Chapter 31

Nuclear Physics and Radioactivity

The atomic nucleus consists of positively charged protons and neutral neutrons.

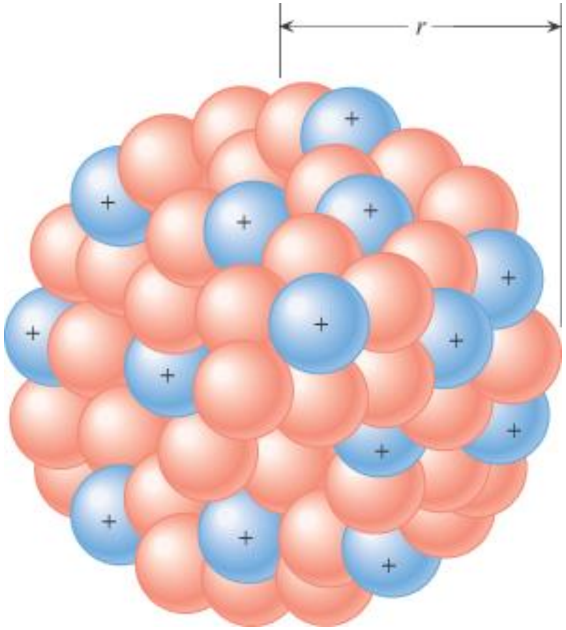


Table 31.1 Properties of Select Particles

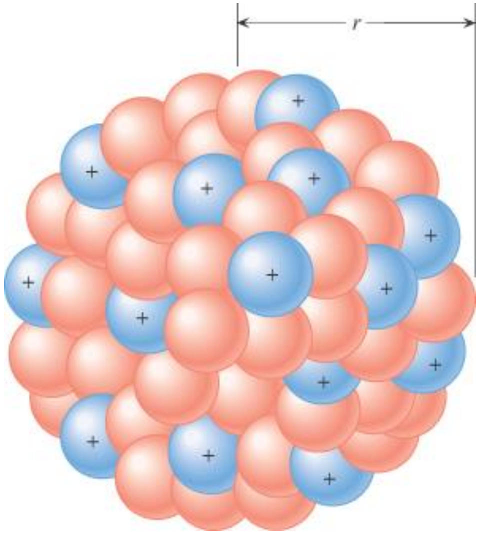
Particle	Electric Charge (C)	Mass: Kilograms (kg)	Mass: Atomic Mass Units (u)
Electron	-1.60×10^{-19}	$9.109\ 382 \times 10^{-31}$	$5.485\ 799 \times 10^{-4}$
Proton	$+1.60 \times 10^{-19}$	$1.672\ 622 \times 10^{-27}$	1.007 276
Neutron	0	$1.674\ 927 \times 10^{-27}$	1.008 665
Hydrogen atom	0	$1.673\ 534 \times 10^{-27}$	1.007 825

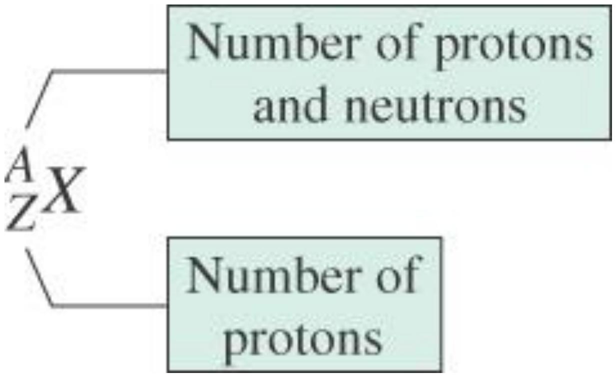
31.1 Nuclear Structure

atomic mass number

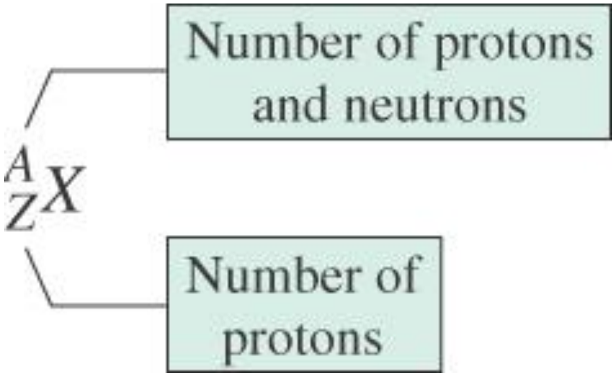
atomic number

$$\underbrace{A}_{\text{Number of protons and neutrons}} = \underbrace{Z}_{\text{Number of protons}} + \underbrace{N}_{\text{Number of neutrons}}$$

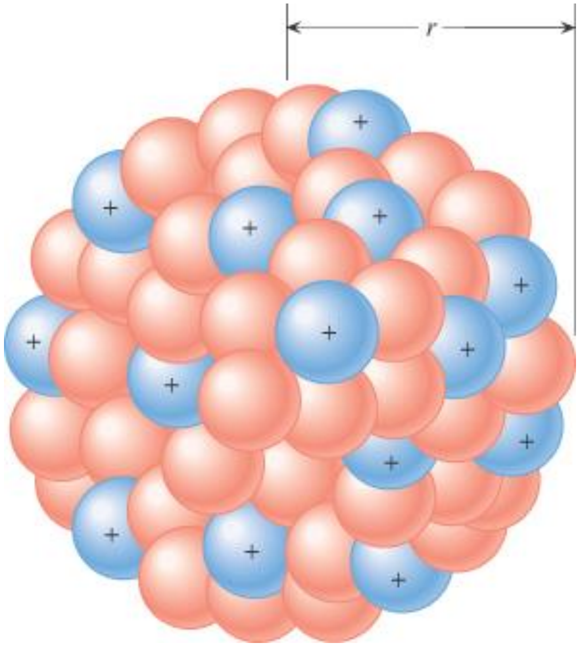




Nuclei that contain the same number of protons but a different number of neutrons are known as ***isotopes***.



