Parity Violation: Past, Present, and Future

M.J. Ramsey-Musolf
NSAC Long Range Plan

• What is the structure of the nucleon?
• What is the structure of nucleonic matter?
• What are the properties of hot nuclear matter?
• What is the nuclear microphysics of the universe?
• What is to be the new Standard Model?
NSAC Long Range Plan

• What is the structure of the nucleon?
• What is the structure of nucleonic matter?
• What are the properties of hot nuclear matter?
• What is the nuclear microphysics of the universe?
• What is to be the new Standard Model?

Parity-Violating Electron Scattering
Outline

• PVES and Nucleon Structure
• PVES and Nucleonic Matter
• PVES and the New Standard Model
Parity-Violating Asymmetry

\[ A_{LR} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{2 \text{Re} \ A_{PV} A_{PC}^*}{|A_{PC}|^2} \]

\[ = \frac{G_F |Q^2|}{4\sqrt{2}\pi\alpha} \left[ Q^P_W + F(Q^2, \theta) \right] \]
PV Electron Scattering Experiments

MIT-Bates

Mainz

SLAC

Jefferson Lab
PV Electron Scattering Experiments

Deep Inelastic eD (1970’s)
PV Moller Scattering (now)
Deep Inelastic eD (2005?)
PV Electron Scattering Experiments

MIT-Bates

Elastic $e^{12}$C (1970’s - 1990)
Elastic ep, QE eD (1990’s - now)
PV Electron Scattering Experiments

Mainz

QE e \(^9\)Be (1980’s)
Elastic ep (1990’s - now)
PV Electron Scattering Experiments

Elastic ep: HAPPEX, G0 (1990’s - now)
Elastic e $^{208}$Pb: PREX
QE eD, inelastic ep: G0 (2003-2005?)
Moller, DIS eD (post-upgrade?)

Jefferson Lab
PVES and Nucleon Structure

What are the relevant degrees of freedom for describing the properties of hadrons and why?

Constituent quarks (QM)

\[ Q^p, \mu^p \]

Current quarks (QCD)

\[ F^p_2(x) \]
PVES and Nucleon Structure

Why does the constituent Quark Model work so well?

- Sea quarks and gluons are “inert” at low energies
- Sea quark and gluon effects are hidden in parameters and effective degrees of freedom of QM (Isgur)
- Sea quark and gluon effects are hidden by a “conspiracy” of cancellations (Isgur, Jaffe, R-M)
- Sea quark and gluon effects depend on C properties of operator (Ji)
PVES and Nucleon Structure

What are the relevant degrees of freedom for describing the properties of hadrons and why?

Strange quarks in the nucleon:

- Sea quarks
- $m_s \sim \Lambda_{QCD}$
- 20% of nucleon mass, possibly -10% of spin

What role in electromagnetic structure?
We can uncover the sea with $G^p_w$

Light QCD quarks:
- $u$: $m_u \sim 5$ MeV
- $d$: $m_d \sim 10$ MeV
- $s$: $m_s \sim 150$ MeV

Heavy QCD quarks:
- $c$: $m_c \sim 1500$ MeV
- $b$: $m_b \sim 4500$ MeV
- $t$: $m_t \sim 175,000$ MeV

Effects in $G^p$ suppressed by

$$(\Lambda_{QCD}/m_q)^4 < 10^{-4}$$

$\Lambda_{QCD} \sim 150$ MeV

Neglect them
We can uncover the sea with $G^p_w$

Light QCD quarks:

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass ($\text{MeV}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>$m_u \sim 5$</td>
</tr>
<tr>
<td>d</td>
<td>$m_d \sim 10$</td>
</tr>
<tr>
<td>s</td>
<td>$m_s \sim 150$</td>
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</tbody>
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Heavy QCD quarks:

<table>
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<th>Mass ($\text{MeV}$)</th>
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<tbody>
<tr>
<td>c</td>
<td>$m_c \sim 1500$</td>
</tr>
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<td>$m_b \sim 4500$</td>
</tr>
<tr>
<td>t</td>
<td>$m_t \sim 175,000$</td>
</tr>
</tbody>
</table>

$m_s \sim \Lambda_{\text{QCD}}$: No suppression

not necessarily negligible
We can uncover the sea with $G^P_w$

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Lives only in the sea
Parity-Violating Electron Scattering

