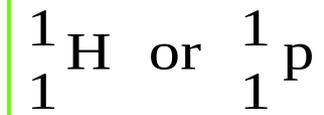


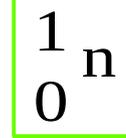
# Nuclear Chemistry

# Subatomic Particles

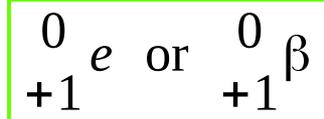
proton



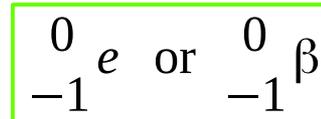
neutron



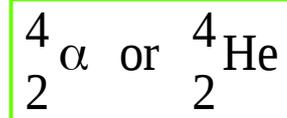
positron



electron



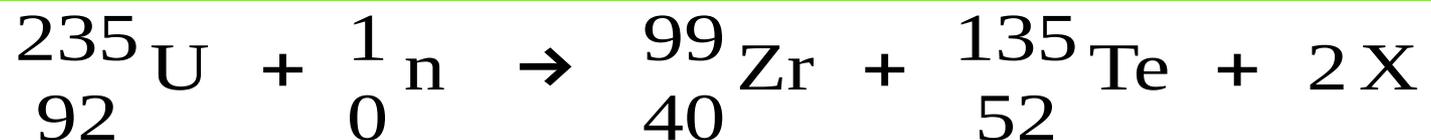
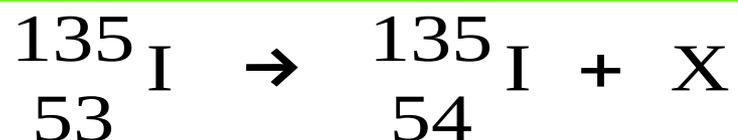
$\alpha$  particle



# Nuclear Reactions

A balanced nuclear equation has the sum of the mass numbers (top left) and the atomic numbers (bottom left) identical on both sides of the arrow.

What is X in each of the following equations?



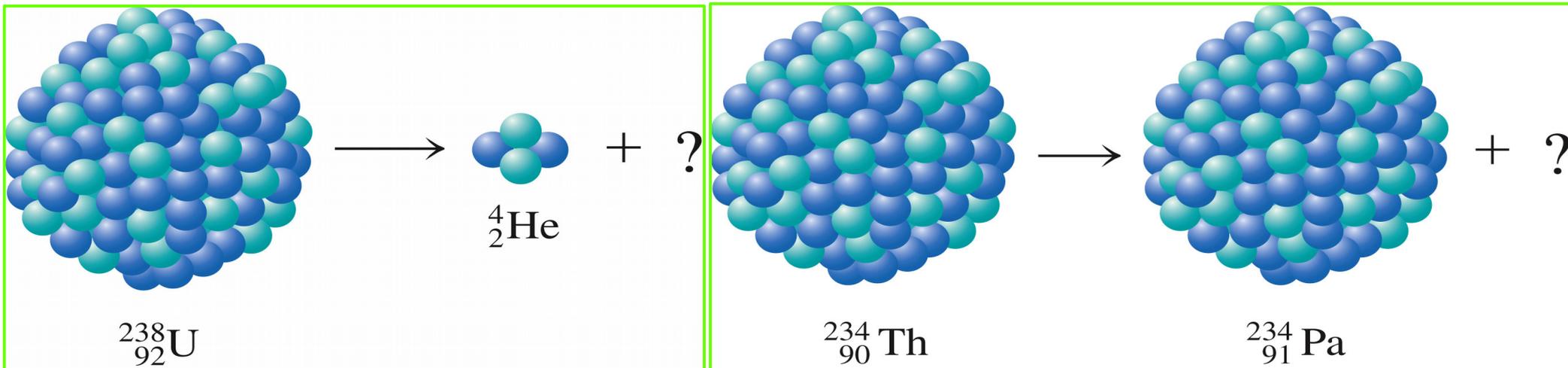
# Nuclear Stability

The nucleus is very dense, protons, all positively charged, are in very close proximity.

The Coulombic repulsion is very high.

