Precision low energy searches for new physics

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Outline

Standard Model of elementary particles and interactions
  Historical Motivation
  Pion and Muon
  Brief Overview of the SM

The PIBETA/PEN Program
  Overall Physics Agenda
  PEN Goals and Motivation
  About the PEN Experiment

Neutron Decay Measurements: Nab and abBA
  Motivation and Goals of Nab/abBA
  Nab Measurement Principles and Apparatus
  Overview of SNS and FnPB
Overall Motivation

Since earliest times (Democritus, Greek atomists, Aristotle) humans have wondered:

a. What is our world really made of?
   Mostly $e$, $p$ and $n$. But, there’s lots more ($\gamma$, $\nu$, …)

b. How is it held together?
   That’s even tougher to answer!

c. How did it come to be this way?

The answers fit together to form a large mosaic called the Standard Model (SM). We’re still fitting pieces, esp. on the edges.
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1909-11 E. Rutherford (Geiger & Marsden) discover the atomic nucleus.

1917-18 E. Rutherford produces protons: $\alpha + N \rightarrow p + X$

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The **PION** (and the **MUON**)

1935  Pion predicted by Yukawa to explain the short range $NN$ force:

- heavy exchanged particle.
- $V(r) = \frac{g}{r} e^{-(mc/\hbar)r} = \frac{g}{r} e^{-r/r_0}$.
- $r_0 \sim 2 \text{ fm} \Rightarrow m \simeq 200 \text{ MeV}/c^2$, hence, the name meson.

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Physical properties of the PION

\[ J^\pi = 0^- \quad \text{(pseudoscalar)} \]

\[ I = 1 \quad \text{(3 charge states: } \pi^+, \pi^0, \pi^-) \]

\[ m_{\pi^\pm} \approx 140 \text{ MeV}/c^2 \quad \tau_{\pi^\pm} \approx 26 \text{ ns} \]
\[ m_{\pi^0} \approx 135 \text{ MeV}/c^2 \quad \tau_{\pi^0} \approx 8.4 \times 10^{-17} \text{ s} \]

Not elementary—has quark substructure:

\[ \pi^+: \bar{u}d \quad \pi^0: (\bar{u}u - \bar{d}d)/\sqrt{2} \quad \pi^-: d\bar{u} \]

For comparison:

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# Pion and Muon Decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Fr.</th>
<th>Nickname</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^+ \rightarrow \mu^+ \nu)</td>
<td>1.0</td>
<td>((\pi_{\mu2}))</td>
</tr>
<tr>
<td>(\mu^+ \nu\gamma)</td>
<td>(\sim 2.0 \times 10^{-4})</td>
<td></td>
</tr>
<tr>
<td>(e^+\nu)</td>
<td>(\sim 1.2 \times 10^{-4})</td>
<td>((\pi_{e2}))</td>
</tr>
<tr>
<td>(e^+\nu\gamma)</td>
<td>(\sim 5.6 \times 10^{-8})</td>
<td></td>
</tr>
<tr>
<td>(\pi^0 e^+\nu)</td>
<td>(\sim 1.0 \times 10^{-8})</td>
<td>((\pi_{\beta}))</td>
</tr>
<tr>
<td>(\pi^0 \rightarrow \gamma\gamma)</td>
<td>(\sim 0.9880)</td>
<td></td>
</tr>
<tr>
<td>(e^+e^-\gamma)</td>
<td>(\sim 1.2 \times 10^{-2})</td>
<td>(Dalitz)</td>
</tr>
<tr>
<td>(e^+e^-e^+e^-)</td>
<td>(\sim 3.1 \times 10^{-5})</td>
<td></td>
</tr>
<tr>
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Fundamental Interactions: the STANDARD MODEL

Strongly Interacting Particles

Quarks \((m \neq 0)\): \(J = \frac{1}{2}\)
\[
\begin{pmatrix}
  u \\
  d \\
  c \\
  s \\
  t
\end{pmatrix}
\]
\[+\frac{2}{3}e\]
\[-\frac{1}{3}e\]

