From Last Time...

- Particles are quanta of a quantum field
- Antiparticles
- Matter is made of leptons and quarks
- Three ‘generations’ of leptons/quarks
- Essay due today

Today

- Generations of leptons and quarks
- Forces
- Composite particles: Hadrons, Baryons, and mesons (made of quarks)
- More on the strong interaction

The ‘generations’

Leptons and quarks: what’s the difference?

- One important difference is how they interact.
- We said the Coulomb interaction is between particles with electrical charge.
- Understood by exchanging photons.
- The other interactions:
  - Weak
  - Strong
  - Gravitational

Electromagnetic Force

In the Standard Model particles are often classified by what forces they interact via.
Which particle doesn’t interact with the electromagnetic force:

A. electron
B. muon
C. photon
D. quark

Uncertainty principle

- The uncertainty principle is important for understanding interaction in quantum field theory.
- We talked about an uncertainty principle, that momentum and position cannot be simultaneously determined.
- There is an equivalent relation in the time and energy domain.
  - Einstein’s relation that space and time or momentum and mass/energy are similar.
Energy uncertainty
• To make a very short pulse in time, need to combine a range of frequencies.
• Frequency related to quantum energy by $E=hf$.
• Heisenberg uncertainty relation can also be stated

\[(\text{Energy uncertainty}) \times (\text{time uncertainty}) \approx (\text{Planck's constant})\]

In other words, if a particle of energy $E$ only exists for a time less than $h/E$, it doesn’t require any energy to create it!

Interactions between particles
• The modern view of forces is in terms of particle exchange.
• These are ‘virtual’ particles of the fields created by the particle charges.

This shows Coulomb repulsion between two electrons. It is described as the exchange of a photon.

Four Gauge forces

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Mediating particle(s)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-</td>
<td>photon</td>
<td>(1)</td>
</tr>
<tr>
<td>magnetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weak</td>
<td>$W^+, W^-$ and $Z^0$</td>
<td>(3)</td>
</tr>
<tr>
<td>Strong</td>
<td>gluons</td>
<td>(8)</td>
</tr>
<tr>
<td>Gravity</td>
<td>graviton</td>
<td>(1)</td>
</tr>
</tbody>
</table>

These all have integer spins, hence are bosons

Exchange bosons
• Each interaction has one or more associated particles that mediate the interaction.
• The exchange particles are associated with the known interactions

Bosons

Interaction via particle exchange

• Exchange boson

Classical collision
Charge

- These are the exchange bosons.
- What are they exchanged between?
- Or on what are the corresponding forces exerted?
- Example:
  - When a photon is exchanged between two particles, there is an electromagnetic or Coulomb force.
  - We know that only particles with electrical charge interact via the Coulomb force.
  - Zero charge -> zero Coulomb interaction

Many Charges

- In this language, we say that the electrical charge is a ‘source’ of an EM field.
- A mass ‘charge’ is the source of a gravitational field.
- A weak ‘charge’ (sometimes called ‘flavor’) is the source of a weak interaction field.
- A strong ‘charge’ (sometimes called ‘color’) is the source of a strong interaction field.

A little complicated

- Quarks and leptons have multiple charges.
- Some of the bosons have charges.

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Quarks: Heavy, Heavier, Heaviest

- 6 different kinds of quarks.
- Matter is composed mainly of up quarks and down quarks bound in the nuclei of atoms.
- Masses vary dramatically (from ~0.005 to 175 [GeV/c^2]).
- Heavier quarks are unstable, rapidly decay to lighter quarks.

Protons/Neutrons are composite

- The forces which hold the protons and neutrons together in the nucleus are VERY strong.
- They interact via the STRONG FORCE.
- Protons and neutrons are among a class of particles called “hadrons” (Greek for strong).
- Particles made of quarks.
- Baryons are hadrons which contain 3 quarks (no anti-quarks).
- Anti-baryons are hadrons which contain 3 anti-quarks (no quarks).
**Protons & Neutrons**

To make a proton:
- We bind 2 up quarks of Q = +2/3 and 1 down quark of Q = -1/3.
- The total charge is $\frac{2}{3} \times 2 + \frac{-1}{3} = +1$.

To make a neutron:
- We bind 2 down quarks of Q = -1/3 with 1 up quark of Q = +2/3 to get:
  $$\frac{-1}{3} \times 2 + \frac{2}{3} = 0$$

Most of the mass is in the binding energy.

**Make some baryons!**

<table>
<thead>
<tr>
<th>Quark</th>
<th>up</th>
<th>down</th>
<th>strange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Q</td>
<td>+2/3</td>
<td>-1/3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q = +1</td>
<td>M = 938 MeV/c^2</td>
</tr>
<tr>
<td>Q = 0</td>
<td>M = 940 MeV/c^2</td>
</tr>
</tbody>
</table>

**Are there baryons other than protons and neutrons?**

Other quarks can combine to form other baryons. For example:
- This combination is called a Lambda baryon, or $\Lambda^0$ for short.
- Charge 0:
  $$\frac{2}{3} \times 1 - \frac{1}{3} \times 1 - \frac{1}{3} \times 1 = 0$$

**More Baryons**

<table>
<thead>
<tr>
<th>Quark</th>
<th>up</th>
<th>down</th>
<th>strange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>+2/3</td>
<td>-1/3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