31.1 Nuclear Structure

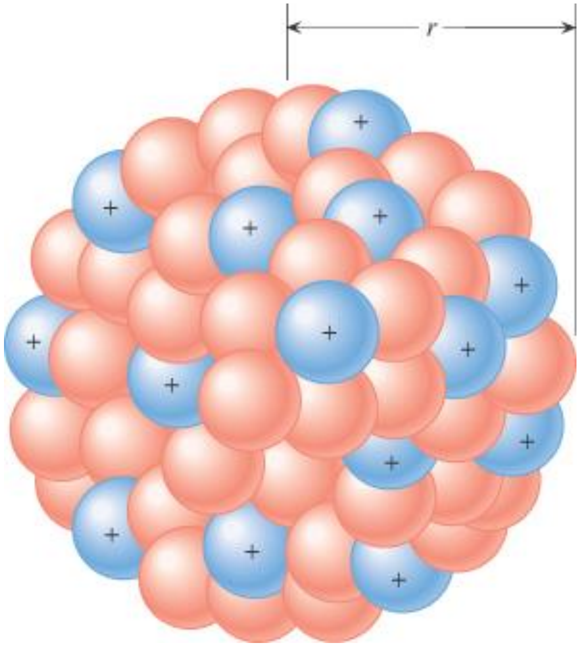


$$r \approx \left(1.2 \times 10^{-15}\,\mathrm{m}\right) A^{1/3}$$

Conceptual Example 1 Nuclear Density

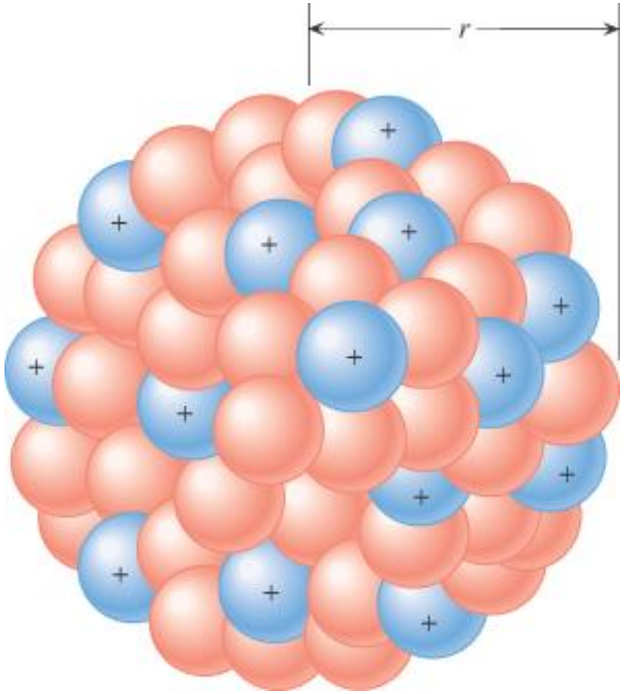
It is well known that lead and oxygen contain different atoms and that the density of solid lead is much greater than gaseous oxygen. Using the equation, decide whether the density of the nucleus in a lead atom is greater than, approximately equal to, or less than that in an oxygen atom.

$$r \approx \left(1.2\times 10^{-15}\,\mathrm{m}\right)A^{1/3}$$

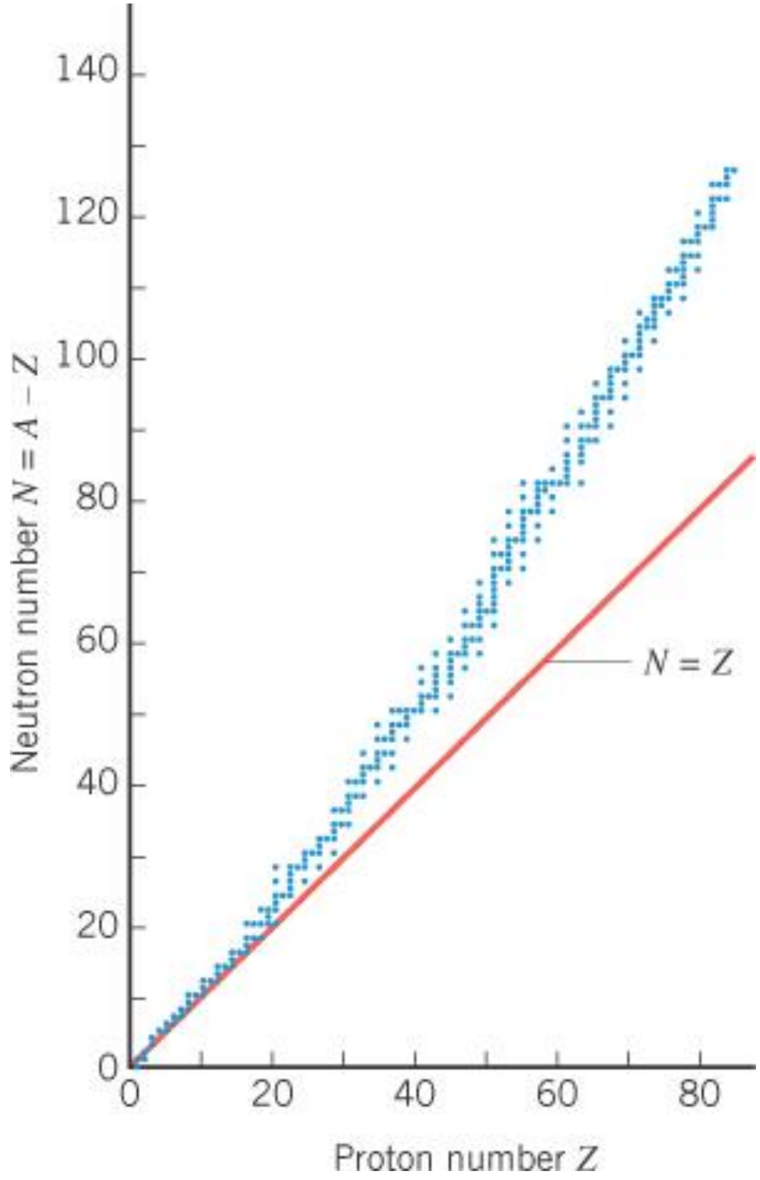


The mutual repulsion of the protons tends to push the nucleus apart. What then, holds the nucleus together?

