Radioactive decay is the spontaneous fragmentation of an atomic nucleus. This is a *random* process, with the probability of decay at any given time being constant for each isotope. However, the probability varies enormously between isotopes. Decay rates are measured in Becquerels (Bq) or Curies (Ci). **Half –life** is the amount of time it takes for half a (large!) sample of radioactive atoms to decay.

1 Becqueral (Bq) is 1 radioactive decay per second   1 Curie (Ci) = 37 GBq $1\text{Ci} = 3.7 \times 10^{10}\,\text{Bq}$

> Transitions from a 'excited' nucleus state can also result in the emission of **gamma rays** i.e. energy release but with no change in number of neutrons or protons

There are several main processes for radioactive decay:

alpha	Emission of a helium nucleus	${}^{Z+N}_{Z}\text{X} \rightarrow {}^{Z+N-4}_{Z-2}\text{Y} + \alpha$	Atomic number (Z) *reduces* by 2 Mass number *reduces* by 4	${}^{229}_{90}\text{Th} \rightarrow {}^{225}_{88}\text{Ra} + \alpha$
β⁺ decay	Emission of a positron and electron neutrino* as a proton is converted into a neutron. A positron is the anti-particle of an electron.	${}^{Z+N}_{Z}\text{X} \rightarrow {}^{Z+N}_{Z-1}\text{Y} + e^{+} + \nu_e$	Atomic number (Z) *decreases* by 1 Mass number *stays the same*	${}^{22}_{11}\text{Na} \rightarrow {}^{22}_{10}\text{Ne} + e^{+} + \nu_e$
β⁻ decay	Emission of an electron and an electron antineutrino as a neutron is converted into a proton	${}^{Z+N}_{Z}\text{X} \rightarrow {}^{Z+N}_{Z+1}\text{Y} + e^{-} + \bar{\nu}_e$	Atomic number (Z) *increases* by 1 Mass number *stays the same*	${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + e^{-} + \bar{\nu}_e$
electron capture	Emission of an electron neutrino as a captured electron converts a proton into a neutron	${}^{Z+N}_{Z}\text{X} + e^{-} \rightarrow {}^{Z+N}_{Z-1}\text{Y} + \nu_e$	Atomic number (Z) *decreases* by 1 Mass number *stays the same*	${}^{22}_{11}\text{Na} + e^{-} \rightarrow {}^{22}_{10}\text{Ne} + \nu_e$

Geiger-Nuttall Law for alpha decay
This predicts alpha particles emitted from a particular isotope will tend to have very similar energies

$$\log t_{\frac{1}{2}} = a + \frac{bZ}{\sqrt{E_\alpha}}$$

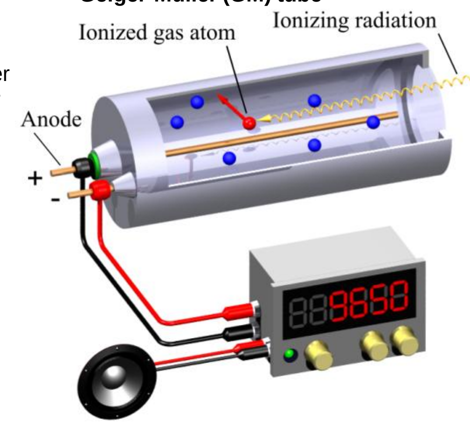
Half life ($t_{\frac{1}{2}}$); Atomic number (Z); Kinetic energy (E_α)

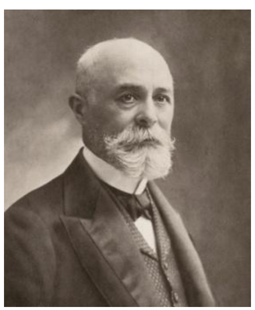
To measure a count in a GM tube, the alpha particle, beta particle or gamma ray must have **sufficient energy to ionize** the Argon gas within it.

A typical α particle has kinetic energy of around **5 MeV.** This is of the order of 100,000 times higher than a typical ionization energy (e.g. for an air molecule). Therefore one would expect this number of ionizations before the α particle has insufficient energy to be detected.

β decay produces electrons with kinetic energies of the order of **0.01 to 10 MeV**, but unlike α particles, there is a *spectrum* of energies for every radioactive isotope.

