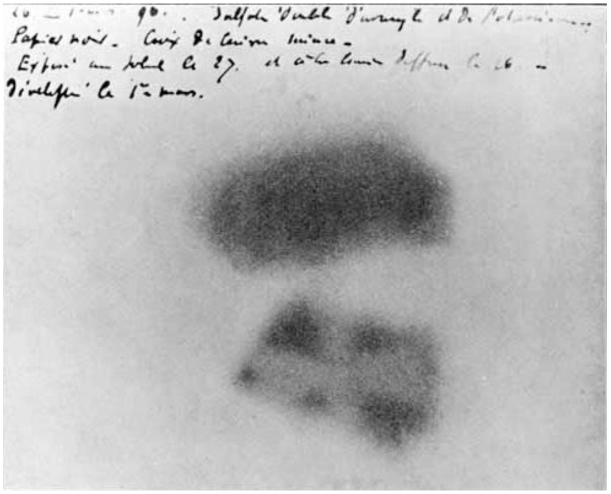
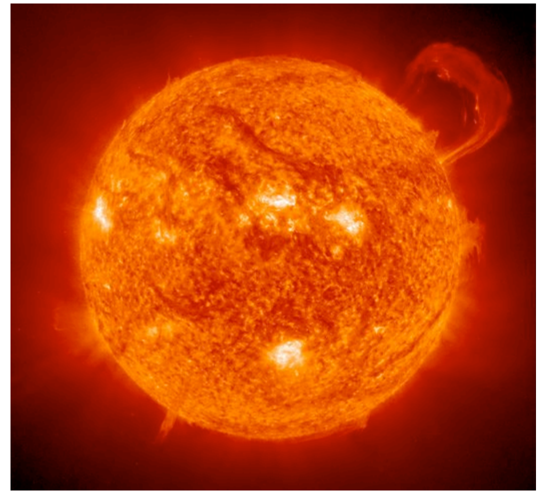


(Henri Becquerel)



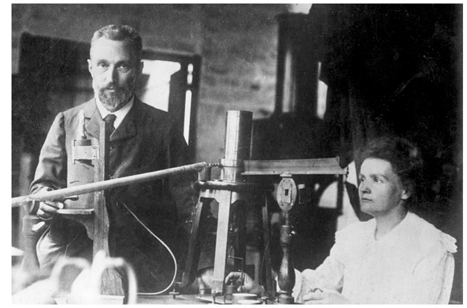
(NASA)

Nuclear Physics in One Lecture

D. Schroeder, 26 November 2012

Outline

- History, clues, data
- Visualizing the nucleus
- Reasons for (in)stability
- Decay processes
- Fusion in the Sun



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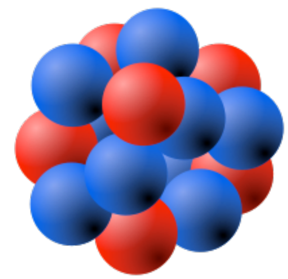

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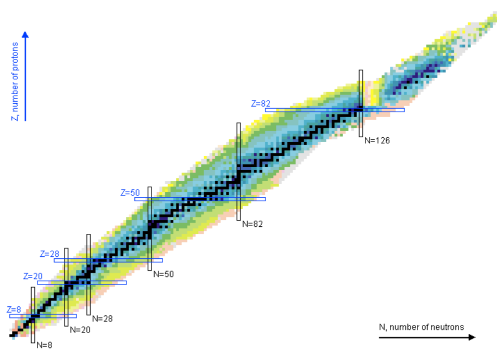
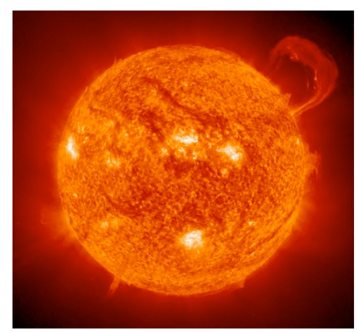


