Parity Violation in Electron Scattering (PVES) and the Standard Model

PV Deep Inelastic Scattering results from Jefferson Lab 6 GeV

Outlook – PVDIS at 12 GeV

(Parity Violation and Our Everyday Life)
Electron Scattering on Fixed Targets

**Before**
- Electron beam
- Target (at rest)

**After**
- Electron beam to detector
- Inclusive: only the scattered electron is detected
Types of Electron Scattering from Nuclear Targets

$Q^2 = -q^2$

$P = (M, 0)$

$W^2 = P'^2$

Cross section

$Q^2 (\text{GeV/c})^2$

$W = M_T$

(elastic)

$W = M$

(quasi-elastic)

$W > 2 \text{ GeV}$

(deep inelastic)
“Elastic”: $W=M_+ \text{ or } M_p$

From cross section we extract “elastic form factors”

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M\left[G_E^2(Q^2), G_M^2(Q^2)\right]$$

$$G_E^p(Q^2=0) = 1 = 2(Q_u) + 1(Q_d)$$

1961

Three Types of Electron Scattering

Cross section

$W = M_+$ (elastic)

$W = M$ (quasi–elastic)

$W > 2 \text{ GeV}$ (deep inelastic)

Constant $W$ (resonances)
Three Types of Electron Scattering

“Resonance”: $1 < W < 2 \text{GeV}$

“Elastic”: $W = M_T$ or $M_p$

$W = M_T$ (elastic)

$W = M$ (quasi-elastic)

$W > 2 \text{ GeV}$ (deep inelastic)

$N_1^*$, $N_2^*$

Cross section

$Q^2 (\text{GeV/c})^2$

$W = 2 \text{ GeV}$

X. Zheng, 2016 International Conference on the Structure of Baryons
“Resonance”: $1 < W < 2 \text{GeV}$

“Deep Inelastic”: $W > 2 \text{ GeV}$, directly probes the quasi-free quarks inside the nucleon.

$10^{-18}$ m or smaller

Three Types of Electron Scattering

“Elastic”: $W = M_T$ or $M_p$
Parity Violation in Electron Scattering

electron beam

?
Parity Violation in Electron Scattering

electron beam

to detector

?
Parity Violation in Electron Scattering

electron beam

to detector

electron beam

to detector

X. Zheng, 2016 International Conference on the Structure of Baryons
Parity Violation in Electron Scattering

Parity, or mirror symmetry, is often referred to as left-right symmetry.
We can access parity violation by the count difference between left- and right-handed beam electrons.

In the electroweak Standard Model, this is given by

\[ A_{PV} \approx \frac{Q^2}{Q^2 + M_Z^2} \approx 10^{-4} \, Q^2 \approx 100 \, \text{ppm} \times Q^2 \]
We can access parity violation by the **count difference** in the detected electrons between left- and right-handed beam electrons.

In the electroweak Standard Model, this is given by

\[ A_{PV} \approx \frac{Q^2}{Q^2 + M_Z^2} \approx 10^{-4} Q^2 \approx 100 \text{ ppm} \times Q^2 \]
Physics Accessed in PVES

The first PVES (SLAC E122, 1978) measured $\sin^2\theta_W$ for the first time, established parity violation in neutral weak current and the Weinberg-Salam-Glashow model.
Physics Accessed in PVES

The first PVES (SLAC E122, 1978) measured $\sin^2 \theta_W$ for the first time, established parity violation in neutral weak current and the Weinbery-Salam-Glashow model.

