**From Last Time...**

- Discussed quarks and their interactions
- Six generation, paired in three generations
- Quarks have electric charge, participate in EM interaction by exchanging photons.
- Quarks also have color charge, participate in color interaction by exchanging gluons.
- Color charge as six varieties
  - Red, green, blue, anti-red, anti-green, anti-blue

**Today**

- The difference between the electromagnetic and the strong force.
- The weak interaction and the W, Z bosons
- Neutrinos
- Quark decay

**Interactions through Exchange of Color Charge**

<table>
<thead>
<tr>
<th>Initial</th>
<th>After gluon emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>RED (quark)</td>
<td>RED-ANTIBLUE (gluon) + BLUE (quark)</td>
</tr>
</tbody>
</table>

**Re-absorption of Gluon**

<table>
<thead>
<tr>
<th>Before gluon absorption</th>
<th>After gluon absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>RED-ANTIBLUE + BLUE (gluon)</td>
<td>RED (quark)</td>
</tr>
</tbody>
</table>

**Gluon interactions**

- Since gluons carry “color charge”, they can interact with each other! (Photons can’t do that)

| Gluon-gluon Scattering | Gluon-gluon Fusion |

**Feynman Diagrams (Quark Scattering)**

- Quark-quark Scattering
- Could also be Quark-antiquark Scattering or Antiquark-antiquark Scattering
- Quark-antiquark Annihilation

**Gluons - Important Points**

- Gluons are the “force carrier” of the strong force.
- They only interact with objects which have color, or color charge.
- Therefore, gluons cannot interact with leptons because leptons do not have color charge!

This cannot happen, because the gluon does not interact with objects unless they have color charge! Leptons do not have color charge!
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Gluons in the hadrons.

- The gluons are all over inside hadrons!!
- In fact there are a lot more than shown here !!!
- That’s where the extra mass comes from. u and d quarks are 0.003 and 0.006 GeV and the proton 1 GeV.

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Confinement

Since the strong force increases as quarks move apart, they can only get so far…
The quarks are confined together inside hadrons.
Hadron jail!

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Confinement

The quarks of a proton are close to one another.
If you try to pull one of the quarks out, the energy required to produce a separation force is enormous.

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The Weak Force

EM

STRICT

WEAK

Carriers of the weak force

- Like the Electromagnetic & Strong forces, the Weak force is also mediated by “force carriers”.
- For the weak force, there are three force carriers:

\[ W^+ \quad W^- \quad Z^0 \]

These “weak force” carriers carry electric charge also !
This “weak force” carrier is electrically neutral

The “charge” of the weak interaction is called “weak charge”

Phy107 Lecture 36

Massive particles

- The \( W^+ \), \( W^- \), and \( Z^0 \) are very massive

\[ W^+ \quad W^- \quad Z^0 \]

\[ 80.4 \text{ MeV}/c^2 \quad 91.2 \text{ MeV}/c^2 \]

Top quark is heaviest known fundamental particle. W, Z have ~ half the mass of the top quark
What interacts?
- Any particle with a ‘weak charge’ will interact via the weak interaction.
- All quarks and leptons carry a weak charge.
- The weak interaction occurs by exchanging a $W^+$, $W^-$, or $Z^0$.
- But all quarks have electric charge, and half the leptons do.
- In this case, weak interaction overwhelmed by electromagnetic interaction.

Exchanging the $Z^0$
- Both of these contribute to the total interaction between electrons.
- $Z^0$ is uncharged particle like the photon, but has mass.
- But the electromagnetic interaction is much larger.