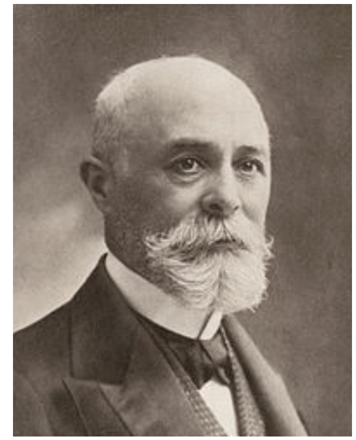
http://www.nndc.bnl.gov/chart/



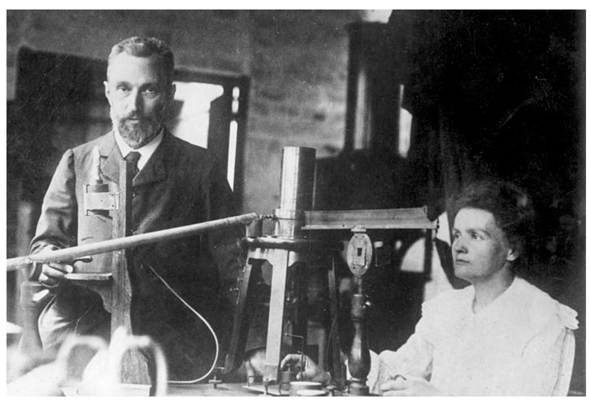
(NASA)

Discovery of Radioactivity

- Becquerel (1896): Uranium salts expose photographic plates
- Curies, Rutherford:
  - – Better detectors
  - – Transmutation of elements
  - – *α* vs. *β*



(Photo by Paul Nadar via Wikimedia Commons)



(Photo from Wikimedia Commons)

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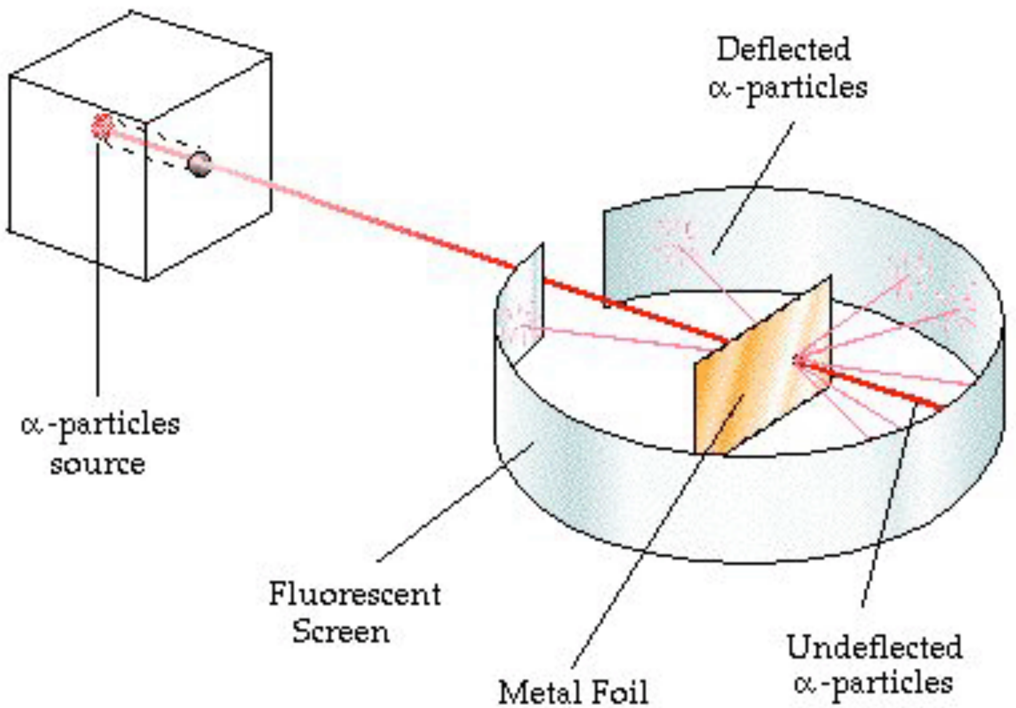
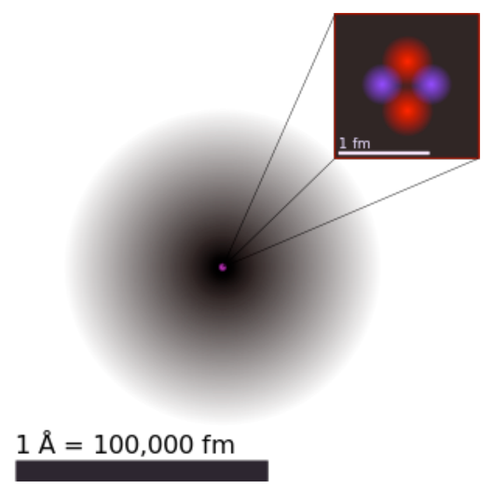
Discovery of the Nucleus
(Rutherford, Geiger, Marsden, 1911)



(Drawing from www.wiredchemist.com)

Scattering angles implied a tiny, massive center of force inside the atom.



