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

Prof. Kent Paschke

Photo: Paul Nicklen
Introduction to Electron Scattering
Introduction to electron scattering
Electron scattering: electromagnetic interaction, described as an exchange of a virtual photon.

If photon carries low momentum
-> long wavelength
-> low resolution

Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures

\( Q^2 \): 4-momentum of the virtual photon
Elastic Form Factors and Extended Targets

The point-like scattering probability for elastic scattering is modified to account for finite target extent by introducing the “form factor”

Assuming spherically symmetric (spin-0) target

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

point-like target, electron spin

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

Form factor is the Fourier transform of charge distribution
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Form factor is the Fourier transform of charge distribution
Elastic Electron-Nucleon Scattering

For targets with spin, must also account for magnetic moment

Electric and Magnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$

$$\frac{d\sigma}{d\Omega_{Rosenbluth}} = \frac{d\sigma}{d\Omega_{Mott}} \left\{ \frac{(G_E^2 + \tau G_M^2)}{1 + \tau} + 2\tau G_M^2 \tan^2(\theta / 2) \right\}$$

With no structure

- $G_E = 1$ (proton charge)
- $G_M = 1$ (magnetic moment = $\mu_B$).

At $Q^2 = 0$, the probe does not resolve the target

- $G_E(0) = 1$ (electric charge)
- $G_M(0) = \mu$ (magnetic moment in units of $\mu_B$)
Standard Model, Weak Interaction, Parity Symmetry, and Parity Violating Electron Scattering
Weak Interaction and parity

1930’s - The weak nuclear interaction was needed to explain nuclear beta decay
1950’s - Discovery of parity-violation by the weak interaction

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 is analogous to reflection in a mirror:

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

**Electric charge determines strength of electric force**

- **Observed**
  - $e^- \rightarrow e^-$
  - $\gamma e^- \rightarrow e^-$

- **Not observed**
  - $\nu \rightarrow \gamma \nu$
  - 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
  - $^{60}\text{Co}$ observed
  - $W^- e_L \rightarrow e_L$
  - $^{60}\text{Ni}$ observed
  - $\bar{\nu}_{e_R} \rightarrow \bar{\nu}_{e_R}$

- **Right-handed particles** (left-handed antiparticles) are “weak charge neutral”
  - $^{60}\text{Co}$ not observed
  - $W^- e_R \rightarrow e_R$
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<table>
<thead>
<tr>
<th>Charge</th>
<th>Left</th>
<th>Right</th>
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<td>$\gamma$ Charge</td>
<td>$q = 0, \pm 1, \pm \frac{1}{3}, \pm \frac{2}{3}$</td>
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<td>$W$ Charge</td>
<td>$T = \pm \frac{1}{2}$</td>
<td>zero</td>
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Electroweak Interaction

Until the 1970's, all known weak interactions could be explained by \( W^{+/-} \) exchange

Weak neutral currents are proposed under electroweak unification (late ‘60s, Weinberg Salam Glashow, but others, also...)

⇒ The weak mixing angle \( \theta_W \) introduced

Gargamelle bubble chamber uncovers \( \nu_\mu \ e^- \) events in 1973, more convincingly in 1976.

This demonstrated the existence of the neutral current \( (Z^0) \) but not its nature

- What is the gauge structure of the underlying theory?
- Is this the electroweak unification of GWS?
- Another EW unification?
- A new interaction?

Landmark experiment (late 1970s): parity-violating electron scattering
Electron Scattering and Parity-violation

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

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \left( \frac{M_Z}{M_\gamma} \right)^2 \]

“Electroweak” models predicted
- interference of electromagnetic and weak amplitudes
- values for electron & quark weak neutral current coupling

\[ \sigma = \left| M_\gamma + M_Z \right|^2 \]
PVeS Verifies the “Standard Model” (1978)

*Parity Non-Conservation in Inelastic Electron Scattering, C.Y. Prescott et. al, 1978*

\[ A_{PV} \approx 100 \pm 10 \text{ ppm} \]

Definitive answer on gauge structure of electroweak interaction

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<td>zero</td>
</tr>
<tr>
<td>( Z ) Charge</td>
<td>( T - q \sin^2 \theta_W )</td>
<td>(-q \sin^2 \theta_W)</td>
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The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".

