Chapter 1: Radioactivity

Radioactivity

- **Radioactivity** is defined as the spontaneous nuclear transformation that results in the formation of new elements.

- **Radioactivity and radioactive properties of nuclides** are determined by nuclear considerations and independent of the chemical and physical states of the radioisotope.

- The **probability of radioactive transformation** depends primarily on two factors:

  - **Nuclear stabili**ty as related to the neutron-to-proton ratio.

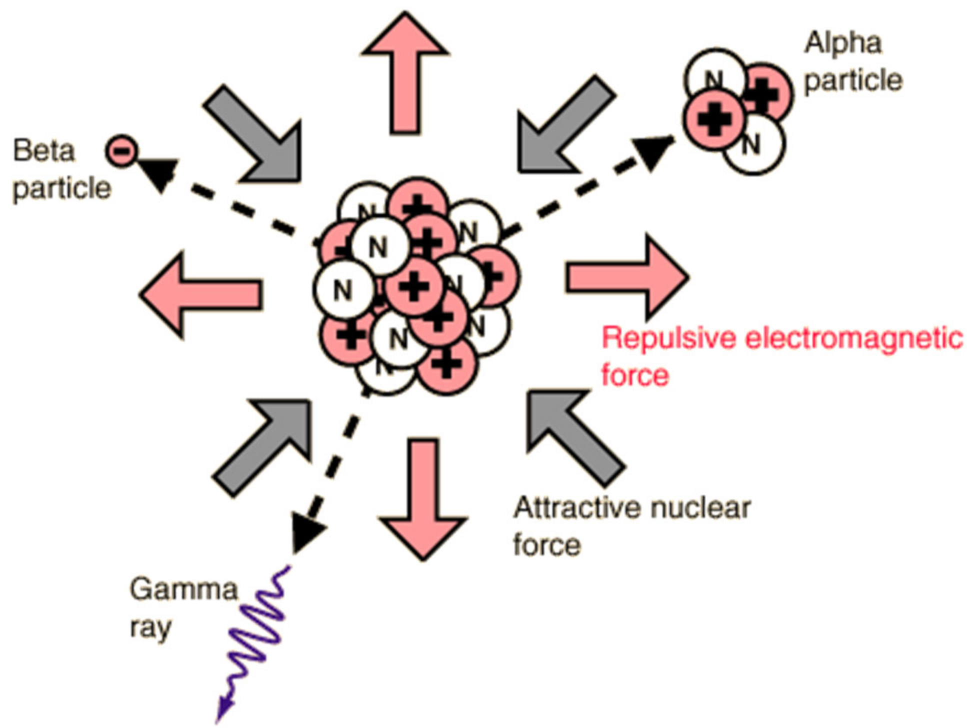
  - **The mass-energy relationship** among the parent nucleus, daughter nucleus, and the emitted particles.

The Origin of Nuclear Radiation and a Few Related Concepts

- Nuclear force and Coulomb barrier.
- Nuclear binding energy and nuclear stability.
- Nuclear transformation as a way to achieve greater nuclear stability and associated energy release.

Nuclear Forces

Within the incredibly small nuclear size （~10^{-15}m）, the two strongest forces in nature, Coulomb force and strong nuclear force, are pitted against each other. When the balance is broken, the resultant radioactivity yields particles of enormous energy.



Coulomb potenital

$V_C = \frac{1}{4\pi\varepsilon_0}\frac{q_1 \cdot q_2}{r}$, where ε_0 is the electrical permitivity

