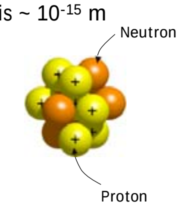
From the Last Time

- Superconductor = zero-resistance material
  - Critical temperature
  - Critical current
  - Critical magnetic field -
  - no superconductivity outside of critical ranges
- Superconductor types
  - Type I - superconductivity at low temperature only
  - High T superconductors
  - Type II - superconductivity in high magnetic fields
- Meissner effect = exclusion of magnetic field

Today: The Nucleus

Physics of the Nucleus

- Nucleus consists of protons and neutrons densely combined in a small space (~10^{-14} m)
  - Protons have a positive electrical charge
  - Neutrons have zero electrical charge (are neutral)
- Spacing between these **nucleons** is ~ 10^{-15} m
- Size of electron orbit is 5×10^{-11} m
- Nucleus is 5,000 times smaller than the atom!

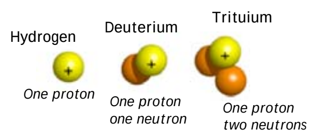


Question

Hydrogen is the element with one electron. Which of the following is NOT the nucleus of an isotope of hydrogen?

A. One proton
B. One proton and one neutron
C. Two protons and one neutron

All with one proton and one electron



Neutrons and Protons

Neutron: zero charge (neutral)
Proton: positive charge (equal and opposite to electron)

- The number of protons in a nucleus is the same as the number of electrons since the atom has a net zero charge.
- The number of electrons determines which element it is.
  - 1 electron → Hydrogen
  - 2 electrons → Helium
  - 6 electrons → Carbon
- How many neutrons?

Carbon

- Example: carbon
- Carbon has 6 electrons (*Z*=6), this is what makes it carbon.
- Zero net charge so there are 6 protons in the nucleus.
- Most common form of carbon has 6 neutrons in the nucleus. Called ^{12}C

A_{number}^{mass} 12 ; Z_{number}^{atomic} 6 ; $^{12}_{6}C$

$N_{number}^{neutron} = A - Z$

Another form of Carbon has 6 protons, 8 neutrons in the nucleus. This is ^{14}C.

Isotopes

- Both ^{12}C and ^{14}C have same chemical properties.
- This is why they are both called carbon. Same # electrons and same # protons in nucleus.
- But the nuclei are different. They have different number of neutrons. These are called isotopes.
- Difference is most easily seen in the binding energy.
- Nuclei that are bound more tightly are less likely to 'fall apart'.
- In fact ^{14}C is radioactive or unstable.

Nuclear Force

- So what holds the nucleus together?
- Coulomb force? Gravity?

- Coulomb force only acts on charged particles
  - *Repulsive* between protons, and doesn't affect neutrons at all.
- Gravitational force is much too weak. Showed before that gravitational force is much weaker than Coulomb force.

The Strong Nuclear Force

- New force.
- Dramatically stronger than Coulomb force.
- But not noticeable at large distances.
  - I.e. Atoms do not attract each other.
- Must be qualitatively different than Coulomb force.
- How can we characterize this force?
  - Range is on the order of the size of nucleus.
  - Stronger than Coulomb force at short distances.

Estimating the strong force

The Coulomb attraction energy (~10 eV) binds the hydrogen atom together.

Protons in nucleus are 50,000 times closer together than electron and proton in hydrogen atom.

The Coulomb energy is inversely proportional to the separation.

Attractive energy must be larger than the Coulomb repulsion, so nuclear binding energies are greater than.

A. 5000 eV

B. 500,000 eV

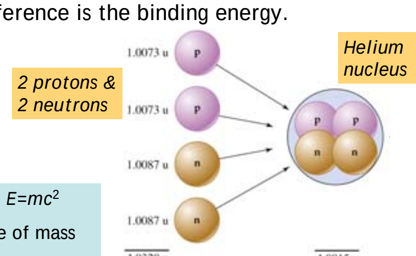
C. 5,000,000 eV

A strong nuclear force

- Electron is bound in atom by Coulomb attraction. Strength ~10 eV.
- Protons in nucleus are 50,000 times closer together. Coulomb repulsion ~500,000 eV = 0.5 MeV
- Nuclear force must be much stronger than this.
- Experimentally, the strong nuclear force is ~ 100 times stronger than Coulomb force
- Nucleons are bound in nucleus by ~ 8 MeV / nucleon (8,000,000 eV / nucleon)

Nuclear Binding Energy

- Mass of nucleus is less than mass of isolated constituents.
- The difference is the binding energy.



