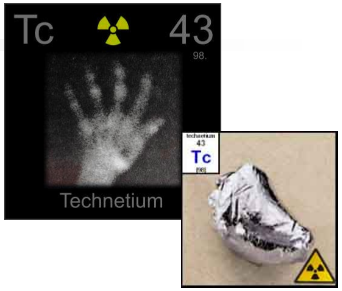
CHEMISTRY 1000

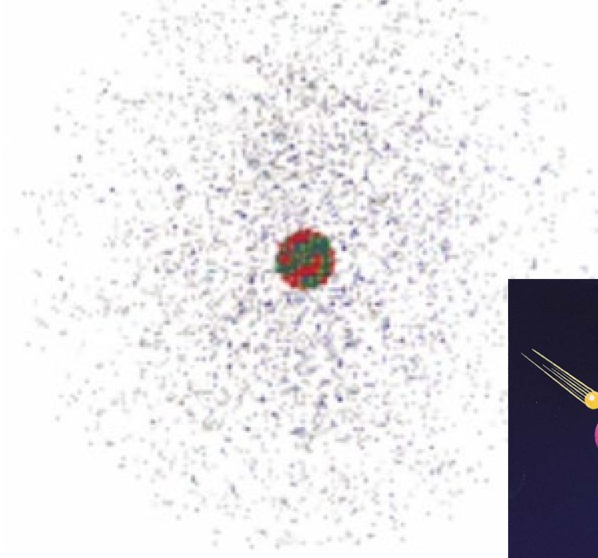


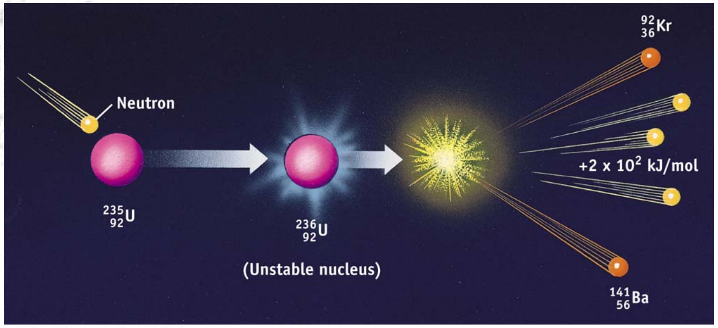
Topic #1: Atomic Structure and Nuclear Chemistry

Fall 2020

Dr. Susan Findlay

See Exercises 2.3 to 2.6





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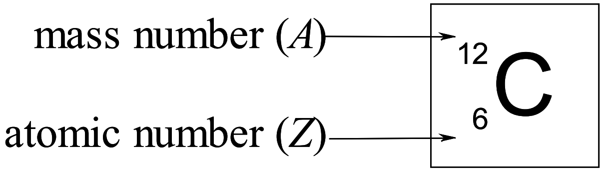
Balancing Nuclear Reactions

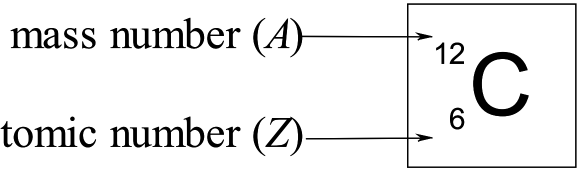


$${}^{12}_{6}\mathrm{C}$$

- In an ordinary chemical reaction, the nuclei are not changed. To balance an ordinary chemical equation, make sure that the number of atoms of each element is conserved and that the total charge is conserved:

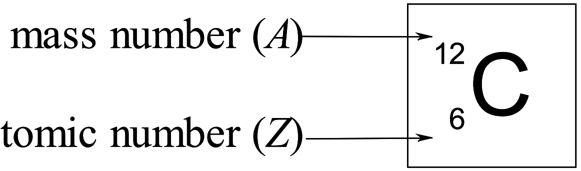
- In a nuclear reaction, the nuclei change and therefore the elements change. To balance a nuclear reaction equation, make sure that the total number of nucleons (A) is conserved and that the total charge (Z) is conserved:

Balancing Nuclear Reactions



- Some particles that commonly appear as products or reactants in nuclear reactions include:
  - Proton:
  - Neutron:
  - Electron (aka beta particle):
  - Positron (antimatter counterpart of electron):
  - Alpha particle (helium-4 nucleus):
- Identify A and Z for each particle listed above.
- Nuclear reactions can also produce radiation with neither mass number nor atomic number. This is not typically written in the balanced equation, but is very important as it can carry large quantities of energy released by the reaction.

