Some Properties of Nuclei

All nuclei are composed of two types of particles: protons and neutrons. The only exception is the ordinary hydrogen nucleus, which is a single proton. We describe the atomic nucleus by the number of protons and neutrons it contains, using the following quantities:

$${}^{A}_{Z}X$$

- **the atomic number** Z, which equals the number of protons in the nucleus (sometimes called the charge number)
- **the neutron number** N, which equals the number of neutrons in the nucleus
- **the mass number** $A = Z + N$, which equals the number of nucleons (neutrons plus protons) in the nucleus

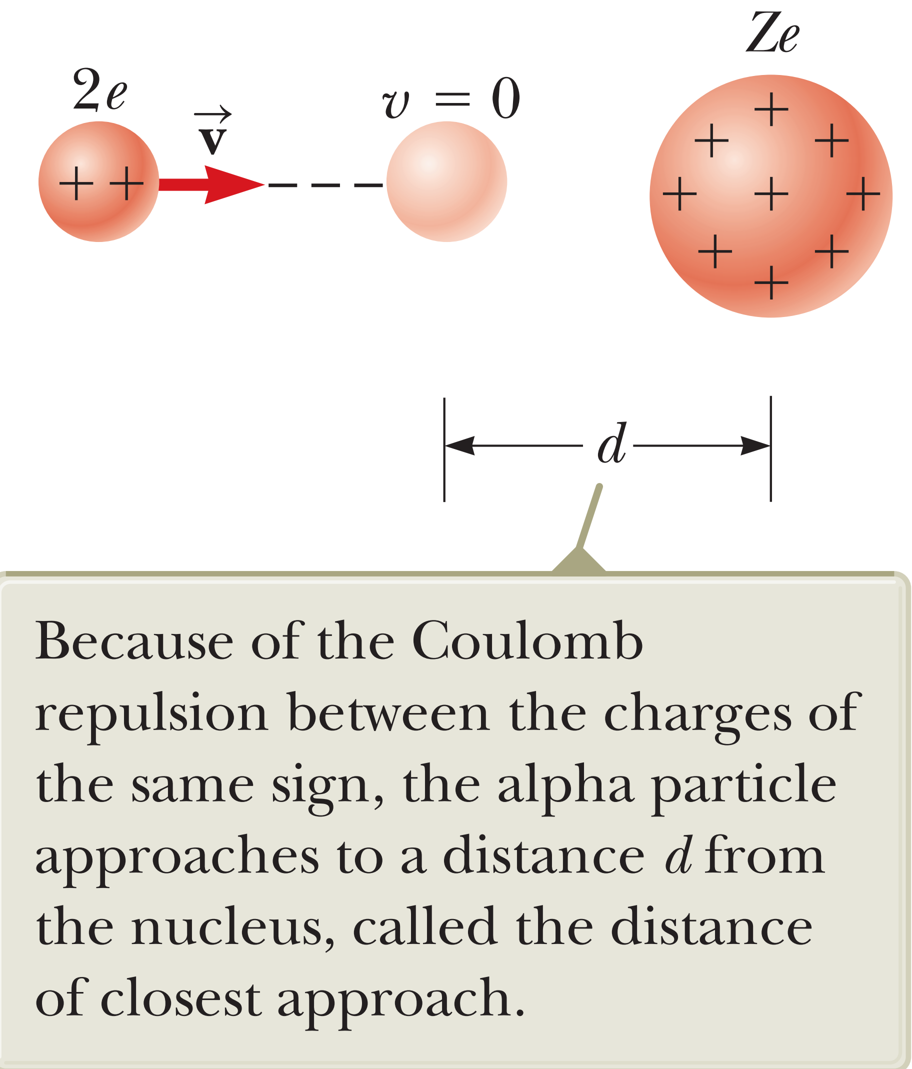
Table 44.1 Masses of Selected Particles in Various Units

	Mass		
Particle	**kg**	**u**	**MeV/c^2**
Proton	$1.672\,62 \times 10^{-27}$	1.007 276	938.27
Neutron	$1.674\,93 \times 10^{-27}$	1.008 665	939.57
Electron (β particle)	$9.109\,38 \times 10^{-31}$	$5.485\,79 \times 10^{-4}$	0.510 999
${}^{1}_{1}$H atom	$1.673\,53 \times 10^{-27}$	1.007 825	938.783
${}^{4}_{2}$He nucleus (α particle)	$6.644\,66 \times 10^{-27}$	4.001 506	3 727.38
${}^{4}_{2}$He atom	$6.646\,48 \times 10^{-27}$	4.002 603	3 728.40
${}^{12}_{6}$C atom	$1.992\,65 \times 10^{-27}$	12.000 000	11 177.9

