Chemistry, The Central Science, 10th edition
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Chapter 21
Nuclear Chemistry

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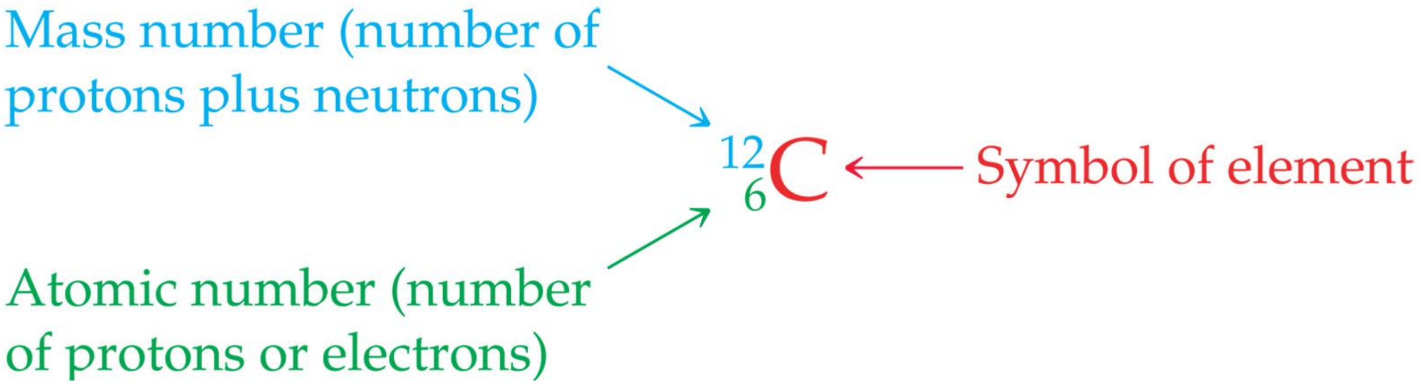
The Nucleus



Mass number (number of protons plus neutrons)

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

Symbol of element

Atomic number (number of protons or electrons)

- 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.

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.

Types of Radioactive Decay

Alpha Decay:

Loss of an α-particle (a helium nucleus)

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

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

Beta Decay:

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

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

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

Positron Emission:

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

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

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

Gamma Emission:

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

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

Electron Capture (K-Capture)

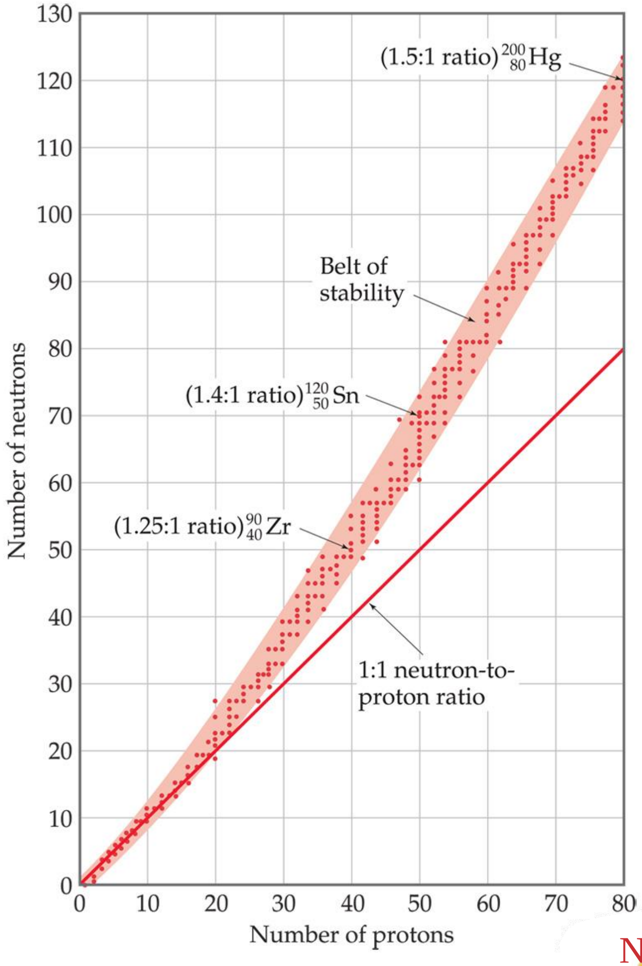
Addition of an electron to a proton in the nucleus