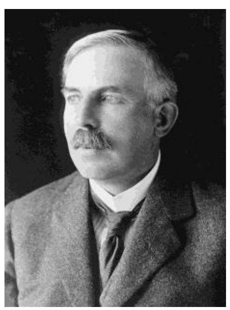
Geiger-Muller (GM) tube



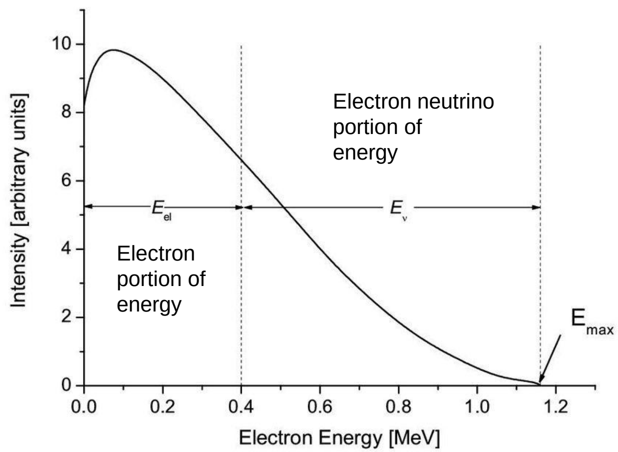


Antoine Henri Becquerel
1852-1908
Spontaneous radioactivity in Uranium salts

Marie Curie
1867-1934
Theory of radioactivity
Isolation of isotopes



Ernest Rutherford
1871-1937
Nuclear model of the atom



Mass number = number of protons + number of neutrons

Element symbol e.g. H, Na, C, Fe

Atomic number = number of protons

$${}^{A}_{Z}X$$

*Neutrinos are *very light* fundamental particles, with masses about 10^{-36} kg

Alpha, beta and gamma radiation have different **penetrating powers**

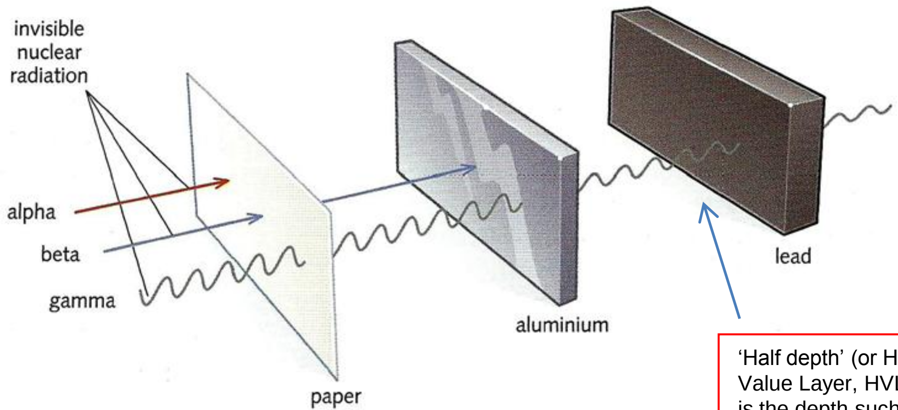
Alpha particles most *easily ionize* air molecules, and therefore lose energy after short distances. A piece of paper is sufficient to shield from typical alpha emissions.

Beta particles are *weakly ionizing*, so they undergo more molecular collisions before they lose their kinetic energy

Gamma radiation is *very weakly ionizing*, and therefore will penetrate all but the most dense of materials

$$I = I_0 e^{-\mu x}$$

The intensity of radiation (counts per second or photons per second) typically will decay *exponentially* with **penetration depth** x. The decay constant will depend on the type of radiation, and the material.