Isotopes

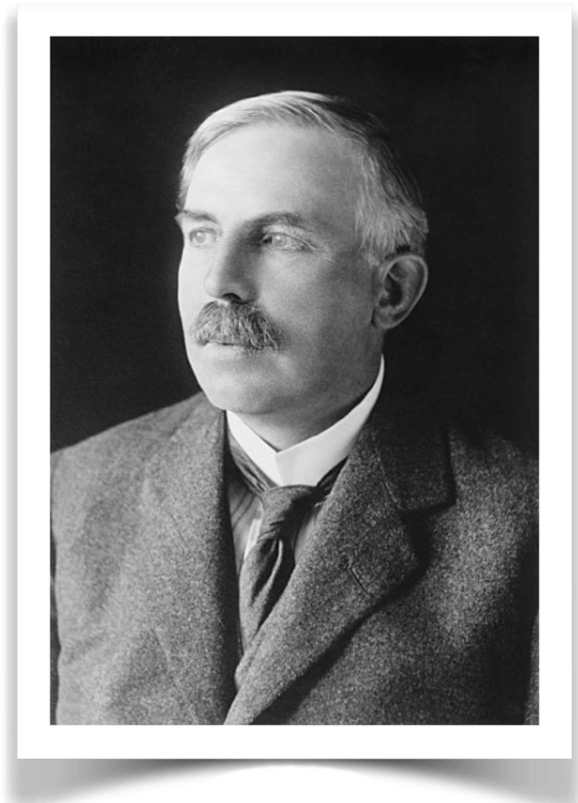
The different **isotopes** of a given element have the **same atomic number** but different mass numbers since they have **different numbers of neutrons**. The chemical properties of the different isotopes of an element are identical, but they will often have great differences in nuclear stability.

The size and structure of nuclei



Rutherford used the isolated system (energy) analysis model to find an expression for the separation distance d at which an alpha particle approaching a nucleus head-on is turned around by Coulomb repulsion.

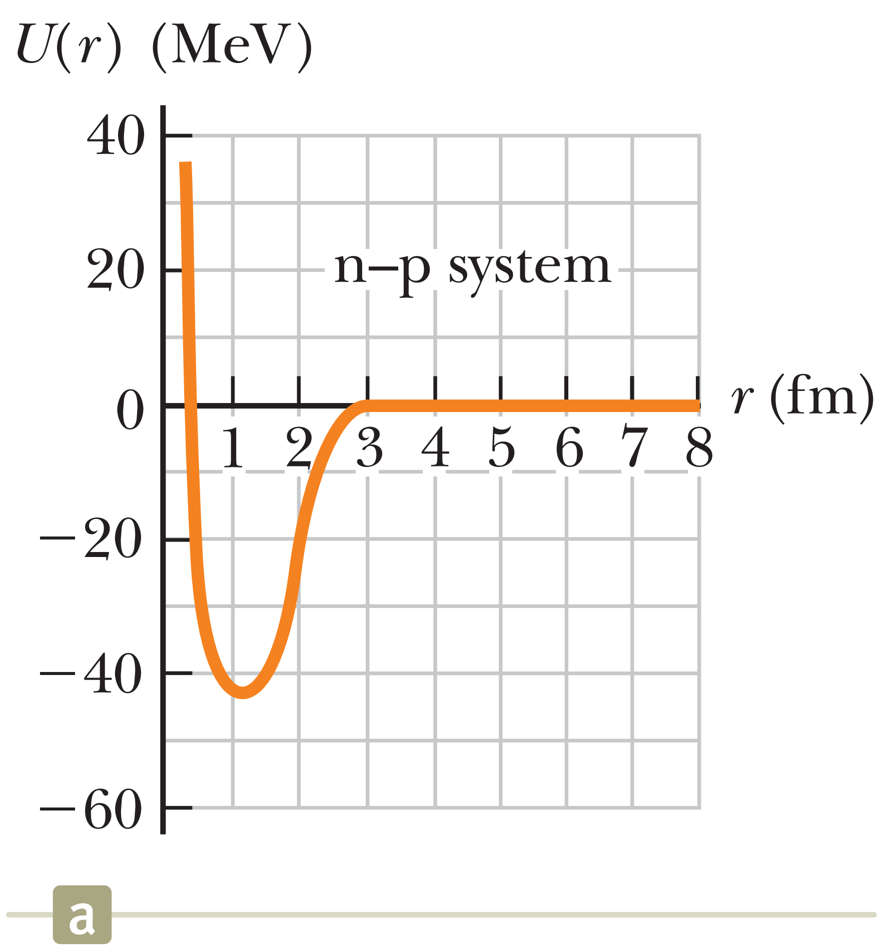
Since the time of Rutherford's scattering experiments, a multitude of other experiments have shown that most nuclei are approximately spherical and have an average radius given by

