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

Light

Heavier

Heaviest

Phy107 Lecture 35
Quarks

Quarks ‘paired’ in generations same way as electron and neutrino

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u up</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>d down</td>
<td>0.006</td>
<td>−1/3</td>
</tr>
<tr>
<td>c charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s strange</td>
<td>0.1</td>
<td>−1/3</td>
</tr>
<tr>
<td>t top</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>b bottom</td>
<td>4.3</td>
<td>−1/3</td>
</tr>
</tbody>
</table>

Light (Gen. I)

Heavy (Gen. II)

Heaviest (Gen. III)
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

Example: 

\[ t \rightarrow b \quad (\sim 10^{-23}\ \text{[s]}) \]

\[ b \rightarrow c \quad (\sim 10^{-12}\ \text{[s]}) \]

\[ c \rightarrow s \quad (\sim 10^{-12}\ \text{[s]}) \]

\[ s \rightarrow u \quad (\sim 10^{-7}-10^{-10}\ \text{[s]}) \]

More on quark decays later...
Protons/Neutrons are composite
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 $\Lambda^0$ 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?
Neutron can be turned into a proton by replacing a down quark by an up quark!
# 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 (Λ)**
  - Q = 0
  - M = 1116 MeV/c^2

- **Sigma (Σ^+)**
  - Q = +1
  - M = 1189 MeV/c^2

- **Sigma (Σ^0)**
  - Q = 0
  - M = 1192 MeV/c^2

- **Sigma (Σ^-)**
  - Q = -1
  - M = 1197 MeV/c^2

- Mass of quarks and baryons:
  - ~5 [MeV/c^2]
  - ~10 [MeV/c^2]
  - ~200 [MeV/c^2]
Quarks have electric charge

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>+ 2/3</td>
</tr>
<tr>
<td>Down</td>
<td>- 1/3</td>
</tr>
<tr>
<td>Charm</td>
<td>+ 2/3</td>
</tr>
<tr>
<td>Strange</td>
<td>- 1/3</td>
</tr>
<tr>
<td>Top</td>
<td>+ 2/3</td>
</tr>
<tr>
<td>Bottom</td>
<td>- 1/3</td>
</tr>
</tbody>
</table>

The neutron contains three quarks. Which three quarks could be used to make a neutron?

The proton contains three quarks. Which three quarks could be used to make a proton?

The pion has a charge of +1 and contains two quarks. Which two quarks—if any—could be used to make a pion?
Quarks have anti-particles

### Quarks and Anti-Quarks

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Charge</th>
<th>Flavor</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>+ 2/3</td>
<td>Anti-Up</td>
<td>- 2/3</td>
</tr>
<tr>
<td>Down</td>
<td>- 1/3</td>
<td>Anti-Down</td>
<td>+ 1/3</td>
</tr>
<tr>
<td>Charm</td>
<td>+ 2/3</td>
<td>Anti-Charm</td>
<td>- 2/3</td>
</tr>
<tr>
<td>Strange</td>
<td>- 1/3</td>
<td>Anti-Strange</td>
<td>+ 1/3</td>
</tr>
<tr>
<td>Top</td>
<td>+ 2/3</td>
<td>Anti-Top</td>
<td>- 2/3</td>
</tr>
<tr>
<td>Bottom</td>
<td>- 1/3</td>
<td>Bottom</td>
<td>+ 1/3</td>
</tr>
</tbody>
</table>

**The Pion**
(Two quarks; charge: + 1)

- Which two quarks could be used to make a pion?

**The Neutron**
(Three quarks; charge: 0)

- Could a neutron have one or more antiquarks?
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”

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 $K^0$
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. Gluons are the carrier of the strong force

2. They keeps 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!
Color

Quark Color Causes Strong Force (Nuclear Force)

In 1965 Moo-Young Han and Yoichiro Nambu suggested quarks possess color.

- Red
- Blue
- Green

- Anti-red
- Anti-blue
- Anti-green

Color is also called color charge.

Like colors repel.

Unlike attract.

Color-AntiColor attraction is stronger.

Blue-AntiBlue stronger than Blue-Red, for example.

The "color" attribute is not traditional color; the name is somewhat arbitrary, and almost as whimsical as the names of the quarks.

Moo-Young Han, Duke Univ
# 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 ($\propto 1/d^2$)</td>
<td>$10^{-14}$ [m] (inside hadrons)</td>
</tr>
</tbody>
</table>

*Phy107 Lecture 35*
Color of Hadrons

Hadrons observed in nature are colorless (but there 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”
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

(quark)

After gluon emission

RED-ANTIGREEN  +  GREEN

(gluon)  (quark)

Emission of Gluon

Re-absorption of Gluon

Before gluon absorption

RED-ANTIGREEN + GREEN

(gluon)

After gluon absorption

RED

(quark)
Gluons carry the color force

*Quarks and Gluons*

Red-antigreen gluon is emitted by a red quark, which is transformed to a green quark.

A green quark, not shown, absorbs the red-antigreen gluon and becomes a red quark.

The strong force is caused by the emission and absorption of *gluons.*

Rule: Sum of colors conserved
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!
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 Scattering
Could also be Quark-antiquark Scattering or Antiquark-antiquark Scattering
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!

This can’t happen because the photon only interacts with electrically charged objects!
BUT GLUONS HAVE COLOR CHARGE !!!

Gluons carry the “charge” of the strong force, which is “color charge”, or just “color”!
Since gluons carry “color charge”, they can interact with each other! (Photons can’t do that)

Gluon interactions

Gluon-gluon Scattering

Gluon-gluon Fusion
And quark-gluon interactions as well!

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

Quark-gluon Scattering

Quark-Antiquark Annihilation
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!!!
Since the strong force increases as quarks move apart, they can only get so far…

The quarks are confined together inside hadrons.

Hadron jail!
Confinement

The quarks of a proton are free to move within the proton volume.

If you try to pull one of the quarks out, the energy required is on the order of 1 GeV per fermi, like stretching an elastic bag.

The energy required to produce a separation far exceeds the pair production energy of a quark-antiquark pair, so instead of pulling out an isolated quark, you produce mesons as the produced quark-antiquark pairs combine.
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: **r̅r**, **g̅g**, or **b̅b** → **colorless**
  They may be spin 0, or spin 1