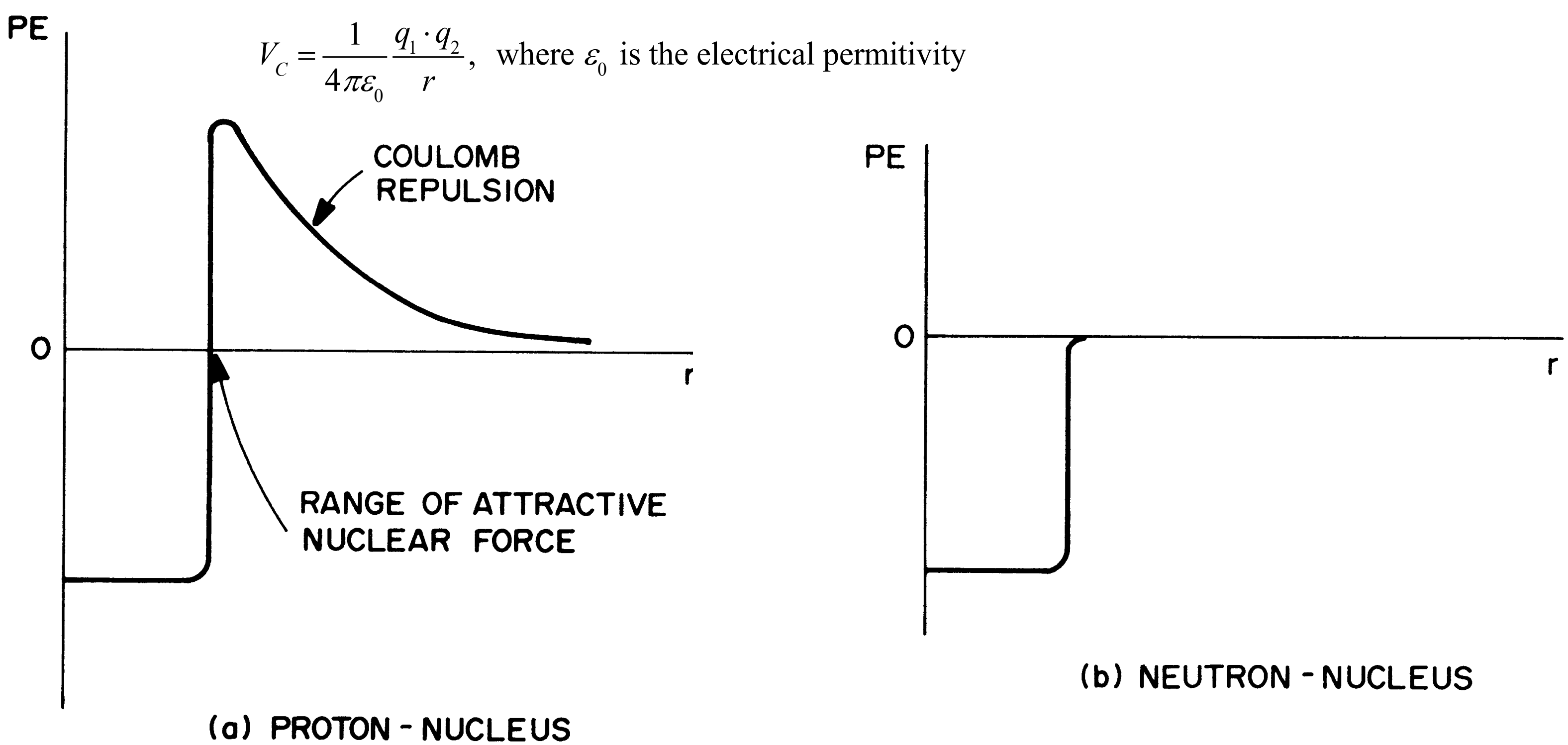
http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html

Potential Energy of Nucleus

- Nucleons are bounded together in nucleus by the strong force, which has a short range of ~10^{-15}m.
- The strong force is powerful enough to overcome the Coulomb repulsion between the positively charged protons.

Coulomb potenital

$$V_C = \frac{1}{4\pi\varepsilon_0}\frac{q_1 \cdot q_2}{r}, \quad \text{where } \varepsilon_0 \text{ is the electrical permitivity}$$

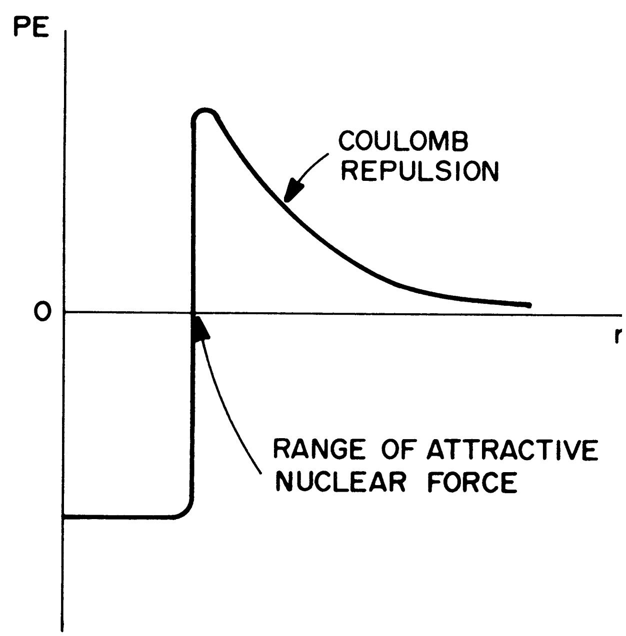


Coulomb Barrier

Example

Estimate the minimum energy that a proton would have to have in order to react with the nucleus of a stationary Cl atom.

In terms of Fig. 3.1(a), the proton would have to have enough energy to overcome the repulsive Coulomb barrier in a head-on collision. This would allow it to just reach the target nucleus.



