L-35 Modern Physics-3
Nuclear Physics

- L-35 Nuclear structure
  - what's inside the nucleus
  - what holds it together
  - isotopes
  - radioactivity
  - half-life

- L-36 Nuclear energy
  - nuclear fission
  - nuclear fusion
  - nuclear reactors
  - nuclear weapons

The first two lectures on Modern Physics dealt mainly with processes involving electrons. The next two lectures deal with processes involving the nucleus of the atom.

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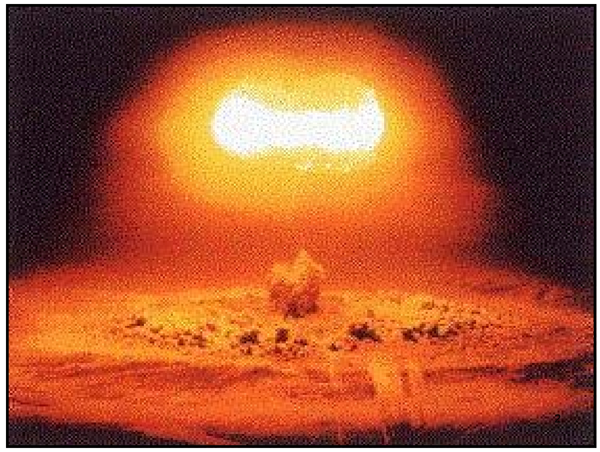
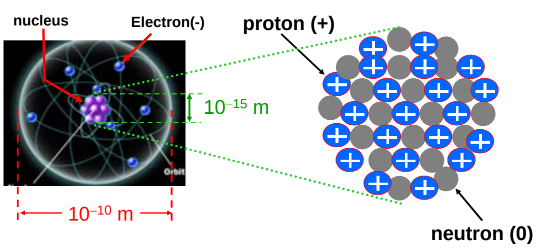


Structure of the nucleus



The diameter of the nucleus is about 10^{-5} times *smaller* than the diameter of the atom.

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The fundamental particles

PARTICLE	DISCOVERER	YEAR
Electron	J. J. Thompson	1896
Proton	E. Rutherford	1917
Neutron	J. Chadwick	1935

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The atom and the nucleus

- the electron and proton have the same charge value, but the electron is – and the proton is +
  - $Q_e = -Q_p$ (charge value is 1.6×10^{-19} C)
  - the neutron has *no charge*, $Q_n = 0$
- the attractive force between the + protons and the – electrons holds the atom together
- the neutron and proton have about the same mass, and are about 2000 times more massive than the electron
  - $m_p \approx m_n$, $m_p \approx 2000 \bullet m_e = 1.67 \times 10^{-27}$ kg
  - the nuclear mass is about 99.9% of the atoms mass
- What role do the neutrons play?

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Nuclear Terminology

- **Atomic number Z** = the number of protons in the nucleus, which is equal to the number of electrons in the atom, since atoms are electrically neutral. The atomic number is what distinguishes one chemical element from another
- **Neutron number N =** the number of neutrons in the nucleus, atoms with the same Z but different N's are called ***isotopes***
- ***Atomic mass number A = Z + N*** = the number of protons + neutrons, A determines the mass of the nucleus

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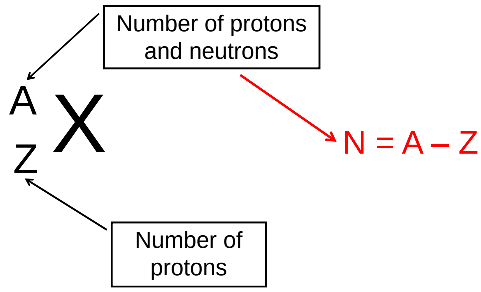
Symbol for the nucleus of element X



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Nuclei having the same number of protons, but different numbers of neutrons are called *isotopes*		
Hydrogen	${}^{1}_{1}H$	1 proton, 0 neutrons
Deuterium	${}^{2}_{1}H$	1 proton, 1 neutron
Tritium	${}^{3}_{1}H$	1 proton, 2 neutrons
Helium-3	${}^{3}_{2}He$	2 protons, 1 neutrons
He-4 (a particle)	${}^{4}_{2}He$	2 protons, 2 neutrons
Carbon	${}^{12}_{6}C$, ${}^{13}_{6}C$, ${}^{14}_{6}C$	6 protons, 6, 7, 8 neutrons
Uranium-235	${}^{235}_{92}U$	92 protons, 235 – 92 = 143 neutrons

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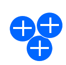
What holds the nucleus together? The *nuclear glue!*