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

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

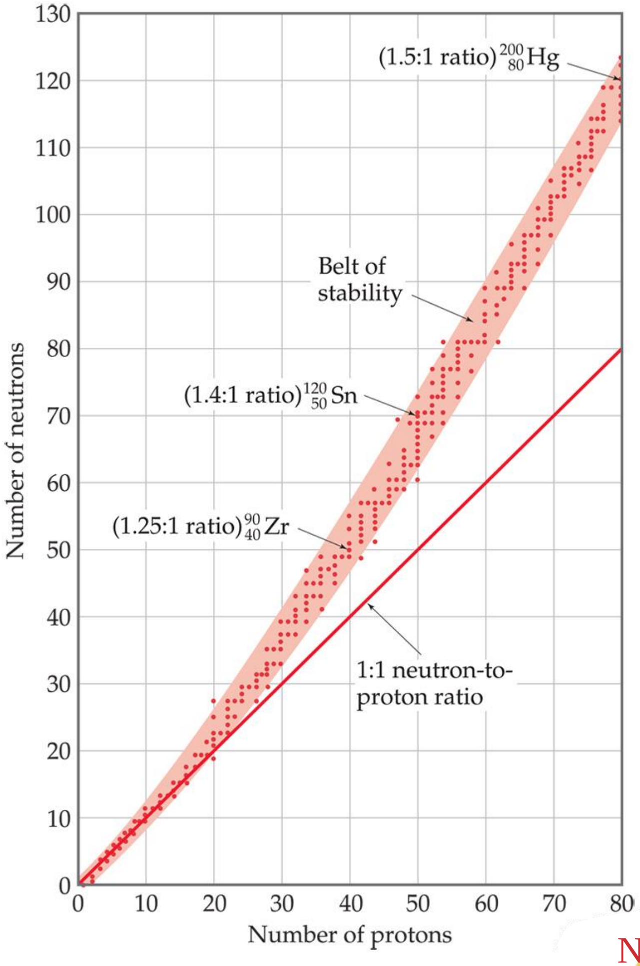
Neutron-Proton Ratios

- 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.



Neutron-Proton Ratios

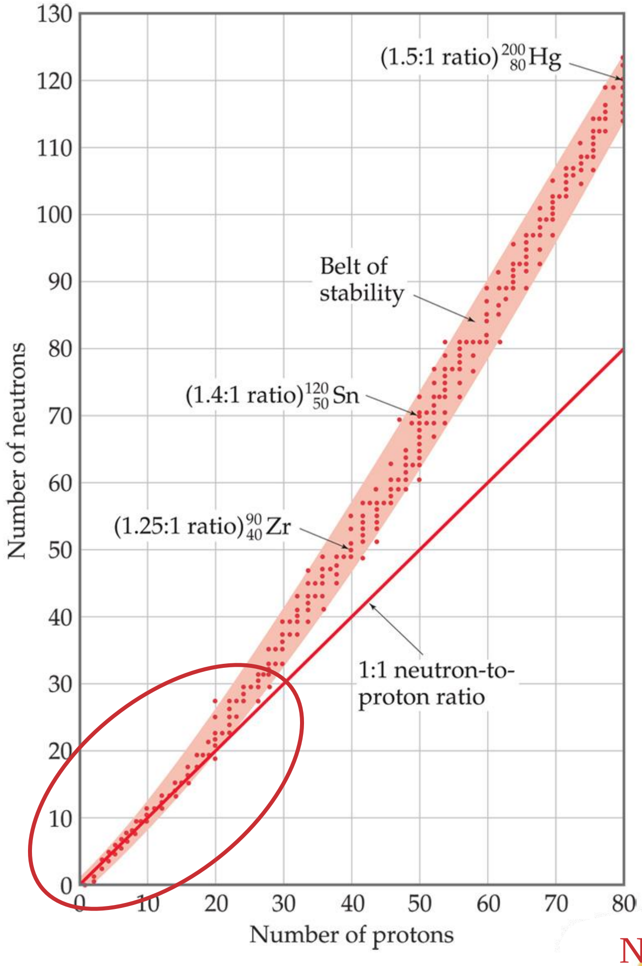
- Neutrons play a key role stabilizing the nucleus.
- Therefore, the ratio of neutrons to protons is an important factor.