The strong nuclear force.

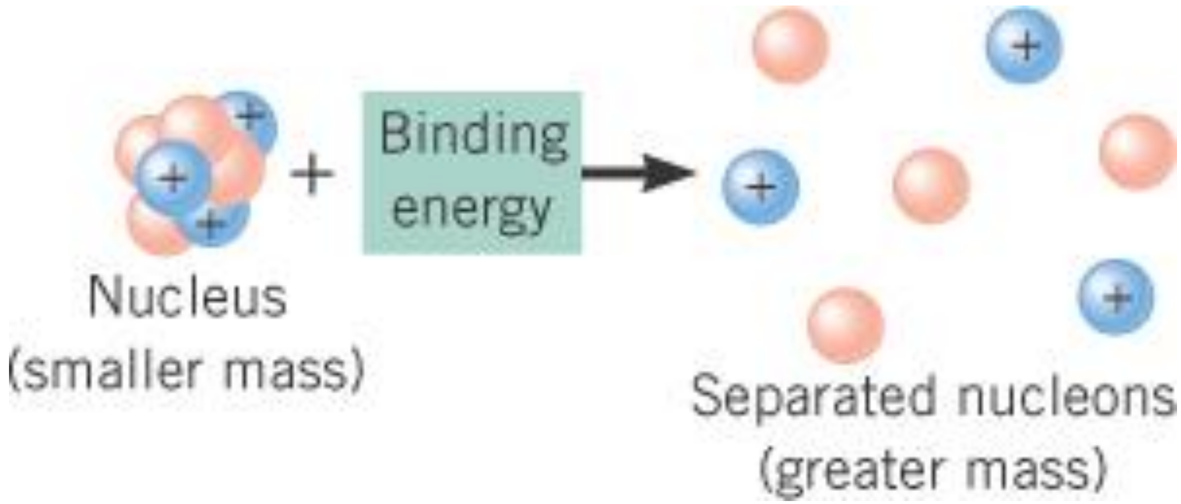


31.2 The Strong Nuclear Force and the Stability of the Nucleus



As nuclei get larger, more neutrons are required for stability.

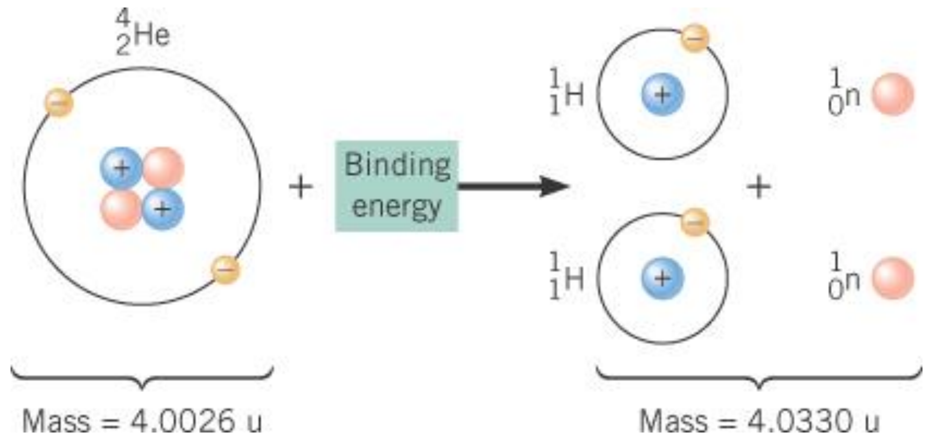
The neutrons act like glue without adding more repulsive force.



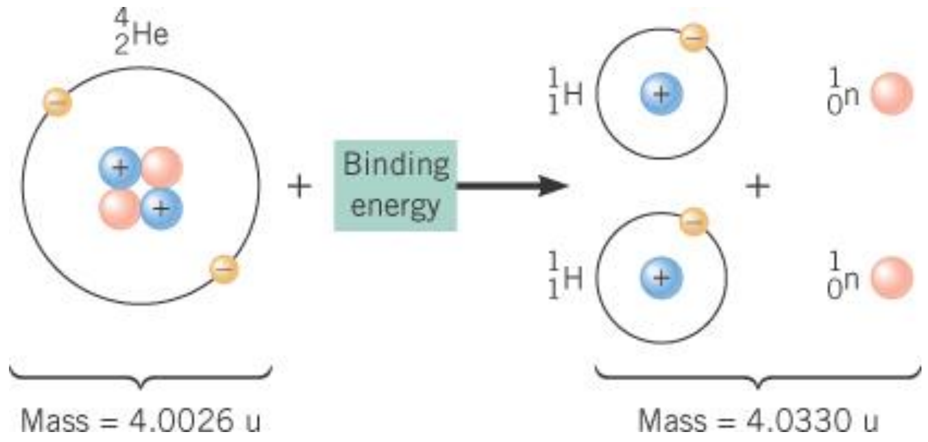
$$\text{Binding energy} = (\text{Mass deficit})c^2 = (\Delta m)c^2$$

Example 3 The Binding Energy of the Helium Nucleus Revisited

The atomic mass of helium is 4.0026u and the atomic mass of hydrogen is 1.0078u. Using atomic mass units, instead of kilograms, obtain the binding energy of the helium nucleus.