(a) PROTON - NUCLEUS

Coulomb Barrier

We can use the following equation to estimate the radiuses of the Cl nucleus and the proton,

$$R \cong 1.3 A^{1/3} \times 10^{-15} m$$

With A=1 and A=35 for the proton and the Cl nucleus, we have

$$r_{\text{p}} = 1.3 \times 1^{1/3} \times 10^{-15} = 1.3 \times 10^{-15} \text{ m},$$

$$r_{\text{Cl}} = 1.3 \times 35^{1/3} \times 10^{-15} = 4.3 \times 10^{-15} \text{ m}.$$

The proton has unit positive charge, $e = 1.60 \times 10^{-19}$ C, and the chlorine ($Z = 17$) nucleus has a charge $17e$. The potential energy of the two charges separated by the distance $r_{\text{p}} + r_{\text{Cl}} = 5.6 \times 10^{-15}$ m is therefore

$$\text{PE} = \frac{8.99 \times 10^9 \times 17 \times (1.60 \times 10^{-19})^2}{5.6 \times 10^{-15}}$$

$$= 7.0 \times 10^{-13} \text{ J} = 4.4 \text{ MeV}.$$

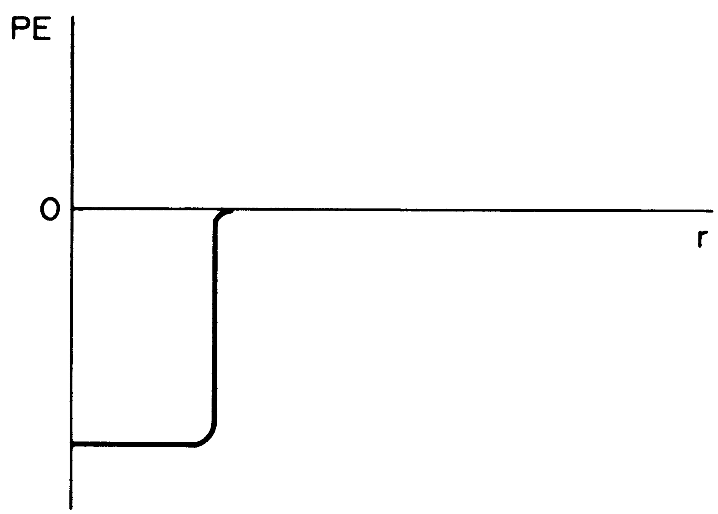
$$V_C = \frac{1}{4\pi\varepsilon_0} \frac{q_1 \cdot q_2}{r},$$

where ε_0 is the electrical permitivity

A Simple Nuclear Reaction

we now consider one of the simplest nuclear reactions, the absorption of a thermal neutron by a hydrogen atom, accompanied by emission of a gamma ray. This reaction, which is very important for understanding the thermal-neutron dose to the body, can be represented by writing

$$ {}^{1}_{0}\mathrm{n} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{0}\gamma, $$



(b) NEUTRON - NUCLEUS

For example, thermal neutron capture by hydrogen nucleus.

Mass Defect and Nuclear Binding Energy

We now consider one of the simplest nuclear reactions, the absorption of a thermal neutron by a hydrogen atom, accompanied by emission of a gamma ray. This reaction, which is very important for understanding the thermal-neutron dose to the body, can be represented by writing

$$ {}_{0}^{1}\mathrm{n} + {}_{1}^{1}\mathrm{H} \rightarrow {}_{1}^{2}\mathrm{H} + {}_{0}^{0}\gamma, \tag{3.7} $$

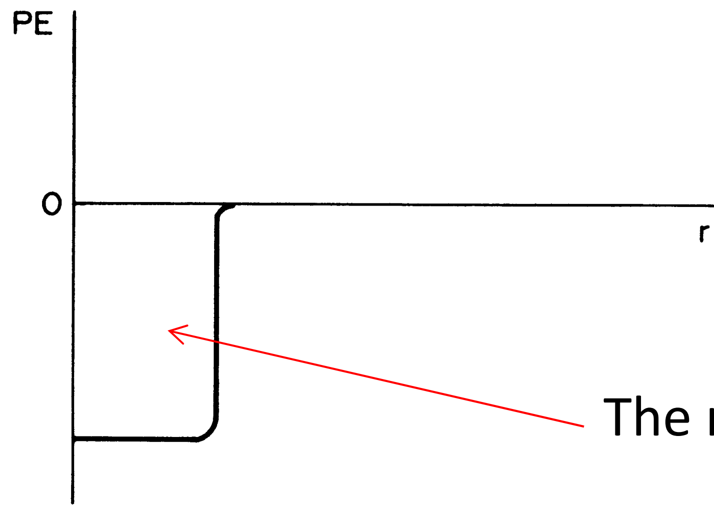
the photon having zero charge and mass. The reaction can also be designated ${}_{1}^{1}\mathrm{H}(\mathrm{n},\gamma){}_{1}^{2}\mathrm{H}$.

In this case, the energy transition due to the mass defect is

$$ Q = 8.0714 + 7.2890 - 13.1359 = 2.2245\ \mathrm{MeV}. $$

Nuclear Binding Energy

$$ {}^{1}_{0}\mathrm{n} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{0}\gamma, $$



