Review Chap. 18: Particle Physics

- Particles and fields: a new picture
- Quarks and leptons: the particle zoo
- The weak interaction
- Unification and mass
- The approach of string theory
Particle physics

• Have talked about several particles
  - Electron, photon, proton, neutron, quark

• There are a plethora of others that we haven’t talked about.

• Most of these are composite, meaning that they have internal constituents.

• Just as an atom is not ‘fundamental’, but has internal constituents electron, proton, neutron.
Pair production, annihilation

- Every fermion has an anti-particle
  - Exactly same mass, but opposite charge

- Particle and anti-particle can ‘annihilate’ to form two photons.

- Photon can ‘disappear’ to form electron-positron pair.
Particles and fields

• What are particles?

• We say that particles are quanta of a corresponding field.

• But what does this mean?

• Think about photons.
  - One photon means the electromagnetic field has \((\text{Planck’s const}) \times \text{(frequency)} = \hbar f\) of energy.
  - Two photons means \(2\hbar f\) of energy.
  - Three photons means \(3\hbar f\) of energy.
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!
The vacuum

- Modern particle physics says that the vacuum is not as simple as one might think.
- The vacuum is continually ‘fluctuating’, with virtual photons, electron-positron pairs, etc.

- Vacuum is really empty at all.
What are these particles?

• Broadly divided into
  - Matter particles (Leptons and quarks)
  - Force particles (Photon, W, Z, gluons)

• In the standard model, these particles are quite different

• Leptons and quarks make up matter

• Other particles are responsible for the fundamental forces.
The Matter Particles

- “Matter is made of atoms”

“Atoms are made of leptons and quarks”

Leptons $\begin{cases} \nu_e \\ e \end{cases}$

Quarks $\begin{cases} u \\ d \end{cases}$
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 lets us understand the ideas without thinking immediately about all the particles.
Generations of matter 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.
The ‘generations’

<table>
<thead>
<tr>
<th>Leptons</th>
<th>spin = 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass GeV/c²</td>
</tr>
<tr>
<td>νₑ</td>
<td>&lt;1×10⁻⁸</td>
</tr>
<tr>
<td>e</td>
<td>0.000511</td>
</tr>
<tr>
<td>νₘ</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>μ</td>
<td>0.106</td>
</tr>
<tr>
<td>νₜ</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>τ</td>
<td>1.7771</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quarks</th>
<th>spin = 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Approx. Mass GeV/c²</td>
</tr>
<tr>
<td>u</td>
<td>0.003</td>
</tr>
<tr>
<td>d</td>
<td>0.006</td>
</tr>
<tr>
<td>c</td>
<td>1.3</td>
</tr>
<tr>
<td>s</td>
<td>0.1</td>
</tr>
<tr>
<td>t</td>
<td>175</td>
</tr>
<tr>
<td>b</td>
<td>4.3</td>
</tr>
</tbody>
</table>
Plus the antiparticles...

- Some of these particles seen experimentally only recently
- But predicted by the standard model.
- Naturally paired into three generations.

<table>
<thead>
<tr>
<th>Family</th>
<th>Leptons</th>
<th>Antileptons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q = -1$</td>
<td>$Q = 0$</td>
</tr>
<tr>
<td>1</td>
<td>$e^-$</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>2</td>
<td>$\mu^-$</td>
<td>$\nu_\mu$</td>
</tr>
<tr>
<td>3</td>
<td>$\tau^-$</td>
<td>$\nu_\tau$</td>
</tr>
</tbody>
</table>

$Q = +1$ $Q = 0$
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: 
\[ t \rightarrow b \] 
\[ b \rightarrow c \] 
\[ c \rightarrow s \] 
\[ s \rightarrow u \]  
\( (~10^{-23} \text{ [s]} ) \) 
\( (~10^{-12} \text{ [s]} ) \) 
\( (~10^{-12} \text{ [s]} ) \) 
\( (~10^{-7}-10^{-10} \text{ [s]} ) \)

More on quark decays later...
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?
Quarks have ‘color charge’

In 1965 Moo-Young Han and Yoichiro Nambu suggested quarks possess color. 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
Particle made from quarks
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.
  • This arises from interactions between internal 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
$$2/3 + 2/3 + (-1/3) = +1 !$$

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

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Mediating particle(s)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-magnetic</td>
<td>photon</td>
<td>(1)</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
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.
Interactions through Exchange of Color Charge

Initially

RED \rightarrow RED\text{-ANTIGREEN} + GREEN
(quark) (gluon) (quark)

After gluon emission

Emission of Gluon

Re-absorption of Gluon

Before gluon absorption

RED\text{-ANTIGREEN} + GREEN \rightarrow RED
(gluon) (quark) (quark)

After gluon absorption
Confinement: Quarks are not alone

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 of quarks

- Discussed quarks and their interactions
- Six generation, 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 as six varieties
  - Red, green, blue, anti-red, anti-green, anti-blue
  - Like colors repel, unlike colors attract.
- Gluons have color charge, which leads to confinement
## Comparison of the Force Carriers