31.3 The Mass Deficit of the Nucleus and Nuclear Binding Energy

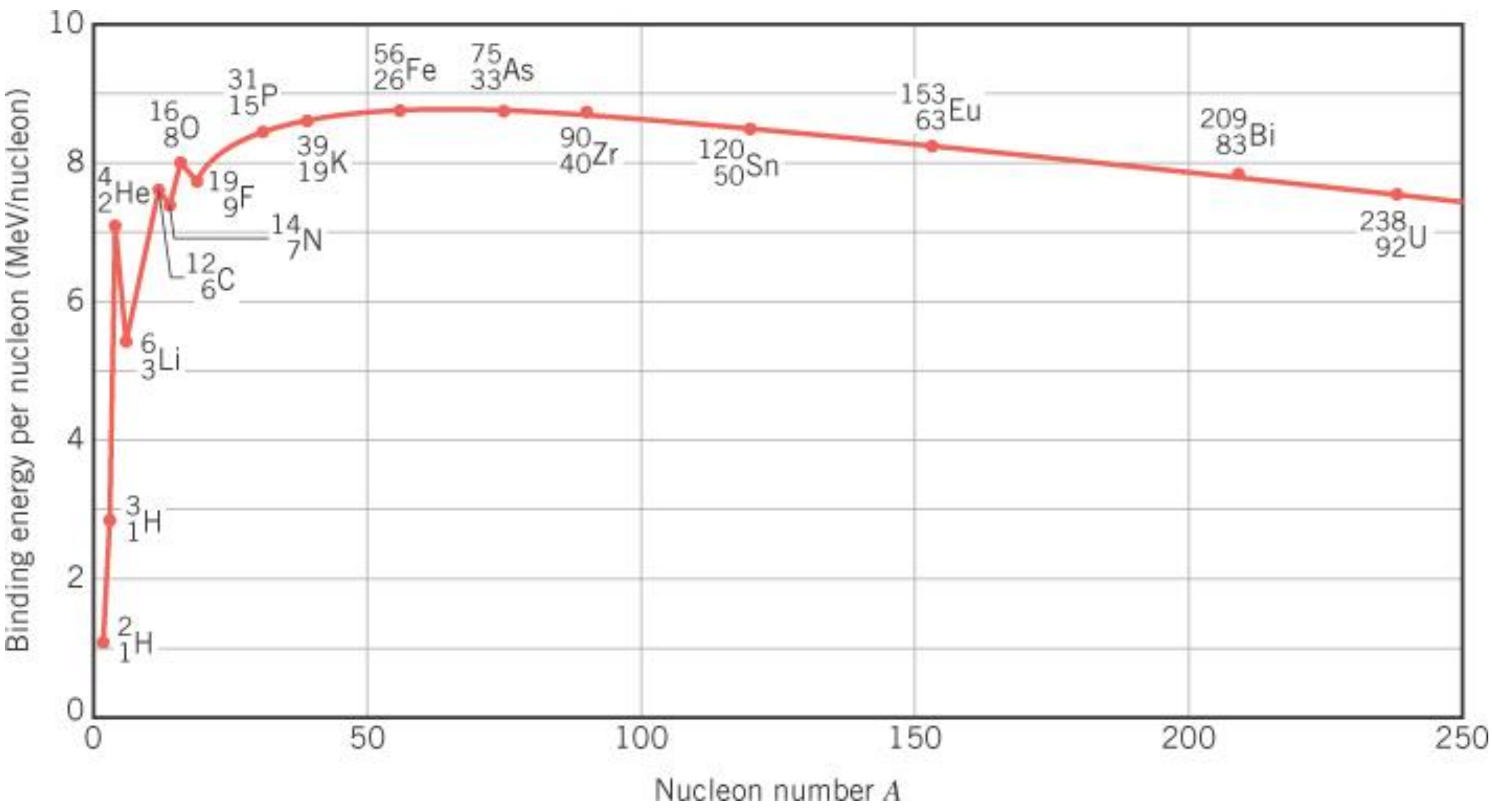


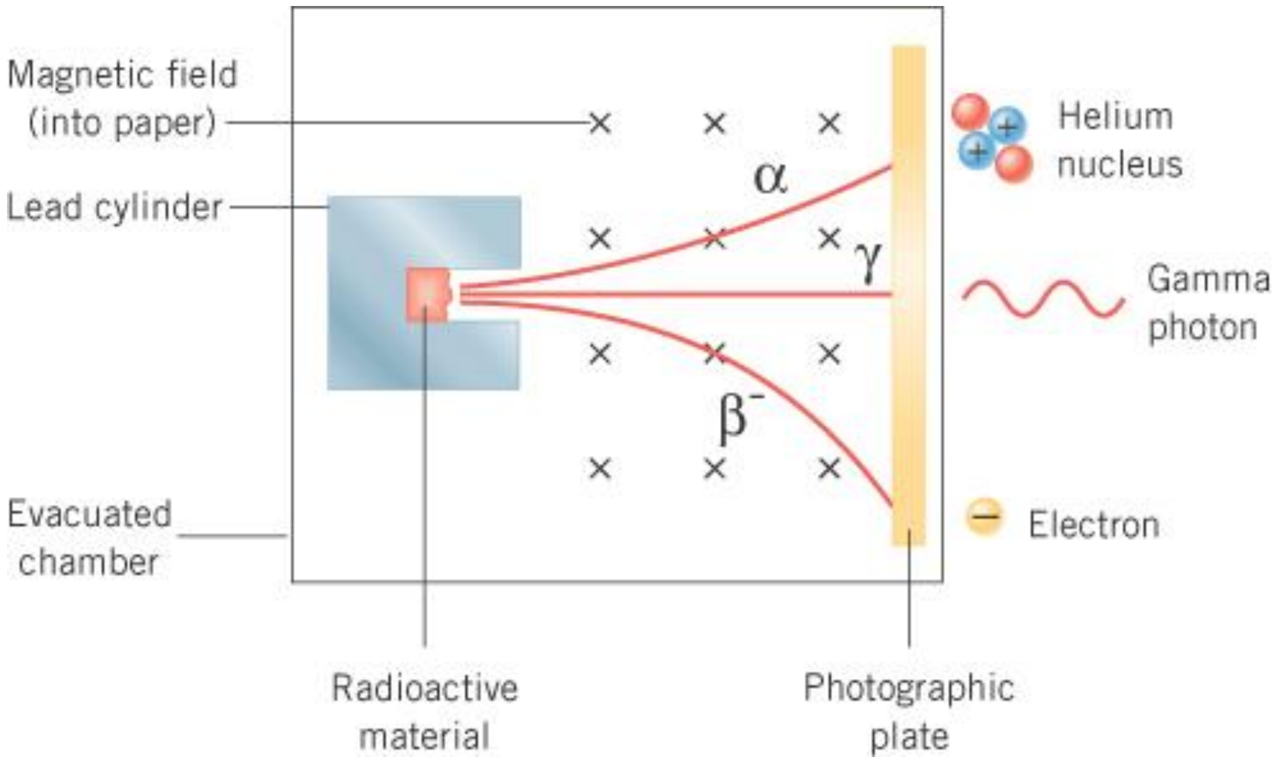
$$\Delta m = 4.0330\,\text{u} - 4.0026\,\text{u} = 0.0304\,\text{u}$$

