Lecture 8

CPT theorem and CP violation
• We have seen that although both charge conjugation and parity are violated in weak interactions, the combination of the two CP turns left-handed antimuon onto right-handed muon, that is exactly observed in nature.
• There is another symmetry in nature – time reversal T (winding the film backward).
• Charge conjugation, C, together with parity inversion, P, and time reversal, T, are connected into the famous CPT theorem.

• CPT theorem is one of the basic principles of quantum field theory. It states that all interactions are invariant under sequential application of C, P and T operations in any order. Any Lorentz invariant local quantum field theory with a Hermitian Hamiltonian must have CPT symmetry.
• It is closely related to the interpretation that antiparticles can be treated mathematically as particles moving backward in time.
Consider a Lorentz boost in a fixed direction $z$. This can be interpreted as a rotation of time axis into the $z$ axis with an imaginary rotation parameter. If this rotation parameter were real, it would be possible for a $180^0$ rotation to reverse the direction of time and of $z$. Reversing the direction of one axis is a reflection of space in any number of dimensions. For a 3 dimensional space, it is equivalent to reflection of all the coordinates, because an additional rotation of $180^0$ in the x-y plane would be included.
Symmetry of time reversal is very difficult to test experimentally. One of its prediction is that some properties of particles and antiparticles should have the same magnitudes, e.g., mass, lifetime, magnetic moment. For most of the cases that has been verified to be true within measurement precision, but not always.

CPT theorem implies that the violation of CP invariance implies violation of time reversal symmetry T.

One of the most important unresolved questions today is the evolution of the universe. If it started with a Big Bang where all interactions had strength of strong forces – then there should be equal amount of matter and antimatter in the universe. CP violation allows for some preference of survival of matter over survival of antimatter, but so far we have not seen sufficient amount of CP violation to account for observations of the Cosmos.
**CP violation**

1955 Gell-Mann and Pais: Second order weak interactions can turn $K^0$ with strangeness $+1$ into its antiparticle $\bar{K}^0$ with strangeness $-1$.

$$ P | K^0 > = - | K^0 > \quad C | K^0 > = | \bar{K}^0 > $$

$$ P | \bar{K}^0 > = - | \bar{K}^0 > \quad C | \bar{K}^0 > = | K^0 > $$

$$ CP | K^0 > = - | \bar{K}^0 > $$

$$ CP | \bar{K}^0 > = - | K^0 > $$

Observed neutral kaons are not single particles but linear combination of the two.

$$ K_1 = \left( \frac{1}{\sqrt{2}} \right) (K^0 - \bar{K}^0) $$

$$ K_2 = \left( \frac{1}{\sqrt{2}} \right) (K^0 + \bar{K}^0) $$

$K_1$ decays into states with $CP=+1$, $K_2$ decays into states with $CP=-1$
Feynman diagrams for $K^0$ oscillations
The neutral kaon

\( K_1 \) decays into two pions \((P = +1, \ C = +1)\)
\( K_2 \) decays into three pions \((P = -1, \ C = +1)\)

\[ K^0 = \left(1/\sqrt{2}\right)(K_1 + K_2) \]

Beam of neutral kaons will start with equal number of \( K_1 \) and \( K_2 \).
\( K_1 \) will oscillate into \( K_2 \) and vice versa.
\( K_1 \) decays faster because the energy released is greater so the composition of the beam is time dependent.

\( K_1 \) is called \( K^0_S \) (short)
\( K_2 \) is called \( K^0_L \) (long)

Similar CP violation has been also observed in neutral charm and bottom mesons \( D^0 \) and \( B^0 \).
The CP is not conserved in weak interactions. There is evidence for the CP violation in strong interactions. The theory of strong interactions in the Standard Model formulation permits such violation due to complex structure of the vacuum. The CP violating interactions in QCD would induce large electric moment for the neutron that is contrary to observation. (Neutron is electrically neutral, but nothing prevents it from having internal spatial distribution of charge generating dipole moment.) One proposed possible solution requires an existence of a new particle called axion that would have to be light and could also be a candidate for dark matter.
**Another neutrino**

A puzzle of the late 1950’s: the absence of $\mu \rightarrow e\gamma$ decays

Experimental limit: $< 1 \text{ in } 10^6 \mu^+ \rightarrow e^+\nu\bar{\nu}$ decays

A possible solution: existence of a new, conserved “muonic” quantum number distinguishing muons from electrons

To allow $\mu^+ \rightarrow e^+\nu\bar{\nu}$ decays, $\bar{\nu}$ must have “muonic” quantum number but not $\nu$ in $\mu^+$ decay the $\bar{\nu}$ is not the antiparticle of $\nu$

$\Rightarrow$ two distinct neutrinos ($\nu_e, \nu_\mu$) in the decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$

Consequence for $\pi$ – meson decays: $\pi^+ \rightarrow \mu^+\nu_\mu$ ; $\pi^- \rightarrow \mu^-\nu_\mu$ to conserve the “muonic” quantum number

High energy proton accelerators: intense sources of $\pi^\pm$ – mesons $\Rightarrow \nu_\mu, \bar{\nu}_\mu$

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**Experimental method**

- **proton beam**
- **target**
- **$\pi$ decay region**
- **Shielding to stop all other particles, including $\mu$ from $\pi$ decay**
- **Neutrino detector**

If $\nu_\mu \rightarrow \nu_e$, then expect $\nu_\mu$ interactions produce $\mu^-$ and not $e^-$ (example: $\nu_\mu + n \rightarrow \mu^- + p$)
1962: $\nu_\mu$ discovery at the Brookhaven AGS
(a 30 GeV proton synchrotron running at 17 GeV for the neutrino experiment)

Neutrino energy spectrum
known from $\pi, K$ production
and $\pi \rightarrow \mu, K \rightarrow \mu$ decay kinematics

Spark chamber
each with 9 Al plates
(112 x 112 x 2.5 cm)
mass 1 Ton

Muon – electron separation
Muon: long track
Electron: short, multi-spark event
from electromagnetic shower

13.5 m iron shielding
(enough to stop 17 GeV muons)
64 “events” from a 300 hour run:
- 34 single track events, consistent with $\mu$ track
- 2 events consistent with electron shower
  (from small, calculable $\nu_e$ contamination in beam)

Clear demonstration that $\nu_\mu \neq \nu_e$

Three typical single-track events in the BNL neutrino experiment