PHY313 - CEI544
The Mystery of Matter
From Quarks to the Cosmos
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Conservation laws in beta decay (rev.)

- Energy Conservation
- Angular momentum conservation
- Charge conservation
- Baryon number conservation
- Lepton conservation

**Please note:** When the d quark changes into a u quark by producing a W Boson the quark color is preserved. Thus I have drawn the d & u arrows in the same color.

**It was noted by a smart student in class that the W cannot carry away color and the color must be preserved.**

\[
\begin{align*}
n &\rightarrow p + e^- + \bar{\nu}_e \\
u dd &\rightarrow uud + e^- + \bar{\nu}_e \\
d &\rightarrow u + e^- + \bar{\nu}_e
\end{align*}
\]
Mirror Symmetry

- The Parity operation $P(1)$ in one dimension flips the shape of an object into its mirror image: If $P(1)$ operates on an arrow it will change it from a right arrow to a left arrow.

- Mirror reflection changes a right-handed screw into a left-handed screw.

The Laws of Nature should not depend on whether we live in a right-handed or a left-handed world.

It should not matter whether we look at the real object or its picture image.

C.N. Yang and T. D. Lee proposed that this statement was wrong for the weak interaction.

http://www.phy.ntnu.edu/java/optics/mirror_e.html

Which is the real picture?
Driving home the point

Left-right Image Reversal

- Image raises right hand

- Object raises left hand

- View of image raising its right hand.
The Parity Operation in 3 Dimensions

- The full parity operation reflects a 3-dimensional object around each direction: the x-axis, the y-axis and the z-axis. Thus we use 3 mirrors, one for each reflection.
- The operation $P(x)$ reflects with a mirror that lies in the y-z plane.
- The operation $P(y)$ reflects with a mirror that lies in the x-z plane.
- The operation $P(z)$ reflects with a mirror that lies in the x-y plane.
- Note: After the first reflection the rotation marker changes direction, but the arrow stays upright. After 3 reflections the rotation has its original sense back but the arrow is inverted.

$P \cdot \text{Shape} (x, y, z) = \text{Shape} (-x, -y, -z)$
Another view at the mirror

Here the screw point into or out of the mirror
Parity violation in the weak interaction

- Parity conservation was first tested in the beta decay of $^{60}\text{Co}$:

  $$^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \bar{\nu}_e$$

- The Co nuclei can be aligned by orienting their spins upwards (or downwards) in a magnetic field. Suppose the electrons are emitted preferentially downward (in the real world), i.e. opposite to the spin direction.

- In the mirror world the spin direction faces downward. The beta rays will still come out downwards. Thus they would now come out in the same direction as the spin.
Wu’s experiment

- For the mirror image NOT be differentiated from the real world electrons must come out equally in the upward and downward direction.
- But Mrs. Wu et al observed that the electrons came out preferentially up or down, depending on the spin direction.
- Thus Parity was NOT conserved.
- Nuclear spin polarization achieved in a large magnetic field at 0.01°K. At low temperature thermal motion does not destroy the alignment. Beta particles from $^{60}$Co decay were detected by a thin scintillator placed above the $^{60}$Co source.
- Flipping the magnetic field flips the $^{60}$Co spin direction, thus producing the mirror situation.
Wu’s results

- Top and middle graph - gamma anisotropy (difference in counting rate between two NaI crystals) shows control of polarization;
- Bottom - β asymmetry - counting rate in the anthracene crystal relative to the rate without polarization (after the set up was warmed up) for two orientations of magnetic field.
- Similar behavior of gamma anisotropy and beta asymmetry.
- Rate was different for the two magnetic field orientations indicating that Parity symmetry was violated.
- This was an epochal result!
Neutrino Helicity: The sense of its spin

• Neutrinos have spin $\frac{1}{2}$. This spin points either in line with the direction of motion or against it.

• If it is in line it has the rotational sense of a right handed screw, i.e. Helicity $h = +1$. If it is opposite it has the sense of a left-handed screw, i.e. Helicity $h = -1$. Electrons have both $h = \pm 1$.