The nuclear binding energy

(b) NEUTRON - NUCLEUS

${}^{1}_{0}n$ ${}^{1}_{1}H$ ${}^{2}_{1}H$

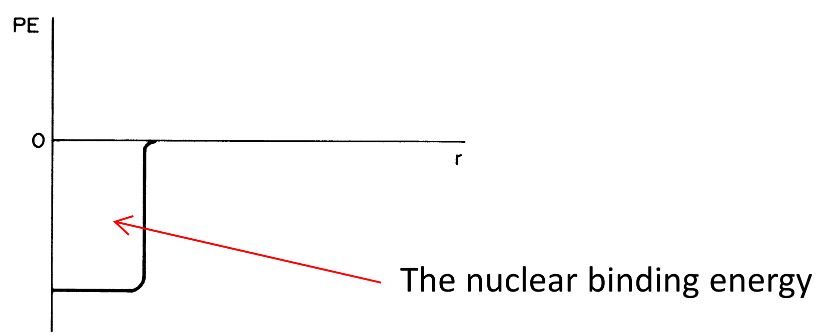
In this case, the binding energy for the deuterium nucleus is given by

$$ Q = 8.0714 + 7.2890 - 13.1359 = 2.2245\ \mathrm{MeV}. $$

Nuclear Binding Energy

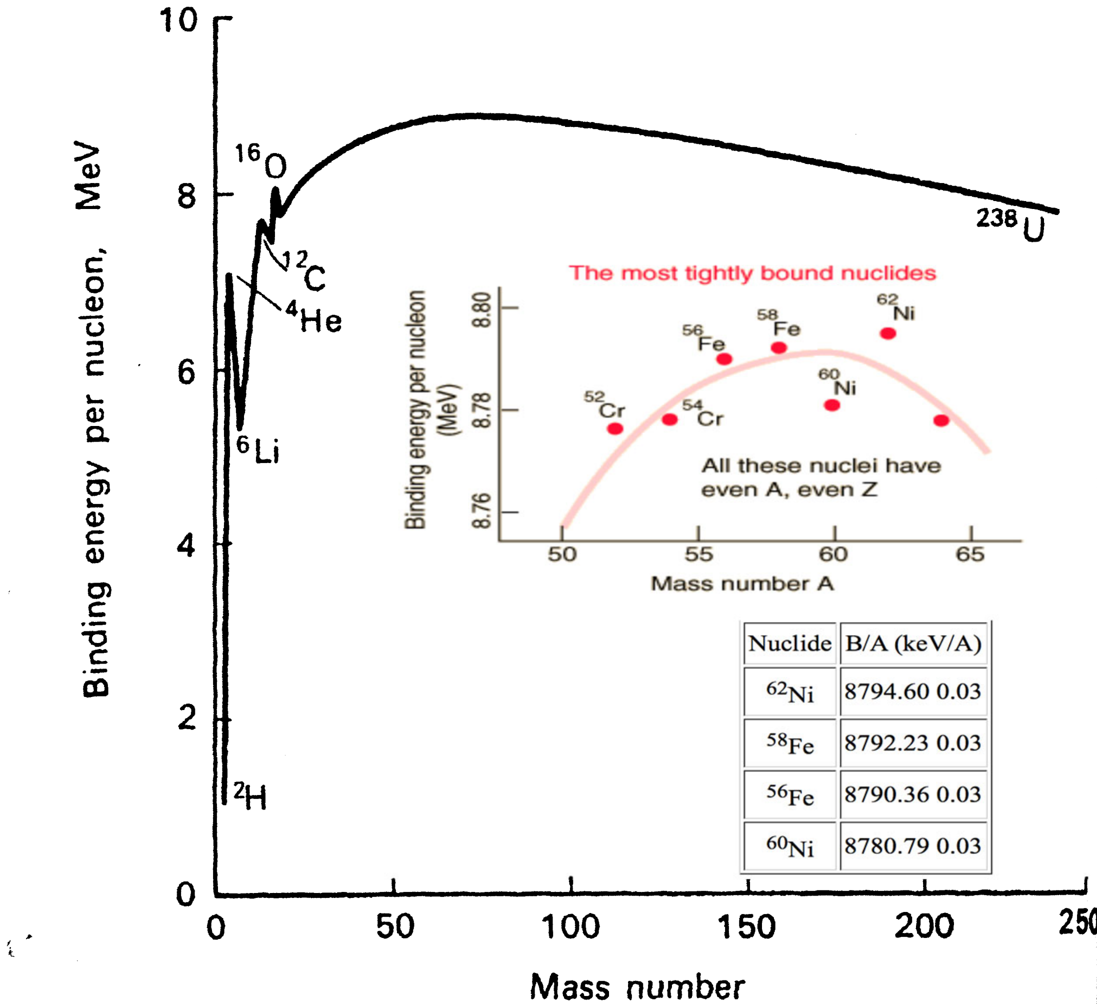
- Nuclei are made up of protons and neutron, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.
- This difference is a measure of the **nuclear binding energy**, which holds the nucleus together. The binding energy can be calculated from the Einstein relationship:

$$\text{Nuclear binding energy} = \Delta m \bullet c^2$$



(b) NEUTRON - NUCLEUS

Average Binding Energy Per Nucleon



Nuclide	B/A (keV/A)
^{62}Ni	8794.60 0.03
^{58}Fe	8792.23 0.03
^{56}Fe	8790.36 0.03
^{60}Ni	8780.79 0.03

FIGURE 3.5. Variation of binding energy per nucleon with atomic mass num

What can we find from this graph?

