Radioactive Dating Game

Atom: Positive charge and mass are concentrated in the nucleus of an atom. Each proton carries one unit of fundamental charge and makes the nucleus positive. The number of protons in the nucleus is the same as the number of electrons outside the nucleus, both of which are equal to the atomic number. Nuclei of isotopes of an element contain the same number of protons but have different numbers of neutrons.

Different types of atoms exist for some elements—they show the same chemical properties but have different mass. These species are called **isotopes**. The average mass of an atom of an element is given as:

$$\text{Average mass of an Atom of element} = \frac{\left\{ \begin{array}{l} \text{Relative abundance X mass of + relative abundance x mass of} \\ \text{of isotope 1} \quad \text{isotope 1} \quad \text{of isotope 2} \quad \text{isotope 2} \end{array} \right\}}{100}$$

Nuclides with the same number of neutrons but different atomic number are called **isotones**.

Closely packed, positively charged protons in the tiny nucleus tend to repel each other (**Coulomb's law**). It is the **strong nuclear force** existing between protons and neutrons in the nucleus that overcomes this electrostatic repulsion between protons. It is repulsive at a very small distance but attractive over slightly larger distances. The energy associated with the strong nuclear force is called the **binding energy**.

When an atom has enough binding energy to hold the nucleus together permanently, it is considered to be **stable**. Many stable nuclei have equal number of protons and neutrons and are found in the "lighter" section of the periodic table. When the strong nuclear forces do not generate enough binding energy to hold the nucleus together permanently, the nucleus is considered **unstable** and is found to be "**radioactive**". Such nuclei either have more neutrons than protons and are called "neutron-rich" or have more protons than neutrons and are called "proton-rich". To become stable and attain a balance in the numbers of neutrons and protons, these unstable nuclei give off neutrons or protons via **radioactive decay**.

Radioactivity is the process where unstable nuclei spontaneously form stable nuclei by releasing energetic subatomic particles, which along with their associated energy, comprise radiation. There are three types of radioactive decay:

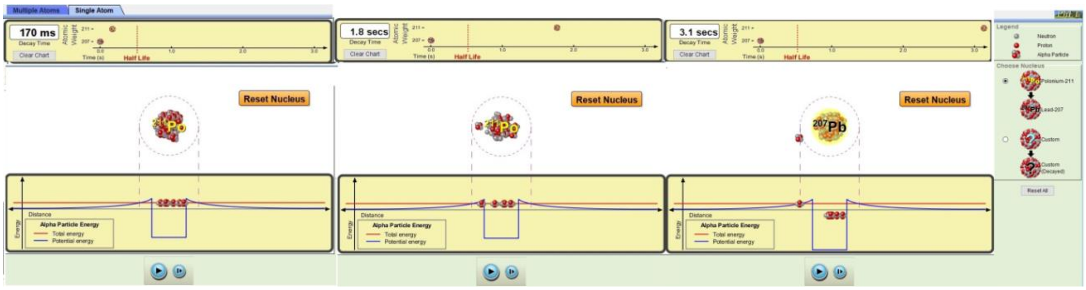
- **α-decay**: an α particle is a helium nucleus made up of 2 protons and 2 neutrons. As there are no electrons, α particles are positively charged particles moving at high speeds. They are released by high mass, proton-rich unstable nuclei. For example, $^{211}Po \rightarrow {}^{207}Pb$
- **β-decay**: Neutrons in the nucleus split to form a proton, a β particle (β^-) and an antineutrino. Inside the nucleus, protons decay to neutrons, a positron (positive β particle) and a neutrino. For example, $^{14}C \rightarrow {}^{12}C$, $^{3}H \rightarrow {}^{3}He$
- **γ-decay**: Nuclei in excited states spontaneously decay to ground state (or lower energy state) by emitting a photon with energy equal to the difference in the two energy levels. This energy (MeV) is radiation of very short wavelength and is emitted to bring a daughter nucleus from excited to ground state after α or β decay occurs.

While we cannot predict when an individual radioactive nucleus will decay, we can measure the time taken for half of the nuclei in a radioactive material to decay. This is called the **half-**

life of the material. In this time, the count rate of a radioactive sample will fall to half of the starting value. Radioactive counts are measured using a **Geiger-Muller tube** which absorbs the radiation and converts it into an electrical pulse. The pulse triggers a counter and is displayed as a count rate.