• Neutrinos have only $h = -1$, antineutrinos only $h = +1$

\[ h = -1 \text{ for all } \nu \]
\[ h = +1 \text{ for all } \bar{\nu} \]

Left-handed particles

Right-handed particles
Electron helicity in weak interactions

- Electrons that emerge from a weak interaction end up with a Helicity that is forced on them by the neutrinos:
  - For electrons with velocity $v$
    \[ h = -\frac{v}{c} \]
  - For positrons with velocity $v$
    \[ h = +\frac{v}{c} \]

Only at $v \sim c$ does the electron spin point exactly in or opposite to the direction of flight.
Example: $\mu^+$ decay at rest

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Note: $\mu$ spin aligned to the right

The spin & helicity of the electron neutrino takes away the spin & helicity of the $\mu$. The spin & helicity of the positron cancels the spin & helicity of the anti-neutrino.

Note: helicity of $e^+$ due to neutrino helicities
Example: $\mu^-$ decay at rest

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

Note: $\mu$ spin aligned to the left

The fact that the neutrino always spins with a left hand screw allows to differentiate between the real world and the mirror world.

Note: helicity of $e^-$ due to neutrino helicities

Note: helicities of neutrinos
Particles & Antiparticles: The Dirac Equation

• Starting ~ 1930 Dirac extended quantum mechanics to include Special Relativity.
• Einstein had written:

\[ E^2 = p^2 + m^2 c^4 \]

• With spin-1/2 electrons, e.g. can never stand still and thus p is never zero.
• If we solve for E we obtain

\[ E = \pm \sqrt{p^2 + m^2 c^4} \]

• What does the ± sign possibility mean?

• Can Energy ever be negative?
• Lifting an electron from a sea of bound particles leaves behind a positive hole: Positron.

Paul M. Dirac

Free particles

Bound particles
Example from an atom

- A Lithium atom has 3 electrons: Two inner ones and one outer one.
- The inner ones are shielding 2 of the 3 nuclear charges and the outer one sees only 1 positive charge.
- If one of the inner electrons is excited to the outer level, the two outer electrons will now see 2 positive charges (approximately).
- Thus the atom gained one negative charge in the outer level and has now a positive hole (a vacancy) in the inner level.
Antiparticles more generally

- More generally the Dirac equation allows to produce particles and antiparticles in pairs from the vacuum, i.e. seemingly from nothing.
- Thus every particle has an antiparticle.
- Particles and their antiparticles have identical mass and spin. Thus an antiproton has positive mass just like a proton. There are only positive masses.

\[ \Delta t = \frac{\hbar}{2mc^2} = 6.6 \times 10^{-25} \text{ GeV} \cdot s / 2 \cdot \text{GeV} \approx 3 \times 10^{-25} \text{ s} \]

\[ \Delta x \equiv c\Delta t = 3 \times 10^8 \text{ m/s} \times 3 \times 10^{-25} \text{ s} \approx 10^{-16} \text{ m} \]

- Thus creating a proton - antiproton pair costs \( \sim 2 \text{ GeV} \) just in mass energy.
- Mr. Heisenberg allows to create such a pair out of nothing for a short time (a virtual pair):
Production of quark-antiquark pair

Run 152507 event 1222318
Dijet Mass = 1364 GeV (corr)
\[ \cos \theta^* = 0.30 \]
z vertex = -25 cm

J2 \( E_T \) = 633 GeV (corr) \hspace{1cm} J1 \( E_T \) = 666 GeV (corr)
J2 \( E \) = 546 GeV (raw) \hspace{1cm} J1 \( E \) = 583 GeV (raw)
J2 \( \eta \) = -0.30 (detector) \hspace{1cm} J1 \( \eta \) = 0.31 (detector)
= -0.19 (correct z) \hspace{1cm} = 0.43 (correct z)

CDF Run 2 Preliminary

A beautiful two-jet event
Properties of Antiparticles

• Antiparticles have the opposite charge of their particle partner.
• Antiquarks have the anti-color of their quarks. All the flavors, electron number, $\mu$ and $\tau$ numbers and baryon numbers change their signs.
• The positron is the antiparticle to the electron
• The $\mu^+$ is the antiparticle to the $\mu^-$.  
• The $\pi^+$ is the antiparticle to the $\pi^-$.  
• Some particles, like the $\pi^0$ and the photon, are their own antiparticles.