\[ \sin^2 \theta_W = 0.20 \pm 0.03 \]
Progress in PVeS studies

Broad program studying the structure of protons and nuclei, and searching for new (beyond Standard Model) physics
Beyond the Standard Model with Precision at Low Energies
Direct vs Indirect Searches

(according to Hans Christian Andersen)
The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions in physics"
**Discovery of the Higgs Boson**

**circa 2012**

- **World average central value**
- **Ruled out**
- **Ruled out**
- **E158**
- **APV (Cs)**
- **A_{LR}(had)**
- **A_{FB}(b)**

(Courtesy: J. Erler)

**Good match to SM Higgs predicted signals**

- **H → γγ**
- **H → ZZ* → 4 leptons**

Amazing consistency of the SM prediction, between directly measured \(m_H, m_W, m_t, \sin^2\theta_W\)
So, what’s wrong with the Standard Model?

Too many parameters, so much fine-tuning...

Cosmology says that we know nothing about most everything!

Neutrino mass - not incorporated, not known, not explained

Baryon asymmetry - where is the antimatter corresponding to our matter?

No role for gravity, even though gravity is fundamental to space-time
Fundamental Interactions at UVa

• Cox, Hirosky, Neu - CMS at CERN
• Dukes, Group - NOvA, Mu2e (Fermilab)
• Baessler, Pocanic - neutrons at SNS and ILL, mesons at PSI
• Paschke, Zheng, Cates, Liyanage - PVeS at JLab
• Arnold, Hung, Thacker, Vaman - Electroweak and QCD theory
What else don’t we know?

A lot of physics focuses on extracting effective degrees of freedom from complex systems, that is, an attempt to model systems that cannot be calculated from the fundamental interactions.

The complete Lagrangian describing the strong force - Quantum Chromodynamics - is known.

At low (i.e. real-world) energies, it cannot be calculated.

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

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

The Higgs particle relates to the origin of mass for fundamental particles... but 99% of the mass of the proton lies in the excited vacuum!

With the discovery of the Higgs, 1% of 4% of the mass of the universe is explained...

Probing QCD in nucleon and nuclear structure:
Cates, Crabb, Day, Liyanage, Norum, Paschke, Zheng
Theory: Liuti
The QWeak Experiment: Peering Beyond the Standard Model with PVeS
New Physics with Precision at Low Energies

Low $Q^2$ offers complementary probes of new physics at multi-TeV scales

EDM, $g_\mu-2$, weak decays, $\beta$ decay, $0\nu\beta\beta$ decay, DM, LFV...

Parity-Violating Electron Scattering: Low energy weak neutral current couplings
(SLAC, Jefferson Lab, Mainz)

Many new physics models give rise to new neutral current interactions

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

$L = L_{\text{SM}} + L_{\text{new}}$

Low energy NC interactions ($Q^2<<M_Z^2$)

Heavy mediators = contact interactions

Contact interaction

for each fermion and handedness combination
reach, characterized by mass scale $\Lambda$, coupling $g$
Measuring APV

Goal: $10^{-7}$ asymmetry measurement at the few percent level

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

![Diagram of APV measurement setup](image)

Measure fractional rate difference between opposing helicity states

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$A_{\text{measured}} \sim -200 \text{ ppb with 4\% precision}$$

N $\sim 1 \times 10^{16}$ electrons!

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 $P_{\text{beam}}$
- Kinematics - Interpretation requires $Q^2$ precision
- False Asymmetries - electronics, beam motion...?
Measuring $A_{PV}$

Elastic signal focused on detector

Rapid (1kHz) measurement over helicity reversals to cancel noise

Analog integration of detector current

$\sim 6 \text{ GHz total rate}$
1 GeV, 180 $\mu$A, 1.5 years

230 ppm at 240 Hz
1ppm precision in 4 minutes
CEBAF at JLab

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

2013 Upgrade A B C
The Qweak Spectrometer

Toroidal Spectrometer separates elastics into each of 8 detectors

- Each detector:
  - 2 meters long
  - lead radiator, fused silica
  - Cerenkov light from shower
  - collected by phototube at each end
The Entire Accelerator Complex is our Apparatus