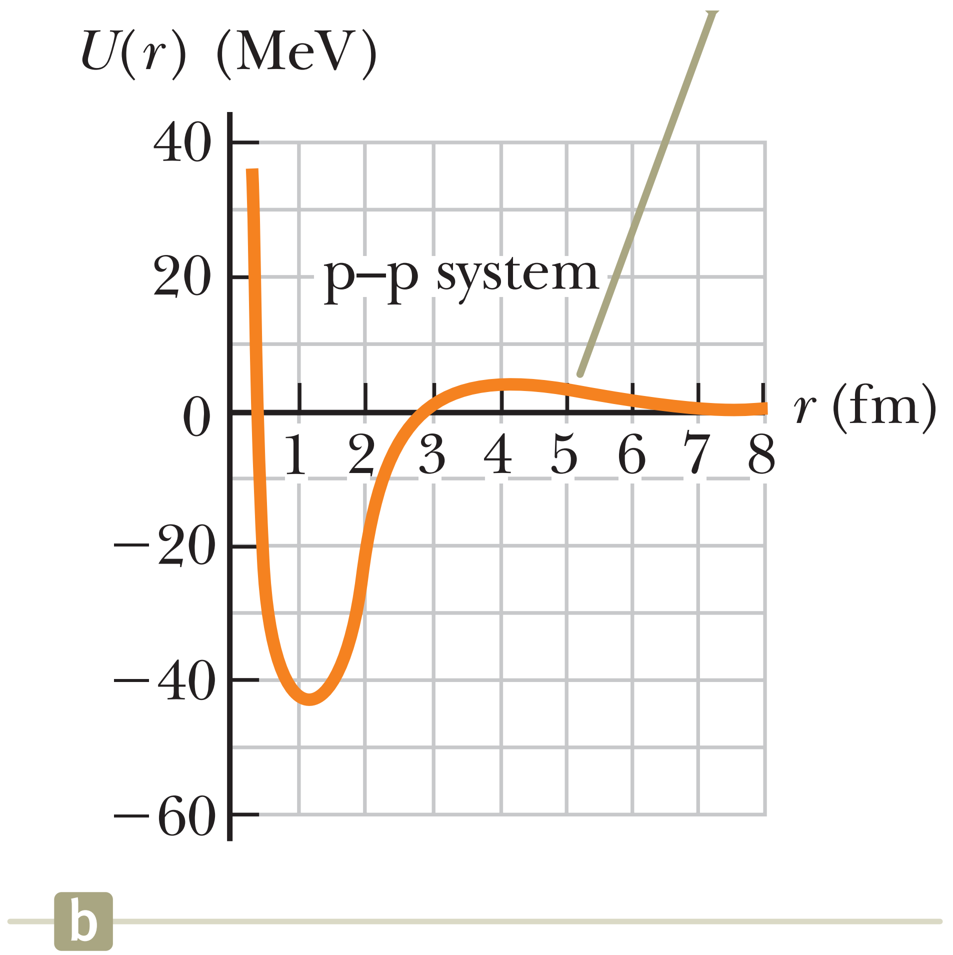


Ernest Rutherford

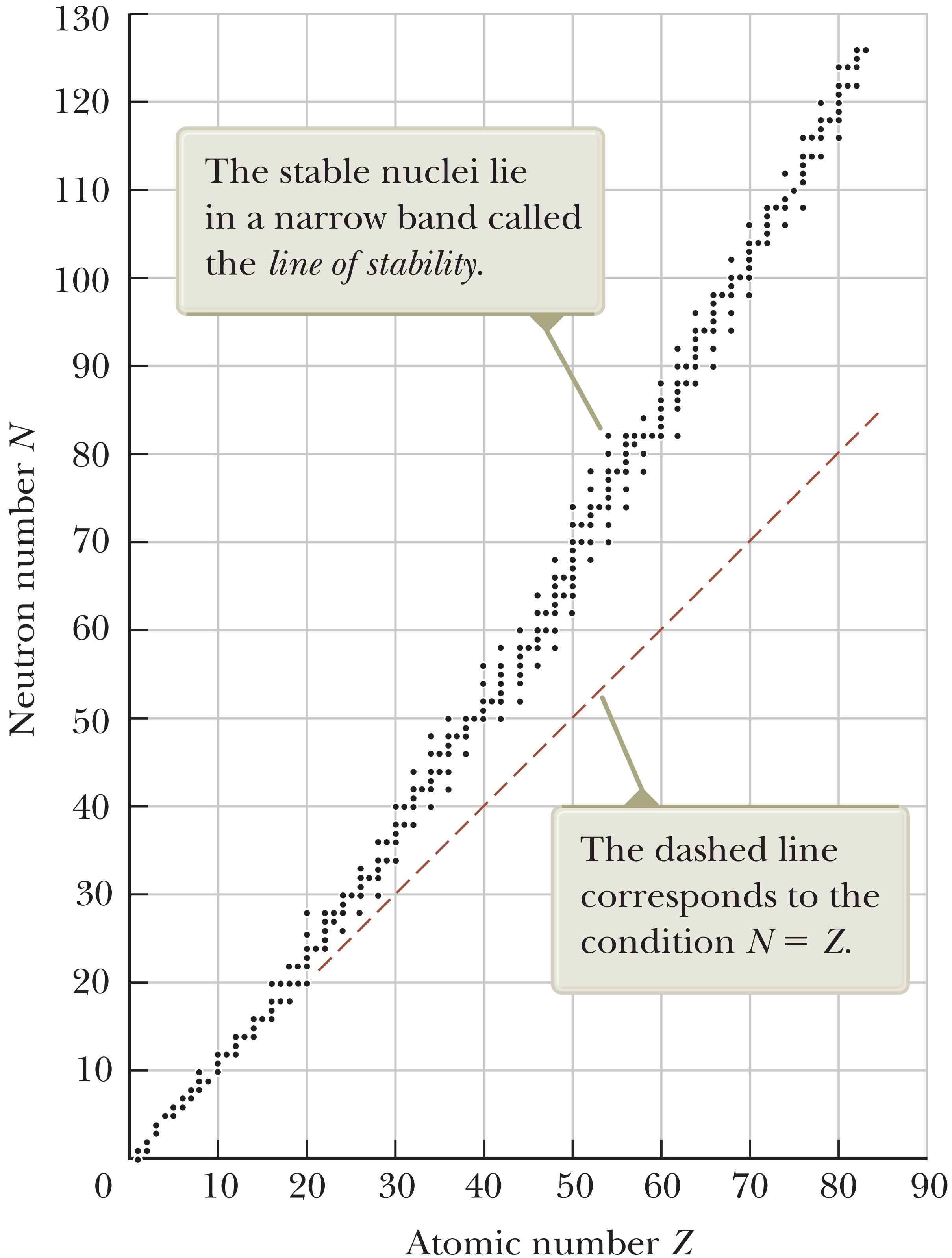
Nuclear structure and stability

The **nuclear force** (or nucleon–nucleon interaction, residual strong force, or, historically, strong nuclear force) is a force that acts between the protons and neutrons of atoms. Neutrons and protons, both nucleons, are affected by the nuclear force almost identically. Since protons have charge $+e$, they experience an electric force that tends to push them apart, but at short range the attractive nuclear force is strong enough to overcome the electromagnetic force. The nuclear force binds nucleons into atomic nuclei.