Nuclear Chemistry

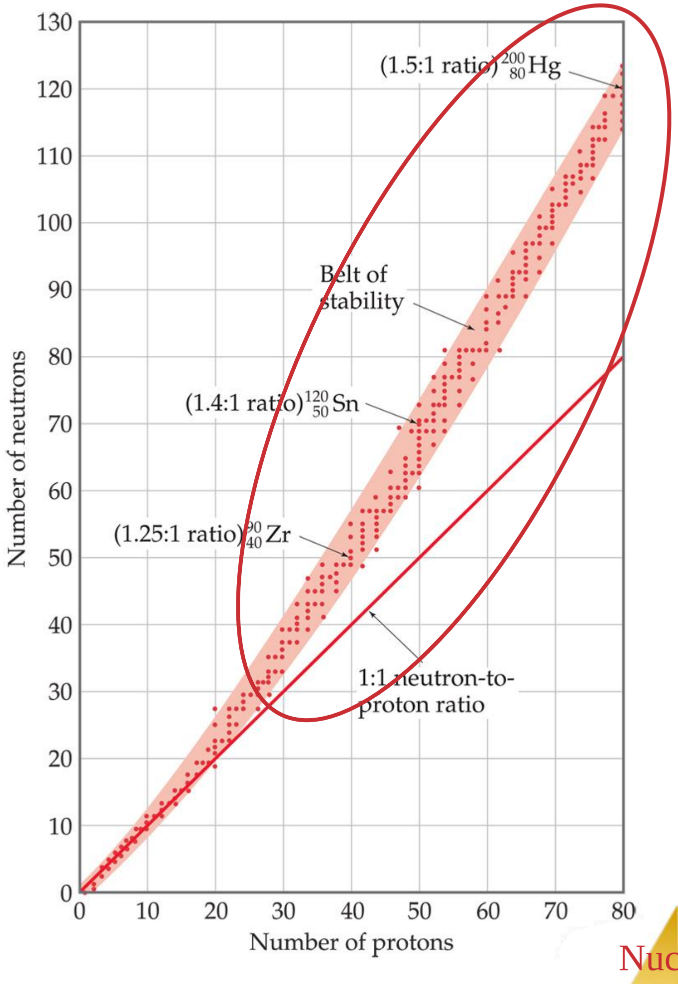
Neutron-Proton Ratios

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



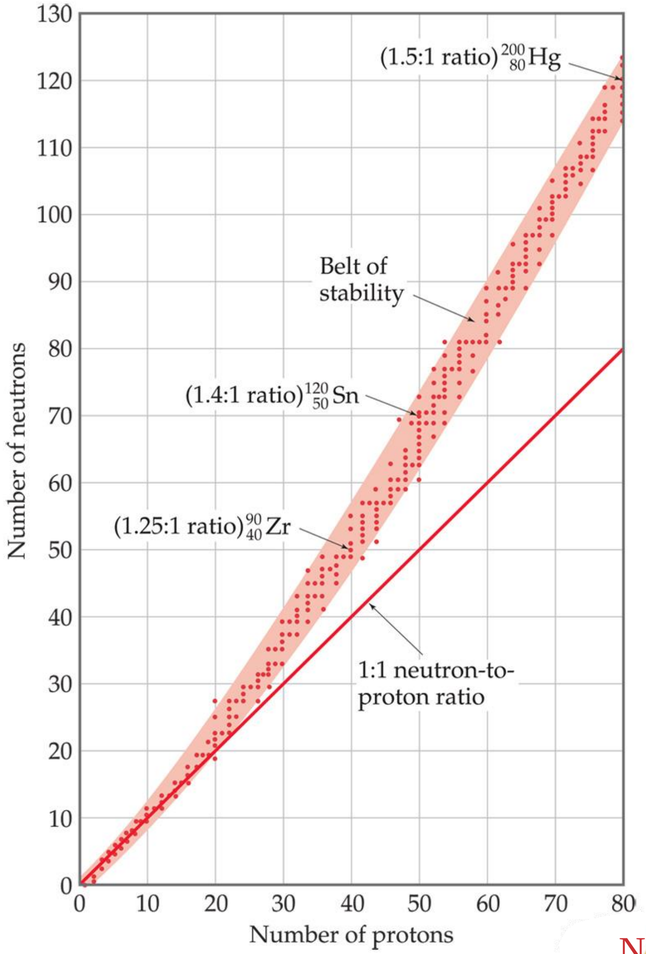
Neutron-Proton Ratios

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



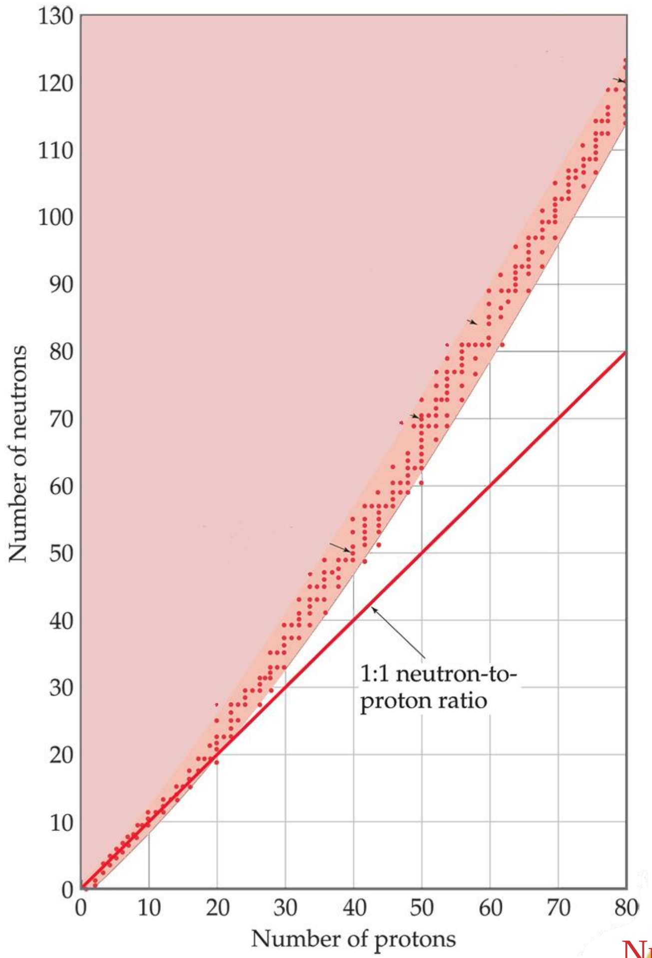
Stable Nuclei

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



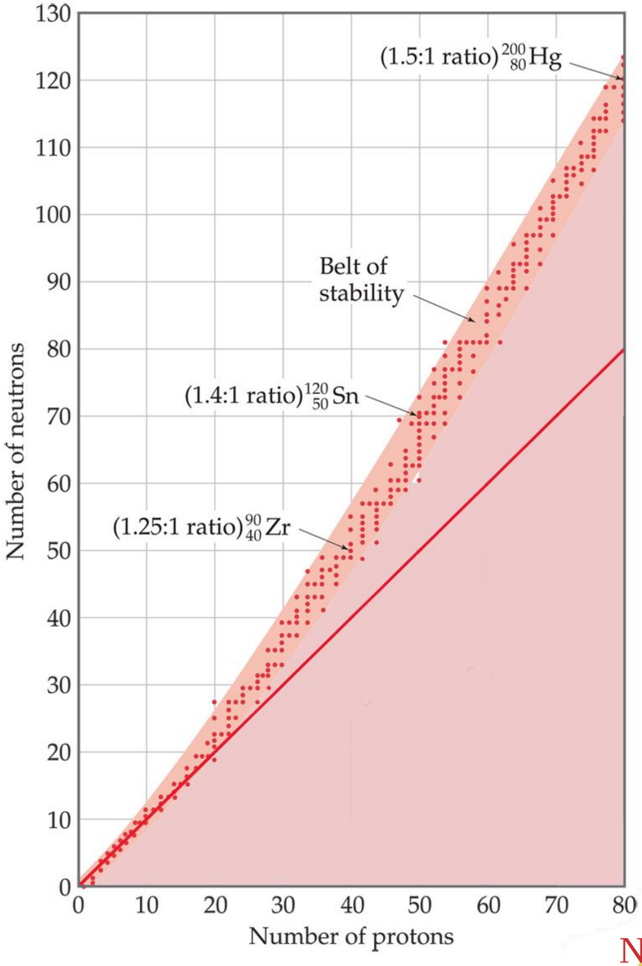