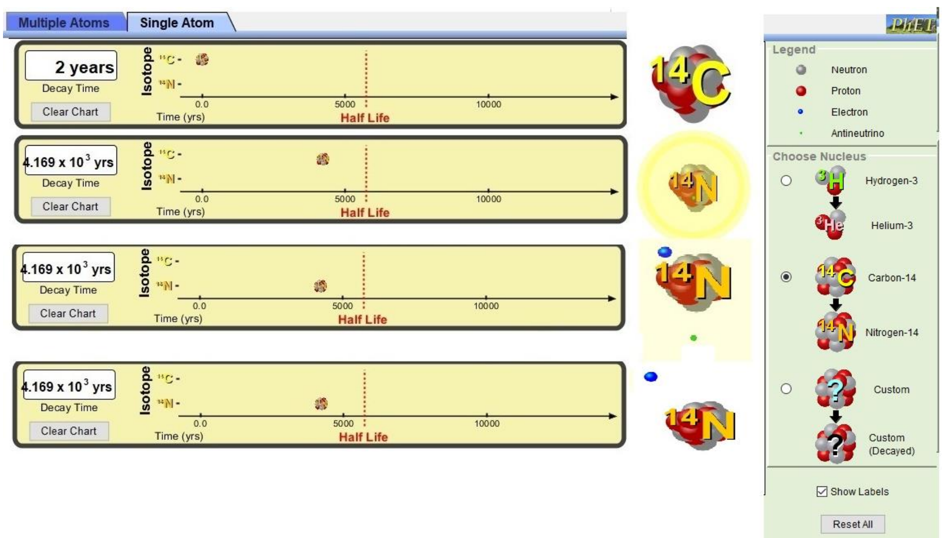
For example, if a radioactive isotope has a half-life of 5 days and there are 1000 unstable nuclei in the sample. Over 5 days, 5000 of these nuclei will undergo radioactive decay and become stable nuclei. Over the next 5 days, 2500 of the remaining unstable nuclei will undergo radioactive decay. In the following 5 days, 1250 of the unstable nuclei will decay and so on. If you plot number of radioactive nuclei (or % counts or something that quantifies the unstable nuclei) versus time, you get a radioactive decay curve.

Alpha decay



The PhET simulation, **Alpha Decay**, describes alpha decay through an example: $^{211}Po \rightarrow {}^{207}Pb$. ^{211}Po emits an alpha particle ($^{4}He_2$ nucleus) and is converted into ^{207}Pb. The **Single Atom** screen describes the **tunnel effect** in **alpha decay**. The alpha particle to be emitted by ^{211}Po is present along with other nucleons (protons and neutrons inside the nucleus). As discussed earlier, although there is electrostatic repulsion between the protons, the strong nuclear force binds the nucleons together inside the nucleus. They are "trapped" inside the blue well shown below the nucleus in the Energy vs Distance graph. But the alpha particle can "tunnel" its way out of the well and once it crosses the barrier of the well, it can escape the strong nuclear force that binds it to the other nucleons and be emitted during the process of alpha decay. Thus, the graph shows how the alpha particle leaves the blue well, leaving behind ^{207}Pb.

Beta decay



Radioactive or **radiometric dating** is used to date bones, wood, rocks and archaeological materials. **Carbon** has two isotopes, C-12 (stable) and C-14 (unstable). N-14 in the upper atmosphere is broken down by cosmic rays to give C-14 which comes to the lower atmosphere via storms. C-14 is rapidly oxidized to CO_2 (like C-12) and so all living organisms on Earth that take in CO_2, also contain C-14 atoms. Even if C-14 decays, it is continuously being absorbed so the ratio of C-14 to C-12 in any organism is the same as the atmospheric ratio. But when organisms die, they don't take in any carbon. So the unstable C-14 now decays to N-14 in the organism and emits a β particle. C-14 levels and ratio of C-14 to C-12 decrease. Half-life of C-14 is 5730 years and by measuring the ratio of C-14 in any sample and comparing it to the amount of a recently deceased sample, you can determine its date (that is, how long it's been dead). Besides radioacarbon dating, K-Ar dating and Ur-Pb dating are also widely used.

Uranium-238 decays into lead-206 through a series of alpha and beta decays called the **uranium-238 decay series**. The entire series takes around 6.5 billion years to complete. Look up this series in books or the Internet.

Tips: 1 million is 1,000,000 (*i.e.*, 10^6)
1 billion is 1,000,000,000 (*i.e.*, 10^9)

1.3 million is 1,300,000