Arises from $E=mc^2$

Equivalence of mass and energy.

Nuclear binding energy

- Helium nucleus has less mass than sum of two neutrons & two protons
- Why is this?
- The 'missing mass' makes up the 'binding energy'

^{12}C has a mass of 12.00000 u (1 u = 1.661×10^{-27} kg)

'Missing mass' in He case is

$$\begin{array}{r} 4.0320\ u \\ -\ 4.0015\ u \\ \hline 0.0305\ u \end{array} = 5.06\times10^{-29}\ kg$$

Nuclear fusion

5.06×10^{-29} kg of mass released as energy when protons & neutrons combined to form Helium nucleus.

This is the 'binding' energy of the nucleus.

$E = mc^2 = (5.06\times10^{-29}\text{ kg})\times(3\times10^{8}\text{ m/s})^2 = 4.55\times10^{-12}\text{ J}$

$= 28$ MeV $= 28$ million electron volts!

Binding energy/nucleon = 28 MeV / 4 = 7 MeV

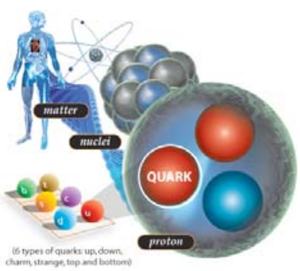
Principle of nuclear fusion:
Energy released when 'manufacturing' light elements.

Nucleus bound very tightly

- To change properties of nucleus, need much larger energies than to change electronic states.
- Properties of nucleus that might change are
  - Exciting nucleus to higher internal energy state
  - Breaking nuclei apart
  - Fusing nuclei together.
- Required high energies provided by impact of high-energy…
  …protons, electrons, photons, other nuclei
- High energies produced in an accelerator facility

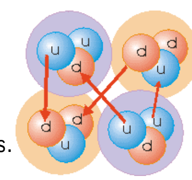
Nucleons are not fundamental

- We now know that protons and neutrons are not fundamental particles.
- They are composed of quarks, which interact by exchanging gluons.



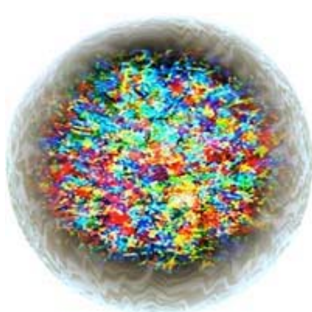
The 'new' nuclear force

- Strong force is actually between quarks in the nucleons.
- Quarks exchange gluons.
- Most of the strong force glues quarks into protons and neutrons.
- But a fraction of this force leaks out, binding protons and neutrons into atomic nuclei



Visualizing a nucleus

A nucleon made up of interacting quarks.



A nucleus of several nucleons, with their interacting quarks

Particles in the nucleus

Can still, however, get an approximate description of nucleus with protons and neutrons.

- Proton
  - Charge +e
  - Mass 1.6726×10^{-27} kg
  - Spin 1/2
- Neutron
  - Charge 0
  - Mass 1.6749×10^{-27} kg
  - Spin 1/2

Both are spin 1/2 particles -> Fermions

One particle per quantum state

What makes a nucleus stable?

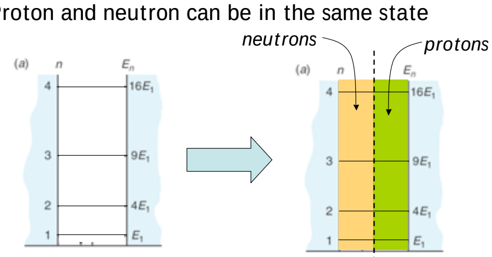
- A nucleus with lower energy is more stable.
- This is a general physical principle, that systems tend to their lowest energy configurations
  - e.g. water flows downhill
  - Ball drops to the ground
  - Hydrogen atom will be in its ground state
- Same is true of nucleus
- Observed internal configuration is that with the lowest energy.

