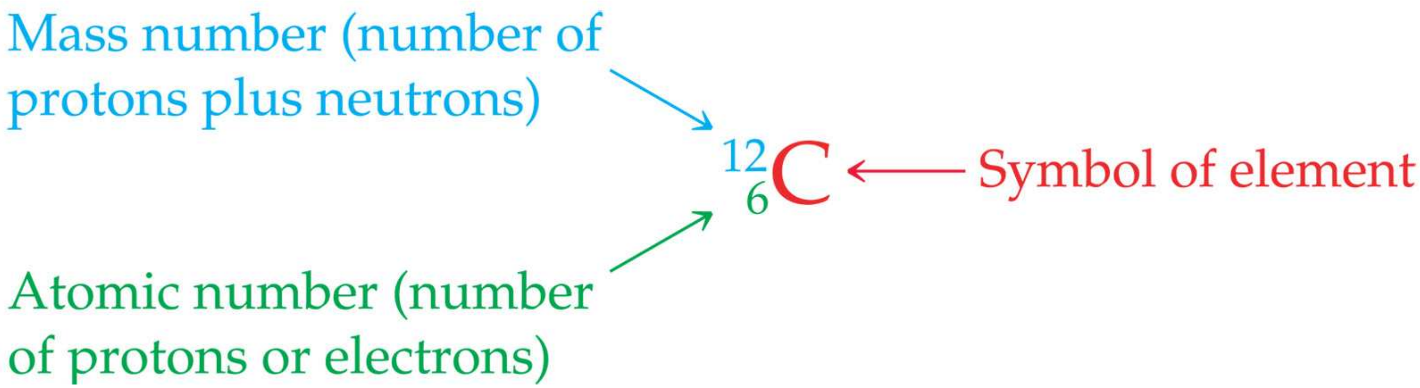
Chemistry, The Central Science, 10th edition
Theodore L. Brown; H. Eugene LeMay, Jr.; and Bruce E. Bursten

Chapter 21
Nuclear Chemistry

John D. Bookstaver
St. Charles Community College
St. Peters, MO

Nuclear Chemistry

The Nucleus



- Remember that the nucleus is comprised of the two nucleons, protons and neutrons.
- The number of protons is the atomic number.
- The number of protons and neutrons together is effectively the mass of the atom.

Nuclear Chemistry

Isotopes

- Not all atoms of the same element have the same mass due to different numbers of neutrons in those atoms.
- There are three naturally occurring isotopes of uranium:
  - Uranium-234
  - Uranium-235
  - Uranium-238

Radioactivity

- It is not uncommon for some nuclides of an element to be unstable, or radioactive.
- We refer to these as radionuclides.
- There are several ways radionuclides can decay into a different nuclide.

Nuclear Equations

$$^{238}_{92}U \longrightarrow \, ^{234}_{90}U + \, ^{4}_{2}He$$

- In a nuclear reaction the atomic mass and atomic number has to add up in the reactants and the products.

Nuclear Chemistry

What product is formed when radium-226 undergoes alpha decay?

Nuclear Chemistry

What product is formed when radium-226 undergoes alpha decay?

Which element undergoes alpha decay to form lead-208?

Nuclear Chemistry

Types of Radioactive Decay

Nuclear Chemistry

Alpha Decay:

Loss of an α-particle (a helium nucleus)

$$^{4}_{2}\mathrm{He}$$

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{U} + {}^{4}_{2}\mathrm{He}$$

Nuclear Chemistry

Beta Decay:

Loss of a β-particle (a high energy electron)

$$^{0}_{-1}\beta \quad \text{or} \quad ^{0}_{-1}e$$

$$^{131}_{53}I \longrightarrow \, ^{131}_{54}Xe + \, ^{0}_{-1}e$$

Nuclear Chemistry

Positron Emission:

Loss of a positron (a particle that has the same mass as but opposite charge than an electron)

$$^{0}_{1}\mathrm{e}$$

$$^{11}_{6}\mathrm{C} \longrightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{1}\mathrm{e}$$

What actually happens is :

$$^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{1}e$$

Nuclear Chemistry

Gamma Emission:

Loss of a γ-ray (high-energy radiation that almost always accompanies the loss of a nuclear particle)

$$^{0}_{0}\gamma$$

Nuclear Chemistry

Electron Capture (K-Capture)

$$^{81}_{37}\text{Rb} + \, ^{0}_{-1}e \text{ (orbital electron)} \rightarrow \, ^{81}_{36}\text{Kr}$$

Addition of an electron to a proton in the nucleus

- As a result, a proton is transformed into a neutron.