Balancing Nuclear Reactions



- Balance the following nuclear reactions.

$$ {}^{7}_{4}Be + {}^{0}_{-1}e \rightarrow \boxed{} $$

$$ {}^{235}_{92}U \rightarrow {}^{231}_{90}Th + \boxed{} $$

$$ \boxed{} \rightarrow {}^{218}_{85}At + {}^{0}_{-1}\beta $$

$$ {}^{206}_{81}Tl \rightarrow \boxed{} + {}^{4}_{2}\alpha $$

$$ {}^{236}_{92}U \rightarrow {}^{141}_{56}Ba + \boxed{} + 3\,{}^{1}_{0}n $$

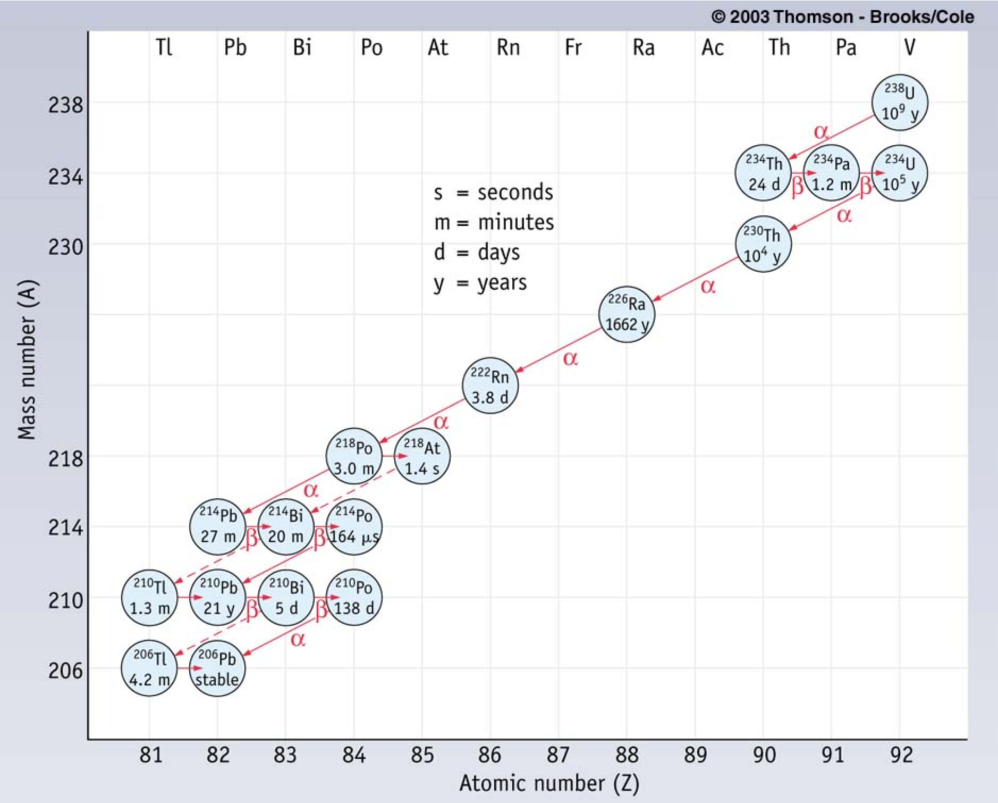
Classes of Nuclear Reactions

- There are seven classes of nuclear reactions:
  - Alpha emission
  - Beta emission
  - Positron emission
  - Electron capture
  - Fission
  - Fusion
  - Bombardment (to make transuranium elements)

“nuclide” = a specific type of nucleus (i.e. containing a specific #protons and #neutrons)

