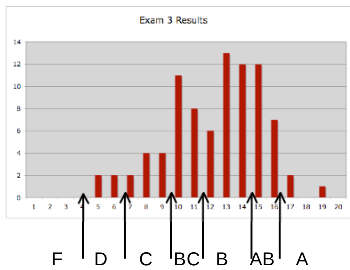
Exam Results

- Exam:
  - Exam scores posted on Learn@UW



- No homework due next week

Particles and fields

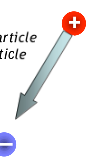
- We have talked about several particles
  - Electron, photon, proton, neutron, quark
- Many particles have internal constituents
  - Not fundamental: proton and neutron
- We have talked about various forces
  - Electromagnetic, strong, weak, and gravity
- And some fields…
  - Electric field
  - Magnetic field
- Modern view is that particles, forces, and fields are intertwined - and all quantized

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.

Force on positive particle due to negative particle

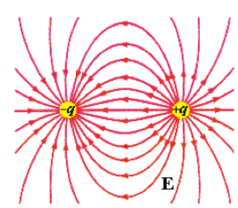


Electrostatic force: $F_E = k\, Q_1\, Q_2 \,/\, r^2$
$k = 9\text{x}10^9\ \text{Nm}^2/\text{C}^2$

Gravitational force: $F_G = GM_1M_2 /\ r^2$
$G = 6.7\text{x}10^{-11}\ \text{Nm}^2/\text{kg}^2$

Electric field lines

- Faraday invented the idea of the Electric field and 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.

Quanta of the EM field

- What about quantum mechanics? What would that tell us about electric, magnetic… fields?
  - Field strength should be quantized
  - Quantization small, not noticeable at large field strength or large times
  - However, for small strength or over a very short time might be noticeable
  - Example: an electron flying be another electron very quickly - Only time to have one quanta of repulsion occur
- Quanta of the field
  - Need to name the thing that conveys the repulsion
  - What particle is mixed up in electricity and magnetism: The photon!

Other particles and fields

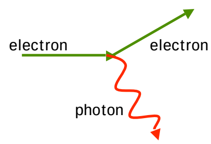
- Electromagnetic field spread out over space.
  - Stronger near the the source of the electric/magnetic charge - weaker farther away.
- Electromagnetic radiation, the photon, is the quanta of the field.
- Describe electron particles as fields:
  - Makes sense - the electron was spread out around the 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.

How is EM (photon) field excited?

- Charged particle can excite the EM field.
- Around a charged particle, photons continually appear and disappear.

Represented by a 'Feynman diagram'.

Electron can excite the EM field, creating a photon

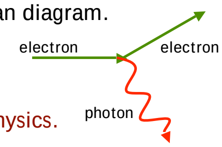


Electrons and Photons: Quantum Electrodynamics: QED

- 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.

Emission of a photon

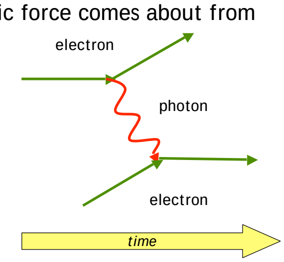
QED: First component of the Standard Model of particle physics.



Quantum Electrodynamics: QED

- If another charged particle is near, it can absorb that photon.
- Normal electromagnetic force comes about from exchange of photons.

Electromagnetic repulsion via emission of a photon



- Attraction a bit more difficult to visualize.

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) ~ (Planck's constant)

In other words, if a particle of energy E only exists for a time less than h/E,

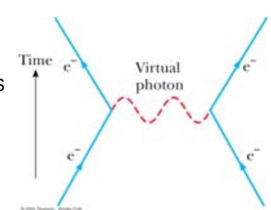
it doesn't require **any** energy to create it!

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.

