From Last Time...

- Particles are quanta of a quantum field
- The vacuum is not ‘empty’
  - Uncertainty principle says particles can spontaneously appear for short times
- Antiparticles
- Matter is made of leptons and quarks
- Three ‘generations’ of leptons/quarks
- Forces are due to exchange of bosons

Today

- Generations of leptons and quarks
- Composite particles:
  - Hadrons, Baryons, and mesons (made of quarks)
- Electrons and neutrinos
- More strong and weak interactions
  - Gluons, W and Z particles

Three generations of particles

Quarks

Protons/Neutrons are composite

Heavy, Heavier, Heaviest

- Six 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

Example: \( t \rightarrow b \)  
\( b \rightarrow c \)  
\( c \rightarrow s \)  
\( s \rightarrow u \) 

More on quark decays later...
### Hadrons / Baryons

- 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).
- Hadrons interact very strongly with other hadrons!

- 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 $2/3 + 2/3 + (-1/3) = +1$!

**To make a neutron:** We bind 2 down quarks of $Q = -1/3$ with 1 up quark of $Q = +2/3$ to get: $(-1/3) + (-1/3) + (2/3) = 0$!

### 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 $\Lambda^+$ for short. (What is the charge of this object?)
- This combination is called a Delta baryon, or $\Delta^+$ for short. What’s this one’s charge?

### Make some baryons!

#### Quark | up | down | strange
---|---|---|---
**Charge** | $+2/3$ | $-1/3$ | $-1/3$

Neutron can be turned into a proton by replacing a down quark by an up quark!

### More Baryons

| Quark | up | down | strange |
---|---|---|---|
**Q** | $+2/3$ | $-1/3$ | $-1/3$

**Quarks have electric charge**

- **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

### Quarks are electric charge
Mesons

- They are formed when a quark and an anti-quark "bind" together.
- Because they are hadrons, they must be colorless.
- So, the quark has color, and the antiquark has "anticolor".

<table>
<thead>
<tr>
<th>Quark</th>
<th>Antiquark</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>d</td>
</tr>
<tr>
<td>d</td>
<td>u</td>
</tr>
<tr>
<td>c</td>
<td>d</td>
</tr>
</tbody>
</table>

What's the charge of this particle?
- Q = +1, and it's called a π.
- Q = -1, and this charm meson is called a D.
- Q = 0, this strange meson is called a K.

Quarks & Gluons

1. Gluons are the carrier of the strong force.
2. They keep quarks bound up inside hadrons.
3. Gluons themselves carry color, so they can interact with each other.
4. This previous property (#3) 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

Strong Force & Color

We hypothesize that in addition to the attribute of "electric charge", quarks have another attribute known as "color charge", or just "color" for short. The attribute's name, color, is just by convention. It's easy to visualize this attribute and how colors combine... (coming up)

The property of color allows quarks to talk to the mediator of the strong interaction, the gluon (g).

Unlike electric charge, we find (experimentally) that there are 3 values for color.
We assign these possible values of color to be: red, green, blue.

Also, unlike Electromagnetism, we find that the carrier of the strong force carries "color charge". Recall the photon is electrically neutral!
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 ($\gamma$)</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 ($\sim 1/d^2$) (inside hadrons)</td>
<td>$10^{-14}$ [m]</td>
</tr>
</tbody>
</table>

Color of Hadrons

- **BARYONS**
  - RED + BLUE + GREEN = "WHITE" or "COLORLESS"

- **MESONS**
  - GREEN + ANTIGREEN = "COLORLESS"
  - RED + ANTIRED = "COLORLESS"
  - BLUE + ANTIBLUE = "COLORLESS"

A meson can be any one of these combinations.

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.

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

Feynman diagram for an interaction between quarks generated by a gluon.

Color Exchange

- Quarks interact by the exchange of a gluon.
- Since gluons carry color charge, it is fair to say that the interaction between quarks results in the exchange of color (or color charge, if you prefer)!

Interactions through Exchange of Color Charge

- Initially
  - RED
- After gluon emission
  - RED-ANTIGREEN + GREEN
- (quark) (gluon) (quark)

- Before gluon absorption
  - RED-ANTIGREEN + GREEN
- After gluon absorption
  - RED
  - (gluon) (quark) (quark)
Gluons carry the color force

Quarks and Gluons

- Red-green gluon is emitted by a red quark, which is transformed into a green quark.
- A green quark, not shown, absorbs the red-green gluon and becomes a red quark.

Rule: Sum of colors conserved

This cannot happen, because the photon does not interact with electrically charged objects!

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!

Feynman Diagrams for the Strong Interaction

- As before, we can draw Feynman diagrams to represent the strong interactions between quarks.
- The method is more or less analogous to the case of EM interactions.
- When drawing Feynman diagrams, we don’t show the flow of color. It’s understood to be occurring though.

Feynman Diagrams (Quark Scattering)

- Quark-antiquark Annihilation
- Quark-quark or Antiquark-antiquark Scattering

Flashback to EM Interactions

Recall that photons do not interact with each other.

Why?

Because photons only interact with objects which have electric charge, and photons do not have electric charge!

But Gluons Have Color Charge!!!

Gluons carry the “charge” of the strong force, which is “color charge”, or just “color”!

This can’t happen because the photon only interacts with electrically charged objects!
Gluon interactions

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

And quark-gluon interactions as well!

Since both quarks and gluons have color, they can interact with each other!!!

Where do the gluons come from?

The gluons are all over inside hadrons!!
In fact there are a lot more than shown here !!!
Notice sizes here: In fact quarks are < 1/1000\(^{th}\) of the size of the proton, so they are still too big in this picture!!
Even protons and neutrons are mostly empty space !!!

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: \(\tau\), \(\pi\), or \(b\bar{b}\) → colorless
    They may be spin 0, or spin 1