$$1\,\text{u} \leftrightarrow 931.5\,\text{MeV}$$

$$\text{Binding energy} = 28.3\,\text{MeV}$$

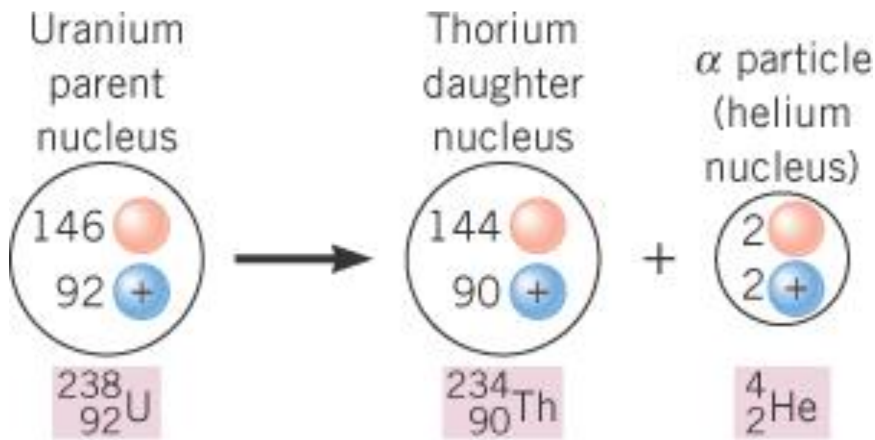
31.3 The Mass Deficit of the Nucleus and Nuclear Binding Energy





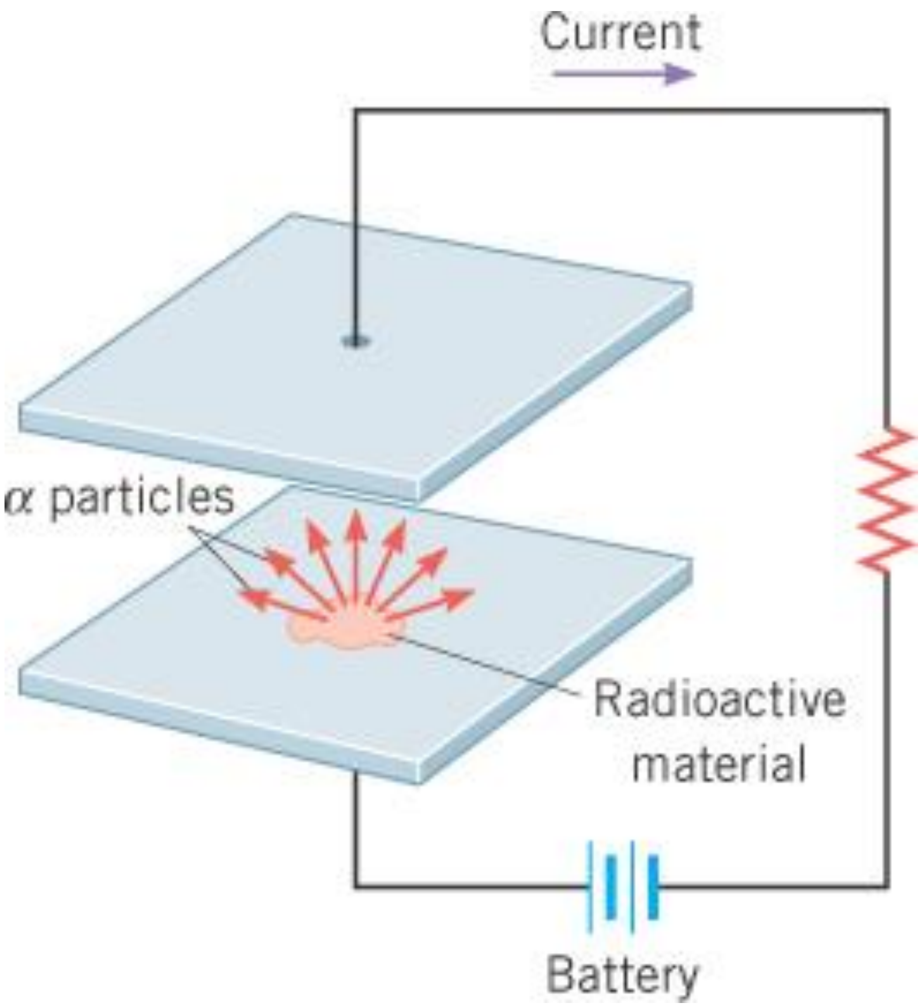
A magnetic field separates the three types of particles emitted by radioactive nuclei.