Classes of Nuclear Reactions

- An unstable nuclide undergoes spontaneous nuclear reaction to form a more stable nuclide. If this product is also unstable, it undergoes another nuclear reaction (and another and another, etc. until a stable nuclide is reached). Such a series of alpha- and beta-emissions is called a **radioactive decay series**: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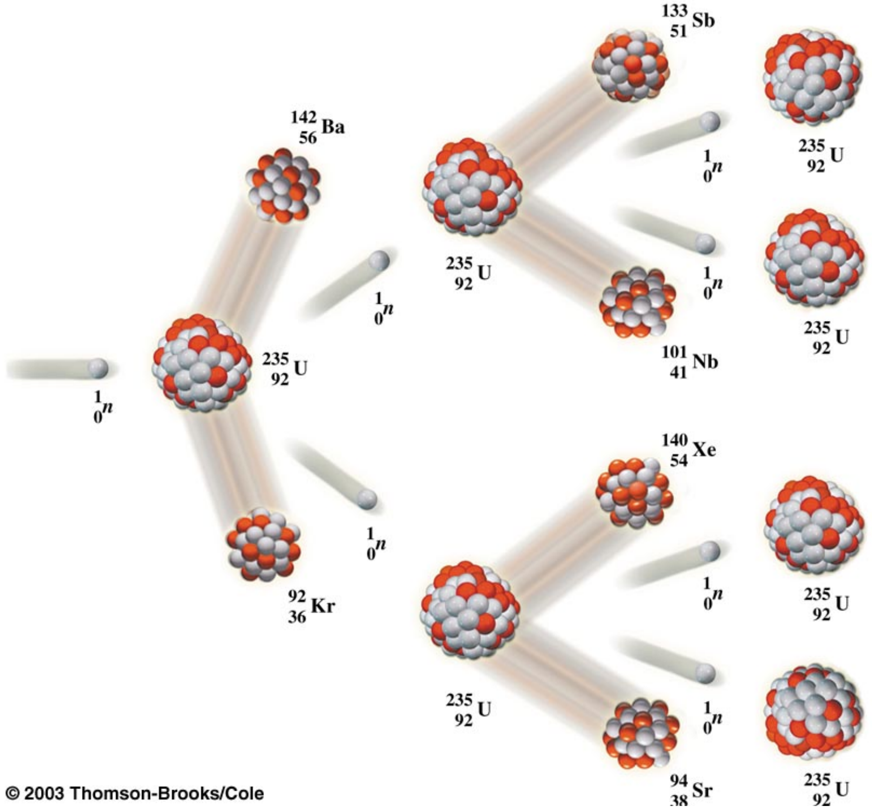
s = seconds
m = minutes
d = days
y = years

Classes of Nuclear Reactions

- Some classes of nuclear reaction, on the other hand, do not typically occur spontaneously. Instead, they must be induced (often by hitting the nucleus with a neutron to generate a highly unstable nucleus which will then undergo the desired nuclear reaction). This is true of fission and bombardment:



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Classes of Nuclear Reactions

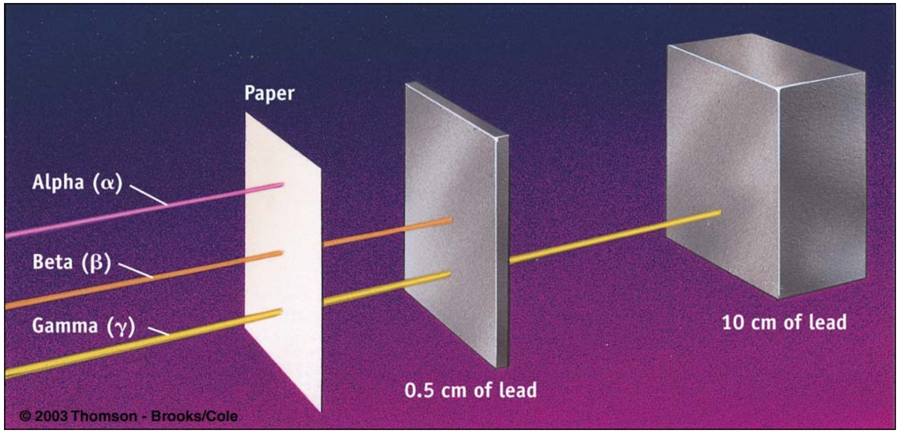
	reactants	**products**[*]	**spontaneous?**
alpha emission	1 nucleus	1 nucleus + 1 alpha particle	yes
beta emission	1 nucleus	1 nucleus + 1 electron	yes
positron emission	1 nucleus	1 nucleus + 1 positron[**]	yes
electron capture	1 nucleus + 1 electron	1 nucleus	yes
fission	1 nucleus	2 nuclei + neutron(s)	no
fusion	2 light nuclei	1 nucleus + neutron(s)	sometimes
bombardment	2 heavy nuclei	1 nucleus + neutron(s)	no