'Half depth' (or Half Value Layer, HVL) is the depth such that the intensity of radiation halves

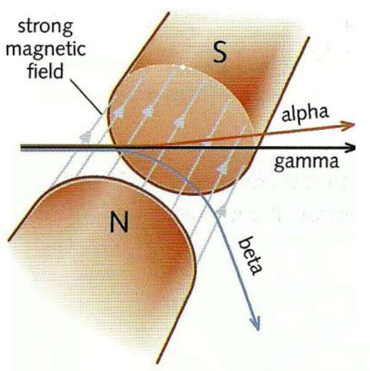
$$\tfrac{1}{2} = e^{-\mu x_{1/2}}$$

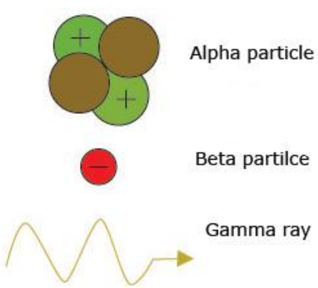
$$\ln 2 = \mu x_{1/2}$$

$$x_{1/2} = \frac{\ln 2}{\mu}$$

$$\Rightarrow \mu = \frac{\ln 2}{x_{1/2}}$$

Differences in mass and charge between alpha, beta and gamma radiation result in different trajectories when exposed to **magnetic fields**.





Some applications of radioactivity

Rutherford used **alpha** particles to investigate the nature of the **atomic nucleus**. (He fired a beam of alpha particles at very thin gold foil and recorded the distribution of particles with glancing angle. Most particles passed straight through, indicating the nucleus is very small compared to an atom, although occasionally ricochets were observed, indicating that the majority of the mass of the atom is concentrated in this tiny, dense, nucleus).

Alpha particles are found in **smoke alarms**. Smoke particles prevent the flow of alpha particles between a source and a detector, which triggers and alarm

Beta particles can be used for **thickness monitoring** in industrial processes. e.g. in a sheet metal factory.

The **beta** decay of **Carbon-14** can be used to determine the **date of death of living matter** Carbon-14 is distributed evenly throughout the biosphere, and will decay to Nitrogen-14 with a half life of about 5730 years. A living creature will continually exchange carbon with the atmosphere during respiration, so the amount of Carbon-14 remains the same. When it dies this exchange process ceases, and the amount of Carbon-14 will decay. Comparing the decay rate of dead material with living tissue can enable a calculation of the time of death to be made.

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + e^{-} + \bar{\nu}_e$$

High energy **gamma** rays can be focussed upon **tumors**. Gamma-ray 'radiotherapy' is an important element of **cancer treatment**

Radioactive **tracers** (typically **gamma**) can be used to map fluid flow. e.g. blood in the human body or water in a geological context

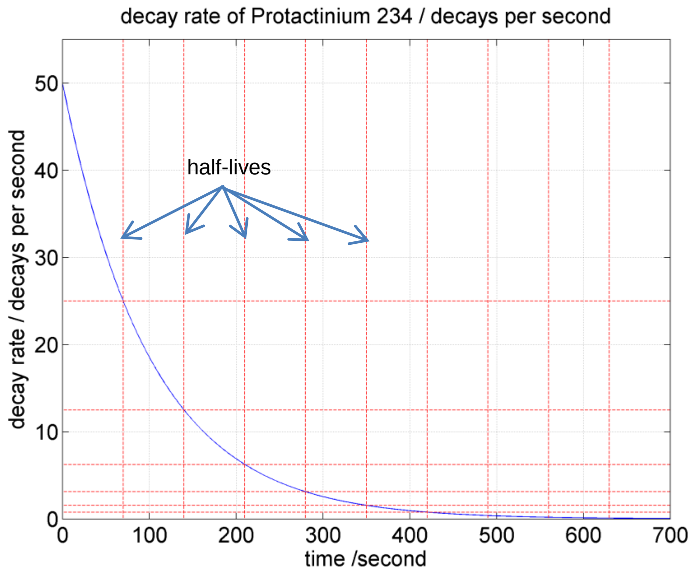
A radioactive **barium** meal can significantly **enhance X-ray** images of certain organs in the human body such as the stomach.