(Yzmo, Wikimedia Commons)

What is the nucleus made of?

Clues in periodic table:

				2 **He** Helium 4.002602
6 **C** Carbon 12.0107	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.9984032	10 **Ne** Neon 20.1797
14 **Si** Silicon 28.0855	15 **P** Phosph. 30.973761	16 **S** Sulfur 32.066	17 **Cl** Chlorine 35.4527	18 **Ar** Argon 39.948
32 **Ge** German. 72.61	33 **As** Arsenic 74.92160	34 **Se** Selenium 78.96	35 **Br** Bromine 79.904	36 **Kr** Krypton 83.80
50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60	53 **I** Iodine 126.90447	54 **Xe** Xenon 131.29
82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98038	84 **Po** Polonium (208.982415)	85 **At** Astatine (209.987131)	86 **Rn** Radon (222.017570)

Masses in amu tend to be close to integers (A), about twice the atomic number (Z).

Rutherford discovered isolated protons coming from nuclei in 1917.

Chadwick discovered the neutron in 1932.

$$m_p \approx m_n \approx 1 \text{ u}$$

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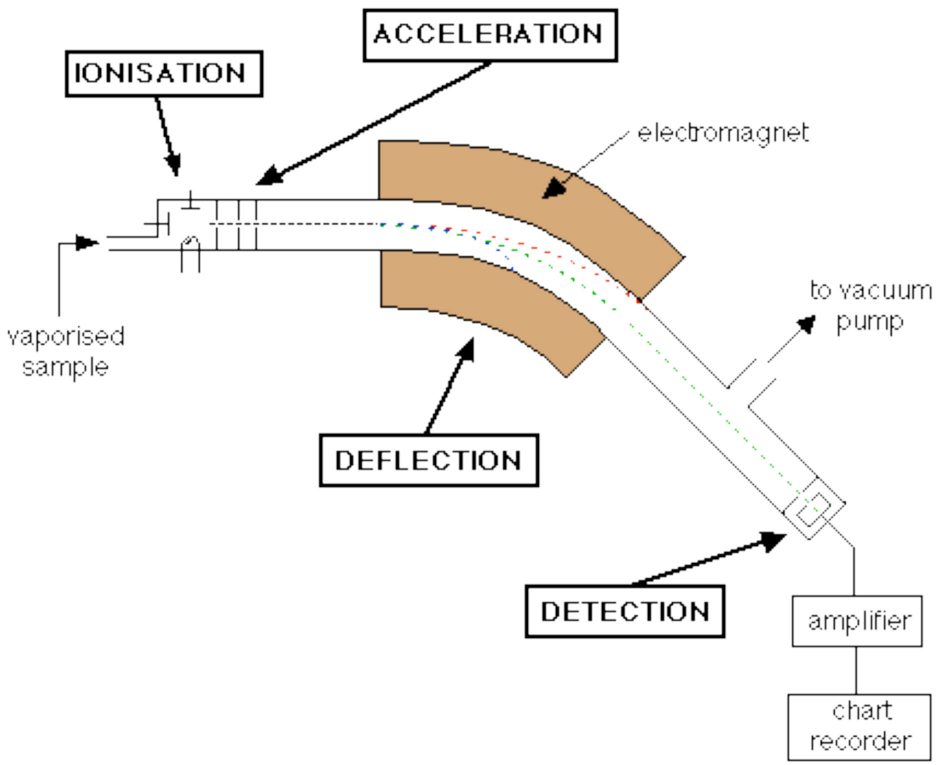
Non-integer masses are from mixtures of different *isotopes* (same number of protons, different numbers of neutrons).