- The nucleus contains positively charged protons, all stuck in a very small volume, repelling each other
- so what keeps the nucleus together?
- the nuclear force (glue)
- this is where the neutrons play a role



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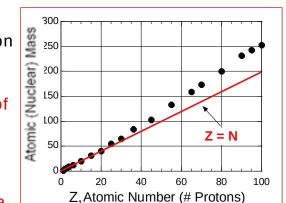
the nuclear (strong) force

- protons and neutrons exert an attractive nuclear force on each other when they are very close to each other.
- However the nuclear force of the protons alone isn't enough to hold the nucleus together, but the neutrons add more **"nuclear glue"** without adding the repulsive electric force.
- stable light (Z < 50) nuclei have as many neutrons as protons
- *stable heavy nuclei (Z > 50) have more neutrons than protons, often many more*



Since the proton and neutron have roughly the same mass, the Nuclear mass is about the mass of the protons plus the mass of the neutrons. Nuclei with the same number of protons and neutrons lie on the straight line. *As Z Increases, N increases more rapidly*.

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What is radioactivity?

- in some nuclei, there is a very delicate balance between electric repulsion and nuclear attraction forces.
- some nuclei are just on the verge of falling apart and need to release some excess energy → an *unstable* nucleus
- an unstable nucleus can disintegrate spontaneously by emitting certain kinds of particles or very high energy photons called gamma rays (γ's) → **radioactivity**

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Natural radioactivity

- some nuclei are naturally radioactive and give off either alpha rays (He nucleus), bets rays (electrons) or gamma rays (high energy photons) *randomly*
- the particles are classified in terms their ability to penetrate matter, gammas are the most penetrating and alphas the least penetrating. Gammas can go right through several inches of lead!
- how do we detect these particles – using a **Geiger counter**

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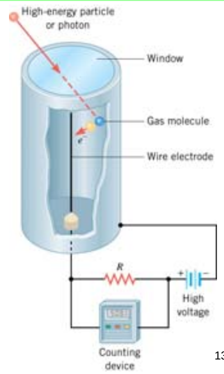
Geiger Counters

- a gas filled metal cylinder with a positively charged wire down the center
- the γ, β, or α ray ionizes the gas, and the resulting electrons are collected by the positive wire
- the result is a pulse (*blip*) of current which is converted to a sound pulse



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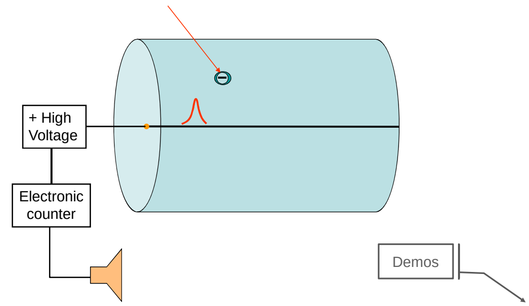
Geiger tube



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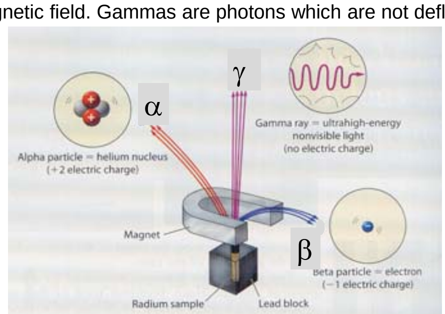
Alpha, beta and gammas in a magnetic field

Alpha and beta particles are charged, so they are deflected by a magnetic field. Gammas are photons which are not deflected.



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Half-Life of radioactive nuclei

- the decay of radioactive nuclei is a random process. If you have a sample of many unstable nuclei, you cannot predict when any one nuclei will disintegrate
- if you start with N_0 radioactive nuclei now, the **HALF LIFE $T_{1/2}$** is defined as the time for half of the nuclei present to disintegrate.

$$N(t) = \frac{1}{2^{t/T_{1/2}}} N_0$$

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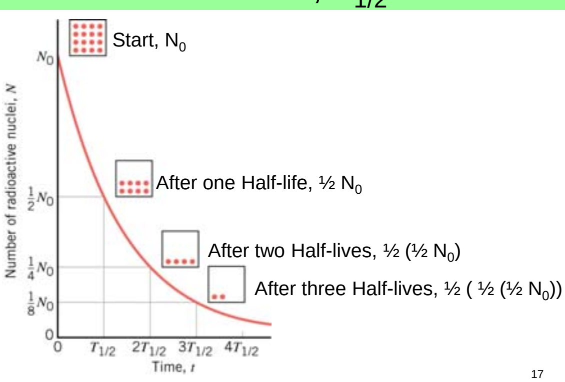
Half Life, $T_{1/2}$



