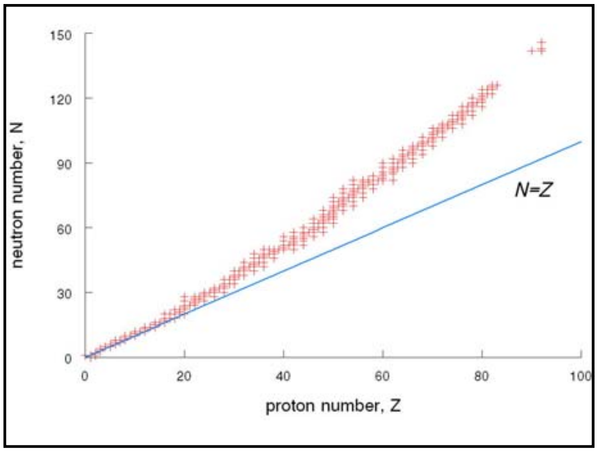
Radioactivity

Why are some nuclei stable and others are unstable?

- There are about 2500 nuclides
- Only about 300 are stable
- As the number of protons in the nucleus increases, the electrostatic repulsion increases
- However, the strong nuclear force does not increase proportionally (it is a short range force)

- Extra neutrons are needed to ensure stability by increasing the nuclear force, but not increasing the electrostatic force
  - However, too many extra neutrons will make the nucleus unstable by favoring decays of neutrons into protons
- In other words, there is a limit to how large a nucleus can get



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)

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

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

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

Beta Positive (β^+)

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

$$p \rightarrow n + \underset{\beta^+}{\underset{\uparrow}{e^+}} + \upsilon\ \nwarrow \text{neutrino}$$

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

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

Electron Capture

- 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

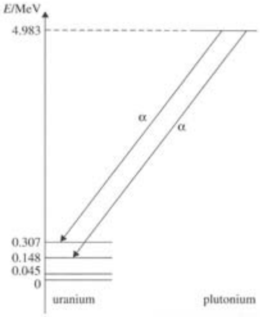
$$^{238}\mathrm{U}^{*} \rightarrow {}^{238}\mathrm{U} + \gamma$$

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

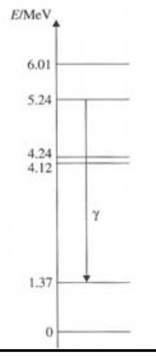
Nuclear Energy Levels

- The nucleus, like the atom, exists in discrete energy levels
- The energies of alpha particles and gamma rays that are emitted by nuclei are discrete
  - (As opposed to beta particles which have a continuous range of energies)

Energy Levels for Plutonium and Uranium



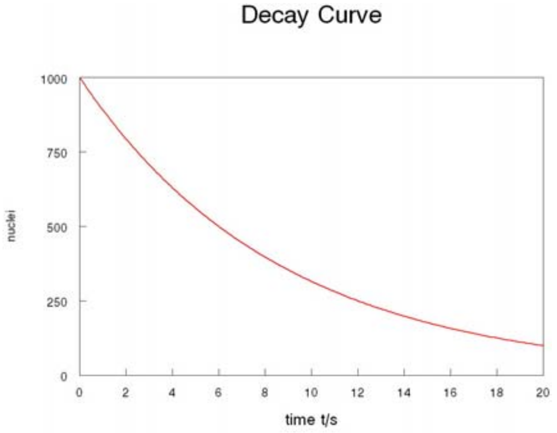
Energy Levels for ^{24}Mg

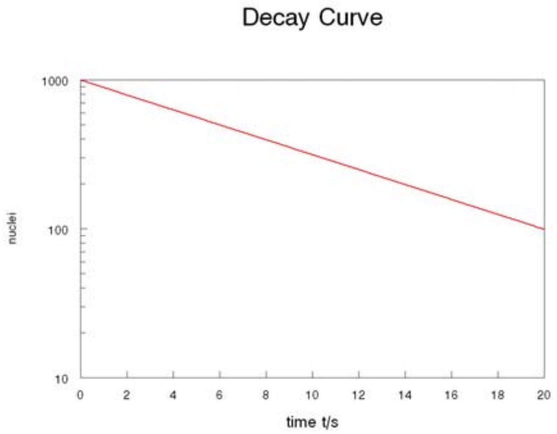


Half-life

- A macroscopic sample of any radioactive isotope consists of a vast number of radioactive nuclei
- 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
- The time it takes for half of the nuclei in a sample to disintegrate is known as the half-life
- We can determine the half-life of a nuclide by plotting a decay curve





The Law of Radioactivity

- The number of nuclei that will decay per second (rate of decay) is proportional to the number of atoms present that have not yet decayed

$$\frac{\Delta N}{\Delta t} \propto -N$$

In other words $\frac{dN}{dt} \propto -N$

So… $\frac{dN}{dt} = -\lambda N$

Decay constant

Solve for N

$$\frac{dN}{N} = -\lambda dt$$

$$\ln N = -\lambda t$$

$$\boxed{N = N_0 \mathrm{e}^{-\lambda t}}$$

Original number of nuclei at t=0

Calculating Half-life

$$N = N_0 \mathrm{e}^{-\lambda t}$$

After one half-life, $T_{1/2}$, half of the nuclei have decayed, so…

$$\frac{N_0}{2} = N_0 \mathrm{e}^{-\lambda T_{\frac{1}{2}}}$$

Solve for $T_{1/2}$

$$\ln 2 = \lambda T_{\frac{1}{2}}$$

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

Activity

- The number of decays per second is called activity
  - – Measured in Becquerel (Bq)

$$A = -\frac{\Delta N}{\Delta t}$$

- Activity also satisfies an exponential law:

$$N = N_0 e^{-\lambda t}$$

$$A = -\frac{dN}{dt}$$

$$\boxed{A = \lambda N_0 e^{-\lambda t}}$$

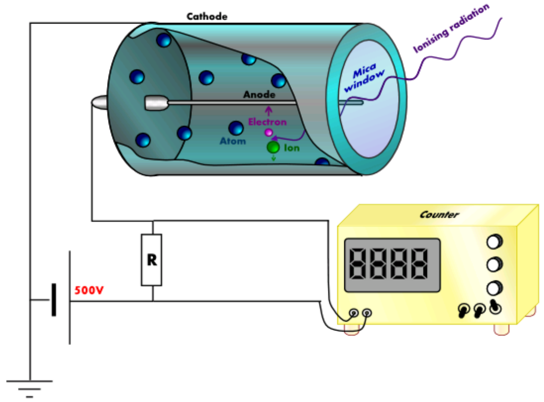
or

$$A = \lambda N$$

Detecting Radiation

- Radiation is detected by using a device known as a Geiger-Muller tube
- The outside of the tube is negatively charged
- Inside the tube is a positively charged cathode
- The tube is charged to a few hundred volts
- The tube is filled with a gas

- Radiation enters the tube through a glass window
- The radiation ionizes the gas
- The positive ions accelerate towards the outside and the negative ions accelerate towards the cathode
- This registers as a current to the counter connected to the tube



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)