Stable Nuclei

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



Stable Nuclei

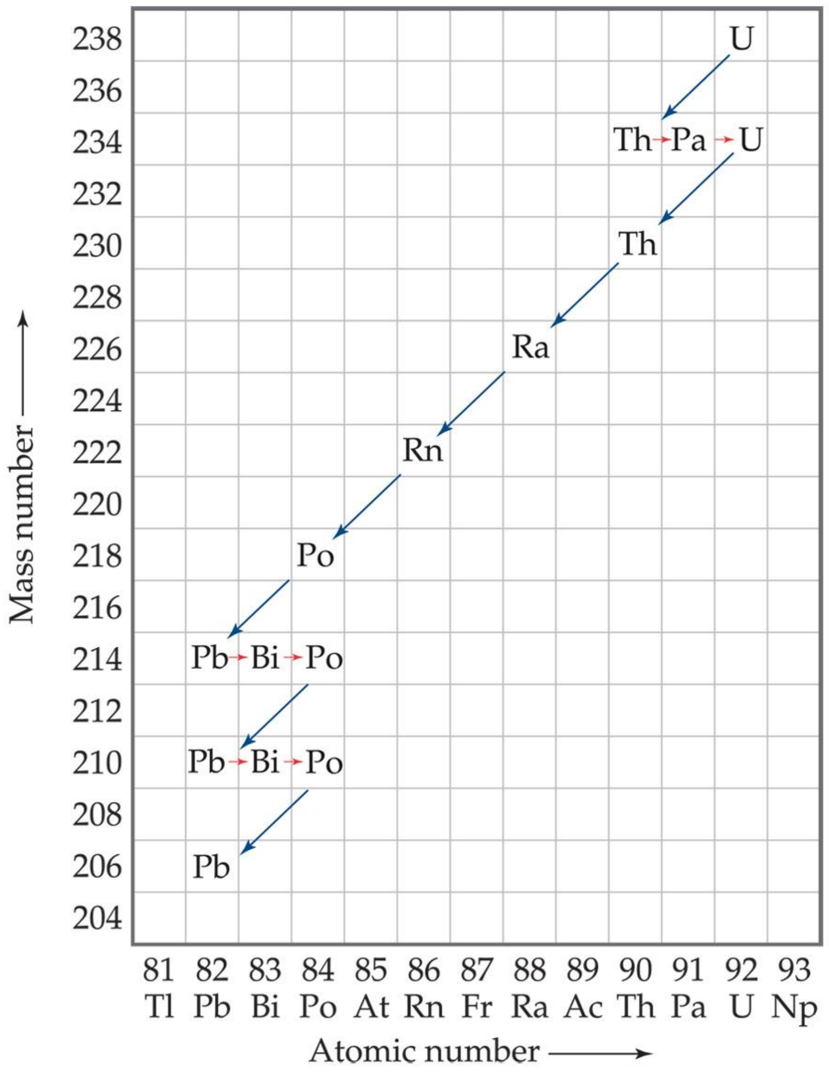
- Nuclei below the belt have too many protons.
- They tend to become more stable by positron emission or electron capture.



Stable Nuclei

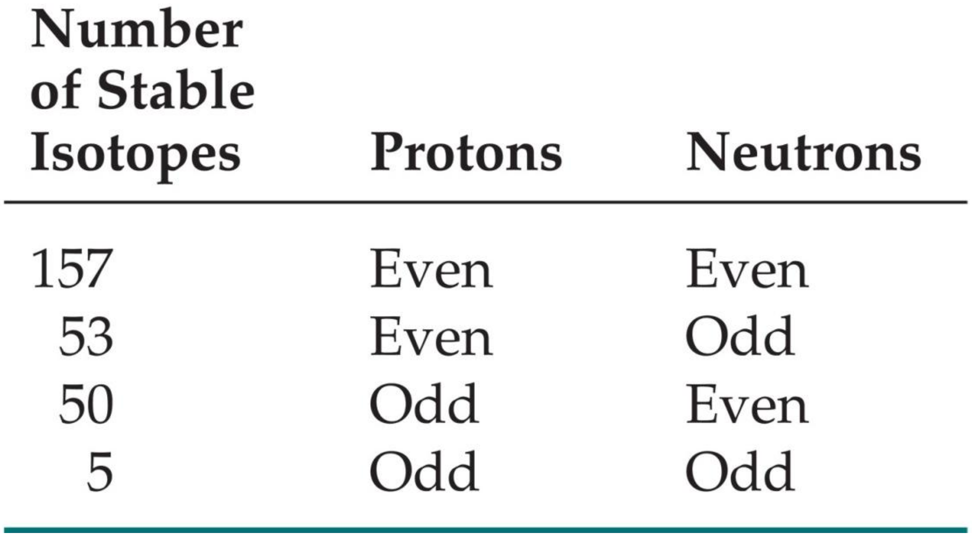
- There are no stable nuclei with an atomic number greater than 83.
- These nuclei tend to decay by alpha emission.

