From before on particle physics

- We have talked about several particles
  - Electron, photon, proton, neutron, quark
- Many particles have internal constituents
  - Not fundamental: proton and neutron
- We have talked about various forces
  - Electromagnetic, strong, weak, and gravity
- Remember: Essay due Monday

Particles and fields

- But what are particles and forces?
- Is there way to describe the two at once?
- An answer lies in considering everything as fields.
- Particles are quanta of a corresponding field.
- What does this mean?
  - One photon means the electromagnetic field has (Planck's const)x(frequency) = hf of energy.
  - Two photons means 2hf of energy.

Particles as fields

- Electromagnetic field spread out over space.
  - Stronger near the source of the electric/magnetic charge - weaker farther away.
- Electromagnetic radiation, the photon, is the quanta of the field.
- Describe electron particles as fields:
  - Makes sense - the electron was spread out around the hydrogen atom.
  - Wasn’t in one place - had locations it was more or less probable to be. Stronger and weaker like the electromagnetic field.
- Electron is the quanta of the electron field.

Quantum field theory: Goals

- Want to:
  - Describe all the particles and forces: Unification
  - A description that incorporates relativity and quantum mechanics.
- One answer was quantum field theory.
- Start with the simplest case:
  - Electron, photons and the electromagnetic force.

Electrons and Photons: Quantum Electrodynamics: QED

- QED is the relativistic quantum theory of electrons and photons, easily generalized to include other charged particles.
- To photon emission or absorption which may be represented by a simple diagram - a Feynman studied the idea that all QED processes reduce Feynman diagram.

Quantum Electrodynamics: QED

- Normal electromagnetic force comes about from exchange of photons.
- Attraction a bit more difficult to visualize.
Quantum Electrodynamics: QED

- Can rotate diagrams

![Diagram](image)

Time goes from left to right. What is an electron going backward in time?

Antiparticles

- Several physicists had an explanation.
- Antimatter!
- There is a particle with exact same mass as electron, but with a positive charge.
- It is called the positron.
- All particles have an antiparticle.
- We’ve seen this particle before. Nuclear beta decay with a positive electron - positron.

Pair production, annihilation

- Electron and positron can ‘annihilate’ to form two photons.
- Photon can ‘disappear’ to form electron-positron pair.
- Relativity: Mass and energy are the same
  - Go from electron mass to electromagnetic/photon energy

![Diagram](image)

Seeing antiparticles

- Photons shot into a tank of liquid hydrogen in a magnetic field.
- Electrons and positrons bend in opposite directions and, losing energy to ionization, spiral to rest.

The story so far

- Electromagnetic force and electrons are both fields.
- The fields have quanta photon and electrons.
- The Quantum field theory QED explains how they interact.
- Very successful theory: explains perfectly all the interactions between electrons and photons
- Predicted a few things we didn’t expect
  - Antiparticles - the positron.
  - Electrons and positrons can be annihilated to photons and vice versa.

Annihilation question

If you annihilate an electron and a positron what energy wavelength/type of photons(two) are made.
Electron mass: 0.5 MeV/c^2

A. 2.5m radio wave
B. 2.5um infrared
C. 2.5pm xray
Fields for other particles

- Works for other particles as well
- An electron is a quantum of the electron field.
- What is the energy?
  - Smallest energy is rest energy of electron =
- Can also work for electron-positron pairs
  - These are also quanta of the field.

Creating more particles

- All that is needed to create particles is energy.
- Energy can be provided by high-energy collision of particles.
- An example:
  - Electron and positron annihilate to form a (virtual) photon.
  - This can then create particles with \( mc^2 < \text{photon energy}. \)

What else can we make this way?

- All that is needed to create particles is energy.
- With more energy maybe we can make something new.
- Can we make protons, neutrons or antiprotons and antineutrons.  
  *Maybe gold and antigold.*

Something unexpected

- Raise the momentum and the electrons and see what we can make.
- Might expect that we make a quark and an antiquark.  
  The particles that make of the proton.
  - Guess that they are 1/3 the mass of the proton 333MeV
  - Muon mass: 100MeV/c^2, electron mass 0.5 MeV/c^2
  - Instead we get a muon, acts like a heavy version of the electron.

High-energy experiments

- Let’s raise the energy of the colliding particles as high as possible to see what we can find!
- Source of high-energy particles required
- Originally took advantage of cosmic rays entering earth’s atmosphere.
- Now experiments are done in large colliders, where particles are accelerated to high energies and then colides.