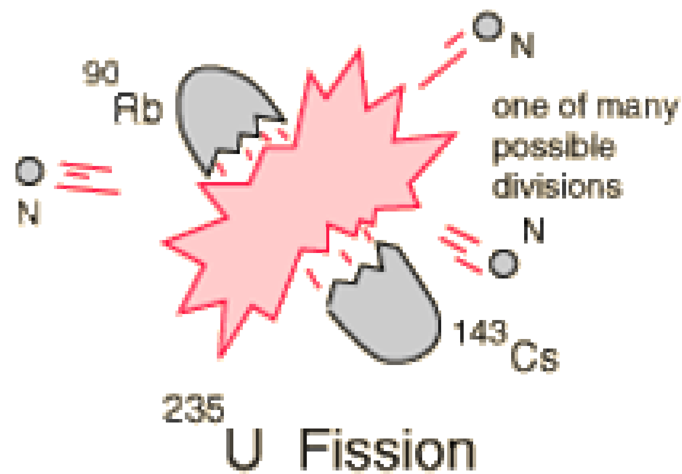
$$^{1}_{1}\text{p} + \, ^{0}_{-1}\text{e} \longrightarrow \, ^{1}_{0}\text{n}$$

Nuclear Chemistry

Where does nuclear energy come from?

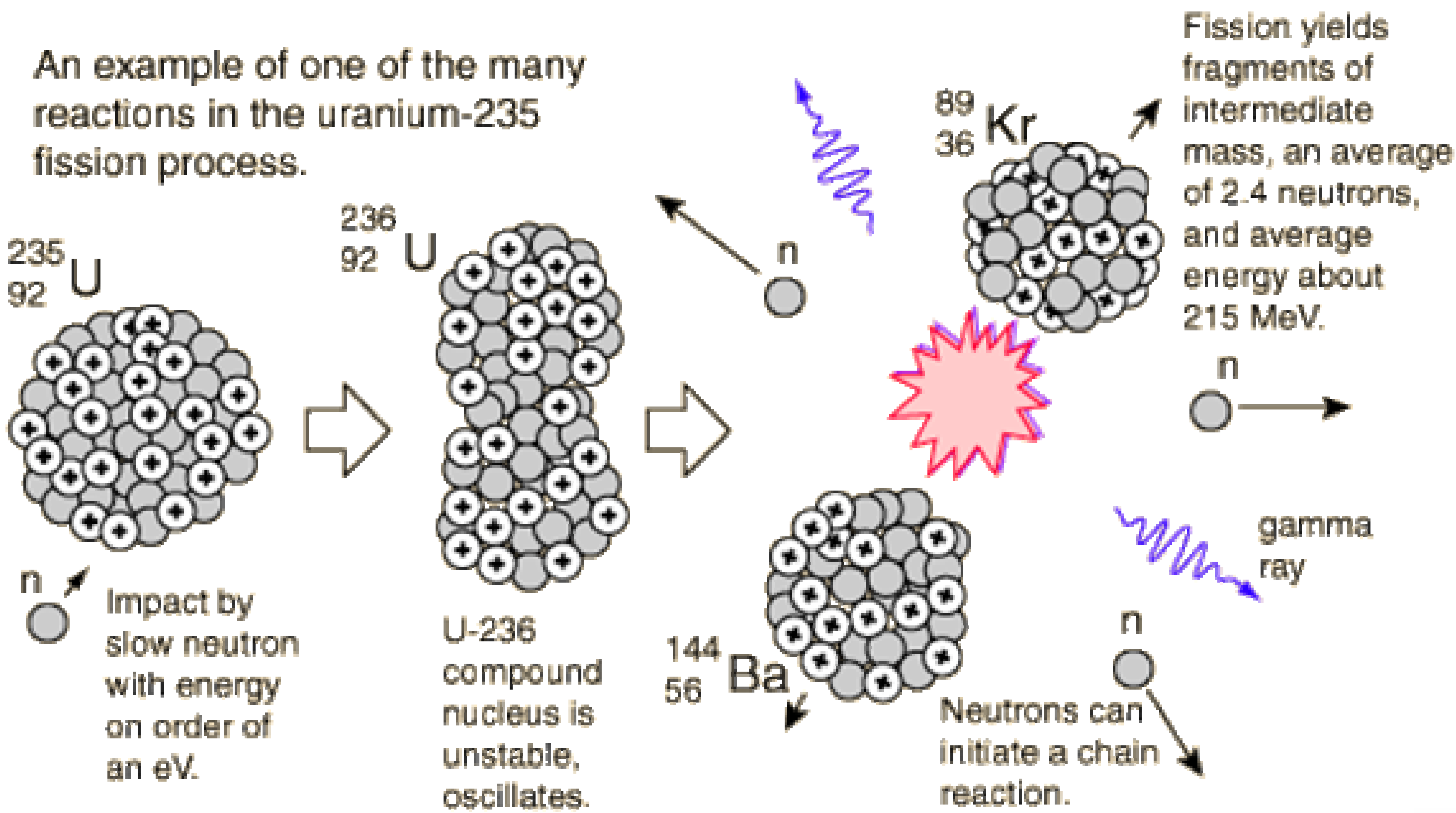
$$^{1}_{0}n + \,^{235}_{92}U \rightarrow \,^{90}_{37}Rb + \,^{143}_{55}Cs + 3\,^{1}_{0}n$$