Radioactive 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).

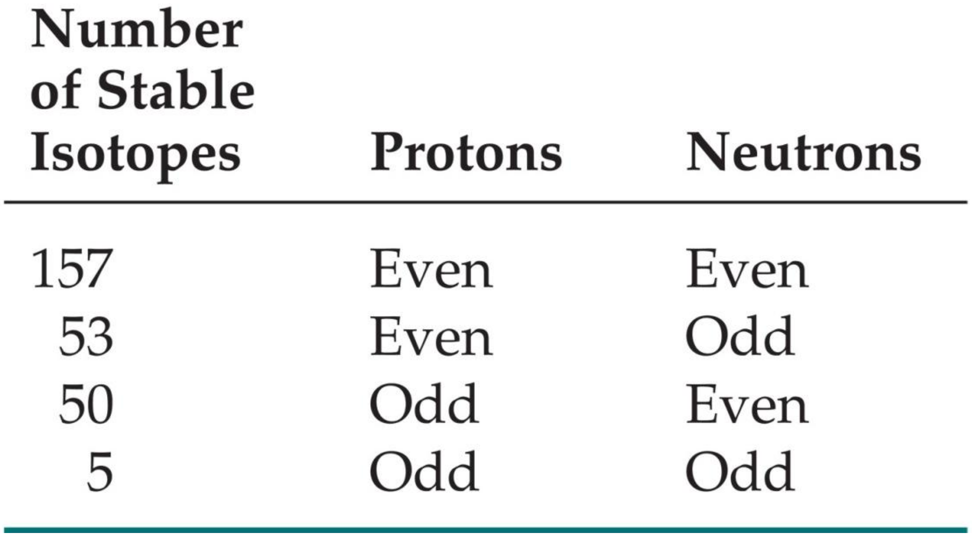
Some Trends



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

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.

Some Trends

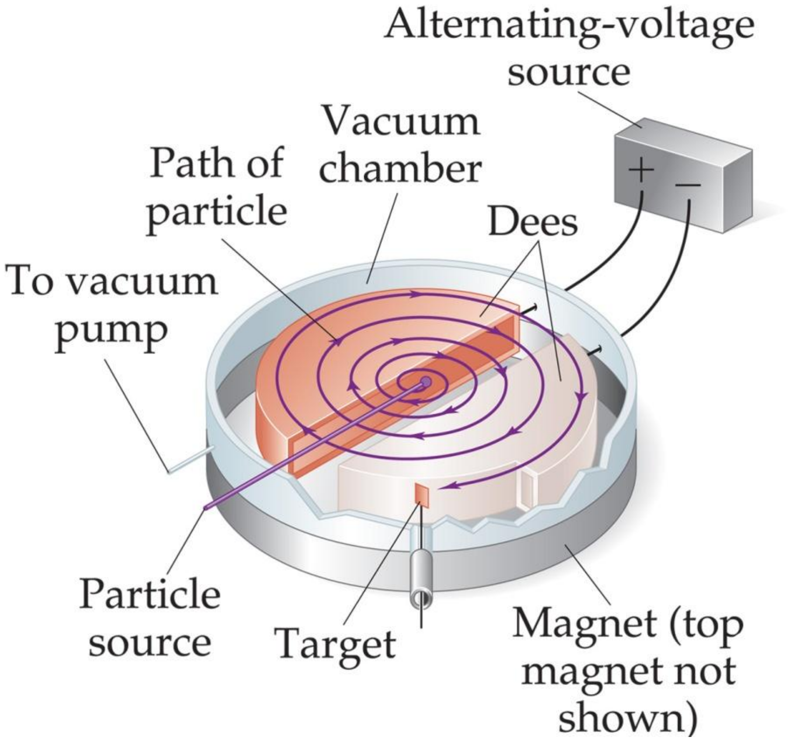


Number of Stable Isotopes	Protons	Neutrons
157	Even	Even
53	Even	Odd
50	Odd	Even
5	Odd	Odd

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

Nuclear Transformations

Nuclear transformations can be induced by accelerating a particle and colliding it with the nuclide.



Particle Accelerators

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

Kinetics of Radioactive Decay

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

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

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.

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*:

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

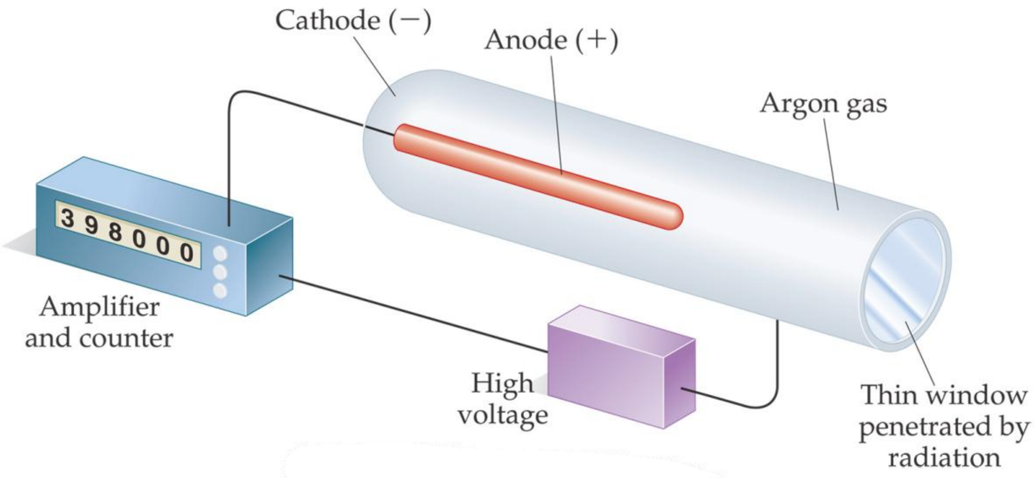
$$\ln \frac{11.6}{15.2} = -(1.21 \times 10^{-4}\ \mathrm{yr}^{-1})\ t$$