Neutral Weak Form Factors

\[ G^P = Q_u \, G^u + Q_d \, G^d + Q_s \, G^s \]

\[ G^n = Q_u \, G^d + Q_d \, G^u + Q_s \, G^s \]

\[ G^P_W = Q_{uw} \, G^u_W + Q_{dw} \, G^d_W + Q_{sw} \, G^s_W \]

SAMPLE (MIT-Bates), HAPPEX (JLab), PVA4 (Mainz), G0 (JLab)

\[ G^u, G^d, G^s \]
Parity-Violating Electron Scattering

Separating $G^E_w, G^M_w, G^A_w$

$G^M_w, G^A_w$ SAMPLE

$G^M_w, G^E_w$ HAPPEX, PVA4

$G^M_w, G^E_w, G^A_w : Q^2$-dependence $G_0$

Published results: SAMPLE, HAPPEX
• s-quarks contribute less than 5% (1σ) to the proton’s magnetic form factor.

• proton’s axial structure is complicated!

\[ G_M^s = 0.14 \pm 0.29 \pm 0.31 \]
\[ G_A^e(T = 1) = 0.22 \pm 0.45 \pm 0.39 \]

Models for \( \mu^s \)

Radiative corrections

Axial Radiative Corrections

"Anapole" effects: Hadronic Weak Interaction

Nucleon Green’s Fn: Analogous effects in neutron β-decay, PC electron scattering...
“Anapole” Effects

Zhu, Puglia, Holstein, R-M (χPT)
Maekawa & van Kolck (χPT)
Riska (Model)

Can’t account for a large reduction in $G^e_A$
Nuclear PV Effects

PV NN interaction

Suppressed by $\sim 1000$

Carlson, Paris, Schiavilla
Liu, Prezeau, Ramsey-Musolf
**SAMPLE Results**


- **125 MeV:**
  - no $\pi$ background
  - similar sensitivity to $G_A^{e}(T=1)$

- **200 MeV data Mar 2003**
  - $s$-quarks contribute less than 5% ($1\sigma$) to the proton’s magnetic moment.

200 MeV update 2003:
- Improved EM radiative corr.
- Improved acceptance model
- Correction for $\pi$ background

- **Radiative corrections**
  
  E. Beise, U Maryland
Strange Quark Form Factors

Theoretical Challenge:

- Strange quarks don’t appear in Quark Model picture of the nucleon
- Perturbation theory may not apply

\[ \frac{\Lambda_{\text{QCD}}}{m_s} \sim 1 \quad \text{No HQET} \]
\[ \frac{m_K}{\Lambda_\chi} \sim \frac{1}{2} \quad \chi\text{PT ?} \]

- Symmetry is impotent

\[ J_{\mu}^s = J_{\mu}^B + 2 J_{\mu}^{\text{EM, I=0}} \]
Theoretical predictions

\[ \mu_s \equiv G_M^s (Q^2 = 0) \]
$Q^2$ -dependence of $G^s_M$

Happex projected

G$^0$ projected

Lattice QCD theory

Dispersion theory

Chiral perturbation theory

“reasonable range” for slope
What $\chi$PT can (cannot) say

Strange magnetism as an illustration

\[ G_M^s(q^s) = \mu_s + \frac{1}{6} q^2 r_{s,M}^2 + \cdots \]

\[ \mu_s = \left( \frac{2M_N}{\Lambda} \right) b_s + \cdots \]

Unknown low-energy constant (incalculable)

Kaon loop contributions (calculable)
What $\chi$PT can (cannot) say

Strange magnetism as an illustration

\[ G_M^s(q^s) = \mu_s + \frac{1}{6} q^2 r_{s,M}^2 + \cdots \]

\[ r_{s,M}^2 = -\frac{6}{\Lambda_\chi} \left\{ \left( \frac{2 M_N}{\Lambda_\chi} \right) b_s^r \right\} \]

\[ + \frac{1}{18} \left( 5D^2 - 6DF + 9F^2 \right) \left( \frac{\pi M_N}{m_K} + 7 \ln \frac{m_K}{\mu} \right) + \cdots \]

LO, parameter free

NLO, unknown LEC

NLO, cancellation
Dispersion theory gives a model-independent prediction

\[ r_{s,M}^2 = \frac{6}{\pi} \int_{9m_{\pi}^2}^{\infty} dt \frac{\text{Im} G_M^s(t)}{t^2} \]

Slope of \( G_M^s \)