There is also a short-range attractive force between nucleons (proton – proton, neutron – neutron, and proton – neutron)

If the repulsion is greater than the attractive forces the nucleus disintegrates emitting particles and/or radiation.



# Patterns of Nuclear Stability

The neutron to proton ratio affects the stability of a nucleus.

The more neutrons there are the more of the short range attractive forces there are.

Heavier elements have more protons, and thus more repulsive forces in their nuclei. A greater neutron to proton ratio is needed to stabilize the nucleus.

# Guidelines for Predicting Nuclear Stability

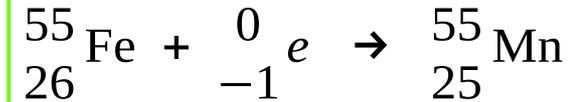
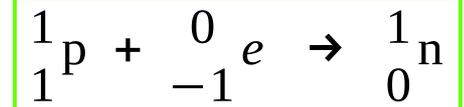
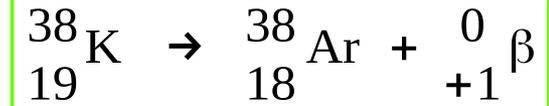
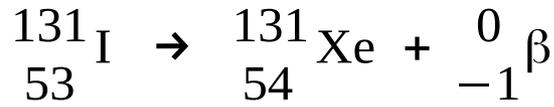
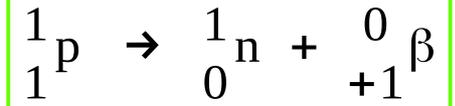
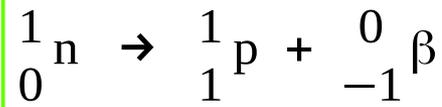
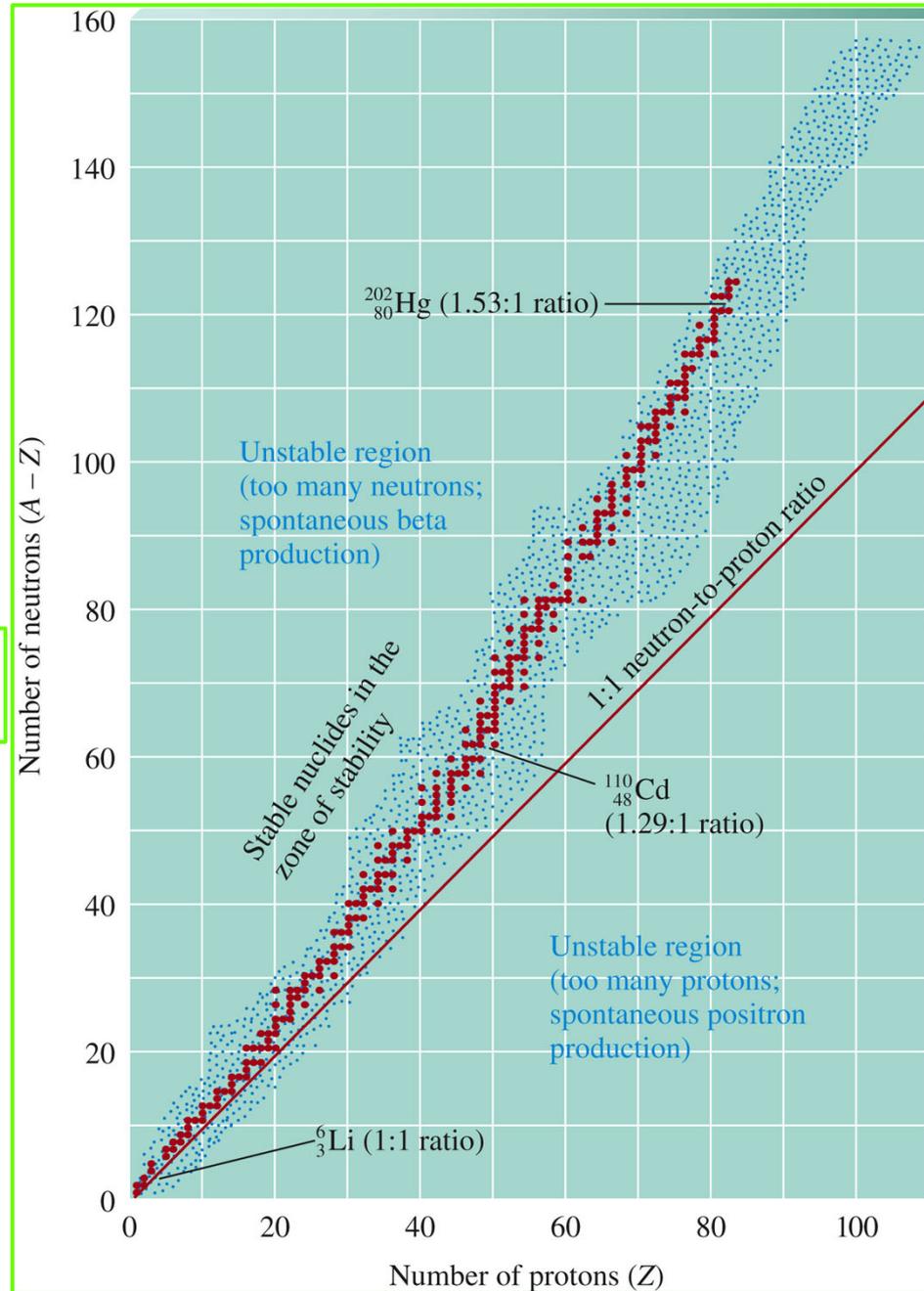
- 1.) There are more stable nuclei containing 2, 8, 20, 50, 82, or 126 (the “magic numbers” protons or neutrons than nuclei that don't have one of these numbers of protons or neutrons.
- 2.) There are many more stable nuclei with even numbers of both protons and neutrons than with odd numbers of these particles.
- 3.) All isotopes of elements with higher atomic numbers than 83 are radioactive.
- 4.) All isotopes of technetium (Tc) and promethium (Pm) are radioactive.