<table>
<thead>
<tr>
<th>Quark configuration of some neutral mesons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
</tr>
<tr>
<td>$\pi^0$-bar</td>
</tr>
<tr>
<td>$K^0$</td>
</tr>
<tr>
<td>$K^0$-bar</td>
</tr>
</tbody>
</table>

• The u-bar quark has charge $-2/3 e$, because the u quark has $+2/3 e$
• The d-bar quark has charge $+1/3 e$ because the d quark has $-1/3 e$.
• Changing the charge of a particle (C-operation) and performing a parity transformation (P-operation) produces the anti-particle

\[
\begin{array}{|c|c|}
\hline
\text{Quark configuration of some neutral mesons} & u-bar + d-bar \\
\hline
\text{$\pi^0$} & u-bar + d-bar \\
\hline
\text{$\pi^0$-bar} & u-bar + d-bar \\
\hline
\text{$K^0$} & d-bar \\
\hline
\text{$K^0$-bar} & s-bar \\
\hline
\end{array}
\]
How many building blocks are there?

- **There are 6 quarks and 6 antiquarks**
- **Each occurs in 3 colors.**
  - The antiquarks have the opposite charge of the related quarks.
  - So there are 36 different quarks.

- **There are 6 leptons and 6 antileptons.**
  - The antileptons have the opposite charge of the related leptons.
  - There are NO colors in the lepton sector.
  - So there are 12 different leptons.
Annihilation & production of particle-antiparticle pairs

- In simplistic terms C changes the sign of the charge and P changes the sign of the arrow of time from forward to backward. Thus $p \rightarrow p\bar{p}$.

- When particles and antiparticles of the same species meet they annihilate each other into photons.

- Conversely, a particle-antiparticle pair can be produced from photons or other bosons of sufficient energy, e.g.

\[ \gamma \text{ or } Z^0 \rightarrow q + q\bar{q} \]
\[ W^+ \rightarrow u + d\bar{u} \]
The Puzzle of CP violation

- As discussed the CP operation transforms between matter and anti-matter.
- We expect nature to be symmetric in respect to the CP operation: There should be as many antiparticles as particles.
- The Big Bang’s initial hot photons should have created as much antimatter as matter.
- But experimentally we know that less than 0.01% of the visible universe consists of antimatter.
- Thus CP symmetry is “badly” violated in terms of the matter contained in the Universe.

- However, most of the energy in the Universe is not in the form of matter: The Universe contains ~ one billion times as many photons as baryons!
- Since the photons presumably came at some point from annihilation of matter with antimatter, the left-over matter indicates actually only a small violation of CP symmetry in the Universe.
- In experiments at BNL in 1964 Fitch and Cronin found that CP was violated in the decay of the K meson by 0.2% of its decays.
- This is very little, but it shows that Nature can do it!
What could produce a large CP violation?

- A very heavy, as yet unknown Boson, the X-Boson, with a mass of $\sim 10^{14}$ GeV.
- **However: If it exists the proton would be unstable.**
- The limit on the proton life time has been measured in large *underground detectors* and is presently $t > 10^{33}$ years.
- So let’s study CP violation once again, but at a higher energy.
- This is being done right now with the so-called *B-factories*
More on Proton Decay

The ultimate end of the universe?

- Proton must live a very long time
  - M. Goldhaber: “We can feel it in our bones.”
    $>10^{16}$ years (1954)
- Standard Model assumes protons are stable!
  - No Justification!
  - But, we haven't seen proton decay
- The Big Water Cherenkov detectors hold the proton decay lifetime records.
  - *Super Kamiokande detector limit $T > 10^{33}$ yrs*
  - Universe is $\sim 10^{12-15}$ years old
  - Neutrino Oscillations which need physics beyond the Standard Model predict finite lifetime of $\sim 10^{33-35}$ years
Why do the leptons not mix when neutrinos do?

• Mixing of neutrino flavors $\nu_e; \nu_\mu; \nu_\tau$ has been observed.

• Why does the lepton sector behave so differently from the quark sector in which all flavors mix? Although the 3 neutrino flavors are mixing, no mixing between the $\tau$ and $\mu$ and $e$ has been observed.