E = mc²



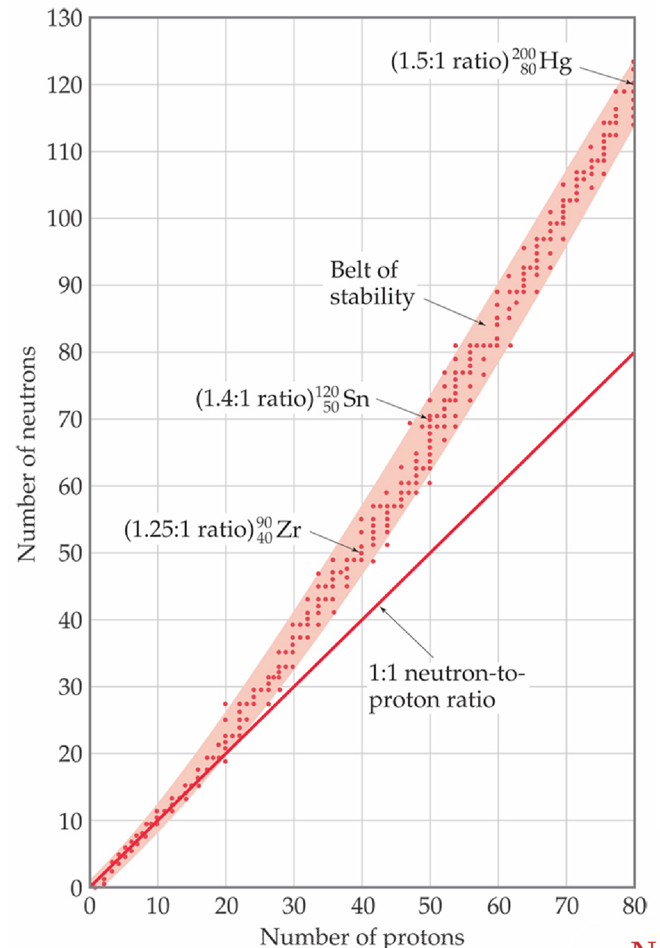
Images from http://hyperphysics.phy-astr.gsu.edu/Hbase/nucene/fission.html

Nuclear Chemistry


An example of one of the many reactions in the uranium-235 fission process.
235 92 U
n
Impact by slow neutron with energy on order of an eV.
236 92 U
U-236 compound nucleus is unstable, oscillates.
n
89 36 Kr
144 56 Ba
Fission yields fragments of intermediate mass, an average of 2.4 neutrons, and average energy about 215 MeV.
n
gamma ray
n
Neutrons can initiate a chain reaction.

Neutron-Proton Ratios

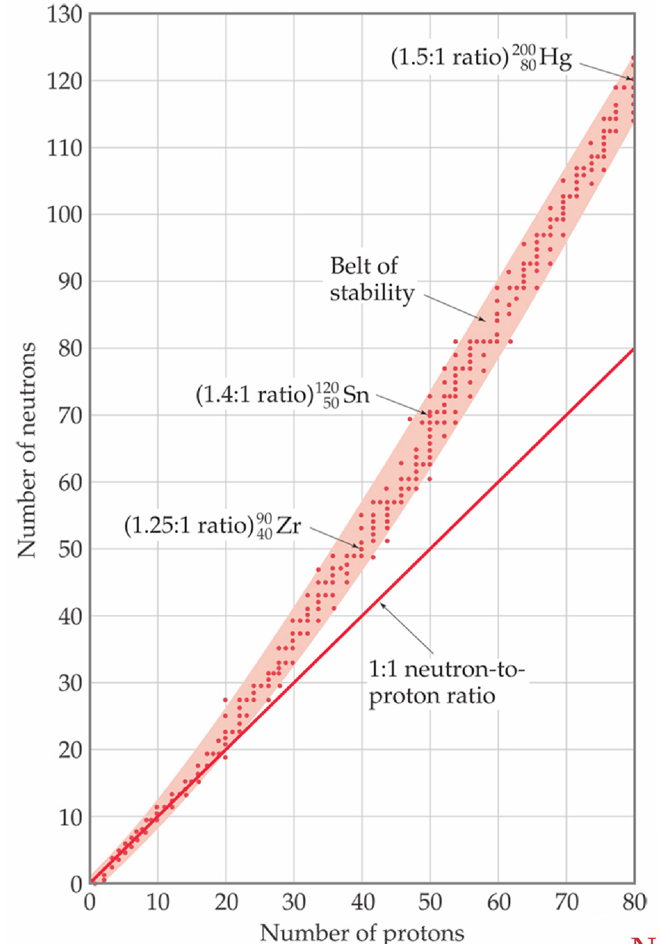
- Any element with more than one proton (i.e., anything but hydrogen) will have repulsions between the protons in the nucleus.
- A strong nuclear force helps keep the nucleus from flying apart.