Cosmic rays

- New particles were discovered in cosmic ray air showers in which a high energy extraterrestrial proton strikes a nucleus (N or O) in the atmosphere and secondary particles multiply.
**Electrostatic Accelerators**

- An electrostatic accelerator uses mechanical means to separate charge and create a potential $V$.
- An electron or proton dropped through the potential achieves an energy $eV$.
- $V \sim 1$ million volts is achievable, $1\ MeV$ for one electron.
- Limited by spark breakdown.

**Linear accelerator: Linac**

- A metal cavity contains a standing wave. An injected particle surfs the wave acquiring energy of order $1\ MeV/m$.
- A succession of cavities yields high energy.
- The Stanford Linear Accelerator (SLAC) is 3 km in length and achieves $50\ GeV$ per electron.
- Limited by breakdown of the field in the cavity. Field literally pull electrons out of the walls of the cavity.

**SLAC**

- Stanford Linear Accelerator Center
- 3km long beam line with accelerating cavities
- Accelerate electrons and positrons and collides them

**Cyclic accelerators**

- Run particles through a linac then and into a circular accelerator. Accelerate using cavities - except the particles go around and around and are accelerated every time around.
- LEP: Large Electrons Positron collider $115\ GeV$ electrons and positrons.
- Fermilab Tevatron: $1000\ GeV$, or $1\ TeV$, proton antiproton collider.
- LHC: Large hadron collider: $7\ TeV$ proton proton
- Limitation is size and the power of magnetic field needed to keep the particles going around in a circle.

**Fermilab**

- Fermi National Accelerator Center, Batavia IL
- Tevatron Cyclic accelerator
- 6.4km, $2\ TeV$

**CERN (Switzerland)**

- CERN, Geneva Switzerland
- LHC Cyclic accelerator
- 27km, $14\ TeV$
Measuring particle collisions
Detectors are required to determine the results of the collisions.

- CDF: Collider Detector Facility at Fermilab

Fundamental Particles
In the Standard Model the basic building blocks are said to be “fundamental” or not more up of constituent parts. Which particle isn’t ‘fundamental’:

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

What have we learned?
Matter is made of atoms
Atoms are made of leptons and quarks

Interact via different forces carried by particles, photons...

Hierarchy of structure
Proton and Neutron

- $R \sim 10^{-15}$ m (strong) protons and neutrons are made from quarks
- $R \sim 10^{-10}$ m (electromagnetic) Atoms are made from protons, neutrons, and electrons
- $R > 10^6$ m (gravitational) We’ll talk about the rest of the universe later

What about the muon?
- The muon found early on.
  - Heavy version of the electron.
- Otherwise would have been fairly simple!

$\mu$, Muon mass: $100\text{MeV}/c^2$, electron mass $0.5\text{MeV}/c^2$
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.

Three happy lepton families...

- In 1975, researchers at the Stanford Linear Accelerator discovered a third charged lepton, with a mass about 3500 times that of the electron. It was named the τ-lepton.
- In 2000, first evidence of the τ’s partner, the tau-neutrino (ντ) was announced at Fermi National Accelerator Lab.

<table>
<thead>
<tr>
<th>Family</th>
<th>Leptons</th>
<th>Antileptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Q = -1</td>
<td>Q = 0</td>
</tr>
<tr>
<td></td>
<td>e⁻</td>
<td>νe</td>
</tr>
<tr>
<td></td>
<td>νe</td>
<td>e⁺</td>
</tr>
<tr>
<td></td>
<td>μ⁻</td>
<td>νμ</td>
</tr>
<tr>
<td></td>
<td>νμ</td>
<td>μ⁺</td>
</tr>
<tr>
<td></td>
<td>τ⁻</td>
<td>ντ</td>
</tr>
<tr>
<td></td>
<td>τ⁺</td>
<td>τ⁻</td>
</tr>
</tbody>
</table>

Three happy quark families...

- In 1995 The CDF and D0 experiments at the Tevatron collider at Fermilab discovered the final quark. The top quark had a mass of 174GeV, 350,000 times that of the electron.
- Interestingly enough about the mass of a gold atom.

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

• Think about the interactions again.
• We talked about an uncertainty principle, that momentum and position cannot be simultaneously determined.
• There is an equivalent relation in the time domain.

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

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
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 a Coulomb force.
  - We know that only particles with electrical charge interact via the Coulomb force
  - Zero charge $\rightarrow$ 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

• But things don’t separate quite so cleanly.
• Electrons interact via the Coulomb force and also the weak force.
• So the electron carries both electric charge and weak charge.
• And the some of the bosons that mediate the weak force carry electrical charge
  - They can absorb and emit photons!

Bosons