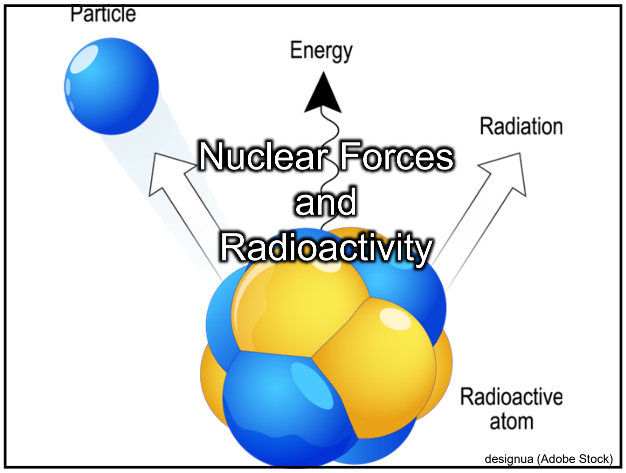
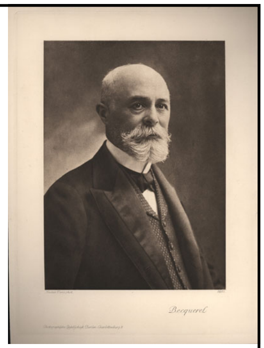
Nuclear Forces and Radioactivity



- 1896: Antoine Henri Becquerel (French) noticed that when a uranium-rich mineral called pitchblende was placed on a completely opaque envelope containing a photographic plate, it darkened spots on the photographic plate.

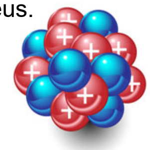


Portrait of Antoine-Henri Becquerel. Photogravure by Photographische Gesellschaft, Berlin (Photographic company), published by Photographische Gesellschaft, Berlin (Photographic company). After Paul Nadar, 1856-1939. Smithsonian Image Id: SIL-SIL14-B2-08 (Public Domain)

- Becquerel reasoned that the pitchblende must emit invisible rays capable of penetrating the opaque material.
- It was soon evident that Becquerel's rays originate in the nuclei of the atoms and have other unique characteristics.

Nuclear Stability

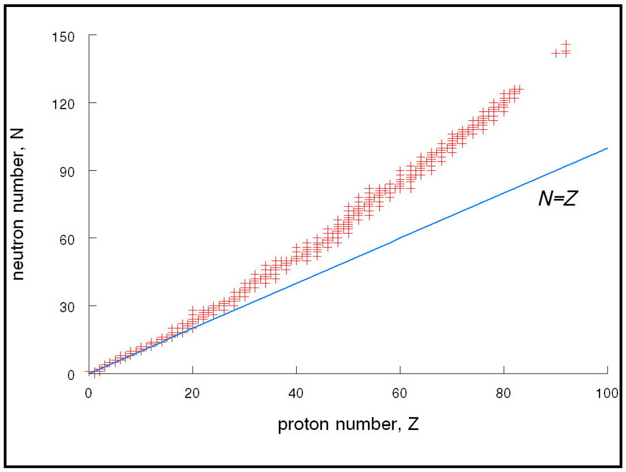
- A variety of experiments indicate that a nucleus behaves something like a tightly packed ball of nucleons.
  - The radius is approximately $r = r_0 A^{\frac{1}{3}}$, where $r_0 = 1.2 \times 10^{-15}$ m and A is the mass number of the nucleus.



O Sweet Nature (Adobe Stock)

- The nucleus is very small and the positively charged protons exert a tremendous amount of repulsive force on each other.
- The nucleus should blow apart, not stick together.
- The **strong nuclear force** hold the nucleus together.
  - The strong force exists between all nucleons and is much stronger than the electromagnetic force if the separation between the particles is less than 10^{-15} m.

- If, for any reason, the electromagnetic force should overcome the nuclear force, components of the nucleus would be projected outward, creating the radiation that Becquerel discovered.
- An increase in the number of protons increases the repulsive electromagnetic force requiring more neutrons to increase the attractive strong nuclear force.
- An imperfect balance between neutrons and protons can result in a nuclear reaction.



Types of Radioactive Decay

- There are three types of radioactive decay.
- They are distinguished on the basis of their ionizing and penetrating power.
- Called alpha, beta, and gamma radiation (or particles).

Alpha (α)

- The nucleus of a helium atom (2p, 2n).

$$^{226}\mathrm{Ra} \rightarrow {}^{222}\mathrm{Rn} + \alpha$$

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{X} + \alpha$$

Beta Negative (β^-)

- Electron (but not an orbital electron)

$$n \rightarrow p + \underset{\substack{\uparrow \\ \beta^-}}{e^-} + \bar{\upsilon}$$

antineutrino

$$^{14}C \rightarrow {}^{14}N + \beta^- + \bar{\upsilon}$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + \beta^- + \bar{\upsilon}$$

Beta Positive (β^+)

- Positron
  - Identical to an electron but with a positive charge.

$$p \rightarrow n + \underset{\substack{\uparrow \\ \beta^+}}{e^+} + \upsilon$$

neutrino

$$^{19}Ne \rightarrow {}^{19}F + \beta^+ + \upsilon$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X + \beta^+ + \upsilon$$