Nuclear Chemistry

Neutron-Proton Ratios

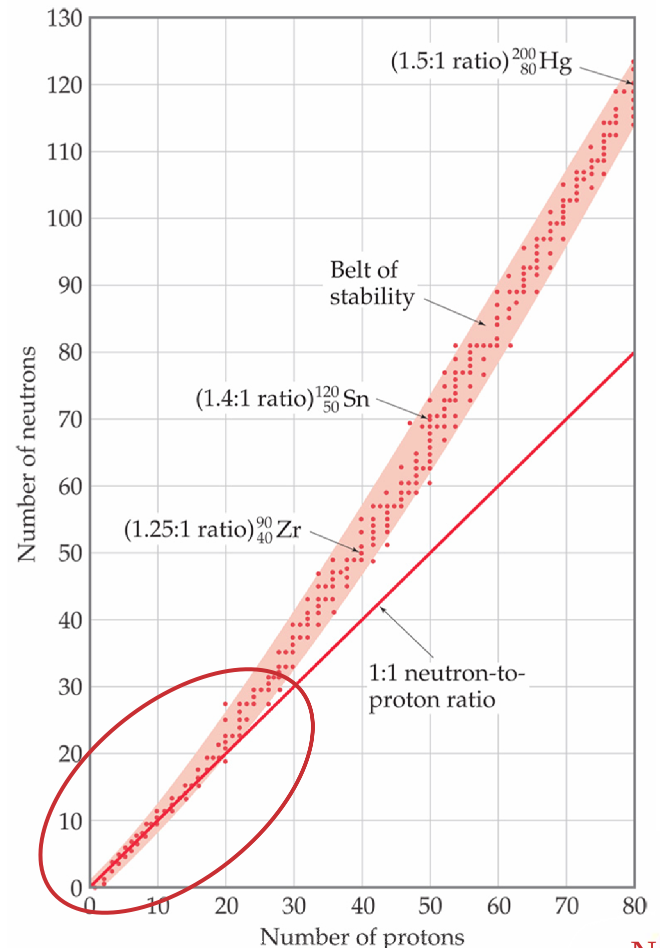
- Neutrons play a key role stabilizing the nucleus.
- Therefore, the ratio of neutrons to protons is an important factor.



Nuclear Chemistry

Neutron-Proton Ratios

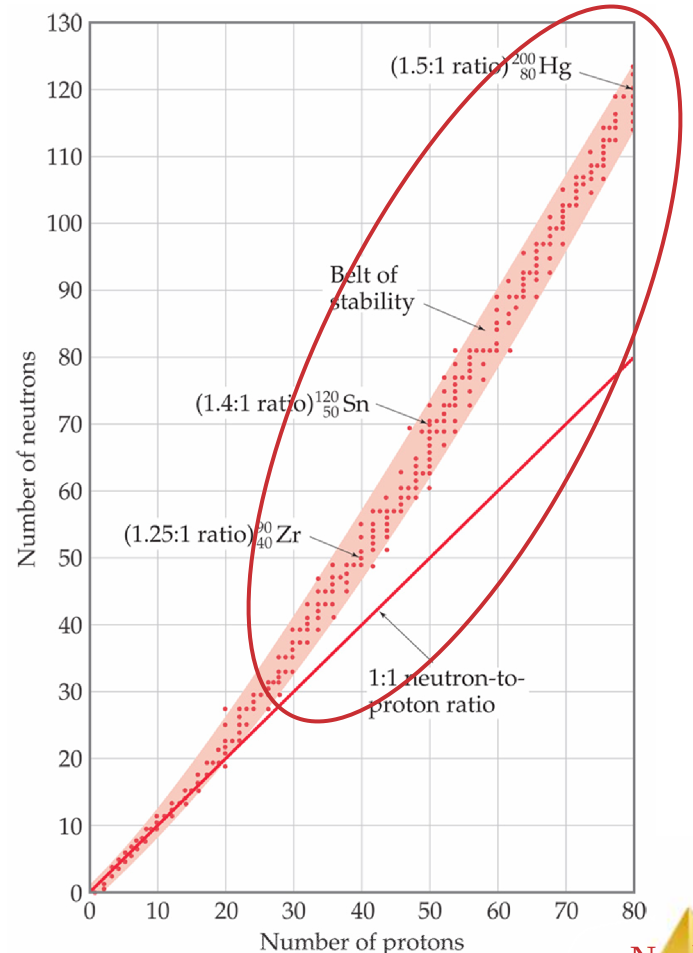
For smaller nuclei ($Z \leq 20$) stable nuclei have a neutron-to-proton ratio close to 1:1.