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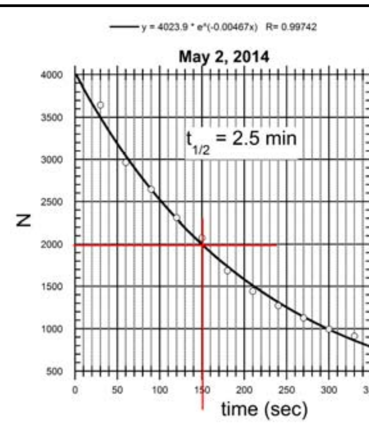

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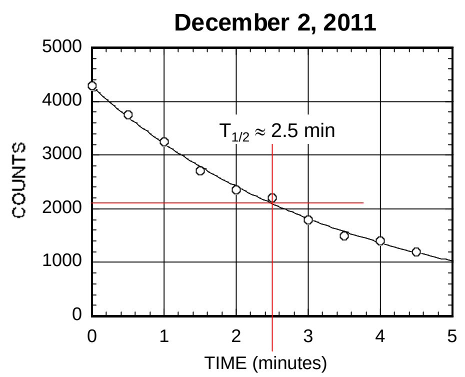

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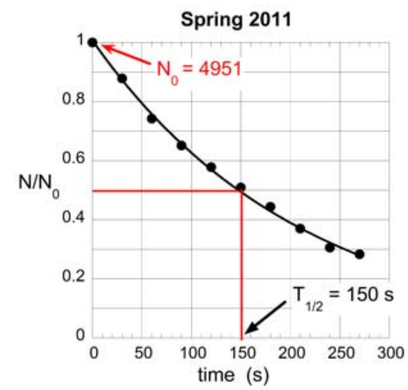

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Nuclear reactions

- ${}^{222}_{86}\mathrm{Rn}$ decays to ${}^{218}_{84}\mathrm{Po}$ by emitting an alpha particle ${}^{4}_{2}\mathrm{He}$ with a half life of 3.8 days

$$\boxed{{}^{222}_{86}Rn \rightarrow {}^{218}_{84}Po + {}^{4}_{2}He}$$

- If we started with 20,000 atoms of Rn-222, then in 3.8 days we would have 10,000 atoms of Rn-222 and 10,000 atoms of Po-218
- In 7.6 days we would have 5000 atoms of Rn-222, in 11.4 days, 2500 Rn-222's, etc
- Cobalt-60, $T_{1/2}$ = 5.27 years; decays by emitting betas and gammas

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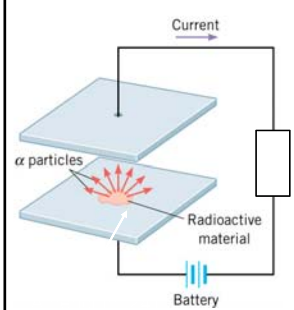
Smoke detectors use radioactivity



Smoke detectors have a radioactive alpha emitting source. The alpha particles ionize the air in the detector creating a current.
If smoke particles enter the detector they can interfere with the current causing it to drop, which sets off the alarm.

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Carbon Dating

- As soon as a living organism dies, it stops taking in new carbon. The ratio of carbon-12 to carbon-14 at the moment of death is the same as every other living thing, but the carbon-14 decays and is not replaced
- The carbon-14 decays with its half-life of 5,700 years, while the amount of carbon-12 remains constant in the sample
- By measuring the ratio of carbon-12 to carbon-14 in the sample and comparing it to the ratio in a living organism, it is possible to determine the age of a formerly living thing fairly precisely.
- e. g. at t = 10,000 years, 17% of C-14 will still remain in a sample.

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Natural Radioactivity

- Radon gas ${}^{222}_{86}\mathrm{Rn}$

  occurs in soil and can leak into basements. It can attach to dust particles and be inhaled.
- cosmic rays – energetic particles from the cosmos enter the atmosphere and decay

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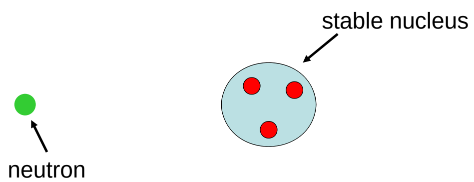
Nuclear activation

Some nuclei that are stable can be *activated* (made unstable) by bombarding them with neutrons.



Cyclotron facility at UIHC

- **Nuclear medicine**
- A **cyclotron** is a device which accelerates charged particles producing beams of energetic protons
- These protons are used to bombard materials to produce radioisotopes: unstable nuclei with a short half-life
- The radioisotopes are implanted in patients for either diagnostic purposes or for cancer treatment