Pleasure is learning and being able to practice often-times what one has learned.
Discovery of Parity Nonconservation

Experimental Test of Parity Conservation in Beta Decay*

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AND


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Fig. 1. Schematic drawing of the lower part of the cryostat.

Fig. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.
"... One day in the early Spring of 1956, Professor T. D. Lee came up to my little office on the thirteenth floor of Pupin Physical Laboratories. He explained to me, first, the $\tau$-$\theta$ puzzle. If the answer to the $\tau$-$\theta$ puzzle is violation of parity—he went on—then the violation should also be observed in the space distribution of the beta-decay of polarized nuclei: one must measure the pseudo-scalar quantity $<\sigma \cdot \mathbf{p}>$ where $\mathbf{p}$ is the electron momentum and $\sigma$ the spin of the nucleus.

... Following Professor Lee's visit, I began to think things through. This was a golden opportunity for a beta-decay physicist to perform a crucial test, and how could I let it pass? ... That Spring, my husband, Chia-Liu Yuan, and I had planned to attend a conference in Geneva and then proceed to the Far East. Both of us had left China in 1936, exactly twenty years earlier. Our passages were booked on the Queen Elizabeth before I suddenly realized that I had to do the experiment immediately, before the rest of the Physics Community recognized the importance of this experiment and did it first. So I asked Chia-Liu to let me stay and go without me.

... As soon as the Spring semester ended in the last part of May, I started work in earnest in preparing for the experiment. ... In the middle of September, I finally went to Washington, D. C. for my first meeting with Dr. Ambler. ... Between experimental runs in Washington, I had to dash back to Columbia for teaching and other research activities. On Christmas eve, I returned to New York on the last train; the airport was closed because of heavy snow. There I told Professor Lee that the observed asymmetry was reproducible and huge. The asymmetry parameter was nearly -1. Professor Lee said that this was very good. This result is just what one should expect for a two-component theory of the neutrino.”
Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain
\[ \pi^+ - \nu^+ - e^{++} \]

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Lee and Yang\(^1\) recently re-examined the problem as to whether parity is conserved in nature

With these facts in mind, we exposed (in early October, 1956) nuclear emulsion pellicles (1 mm thick) to a \(\pi^+\) beam of the University of Chicago synchrocyclotron.

From these preliminary data we find\(^4\)

\[
\left( \int_{0}^{180^\circ} |W(\theta)| d\Omega - \int_{0}^{90^\circ} |W(\theta)| d\Omega \right) / \int_{0}^{180^\circ} W(\theta) d\Omega
\]

\[= 0.062 \pm 0.027,\]

\(^{\dagger}\) For technical reasons, this Letter could not be published in the same issue as that of Garwin, Lederman, and Weinrich, Phys. Rev. 105, 1415 (1957).
Two Corner Stones of Electroweak

1. CKM
   \[(u, c, t) \rightarrow (d, s, b)\]

2. Neutrino Mapping
   \[(e, \mu, \tau) \rightarrow (\nu_1, \nu_2, \nu_3)\]
$U_{CKM} \approx \begin{pmatrix}
0.974 & 0.227 & (2 - 3i)10^{-3} \\
-0.227 & 0.973 & 0.04 \\
(7 - 3i)10^{-3} & -0.04 & 0.999
\end{pmatrix} + \text{small corrections}$
Neutrino Mapping

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}
\quad =
\quad U
\quad \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

\[
U = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]

\[
c_{ij} = \cos \theta_{ij}, \quad s_{ij} = \sin \theta_{ij}
\]

\[
s_{12}^2 = 0.314(1 +0.18 \quad -0.15 )
\]

\[
s_{23}^2 = 0.44(1 +0.41 \quad -0.21 )
\]

\[
s_{13}^2 = 0.9 \quad 2.3 \quad 9 \times 10^{-2}
\]

\[
|m_2^2 - m_1^2| = 7.92(1 \pm 0.09) \times 10^{-5}\text{eV}^2
\]

\[
|m_3^2 - \frac{m_1^2 + m_2^2}{2}| = 2.4 \times (1 +0.21 \quad -0.26 ) \times 10^{-3}\text{eV}^2.
\]
Neutrino Mass Operator

\[ M = m_1 \bar{\nu}_1 \nu_1 + m_2 \bar{\nu}_2 \nu_2 + m_3 \bar{\nu}_3 \nu_3 \]

\[ \nu_i = \psi(\nu_i) \quad \text{and} \quad \bar{\nu}_i = \psi^\dagger(\nu_i) \gamma_4 \]