[*] Most nuclear reactions also emit gamma radiation and/or neutrinos. Emitting an α or β particle leaves the nucleus in an excited state so it emits a photon as it returns to the nuclear ground state. The energy of the radiation emitted is specific to the nuclear reaction.

[**] As antimatter, positrons are not directly observable. A positron is annihilated as soon as it collides with an electron, releasing high energy radiation.

Radioactivity and Radiation

- Nuclear reactions generate much more energy than ordinary chemical reactions. In doing so, they release radiation.
- The term **ionizing radiation** refers to radiation capable of exciting electrons out of atoms or molecules (making ions!). To do so, the radiation must interact with matter and must be carrying enough energy to eject one or more charged particles.
- Nuclear reactions release different types of radiation. These different types of radiation have different properties based on their masses and charges.



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Radioactivity and Radiation

- **Alpha radiation** $\left({}^{4}_{2}\alpha\right)$
  - 2 protons + 2 neutrons = most massive form of radiation
  - +2 charge
  - easily stopped but highly damaging if ingested, inhaled, etc.

- **Beta radiation** $\left({}^{0}_{-1}\beta\right)$
  - electron = 0.0136% of mass of alpha particle
  - -1 charge
  - higher penetrating power than α radiation but lower than others
  - can cause radiation burns and other biological damage

- **Gamma radiation** $\left({}^{0}_{0}\gamma\right)$
  - high energy electromagnetic radiation (like visible or UV light)
  - no mass and no charge so it often passes right through matter
  - can cause serious biological damage (e.g. mutations) when it does interact with matter

Radioactivity and Radiation

- **Neutrons** $\left({}^{1}_{0}n\right)$
  - ¼ mass of alpha particle but 1800 times mass of beta particle
  - neutral charge
  - tend to pass through matter; however, they can induce fission or knock light nuclei out of molecules

- **Neutrinos** $\left({}^{0}_{0}\nu\right)$
  - less than one millionth of the mass of beta particle
  - neutral charge
  - interact too weakly with matter to cause biological damage
  - important because they carry most of the energy generated in many nuclear reactions

Radioactivity and Radiation

- Rank the different types of radiation from highest to lowest mass and from highest to lowest charge.

$${}^{4}_{2}\alpha \qquad {}^{0}_{-1}\beta \qquad {}^{0}_{0}\gamma \qquad {}^{1}_{0}n \qquad {}^{0}_{0}\nu$$

- Ranked by mass:

highest lowest

- Ranked by charge (magnitude not sign):

highest lowest

^{1}H: M = 1.007 825 032 u
^{2}H: M = 2.014 101 778 u

Energy of Nuclear Reactions

- Where does the energy released from a nuclear reaction come from? Consider the reaction between two hydrogen-1 atoms to make hydrogen-2 (aka deuterium) and a positron:

- Ignoring the positron, calculate the total mass of the reactants and the total mass of the products. They are not the same! What happened?! *(It wasn't the positron; we'll get to that soon.)*

^{1}H: M = 1.007 825 032 u
^{2}H: M = 2.014 101 778 u

Energy of Nuclear Reactions

- We can use this mass difference to calculate the amount of energy released in this reaction.
- Using the same formula, we can calculate:
  - The energy released by two ^{1}H atoms colliding (in J):
  - The energy released by two moles of ^{1}H atoms colliding (in J/mol):

$$\boxed{\Delta E = \Delta mc^2}$$

These two values are very different! Why?