Quantum states in the nucleus

- Just like any quantum problem, proton and neutron states in the nucleus are quantized.
- Certain discrete energy levels available.
- Neutrons and protons are Fermions
  - 2 protons cannot be in same quantum state
  - 2 neutrons cannot be in same quantum state
- But neutron and proton are distinguishable, so proton and neutron can be in same quantum state.

Proton and Neutron states

- Various quantum states for nucleons in the nucleus
- Proton and neutron can be in the same state

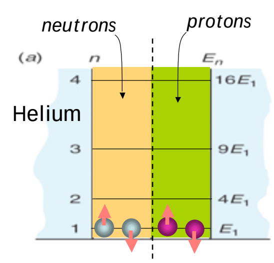


Nucleon quantum states in the nucleus

Schematic indicating neutron & proton can occupy same state

Populating nucleon states

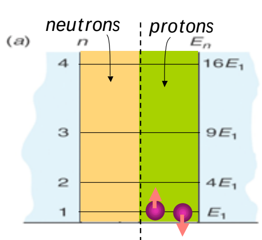
- Various quantum states for nucleons in the nucleus
- Similar to the hydrogen atom: one electron in each quantum state.
- Two states at each energy (spin up & spin down)



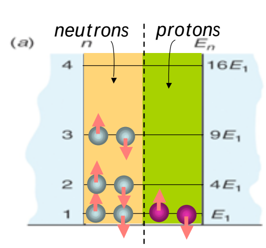
This is ^{4}He, with 2 neutrons and 2 protons in the nucleus

Other helium isotopes

Too few neutrons, -> protons too close together. High Coulomb repulsion energy



Too many neutrons, requires higher energy states.



Nuclear spin

- Since nucleus is made of protons and neutrons, and each has spin, the nucleus also has a spin (magnetic moment).
- Can be very large.
- Turns out to have a biological application.
- Water is ubiquitous in body, and hydrogen is major element of water (H_2O)
- Nucleus of hydrogen is a single proton.
  - Proton has spin 1/2

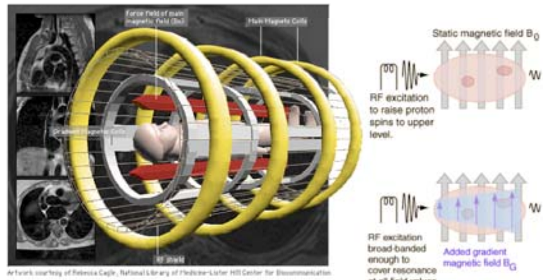
Magnetic resonance imaging

- 80% of the body's atoms are hydrogen atoms,
- Once excited by the RF signal, the hydrogens will tend to return to their lower state in a process called "relaxation" and will re-emit RF radiation at their Larmor frequency. This signal is detected as a function of time, and then is converted to signal strength as a function of frequency by means of a Fourier transformation.

Figure 1
Randomly oriented
nuclear magnetic moments

Figure 2
Nuclear magnetic moments
in the presence of an external field

Magnetic resonance imaging



MRI detects photon resonance emission and absorption by the proton spins.

Energy of nucleus

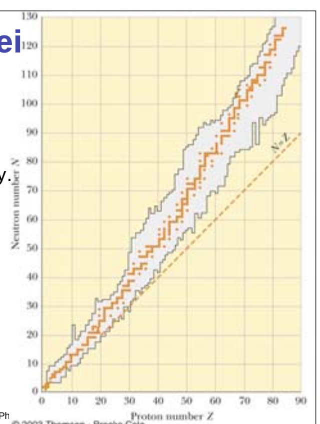
- Most stable nuclei have about same number of protons as neutrons.
- Nucleons attracted by nuclear force, so more nucleons give more attractive force.
  - This lowers the energy.
- But more nucleons mean occupying higher quantum states, so higher energy required.
- Tradeoff gives observed nuclear configurations