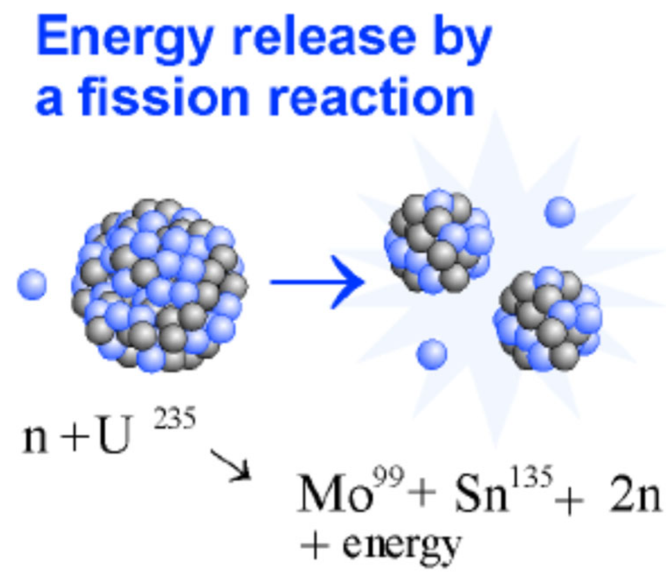
- What are the more stable elements?
- What are the spikes on the left-hand side telling us?
- If we look at nuclear reactions from the viewpoint of energy production, can you give a few examples for producing energy through nuclear reactions?
- Which one(s) are more efficient in producing energy (say energy/kg fuel)?

Nuclear Binding Energy

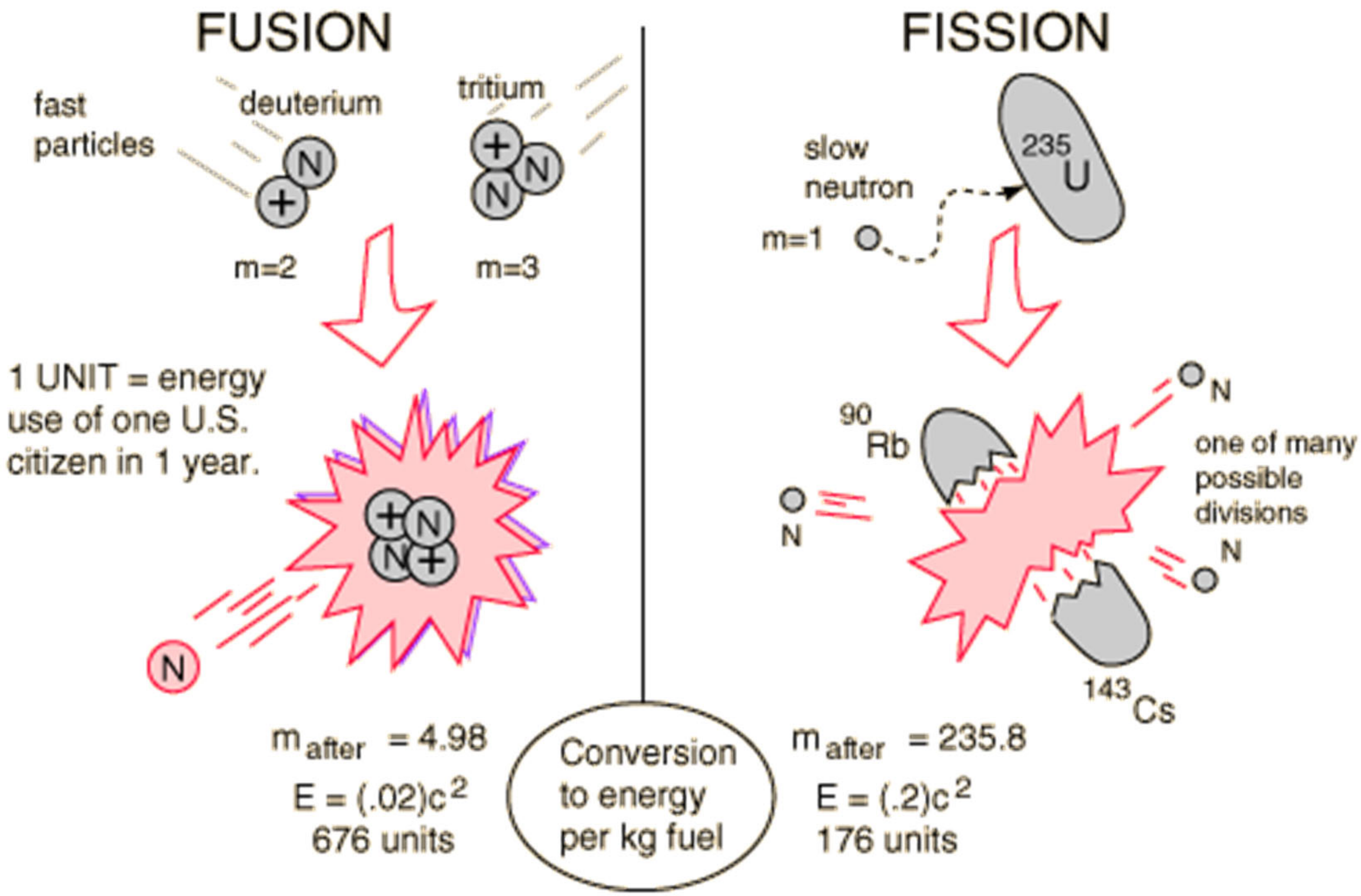
- Binding energy is **always positive**.
- The average binding energy per nucleon peaks for A = 40 to 120, with a **maximum of ~8.5MeV**.
- It then drops off for either higher or lower A.
- There are a few nuclei, ^{4}He, ^{12}C and ^{16}O at the lower mass number end that have binding energies (per nucleon) well above that for adjacent nuclei.
- In fact, these nuclei are all "multiples" of the alpha particle.
- And …

