Atomic Parity Violation

*(History and Update)*

or

How Jon and I spent
Summer 1990 in Colorado

William J. Marciano

(April 1, 2011)
Parity Violating Weak Neutral Currents

By 1975 the SU(2)$_L \times$U(1)$_Y$ structure of the Glashow-Weinberg-Salam Model was nearly established. Predicted Weak Neutral Currents seen in neutrino scattering at CERN! But did the NC have the right coupling?

$$g/\cos\theta_W Z^\mu f_{\gamma\mu} (T^3_f - 2Q_f \sin^2\theta_W - T^3_f \gamma_5)f$$

$$\theta_W = \text{Weak Mixing Angle}$$

A New Form of Parity Violation!

Non Maximal but Distinctive

$\gamma$-Z Interference $\rightarrow$ Parity Violation Everywhere!
Atomic Parity Violation (APV)

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

\[ Q_W(p) = 1 - 4\sin^2\theta_W \approx 0.07 \]  Hydrogen

\[ Q_W(209\text{Bi}_{83}) = -43 - 332\sin^2\theta_W \approx -127 \]

Bi Much Larger but Complicated Atomic Physics

Originally APV not seen in Bi (1977) → SM Ruled Out?

\[
-29 \leq Q_W(209\text{Bi}_{83}) \leq 16 \text{ (Washington)} \\
-20 \leq Q_W(209\text{Bi}_{83}) \leq 74 \text{ (Oxford)}
\]

Note \(-230 \leq Q_W(209\text{Bi}_{83}) \leq -87 \text{ (Novosibirsk 1978)}\)

(Later APV clearly seen in Tl, Bi, Cs…)

*But Meanwhile…*
1978 SLAC Polarized eD Asymmetry
(Prescott, Hughes...)

e+D→e+X γ-Z Interference

\[ A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto 2 \times 10^{-4} Q^2 \text{GeV}^{-2} (1 - 2.5 \sin^2 \theta_W) \]

\( \sim 10^{-4} \) Expected

Exp. Gave \( A_{RL}^{exp} = 1.5 \times 10^{-4} \rightarrow \sin^2 \theta_W = 0.21(2) \)

Confirmed SU(2)_L x U(1)_Y SM!

±10% Determination of \( \sin^2 \theta_W \) Precision!

Major Discovery - Nobel Prize Material
• **L. Wolfenstein**: “Eventually, Atomic Physicists will make extremely precise APV measurements”

*words of encouragement*

• 1982-84 A. Sirlin and WJM calculate radiative corrections to atomic parity violation

  *Theoretically very clean*

  *Precise* $Q_W$ *Predictions!* $\pm 0.2\%$!

  *Wait for Experiment*
**Atomic Parity Violation Becomes Precise**

1985-1988 \( Q_W(Cs)^{\text{exp}} = -71.04(1.38)(0.88) \)

C. Wieman et al. PRLs

Techniques developed later used to create

Bose-Einstein Condensation \( \rightarrow \) “Nobel Prize”!

Theory \( \rightarrow \) \( Q_W(Cs)^{\text{SM}} = -73.20(13) \) very precise

Good Agreement at \( \pm 2\text{-}3\% \)
Snowmass, Colorado Summer 1990

- J. Rosner seminar on S, T & U parameters loop corrections of Peskin & Takeuchi
  Emphasized the importance of
  \[ S \approx + \frac{N_D}{6\pi} \]  
  \((N_D = \# \text{ of heavy new doublets}, \text{eg 4th generation} \rightarrow N_D = 4, S = +0.2)\)

Enhanced in Technicolor x 2 if QCD like:
\[ S \approx 0.1 \times N_{TC} \times N_D\]

Many doublets! \( S \geq +2 \) expected

*Constraint from APV?*
Following Week: Separate Seminars

- WJM Aspen Center for Physics
- J. Rosner  Second Snowmass Talk
  *(Carl Wieman in attendance)*

Join Forces → Very Enjoyable & Productive Collaboration

Atomic Parity Violation Sensitive to $S$!
Essentially no $T$ dependence! ($\alpha$, $G_\mu$ & $m_Z$ input)

$$Q_W(Cs) = Q_W(Cs)_{SM}(1 + 0.011S)$$

Experiment $\rightarrow S = -2.7 \pm 2.0 \pm 1.1$

Was $S$ really **Negative**? What did it mean?

**Large $N_{TC}$ & $N_D$ Technicolor Unlikely - Ruled Out?**

**Supersymmetry ($S \approx 0$) Wins by Default!**
 Atomic Parity Violation as a Probe of New Physics

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Effects of physics beyond the standard model on electroweak observables are studied using the Peskin-Takeuchi isospin-conserving, S, and -breaking, T, parametrization of “new” quantum loop corrections. Experimental constraints on S and T are presented. Atomic parity-violating experiments are shown to be particularly sensitive to S with existing data giving \( S = -2.7 \pm 2.0 \pm 1.1 \). That constraint has important implications for generic technicolor models which predict \( S = 0.1 N_T N_D \) (\( N_T \) is the number of technicolors, \( N_D \) is the number of technidoublets).
If heavy $Z_{\chi}$ boson of SO(10) exists

\[ Q_w(Cs) = Q_w(Cs)^{SM}(1 + 0.011S - 0.9(m_Z/m_{Z_{\chi}})^2 + \ldots) \]

