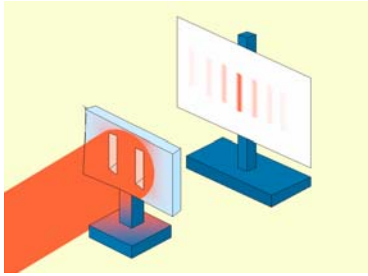
Today

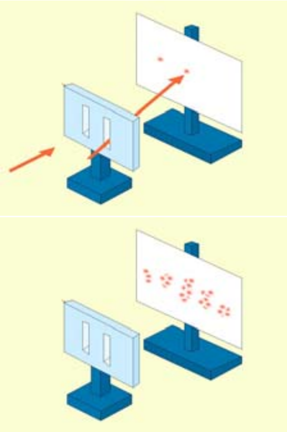
- Announcements:
  - HW#7 is due October 26th.
- Quantum mechanics (the wave nature of particles)- Absolutely essential development in our understanding of our world. Nearly all modern day electronics rest on these principles.
- The strong force (nuclei)
- The weak force (radioactive decay)

Review

- Light can be described as an electromagnetic wave or a little bundle of energy (a photon). Light has particle and wave character.
- Waves can overlap – this is called interference
- Particles, for example electrons, have wave and particle properties.
- The thing that is waving in the case of a particle is probability. The square of the height of the wave (wave function) is a measure of the probability density.
- All objects (atoms, molecules, etc.) exist in defined states of energy. The energy is quantized (quantum mechanics)

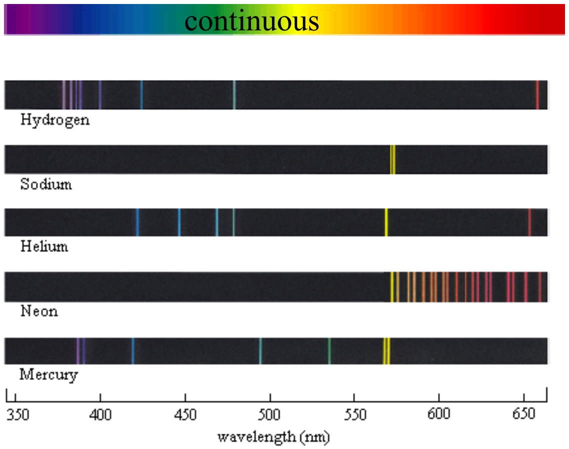
Two-slit interference of electrons or photons



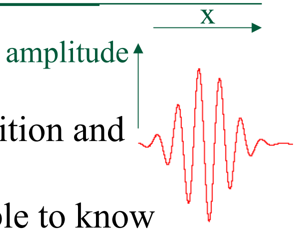


If we cover one slit we get just one spot. This means that somehow, the photons sample all possible paths.

Atoms exist in definite states of energy



Heisenberg's Uncertainty Principle



- If a particle has a wavelength, its position and speed are not perfectly defined.
- Uncertainty Principle: It is not possible to know exactly the position and momentum of a particle at the same time. $\Delta x \Delta p \geq \frac{h}{4\pi}$
- There is no absolute knowledge. The Newtonian view of the world (if everything were known, everything could be predicted) in not attainable.

An example

Suppose we measure the location of a proton to within 1.2 μm, what is the best precision with which we can know the velocity?
DATA: mass of proton 1.673E-27 kg

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

$$\Delta p = m\Delta \mathrm{v} = \frac{h}{4\pi\Delta x}$$

$$\Delta \mathrm{v} = \frac{h}{m4\pi\Delta x} = \frac{6.625\times10^{-34}\,Js}{1.672\times10^{-27}\,kg\cdot4\cdot3.1415\cdot1.2\times10^{-6}\,m}$$

$$\Delta \mathrm{v} = 0.0263\frac{m}{s}$$

Alternative version of the uncertainty principle

Time and energy also also related.

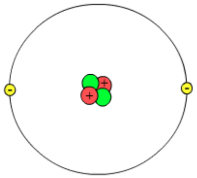
$$\Delta E \Delta t \geq \frac{h}{4\pi} \qquad \Delta x \Delta p \geq \frac{h}{4\pi}$$

It is possible for a short time to get something for nothing. But, it has to be paid back.

On the very small scale, empty space is alive with "fluctuations".

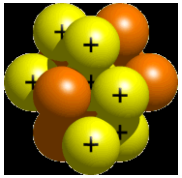
From large to small

Atoms



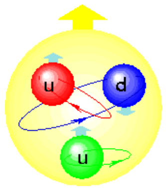
Made of nuclei and electrons. Size: 10^{-9}m

