Studies of CP Violation and other diversions of an accidental physicist.

Talk to SPS

Daniel Marlow
Princeton University

November 14, 2003
Warning!

• The following talk contains advanced material that may not be suitable for those under the age of 21 who have not studied quantum mechanics. These individuals may not follow the talk in full detail, but if they are patient, they will garner a flavor for contemporary research in particle physics.
What is CP Violation?

• CP violation represents a tiny difference in the behavior of matter and antimatter.
• It is required to explain the fact that our universe is matter dominated.
• It was first observed in 1964 by Val Fitch and Jim Cronin (both at Princeton at the time), who were subsequently awarded the Nobel Prize in physics.
• The Fitch and Cronin discovery established the existence of CP violation, but left a number of unanswered questions.
The Matter-Antimatter Asymmetry: the 1st ms

- Anti-quark
- Quark

Baryon Violation
CP Violation

Quark Antiquark Annihilation ⇒ ~ $10^9$ photons

$10^{-35}$ SECOND

# Quarks = # Antiquarks
(From Jon Dorfan)

$10^{-32}$-$10^{-4}$ SECOND

Slight excess ~ few parts / $10^{10}$ of Quarks Over Antiquarks

$10^{-3}$ SECOND - NOW

Excess Quarks survive to produce protons, neutrons ie. Matter
For every billion ordinary particles annihilating with antimatter in the early universe, one extra was left “standing!”

--The Smithsonian
The CPT Theorem

There is a quantum mechanical operator called CPT, where “T” stands for time-reversal.

Although the experimental tests of CPT are somewhat limited, the CPT theorem is part of the “theoretical bedrock” of field theory. If we assume that CPT is a good symmetry, then

\[ CP \Rightarrow T \]
Time Reversal

In non-relativistic QM, the time-reversal operator is such that:  \( i \rightarrow -i \)  \&  \( t \rightarrow -t \)

\[
T | f \rangle = | f^* \rangle
\]

thus

\[
\Psi(x, t) = \Psi_0 e^{-i(kx - \omega t)} \rightarrow \Psi_0^* e^{i(kx + \omega t)}
\]

left-mover  right-mover

As one would expect, the T operator reverses momenta (but not positions).
Time Reversal

The expectation value of an operator transformed by T is

\[ \langle Q \rangle_K = \int \Psi^*_K Q \Psi_K \, dV = \int \Psi Q \Psi^* \, dV \]

\[ = \int (Q \Psi)^* \Psi \, dV = \int \Psi^* Q^* \Psi \, dV \]

\[ = \langle Q^* \rangle \]

Operators with complex phases (e.g., p and L), are not T invariant (and therefore are not CP invariant).
The Standard Model

**Leptons**

<table>
<thead>
<tr>
<th>Charge</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\nu_e$, $e^-$, $\mu^-$, $\tau^-$</td>
</tr>
<tr>
<td>$-e$</td>
<td>$\bar{e}$, $\bar{\mu}$, $\bar{\tau}$</td>
</tr>
</tbody>
</table>

**Quarks**

<table>
<thead>
<tr>
<th>Charge</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2/3e$</td>
<td>$u$, $d$, $s$, $c$, $t$</td>
</tr>
<tr>
<td>$-1/3e$</td>
<td>$b$</td>
</tr>
</tbody>
</table>

**Forces Carriers**

- **EM**
  - photon ($\gamma$)

- **Weak**
  - $W^\pm$, $Z^0$

- **Strong**
  - gluon ($g$)

**Hadrons**

- **EM**
  - $p = uud$

- **Weak**
  - $\pi^+ = u\bar{d}$
  - $\pi^- = \bar{u}d$
  - $\pi^0 = (u\bar{u} + d\bar{d})/\sqrt{2}$

- **Strong**
  - $K^- = s\bar{u}$
  - $K^0 = \bar{s}d$
  - $B^- = b\bar{u}$
  - $B^0 = \bar{b}d$
Feynman Diagrams

Electron radiates a photon

Electron absorbs a photon
Feynman Diagrams

$e^-$ $\gamma$ $e^-$

Electron -electron scattering

Photon is never seen
Feynman Diagrams

\[
\begin{pmatrix}
\nu_\mu \\
\mu^-
\end{pmatrix}
\]

\[\mu^- \rightarrow W^- \]

Muon radiates a W boson

The W rematerializes as an electron and an anti-electron neutrino.

\[
\begin{pmatrix}
\nu_e \\
\bar{\nu}_e
\end{pmatrix}
\]

\[\begin{pmatrix}
W^- \\
e^-
\end{pmatrix}
\]
Feynman Diagrams

Muon decay
Feynman Diagrams

\[
\begin{pmatrix}
u \\ d
\end{pmatrix}
\rightarrow
\begin{pmatrix}W^+ \\ d
\end{pmatrix}
\]