α DECAY

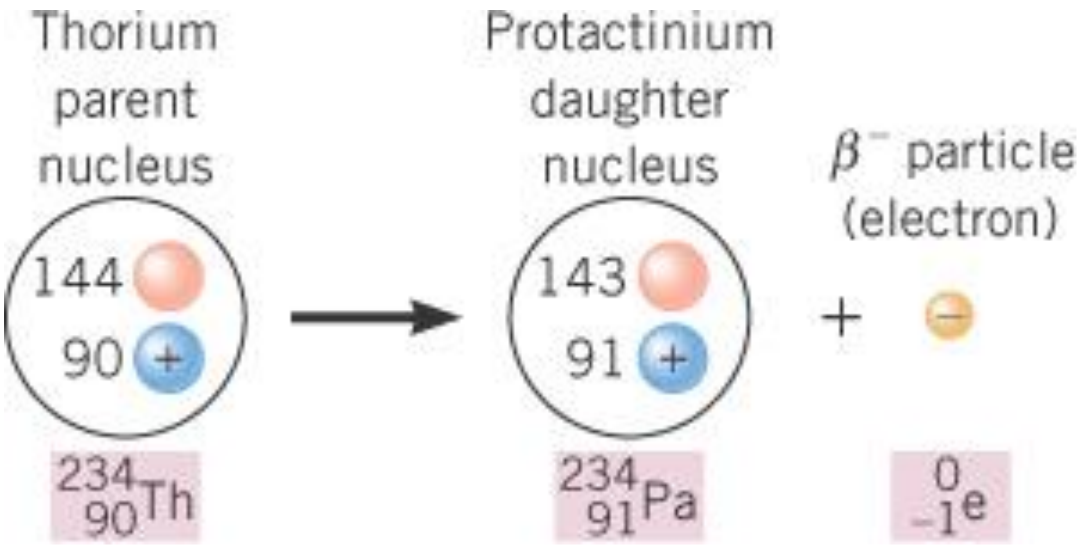


$$ {}^{A}_{Z}\mathrm{P} \rightarrow {}^{A-4}_{Z-2}\mathrm{D} + {}^{2}_{2}\mathrm{He} $$

A smoke detector



β DECAY



$$ {}^{A}_{Z}\mathrm{P} \rightarrow {}^{A}_{Z+1}\mathrm{D} + {}^{0}_{-1}\mathrm{e} $$

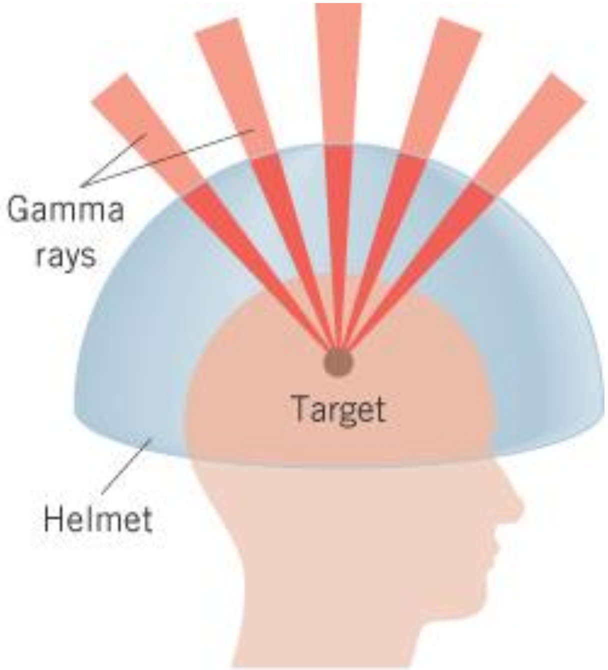
γ DECAY

$$^{A}_{Z}\mathrm{P}^{*} \rightarrow {}^{A}_{Z}\mathrm{P} + \gamma$$

excited energy state

lower energy state

(a)

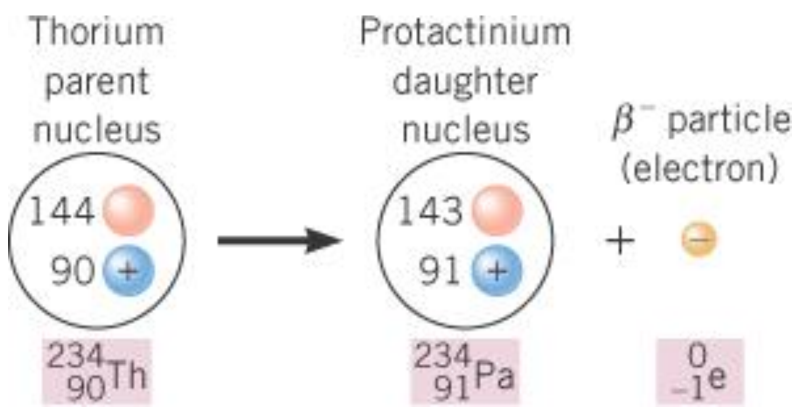


(b)