Radioactivity

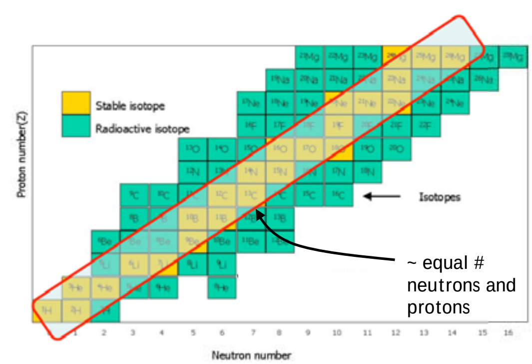
- Most stable nuclei have about same number of protons as neutrons.
- If the energy gets too high, nucleus will spontaneously try to change to lower energy configuration.
- Does this by changing nucleons inside the nucleus.
- These nuclear are unstable, and are said to decay.
- They are called radioactive nuclei.

Stability of nuclei

- Dots are naturally occurring isotopes.
- Larger region is isotopes created in the laboratory.
- Observed nuclei have ~ *N=Z*
- Slightly fewer protons because they cost Coulomb repulsion energy.



Radioactive nuclei



~ equal # neutrons and protons

Radioactive decay

- Decay usually involves emitting some particle from the nucleus.
- Generically refer to this as radiation.
- Not necessarily electromagnetic radiation, but in some cases it can be.
- The radiation often has enough energy to strip electrons from atoms, or to sometimes break apart chemical bonds in living cells.

Discovery of radioactivity

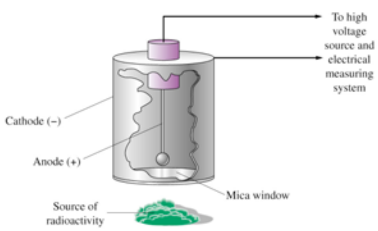
- Accidental discovery in 1896
- Henri Becquerel was trying to investigate x-rays (discovered in 1895 by Roentgen).
- Exposed uranium compound to sunlight, then placed it on photographic plates
- Believed uranium absorbed sun's energy and then emitted it as x-rays.
- On the 26th-27th February, experiment "failed" because it was overcast in Paris.
- Becquerel developed plates anyway, finding strong images,
- Proved uranium emitted radiation without an external source of energy.

Detecting radiation

- A Geiger counter
- Radiation ionizes (removes electrons) atoms in the counter

Leaves negative electrons and positive ions.

Ions attracted to anode/cathode, current flow is measured

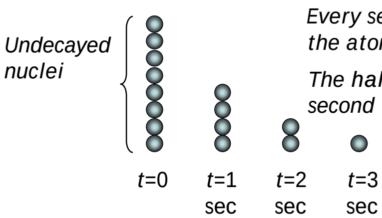


A random process

- The particle emission is a random process
  - It has some probability of occurring.
- For every second of time, there is a probability that the nucleus will decay by emitting a particle.
- If we wait long enough, all the radioactive atoms will have decayed.

Radioactive half-life

- Example of random decay.
- Start with 8,000 identical radioactive nuclei
- Suppose probability of decaying in one second is 50%.



Every second, half the atoms decay

The half-life is one second

Radioactive decay question

A piece of radioactive material is initially observed to have 1,000 decays/sec.

Three hours later, you measure 125 decays / second.

The half-life is

A. 1/2 hour
B. 1 hour
C. 3 hours
D. 8 hours

In each half-life, the number of radioactive nuclei, and hence the number of decays / second, drops by a factor of two.

After 1 half life, the decays/sec drop to 500.
After 2 half lives it is 250 decays/sec
After 3 half lives there are 125 decays/sec.

Another example

- ^{232}Th has a half-life of 14 billion years
- Sample initially contains 1 million ^{232}Th atoms
- Every 14 billion years, the number of ^{232}Th nuclei goes down by a factor of two.