucleon Scattering

**If proton is point-like:** The differential cross-section (scattering probability) is given by simple scattering theory.

\[ \frac{d\sigma}{d\Omega} \text{ Dirac} = \frac{d\sigma}{d\Omega} \text{ Mott} \left\{ 1 + 2\tau \tan^2 (\theta / 2) \right\} \]

\[ \tau = \frac{Q^2}{4M^2} \] is a convenient kinematic factor.

**If proton is not point-like:** The electric and magnetic form factors \( G_E \) and \( G_M \) parameterize the effect of proton structure.

\[ \frac{d\sigma}{d\Omega} \text{ Rosenbluth} = \frac{d\sigma}{d\Omega} \text{ Mott} \left\{ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 (\theta / 2) \right\} \]

If the proton were like the electron:
- \( G_E = 1 \) (proton charge)
- \( G_M = 1 \) (and the magnetic moment would be 1 Bohr magneton).

\[ \mu_p = 2.79 \mu_B \text{ (Stern, 1932)} \]
Charge & Current Distributions

Form factors $G_E, G_M$ are functions of $Q^2$

$\rightarrow$ they measure scattering probability as a function of wavelength

Where recoil can be neglected (low $Q^2$): Fourier transform of the charge and magnetic current distributions

At $Q^2 = 0$, the form factor represents an integral over the nucleon

At $Q^2=0$  $G_E$  $G_M$

<table>
<thead>
<tr>
<th></th>
<th>$G_E$</th>
<th>$G_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>1</td>
<td>2.79</td>
</tr>
<tr>
<td>neutron</td>
<td>0</td>
<td>-1.91</td>
</tr>
</tbody>
</table>

Do strange sea quarks play a significant role in the electric/magnetic charge distributions in the nucleon?

Proton flavor distribution

Anomalous magnetic moment

Charge
Strangeness in the Sea

The sea contains all flavors, but

- the u and d sea can’t be distinguished from the valance
- the heavier quarks (c,b,t) are too heavy to contribute much

From hard-scattering, we know that the strange sea exists.

~4% of the momentum of the nucleon is carried by strange quarks

But this is a “deep” probe... Do the strange quarks affect the static properties of the nucleon?

Low-$Q^2$ Elastic electron scattering from the nucleus measures charge radius and magnetic moment

A strange contribution would be the first unambiguous low-energy failure of the naïve quark model

Measuring all three enables separation of up, down and strange contributions
Experimental Overview

**SAMPLE**
- Open geometry, integrating, back-angle only

**HAPPEX**
- Precision spectrometer, integrating
- Forward angle, also $^4$He at low $Q^2$

**HAPPEX-3:** $G_E^s + 0.52 G_M^s$ at $Q^2 = 0.62 \text{ GeV}^2$

**A4**
- Open geometry
- Fast counting calorimeter for background rejection
- Forward and Backward angles

**G0**
- Open geometry
- Fast counting with magnetic spectrometer + TOF for background rejection
- Forward and Backward angles over a range of $Q^2$
Global fit of all world data

- Data set appears to show consistent preference for positive effect
- Significant contributions at higher $Q^2$ are not ruled out.

Simple fit:

$G_E^s = \rho_s \ast \tau$

$G_M^s = \mu_s$

Fit includes all world data $Q^2 < 0.65 \text{ GeV}^2$

G0 Global error allowed to float with unit constraint
Lead - Lucite Cerenkov Shower Calorimeter
- phototube current integrated over fixed time periods

Very clean separation of elastic events by HRS optics
no PID needed; detector sees only elastic events

\[ Q \]

\[ \text{Dipole} \]

\[ \text{Quad} \]

\[ \text{Elastic} \]

\[ \text{Inelastic} \]

\[ \text{Detector Plane Dist.} \]

27M measurements
RMS = 3733 ppm

Integrating in the High Resolution Spectrometers

Entries: 2.694749e+07
RMS: 3733

parts per million

\[ 10^6 \]

\[ 10^5 \]

\[ 10^4 \]

\[ 10^3 \]

\[ 10^2 \]

\[ 10^1 \]

\[ 10^0 \]

\[ 10^{-1} \]

\[ 10^{-2} \]

\[ 10^{-3} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-6} \]
### HAPPEX-III Error Budget

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta A_{PV}$ (ppm)</th>
<th>$\delta A_{PV} / A_{PV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>0.202</td>
<td>0.85%</td>
</tr>
<tr>
<td>$Q^2$ Measurement</td>
<td>0.160</td>
<td>0.67%</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.194</td>
<td>0.82%</td>
</tr>
<tr>
<td>Linearity</td>
<td>0.129</td>
<td>0.54%</td>
</tr>
<tr>
<td>Finite Acceptance</td>
<td>0.048</td>
<td>0.20%</td>
</tr>
<tr>
<td>False Asymmetries</td>
<td>0.041</td>
<td>0.17%</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>0.353</td>
<td>1.49%</td>
</tr>
<tr>
<td>Statistics</td>
<td>0.776</td>
<td>3.27%</td>
</tr>
<tr>
<td>Total Experimental</td>
<td>0.853</td>
<td>3.59%</td>
</tr>
</tbody>
</table>