Protons	Neutrons	Number of stable isotopes
Odd	Odd	4
Odd	Even	50
Even	Odd	53
Even	Even	164

Nuclei above the belt of stability have a neutron to proton ratio that is too high. These will undergo  $\beta^-$  emission to reach the belt.

# The Belt of Stability

Nuclei below the belt of stability have a neutron to proton ratio that is too low. These will undergo positron emission or electron capture to reach the belt.



# Thermodynamic Stability of Nuclei

Consider forming an oxygen – 16 nucleus from its protons and neutrons:



The mass of 8 neutrons + 8 protons =

$$8(1.67493 \times 10^{-24} \text{ g}) + 8(1.67262 \times 10^{-24} \text{ g}) = 2.67804 \times 10^{-23} \text{ g}$$

The mass of an oxygen – 16 nucleus =  $2.65535 \times 10^{-23} \text{ g}$

The difference in mass for 1 nucleus is

$$2.65535 \times 10^{-23} \text{ g} - 2.67804 \times 10^{-23} \text{ g} = -2.269 \times 10^{-25} \text{ g}$$

For 1 mol of nuclei the difference is

$$(-2.269 \times 10^{-25} \text{ g/nucleus})(6.022 \times 10^{23} \text{ nuclei/mol}) = -0.1366 \text{ g/mol}$$

This difference is called the mass defect.

# Thermodynamic Stability of Nuclei

Where does this mass go? According to Einstein mass and energy are equivalent:

$$E = mc^2$$

So the change in mass ( $\Delta m$ ) corresponds to a change in energy ( $\Delta E$ ):

$$\Delta E = \Delta mc^2$$

So the formation of the oxygen – 16 nucleus results in a change in energy of:

$$\Delta E = (-1.366 \times 10^{-4} \text{ kg/mol})(2.998 \times 10^8 \text{ m/s})^2 = -1.228 \times 10^{13} \text{ J/mol}$$

or the change in energy per nucleus is

$$\frac{-1.23 \times 10^{13} \text{ J/mol}}{6.022 \times 10^{23} \text{ nuclei/mol}} = -2.039 \times 10^{-11} \text{ J/nucleus}$$

And per nucleon:

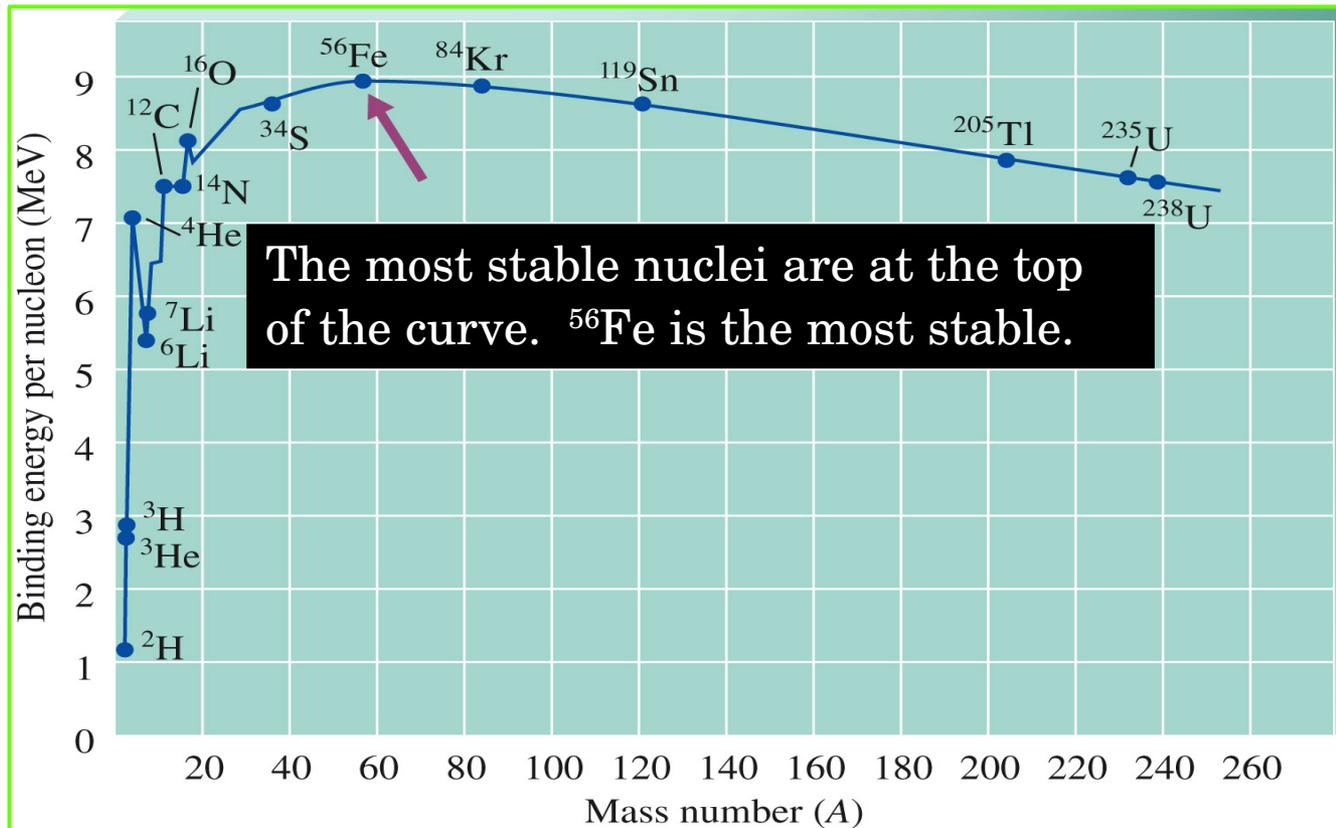
$$\frac{-2.039 \times 10^{-11} \text{ J/nucleus}}{16 \text{ nucleons/nucleus}} = -1.274 \times 10^{-12} \text{ J/nucleon}$$

# Nuclear Binding Energy

So  $1.274 \times 10^{-12}$  joules of energy per nucleon will be released upon forming the oxygen – 16 nucleus from protons and neutrons.