Notation: $^{A}_{Z}\mathrm{X}$

For example,

$$^{4}_{2}\mathrm{He} \quad ^{14}_{6}\mathrm{C} \quad ^{235}_{92}\mathrm{U}$$

Mass Spectrometry



(Drawing from www.chemguide.co.uk)

Electrostatic acceleration:

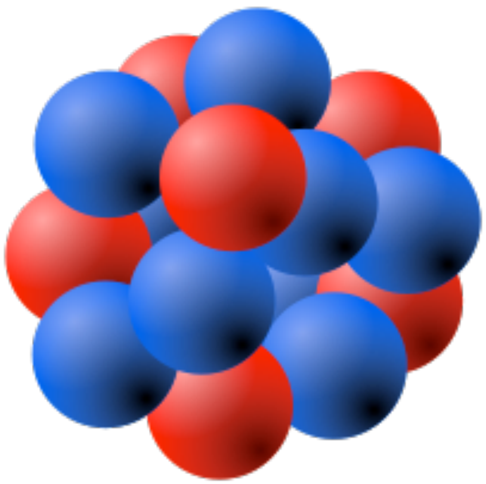
$$\frac{1}{2}mv^2 = q\,\Delta V$$

Magnetic bending:

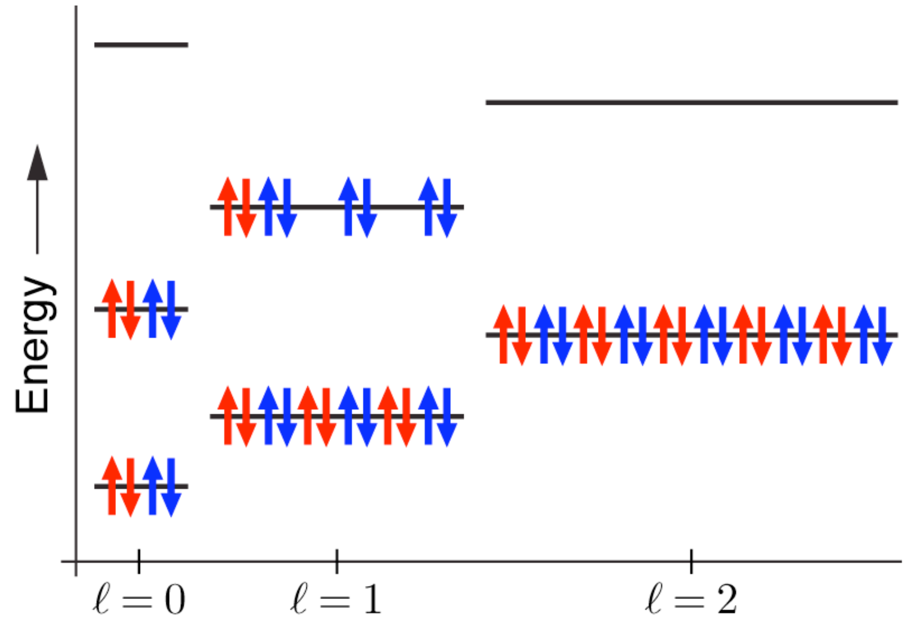
$$\frac{mv^2}{r} = qvB$$

Solve: $r = \sqrt{\dfrac{2m\,\Delta V}{qB^2}}$

Two Wrong Pictures



(Marekich, Wikimedia Commons)

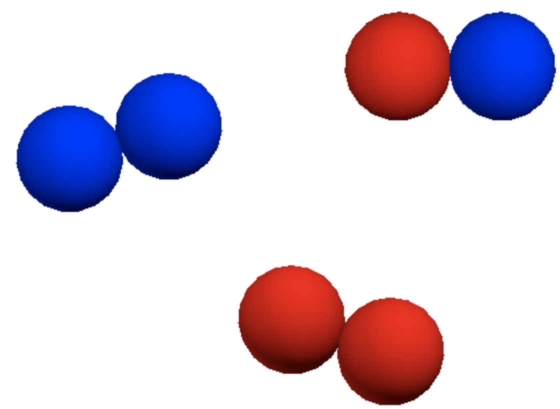


Correctly predicts size, about 8 fm^3 per nucleon

Fermions confined in a spherical potential well (many effects omitted!)