Range of the interaction
- Electron doesn’t have enough energy to create $Z^0$.
- $Z^0$ only present due to uncertainty relation:
  \[(\text{Energy uncertainty}) \times (\text{Time uncertainty}) \sim \text{Planck const}\]
- It can only exist for a time determined by:
  \[
  \text{Time uncertainty} = \frac{\text{Planck const}}{\text{Particle mass}}
  \]
- Farthest it can travel in that time is:
  \[
  \text{Range} \sim (\text{Light Speed}) \times \frac{\text{Planck const}}{\text{Particle Mass}} \times 10^{-18} \text{ m}
  \]

Mass and Interaction Range
- Interaction range determined by particle mass.
- Heavier exchange particles have shorter range.
- Photon has zero mass, infinite range.
- Weak exchange bosons are massive, have very short range.
- So mass seems very important.
- But present theory do not explain why different particles have different masses.

Neutrinos
- Neutrino has no electric charge.
- Interacts only via the weak force.
- How weak is weak?
  - Neutrino traveling in solid lead would interact only once every 22 light-years!
  - And weak force only “kicks in” for $d < 10^{-18}$ m, a distance – 1000 times smaller than the nucleus.
- But there are lots of neutrinos, so it is possible to observe an interaction.

Detecting neutrinos
- Neutrinos interact with all matter, since all matter particles have a weak charge.
- But the interaction is extremely weak.
- Need large volumes, sensitive detectors, to see neutrinos.
- Examples of neutrino detectors:
  - Super Kamiokande (Japan)
  - Ice Cube (UW-Madison at Antarctica)
Scattering from quarks in a nucleus

- What Ice Cube looks for is neutrinos emerging from collisions as muons.
- The neutrino interacts with quarks bound inside nucleons in the nucleus.
- Neutrino emits $W^+$, changing flavor into muon.
- Down quark bound in a neutron absorbs $W^+$, changing into a up quark.
- The nucleon then has two ups and one down quark, which is a proton.

Similar to nuclear beta decay

- Interaction via the W explains nuclear beta decay.
- A quark emits a W, changing flavor into a u quark.
- W decays to an electron and anti-electron neutrino.
- The nucleon then has two ups and one down quark, which is a proton.
- Similar to the rotated Feynman diagram we studied with the electromagnetic force.

Neutron Decay

A neutron outside the confines of the nucleus is not stable. It decays with a lifetime of about 14 minutes.

Changing flavors

- When a lepton emits a $W^+$ or $W^-$ it changes flavor.
- Experimentally this occurs within a lepton generation.

<table>
<thead>
<tr>
<th>Generation I</th>
<th>Generation II</th>
<th>Generation III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^-$</td>
<td>$\tau^-$</td>
<td></td>
</tr>
<tr>
<td>$\tau^-$</td>
<td>$\tau^-$</td>
<td></td>
</tr>
<tr>
<td>$\tau^-$</td>
<td>$\tau^-$</td>
<td></td>
</tr>
</tbody>
</table>

$\mu^- \rightarrow W^- + \nu_\mu 
(2 \times 10^{-6} \text{ sec})$

$\tau^- \rightarrow W^- + \nu_\tau
(3 \times 10^{-12} \text{ sec})$
Lepton pairs

- Think of lepton pairs as a single particle with two states.
- Emitting or absorbing W toggles it between the states.
- Can say that the W carries away ‘weak charge’ (also called ‘flavor charge’) in addition to electric charge (actually isospin)
- E.g. when a muon emits a W⁻, this ‘flips’ the lepton pair into a ‘different orientation’, which we see as a neutrino.

Lepton decay

- Flavor change can occur spontaneously if the particle is heavy enough.

Quarks and the weak force

- Quarks have color charge, electric charge, and weak charge — other interactions swamp the weak interaction
- But similar to leptons, quarks can change their flavor (decay) via the weak force, by emitting a W particle.

Flavor change between generations

- But for quarks, not limited to within a generation!

‘Combining’ the quarks

- In this sense, different quarks can be considered as different ‘manifestations’ of the same particle.
- Just as we wouldn’t call spin-up and spin-down electrons different particles, the different flavor quarks don’t have to be considered as different particles.
- Three generations, six quarks, can be considered different ‘facets’ of same field.
- Why six? We would like to know.