- Lambda ($\Lambda$):
  - Q = 0
  - M = 1116 MeV/c^2

- Sigma ($\Sigma^+$):
  - Q = +1
  - M = 1189 MeV/c^2

- Sigma ($\Sigma^0$):
  - Q = 0
  - M = 1192 MeV/c^2

- Sigma ($\Sigma^-$):
  - Q = -1
  - M = 1197 MeV/c^2

**Excited state - Higher energy/mass**

**Another baryon:**
- What’s this baryon’s electric charge?
  - Delta baryon, or $\Delta^+$ for short.
  - Charge: +2
  $$\frac{2}{3} \times 1 + \frac{2}{3} + \frac{2}{3} = +2$$

A. 0
B. +1
C. +2

**Mesons**

- They are formed when a quark and an anti-quark “bind” together.
- So far we’ve only seen 3 quark combinations. There are also 2 quark combinations.
- The hadrons: 2 quarks, meson and 3 quarks, baryon.

- What’s the charge of this particle?
  - Q = +1, and it’s called a $\pi^+$

- What’s the charge of this particle?
  - Q = -1, and this charm meson is called a $D^-$

- What’s the charge of this particle?
  - Q = 0, this strange meson is called a $K^0$
**Making a Meson**

- Mesons can be made in high energy collisions just like many other particles.
- Before when we were looking for quark and anti-quark pairs we found the muon.
- Needed more energy!

2 muons - mass: 200MeV/c²
phi, φ - mass: 1000MeV/c²

**The Many Charges of the Quarks**

- Quarks interact via all the forces - have all the charges
- Electron charge - electromagnetic force.
  Can make quarks in e+e- collisions.
- Mass ‘charge’ - gravitations force.
  Earth is mainly protons and neutrons - feels gravity.
- Weak or ‘charge’ (flavor) - weak force.
  Atoms decay via the weak force.
- Strong 'charge' (color) - strong force.
  Binds the quarks into hadrons.

**‘Electric Charge’**

<table>
<thead>
<tr>
<th>Quark</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>+2/3 e</td>
</tr>
<tr>
<td>e</td>
<td>-1</td>
</tr>
</tbody>
</table>

What does it really mean for a particle to have electric charge?
It means the particle has an attribute which allows it to talk to (or couple to) the photon, the mediator of the electromagnetic interaction.

The ‘strength’ of the interaction depends on the amount of charge.

Which of these might you expect experiences a larger electrical repulsion?

**Quarks & Gluons**

1. There are three color charges
2. Gluons are the carrier of the strong force
3. They keeps quarks bound up inside hadrons
4. Gluons themselves carry color, they can interact with each other.
5. This previous property (#4) is fully responsible for the humungous difference between the nature of the EM force & the Strong force:
   - EM Force: gets weaker as (electrical) charges move apart
   - Strong Force: gets stronger as (color) charges move apart

**Why Three Colors?**

Remember the Delta baryon, or Δ++

The quarks are fermions: Fermions are identical and are not allowed to be in the same state. The wave function would disappear.

The electrons in an atom could be in the same energy state if they had different spins.

The same same is true of three quarks if something is different about them. Color!

**Comparison Strong and EM force**

<table>
<thead>
<tr>
<th>Property</th>
<th>EM</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Carrier</td>
<td>Photon (γ)</td>
<td>Gluon (g)</td>
</tr>
<tr>
<td>Mass</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Charge ?</td>
<td>None</td>
<td>Yes, color charge</td>
</tr>
<tr>
<td>Charge types</td>
<td>+, -</td>
<td>red, green, blue</td>
</tr>
<tr>
<td>Mediates interaction between:</td>
<td>All objects with electrical charge</td>
<td>All objects with color charge</td>
</tr>
<tr>
<td>Range</td>
<td>Infinite (≪ 1/d²)</td>
<td>10^{-17}[m] (inside hadrons)</td>
</tr>
</tbody>
</table>
**Color of Hadrons**

**BARYONS**

RED + BLUE + GREEN = "WHITE" or "COLORLESS"

**MESONS**

GREEN + ANTIGREEN = "COLORLESS"
RED + ANTIRED = "COLORLESS"
BLUE + ANTIBLUE = "COLORLESS"

Hadrons observed in nature are colorless (but their constituents are not)

**Quark interactions: gluons**

- Gluon carries color charge.
- So when a quark emits a gluon, it changes color.
- But this also means that gluons can interact via the color force.

Each of the 8 color combinations have a "color" and an "anti-color"

**Interactions through Exchange of Color Charge**

Initially

RED → RED-ANTIGREEN + GREEN
(quark) (gluon) (quark)

After gluon emission

Re-absorption of Gluon

Before gluon absorption

RED-ANTIGREEN + GREEN
(gluon) (quark) (quark)

After gluon absorption

RED
(quark) (quark)

**Gluon interactions**

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

**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 object 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!
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 and the proton 1 GeV

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!

Summary

- **Up & down** quarks make up protons & neutrons
- Quarks have an intrinsic property known as **color**, of which there are 3 varieties: red, green or blue.
- Quarks also have a property known as **Spin**, and have Spin = 1/2.
- **Hadrons** refer to strongly interacting particles: **Baryons & Mesons**
- Baryons contain 3 quarks: 1 red + 1 green + 1 blue → colorless. They may have spin 1/2 or spin 3/2.
- Mesons contain 1 quark & 1 antiquark: \( \pi^+, \rho, \), or \( b \) → colorless. They may be spin 0, or spin 1