Quark transitions

\[
\begin{pmatrix}
u \\ d
\end{pmatrix}
\]

\[
\begin{pmatrix}c \\ s
\end{pmatrix}
\rightarrow
\begin{pmatrix}W^+ \\ c
\end{pmatrix}
\]

\[
\begin{pmatrix}c \\ \bar{s}
\end{pmatrix}
\]
Quark Mixing

Experimentally we know that the eigenstates of the weak Hamiltonian and the mass eigenstates are different. For simplicity we start with a two-quark-doublet version of nature, i.e.,

\[
q = + \frac{2}{3} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}
\]

If the quarks acted like leptons, then only vertical transitions would be allowed and the s quark would be stable.

However, the kaon decays in 12 ns. It appears that there are generation-crossing transitions.
Quark Mixing

Rather than saying that the strange quark is decaying directly to an up quark, we write the following

\[
\begin{pmatrix}
    d' \\
    s'
\end{pmatrix} = \begin{pmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
    d \\
    s
\end{pmatrix}
\]

And say that the s-quark in the kaon has a \( d' \) component that can decay into a u-quark.

\[
\begin{pmatrix}
    u \\
    d'
\end{pmatrix} \quad \text{Weak eigenstate}
\quad \begin{pmatrix}
    u \\
    d
\end{pmatrix} \quad \text{Mass eigenstate}
\]

Q: What does this have to do with CP violation?
Quark Mixing

Ans: Nothing! (yet)

However, even before the discovery of the c-quark (and two decades before the observation of the t-quark) Kobayashi and Maskawa proposed a three-generation scheme

\[
\begin{pmatrix}
  u \\
  d'
\end{pmatrix}
\begin{pmatrix}
  c \\
  s'
\end{pmatrix}
\begin{pmatrix}
  t \\
  b'
\end{pmatrix}
\]

Weak eigenstates

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}
\begin{pmatrix}
  c \\
  s
\end{pmatrix}
\begin{pmatrix}
  t \\
  b
\end{pmatrix}
\]

Mass eigenstates
Both Cabibbo (2x2) and KM (3x3) mixing are described by unitary transformations. In general

\[ \tilde{d}' = M \tilde{d} \]

where \( M^\dagger M = 1 \)
Quark Mixing

<table>
<thead>
<tr>
<th>Parameter(s)</th>
<th>( N_{\text{gen}} )</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_1, \theta_2, \theta_3, e^{i\delta} )</td>
<td>3 \times 3</td>
<td>KM</td>
</tr>
<tr>
<td>( \theta_C )</td>
<td>2 \times 2</td>
<td>Cabibbo</td>
</tr>
</tbody>
</table>

The essential contribution of Kobayashi and Maskawa was the observation that only a 3x3 scheme would provide the phase needed for T violation (and hence CP violation).
Quark Mixing

The Kobayashi-Maskawa quark-mixing matrix:

\[
M = \begin{pmatrix}
  c_1 & -s_1c_3 & -s_1s_3 \\
  s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\
  s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_1s_2s_3 - c_2c_3e^{i\delta}
\end{pmatrix}
\]

where \( s_i = \sin \theta_i \) & \( c_i = \cos \theta_i \)

A key point is the appearance of the complex phase \( \delta \).
Quark Mixing

The appearance of the KM phase $\delta$ offers a natural explanation for standard-model CP violation. Moreover, there is a wealth of other (non-CP) experimental data that supports the KM picture. Until recent B-physics measurements, however, there have been no quantitative tests of its predictions regarding CP violation.
A Technical “Detail”

• It turns out that one cannot see the effects of the KM phase without doing some sort of “interference” measurement.

• This “detail” leads to a tremendous technical challenge and is one of the reasons that 20 years went by between the time that it became evident that the experiment to be described was possible and the time it was actually carried out.

• The required interference is achieved using another type of “mixing.”
Matter-Antimatter Oscillations

First observed in the neutral kaon (strange quark) system, neutral meson mixing represents an oscillation between matter and anti-matter. In the neutral B system, the reaction proceeds by the following Feynman diagram:
Matter-Antimatter Oscillations

As a consequence, an initially pure $B^0$ develops in time according to the expression given below.

$$\left| B^0 (t) \right\rangle = e^{-i(m-\Gamma)/2} \times \left[ \cos\left(\frac{\Delta m t}{2}\right) \left| B^0 \right\rangle + i \sin\left(\frac{\Delta m t}{2}\right) e^{-2i\phi_m} \left| \bar{B}^0 \right\rangle \right]$$

where the KM matrix element $V_{td}$ determines $\Delta m$.
Indirect CP Violation