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

$$2233\ \mathrm{yr} = t$$

Measuring Radioactivity

- One can use a device like this Geiger counter to measure the amount of activity present in a radioactive sample.
- The ionizing radiation creates ions, which conduct a current that is detected by the instrument.



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.

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.

Energy in Nuclear Reactions

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

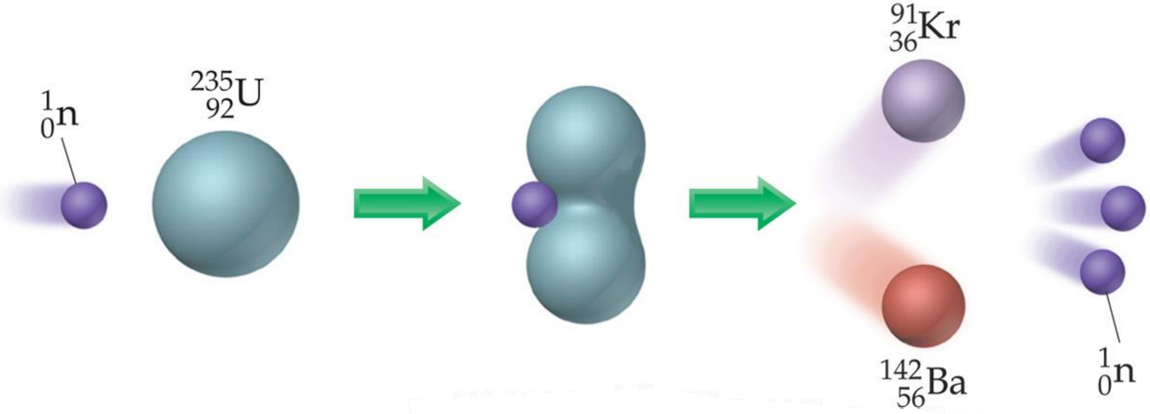
The change in energy, ΔE, is then

$$\begin{aligned} \Delta E &= (\Delta m)\, c^2 \\ &= (-4.6 \times 10^{-6}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2 \\ &= -4.1 \times 10^{11}\ \text{J} \end{aligned}$$

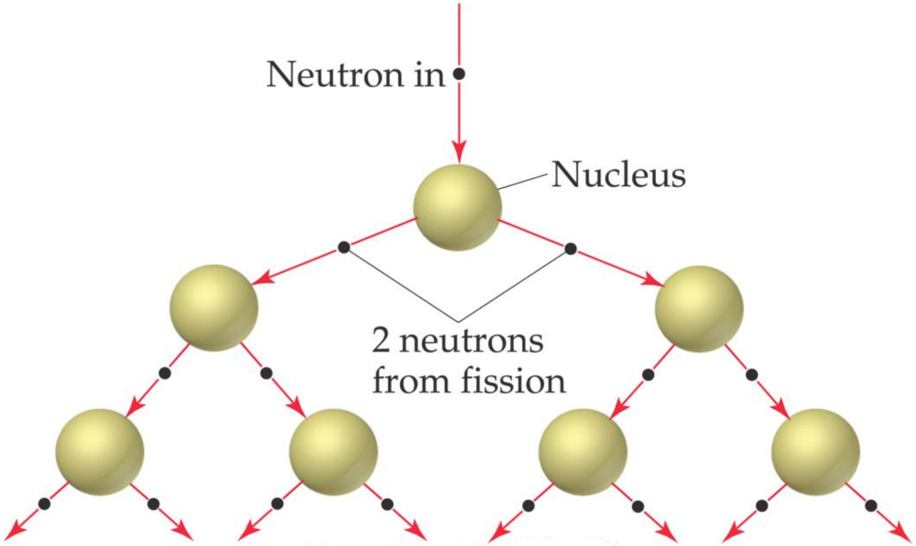
Nuclear Fission

- How does one tap all that energy?
- Nuclear fission is the type of reaction carried out in nuclear reactors.