Fission Reactions

- A fission reaction splits up a large nucleus into smaller pieces.
- A fission reaction typically happens when a neutron hits a nucleus with enough energy to make the nucleus unstable.



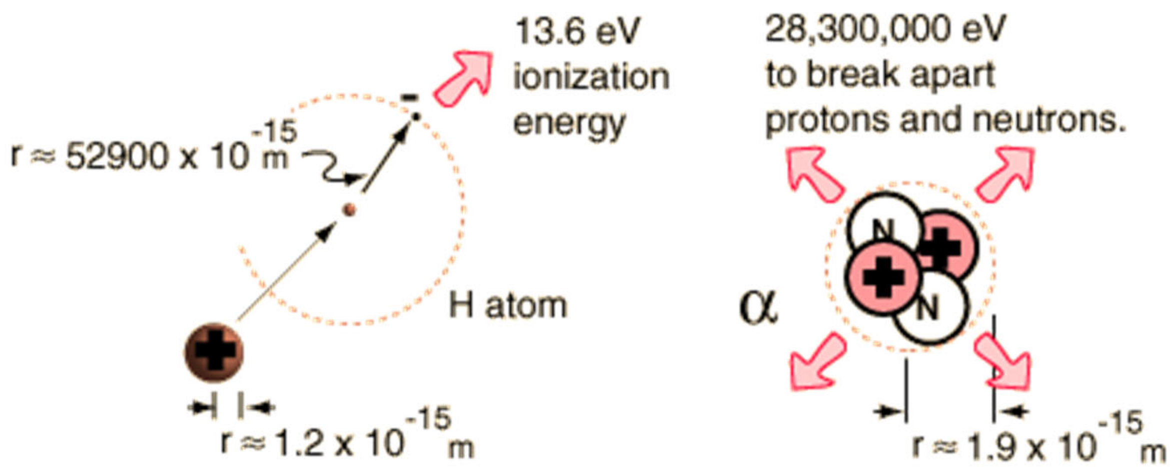
Average Binding Energy Per Nucleon Comparing Fusion and Fission Reactions



http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html

Binding Energy of Atoms

The loss of mass that accompanies the binding of particles is not a specifically nuclear phenomenon. The mass of the hydrogen atom is smaller than the sum of the proton and electron masses by 1.46×10^{-8} AMU. This is equivalent to an energy 1.46×10^{-8} AMU $\times$ 931 MeV/AMU^{-1} $= 1.36 \times 10^{-5}$ MeV $= 13.6$ eV, the binding energy of the H atom.