Reasons for (in)stability

- "Strong" force
  - Equally strong between *pp*, *nn*, *pn*
  - Short range



- Electrostatic repulsion
  - Protons only
  - Long range

$$\frac{k_e q_1 q_2}{r} \sim \frac{(9 \times 10^{9})(1.6 \times 10^{-19})}{2 \times 10^{-15}}\ \mathrm{eV} = 0.7\ \mathrm{MeV}$$

Reasons for (in)stability

- Quantum confinement energy

$$\frac{p^2}{2m} = \frac{h^2}{2m_p\lambda^2} \sim 100\ \mathrm{MeV}$$

- Magnetic forces

- *p*-*n* conversion ("weak" interaction)

$$n \longrightarrow p + e^- + \bar{\nu}$$

$$p \longrightarrow n + e^+ + \nu$$

$$(m_n - m_p = 1.3\ \mathrm{MeV})$$

Decay Processes

- α (^{4}He) $\quad {}^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$
- β^- (e^-) $\quad {}^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e^- + {}^{0}_{0}\bar{\nu}$
- β^+ (e^+) $\quad {}^{11}_{6}\mathrm{C} \longrightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{1}e^+ + {}^{0}_{0}\nu$
- e^- capture $\quad {}^{40}_{19}\mathrm{K} + {}^{0}_{-1}e^- \longrightarrow {}^{40}_{18}\mathrm{Ar} + {}^{0}_{0}\nu$
- γ (photon) $\quad {}^{99\mathrm{m}}_{43}\mathrm{Tc} \longrightarrow {}^{99}_{43}\mathrm{Tc} + \gamma$

- All reactions conserve: electric charge, total number of nucleons.
- For spontaneous decays, total mass must decrease.

Decay Rates

- Each decay is a quantum process with a fixed probability per unit time, λ.

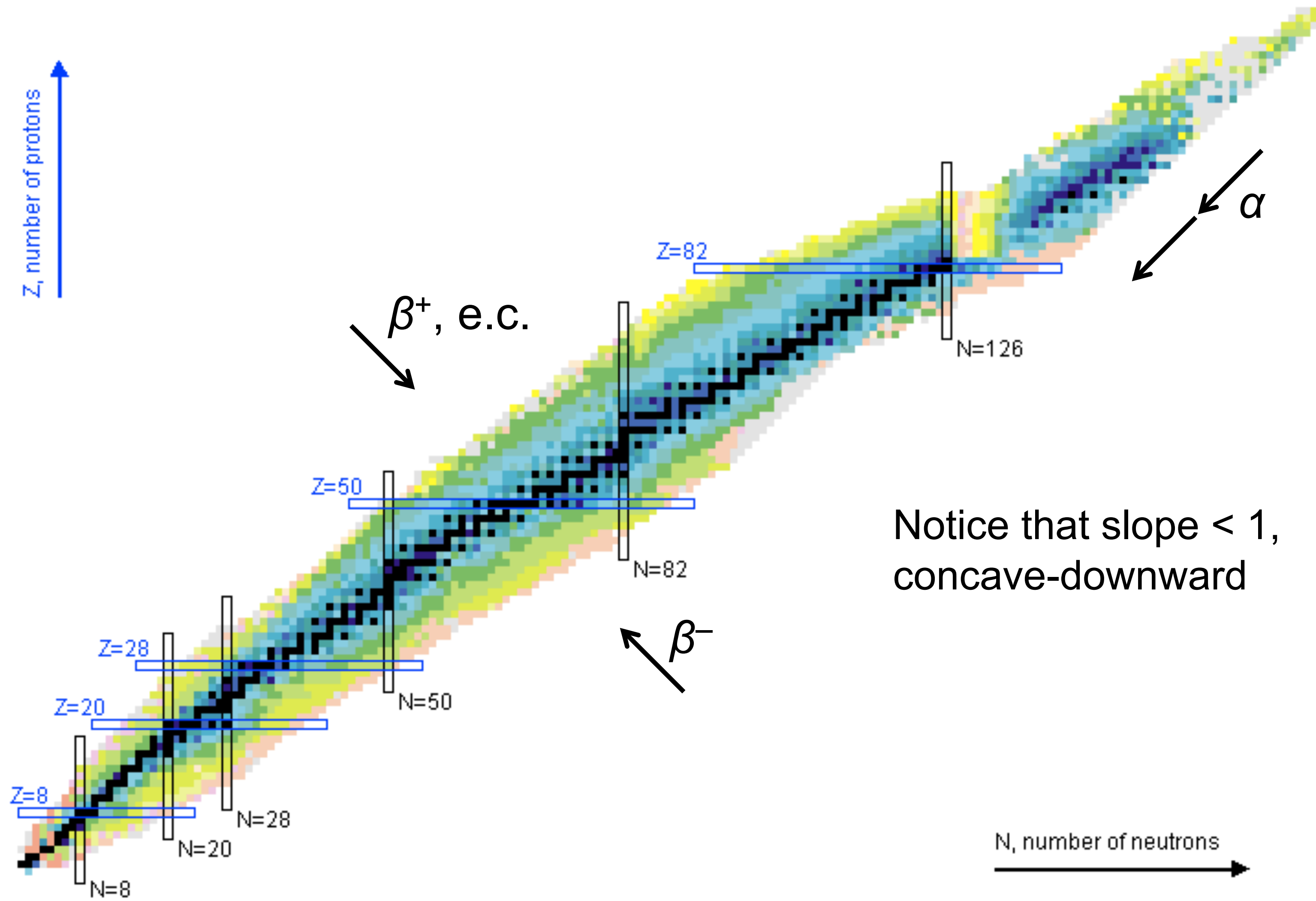
$$\frac{dN}{dt} = -\lambda N \quad \Rightarrow \quad N(t) = N(0) \cdot e^{-\lambda t}$$