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \begin{array}{l} \nearrow {}^{137}_{52}\mathrm{Te} + {}^{97}_{40}\mathrm{Zr} + 2\,{}^{1}_{0}\mathrm{n} \\ \searrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n} \end{array} $$

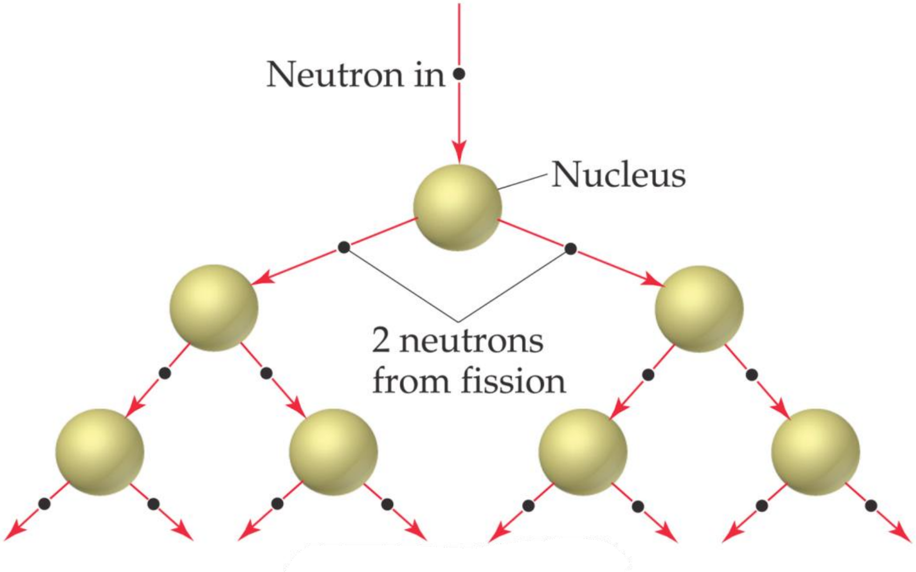


Nuclear Fission



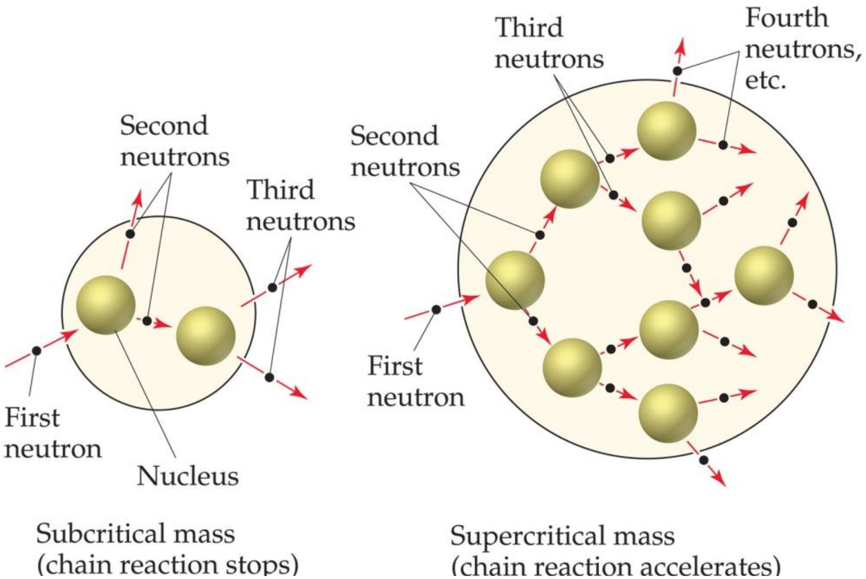
- Bombardment of the radioactive nuclide with a neutron starts the process.
- Neutrons released in the transmutation strike other nuclei, causing their decay and the production of more neutrons.

Nuclear Fission



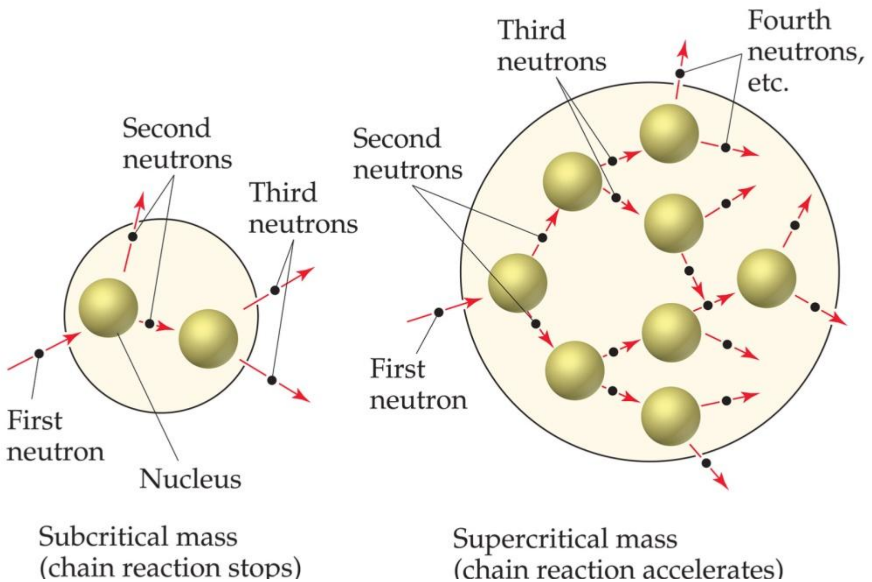
This process continues in what we call a **nuclear chain reaction**.

Nuclear Fission



If there are not enough radioactive nuclides in the path of the ejected neutrons, the chain reaction will die out.