This is also the amount of energy that is required to decompose an oxygen – 16 nucleus. This is called the binding energy. It is commonly given in MeV:

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$$



# Nuclear Binding Energy

Calculate the binding energy, in MeV, per nucleon for  ${}^6\text{Li}$ . The mass of a lithium – 6 atom is 6.941 amu including the three electrons. The mass of a hydrogen atom is 1.00794 amu including the one electron.  $1 \text{ amu} = 1.66054 \times 10^{-27} \text{ kg}$ ,  $c = 2.998 \times 10^8 \text{ m/s}$ ,  $1\text{MeV} = 1.602 \times 10^{-13} \text{ J}$ .

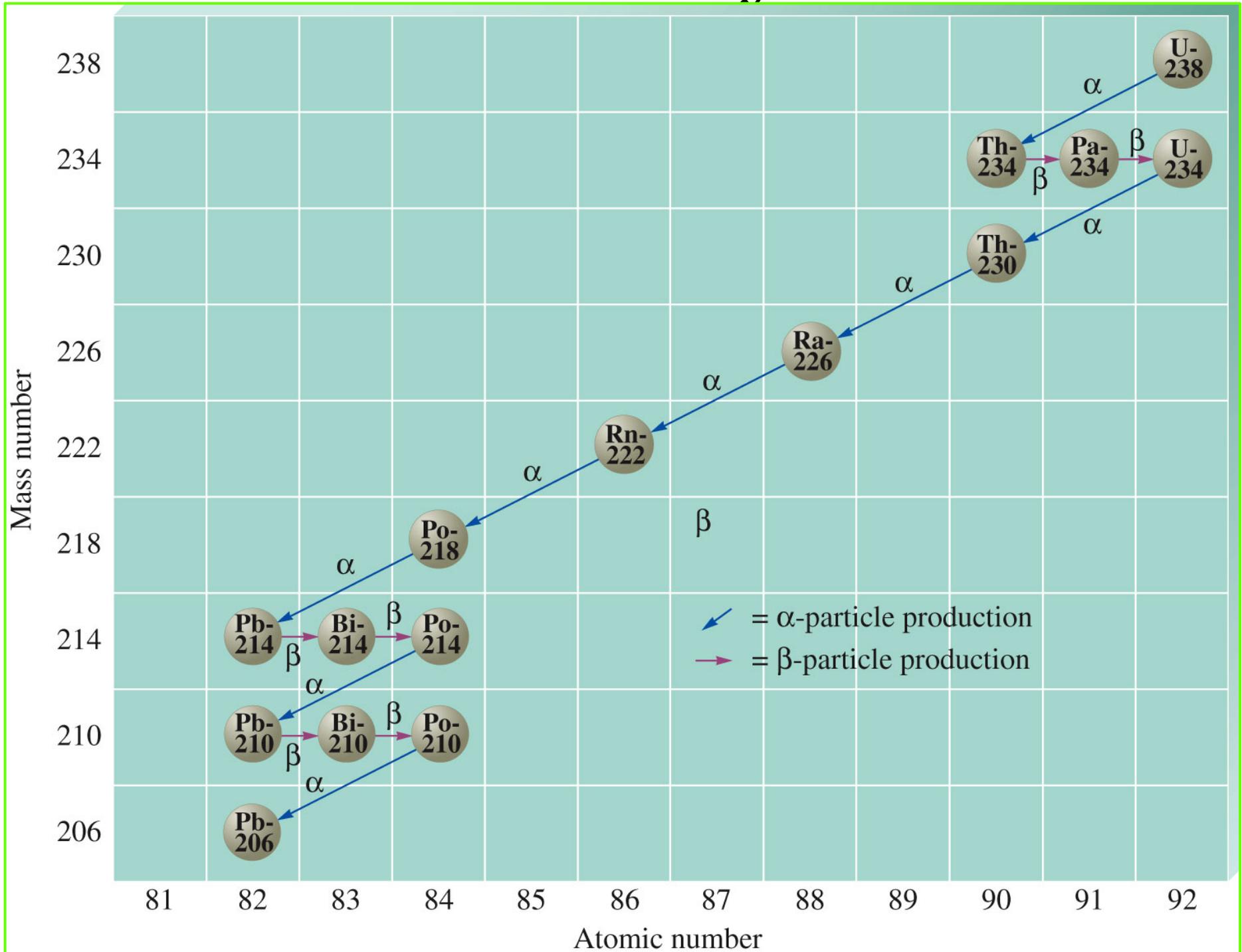
# Radioactive Decay

Nuclei outside of the belt of stability tend to undergo spontaneous emission of particles, electromagnetic radiation, or both. This is called radioactivity. The primary types of radioactivity are:

- 1.)  $\alpha$  – emission
- 2.)  $\beta$  – emission
- 3.)  $\gamma$  – emission ( $\gamma$  – rays)
- 4.) positron emission
- 5.) electron capture (usually a 1s electron)

When a nucleus decays it is often the beginning of a radioactive decay series: a sequence of nuclear reactions that end up forming a stable isotope.

# The $^{238}\text{U}$ Decay Series



# Kinetics of Radioactive Decay

The rate of decay for radioactive isotopes is a first order process and obeys the integrated rate for first order kinetics:

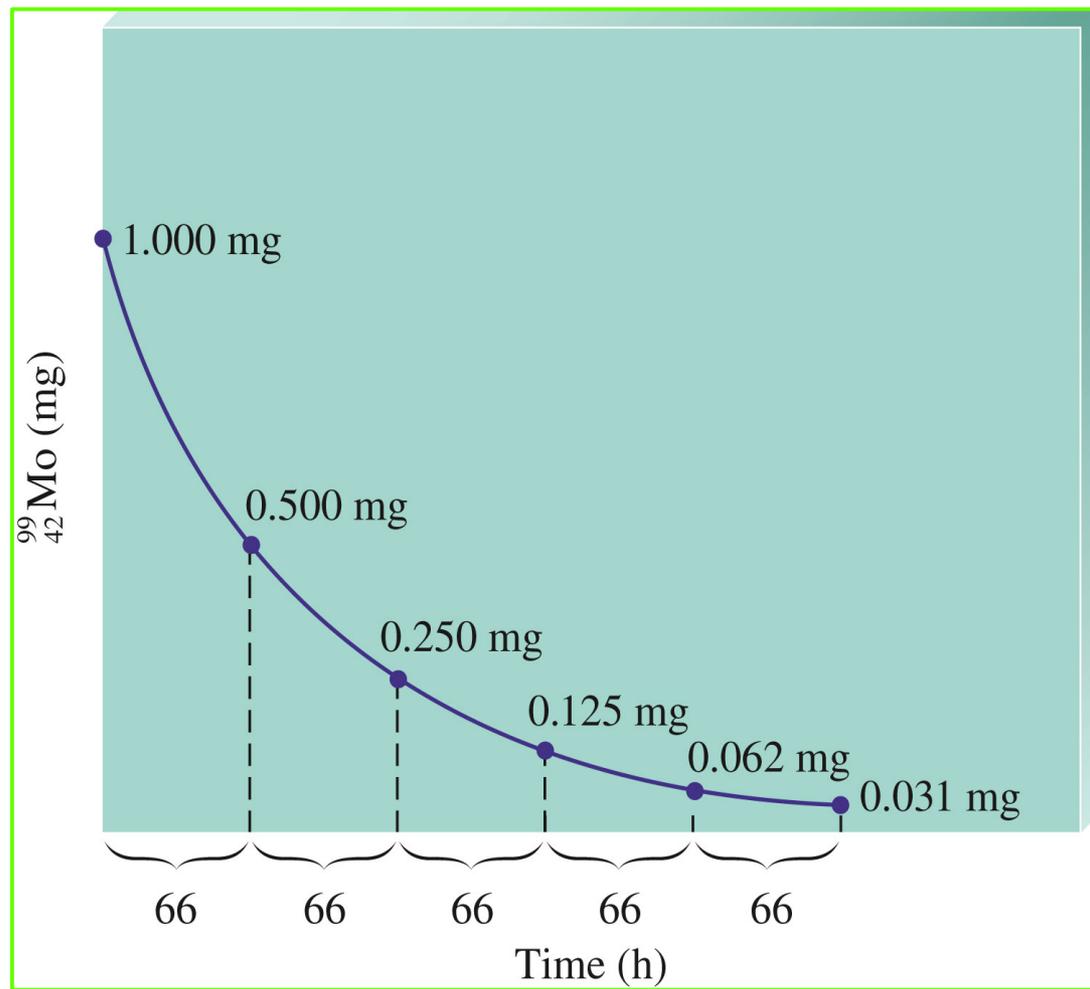
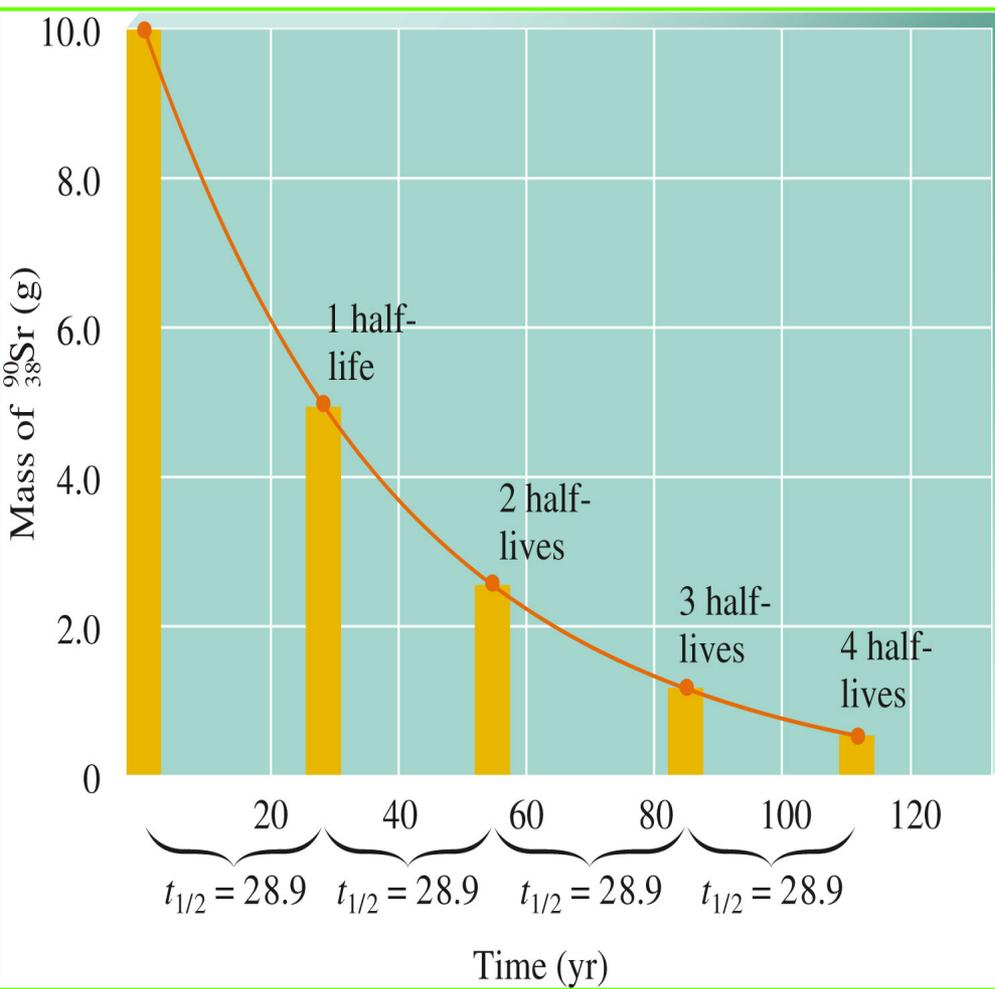
$$\ln \left( \frac{N}{N_0} \right) = -kt$$

Here  $N_0$  is the number of nuclides at  $t = 0$  and  $N$  is the number remaining at time  $t$ .

The half-life,  $t_{1/2}$ , is defined as the time required for half of the nuclides originally present to decay.

$$t_{1/2} = \frac{\ln(2)}{k}$$

$t_{1/2}$



$$t_{1/2}$$

Define “third – life” like half – life. What is the “third – life” for a nuclide that has a half – life of 28.9 years?

Plutonium – 239 (produced in breeder reactors) has a half – life of 24,100 years. How long will it take for a sample of plutonium – 239 to decay to 0.1% of it's original value?