Nuclear Chemistry

Neutron-Proton Ratios

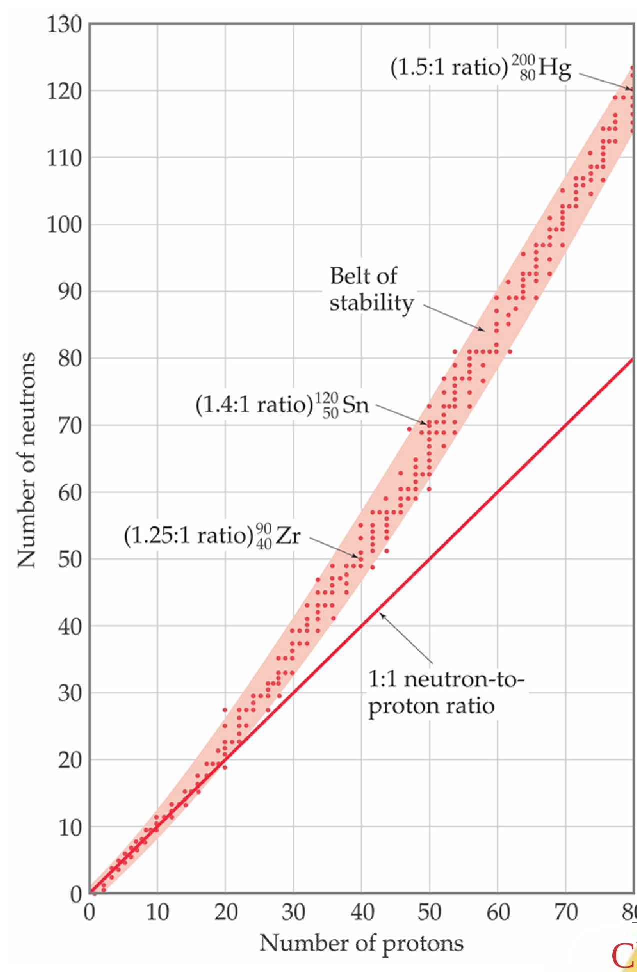
As nuclei get larger, it takes a greater number of neutrons to stabilize the nucleus.



Nuclear Chemistry

Stable Nuclei

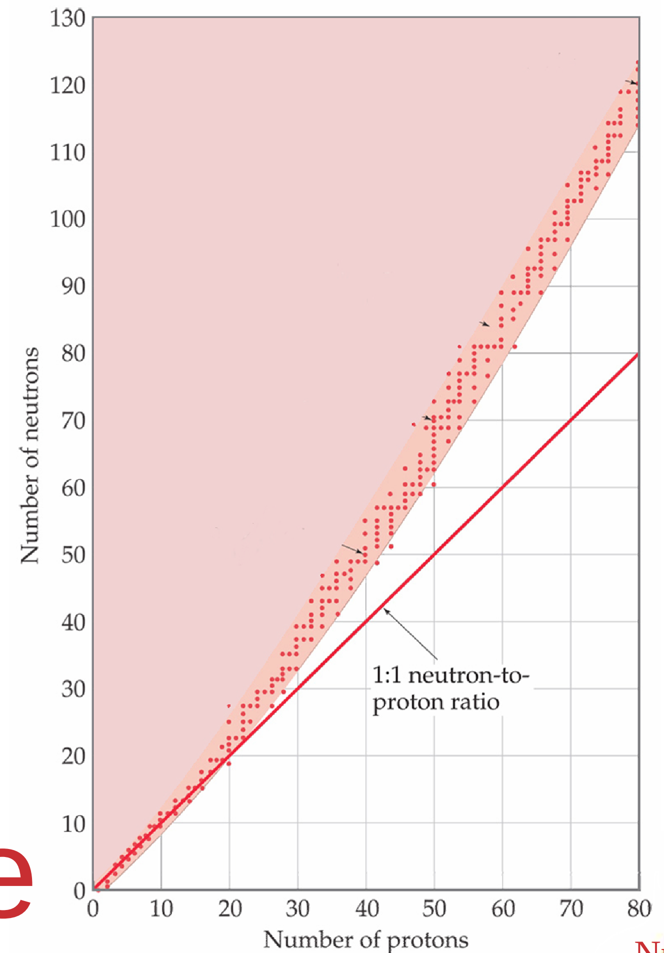
The shaded region in the figure shows what nuclides would be stable, the so-called **belt of stability**.



Nuclear Chemistry

- Nuclei above this belt have too many neutrons.
- They tend to decay by emitting beta particles.