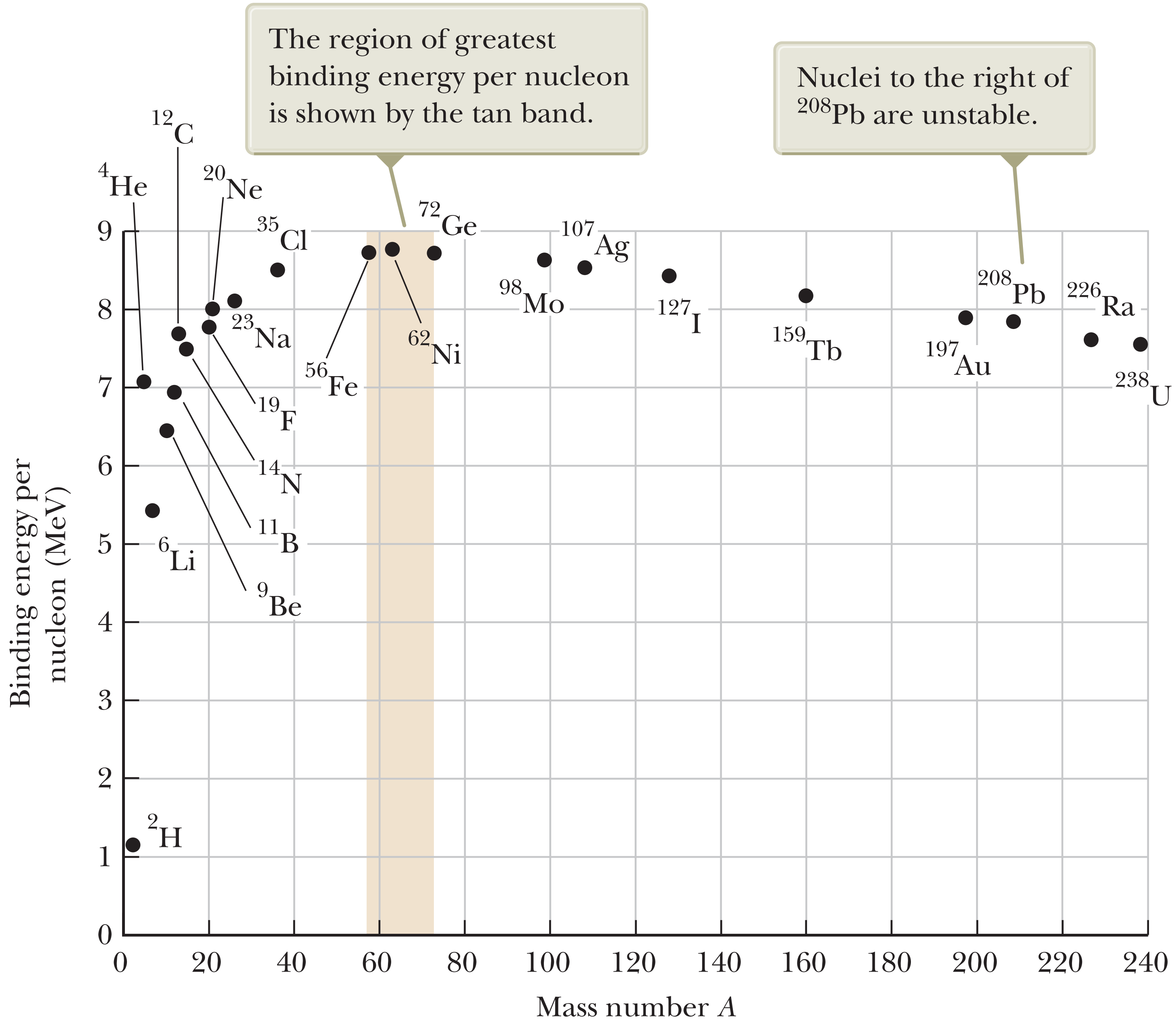
Nuclear structure and stability



The stable nuclei are represented by the black dots, which lie in a narrow range called the line of stability. Notice that the light stable nuclei contain an equal number of protons and neutrons; that is, $N = Z$. Also notice that in heavy stable nuclei, the number of neutrons exceeds the number of protons: above $Z > 20$, the line of stability deviates upward from the line representing $N = Z$. ***Why?***

Nuclear binding energy

The total mass of a nucleus is less than the sum of the masses of its individual nucleons. Therefore, the rest energy of the bound system (the nucleus) is less than the combined rest energy of the separated nucleons. This difference in energy is called the **binding energy** of the nucleus and can be interpreted as the energy that must be added to a nucleus to break it apart into its components.