**Suggested** $m_{Z_{\chi}} \approx 500\text{GeV}$

(positive evidence for $Z_{\chi}$?) Jon likes Z’ Bosons

We also pointed out that $S$ could be precisely obtained from

$\alpha^{-1} = 137.035999$, $G_{\mu} = 1.1663788(7) \times 10^{-5}\text{Gev}^{-2}$

\[ + m_w \& \sin^2\theta_w(m_Z) \]

\[ S \approx 118 \left[ 2 \left( \frac{m_W - 80.2\text{ GeV}}{80.2\text{ GeV}} \right) + \frac{\bar{s} - 0.2323}{0.2323} \right] \]

Expected experiments to reach $S \approx \pm 0.2$
Precision measurements at the Z Pole
\((e^+e^- \rightarrow Z \rightarrow ff)\)

Best Determinations:

\[
\sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23070(26) \quad A_L (\text{SLAC})
\]

\[
\sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23193(29) \quad A_{FB}(bb) (\text{CERN})
\]

(3.2 sigma difference!)

World Average: \(\sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23125(16)\)

**IS IT CORRECT?**

(Major Implications)
$\alpha^{-1} = 137.035999$, $G_\mu = 1.1663788(7) \times 10^{-5}\text{Gev}^{-2}$, $m_Z = 91.1875\text{GeV}$

$+ m_W = 80.398(25)\text{GeV}$ & $\sin^2\theta_W(m_Z)_{\text{MS}} = 0.23125(16)$

**Implications**: $114\text{GeV} < m_{\text{Higgs}} < 150\text{GeV}$.

New Physics Constraints From: $m_W$, $\sin^2\theta_W$, $\alpha$, & $G_\mu$

$S = N_D/6\pi = 0.1 \pm 0.1$, 4th generation $\rightarrow N_D = 4 \rightarrow S = 0.2$ (tension)

$m_{W^*} = \text{Kaluza-Klein Mass (Extra Dimensions)} > 3\text{TeV}$

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2\theta_W(m_Z)_{\text{MS}}$</th>
<th>$S$</th>
<th>$N_D$ &amp; $m_{W^*}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td>0.23125(16)</td>
<td>+0.11(11)</td>
<td>2(2), $m_{W^*} \geq 3\text{TeV}$</td>
</tr>
<tr>
<td>$A_{LR}$</td>
<td>0.23070(26)</td>
<td>-0.18(15)</td>
<td>(SUSY)</td>
</tr>
<tr>
<td>$A_{FB}(bb)$</td>
<td>0.23193(29)</td>
<td>+0.46(17)</td>
<td>9(3)! Heavy Higgs, $m_{W^*} \sim 1-2\text{TeV}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4th generation…</td>
</tr>
</tbody>
</table>

**Very Different Interpretations. We failed to nail $\sin^2\theta_W(m_Z)_{\text{MS}}$!**
Atomic Exp. & Theory Improve

Currently: \( Q_W^{\text{SM}}(\text{Cs}) = -73.16(3) \)

1990 \( Q_W^{\text{exp}}(\text{Cs})_{\text{AtH}} = -71.04(138)(88) \) C. Wieman et al.

1997 \( Q_W^{\text{exp}}(\text{Cs})_{\text{AtH}} = -72.11(27)(89) \) Better Experiment

*1999 \( Q_W^{\text{exp}}(\text{Cs})_{\text{AtH}} = -72.06(28)(34) \) Exp. \( \rightarrow \) Better ATh

2008 \( Q_W^{\text{exp}}(\text{Cs})_{\text{AtH}} = -72.69(28)(39) \) \( \sin^2 \theta_W^{\text{Ms}}(m_Z) = 0.2290(22) \)

2009 \( Q_W^{\text{exp}}(\text{Cs})_{\text{AtH}} = -73.16(29)(20) \) \( \sin^2 \theta_W^{\text{Ms}}(m_Z) = 0.2312(16) \)

Porsey, Beloy & Derevianko PRL

\( \pm 0.5\% \) \( \rightarrow \) Major Constraint On “New Physics”

\[ Q_W(\text{Cs}) = Q_W(\text{Cs})^{\text{SM}}(1 + 0.011S - 0.9(m_Z/m_{Z\chi})^2 + \ldots) \]

\( \rightarrow S = 0.0 \pm 0.4 \) \( m_{Z\chi} \geq 1.2 \text{TeV} \), leptoquark bounds, …

No Sign of “New Physics” \( \rightarrow \) Wait for the LHC!
Future Atomic Parity Violation?

- Do several (strings of) isotopes (C. Wieman idea) Ratios Independent of Atomic Theory (Idea championed by Jon) Try Hydrogen Again? Challenging ($Q_W(p)$ better measured with elastic polarized ep scattering asymmetries – JLAB) (in Progress) Can low energy compete with Z pole studies? High vs Low $Q^2$ tests Running of $\sin^2\theta_W(Q)$
Running of $\sin^2 \theta_W(Q) + \text{future JLAB}$
• It was a pleasure to have crossed paths with Jon in Colorado

  We wrote a good/lasting paper
  Shook up Technicolor
  Participated in the Carl Wieman story
  APV→Bose-Einstein Condensation
  &

  Enjoyed Ourselves!