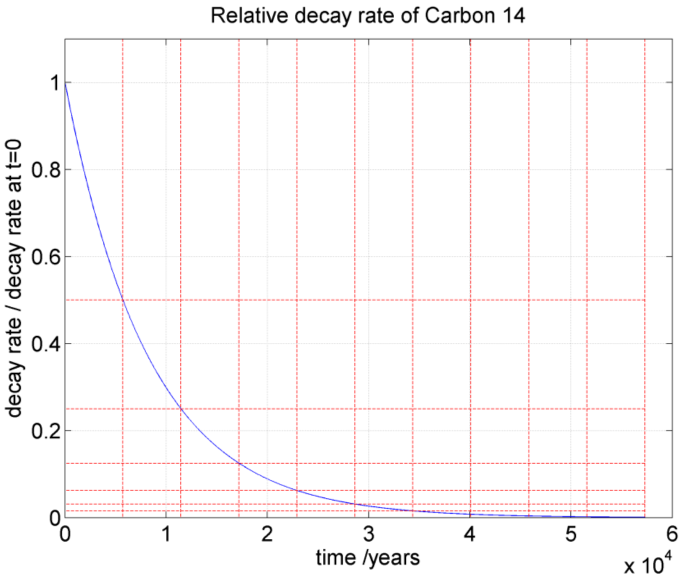
Gamma rays can be used to detect small **defects** in materials such as aircraft parts

Some of the most energetic astronomical objects in the **Cosmos** are Gamma ray sources. Viewing the Universe with a **gamma ray imaging** device will reveal information invisible at other (e.g. visible, infra-red) wavelengths.

Hazard: Alpha particles ingested into the human body can damage cells since they are highly ionizing.
Mitigation: Penetration depth is very small, so gloves, eye protection etc and care handling alpha sources should be sufficient risk mitigation.

Hazard: Gamma radiation is highly penetrating. Exposure can result in cell damage.
Mitigation: Medical radiographers should work beyond a partition wall made of lead/concrete etc which will absorb any excess radiation. As with X-rays (slightly lower energy electromagnetic waves than gamma), patient radiation dose should be carefully controlled.





Decay curves for two different isotopes. **Protactinium 234** has a half life of about 70s, which makes it very useful as an educational tool. **Carbon-14** has a half life of about 5370 years. When living tissue dies, it ceases to exchange carbon with the biosphere, hence the amount of Carbon-14 decays. A comparative measurement of Carbon-14 decay rate can therefore be used to date a sample.

A large number of radioactive atoms (of the same isotope) will undergo the same **decay law**. i.e. since the probability of any given decay is a constant, the rate of decay will be proportional to the number of radioactive atoms that have not yet decayed.

