From Last Time...

• Discussed quarks and their interactions
• Six quarks, 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 comes in six varieties
  - Red, green, blue, anti-red, anti-green, anti-blue

Quark interactions

• Quarks interact by exchanging gluons
• Opposite colors quarks attract most strongly
  - Red and anti-red attract strongly to form a meson
  - Red and green, red and blue, etc attract, but less strongly
• Like colors repel
  - Red and red repel
  - Blue and blue repel, etc.
• But gluons also have a color charge
  - They can interact via the strong interaction

Consequences of gluon color charge

• Gluon has a color charge - couples to the gluon field, excites more gluons - stronger force
• As quarks get farther apart, gluons have more ‘room’ to interact.
• Force gets stronger as quarks get further apart!
• Eventually have enough energy to make more quarks.

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!

Question

Quarks have color charge, and interact via the strong force. In analogy with electric charges, which of these interactions might be repulsive?

A. Red-Green
B. Red-AntiRed
C. Red-Red
D. Red-Blue

Pulling apart quarks

Electron-positron collide and produce charm-anticharm quark pair with lots of kinetic energy.

Quark pair flies apart, interaction energy increases until enough is available to excite a quark-antiquark pair.
Mesons (bound quark pair) result.
The Standard Model

- 6 leptons
- 6 quarks
- 4 interactions
  - Electromagnetic, Gravitational, Strong, Weak
  - ‘mediated’ by 13 exchange bosons, which are excitations of the corresponding fields.

Leptons

- The cats have an electrical charge of -e
- The fleas (neutrinos) have zero charge (neutral).

Lepton generations

Each electron-like particle and neutrino paired in a generation.

<table>
<thead>
<tr>
<th>Generation I</th>
<th>Generation II</th>
<th>Generation III</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^- )</td>
<td>( \mu^- )</td>
<td>( \tau^- )</td>
</tr>
<tr>
<td>( \nu_e )</td>
<td>( \nu_\mu )</td>
<td>( \nu_\tau )</td>
</tr>
</tbody>
</table>

Question

The difference between the different generations of leptons is

A. their charge
B. their mass
C. their color
D. their spin

EM interaction

- Charged particles interact via the electromagnetic (EM) interaction
  - A charged particle couples to the photon field
  - It excites a photon (excited state of photon field) and loses energy.
  - Another charged particle can absorb the energy from the photon field (photon disappears).

Only particles with an electric charge couple to the photon field.

Quarks

Six different kinds of quarks, analogous to the six leptons

- All quarks have an electric charge, they couple to photon field.
- But they also have a ‘color’ charge, and they couple to the gluon field.

Coupling of quarks to the gluon field is the ‘strong’ interaction.
Quark generations

- Six different quarks, but two per generation
  - Just like the leptons

<table>
<thead>
<tr>
<th>Generation I</th>
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<th>Generation III</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>c</td>
<td>t</td>
<td>+2/3</td>
</tr>
<tr>
<td>d</td>
<td>s</td>
<td>b</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Four interactions

- The four fundamental interactions all have associated fields and mediating particles.
- Talked about
  - EM interaction between electrically charged particles by exchange of photons
  - Strong interaction between ‘color’ charged particles by gluon exchange

The weak interaction

- Weak interaction is ‘not strong’, but is important. It can change one particle into another!
- Muon, tau, can turn into neutrinos!
- Quarks can turn into other quarks
- Particles with a ‘weak charge’ (quarks and leptons) couple to the ‘weak field’
- Excitations of the weak field are the Z and W bosons.

Importance of weak interaction

- Weak interaction is much weaker than strong and electromagnetic interactions
- But it’s existence is of great importance, as well as its strength.
- Fusion in the sun:
  - First part is hydrogen → into heavy hydrogen (deuterium),
  - Caused by by the weak force. Without this force solar energy production would not be possible.
  - If weak force been stronger, sun’s life span too short for life to have had time to evolve on any planet!
- Practical applications:
  - Radioactive elements used in medicine and technology (Usually beta-radioactive), and in the beta-decay of carbon-14 (carbon-dating)

Question

Quarks interact only via the

A. weak force
B. strong force
C. gravitational force
D. all of the above

The Weak Force
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:
  - $W^+$
  - $W^-$
  - $Z^0$

These “weak force” carriers carry electric charge also!

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

Massive particles
- The $W^+$, $W^-$, and $Z^0$ are very massive
  - $W^+$
  - $W^-$
  - $Z^0$

These “weak force” carriers carry electric charge also!

$W^+$: 80.4 GeV/c²
$W^-$: 91.2 GeV/c²
$Z^0$:

$W$ and $Z$ have almost half the mass of the top quark, the heaviest fundamental particle

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.

The Neutrino

Why can the neutrino pass through light years of material without interacting with anything.

A. It has no mass
B. It is very small
C. It interacts only via the weak force
D. It interacts only via the EM force

Neutrinos
- Neutrino has no electric charge
- Interacts only via the weak force.
- How weak is it?
  - 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)
Ice Cube

Exchanging the W

- In the movie, talked about interaction where neutrino emerges from the collision as a muon.

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

- \( W^+ \) (pos. electric charge) emitted by neutrino
- Neutrino turns into muon
- We say that the neutrino has "changed flavor"