• Could the lepton sector be responsible for the large CP violation?

• New Experiment MECO seeks limit of $10^{-17}$ !

Lepton flavor changing limits over the years
Quark “decay” within the Standard Model

- The weak interaction can change a quark into another kind of quark
- It does so by using the $W^{\pm}$ Boson, for example
  
  $$u \ (+2/3e) \rightarrow d \ (-1/3e) \ + W^{+} \ b \ (-1/3e) \rightarrow u \ (+2/3e) \ + W^{-}$$

  (of course this can happen only if enough energy is available)

- Because of this possibility of decay all heavy quarks have decayed to hadrons that contain only $u, d$ quarks.

<table>
<thead>
<tr>
<th>Heavy quarks:</th>
<th>+2/3e</th>
<th>1.5 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charmed $c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom $b$</td>
<td>-1/3e</td>
<td>5 GeV</td>
</tr>
<tr>
<td>Top $t$</td>
<td>+2/3e</td>
<td>178 GeV</td>
</tr>
</tbody>
</table>
The CKM Matrix: Are we an accident?

• The quarks of the 3 families can change into quarks of the other families.
• The Cabibbo-Kobayashi-Mascawa Matrix represents the array of all possible couplings between quarks.
• Each of these elements is different but the Standard Model can predict them. They are now being checked.
• This SM prediction includes a small CP violation, which can be checked by experiment.

\[
\begin{array}{ccc}
  d & s & b \\
  V(ud) & V(us) & V(ub) \\
  V(cd) & V(cs) & V(cb) \\
  V(td) & V(ts) & V(tb) \\
\end{array}
\]

Possibility of a CP violation rests on the fact that this Matrix has more than 4 elements i.e. that there are more than 2 families of quarks.

If there were only 4 instead of 6 quarks, CP violation would be precluded.
The B-Meson

• B mesons have a mass of 5.28 GeV. Most of that mass comes from the b-quark inside.
• The B0 consists of the quark combination $b\bar{b}d$
• The B0bar consists of $b\bar{d}$
• The B0 meson decays by changing a b-quark into a t, c, or u quark.
• Because this transformation is done by the weak interaction, the lifetime of a B-meson is $\sim 10^{-12}$ s. When produced in motion, they can travel distances of $\sim 500$ μm before decay.
Asymmetric B-factories

• The idea is to produce B and Bbar mesons simultaneously and observe any differences in the b and bbar decay between the two. Any such difference would be due to CP violation

• Special “golden events” with nice experimental features occur only in one of every 100,000 events.

• Thus copious numbers of B and Bbars must be produced: hence the term **B-Factory**

• The B-Factories collide electrons with positrons, but with unequal energies. Thus the B’s are produced in motion.

• Two such facilities were built:
  1. At SLAC at Stanford University
  2. At the KEL Laboratory in Japan

9 GeV electrons

3.1 GeV positrons

Recoiling Bs and B-bars
The Stanford B-Factory

SLAC/LBL/LLNL
SLAC-Based B Factory:
PEP-II and BaBar

Both Rings Housed in Current PEP Tunnel
The KEK B-Factory

- Asymmetric collisions with 8 GeV electrons and 3.5 GeV positrons.
- Ring circumference 3 km.
- Produces more than 300 Million B-meson pairs per year.
- Highest intensity electron storage rings today.
- Total cost $ 8 Billion (?)
What has been found so far?

- B-factory completed in 1998.
- Analysis of 88 Million events yields the following:

  Our measurement of \( \sin^2 \beta \) is consistent with, but improves substantially on the precision of, previous determinations [9]. The central value is consistent with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements [10]; it is also consistent with no CP asymmetry at the 1.7\( \sigma \) level.

  Thus the Standard Model triumphs again. Observed CP violation is too small to explain matter dominance.
The Babar detector at SLAC

• In order to detect the decay of the B0 and B0-bar the detector must digest a huge number of events and fish out one good one among 100,000 bad ones.

• It must track the decay of the two mesons with very good spatial accuracy; \(\sim 50\ \mu\text{m}\). This is done with a silicon vertex detector (SVT)

• The SVT tracks charged particles with high resolution from the initial point of interaction (the “vertex”).