Strong interaction scattering amplitudes

\( e^+ e^- \rightarrow K^+ K^-, \text{ etc.} \)

Jaffe
Hammer, Drechsel, R-M
Dispersion theory gives a model-independent prediction

\[ r_{s,M}^2 = \frac{6}{\pi} \int_0^\infty dt \frac{\text{Im} G_M(t)}{t^2} \]

Perturbation theory (1-loop)
Dispersion theory gives a model-independent prediction

\[ r_{s,M}^2 = \frac{6}{\pi} \int_{4m_K^2}^{\infty} dt \frac{\text{Im} G_M(t)}{t^2} \]

Perturbation theory (1-loop)

Hammer & R-M
Dispersion theory gives a model-independent prediction

\[ r_{s,M}^2 = \frac{6}{\pi} \int_0^\infty \frac{d t}{4m_k^2 t^2} \text{Re}G_M^s(t) \]

Can’t do the whole integral

- Are there higher mass excitations of s s pairs?
- Do they enhance or cancel low-lying excitations?

Experiment will give an answer
PVES and Nucleonic Matter

What is the equation of state of dense nucleonic matter?

We know a lot about the protons, but lack critical information about the neutrons.
PVES and Nucleonic Matter

The $Z^0$ boson probes neutron properties

\[ Q_W = Z(1 - 4 \sin^2 \theta_W) - N \]

\[ \sim 0.1 \]

PREX (Hall A): $^{208}$Pb

Donnelly, Dubach, Sick

Horowitz, Pollock, Souder, & Michels
Neutron star

Crust thickness decreases with $P_n$

Skin thickness $(R_n - R_p)$ increases with $P_n$

$^{208}$Pb

Horowitz & Piekarewicz

PVES and Neutron Stars
Neutron star properties are connected to density-dependence of symmetry energy.

PREX probes $R_n - R_p$ a meter of $E(\rho)$
PVES and the New Standard Model

We believe in the Standard Model, but it leaves many unanswered questions

- What were the symmetries of the early Universe and how were they broken?
- What is dark matter?
- Why is there more matter than anti-matter?
PVES and the New Standard Model

Present universe

Early universe

Weak scale

Planck scale

High energy desert

\[ \frac{4 \pi}{g_i^2} \]

\[ \log_{10} \left( \frac{\mu}{\mu_0} \right) \]
PVES and the New Standard Model

Present universe

A “near miss” for grand unification

Early universe

Weak scale

Planck scale

\[ \log_{10} \left( \frac{\mu}{\mu_0} \right) \]

Standard Model

High energy desert
PVES and the New Standard Model

Present universe

Weak scale is unstable against new physics in the desert

$G_F$ would be much smaller

Early universe

High energy desert

Planck scale

Weak scale

$\log_{10} \left( \frac{\mu}{\mu_0} \right)$

Planck scale

Weak scale

High energy desert

Early universe

Present universe

Weak scale is unstable against new physics in the desert

$G_F$ would be much smaller

$\log_{10} \left( \frac{\mu}{\mu_0} \right)$
PVES and the New Standard Model

Present universe

Not enough CP-violation for weak scale baryogenesis

\[ n_B - n_{\bar{B}} \sim 10^{10} n_\gamma \]

Early universe

Weak scale

Planck scale

High energy desert

\[ \log_{10} \left( \frac{\mu}{\mu_0} \right) \]

Standard Model
Neutral current mixing depends on electroweak symmetry

\[ J_{\mu}^{\text{WNC}} = J_{\mu}^0 + 4Q \sin^2 \theta_W \cdot J_{\mu}^{\text{EM}} \]

\[ \sin^2 \theta_W = \frac{g_Y^2}{g^2 + g_Y^2} \]

SU(2)_L \quad \quad \quad \quad \quad \quad \quad \quad \quad U(1)_Y
Weak mixing also depends on scale

\[ \sin^2 \theta_W \]

\[ \mu \text{ (GeV)} \]

\[ M_Z \]