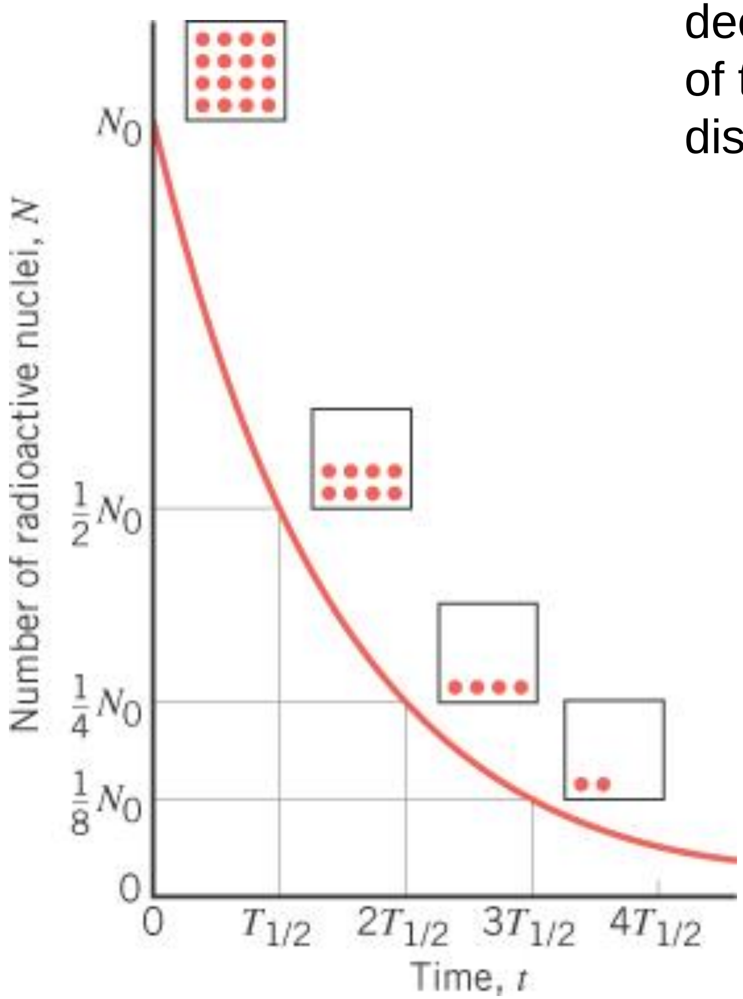
Gamma knife

During beta decay, energy is released. However, it is found that most beta particles do not have enough kinetic energy to account for all of the energy released.

The additional energy is carried away by a ***neutrino***.



$$^{234}_{90}\mathrm{Th} \rightarrow \, ^{234}_{91}\mathrm{Pa} + \, ^{0}_{-1}\mathrm{e} + \bar{\nu}$$



The half-life of a radioactive decay is the time in which ½ of the radioactive nuclei disintegrate.

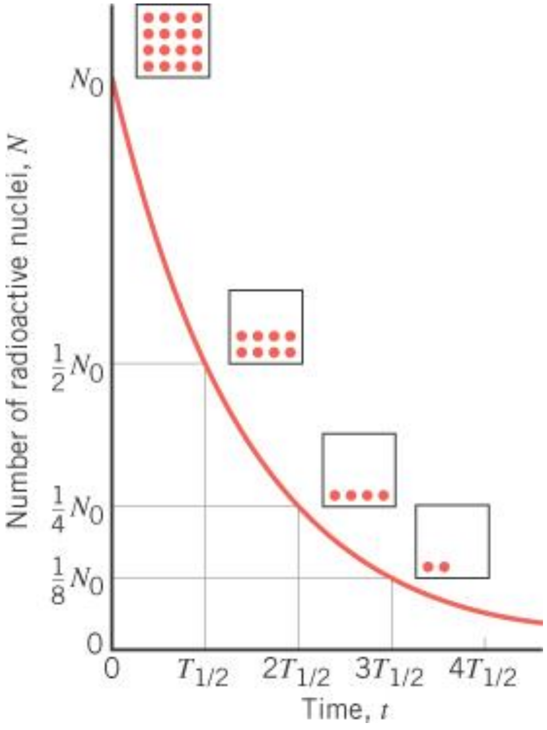
$$N = N_o e^{-\lambda t}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

Table 31.2 Some Half-Lives for Radioactive Decay

Isotope		Half-Life
Polonium	$^{214}_{84}Po$	1.64×10^{-4} s
Krypton	$^{89}_{36}Kr$	3.16 min
Radon	$^{222}_{86}Rn$	3.83 d
Strontium	$^{90}_{38}Sr$	29.1 yr
Radium	$^{226}_{88}Ra$	1.6×10^{3} yr
Carbon	$^{14}_{6}C$	5.73×10^{3} yr
Uranium	$^{238}_{92}U$	4.47×10^{9} yr
Indium	$^{115}_{49}In$	4.41×10^{14} yr

31.7 Radioactive Dating



Conceptual Example 12 Dating a Bottle of Wine

A bottle of red wine is thought to have been sealed about 5 years ago. The wine contains a number of different atoms, including carbon, oxygen, and hydrogen. The radioactive isotope of carbon is the familiar C-14 with ½ life 5730 yr. The radioactive isotope of oxygen is O-15 with a ½ life of 122.2 s. The radioactive isotope of hydrogen is called tritium and has a ½ life of 12.33 yr. The activity of each of these isotopes is known at the time the bottle was sealed. However, only one of the isotopes is useful for determining the age of the wine. Which is it?

31.8 Radioactive Decay Series

The sequential decay of one nucleus after another is called a ***radioactive decay series***.