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

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

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

$$\int_{N_0}^{N} \frac{1}{N} dN = -\lambda t$$

$$\ln N - \ln N_0 = -\lambda t$$

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t$$

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

$$\frac{dN}{dt} = -\lambda N_0 e^{-\lambda t}$$

$$\left.\frac{dN}{dt}\right|_{t=0} = -\lambda N_0$$

$$\frac{dN}{dt} \Big/ \left.\frac{dN}{dt}\right|_{t=0} = e^{-\lambda t}$$

$$\tfrac{1}{2} = e^{-\lambda t_{1/2}}$$

$$-\ln 2 = -\lambda t_{1/2}$$

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

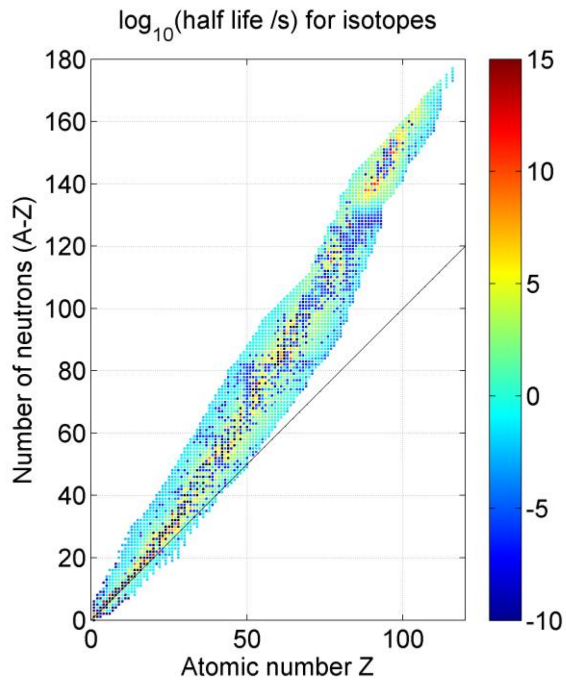
$$N(t) = N_0 e^{-\lambda t}$$

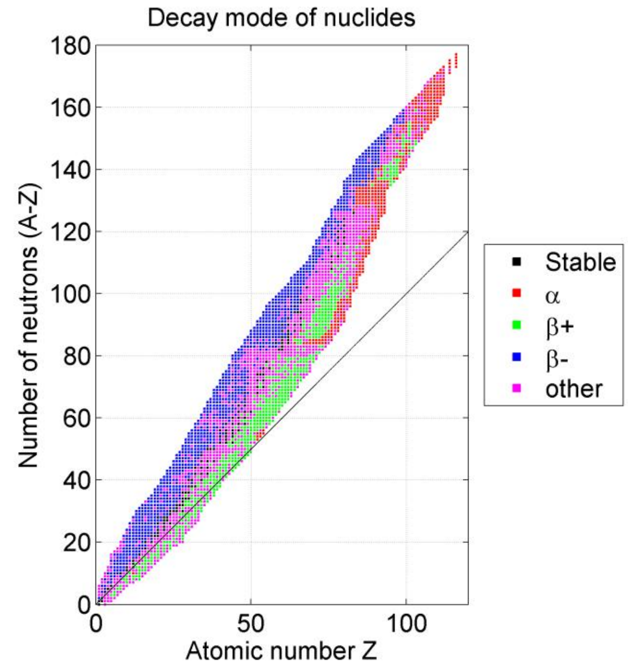
$$\frac{dN}{dt} = -\lambda N_0 e^{-\lambda t}$$

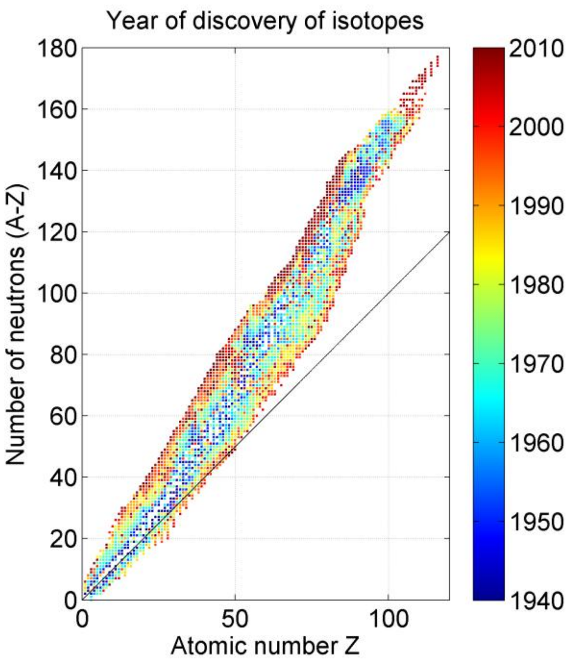
Alternatively:

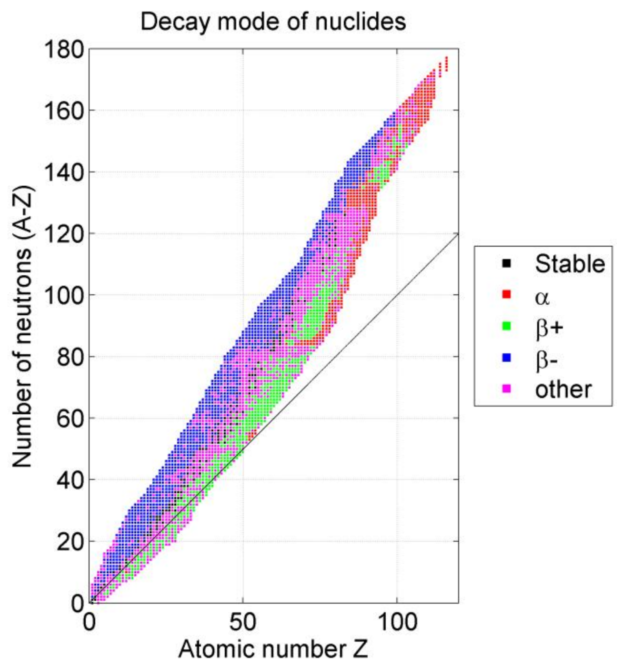
$$N = N_0 \times 2^{-\frac{t}{t_{1/2}}}$$