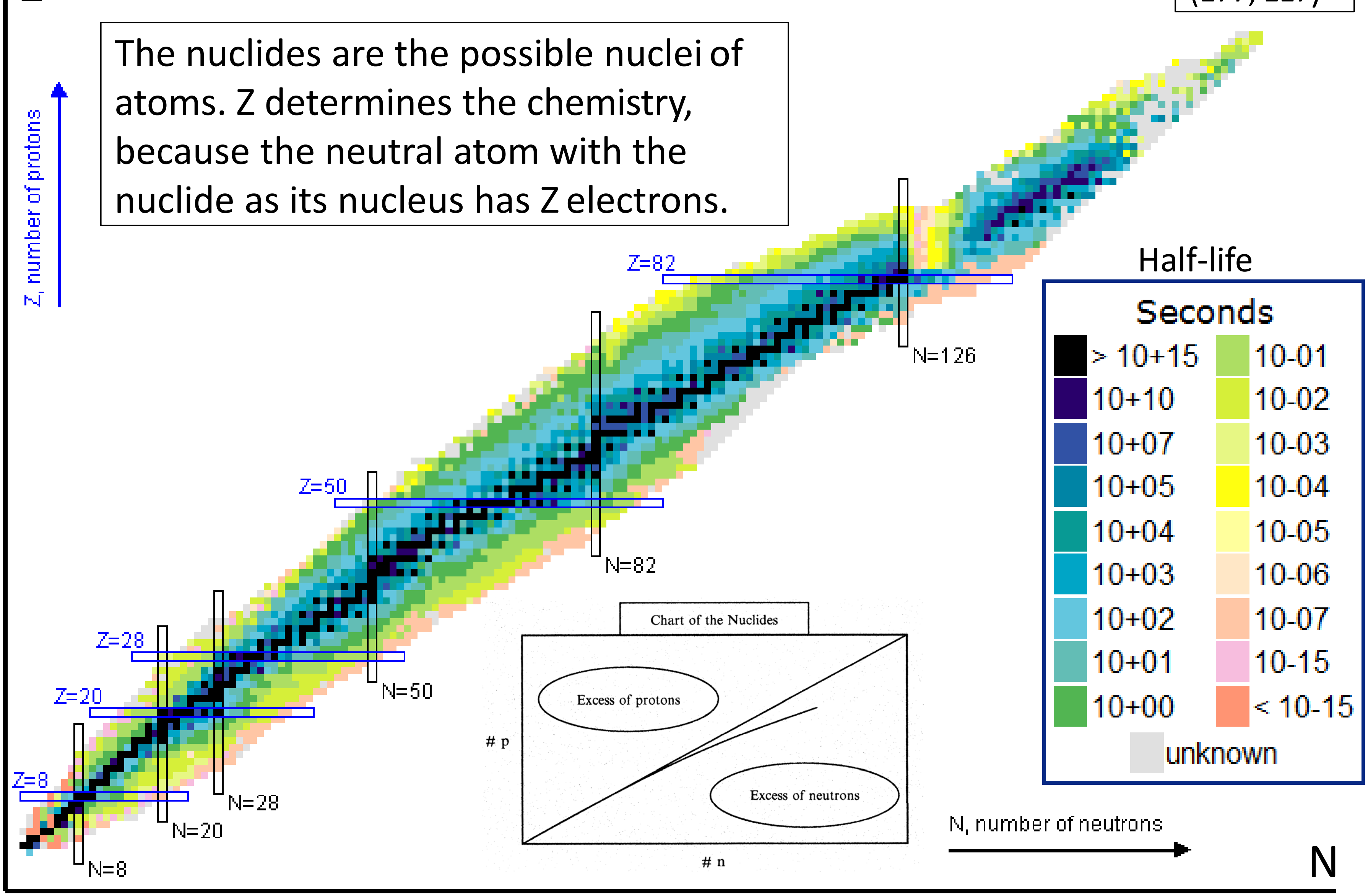


Comparison of atomic and nuclear scales and binding energy

http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html

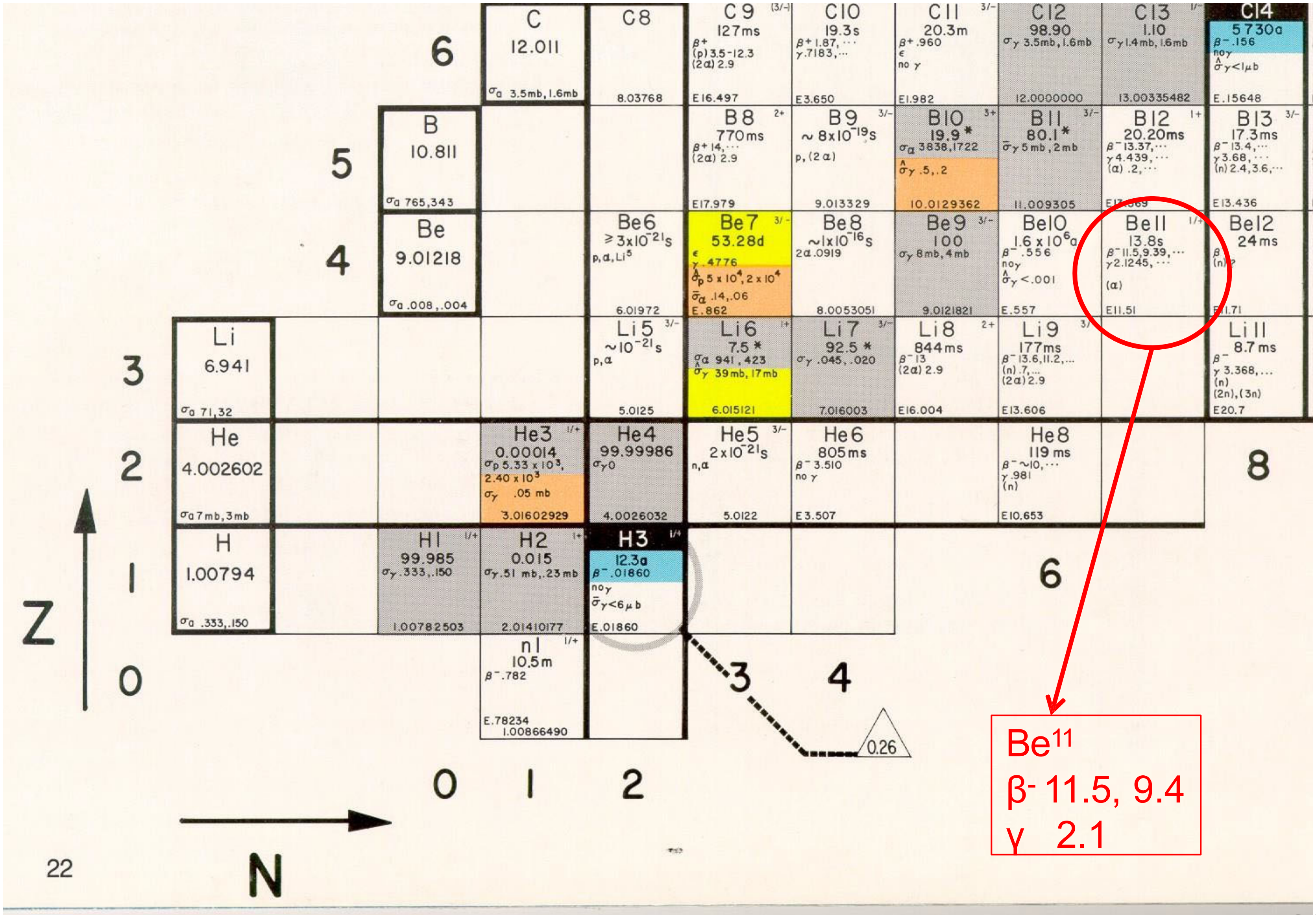
Chart of the Nuclides

The nuclides are the possible nuclei of atoms. Z determines the chemistry, because the neutral atom with the nuclide as its nucleus has Z electrons.



Source: http://www.nndc.bnl.gov/chart/reZoom.jsp?newZoom=5

Chart of the Nuclides



Nuclear Stability and the Origin of Radioactivity

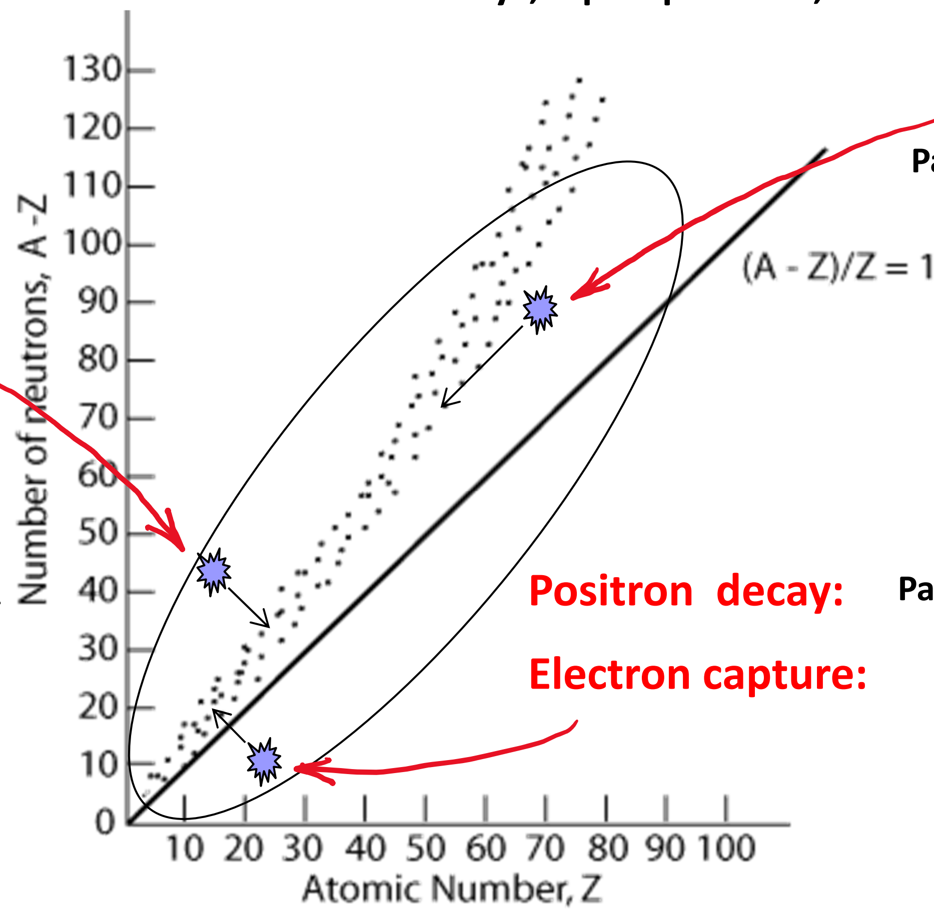
Secondary radiations, e.g., gamma-rays, X-rays, alpha-particles, and electrons

Beta decay:

Parent (Z, N) → Daughter (Z+1, N-1)

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

$${}^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + {}^{\;\;0}_{-1}\beta + {}^{0}_{0}\bar{\nu}.$$



Alpha decay

Parent (Z, N) → Daughter (Z-2, N-2)

$${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He$$

Positron decay: **Parent (Z, N) → Daughter (Z-1, N+1)**

Electron capture:

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

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

$${}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + {}^{0}_{1}\beta + \upsilon$$