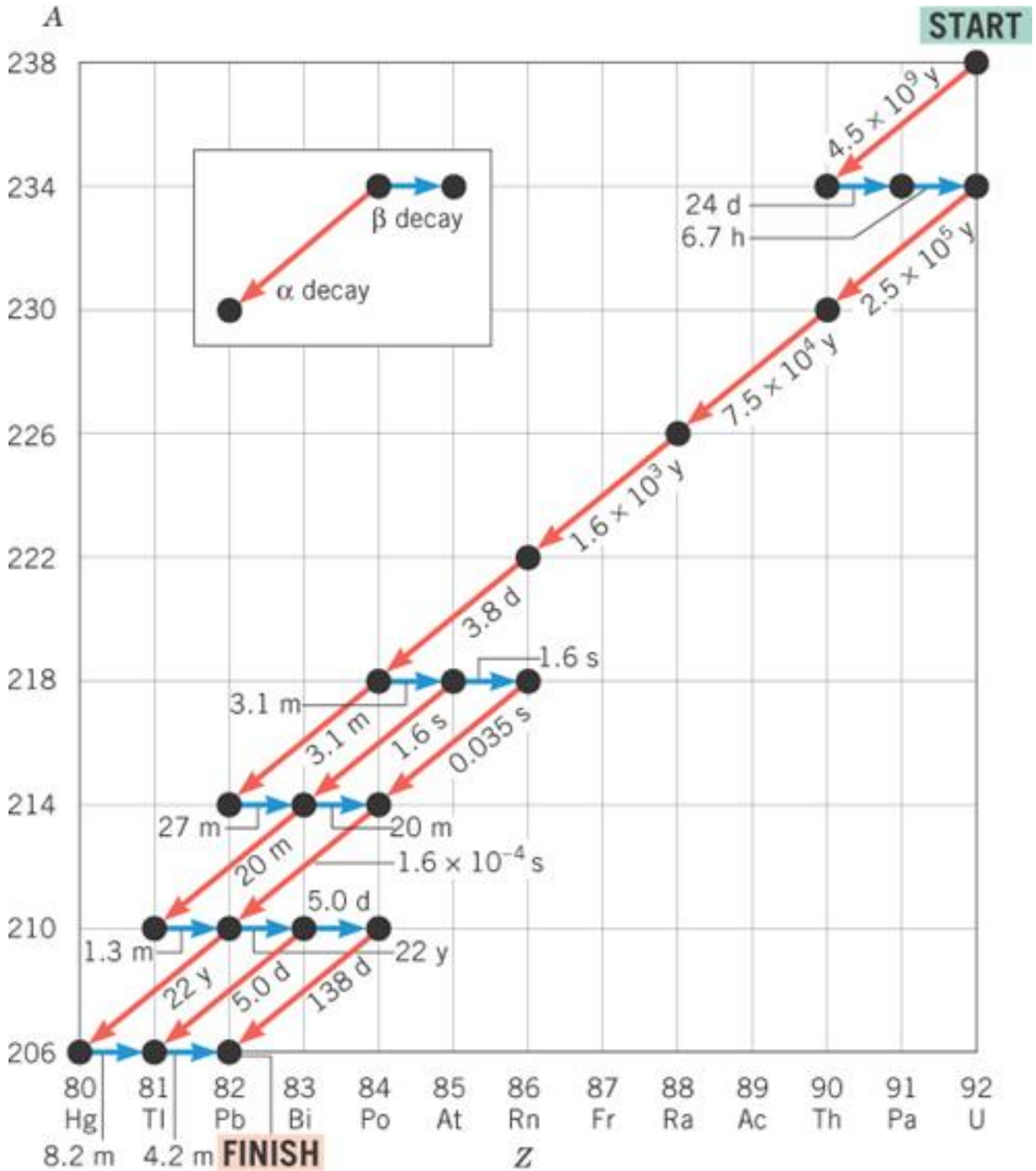
Uranium → Thorium

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

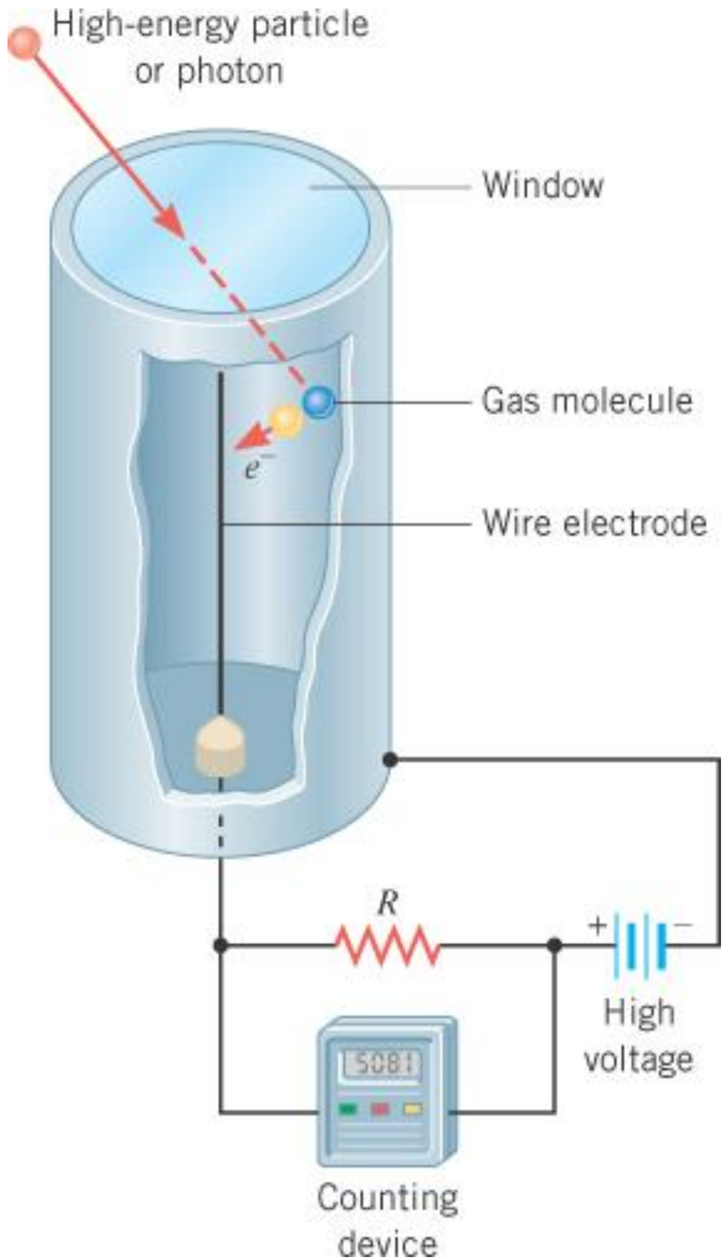
$$^{234}_{90}\text{Th} \longrightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e}$$

Protactinium

31.8 Radioactive Decay Series



A Geiger counter



A scintillation counter