Czarnecki & Marciano
Erler, Kurylov, R-M
$\sin^2 \theta_W(\mu)$ depends on particle spectrum

\[
\begin{align*}
\ell & \quad p \\
\ell & \quad p \\
\ell & \quad p
\end{align*}
\]

\[
\begin{align*}
\ell & \quad p \\
\ell & \quad p \\
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\]
$$\sin^2 \theta_w(\mu) \text{ depends on particle spectrum}$$
\( \sin^2 \theta_W(\mu) \) depends on particle spectrum

\[ e^- + Z^0 + e^+ \] + \[ e^- + Z^0 + \gamma \] + \[ Z^0 + \gamma \] = \[ W^+ + Z^0 + \gamma + W^- \] + \cdots
New Physics & Parity Violation

\[ Q^e_W = -1 + 4\sin^2\theta_W \]

\[ Q^P_W = 1 - 4\sin^2\theta_W \]

\[ Q^{Cs}_W = Z(1 - 4\sin^2\theta_W) - N \]

\(\sin^2\theta_W\) is scale-dependent
Weak mixing also depends on scale

$\sin^2 \theta_W$

Atomic PV

$\nu N$ deep inelastic

$e^+e^-$ LEP, SLD

SLAC E158

JLab Q-Weak

$\mu$ (GeV)
Additional symmetries in the early universe can change scale-dependence

**Supersymmetry**

<table>
<thead>
<tr>
<th>Fermions</th>
<th>Bosons</th>
</tr>
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<tbody>
<tr>
<td>$e_{L,R}$, $q_{L,R}$</td>
<td>$\tilde{e}<em>{L,R}$, $\tilde{q}</em>{L,R}$</td>
</tr>
<tr>
<td>$\tilde{W}, \tilde{Z}, \tilde{\gamma}, \tilde{g}$</td>
<td>$W, Z, \gamma, g$</td>
</tr>
<tr>
<td>$\tilde{H}_u, \tilde{H}_d$</td>
<td>$H$</td>
</tr>
</tbody>
</table>

$\tilde{W}, \tilde{Z}, \tilde{\gamma}, \tilde{H}_{u,d} \Rightarrow \tilde{\chi}^\pm, \tilde{\chi}^0$  
Charginos, neutralinos
Electroweak & strong couplings unify with supersymmetry

Weak scale & $G_F$ are protected

Weak scale

Planck scale

Present universe

Early universe

$\log_{10} \left( \frac{\mu}{\mu_0} \right)$

$\frac{4\pi}{g_i^2}$

Supersymmetry

Standard Model

$\alpha_y^{-1}$

$\alpha_L^{-1}$

$\alpha_s^{-1}$
SUSY will change $\sin^2 \theta_W(\mu)$ evolution

\[ e \rightarrow \tilde{e} + e \rightarrow \tilde{e} + \cdots \]

\[ p \rightarrow p + p \rightarrow p + \cdots \]

\[ Z^0 \rightarrow \gamma + \gamma \rightarrow \chi^+ + \cdots \]
SUSY will change $\sin^2\theta_W(\mu)$ evolution

\[ e + p \rightarrow e + p + \cdots \]

\[ e + \bar{e} \rightarrow e + \bar{e} + \cdots \]

\[ Z^0 + \gamma \rightarrow Z^0 + \gamma + \cdots \]
Comparing $Q_w^e$ and $Q_w^p$

3000 randomly chosen SUSY parameters but effects are correlated

SUSY loops

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
Can SUSY explain dark matter?

Expansion

Rotation curves

Cosmic microwave background
SUSY provides a DM candidate

\[ \tilde{\chi}^0 \]

Neutralino

- Stable, lightest SUSY particle if baryon (B) and lepton (L) numbers are conserved

- However, B and L need not be conserved in SUSY, leading to neutralino decay

\[ \tilde{\chi}^0 \rightarrow e^+ \mu^- \nu_e \]

e.g.
B and/or L Violation in SUSY can also affect low-energy weak interactions

$\bar{\nu}_e$  \hspace{1cm} $\tilde{\nu}_R^k$  \hspace{1cm} $\tilde{e}_R^k$  \hspace{1cm} $\nu_{\mu}$

$\lambda_{12k}$  \hspace{2cm} $e^-$

$\mu^-$  \hspace{2cm} $\lambda_{12k}$  \hspace{2cm} $\nu_{\mu}$

$\Delta L = 1$

$\beta$-decay, $\mu$-decay, ...