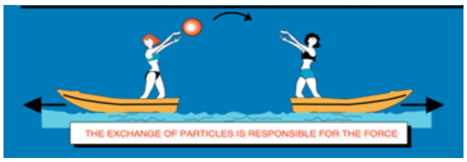
Momentum is uncertain over the short time: Could be negative: attraction



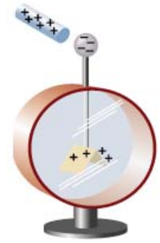
Forces and particles

'Classical' collision

Interaction by particle exchange

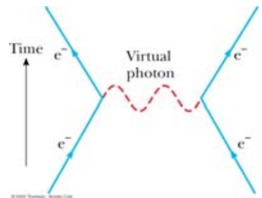


Interactions between charges



The like-charges on the leaves repel each other.

This repulsion is the Coulomb force

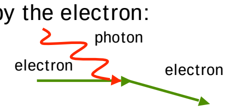


Modern view of Coulomb repulsion between two electrons.

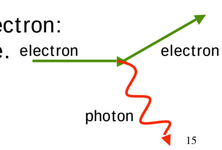
It is described as the exchange of a photon.

Electrons and Photons

- Non virtual interactions possible also: Photon is a real particle that is seen before or after the interaction
- Photon could be absorbed by the electron: Photoelectric effect



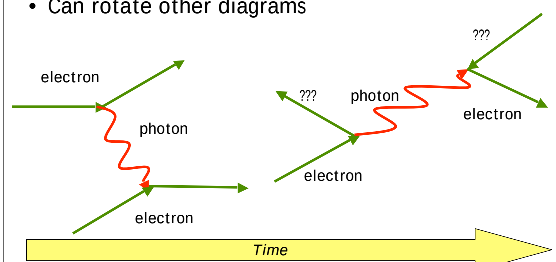
- Could be emitted by the electron: Decay from an excited state.



- Still a QED interaction
- Diagrams rotated

QED: Rotated Diagrams

- Can rotate other diagrams



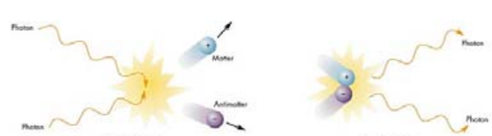
What is an electron going backward in time?

Antiparticles

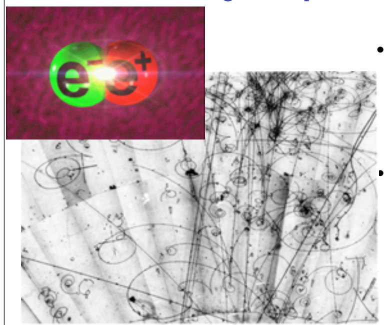
- Several physicists had an explanation.
- Antimatter!
- There is a particle with exact same mass as electron, but with a positive charge.
- It is called the positron.
- All particles have an antiparticle.
- We've seen this particle before. Nuclear beta decay with a positive electron - positron.

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.

Annihilation question

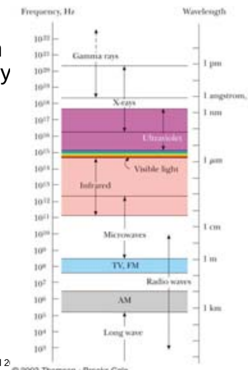
If you annihilate an electron and a positron what energy wavelength/type of photons(two) are made.

Electron mass: 0.5 MeV/c^2

A. 2.5m radio wave

B. 2.5um infrared

C. 2.5pm x-ray



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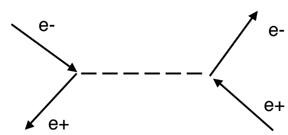
The story so far

- Electromagnetic force and electrons are both fields.
- The fields have quanta: photon and electrons.
  - Note electron is the smallest quanta of the electron field with energy equal to the electron rest mass
- 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 positions: can be annihilated to photons and vice versa.

