L 36 Modern Physics

• [L36] Nuclear physics
  – what’s inside the nucleus and what holds it together
  – what is radioactivity
  – carbon dating
• [L37] Nuclear energy
  – nuclear fission
  – nuclear fusion
  – nuclear reactors
  – nuclear weapons

Structure of the nucleus

The diameter of the nucleus is about 10 million times smaller than the overall diameter of the atom.

The atom and the nucleus

• the attractive force between the positive protons and the negative electrons is what holds the atom together
• the neutrons and protons have about the same mass, and are each about 2000 times more massive than the electrons
• the nucleus accounts for about 99.9% of the total mass of the atom
• the neutrons have no charge, so what role do they play?

The structure of the nucleus

• terminology
  – atomic number \( Z \) – the number of protons in the nucleus, this is equal to the number of electrons in the atom, since atoms are electrically neutral. The atomic number is what distinguishes one atom from another
  – \( N \) = 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

Symbol for a nucleus for a chemical \( X \)

Number of protons and neutrons

Number of protons
examples

- Hydrogen $^1{}\text{H}$: 1 proton, 0 neutrons
- Deuterium $^2{}\text{H}$: 1 proton, 1 neutron
- Tritium $^3{}\text{H}$: 1 proton, 2 neutrons
- Alphas $^2{}\text{He}$: 2 protons, 2 neutrons
- Carbon $^{12}{}\text{C}$, $^{13}{}\text{C}$, $^{14}{}\text{C}$: 6 protons, 6, 7, 8 neutrons
- Uranium-235 $^{235}{}\text{U}$: has 235 – 92 = 143 neutrons

What holds the nucleus together?  
the nuclear glue

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

What is radioactivity?

- in some nuclei, there is a very delicate balance between electric repulsion and nuclear attraction forces.
- sometimes the nucleus is just on the verge of falling apart and needs 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

the nuclear force

- in addition to the repulsive electric force between the protons, the protons and neutrons also exert an attractive nuclear force on each other when they are very close to each other.
- However the nuclear force of the protons isn’t enough to hold the nucleus together, but the neutrons add more “nuclear glue” without adding the repulsive electric force.
- stable nuclei have as many neutrons as protons or more neutrons than protons

Natural radioactivity

- some nuclei are naturally radioactive and give off either alpha rays (He nucleus), beta 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

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
Gamma Knife Radiosurgery

Gamma rays (from Cobalt-60) are focused to a point in the brain to kill tumors.

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 of them will disintegrate.
- If you start with \( N_0 \) radioactive nuclei now, then the **half-life** \( T_{1/2} \) is defined as the time for half of the nuclei present to disintegrate.
Nuclear reactions

- $^{222}\text{Rn}$ decays to $^{218}\text{Po}$ by emitting an alpha particle [$^4\text{He}$] with a half life of 3.8 days.
- 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.
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.

Dating a Fossil

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 looking at 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.

Natural Radioactivity

- Radon gas $^{222}_{86}$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

Nuclear activation

- Some nuclei that are stable can be activated (made unstable) by exposing them to neutrons.

Cyclotron/PET facility at UIHC

- A cyclotron is a device used to produce the radioisotopes (radioactive chemical elements) which are used to synthesize the radiopharmaceuticals (the actual substances which are used to make the functional images of the body).
- PET- positron emission tomography