Gluons: \(J = 1, m = 0\); Mesons: \(q\bar{q}\)

Baryons: \(qqq\)

Particles Not Interacting Strongly

Leptons: \(J = \frac{1}{2}\)
\[
\begin{pmatrix}
  e \\
  \nu_e \\
  \mu \\
  \nu_\mu \\
  \tau \\
  \nu_\tau
\end{pmatrix}
\]
\[-e\]

Gauge Bosons: \(J = 1\)
\[
\begin{array}{l}
  W^\pm \\
  Z^0 \\
  \gamma
\end{array}
\]
\[
\begin{array}{l}
  m \text{ (GeV)} \\
  80 \\
  91 \\
  0
\end{array}
\]
Fundamental Interactions: the STANDARD MODEL

Strongly Interacting Particles

Quarks \( (m \neq 0) \): 
\[
J = \frac{1}{2} \begin{pmatrix} u \\ d \\ c \\ s \\ t \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 3 \\ 1/2 \\ -3/2 \end{pmatrix} + \frac{2}{3}e - \frac{1}{3}e
\]

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Particles Not Interacting Strongly

Leptons: 
\[
J = \frac{1}{2} \begin{pmatrix} e \\ \nu_e \\ \mu \\ \nu_\mu \\ \tau \\ \nu_\tau \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} - e
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Gauge Bosons: 
\[
J = 1 \\
m (GeV) \\
W^\pm 80 \\
Z^0 91 \\
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Gauge Bosons: \( J = 1 \)  
\( m (\text{GeV}) \)  
\begin{array}{c|ccc}
W^\pm & Z^0 & \gamma \\
80 & 91 & 0 \\
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Some Shortcomings of the Standard Model

- arbitrary fermion (quark, lepton) masses,
- arbitrary number of generations, (is there a fourth?)
- origin of the masses? (Higgs)
- quark mixing (CKM parameters, CP symmetry breaking . . . ),
- quark confinement, hadron properties at low energies, transition to asymptotic freedom,
- exotic particles (leptoquarks, supersymmetric partners, $\nu_R$, . . .)
- new level of substructure?
- . . .
The PIBETA/PEN program of measurements

Perform precision checks of Standard Model and QCD predictions:

- $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ – main goal
  - SM checks related to CKM unitarity
- $\pi^+ \rightarrow e^+ \nu_e \gamma$ (or $e^+ e^-$)
  - $F_A/F_V$, $\pi$ polarizability ($\chi$PT prediction)
  - tensor coupling besides $V - A$ (?)
- $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma$ (or $e^+ e^-$)
  - departures from $V - A$ in $\mathcal{L}_{\text{weak}}$

2nd phase: The PEN experiment

- $\pi^+ \rightarrow e^+ \nu_e$
  - $e-\mu$ universality
  - pseudoscalar coupling besides $V - A$
  - $\nu$ sector anomalies, Majoron searches, $m_{h^+}$, PS $l$-$q$’s, $V$ $l$-$q$’s, …
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The PIBETA/PEN Program  

PEN Goals and Motivation

$\pi \to e\nu$ decay: SM predictions; measurements

Modern theoretical calculations:

\[
B_{\text{calc}} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))_{\text{calc}}}
\]

\[
\begin{align*}
1.2352 (5) \times 10^{-4} & \quad \text{Marciano and Sirlin, [PRL 71 (1993) 3629]} \\
1.2354 (2) \times 10^{-4} & \quad \text{Decker and Finkemeier, [Phys. Lett. B 387 (1996) 391]} \\
1.2352 (1) \times 10^{-4} & \quad \text{Cirigliano and Rosell, [PRL 99, 231801 (2007)]}
\end{align*}
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Experiment, world average [current PDG]:

\[
\frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))_{\text{exp}}} = (1.230 \pm 0.004) \times 10^{-4}
\]

PEN goal:

\[
\frac{\delta B}{B} \approx 5 \times 10^{-4}.
\]
\[ \pi \rightarrow e\nu \text{ decay: SM predictions; measurements} \]