^{1}H: M = 1.007 825 032 u
^{2}H: M = 2.014 101 778 u

Energy of Nuclear Reactions

- Some of this energy will be carried by the positron; most is carried by a neutrino.
- So, why can we ignore the mass of the positron when calculating Δm for this reaction? *Hint: Consider all components of the reactant and product atoms.*

Note: While you should ignore the masses of electrons and positrons in this type of calculation, you must include the masses of alpha particles and neutrons.

Energy of Nuclear Reactions

- For practice, calculate the energy released in the fission of uranium-235 (induced by a neutron) to give cesium-133 and rubidium-100. Report your answer in J/mol.

^{1}n M = 1.008 664 916 u
^{100}Rb M = 99.949 9 u
^{133}Cs M = 132.905 451 933 u
^{235}U M = 235.043 929 9u

Radioactivity and Radiation

- When considering exposure to radiation, we cannot assume that all of the energy produced by the nuclear reaction will always be absorbed. If a person swallows something radioactive, that may be the case, but when standing near a radioactive object, they will only be exposed to the radiation traveling in their direction. Also, we must factor in the mass of the tissue absorbing the radiation. (A small child will suffer more damage than an adult from exposure to the same amount of energy.)

- The **absorbed dose** is a measure of the amount of radiation absorbed by a given mass of tissue.

- The unit for absorbed dose is the gray (Gy) where 1 Gy = 1 J/kg (1 Joule of energy absorbed by 1 kg tissue).

Radioactivity and Radiation

- Absorbed doses can be compared when the type of radiation is the same; however, we saw earlier that different types of radiation have different penetrating power and interact with matter to different degrees. For medical purposes, we therefore need another term – one that describes the amount of biological damage done by a given dose of radiation in a standardized way.

- The **equivalent dose** is a measure of how much biological damage can be done by the radiation absorbed. Essentially, the absorbed dose is multiplied by a 'radiation weighting factor' (W_R) to calculate the dose in gamma rays required to cause the same amount of biological damage.

- The unit for equivalent dose is the sievert (Sv) where 1 Sv = 1 J/kg (does the same amount of damage as 1 Joule of energy from gamma radiation absorbed by 1 kg tissue).

Radioactivity and Radiation

- How much exposure to radiation is safe?
  - Annual exposure to background radiation in Canada depends on location but typically about 3 mSv (mostly from cosmic rays, radiation from naturally occurring isotopes in environment, etc.)
  - The legal limit for radiation exposure at work is 50 mSv in a single year, and no more than 100 mSv accumulated over five years.
  - Most workers exposed to radiation receive less than 50 mSv over their entire career. This results in a slight increase in their lifetime cancer risk (~26% for worker vs. ~25% for general population). A worker exposed to the maximum legal limit for a 30-year career would have a more significantly increased lifetime cancer risk (~40% instead of ~25%).
  - Single doses have very different effects and risks than the same dose spread over time – especially if the single dose is focused on one part of the body.
  - The single-dose LD_{50} (dose that is lethal 50% of the time) is 4 Sv, or 4000 mSv. This is obviously not a *safe* dose, but is provided for comparison.

Radioactivity and Radiation

- A radiation worker weighing 75 kg is exposed to a ^{252}Cf neutron source, receiving an estimated dose of 10^{12} neutrons in the process. For this source, $W_R = 20$ and the neutrons have an average energy of 3×10^{-13} J.

  Calculate the absorbed dose and the equivalent dose.

  How does the equivalent dose compare to legal exposure limits?

Why Do Nuclear Reactions Occur?

- What factors affect stability of a particular nuclide?
  - A nucleus consists of protons and neutrons held together by the **strong nuclear force,** an attractive force between nucleons which decreases exponentially with distance (maximum strength at ~1 fm between nucleon centers; negligible strength at ~2.5 fm).