To study nucleon structure not accessible in electromagnetic interaction:
- elastic PVES: nucleon strange form factors (MIT Bates, Mainz, JLab); “neutron skin” in heavy nucleus (JLab)

To test the electroweak Standard Model (effective couplings):
- e-e (E158/SLAC, future Moller)
- elastic PVES near $Q^2=0$ (Qweak)
- PVDIS (6 GeV, future 12 GeV)
Parity Violation in the Standard Model

- In weak interaction, all elementary fermions behave differently under parity (mirror) transformation.
- They all have a preferred chiral state when coupling to the $Z^0$. 
Effective Couplings $C_{1,2}$ in the Standard Model

Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or "vector" and "axial" weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$

\[ -i \frac{g_Z}{2} \gamma^\mu [g^e_V - g^e_A \gamma^5] \]

\[
\begin{array}{c|c|c}
\text{fermions} & g^f_A = I_3 & g^f_V = I_3 - 2 Q \sin^2 \theta_W \\
\hline
\nu_e, \nu_\mu & \frac{1}{2} & \frac{1}{2} \\
\hline
\nu_e, \nu_\mu & -\frac{1}{2} & -\frac{1}{2} + 2 \sin^2 \theta_W \\
\hline
\nu_e, \nu_\mu & \frac{1}{2} & \frac{1}{2} - \frac{4}{3} \sin^2 \theta_W \\
\hline
u, c & \frac{1}{2} & -\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W \\
\hline
d, s & -\frac{1}{2} & -\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W \\
\end{array}
\]
Effective Couplings $C_{1,2}$ in the Standard Model

- Unlike electric charge, need two charges (couplings) for weak interaction: $g_L$, $g_R$
- or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$
- PVES asymmetry comes from $V(e) \times A(\text{targ})$ and $A(e) \times V(\text{targ})$
Effective Couplings $C_{1,2}$ in the Standard Model

Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$, $g_A \sim (g_L - g_R)$

PVES asymmetry comes from:

$C_{1q} \equiv 2 g_A^q g_V^e$, $C_{2q} \equiv 2 g_V^e g_A^q$

“electron-quark effective couplings”
Effective Couplings and New Contact Interactions

Unlike electric charge, need two charges (couplings) for weak interaction: $g_L, g_R$

or “vector” and “axial” weak charges: $g_V \sim (g_L + g_R)$  $g_A \sim (g_L - g_R)$

PVES asymmetry comes from:

$$C_{1q} = g_{AV}^{eq}, C_{2q} = g_{VA}^{eq}$$

“electron-quark effective couplings”

“new contact interactions”

Accessing $C_{1q}$ in Elastic PVES

**Elastic PVES:**

- Hadronic effects suppressed at $Q^2=0$, directly probes $C_{1q}$ as the proton weak charge

\[
A_{PV}^{\text{elastic}} \propto -Q^2 [Q_W^p + F(\theta, Q^2)]
\]

\[
Q_W^p = -2(2C_{1u} + C_{1d})
\]

or

\[
-2(2g_{AV}^{eu} + g_{AV}^{ed}) = 1 - 4 \sin^2 \theta_W
\]

Electron axial weak charge (L-R) * by

\[
G_E^p(Q^2=0) = 1 = 2(Q_u) + 1(Q_d)
\]

Quark vector weak charge (L+R)
Best Data on $C_{1q}$ (eq AV couplings) from PVES+APV

Androic et al., PRL 111, 141803 (2013);
Accessing $C_{2q}$ in PVES

**Elastic PVES:**

- Hadronic effects suppressed at $Q^2=0$, directly probes $C_{1q}$, as the proton weak charge;

- Hadronic parity violation shows up as the nucleon axial form factor $G_A$, and extracting $C_{2q}$ from $G_A$ is model dependent (almost like extracting the nucleon magnetic moment from $G_m$)
Accessing $C_{2q}$ in PVES

**Elastic PVES:**
- Hadronic effects suppressed at $Q^2=0$, directly probes $C_{1q}$, as the proton weak charge;
- Hadronic parity violation shows up as the nucleon axial form factor $G_A$, and extracting $C_{2q}$ from $G_A$ is model dependent.