Less is more!

- At this point, this flipping is only considered in a particular lepton pair. Other generations separate.
- But strong evidence for ‘decays’ between neutrinos in different generations
  - (Neutrino oscillations)
- In a unified theory, all leptons may just be different states of a single particle!
- This is appealing since the only difference between generations is mass.
Are there free quarks?

- Quarks are bound into hadrons
  - baryons (3 bound quarks), mesons (2 bound quarks).
- But the internal quarks can still emit W particles and change into something else.
- Most of the time, hadrons containing heavy quarks (c, s, b) decay by "emitting" a W and transforming into the next lightest quark

Decay of heavy quarks

- Top quark decays so fast \((10^{-23}\text{ s})\), it doesn't have time to form a meson.
  \[ t \rightarrow b + t^* + n_t \]
- \(B^-\) particle decays within \(1.5x10^{-12}\text{ s}\).
  \[ B^- \rightarrow D^0 + \mu^- + \nu_{\mu} \]
- The \(D^0\) meson decays within \(0.5x10^{-12}\text{ s}\).
  \[ D^0 \rightarrow K^- + e^- + \nu_e \]

Can create anything!

- Showed W decaying into leptons.
- But W can create any particles that
  - Have a weak charge (couple to the weak force)
  - Conserve charge
  - Conserve energy (mass)
- W commonly decays into two quarks:
  \[ W^+ \rightarrow u \text{ or } d, \quad W^- \rightarrow \bar{u} \text{ or } \bar{d} \]

What happens to the quarks?

- Since quarks cannot be free, they must form a bound state.
- In simplest case, the two quarks from W decay bind to form a meson
  - For instance:
  \[ W^+ \rightarrow u \text{ or } d, \quad W^- \rightarrow \bar{u} \text{ or } \bar{d} \]

Top quark discovery 1995

- Proton-antiproton collision at Fermilab
- Only final decay products are observed.
- Infer existence of other particles by thinking about decays.
Basic ideas

- As far as the weak interaction goes, leptons and quarks are basically identical.
- All carry a weak charge.
- \( W \) particles can decay into anything consistent with charge and energy conservation.
- In this sense it is an important interaction, even though the consequences are not always dramatic compared with EM or strong interaction.

Particles & their Interactions (Summary)

<table>
<thead>
<tr>
<th></th>
<th>Quarks</th>
<th>Charged leptons (e, μ, τ)</th>
<th>Neutral leptons (ν)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>EM</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>‘Weak’</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

- Quarks can participate in Strong, EM & Weak Interactions.
- All quarks & all leptons carry weak charge.
- Neutrinos only carry weak charge.

Comparison of the Force Carriers

<table>
<thead>
<tr>
<th>Force Carrier</th>
<th>EM</th>
<th>Strong</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Carrier</td>
<td>Photon (γ)</td>
<td>Gluon (g)</td>
<td>( W^+, W^- )</td>
</tr>
<tr>
<td>Charge of force carrier</td>
<td>None</td>
<td>Color</td>
<td>Electric &amp; Weak</td>
</tr>
<tr>
<td>Coupled to</td>
<td>Particles w/ electric charge</td>
<td>Particles w/color charge (Quarks, gluons)</td>
<td>Particles w/weak charge (Quarks, leptons) ( W, Z )</td>
</tr>
<tr>
<td>Range</td>
<td>Infinite ( (1/d) )</td>
<td>(&lt; 10^{-18} ) m ( \text{(inside hadrons)} )</td>
<td>(&lt; 2 \times 10^{-18} ) m</td>
</tr>
</tbody>
</table>

Unification

- It may be possible that all quarks and leptons can be viewed as different components of the same particle.
- Also may be possible to unify the forces (exchange bosons).
- Electromagnetic and Weak force have already been unified (next time).
- People working hard to include the strong force and gravitational force in this.