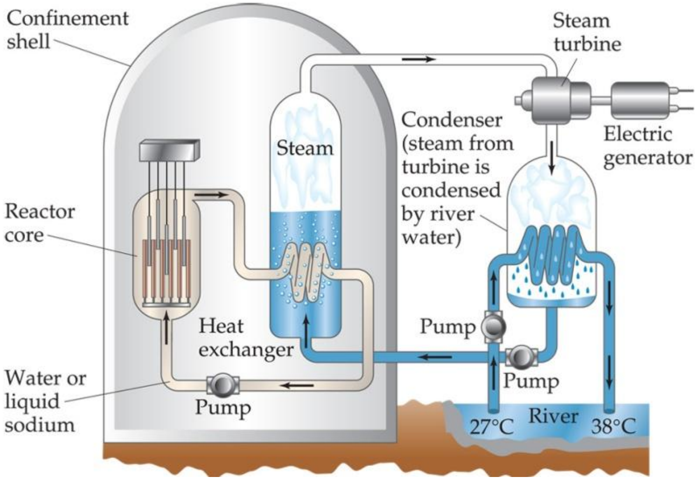
Nuclear Fission

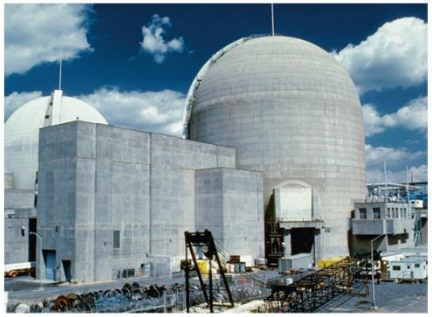


Therefore, there must be a certain minimum amount of fissionable material present for the chain reaction to be sustained: Critical Mass.

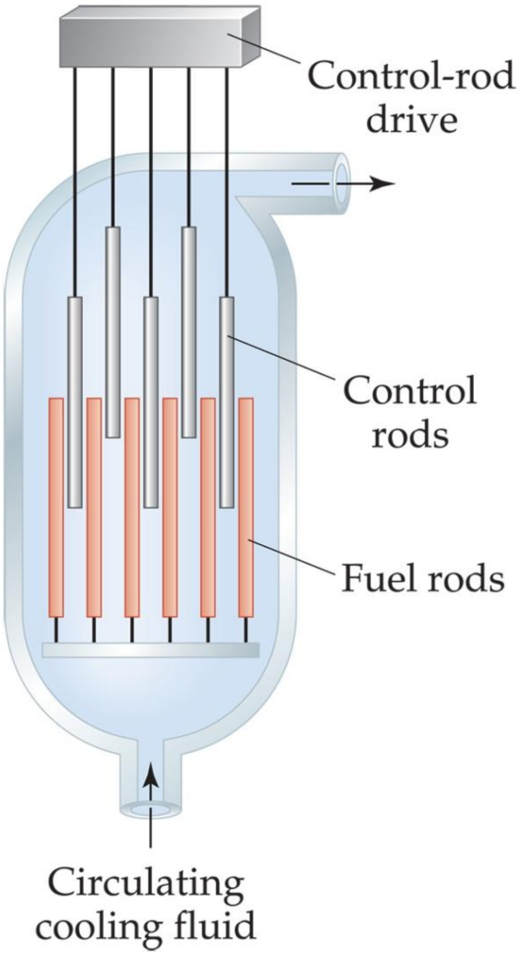
Nuclear Reactors

In nuclear reactors the heat generated by the reaction is used to produce steam that turns a turbine connected to a generator.





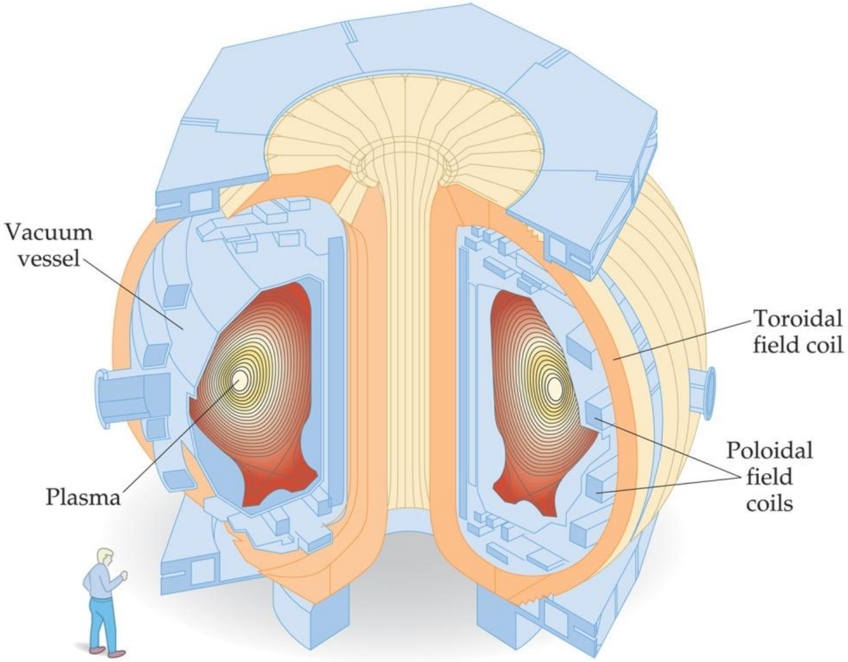
Nuclear Reactors



- The reaction is kept in check by the use of control rods.
- These block the paths of some neutrons, keeping the system from reaching a dangerous supercritical mass.

Nuclear Fusion

- Fusion would be a superior method of generating power.
  - The good news is that the products of the reaction are not radioactive.
  - The bad news is that in order to achieve fusion, the material must be in the plasma state at several million kelvins.



Nuclear Fusion

- Tokamak apparati like the one shown at the right show promise for carrying out these reactions.
- They use magnetic fields to heat the material.