$$^{131}_{53}I \longrightarrow ^{131}_{54}Xe + ^{0}_{-1}e$$

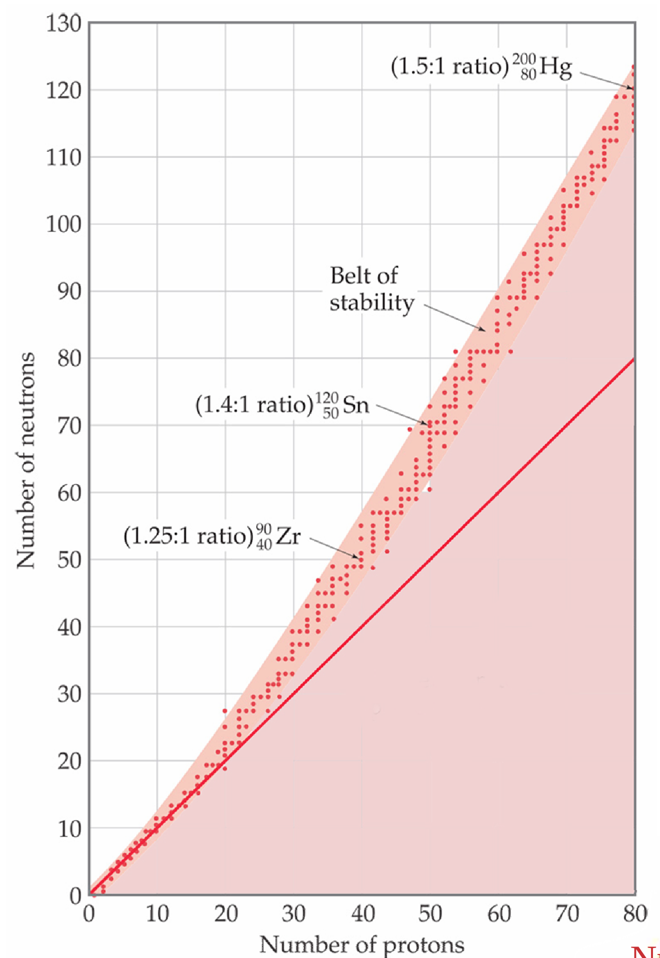


Nuclear Chemistry

- Nuclei below the belt have too many protons.
- They tend to become more stable by positron emission or electron capture.

$$^{11}_{6}\mathrm{C} \longrightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{1}\mathrm{e}$$

$$^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{1}_{0}\mathrm{n}$$



Nuclear Chemistry

Predict the mode of decay of

(a) carbon-14,

(b) xenon-118.

Predict the mode of decay of (a) carbon-14,

Solve: **(a)** Carbon has an atomic number of 6. Thus, carbon-14 has 6 protons and 14 –6 = 8 neutrons, giving it a neutron-to-proton ratio of $\frac{8}{6} = 1.3$. Elements with low atomic numbers normally have stable nuclei with approximately equal numbers of neutrons and protons. Thus, carbon-14 has a high neutron-to-proton ratio, and we expect that it will decay by emitting a beta particle:

$$^{14}_{6}\text{C} \longrightarrow {}^{0}_{-1}\text{e} + {}^{14}_{7}\text{N}$$

(b) (b) xenon-118.

(b) Xenon has an atomic number of 54. Thus, xenon-118 has 54 protons and 118 – 54 = 64 neutrons, giving it a neutron-to-proton ratio of $\frac{64}{54} = 1.2$. According to Figure 21.2, stable nuclei in this region of the belt of stability have higher neutron-to-proton ratios than xenon-118. The nucleus can increase this ratio by either positron emission or electron capture:

$$^{118}_{54}\text{Xe} \longrightarrow {}^{0}_{1}\text{e} + {}^{118}_{53}\text{I}$$

$$^{118}_{54}\text{Xe} + {}^{0}_{-1}\text{e} \longrightarrow {}^{118}_{53}\text{I}$$