#### Systematic uncertainties are well controlled - experiment is statistics dominated

#### total correction $\sim 2.5\% +$ polarization

#### OUT / IN from “slow” spin reversals to cancel systematics

*combined 2-arm data*

- OUT A=21.086 +/- 0.975 ppm, N=381, $\chi^2=1.00$, P=0.51
- IN A=22.170 +/- 0.989 ppm, N=409, $\chi^2=1.09$, P=0.09
- AVG A=21.620 +/- 0.694 ppm, N=791, $\chi^2=1.05$, P=0.18
HAPPEX-III Result

\[ A_{PV} = -23.803 \pm 0.778 \text{ (stat)} \pm 0.362 \text{ (syst)} \text{ ppm} \]

\[ Q^2 = 0.6241 \pm 0.0032 \text{ (GeV/c)}^2 \]

\[ A(G^s=0) = -24.062 \text{ ppm} \pm 0.734 \text{ ppm} \]
HAPPEX-III Result

\[ A_{PV} = -23.803 \pm 0.778 \text{ (stat)} \pm 0.359 \text{ (syst) ppm} \]

\[ Q^2 = 0.6241 \pm 0.0032 \text{ (GeV/c)}^2 \]

\[ A(G^s=0) = -24.062 \text{ ppm} \pm 0.734 \text{ ppm} \]

\[ G_E^s + 0.52 \ G_M^s = 0.003 \pm 0.010_{(stat)} \pm 0.004_{(syst)} \pm 0.009_{(FF)} \]
\[ Q^2 = 0.62 \text{ GeV}^2 \text{ in combination} \]

Combined fit includes form-factor uncertainties, experimental bands do not

Zhu constraint is used for axial form-factor
Strange Vector Form Factors Are Small

HAPPEX-III provides a clean, precise measure of $A_{PV}$ at $Q^2=0.62 \text{ GeV}^2$, consistent with no strangeness contribution.

Further improvements in precision would require additional theoretical and empirical input for interpretation.
Peering Beyond the Standard Model
Direct vs Indirect Searches

(according to Hans Christian Andersen)
Electroweak Physics Away from Z pole

\[ A_X \propto \frac{1}{Q^2 - M_X^2} \]
\[ \sim \frac{4\pi}{\Lambda^2} \]

On Z resonance, \( A_Z \) dominates. Interference with other contact interactions is not visible!

Precision Z observables establish anchor points for the Standard Model

For low energy measurements, interference with New Physics terms can be found

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

\[ \mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} f_{1i} \gamma_\mu f_{1j} \bar{f}_{2j} \gamma_\mu f_{2j} \]

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

New terms arise in models for new physics with \( \Lambda \)'s at the TeV scale

Eichten, Lane and Peskin, PRL50 (1983)
Proton weak charge precisely known from EW gauge theory and precision EW at the Z-pole

If measurement at low energy comes up different, indicates proton charged for some other (parity-violating) interaction

Global fit of existing strange-quark program data provides constraint on Standard Model
QWeak

Measuring the proton form-factor weak charge

Small angle, low $Q^2 \sim 0.03 \text{ GeV}^2$ to suppress target structure

Proton structure $F$, constrained by strange quark program, contributes ~30% to asymmetry, ~2% to $\delta(Q_w^p)/ Q_w^p$

$$A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2\pi\alpha}} [Q_W^p + F(\theta, Q^2)]$$

$$F \sim \frac{Q^2}{4M_p^2} (1 + \mu_p)\mu_n + \text{ strange quarks } \mathcal{O}(Q^2) + \mathcal{O}(Q^4)$$

$A_{PV} \approx -230 \pm 5 \pm 4 \text{ ppb}$

$\delta Q_w^p = \pm 4\% \implies \delta(\sin^2 \theta_W) = \pm 0.3\%$

A new standard in precision

- New Spectrometer system
- Control and correction for beam systematics
- Polarimetry approaching 1% (new)
- Low system noise - 5 GHz rate!
- High rate, radiation hard readout
- Background and calibration precision

mid-2010 through 2012
Proton Weak Charge with Q\text{weak}

\[ Q_{pW} = 2 C_{1u} + C_{1d} \]

\[ C_{1q} = (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \]

\[ \delta Q_{W}^{p} = 4\% \]

- Non-perturbative theory \( g \sim 2\pi \quad \Lambda \sim 29 \text{ TeV} \)
- Extra Z' \( g \sim 0.45 \quad m_{Z'} \sim 2.1 \text{ TeV} \)

R. Young et al., PRL 99 122003 (2007)
Qweak

Width well understood

Counting statistics: 215 ppm
Detector Resolution: 232 ppm
Current normalization and estimate of target boiling: 236 ppm

width at 240 Hz: 236 ppm

1ppm precision in 4 minutes

~25% data collected: final run starting November 2011
Liquid Hydrogen: 35cm cell, 180 μA