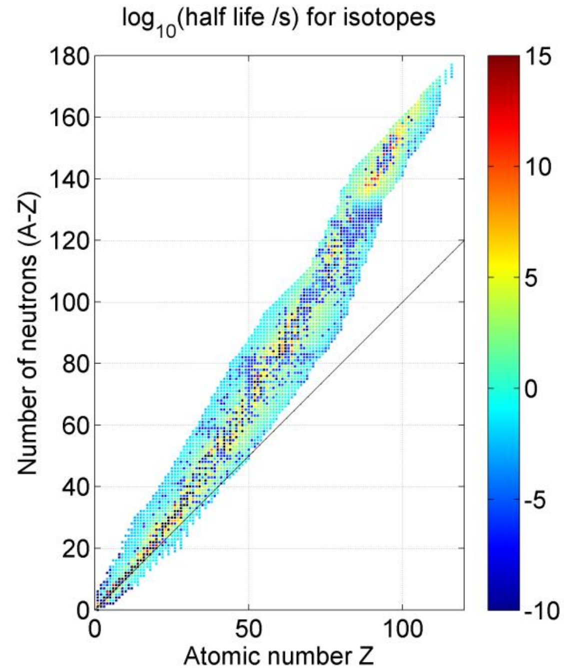
Willard Libby
1908-1980
Radiocarbon dating

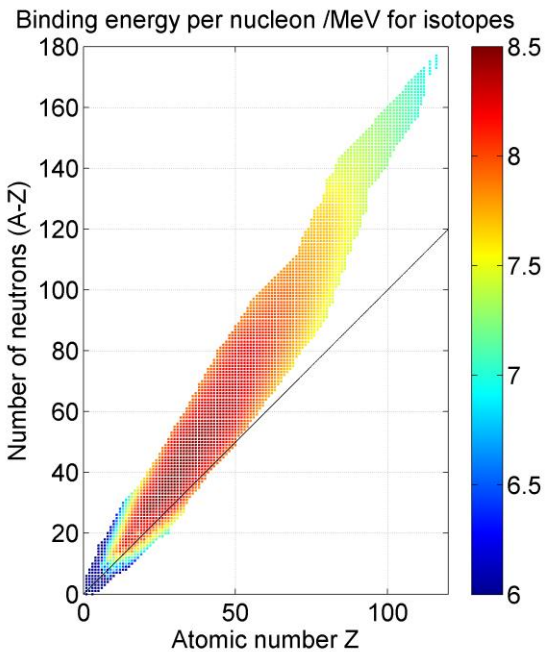


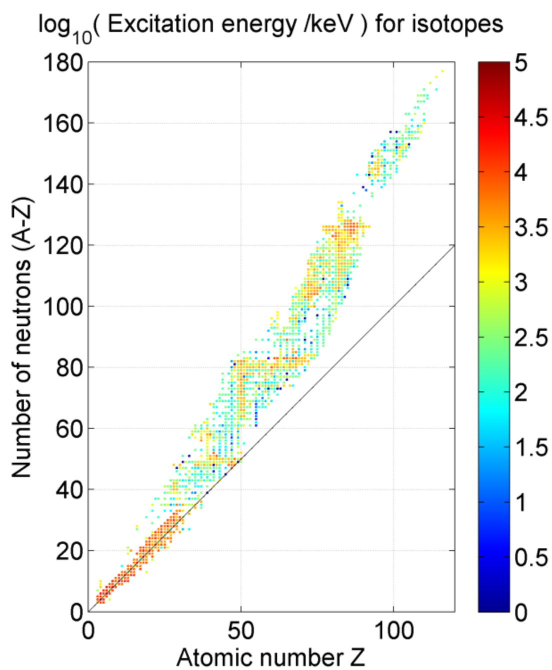












A visual summary of the NUBASE isotope database

Binding energy is the energy required to break up a nucleus into its constituent protons and neutrons.

When a nucleus fragments (fission) or joins with another (fusion) the resulting mass is *less* than the sum of the component parts. This is because the mass difference is now stored as the binding energy.

This is an illustration of Einstein's mass-energy equivalence

$$E = mc^2$$

Differences in binding energy between nuclei that undergo radioactive decay result in the **radiation energy**. Since, per atom, these energies are of the order of 1MeV, this explains why nuclear sources of power are significantly more effective than chemical processes, which are of the order of 1eV per atom.

1 eV (electron-volt) is approximately 1.6 x 10^{-19} J