• Note that the detector is not left-right symmetric because the accelerator is asymmetric.
BaBar: CPV with $B^0 \rightarrow K_s \pi^0 [b \rightarrow s d \bar{d}bar]$

Reconstruct $B \rightarrow K_s \pi^0$ vertex using $K_s$ trajectory and *boost* trajectory

*boosted* $\Upsilon(4s)$

In the absence of New Physics, $S = \sin(2\phi_1) = 0.731 \pm 0.056$

Consistent

Seems Fine

**Events / 3 MeV/c^2**

$S_{K_s\pi^0}$

$\Delta z$

$N = 123 \pm 16$

$C = 0.40^{+0.27}_{-0.28} \pm 0.10$

$S = 0.48^{+0.38}_{-0.47} \pm 0.11$

$S (C=0) = 0.41^{+0.41}_{-0.48} \pm 0.11$
The BELLE Results

• The first evidence for direct CP violation in B meson decay was reported by the Belle group in January 2004 in the disintegration of the B meson into two pi mesons. From a sample of 152 million B meson pairs, Belle observed 264 anti-B meson decays but only 219 B meson decays, establishing direct CP violation with more than 99.8% probability.

• Yes, CP Violation has been observed, but it is still small.
Gauge Symmetry

• Physically relevant variables must be independent of the choice of local frames of measurement.
• The answer of a calculation should not depend on whether a length is measured in inches here and in cm there. The description of a result should not depend on the measuring “gauge”.
• Gauge transformations transform a description of a solution at one point in space to another description in another point in space.

• "My work always tried to unite the truth with the beautiful, but when I had to choose one or the other, I usually chose the beautiful."

• Herman Weyl;
the master of symmetries
• Description A of the moving system must transform uniquely into Description B describing the same phenomenon.

• This is a powerful requirement that underlies almost all basic physical theories. For example:
  1. It requires that there should be force carrying Bosons for each gauge invariant interaction, such as the Photon, the W±, the Z0.
  2. These Bosons are also called Gauge Bosons.
Why are Symmetries important in Physics

• Symmetries that exist in Nature impose a general structure on the equations that describe Nature.
• Gauge Invariance alone completely determines e.g. the basic equations for the Electromagnetic Theory (Maxwell’s Equations) and the QCD equation.
• Often symmetries exist in an ideal world but then are broken in the real world.

• The Standard Model has the symmetries
  SU(3) x SU(2) x U(1)

  1. SU(3) is the Symmetric Unitary Group with 3 colors. As we know this requires 8 gluons (the gauge bosons of the strong interaction) to carry color between quarks.

  2. S(2) x U(1) is the symmetry associated with the Electro-weak theory. It contains the gauge Bosons W±, Z0 and γ
Tenth Homework Set, due April 21, 2005

1. Describe briefly how you could tell a neutrino from an anti-neutrino (if you “see” them experimentally).

2. What is the antiparticle to the electron: list how its properties differ or do not differ from those of an electron.

3. What is the antiparticle to the proton? How do its properties differ from those of the proton.

4. Where did Mr. Dirac get his inspiration that negative energy must have a physical meaning

5. What would happen if the Universe would consist of exactly equal amounts of matter and antimatter?

6. Which two facilities are working hard to observe the violation of matter-antimatter symmetry, and what is their result so far?
1. Describe briefly the various distinct stages of the evolution of the Universe as it cooled down after the Big Bang.

2. How does the Relativistic Heavy Ion Collider (RHIC) reproduce the conditions of the Universe when quarks were “deconfined”. For how long a time period can experiment hope to recreate this early universe? (Hint: consider how long it takes for a relativistic quark to fly through the hot nuclear volume formed by the ~400 combined nucleons (200 from each Gold projectile))

3. What experimental evidence shows that experiment has succeeded in recreating these conditions? Explain one piece briefly.)

4. How can we understand Baryon Conservation in terms of the quark model. Use the example of the beta decay of the neutron.

5. Are the human hands mirror symmetric? Do the experiment with a mirror!

6. Describe the symmetries of the rectangle shown in slide 25, in two dimensions (i.e. in the plane of the paper).