2300 Watts

Doesn’t “boil” (much)

Boiling Noise versus Current:

Boiling <60ppm = about 4% excess noise

Low frequency noise onsets at higher currents:

Flip Rate: 960Hz

Small contribution added in quadrature with statistical width

Current Scan @ 3.5x3.5 mm² Raster

σₙ = -0.0 + 1.242E-05 * x⁰3.000

Runs 8862-8877

Jan 2011
Compton Polarimeter
1% electron beam polarimetry

UVa-built Fabry-Perot resonant optical cavity at 1.7kW

Each point represents ~1hr of data
Weak mixing angle $\sin^2 \theta_W$

Weak mixing angle defines weak neutral-current charges

Renormalization scheme defines $\sin^2 \theta_W$ at the Z-pole.

$\gamma$-Z mixing and other diagrams are absorbed into the coupling constant

Off the Z-pole, Qweak measures for (new) parity-violating interactions

Qweak will be the most precise low-energy measurement... until...
The Future of Parity-Violation Electron Scattering
**Møller Scattering at 11 GeV**

**MOLLER**: Measurement Of a Lepton-Lepton Electroweak Reaction

- **A_{PV} = -35.6 ppb**  
  \( \delta A_{PV} = 0.73 \) ppb

\[ \delta (Q^e_W) = \pm 2.1\% \text{ (stat)} \pm 1.0\% \text{ (syst)} \]

\[ \delta (\sin^2 \theta_W) = \pm 0.00026 \text{ (stat)} \pm 0.00012 \text{ (syst)} \]

- **L_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j**

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

- Address important ambiguity in existing electroweak data
- Provide important complementary sensitivities to make sense of emerging LHC data
- Test for new parity-violating interactions to mass scales >25 TeV

- **\( A_{PV} \propto E_{lab} Q^e_W \) \quad \text{If} \quad Q^e_W \sim 1 - 4\sin^2 \theta_W \approx 150 \text{ GHz}!**

- Best contact interaction reach for leptons at low OR high energy, without Z factory, linear collider, neutrino factory, or muon collider
There are only 3 fundamental parameters in the electroweak Standard Model (plus a few others from loop corrections).

Fits over global data set show good consistency (with a few sore points).
Example of Complementarity to LHC

- Most unified theories predict additional neutral $Z'$
- LHC can find these $\sim 5$ TeV, can determine properties 1-2 TeV
- 11 GeV Moller can help pin down couplings

Moller sensitivity:
\[
\frac{g_{RR}^2 - g_{LL}^2}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2} \sim \frac{1}{(7.5\text{TeV})^2}
\]

With mass, width, and $A_{FB}$, LHC can constrain ratio
\[
\frac{e_R}{e_L}
\]
MOLLER Aparatus

• Polarized Beam
  – Unprecedented stability
  – Requires best-ever JLab polarimetry
  – Beam monitoring (RF, optical techniques?)

• Liquid Hydrogen Target
  – 5kW dissipated power
  – unprecedented luminosity stability, 1.5 meters length

• Toroidal Spectrometer
  – Novel 2-toroid, 7 coil “hybrid” design, 100% azimuthal acceptance
  – warm magnets, but aggressive engineering
  – background suppression/study

• Integrating Detectors
  – Novel 2-toroid, 7 coil “hybrid” design
  – 135 GHz rate, 83 ppm/1kHz measurement
Spectrometer Concept

Highly boosted lab frame

Figure of merit highest at $\theta_{\text{CM}} = 90^\circ$

All of those rays of $\theta_{\text{CM}} = [90,120]$ that you don’t get here...

... are collected as $\theta_{\text{CM}} = [60,90]$ over here!
Two Toroid Spectrometer

Layout in Hall A

1 meter radial focus, 30 meters from target
Clean separation from backgrounds

Radial Fields (edge effect) creates azimuthal defocussing which populates the full ring at the detector

Designed by UVa (Clayton Davis)
MIE (Major Item of Equipment) proposal submitted to DOE. Project cost near 20M$, timeline for installation starting in 2016
Deep Inelastic Scattering: SoLID

Deep Inelastic Regime: Scattering from quarks

Parity-violation in DIS is uniquely sensitive to the poorly known quark axial charges $C_{2u}$ and $C_{2d}$

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

$$a(x) = (2C_{1u} - C_{1d})$$

$$b(x) = (2C_{2u} - C_{2d})$$

$$C_{1q} = (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

$$C_{2q} = (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$

Requires Dedicated New Spectrometer System and a broad program of study to separate hadronic and electroweak physics

Proposed design provides sufficient acceptance, resolution, and shielding for broad PVDIS program

- charge symmetry violation
- $C_{2q}$‘s and new physics
- higher twist and quark correlations
- $d/u$ in proton at high $x$
- PV analog of EMC, nuclear media induced charge asymmetry

Discussed in detail in X.Zheng’s colloquium Oct. 31
Summary

Parity-violating electron scattering has a record of accomplishment
... and a very bright future