Creating more particles

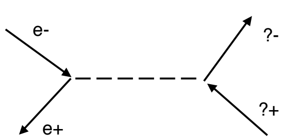
- All that is needed to create particles is energy.
- Energy can be provided by high-energy collision of particles.
- An example:
  - Electron and positron annihilate to form a (virtual) photon.
  - This can then create particles with mc^2<photon energy.



Feynman's rotated diagrams that we've already seen.

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.

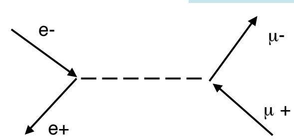


Annihilation produces new antiparticle pair

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

μ, 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 collides.

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

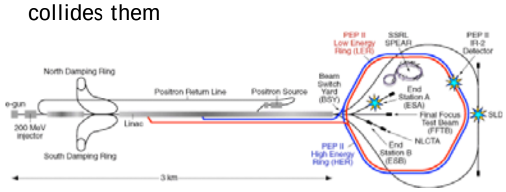
- An electrostatic accelerator uses mechanical means to separated charge and create a potential V.
- An electron or proton dropped through the potential achieves an energy eV.
- V~ 1 million volts is achievable, 1 MeV for one electron.
- Limited by spark break down.

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



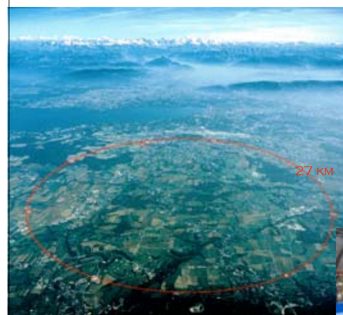
Cyclic accelerators

- 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 115GeV electrons and positrons.
- Fermilab Tevatron: 1000GeV, or 1TeV, proton antiproton collider.
- LHC: Large hadron collider: 7TeV 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, 2TeV

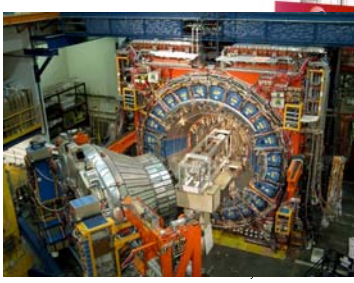
CERN (Switzerland)



- CERN, Geneva Switzerland
- LHC Cyclic accelerator
- 27km, 14TeV

Measuring particle collisions

Detectors are required to determine the results of the collisions.



- CDF: Collider Detector Facility at Fermilab

Fundamental Particles

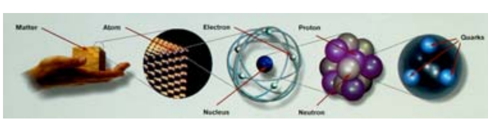
In the Standard Model the basic building blocks are said to be 'fundamental' or not more up of constituent parts.

Which particle isn't 'fundamental':

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

What have we learned?

Matter is made of atoms

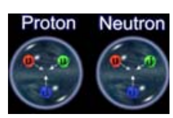


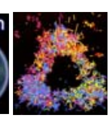
Atoms are made of leptons and quarks

Leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ Quarks $\begin{pmatrix} u \\ d \end{pmatrix}$

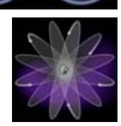
Interact via different forces carried by particles, photons…

Hierarchy of structure





R ~ 10^{-15} m (strong)
protons and neutrons are made from quarks



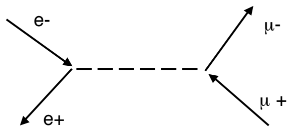
R ~ 10^{-10} m (electromagnetic)
Atoms are made from protons, neutrons, and electrons

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!

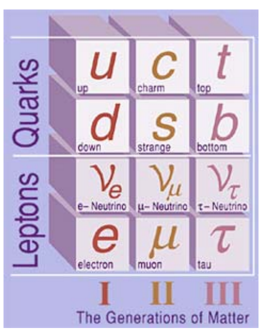
μ, Muon mass: 100MeV/c^2,
electron mass 0.5 MeV/c^2



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 ‘generatations’ 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.