Particles and fields
- 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
- And some fields...
  - Electric field
  - Magnetic field

Today: more fields and more particles!

Interactions between charges
Why did the electrons flow?

attractive force between positive and negative charges.
repulsive force between two positive or two negative charges.

The positively charged rod attracts negative charges to the top of the electroscope. This leaves positive charges on the leaves. The like-charges on the leaves repel each other.

Force between charges

Opposite charges attract
Like charges repel.
- Other than the polarity, they interact much like masses interact gravitationally.
- Force is along the line joining the particles.

Electrostatic force:
\[ F_E = k \frac{Q_1 Q_2}{r^2} \]
\[ k = 9 \times 10^9 \text{ Nm}^2/\text{C}^2 \]

Gravitational force:
\[ F_G = \frac{GM_1 M_2}{r^2} \]
\[ G = 6.7 \times 10^{-11} \text{ Nm}^2/\text{kg}^2 \]

Electric field lines

Faraday invented the idea of field lines following the force to visualize the electric field.

Field lines emanate from positive charge and terminate on negative charge. Local electric field is same direction as field lines. Force is parallel or antiparallel to field lines. Charged particle will move along these field lines.

Magnetism: Permanent magnets

North Pole and South Pole
- This is the elementary magnetic particle
- Called magnetic dipole (North pole and south pole)
- There are no magnetic 'charges'

Likes attract
- Unlikes repel
**Field lines of a magnet**
- Field lines indicate direction of force
- Density indicates strength of force
- Similar to electrostatic force, but force is felt by magnetic dipole

**Electromagnetic wave**
- Oscillating electric and magnetic fields
- Present without associated charges or currents
- Fields exist on their own

**Particles and fields**
- “Field Theory” says that everything is a field
- Even particles
- Particles are quanta of a corresponding field
  - What does this mean?
  - Think about photons.
    - One photon means the electromagnetic field has \((\text{Planck's const})x\text{(frequency)} = \hbar\text{f}\) of energy.
    - Two photons means \(2\hbar\text{f}\) of energy.

**Quanta of the EM field**
- Quantum mechanically, brightness can only be changed in steps, with energy differences of \(\hbar f\).
- Possible energies for green light (\(\lambda=500\) nm)
  - One quantum of energy: one photon
  - Two quanta of energy: two photons
  - etc
  - A photon is an excitation of the EM field.

**Question**
Consider the field for red photons (620 nm wavelength). How much energy is required to excite the field from the 3rd quantum state to the 5th quantum state?

- A. 1 eV
- B. 2 eV
- C. 4 eV
- D. 200 eV
- E. 4 MeV

**How is EM (photon) field excited?**
- Charged particle can excite the EM field.
  - A photon is produced
- Around a charged particle, photons continually appear and disappear.

Here the photon field is excited by an electron, then reabsorbs the energy and the photon disappears.
Other particles and 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.

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 - Feynman studied the idea that all QED processes reduce Feynman diagram.

Uncertainty principle
• The uncertainty principle is important for understanding interaction in quantum field theory.
  - We talked about an uncertainty principle, that momentum and position cannot be simultaneously determined.
  - There is an equivalent relation in the time and energy domain.
    - Einstein’s relation that space and time or momentum and mass/energy are similar.

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
    (Energy uncertainty) x (time uncertainty) \( \approx \) (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!

Quantum Electrodynamics: QED
• This is the Coulomb interaction.
  - Normal electromagnetic force comes about from exchange of photons.
  - Attraction a bit more difficult to visualize.

Question
This Feynman diagram shows two electrons and a photon.
Here, electron 1
A. Changes energy only
B. Changes momentum only
C. Neither energy nor mom. changed
D. Changes both energy and mom.
E. This interaction cannot occur
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.

Forces and particles

‘Classical’ collision
Interaction by particle exchange

Interactions between charges

The like-charges on the leaves repel each other.
This repulsion is the Coulomb force

Modern view of Coulomb repulsion between two electrons.
It is described as the exchange of a photon.

Quantum Electrodynamics: QED

- Can rotate diagrams

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
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.

Positron Emission Tomography

PET scan

<table>
<thead>
<tr>
<th>Labeling agent</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon-11</td>
<td>20.3 minutes</td>
</tr>
<tr>
<td>oxygen-15</td>
<td>2.03 minutes</td>
</tr>
<tr>
<td>fluorine-18</td>
<td>109.8 minutes</td>
</tr>
<tr>
<td>bromine-75</td>
<td>98.0 minutes</td>
</tr>
</tbody>
</table>

Oxygen-15: used to label O$_2$ gas for oxygen metabolism, CO for the study of blood volume, H$_2$O for the study of blood flow in the brain.

Fluorine-18: is attached to a glucose molecule (called FDG) measure of the brain’s sugar metabolism.

Brain activity analysis

- Radioactive isotopes decay by positron emission.
- Positron annihilates with electron, producing gamma ray (photon).

Brain Metabolism in Alzheimer’s Disease: PET Scan

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 radiation  
C. 2.5pm x-ray

$$E = \frac{hc}{\lambda} = \frac{1240\text{eV} - \text{nm}}{\lambda}$$