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\frac{\Gamma (\pi \rightarrow e\bar{\nu}(\gamma))}{\Gamma (\pi \rightarrow \mu\bar{\nu}(\gamma))}_{\exp} = (1.230 \pm 0.004) \times 10^{-4}
\]

PEN goal:

\[
\frac{\delta B}{B} \simeq 5 \times 10^{-4}.
\]
\[ \pi \to e\bar{\nu} \text{ decay: SM predictions; measurements} \]

Modern theoretical calculations:

\[
B_{\text{calc}} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))_{\text{calc}}} =
\]

\[
\begin{cases}
1.2352 \ (5) \times 10^{-4} & \text{Marciano and Sirlin, [PRL 71 (1993) 3629]} \\
1.2354 \ (2) \times 10^{-4} & \text{Decker and Finkemeier, [Phys. Lett. B 387 (1996) 391]} \\
1.2352 \ (1) \times 10^{-4} & \text{Cirigliano and Rosell, [PRL 99, 231801 (2007)]}
\end{cases}
\]

Experiment, world average [current PDG]:

\[
\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))_{\text{exp}}} = (1.230 \pm 0.004) \times 10^{-4}
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PEN goal:

\[ \frac{\delta B}{B} \simeq 5 \times 10^{-4}. \]
The PIBETA/PEN Program

PEN Goals and Motivation

**πe2 Decay and the SM**

\[ B(\pi \to e\nu) = \frac{\Gamma(\pi e_2)}{\Gamma(\pi \mu_2)} \text{ given in SM to } 10^{-4} \text{ accuracy; dominated by helicity suppression } (V - A). \]

Deviations can be caused by:

(a) charged Higgs in theories with richer Higgs sector than SM,
(b) PS leptoquarks in theories with dynamical symmetry breaking,
(c) V leptoquarks in Pati-Salam type GUT's,
(d) loop diagrams involving certain SUSY partner particles,
(e) non-zero neutrino masses (and mixing).

Proc’s. (a)–(d) ⇒ PS currents. Most general 4-fermion \( \pi e_2 \) amplitude:

\[
\frac{G_F}{\sqrt{2}} \left[ (\bar{d}\gamma_\mu \gamma^5 u) (\bar{\nu}_e \gamma^\mu \gamma^5 (1 - \gamma^5)e) f^{e}_{AL} + f^{e}_{PL} (\bar{d}\gamma^5 u) (\bar{\nu}_e \gamma^5 (1 - \gamma^5)e) \right] + \text{r.h. } \nu \text{ term}
\]

In the SM: \( f_{AL}^l = 1 \), while \( f_{XR}^l = f_{PX}^l = 0 \), with \( l = e, \mu \).
The $f_{PL}^e$ and Mass Bounds

Allowing for LH pseudoscalar coupling \cite{Shanker, NP B204 (82) 375}:

$$B_{\pi e^2} = B_{SM} \left( 1 + \frac{2m_\pi a_P}{m_e a_A} f_{PL}^e \right) / \left( 1 + \frac{2m_\pi a_P}{m_\mu a_A} f_{PL}^\mu \right),$$

where 2nd term in denominator is negligible because $f_{PL}^e \approx f_{PL}^\mu$, while

$$\frac{a_P}{a_A} \approx \frac{m_\pi}{m_u + m_d} \approx 14.$$

Therefore

$$\left( B_{\pi e^2}^{obs} - B_{\pi e^2}^{SM} \right) / B_{\pi e^2}^{SM} = \frac{\Delta B}{B_{SM}} \approx \frac{2m_\pi a_P}{m_e a_A} f_{PL}^e \approx 7700 f_{PL}^e!$$

PEN goal is $\Delta B / B \approx 5 \times 10^{-4}$, giving a $1\sigma$ sensitivity of

$$\delta f_{PL}^e \approx 6.5 \times 10^{-8}.$$

We can use this sensitivity to get estimates of the mass reach of PEN.
PEN Mass Bounds Cont’d.