**PV in Deep Inelastic Scattering (PVDIS):**
- measure both $C_{1q}$ and $C_{2q}$ explicitly.
Formalism for Parity Violation in DIS

For an isoscalar target \((^2\text{H})\), structure functions largely simplifies:

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

\[
a(x) = \frac{1}{2} g^e_A \frac{F_1^{YZ}}{F_1^y} = \frac{1}{2} \sum_i C_{1i} Q_i q_i^+(x) \]

\[
b(x) = \frac{1}{2} g^e_V \frac{F_3^{YZ}}{F_1^y} = \frac{1}{2} \sum_i C_{2i} Q_i q_i^-(x) \]

\[
x \equiv x_{Bjorken} \quad y \equiv 1 - E'/E
\]

\[
q_i^+(x) \equiv q_i(x) + \bar{q}_i(x)
\]

\[
q_i^-(x) = q_i^y(x) \equiv q_i(x) - \bar{q}_i(x)
\]

\[
a(x) = \frac{3}{10} (2 C_{1u} - C_{1d})(1 + \frac{0.6 s^+}{u^+ + d^+})
\]

\[
b(x) = \frac{3}{10} (2 C_{2u} - C_{2d})\left(\frac{u_v + d_v}{u^+ + d^+}\right)
\]
Formalism for Parity Violation in DIS

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

For an isoscalar target \(^2\mathrm{H}\), structure functions largely simplifies:

\[
\begin{align*}
    a(x) &= \frac{1}{2} g_A^e \frac{F_{1y}^Z}{F_1^y} = \frac{1}{2} \sum_i C_{1i} Q_i q_i^+(x) \\
    b(x) &= g_v^e \frac{F_{3y}^Z}{F_1^y} = \frac{1}{2} \sum_i C_{2i} Q_i q_i^-(x)
\end{align*}
\]

\[
\begin{align*}
    a(x) &= \frac{3}{10} \left( 2 C_{1u} - C_{1d} \right) \left( 1 + \frac{0.6 s^+}{u^+ + d^+} \right) \\
    b(x) &= \frac{3}{10} \left( 2 C_{2u} - C_{2d} \right) \left( \frac{u_v^+ + d_v^+}{u^+ + d^+} \right)
\end{align*}
\]

If neglecting sea quarks, asymmetry is no longer sensitive to PDFs → "static limit"

\[
\begin{align*}
    x &\equiv x_{Bjorken} \\
    y &\equiv 1 - E'/E \\
    q_i^+(x) &\equiv q_i(x) + \bar{q}_i(x) \\
    q_i^-(x) &\equiv q_i^y(x) \equiv q_i(x) - \bar{q}_i(x)
\end{align*}
\]
$C_{2q}$ from Elastic PVES and E122
then zoom in

$2C_{2u} - C_{2d}$

$2C_{1u} - C_{1d}$
It is difficult to determine $C_{2q}$'s.

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

\[ a(x) = \frac{3}{10} \left( 2 C_{1u} - C_{1d} \right) \left( 1 + \frac{0.6 s^+}{u^+ + d^+} \right) \]

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

\[ -\frac{3}{2} + \frac{10}{3} \sin^2 \theta_W \]

\[ -\frac{3}{2} \left( 1 - 4 \sin^2 \theta_W \right) \]
PVDIS at 6 GeV (JLab E08-011)
PVDIS at 6 GeV (JLab Hall A)

- Measured two DIS points: $Q^2 = 1.085$ and $1.901 \text{ (GeV/c)}^2$

- 100uA, 90% polarized electron beam

- Ran from Oct-Dec 2009

- Dedicated DAQ system counted 170 billion (E9) electrons in total
Compare to Standard Model?

