• Main points of today’s lecture:
  – Charmonium etc.
  – fragmentation
  – weak interactions

• Main points of last lecture:
  – $e^+e^-$ scattering, baryon production and color
  – Color
    • quark color
    • gluon color
    • color wavefunctions
    • hadron color
In Charmonium

- We consider the $c\bar{c}$ bound state:

$$1 + m = m_{\Psi} c^2 - 2m_c^2 + E$$

$$E \Psi_{c\bar{c}} = \left( \frac{\rho^2}{2\mu} + V_{\text{cont}} + V_{\text{HF}} \right) \Psi_{c\bar{c}}$$

Where:

$$V_{\text{cont}} = -\frac{4}{3} \alpha_s \frac{\hbar c}{r} + F_0 r$$

$$\Delta V_{\text{me}} = \frac{2e^2}{m_c c^2} \left\{ \frac{1}{\sqrt{3}} \left[ 3 (\hat{s}_p \cdot \hat{r}) (\hat{s}_q \cdot \hat{r}) - \hat{s}_p \cdot \hat{s}_q \right] + \frac{8}{3} (\hat{s}_p \cdot \hat{s}_q) \hat{s}_r \right\}$$

Except for $F_0$, this is analogous to positronium.
The resulting spectrum

- Solving the Schrodinger equation:
  - Below \( \bar{D}D \) threshold can have purely EM decays
  - Structure helps to understand how quarks \( \rightarrow \) hadrons
  - \( 3S_1 \) is higher than \( 1S_0 \) = strong \( \lambda \) hyper fine int.
Comparison to Positronium

- The systems are qualitatively similar.
Light quark pairs?

- light mesons as \( \bar{q}q \) states
  - Relativistic equation is harder to solve
  - Gluon energies are significant part of the mass

- Charmonium success depends on
  - High quark masses \( \rightarrow \) non-rel. desc.
  - Major part of wavefunction is at small \( r \)
    \[ V \sim -\frac{4}{3} \alpha_s \frac{\hbar}{r} \]
  - \( ds \sim \frac{1}{r} \) smaller at small \( r \) \& asymptotic freedom where confinement can be neglected.
Fragmentation?

• What happens when energetic $q\bar{q}$ pairs are created?

$U - F_0 r$

$F_0 \sim 10^{-16} \text{ Tons}$

$U \text{ which linearly increases } \propto r$

at large distances
Example

- consider the creation of an energetic $c\bar{c}$ pair.
Weak interactions

• Examples of weak interactions:

- β decay

  \[(Z, A) \rightarrow (Z + 1, A) + e^- + \bar{\nu}_e\]
  \[(Z, A) \rightarrow (Z - 1, A) + \bar{e}^+ + \nu_e\]
  \[e^- + (Z, A) \rightarrow (Z - 1, A) + \nu_e\]

- Hadron decays

  \[u\bar{d} \rightarrow k^+ \rightarrow \pi^+ + \pi^0\]
  \[s = 1 \quad \text{Strangeness Violation}\]
  \[s = 0 \quad \text{Strangeness Violation}\]

- Lepton decays

  \[\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu\]
Structure of weak decays

- Let’s consider microscopic behavior:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

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

- **Weak decay dominates (for hadrons)**
  - when there is a *flavor change*

- **Weak decay dominates (for leptons)**
  - lepton number *(flavor) change*

  - electron lepton #
  - muon lepton #
  - Tau lepton #
Looking ahead

0 lepton generations in S.M.

\[ m_e c^2 = 0.511 \text{ MeV} \quad m_\mu c^2 = 106 \text{ MeV} \quad m_\tau c^2 = 1.8 \text{ GeV} \]

\[ e^- e^+ \quad \mu^- \mu^+ \quad \tau^- \tau^+ \]

\[ \nu_e \quad \bar{\nu}_e \quad \nu_\mu \quad \bar{\nu}_\mu \quad \nu_\tau \quad \bar{\nu}_\tau \]

\[ l_e^+ = 1 \quad l_e^- = -1 \quad l_\mu^+ = 1 \quad l_\mu^- = -1 \quad l_\tau^+ = 1 \quad l_\tau^- = -1 \]

Vertices conserve lepton number in S.M.

in S.M. \( m_\nu = 0 \)

if \( m_e < m_\tau \) from oscillation

\[ m_\tau c^2 \sim 0.062 \text{ eV} \]
Beta decay, double beta decay.

- two neutrino double beta decay

\[ n \rightarrow p + e^- + \bar{\nu}_e \quad \text{left handed antineutrinos are "left handed"} \]
\[ p \rightarrow n + e^+ + \nu_e \quad \text{left handed neutrinos are "left handed"} \]

Right handed Dirac neutrinos are not observed \( \nu_e \neq \bar{\nu}_e \)

Left handed antineutrinos are not observed.