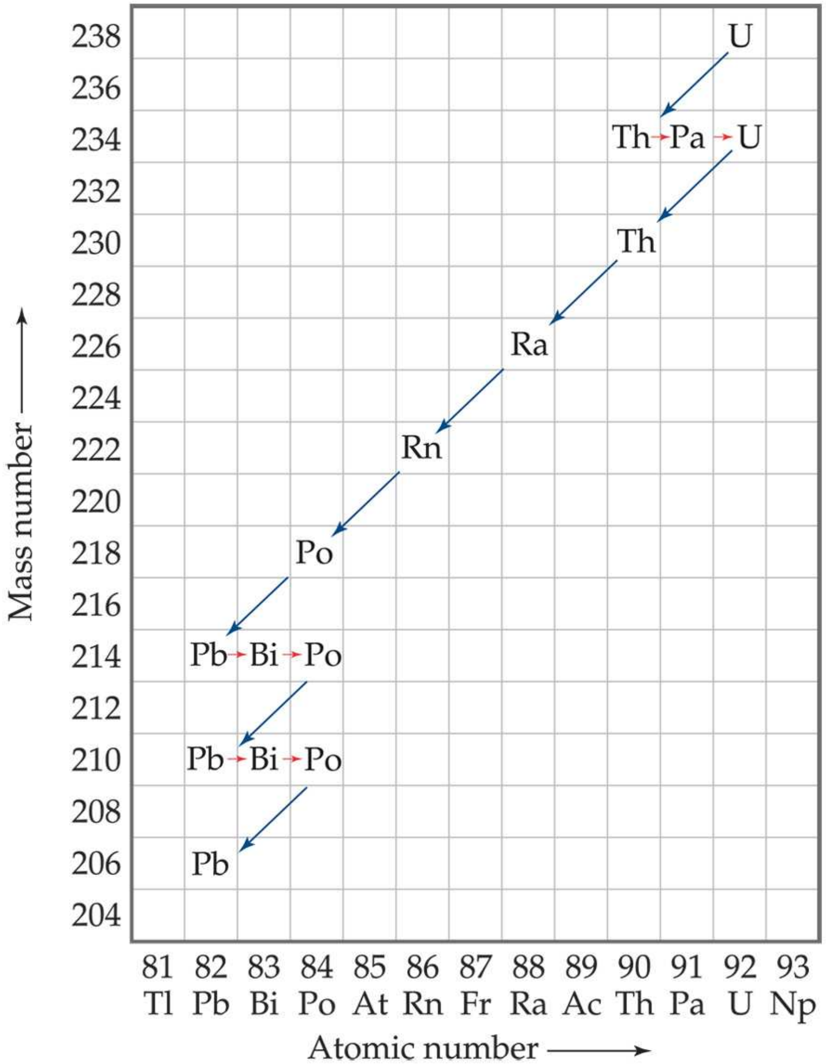
Nuclear Chemistry

Stable Nuclei

- There are no stable nuclei with an atomic number greater than 83.
- These nuclei tend to decay by alpha emission.

Nuclear
Chemistry

Radioactive Series
Or
Nuclear Degenerative Series



- Large radioactive nuclei cannot stabilize by undergoing only one nuclear transformation.
- They undergo a series of decays until they form a stable nuclide (often a nuclide of lead).

Nuclear Chemistry

Some Trends

Nuclei with 2, 8, 20, 28, 50, or 82 protons or 2, 8, 20, 28, 50, 82, or 126 neutrons tend to be more stable than nuclides with a different number of nucleons. These numbers are called *magic numbers*.

Paired neutrons and protons have a special stability something like the paired electrons have a special stability

Some Trends

Number of Stable Isotopes	Protons	Neutrons
157	Even	Even
53	Even	Odd
50	Odd	Even
5	Odd	Odd

Nuclei with an even number of protons and neutrons tend to be more stable than nuclides that have odd numbers of these nucleons.

- In the radioactive series all the elements end in a Pb nucleus which has the magic number of 82

Nuclear Transformations

- Rutherford in 1919 performed the first nuclear transformation.

$$^{14}_{7}\text{N} + {}^{2}_{4}\text{He} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{H}$$

- The transmutations are sometimes represented by listing in order, the target nucleus, the bombarding particle, the ejecting particle and the product nucleus.
- The above equation becomes:

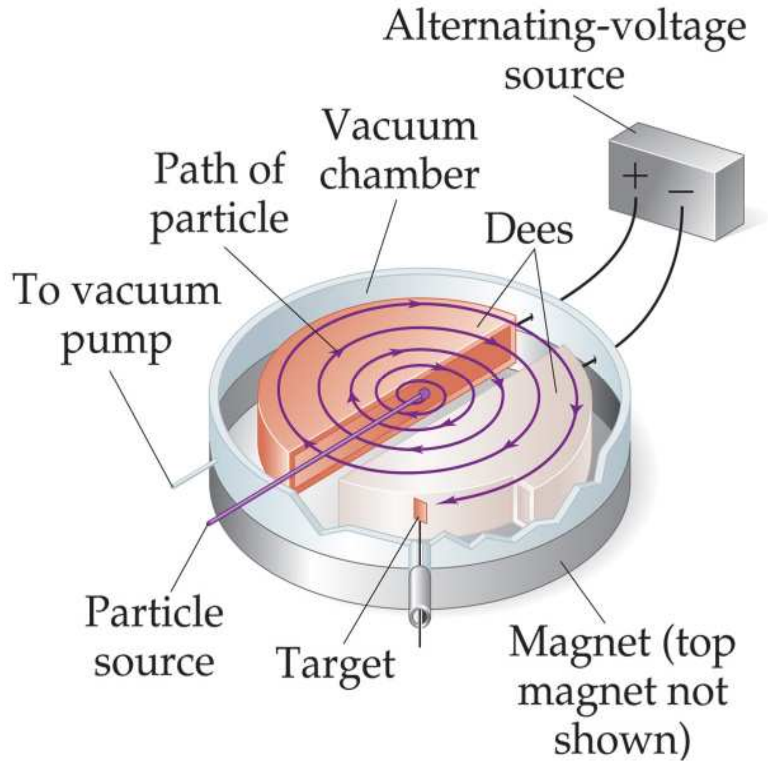
$$^{14}_{7}\text{N}(\alpha,\text{p})\,{}^{17}_{8}\text{O}$$

Nuclear Chemistry

Write the balanced nuclear equation for the process summarized as $^{27}_{13}\mathrm{Al}(\mathrm{n}, \alpha)^{24}_{11}\mathrm{Na}$.

Nuclear Chemistry

Nuclear Transformations



Nuclear transformations can be induced by accelerating a particle and colliding it with the nuclide in particle accelerators called cyclotrons or synchrotrons or *particle smashers*.

Particle Accelerators

These particle accelerators are enormous, having circular tracks with radii that are miles long.

Fermi National Accelerator Laboratory, Batavia, Illinois

Nuclear Chemistry

- The synthetic isotopes used in medicine are synthesized using neutrons as the projectiles. Since neutrons are neutral they do not need to be accelerated to overcome the electrostatic repulsion of the nucleus.