<table>
<thead>
<tr>
<th>Force Carrier</th>
<th>EM</th>
<th>Strong</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Carrier</td>
<td>Photon (γ)</td>
<td>Gluon (g)</td>
<td>W⁺, W⁻</td>
</tr>
<tr>
<td>Charge of force carrier</td>
<td>None</td>
<td>Color</td>
<td>Electric &amp; Weak</td>
</tr>
<tr>
<td>Couples to:</td>
<td>Particles w/ elect. charge</td>
<td>Particles w/ color charge (Quarks, gluons)</td>
<td>Particles w/ weak charge (Quarks, leptons W,Z)</td>
</tr>
<tr>
<td>Range</td>
<td>Infinite (1/d²)</td>
<td>&lt; 10⁻¹⁴ m (inside hadrons)</td>
<td>&lt; 2 x 10⁻¹⁸ m</td>
</tr>
</tbody>
</table>
The Weak Force

Elementary Particles

Quarks

Leptons

Force Carriers

Strong

Weak

Electromagnetic
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:

\[ \begin{align*} 
W^+ & \quad W^- \\
Z^0 & 
\end{align*} \]

These “weak force” carriers carry electric charge also!

This “weak force” carrier is electrically neutral

The “charge” of the weak interaction is called “weak charge”
Example: neutrino scattering

- The neutrino interacts with quarks bound inside nucleons in the nucleus.
- Neutrino emits $W^+$, changing into muon.
- Down quark bound in a neutron absorbs $W^+$, changing into up quark.
- The nucleon then has two ups and one down quark, which is a proton.
Lepton decay

- Weak interaction is responsible for particle decay

<table>
<thead>
<tr>
<th>Generation I</th>
<th>Generation II</th>
<th>Generation III</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^- ) ( \nu_e )</td>
<td>( \mu^- ) ( \nu_\mu )</td>
<td>( \tau^- ) ( \nu_\tau )</td>
<td>-1 ( \downarrow ) 0</td>
</tr>
</tbody>
</table>

Electron is stable
Emit \( W^- \) 2x10\(^{-6}\) seconds
Emit \( W^- \) 3x10\(^{-13}\) seconds
And also quark decay

- Quarks have color charge, electric charge, and weak charge — other interactions swamp the weak interaction
- But similar to leptons, quarks can change their flavor (decay) via the weak force, by emitting a $W$ particle.

<table>
<thead>
<tr>
<th>Generation I</th>
<th>Generation II</th>
<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>

- Emit $W^+$:
  - Generation I: $2 \times 10^{-12}$ seconds
  - Generation II: $10^{-23}$ seconds

---

Phy107 Lecture 39
Flavor change between generations

- But for quarks, not limited to within a generation
- Similar to leptons, quarks can change their flavor (decay) via the weak force, by emitting a $W$ particle.

\[
\begin{align*}
\text{Generation I} & : & \begin{pmatrix} u \\ d \end{pmatrix} \\
\text{Generation II} & : & \begin{pmatrix} c \\ s \end{pmatrix} \\
\text{Generation III} & : & \begin{pmatrix} t \\ b \end{pmatrix}
\end{align*}
\]
Decay of internal quarks

A neutron outside the confines of the nucleus is not stable. It decays with a lifetime of about 14 minutes.

\[ n \rightarrow p + e^- + \nu_e \]
Unification

• Details of weak interaction suggest that
  - Different quarks are diff. ‘orientations’ of the same particle.
  - Different leptons are diff. ‘orientations’ of the same particle.
  - Weak and EM interactions are different parts of a single ‘electroweak’ force.

• Grand Unified Theories (GUTs)
  - Will ‘combine’ leptons and quarks
  - Unify strong and electroweak interactions
What is mass?

• Think of inertial mass:
  - inertial mass is a particle’s resistance to changes in velocity.

• When you apply the same force to particles, the smaller the mass, the larger the acceleration.

• What is the origin of mass?
  - Particles get mass by interacting with Higgs field
  - Higgs boson is an excitation of the Higgs field
Mass in the SM

- In the standard model (SM), particles have mass because they interact with something that pervades the universe.

This something is the Higgs field.

Particles ‘hit’ the Higgs field when you try to accelerate them.

Mass = (chance of hit) x (Higgs density)

Coupling constant
String theory

• A string is a fundamental quantum mechanical object that has a small but nonzero spatial extent.

• Just like a particle has a mass, a string has a ‘tension’ that characterizes its behavior.

• Quantum mechanical vibrations of the string correspond to the particles we observe.
Strings on Nova

This Week on NOVA

"The Elegant Universe: Einstein's Dream" and "String's the Thing" airs on PBS Tuesday, December 21 from 8 to 10 p.m. Check local listings as dates and times vary.
• Strings can vibrate in different ways

For example:

Guitar string

Different vibration → Different sound!

• Fundamental string

Different vibration → Different particles!

 electron  photon  graviton

Not exactly!
Extra dimensions in string theory

- Superstring theory requires a 10 dimensional spacetime, to eliminate quantum states with unphysical negative probabilities (ghosts).

- How do we get from 10 dimensions down to 4?

- Two main proposals:
  - Roll up the extra dimensions into some very tiny space of their own. Kaluza-Klein compactification.
  - Make the extra dimensions really big, but constrain all the matter and gravity to propagate in a 3D subspace called the three-brane. These types of theories are called braneworlds.
Results of the theory

- The first string excitation is a particle with *imaginary* mass — a tachyon (negative mass squared = negative energy)
- Clearly off-base.
- But the next excitation is a massless spin-2 particle satisfying general relativity
  - The graviton!
- So string theory became a theory of gravity