Atomic Nucleus



Made of neutrons and proton. Size 10^{-14} m

A proton

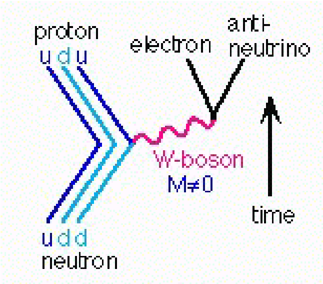


Made of quarks: Size 10^{-15} m
A neutron has ddu

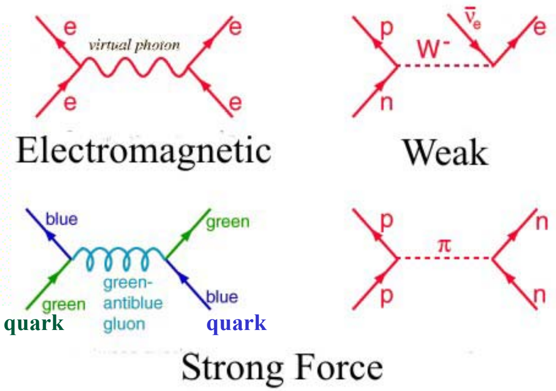
There are two more forces in nature

- Strong force
  - A force that exists between quarks
  - The carrier of the force is the gluon
  - No isolated quarks are found in nature
  - The force between protons-proton, protons-neutrons, and neutrons-neutrons is the result of the exchange of pairs of quarks. Pairs of quarks are called mesons (the pion is the lightest meson)
- Weak force
  - A force between electrons and protons (or neutrons)
  - The carrier of the force are called weak vector bosons (W,Z)
  - This force allows a neutron to change into a proton

A way to picture forces – Feynman Diagrams

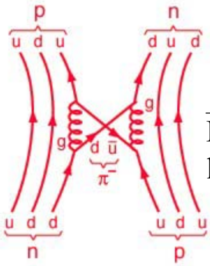


Decay of a neutron into a proton by the Weak force

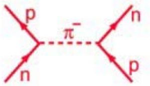


Equations – sort of

Strong force



Looks like



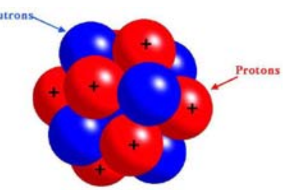
This is called an exchange force. The probability of an interaction decreases exponentially with the mass of the exchanges particle.

$$\Delta E\Delta t = mc^2\Delta t \geq \frac{h}{4\pi} \rightarrow range = c\Delta t = \frac{h}{4\pi cm}$$

A summary of the forces of nature

Force	Strength	Carrier	Range (m)
Strong	1	Gluon-quarks Mesons-protons/neutrons	10^{-15} size of a proton
Electromagnetic	1/137	photon	infinite
Weak	10^{-6}	Vector Bosons	10^{-16} Only 0.1 width of proton
Gravity	$6\text{x}10^{-39}$	Graviton (?)	infinite

Atomic Nuclei and Elements



The number of protons determine the element (oxygen)
The number of neutrons+protons determine the atomic mass (16 as shown)

This nucleus is O-16

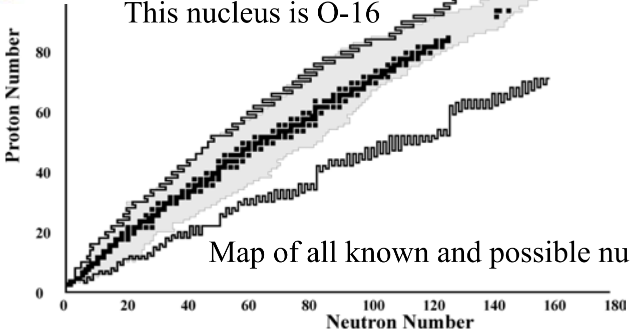


Chart of nuclides

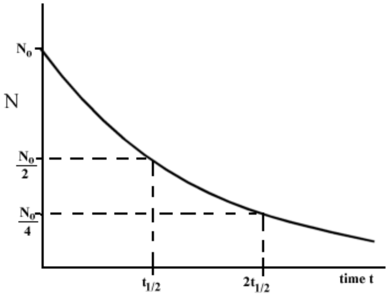
Map of all known and possible nuclei

Radioactive decay – common in our environment

There are many types. The most common are:
- beta-decay where a neutron (proton) changes into a proton (neutron) by the weak force. An example of this is 40-K decay to 40-Ca or 40-Ar.
- alpha-decay where a nucleus spits out a helium nucleus as a result of the coulomb and strong forces. An example is the decay of Uranium.
- gamma-decay where a nucleus gives off energy by emitting a gamma-ray photon by the coulomb force
- fission where a large nucleus breaks into two smaller pieces. Used to power nuclear reactors (strong force)
- The SI unit is the Becquerel (Bq), which is 1 decay/s.

Half life

Radioactive decay is governed by the rules of quantum mechanics. If we start with N atoms, in the time of one half-life on average half will have decayed. In the next half life, half of those remaining will have decayed, and so on.



$$N(t) = N_0\left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

$$N(2t_{1/2}) = N_0\left(\frac{1}{2}\right)^2 = \frac{N_0}{4}$$

Sample problem

Suppose we find a sample of material that has 43.5% of the expected amount. The half life of the material is 23 days. What is the best estimate for the age of the sample?

$$N(t) = N_0\left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}} \qquad \frac{N}{N_0} = 0.435 = \left(\frac{1}{2}\right)^{\frac{t}{23d}}$$

$$\ln(0.435) = \frac{t}{23.0d}\ln(1/2) \rightarrow t = \frac{23.0d \cdot \ln(0.435)}{\ln(1/2)} = 27.6d$$

Examples used in science

- C-14 (half life = 5730 y) is used to date archeological objects. Normal living material has a certain amount of C-14, which is produced in the atmosphere.
- K-40 (half life = 1.25 Gy) is used to date rocks. It decays 10% of the time to Ar-40 which is not naturally found in most rocks.
- U-238 (half life = 4.5 Gy) is used to date the Earth, Sun and other stars. This is one of the ways we estimate that the Earth is 4.5 Gy old.