Thus for a decay $B^0 \rightarrow f$ where $f$ is a CP eigenstate, we have two “indistinguishable” decay paths

Working through the algebra, yields a time-dependent CP asymmetry

$$A_{CP}(\Delta t) = \frac{\Gamma(B^0 \rightarrow f) - \Gamma(\bar{B}^0 \rightarrow f)}{\Gamma(B^0 \rightarrow f) + \Gamma(\bar{B}^0 \rightarrow f)}$$

$$= -2\eta_f \sin(\Delta m \Delta t) \sin 2(\phi_M + \phi_D)$$

Where $\phi_M$ and $\phi_D$ are the weak phases for the mixing and decay diagrams, respectively and

$$CP |f\rangle = \eta_f |f\rangle$$

$\eta_f = \pm 1$
Indirect CP Violation

\[ A_{CP}(\Delta t) = \frac{\Gamma(B^0 \rightarrow f') - \Gamma(\bar{B}^0 \rightarrow f')}{\Gamma(B^0 \rightarrow f') + \Gamma(\bar{B}^0 \rightarrow f')} \]

One complication is that since CP eigenstates are neutral, they give no information as to whether the decaying meson was a \( B^0 \) or a \( \bar{B}^0 \).

Fortunately there is a solution in the form of . . .
Quantum Weirdness

One way to make $B^0_s$ is to produce $B^0\bar{B}^0$ pairs at an $e^+e^-$ collider. In practice this means making using of resonant production, i.e.,

$$e^+e^- \rightarrow Y(4S) \rightarrow B^0\bar{B}^0$$

Where the $Y(4S)$ is a radial excitation of a “quarkonium” bound state. The important point is that the $B^0\bar{B}^0$ pair is produced in a coherent state.
If $t_1 = t_2$ then the particle on the CP eigenstate side must be a $B^0$. Note that the tagging information is (apparently) communicated across space instantaneously despite the fact that the B’s could be separated by a finite distance (a few hundred microns). This is an instance of the EPR paradox.
The times involved are too short (~1 ps) to measure directly, instead we measure the decay positions and convert these positions to times.

But the distances are also small, since light travels only 300 μm in one ps.
The Measurement

The time-dependent asymmetry appears mainly as a mean shift in the $\Delta z$ distribution between events tagged as $B^0$ decays and events tagged as $\bar{B}^0$ decays.
The KEK-B Asymmetric $e^+e^-$ Collider

KEK-B is a recently completed accelerator situated in Tsukuba City, Japan.

It is designed to produce an order of magnitude more luminosity (collisions per unit cross section) than any existing machine.
Electron Source
The Linac
The Storage Rings

RF Cavity Stations
The Storage Rings

Arc Section
The “IR”

Where matter and anti-matter collide!

November 14, 2003
BELLE Detector

1. Silicon Vertex Detector
2. Central Drift Chamber
3. Aerogel Cherenkov Counter
4. Time of Flight Counter
5. CsI Calorimeter
6. KLM Detector
7. Superconducting Solenoid
8. Superconducting Final Focussing System
The Sun Never Sets on the Belle Collaboration
The BELLE Collaboration

Belle comprises ~250 physicists from 50 institutions in about ten countries.
Cosmic Ray

How I spent my sabbatical year!
Meters to Microns
The Magnet
The Silicon Vertex Detector
The Central Drift Chamber
The Aerogel

Silica aerogel is a very low-density glass that provides just the right index of refraction to produce Cerenkov light.

In the momentum range of interest pions emit Cerenkov light while the somewhat heavier kaons don’t.
The Cesium Iodide Detector

Upper management looks on anxiously while $35M worth of salt is craned into place.

Each scintillator crystal is read by two photodiodes.
K_L Muon Detector

The muon detectors, which are the largest, are made from standard soda-lime float glass (window glass).

An endcap module is installed.
Data Acquisition

The tip of the electronic iceberg.
Our First Event (1999)
Latest Result

CP violation shows up as a mean shift between the red and blue curves (one is matter, the other is anti-matter).

\[ \sin^2 \phi_1 = 0.733 \pm 0.057 \text{(stat)} \pm 0.028 \text{(syst)} \]
Other diversions . . .

• Teaching . . . a generally terrifying (but tremendously rewarding) experience.

• Administration. Somebody has to do it.

• Ham Radio. Started this as a kid, and never lost interest. Favorite activity is international contesting, but also have an interest in something called software defined radio.
Ham Radio

A way to move up in the world.

One way to be competitive in radio contests is to go to an obscure location.
Software Defined Radio

Most of the functionality of a radio can be implemented in software. Given all of the excess computing capacity around, it makes sense to put it to good use.

The idea is to replace pricey hardware with relatively inexpensive software.

Collaborators are welcome!