Electron Capture

- The nucleus absorbs an “orbiting” electron.
- Inside the nucleus, the electron combines with a proton to become a neutron and a neutrino ($e^- + p \rightarrow n + \upsilon$).

$$^{7}Be + e^- \rightarrow {}^{7}Li + \upsilon$$

$$^{A}_{Z}X + e^- \rightarrow {}^{A}_{Z-1}X + \upsilon$$

Gamma (γ)

- Photons with very high energy
- The decaying nucleus is in an excited state

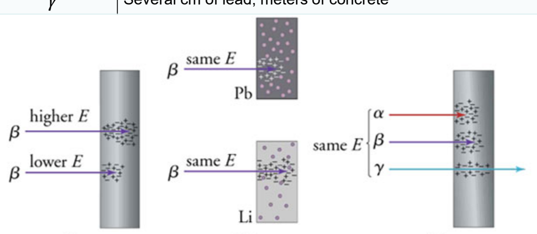
$$^{238}\mathrm{U}^{*} \rightarrow {}^{238}\mathrm{U} + \gamma$$

$$^{A}_{Z}\mathrm{X}^{*} \rightarrow {}^{A}_{Z}\mathrm{X} + \gamma$$

Properties of Radiation

- Alpha
  - Quickly interact with ions in the air and electrons within metals.
  - Short range and short penetrating distance.
- Beta
  - Larger range and larger penetrating distance.
- Gamma
  - Little electric interaction with particles and travel much farther.

Radiation Type	Range
α	A sheet of paper, a few cm of air, fractions of a mm of tissue
β	A thin aluminum plate, tens of cm of tissue
γ	Several cm of lead, meters of concrete



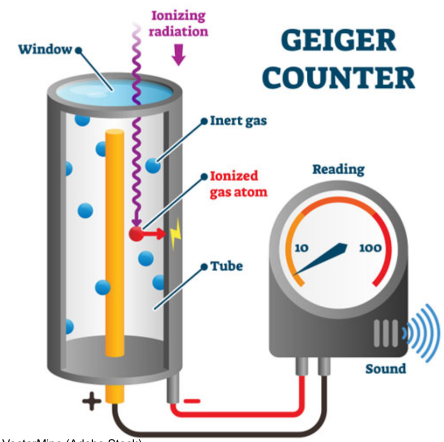
(a) Greater energy means greater range.

(b) Radiation has a smaller range in materials with high electron density.

(c) Range: $\gamma > \beta > \alpha$

Detecting Radiation

- Radiation is detected by using a device known as a Geiger-Muller tube.
  - Voltage applied between the cylinder and wire in a Geiger tube affects ions and electrons produced by radiation passing through the gas-filled cylinder. Ions move toward the cylinder and electrons toward the wire. The resulting current is detected and registered as a count.



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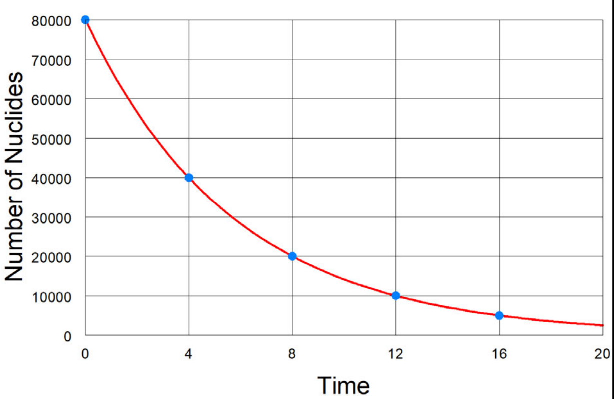
Half-life

- Unstable nuclei decay.
- The nuclei decay one by one randomly over a period of time.
- It is assumed that each nucleus has the same probability of decaying in each second it exists.

- Therefore, we can determine on a probabilistic basis approximately how many disintegrations will occur over a given time period, t.
- The time it takes for half of the nuclei in a sample to disintegrate is known as the half-life, $T_{1/2}$.
- We can determine the half-life of a nuclide by plotting a decay curve.



- After one half-life passes, half of the remaining nuclei will decay in the next half-life.
- Then, half of that amount in turn decays in the following half-life.
- Therefore, the number of radioactive nuclei decreases from N_0 to $\frac{N_0}{2}$ in one half-life, to $\frac{N_0}{4}$ in 2 half-lives, to $\frac{N_0}{8}$ in 3 half-lives, and so on.

- We can, therefore, calculate the number of remaining particles for any number of half-lives, n.

$$N = \frac{N_0}{2^n}$$

- The number of half-lives can be calculated by dividing the decay time, t, by the half-life.

$$n = \frac{t}{T_{1/2}}$$

- Combine these equations.

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

Example

- A sample contains 2×10^{23} particles. The half-life of the sample is 6 hours. How many particles are left after 60 hours?

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

$$N = \frac{2 \times 10^{23}}{2^{\left(\frac{60}{6}\right)}} \quad = 1.95 \times 10^{20} \text{ particles}$$

Measuring Half-life

- Half-life is measured by counting the number of decays that occur over a period of time (activity).
- If the sample has a short half-life, we can measure the activity for short time intervals (seconds).
- If the sample has a long half-life, we must count for longer periods of time (maybe days).