  - At the same time, there is **electrostatic repulsion** between the positively-charged protons. If this repulsion is too great, the nucleus will be unstable. This force also decreases with distance ($F \propto 1/r^2$) – but much less quickly than the strong nuclear force.

Why Do Nuclear Reactions Occur?

- Neutrons add strong force stabilization and decrease electrostatic repulsion (by increasing distance between protons); however, neutrons are inherently less stable than protons. Excess neutrons will decompose into proton/electron pairs:

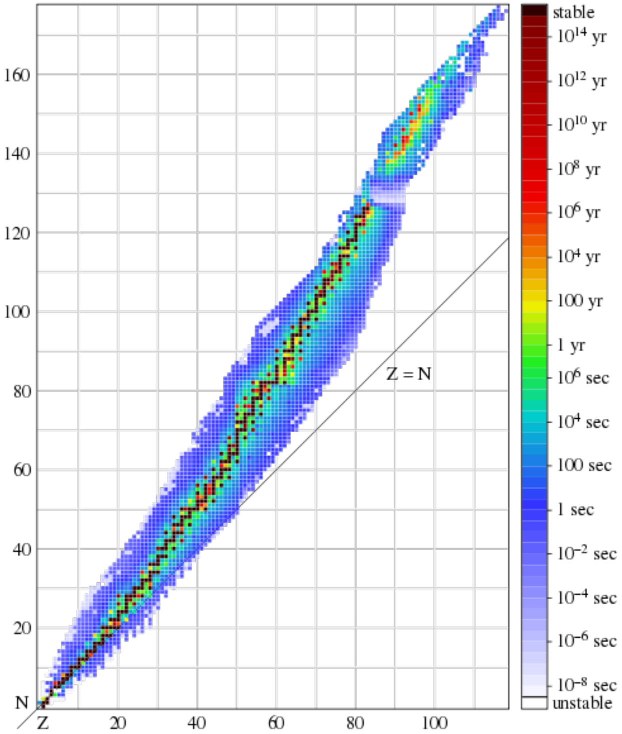
	mass
electron	0.00054858 u
proton	1.007276 u
neutron	1.008665 u

Why Do Nuclear Reactions Occur?

- It is therefore possible to make a few generalizations:
  - Nuclides that are too large are not stable. (The heaviest stable nucleus is ^{208}Pb.) Why not?
  - Nuclides containing more protons need more neutrons. Why?

Why Do Nuclear Reactions Occur?

- The number of stable nuclides is relatively small. Plotting #protons (Z) vs. #neutrons (N) for all nuclides ever observed gives a narrow band of stable nuclides *(black dots)* surrounded by a wider band of unstable nuclides *(coloured dots)*. The stable nuclides form the **band of stability**.



- Nuclides farthest from the band of stability are least stable, decaying fastest.
- N-to-Z ratio in stable nuclides is predictable:
  - If Z = 1-20 (H to Ca), N ≈ Z is ideal
  - If Z = 20-82 (Sc to Pb), N > Z up to N ≈ 1.5 Z
  - If Z ≥ 83 (Bi and larger), no stable nuclides exist
- Even values for Z & N are conducive to stability. Almost 60% of stable nuclides have both even. Less than 2% of stable nuclides have both odd!

Image from http://commons.wikimedia.org/wiki/File:Isotopes_and_half-life.svg

Why Do Nuclear Reactions Occur?

- The type of nuclear reaction which a nuclide is most likely to undergo can be predicted from its N-to-Z ratio.
  - A nucleus which has “too many neutrons” (i.e. N/Z is too high) will tend to undergo beta emission. How does this improve N/Z?
  - A small nucleus which has “too many protons” (i.e. N/Z is too low) will tend to undergo either positron emission or electron capture. How does this improve N/Z?
  - A large nucleus which has “too many protons” (i.e. N/Z is too low) will tend to undergo alpha emission. How does this improve N/Z?