In Standard model
Physics 492 Lecture 35

• Main points of last lecture:
  – Charmonium etc.
  – fragmentation
  – weak interactions
  – leptons

• Main points of today’s lecture:
  – Weak interactions and;
    • double beta decay
    • lepton number conservation in vertices
    • W, Z bosons
    • quarks
Beta decay, double beta decay.

- two neutrino double beta decay

$\nu \rightarrow \nu \rightarrow \nu^- + e^- + \bar{\nu}_e$

$\nu \rightarrow \nu \rightarrow e^- + \nu_e$

In Standard model

- antineutrino's are right handed
- neutrinos are "left handed"

Right handed Dirac neutrinos are not observed $\nu_e \neq \bar{\nu}_e$

Left handed antineutrinos are not observed.
Beta decay, double beta decay.

- $^{82}\text{Se} \rightarrow ^{82}\text{Br} + e^- + \bar{\nu}_e$
- $^{82}\text{Br} \rightarrow ^{82}\text{Kr} + e^- + \bar{\nu}_e$

This can only occur if little time elapses between the 2 decays:

$^{82}\text{Se} \rightarrow ^{81}\text{Kr} + 2e^- + 2\bar{\nu}_e$

$^{36}\text{S} \rightarrow 36$

2 neutrino $2\beta$ Beta decay.
0 Neutrino Double beta decay

For a Majorana neutrino, the difference between neutrino and antineutrino is mainly the orientation of the spin relative to the momentum

\[ \nu_e = \bar{\nu}_e = \bar{\nu} \]

neglecting orientation of s and p.

we had:

\[ ^{82}\text{Sc} \rightarrow ^{82}\text{Br} + e^- + \bar{\nu}_e \]

\[ ^{82}\text{Br} \rightarrow ^{82}\text{Kr} + e^- + \nu_e \]

\[ \nu_e + ^{82}\text{Br} \rightarrow ^{82}\text{Kr} + e^- \]

\[ ^{82}\text{Sc} \rightarrow ^{82}\text{Br} + e^- + \bar{\nu}_e \]

\[ ^{82}\text{Br} \rightarrow ^{82}\text{Kr} + e^- \]

\[ ^{82}\text{Sc} \rightarrow ^{82}\text{Kr} + 2e^- + 3.05 \text{ MeV} \]

but no neutrinos

Nucl \[\Rightarrow\] Nuclear Process \[\Rightarrow\] Nucl'
Double beta decay

- Present situation

  2ν double decay has been seen for:
  48Ca, 76Ge, 82Se, 96Zr, 100Mo, 136Cd, 128Te, 130Te, 131Te, Nd, U

  - Neutrinoless double beta decay reported by Klapdor but not confirmed

  - Issue is complicated

    decay produces right handed $\bar{\nu}_e$
    capture requires left handed $\nu_e$

    can change orientation of p relative to $s$ by a large Lorentz boost opposite to the direction of p

  - Majorana $\nu \rightarrow$ double beta w/ 0 neutrinos

    $V$ must be
    Lepton is not conserved
    Majorana neutrino
    $V = \bar{V}$
Lepton number conservation?

- What does experiment say about lepton number conservation?
  - are the muon and electron neutrinos different?

  \[ \nu_e = \nu_m \quad \text{or} \quad \nu_e = \nu_\tau \]

  - if so, lepton number is not conserved

  \[ \pi^+ \to e^+ + \nu_m + \bar{\nu}_e \quad \Rightarrow \quad \pi^+ \to e^+ + \gamma \quad \text{looked for but not observed} \]

  - Positive demonstration

  \[ \nu_m + n \to p + \mu^- \quad \text{observed} \]

  don't see \[ \nu_m + n \to p + e^- \quad \text{not observed} \]
Other examples of Lepton number conservation.

\[ \tau^+ \rightarrow \pi^+ + \bar{\nu}_\tau \]

\[ \Lambda \rightarrow p + e^- + \bar{\nu}_e \]

Conserves \( L_e \) at vertex.
W bosons

- W mass

  \[ m_{Wc^2} = 80 \text{ GeV} \]

- Vertex rules involving W’s

  1. Charge is conserved
  2. Lepton \( \pm \) is conserved
  3. Quark \( \pm \) is conserved
  4. Quark flavor is not conserved
  5. Quark color is conserved
Things that do not occur at vertices

- Focus on behavior at short times.

- Lepton generation does not change

- Forget about neutrino oscillations for the none-
Quarks and quark flavors

- The rules governing quark flavor conservation are more complex:

\[
\begin{align*}
Q &= \pm \frac{2}{3} \\
Q &= -\frac{1}{3}
\end{align*}
\]