- Polarized Source Laser - rapid reversal, keep spin states the same intensity, position, shape...
- Spin Manipulation - crossed E and B fields, to rotate spin in low energy injector
- Position/Energy Modulation - for calibrating detector sensitivity
- Polarimeters
- Precise monitors for beam current and position
Result: ~0.6% precision on 89% polarization
Green cavity development at UVa
Controlling Beam Asymmetries

- Photoemission from GaAs photocathode
- Rapid-flip of beam helicity by reversing laser polarization
- Pockels cell to flip laser polarization
- Beam must look the same for the two polarization states
- Photocathode has preferred axis: analyzing power for linear light

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<tr>
<td>X</td>
<td>-2.7 nm</td>
</tr>
<tr>
<td>X'</td>
<td>-0.14 nrad</td>
</tr>
<tr>
<td>Y</td>
<td>-1.9 nm</td>
</tr>
<tr>
<td>Y'</td>
<td>-0.05 nrad</td>
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<tr>
<td>Energy</td>
<td>-0.6 ppb</td>
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A non-zero 1st moment creates a position difference
New Result from Qweak

with usual convention for contact interactions

\[ g = \sqrt{4\pi} \]

the exclusion limits are

\[ \frac{\lambda}{g} \approx 7.5 \text{ TeV} \rightarrow \lambda \approx 27 \text{ TeV} \]
Future: MOLLER at 11 GeV JLab

- 11 GeV, 90% polarized, 60 μA electron beam
- Luminosity $3 \times 10^{39}$, rate ~ 130 GHz
- LH$_2$ target: 150 cm, 5 kW

- Novel two (warm) toroid spectrometer
- 100% azimuth, $E' = 2.5$-8.5 GeV, $\theta_{\text{lab}} = 0.3^\circ$-1.1$^\circ$
- Segmented integrating detectors,
- counting detectors for calibration

just fits into Hall A

$A_{PV} = 35.6 \text{ ppb}$
$\delta(A_{PV}) = 0.73 \text{ parts per billion}$
$\delta(Q^e_W) = \pm 2.1 \% \text{ (stat)} \pm 1.0 \% \text{ (syst)}$

UVa Undergrad Clayton Davis designed the spectrometer at the heart of this experimental effort

Outlook:
- ~25M$\$$ required
- 2-3 years construction
- 3-4 years running
Nuclear theory predicts a neutron “skin” on heavy nuclei.

\[
A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_W}{F_{ch}}
\]

for spin-0 nucleus

• Neutron skin thickness is highly sensitive to the pressure in neutron-rich matter.
• The greater the pressure, the thicker the skin as neutrons are pushed out against surface tension.

Knowledge of \( r_n \) highly model dependent, not well constrained by robust measurements.
Nuclear Structure Models Reach Back to the Cradle of Our Raw Material

Nucleosynthesis in the r-process

Nucleosynthesis in supernovae

Fundamental test of nuclear structure models
Measuring Neutron Skins at JLab

PREX ($^{208}$Pb)
- important check on nuclear structure data set
- uniform nuclear matter
- terrestrial laboratory for n-star matter

CREX ($^{48}$Ca)
- isovector probe in moderate size system
- finite size effects
- Within reach of microscopic calculations

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

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Spring 2019:
PREX (3% APV, $r_n$ to 0.06 fm)
CREX (2.5% APV, $r_n$ to 0.02 fm)
Nuclear and Electroweak Symmetries Group

Technical R&D and analysis techniques for polarimetry and control of false asymmetries

Development of future experiments (PREX, CREX, MOLLER and PV-DIS)

Former Group Members

Recent Undergrads:
Ricky Elwell
Ben Gilbert

Manolis Kargiantoulakis
Fermilab postdoc on μ2e

Mark Dalton - Now JLab Staff Scientist

Rupesh Silwal - now UVA postdoc

Donald Jones
Research Prof at Temple

Ciprian Gal (postdoc)

Not pictured: Paul Landini

Caryn Palatchi

Amali Premathilake

Adam Zec