- Cobalt-60 used in cancer therapy is made by the following reaction:

$$^{58}_{26}Fe + ^{1}_{0}n \rightarrow ^{56}_{26}Fe$$

$$^{56}_{26}Fe \rightarrow ^{59}_{27}Co + ^{0}_{-1}e$$

$$^{59}_{27}Co + ^{1}_{0}n \rightarrow ^{60}_{27}Co$$

Nuclear Chemistry

Transuranium Elements

- Artificial elements that have been produced in labs
- These have an atomic number above 92.
- They are short lived.
- Elements 113 and 114 have not even been assigned a name or symbol.

Nuclear Chemistry

Kinetics of Radioactive Decay

- Nuclear transmutation is a first-order process.
- The kinetics of such a process, you will recall, obey this equation:

$$\ln \frac{[A]_t}{[A]_0} = -kt$$

- We can substitute the number of nuclei for concentration:

$$\ln \frac{N_t}{N_0} = -kt$$

Kinetics of Radioactive Decay

- The half-life of such a process is:

$$\frac{0.693}{k} = t_{1/2}$$

- Comparing the amount of a radioactive nuclide present at a given point in time with the amount normally present, one can find the age of an object.

Nuclear Chemistry

The half-life of cobalt-60 is 5.3 yr. How much of a 1.000-mg sample of cobalt-60 is left after a 15.9-yr period?

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- Answer 0.125 mg

Kinetics of Radioactive Decay

A wooden object from an archeological site is subjected to radiocarbon dating. The activity of the sample that is due to ^{14}C is measured to be 11.6 disintegrations per second. The activity of a carbon sample of equal mass from fresh wood is 15.2 disintegrations per second. The half-life of ^{14}C is 5715 yr. What is the age of the archeological sample?

Kinetics of Radioactive Decay

First we need to determine the rate constant, *k*, for the process.

$$\frac{0.693}{k} = t_{1/2}$$

$$\frac{0.693}{k} = 5715\ \text{yr}$$

$$\frac{0.693}{5715\ \text{yr}} = k$$

$$1.21 \times 10^{-4}\ \text{yr}^{-1} = k$$

Kinetics of Radioactive Decay

Now we can determine *t*:

$$\ln \frac{N_t}{N_0} = -kt$$

$$\ln \frac{11.6}{15.2} = -(1.21 \times 10^{-4}\ \text{yr}^{-1})\ t$$

$$\ln 0.763 = -(1.21 \times 10^{-4}\ \text{yr}^{-1})\ t$$

$$2235\ \text{yr} = t$$

Nuclear Chemistry

- In Nature U 238 decays to Pb 206.

Nuclear Chemistry

A rock contains 0.257 mg of lead-206 for every milligram of uranium-238. The half-life for the decay of uranium-238 to lead-206 is 4.5×10^9 yr. How old is the rock?

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1. Find the original amount of U 238

$$1 \text{ mg} + \frac{238 \text{ g/atom}}{206 \text{ g/atom}} \times 0.257 \text{ mg} = (1.297\text{mg})$$

Nuclear Chemistry

A rock contains 0.257 mg of lead-206 for every milligram of uranium-238. The half-life for the decay of uranium-238 to lead-206 is 4.5×10^9 yr. How old is the rock?

1. Find the original amount of U 238

$$1 \text{ mg} + \frac{238 \text{ g/atom}}{206 \text{ g/atom}} \times 0.257 \text{ mg} = (1.297\text{mg})$$

2. Calculate k from

$$k = 0\frac{.692}{t_{1/2}} = \frac{0.692}{4.5 \times 10^9 \text{ years}} = (1.5 \times 10^{-10} / \text{yr})$$

Nuclear Chemistry

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2. Calculate k from

$$k = \frac{0.692}{t_{1/2}} = \frac{0.692}{4.5 \times 10^{9} \text{ years}} = (1.5 \times 10^{-10} / \text{yr})$$

3. Calculate t from

$$\ln \frac{N_t}{N_0} = -kt$$

$$t = \frac{-1}{k} \ln \frac{N_t}{N_0} = 1.7 \times 10^{9} \text{ years}$$

Nuclear Chemistry

Energy in Nuclear Reactions

- There is a tremendous amount of energy stored in nuclei.
- Einstein’s famous equation, $E = mc^2$, relates directly to the calculation of this energy.

Nuclear Chemistry

Energy in Nuclear Reactions

- In the types of chemical reactions we have encountered previously, the amount of mass converted to energy has been minimal.
- However, these energies are many thousands of times greater in nuclear reactions.

Nuclear Chemistry

Energy in Nuclear Reactions

For example, the mass change for the decay of 1 mol of uranium-238 is −0.0046 g.

The change in energy, ΔE, is then

$$\Delta E = (\Delta m)\, c^2$$

$$= (-4.6 \times 10^{-6}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2$$

$$= -4.1 \times 10^{11}\ \text{J}$$