\[
A_{Q^2=1.085, x=0.241}^{\text{phys}} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm}
\]

\[
A^{\text{SM}} = (1.156 \times 10^{-4}) \left[ (2 \, C_{1u} - C_{1d}) + 0.348 (2 \, C_{2u} - C_{2d}) \right] = -87.7 \text{ ppm}
\]

\[
A_{Q^2=1.901, x=0.295}^{\text{phys}} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm}
\]

\[
A^{\text{SM}} = (2.022 \times 10^{-4}) \left[ (2 \, C_{1u} - C_{1d}) + 0.594 (2 \, C_{2u} - C_{2d}) \right] = -158.9 \text{ ppm}
\]
Extracting Effective Couplings

\[ A_{Q^2=1.085, x=0.241}^{\text{phys}} = -91.10 \pm 3.11 \pm 2.97 \text{ ppm} \]

\[
A^{SM} = \left( 1.156 \times 10^{-4} \right) \left[ (2 C_{1u} - C_{1d}) + 0.348 (2 C_{2u} - C_{2d}) \right] = -87.7 \text{ ppm}
\]

uncertainty due to PDF: 0.5% 5%
uncertainty due to HT: 0.5%/\(Q^2\), 0.7 ppm

\[ A_{Q^2=1.901, x=0.295}^{\text{phys}} = -160.80 \pm 6.39 \pm 3.12 \text{ ppm} \]

\[
A^{SM} = \left( 2.022 \times 10^{-4} \right) \left[ (2 C_{1u} - C_{1d}) + 0.594 (2 C_{2u} - C_{2d}) \right] = -158.9 \text{ ppm}
\]

uncertainty due to PDF: 0.5% 5%
uncertainty due to HT: 0.5%/\(Q^2\), 1.2 ppm
On the e-q VA Couplings

Previous data: E122, Elastic PVES + APV

$2C_{2u} - C_{2d}$ vs $2C_{1u} - C_{1d}$

$C_{1u}, C_{1d}$
On the e-q VA Couplings
On the e-q VA Couplings

$2C_{2u} - C_{2d}$

Wang et al., Nature 506, no. 7486, 67 (2014); X. Zheng, 2016 International Conference on the Structure of Baryons

best fit

factor five improvement

$2C_{1u}$
Quarks are not ambidextrous

By separately scattering right- and left-handed electrons off quarks in a deuterium target, researchers have improved, by about a factor of five, on a classic result of mirror-symmetry breaking from 35 years ago. See Letter p67

Marciano., Nature 506, no. 7486, 43 (2014);

"Measurement of parity violation in electron-quark scattering"

Wang et al., Nature 506, no. 7486, 67 (2014);

2σ from zero - clearly identified parity-violating contribution from quarks' parity-violating property
Complementary to LHC results on the mass limit of electron-quark contact interactions
Coherent PVDIS Program with SoLID @ 12 GeV

Planned for Hall A, SoLID
Physics topics include:

- PVDIS
- SIDIS
- $J/\psi$
Goal on $C_{2q}$: one order of magnitude improvement over 6 GeV
Coherent PVDIS Program with SoLID @ 11 GeV

\[ [2 g^{e_u} - g^{e_d}]_{AV} \]

\[ [2 g^{e_u} - g^{e_d}]_{VA} \]

X. Zheng, 2016 International Conference on the Structure of Baryons
**LOI: PVDIS between unpolarized beam and a polarized 3He target**

\[ A_{PV}^U = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[ g_A^e \frac{F_1^{yz}}{F_1^y} + Y(y) g_V^e \frac{F_3^{yz}}{F_1^y} \right] \]

\[ A_{PV}^L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[ Y(y) g_A^e g_1^{yz} \frac{F_1^y}{F_1} + g_V^e g_5^{yz} \frac{F_1^y}{F_1} \right] \]

Need: target luminosity x10 upgrade + SoLID

Can measure asymmetry to 10% at \( x=(0.2,0.3) \)

g1(γZ) term dominates 95% of asymmetry

Directly measure quark spin contribution to the nucleon spin.

\[ g_{1,γZ} = Q_u g_V^u (\Delta u + \Delta \bar{u} + \Delta c + \Delta \bar{c}) + Q_d g_V^d (\Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) \]

\[ \approx \frac{1}{9} (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta c + \Delta \bar{c} + \Delta s + \Delta \bar{s}) \]

X. Zheng, 2016 International Conference on the Structure of Baryons
Parity Violation in Our Daily Life
Our everyday life is so complicated that we keep searching for simplicity. Symmetry fulfills this strong desire.
But the Universe Would be Very Boring if All Symmetry were Exact

CP violation

10,000,000,000 10,000,000,001

The existence of our universe

X. Zheng, 2016 International Conference on the Structure of Baryons
Homochirality

All living organisms contain almost only ‘left-handed’ amino-acids and ‘right-handed’ sugars.