Nuclear Binding Energy

- If individual nucleons (protons and neutrons) come together to make a nucleus, a huge amount of energy would be released:

protons + neutrons → nucleus

or

protons + neutrons + electrons → atom

- The energy change for this hypothetical reaction is referred to as the nuclide's **nuclear binding energy** (ΔE)

$$\Delta E = \Delta mc^2 = \left(m_{nucleus} - \sum m_{nucleons}\right) \times c^2$$

or

$$\Delta E = \Delta mc^2 = \left(m_{isotope} - \sum m_{subatomic\ particles}\right) \times c^2$$

Nuclear Binding Energy

- To avoid a bias toward larger nuclides seeming more stable than they actually are, a more useful quantity is the **nuclear binding energy per nucleon** (E_b):

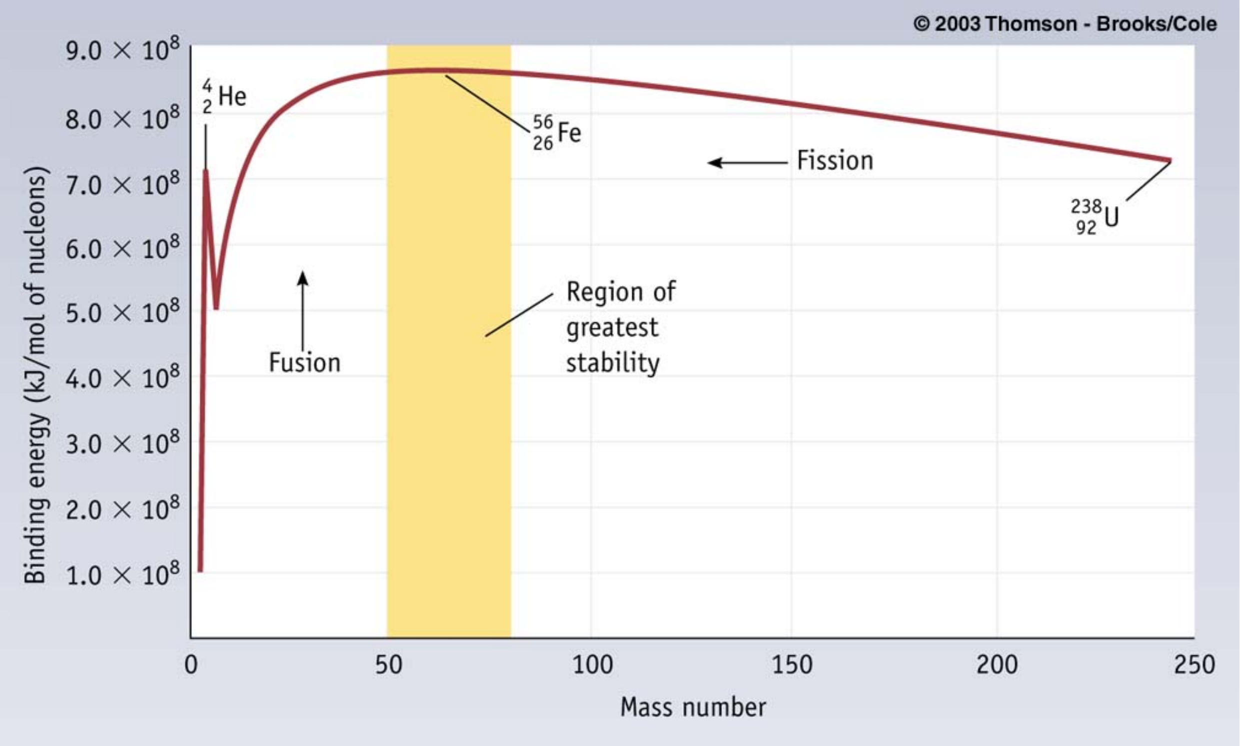
$$\boxed{E_b = \frac{\Delta E}{A}}$$

where A = mass number = #nucleons = Z + N

- Nuclides with larger E_b values are more stable.

Nuclear Binding Energy

- ^{4}He is unusually stable for its size. Until recently, the most stable nuclide was thought to be ^{56}Fe; it's now thought to be ^{62}Ni:



- This plot also shows which nuclides can undergo fusion (E_b increases as mass number increases) and which nuclides can undergo fission (E_b increases as mass number decreases).