$d$  \hspace{1cm} $\tilde{q}_L^j$  \hspace{1cm} $\nu_{\mu}$

$\lambda'_{1j1}$  \hspace{2cm} $e^-$

$\lambda'_{1j1}$  \hspace{2cm} $d$

$\Delta L = 1$

$\text{Q}^P_W$ in PV electron scattering
Comparing $Q_w^e$ and $Q_w^p$

No SUSY dark matter

$\chi^0 \rightarrow e\mu^+\nu_e$

$\nu$ is Majorana

SUSY loops

RPV 95% CL

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
Comparing $Q_w^e$ and $Q_w^p$

Can be a *diagnostic tool* to determine whether or not

- the early Universe was *supersymmetric*
- there is *supersymmetric* dark matter

The weak charges can serve a similar diagnostic purpose for other models for high energy symmetries, such as *left-right symmetry, grand unified theories with extra $U(1)$ groups*, etc.
Weak mixing also depends on scale

\[ \sin^2 \theta_W \]

\[ \mu \text{ (GeV)} \]

Atomic PV

\( e^+e^- \text{ LEP, SLD} \)

\( \nu N \text{ deep inelastic} \)

DIS-Parity, SLAC

DIS-Parity, JLab

JLab Q-Weak

Moller, JLab

SLAC E158
Comparing $Q_w^e$ and $Q_w^p$

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

No SUSY dark matter

SUSY loops

E158 & Q-Weak

JLab Moller

RPV 95% CL

Kurylov, R-M, Su
Interpretation of precision measurements

How well do we now the SM predictions? Some QCD issues

Proton Weak Charge

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

Weak charge

Form factors: MIT, JLab, Mainz

\[ Q^2 = 0.03 \text{ (GeV/c)}^2 \]

\[ Q^2 > 0.1 \text{ (GeV/c)}^2 \]
Interpretation of precision measurements

How well do we now the SM predictions? Some QCD issues

Proton Weak Charge

\[ A_{LR} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ Q^p_W + F^p(Q^2, \theta) \right] \]

\[ F^p(Q^2, \theta \rightarrow 0) \sim Q^2 \]

Use \( \chi \)PT to extrapolate in small \( Q^2 \) domain and current PV experiments to determine LEC’s
**Summary**

- Parity-violating electron scattering provides us with a well-understood tool for studying several questions at the forefront of nuclear physics, particle physics, and astrophysics:
  - Are sea quarks relevant at low-energies?
  - How compressible is neutron-rich matter?
  - What are the symmetries of the early Universe?
- Jefferson Lab is *the* parity violation facility
- We have much to look forward to in the coming years
QCD Effects in $Q_W^P$

Box graphs

$\delta Q_W \sim 26\%$

$\delta Q_W \sim 3\%$

$\delta Q_W \sim 6\%$

$k_{\text{loop}} \sim M_W$: pQCD

$\Lambda_{\text{QCD}} < k_{\text{loop}} < M_W$: non-perturbative
Box graphs, cont’d.

\[
M_{WW} = -\frac{G_F}{2\sqrt{2}} \frac{\hat{\alpha}}{4\pi S^2} \left[ 2 + 5 \left( 1 - \frac{\alpha_s(M_W^2)}{\pi} \right) \right]
\]

Protected by symmetry

Short-distance correction: OPE

\[
\delta Q_{Wp}^{\text{QCD}}(\text{QCD}) \sim -0.7\% \quad \text{WW}
\]

\[
\delta Q_{Wp}^{\text{QCD}}(\text{QCD}) \sim -0.08\% \quad \text{ZZ}
\]
Box graphs, cont’d.

\[ M_{Z\gamma} = -\frac{G_F}{2\sqrt{2}} \frac{5\hat{\alpha}}{2\pi} (1 - 4s^2) \left[ \ln \left( \frac{M_Z^2}{\Lambda^2} \right) + C_{\gamma Z}(\Lambda) \right] \]

Fortuitous suppression factor: box + crossed \( \sim \) \( \varepsilon^{\mu\nu\alpha\beta} k_{\nu} J^\alpha_{\gamma} J^Z_{\beta} \sim A_\mu \) \( \rightarrow \) \( g_v^e = (-1 + 4 \sin^2 \theta_W) \)

Long-distance physics: not calculable
Neutron $\beta$-decay

\[ M_{W\gamma} = \frac{G_F}{\sqrt{2}} \frac{\hat{\alpha}}{2\pi} \left[ \ln \left( \frac{M_Z^2}{\Lambda^2} \right) + C_{\gamma W}(\Lambda) \right] \]

\[ |\delta C_{\gamma W}| < 2 \quad \text{to avoid exacerbating CKM non-unitarity} \]

\[ |\delta C_{\gamma Z}| < 2 \quad \Rightarrow \quad \delta Q_{W}^p < 1.5\% \]