An object that cannot be superimposed on its mirror image is called chiral.

Most DNAs are right-handed double-helix.

Natrulose (left-handed sugar) - blessing or curse?

pharmaceuticals must be chirally correct to work.

X. Zheng, 2016 International Conference on the Structure of Baryons
Homochirality

The evolution of life is a never-ending saga of increased complexity.

Although the exact mechanism is not yet understood, it is a common belief now that left-right asymmetry is a key ingredient in the origin of life.
How Does Parity Symmetry Affect Us?

CP violation

Parity violation, or some equivalent mechanism,

The existence of our universe

10,000,000,000 10,000,000,001

The existence of life

X. Zheng, 2016 International Conference on the Structure of Baryons
Physicists have found hints that the asymmetry of life — the fact that most biochemical molecules are 'left-handed' or 'right-handed' — could have been caused by electrons from nuclear decay in the early days of evolution. In an experiment that took 13 years to perfect, the researchers have found that these electrons tend to destroy certain organic molecules slightly more often than they destroy their mirror images.
Summary and Perspectives

60 Years after the establishment of parity violation, and nearly 40 years after SLAC E122, PVES has served as a precision tool to test the Standard Model of Electroweak Physics and to Search Beyond the Standard Model.

New constraints on eq VA contact interactions from JLab’s and PVDIS

Future: PVDIS, Moller
Acknowledgement: JLab Hall A and PVDIS collaborations; and CJ PDF group, T. Gay for useful discussions.

The Jefferson Lab PVDIS Collaboration

Mass Limits on eq AV and VA BSM Physics

Complementary to LHC results on the mass limit of eq contact interactions

Figure from: J. Erler, C.J. Horowitz, S. Mantry, P.A. Souder, arxiv/1401.6199, Annual Review of Nucl and Part. Science, 64 (2014)
## E08-011 Kinematics

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<th>Kine#</th>
<th>HRS</th>
<th>$E_b$ (GeV)</th>
<th>$\theta_0$ (deg)</th>
<th>$E'_0$ (GeV)</th>
<th>$R_e$ (kHz)</th>
<th>$R_{\pi^-}/R_e$</th>
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<td>Left</td>
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<td>$\approx 130$</td>
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</table>
Resonance PV Asymmetry Results

A: Matsui, Sato, Lee, PRC72, 025204 (2005)
B: Gorchtein, Horowitz, Ramsey-Musolf, PRC84, 015502 (2011)
C: Hall, Blunden, Melnitchouk, Thomas, Young, PRD88, 013011 (2013)

“duality works at the (10-15)% level”
helps to constraint γ-Z box diagram correction for PVES experiments

Will a better measurement of res-parity help to constrain γ-Z models?
Parity-Violating Electron Scattering – Past, Present, and Future

Coming Next:
- SoLID (PVDIS) and Moller have both been recommended by the 2015 NSAC Long Range Plan
Estimation of HT on the $a_3$ term

We could use HT results on $F_3^\gamma Z$ from neutrino data in 0710.0124(hep-ph) to correct the $a_3$ term:

$$F_{2,T,3}(x,Q^2) = F_{2,T,3}^{\tau=2}(x,Q^2) + \frac{H_{2,T,3}^{\tau=4}(x)}{Q^2} + \frac{H_{2,T,3}^{\tau=6}(x)}{Q^4} + \ldots$$

for $F_2^\gamma$ and $F_2^1$

for any target

$$F_3^\gamma = 2[ d+s-\bar{u}-c ]$$

for deuteron

$$F_3^\gamma = 2[ u_v + d_v + 2s - 2\bar{c} ]$$