- Half-life:

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

- $t_{1/2}$ varies from <10^{-15} s to >10^{24} years!

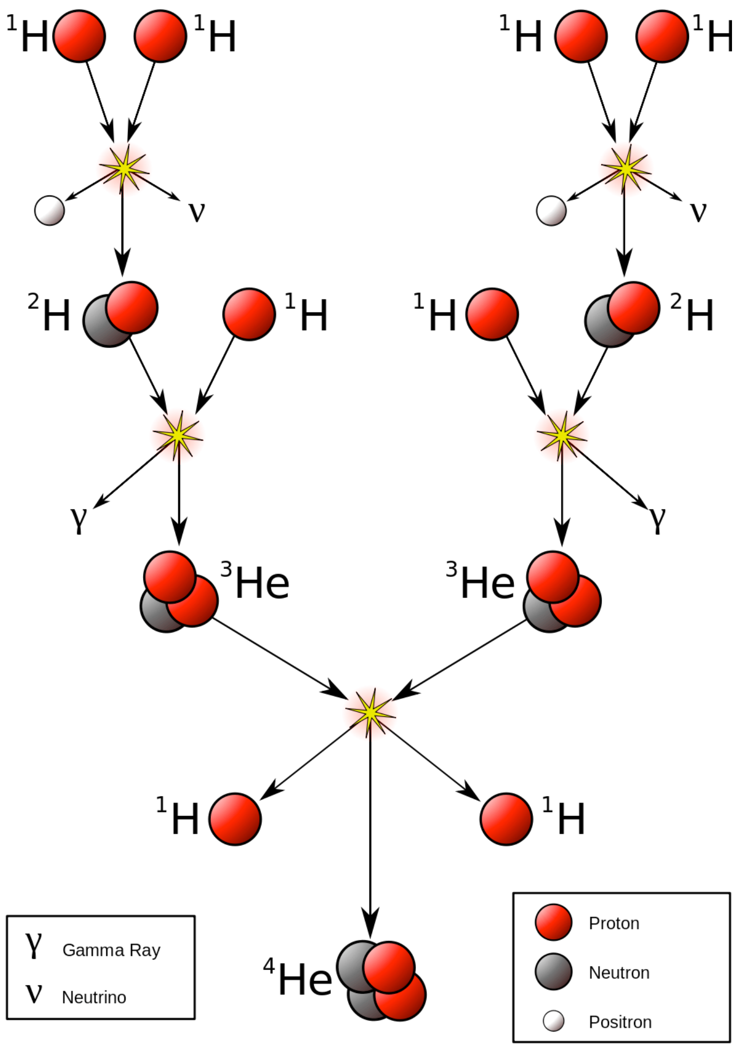
Chart of the Nuclides



Notice that slope < 1, concave-downward

http://www.nndc.bnl.gov/chart/

Application: Fusion in the Sun



(Borb, Wikimedia Commons)

Net reaction:

$$4p + 2e^{-} \longrightarrow$$
$$^{4}\mathrm{He} + 2\nu + 6\gamma$$

Mass loss: 0.7%

$$(\Delta m)c^{2} = 26.7\ \mathrm{MeV}$$

x 10^{38} reactions/second

≈ 4 x 10^{26} watts