Friedberg-Lee assumption (without T violation)

\[ M = a(\bar{\nu}_\tau - \bar{\nu}_\mu)(\nu_\tau - \nu_\mu) + b(\bar{\nu}_\mu - \bar{\nu}_e)(\nu_\mu - \nu_e) \]

\[ + c(\bar{\nu}_e - \bar{\nu}_\tau)(\nu_e - \nu_\tau) \]

\[ + m_0(\bar{\nu}_e \nu_e + \bar{\nu}_\mu \nu_\mu + \bar{\nu}_\tau \nu_\tau) \]

- \( \text{Sym}(m_0 = 0) : \nu_i \rightarrow \nu_i + z, \quad \{\nu_i, z\} = 0 \)

- This sym. determines \( U(3) \) with only one real parameter \( \theta \)
Phase Convention

\[ \nu_e \rightarrow -\nu_e, \quad \nu_\mu \rightarrow -\nu_\mu, \quad \nu_\tau \rightarrow \nu_\tau \]

Neutrino Mass Matrix (in terms of \( \nu_e, \nu_\mu, \nu_\tau \))

\[ M = m_0 + \begin{pmatrix} b+c & -b & c \\ -b & a+b & a \\ c & a & c+a \end{pmatrix}, U^\dagger MU = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \]

**Theorem**

Let \( \phi = \sqrt{\frac{1}{3}} \begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix} \)

\[ (M - m_o) \phi = 0 \]
\[ U = \begin{pmatrix}
\frac{\sqrt{2}}{3} \cos \frac{\theta}{2} & \frac{1}{3} & -\frac{\sqrt{2}}{3} \sin \frac{\theta}{2} \\
-\frac{1}{6} \cos \frac{\theta}{2} + \frac{1}{2} \sin \frac{\theta}{2} & \frac{1}{3} \sin \frac{\theta}{2} + \frac{1}{2} \cos \frac{\theta}{2} \\
\frac{1}{6} \cos \frac{\theta}{2} + \frac{1}{2} \sin \frac{\theta}{2} & -\frac{1}{3} & -\frac{1}{6} \sin \frac{\theta}{2} + \frac{1}{2} \cos \frac{\theta}{2}
\end{pmatrix} \]

\[ \overline{OX} = \nu_e, \quad \overline{OY} = \nu_\mu \\
\overline{OZ} = \nu_\tau, \quad \overline{OB} = \nu_2 \]

\[ |\theta| << 1 \]

\[ |a| >> |b| + |c| \]
$U_{th}(\theta = 0) = \begin{pmatrix}
\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\
-\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\
\sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}}
\end{pmatrix} \cong \begin{pmatrix}
.8165 & .5773 & 0 \\
-.4082 & .5773 & .7071 \\
.4082 & -.5773 & .7071
\end{pmatrix}$

$U_{exp} \cong \begin{pmatrix}
0.84 & 0.56 & s_{13}e^{-i\delta} \\
-0.4 - 0.6s_{13}e^{-i\delta} & 0.6 - 0.4s_{13}e^{-i\delta} & 0.7 \\
0.4 - 0.6s_{13}e^{-i\delta} & -0.6 - 0.4s_{13}e^{-i\delta} & 0.7
\end{pmatrix}$

- $U_{th}(\theta)$ were derived before by Harrison and Scott ('02), Hassison, Perkins and Scott ('02), Z. Z. Xing ('02), X. G. He and A. Zee('03)

- Our starting point and our symmetry are different
Daya Bay collaboration

Europe (3)
- JINR, Dubna, Russia
- Kurchatov Institute, Russia
- Charles university, Czech

North America (9)
- LBNL, BNL, Caltech, UCLA
- Univ. of Houston, Iowa state Univ.
- Univ. of Wisconsin, Illinois Inst. Tech.
- Univ. of Illinois

China (12)
- IHEP, CIAE, Tsinghua Univ.
- Zhongshan Univ., Nankai Univ.
- Beijing Normal Univ.
- Shenzhen Univ., Hong Kong Univ.
- Chinese Hong Kong Univ.
- Taiwan Univ., Chiao Tung Univ.
- National United univ.
Daya Bay nuclear power plant

- 4 reactor cores, 11.6 GW
- 2 more cores in 2011, 5.8 GW
- Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds
Opening Sentences of Confucius’ Analects

学而时习之不亦悦乎
有朋自远方来不亦乐乎

Pleasure is learning and being able to practice often-times what one has learned.
Happiness is having old friends coming from far away.