From Last Time...

- Particles are quanta of a quantum field
  - Represent excitations of the associated field
  - Particles can appear and disappear
- Quarks and leptons
  - Three generations of leptons, quarks
  - Different only by masses
- Today:
  - Making other particles from quarks
  - Quark interactions

Leptons: electron-like particles

<table>
<thead>
<tr>
<th>Charge</th>
<th>Spin</th>
<th>Mass (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>-e</td>
<td>1/2</td>
</tr>
<tr>
<td>Muon</td>
<td>-e</td>
<td>1/2</td>
</tr>
<tr>
<td>Tau</td>
<td>-e</td>
<td>1/2</td>
</tr>
</tbody>
</table>

These are referred to as three ‘generations’ of particles.
Difference between them is only mass

Antiparticles

- Each of these has an antiparticle, different only by charge.
- Electron antiparticle = positron
- Muon antiparticle = anti-muon
- Tau antiparticle = anti-tau

Matter and anti-matter can annihilate creating energy

Three neutrinos

Both the muon and tau have
Muon-neutrino
Tau-neutrino (detected in 2000)

<table>
<thead>
<tr>
<th>Charge</th>
<th>Spin</th>
<th>Mass (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron-neutrino</td>
<td>0</td>
<td>1/2</td>
</tr>
<tr>
<td>Muon-neutrino</td>
<td>0</td>
<td>1/2</td>
</tr>
<tr>
<td>Tau-neutrino</td>
<td>0</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Three ‘generations’ of particles.

Six quarks

<table>
<thead>
<tr>
<th>Charge</th>
<th>Spin</th>
<th>Mass (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>+(2/3)e</td>
<td>1/2</td>
</tr>
<tr>
<td>Down</td>
<td>-(1/3)e</td>
<td>1/2</td>
</tr>
<tr>
<td>Charmed</td>
<td>+(2/3)e</td>
<td>1/2</td>
</tr>
<tr>
<td>Strange</td>
<td>-(1/3)e</td>
<td>1/2</td>
</tr>
<tr>
<td>Top</td>
<td>+(2/3)e</td>
<td>1/2</td>
</tr>
<tr>
<td>Bottom</td>
<td>-(1/3)e</td>
<td>1/2</td>
</tr>
</tbody>
</table>

The particle garden

- Particle physics at this point has settled on a countable number of ‘fundamental particles’.
- The bad news - there are:
  - (6 leptons + 6 quarks) + (4 electroweak bosons + 8 gluons + 1 graviton) = 25 fundamental particles, not counting antiparticles!
- The good news:
  - These are not just random, but have some relationships that let us understand the ideas without thinking immediately about all the particles.
Three ‘generations’ of particles

• Three generations differentiated primarily by mass (energy).
  • First generation:
    - One pair of leptons, one pair of quarks
  • Leptons:
    - Electron, electron-neutrino.
  • Quarks: Up, down.

All have spin 1/2.

The generations of ‘matter particles’

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass (GeV/c²)</td>
</tr>
<tr>
<td>e⁺, e⁻, νₑ</td>
<td>&lt;1.0 MeV/c²</td>
</tr>
<tr>
<td>μ⁺, μ⁻, νₑ</td>
<td>&lt;0.002 MeV/c²</td>
</tr>
<tr>
<td>τ⁺, τ⁻, νₑ</td>
<td>&lt;0.02 MeV/c²</td>
</tr>
</tbody>
</table>

Use up and down quarks

<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>

Proton: Q = +1
M = 938 MeV/c²
Neutron: Q = 0
M = 940 MeV/c²

Most of the mass is in the binding energy.

Making more composite particles

• 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 quarks.
• Baryons are hadrons which contain 3 quarks (no anti-quarks).
• Anti-baryons are hadrons which contain 3 anti-quarks (no quarks).

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 Λ for short.
Charge 0:
\[(2/3) + (-1/3) + (-1/3) = 0\]

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>

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambda (Λ)</td>
<td>M = 1116 MeV/c²</td>
</tr>
<tr>
<td>Sigma (Σ⁺)</td>
<td>M = 1189 MeV/c²</td>
</tr>
<tr>
<td>Sigma (Σ⁺)</td>
<td>M = 1192 MeV/c²</td>
</tr>
<tr>
<td>Sigma (Σ⁻)</td>
<td>M = 1197 MeV/c²</td>
</tr>
</tbody>
</table>

Excited state - Higher energy/mass
Another baryon:
What's this baryon's electric charge?
Delta baryon, or Δ++ for short.
Charge: +2
\[\frac{2}{3} + \frac{2}{3} + \frac{2}{3} = +2!\]

A. 0
B. +1
C. +2

Leptons and quarks: what's the difference?
• One important difference between leptons and quarks is how they interact.
Which of these interactions are NOT common to both leptons (e.g. electrons) and quarks.
A. Electromagnetic force
B. gravitational force
C. strong force

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 π^+
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

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.
**Exchange bosons**
- Each interaction has one or more associated particles that mediate the interaction.
- The exchange particles are associated with the known interactions:
  - **Electromagnetic**
    - Mediating particle: photon
    - Number: 1
  - **Weak**
    - Mediating particles: W⁺, W⁻, Z⁰
    - Number: 3
  - **Strong**
    - Mediating particle: gluons
    - Number: 8
  - **Gravity**
    - Mediating particle: graviton
    - Number: 1
- These all have integer spins (bosons)

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**Electromagnetic Force**
- Particles are often classified using the forces by which they interact.
- Which of these particles does not interact with the electromagnetic force?
  - A. electron
  - B. muon
  - C. photon
  - D. quark

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**Charge**
- How do we know which interactions apply?
- The particle must be able to couple to the field of the “mediating” particle.
- 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

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**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.

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**Electric Charge**
- What does it really mean for a particle to have electric charge?
- It means the particle has an attribute which allows it to couple to the photon, which mediates 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?

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**The Many Charges of the Quarks**
- Quarks interact via all the forces - have all the charges.
  - Mass ‘charge’ - gravitational 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.
1. There are three color charges
2. Gluons are the carrier of the strong force
3. They keep quarks bound up inside hadrons
4. Gluons themselves carry color, they can interact with each other!

Interactions through Exchange of Color Charge

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!

Gluons in the hadrons.
- The gluons are all over inside hadrons!!
- There are a lot more than shown here !!!

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!
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: \( \uparrow \uparrow, \g\g, \text{ or } \b\b \) → colorless
    They may be spin 0, or spin 1.