(a) **Charged Higgs,** \( m_{H^+} \)

Given a mixing angle suppression \( S \approx 10^{-2} \), we get

\[
f_{PL}^e \approx S \frac{m_t m_\tau}{m_{H^+}^2} \quad \text{yielding} \quad m_{H^+} > 6.9 \text{ TeV}.
\]

(b) **Pseudoscalar leptoquarks,** \( m_P \)

Given an estimated effective Yukawa coupling of \( y \approx 1/250 \), we can find

\( m_P \), mass of the color-triplet PS \( l-q \):

\[
f_{PL}^e \approx \sqrt{2} \frac{y^2}{G_F} \frac{1}{2m_P^2} \quad \text{yielding} \quad m_P > 3.8 \text{ TeV}.
\]

(c) **Vector leptoquarks,** \( M_G \)

Following Shanker who assumes gauge coupling \( g \approx g_{SU(2)} \), we have:

\[
f_{PL}^e \approx \frac{4M_W^2}{M_G^2} \quad \text{yielding} \quad M_G > 630 \text{ TeV}.
\]
The PEN Apparatus

- stopped $\pi^+$ beam
- active target counter
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity

PEN Detector 2008

D. Počanić (UVa)
The PEN Apparatus

- stopped $\pi^+$ beam
- active target counter
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity
PIBETA Detector Assembly (1998)
PIBETA Detector on Platform (1998)

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Home page – http://pen.phys.virginia.edu
Neutron Decay Parameters (SM): \( n \rightarrow pe\bar{\nu}_e + 782 \text{ keV} \)

\[
\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \simeq k_e E_e (E_0 - E_e)^2 \times \left[ 1 + a \frac{k_e \cdot k_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \begin{pmatrix} \frac{k_e}{E_e} & \frac{k_\nu}{E_\nu} & \frac{k_e \times k_\nu}{E_e E_\nu} \end{pmatrix} \right]
\]

with:

\[
a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2}, \quad A = -2 \frac{|\lambda|^2 + \text{Re}(\lambda)}{1 + 3|\lambda|^2}
\]

\[
B = 2 \frac{|\lambda|^2 - \text{Re}(\lambda)}{1 + 3|\lambda|^2}, \quad D = 2 \frac{\text{Im}(\lambda)}{1 + 3|\lambda|^2}
\]

\[
\lambda = \frac{G_A}{G_V}
\]

\((D \neq 0 \Leftrightarrow T \text{ invariance violation.})\)
Goals of the **Nab** and **abBA** Experiments

\[
\frac{\delta a}{a} \lesssim 1 \times 10^{-3}
\]

\[
\frac{\delta b}{b} \lesssim 3 \times 10^{-3}
\]

\[
\frac{\delta A}{A} \lesssim 3 \times 10^{-3}
\]

\[
\frac{\delta B}{B} \lesssim 1 \times 10^{-3}
\]
n-decay Correlation Parameters Beyond $V_{ud}$

- Beta decay parameters constrain L-R symmetric model extensions to the SM.  
  [Review: Herczeg, Prog. Part. Nucl. Phys. 46, 413 (2001)]

- Measurement of the electron-energy dependence of $a$ and $A$ can separately confirm CVC and absence of SCC.  

- Fierz interference term, never measured for the neutron, offers a sensitive test of non-($V - A$) terms in the weak Lagrangian ($S, T$).

- A general connections exists between non-SM (e.g., $S, T$) terms in $d \rightarrow ue\bar{\nu}$ and limits on $\nu$ masses.  
  [Ito + Prézaeu, PRL 94 (2005)]
**Nab Measurement principles:** Proton phase space

Note: For a given $E_e$, $\cos \theta_{ev}$ is a function of $p_p^2$ only.
Measurement principles: Proton TOF response functions

\[ \text{Slope} = a \]
Measurement principles: Spectrometer sketch

- Neutron Beam
- Decay Volume
- TOF region
- Transition region
- Acceleration region
- Segmented Si detector

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The Spallation Neutron Source
The Fundamental Neutron Physics Beamline
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