Exercise

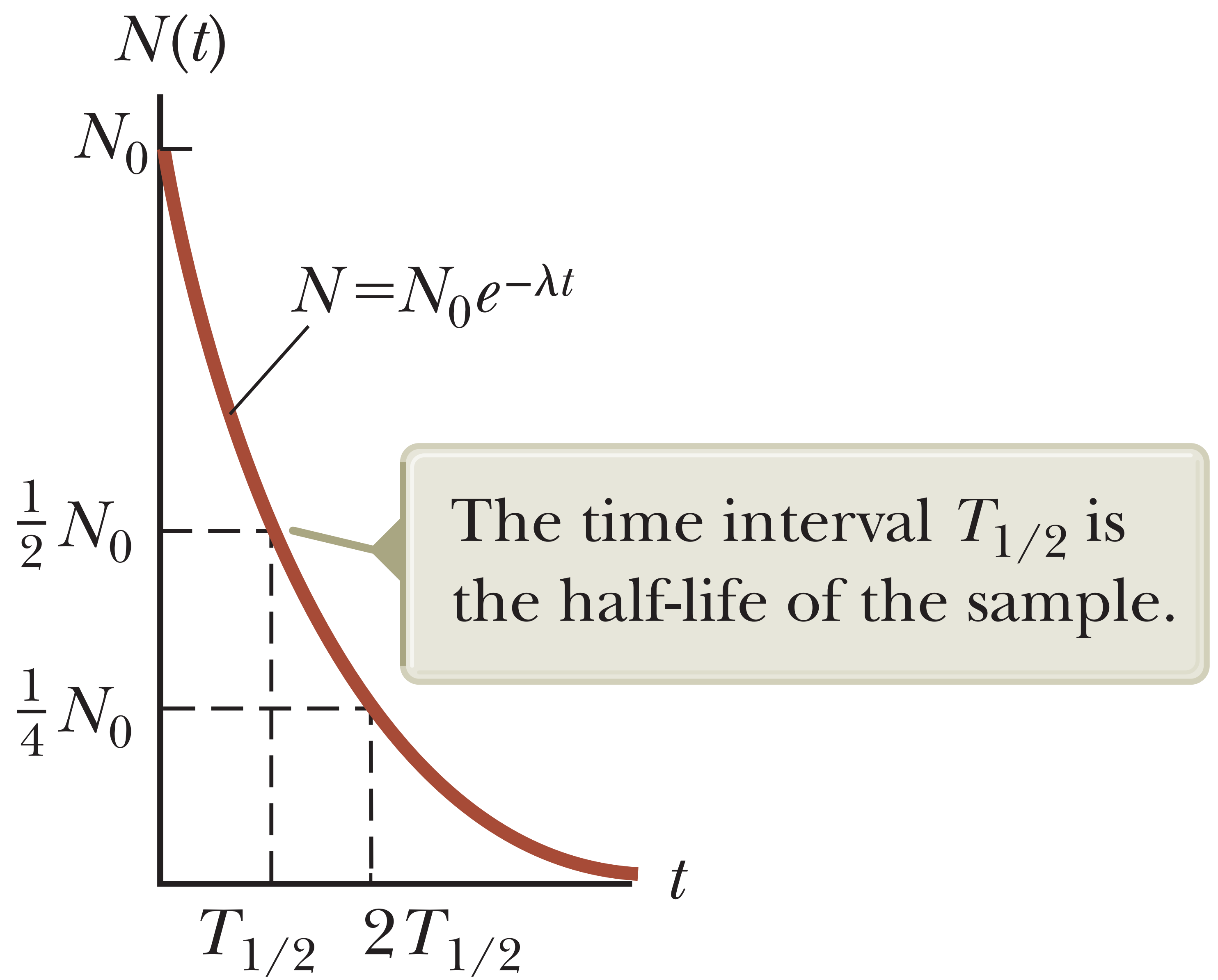
Assume a hydrogen atom is a sphere with diameter 0.100 nm and a hydrogen molecule consists of two such spheres in contact.

(a) What fraction of the space in a tank of hydrogen gas at 0°C and 1.00 atm is occupied by the hydrogen molecules themselves?

(b) What fraction of the space within one hydrogen atom is occupied by its nucleus, of radius 1.20 fm?

Radioactivity

The decay process is probabilistic in nature and can be described with statistical calculations for a radioactive substance of macroscopic size containing a large number of radioactive nuclei. For such large numbers, the rate at which a particular decay process occurs in a sample is proportional to the number of radioactive nuclei present (that is, the number of nuclei that have not yet decayed).



Radioactivity

Decay rate R and activity:

Half-life: The half-life of a radioactive substance is the time interval during which half of a given number of radioactive nuclei decay.

Unit of activity: curie (Ci) and becquerel (Bq)

Exercise

The radioactive isotope Au-198 has a half-life of 64.8 h. A sample containing this isotope has an initial activity ($t = 0$) of 40.0 mCi. Calculate the number of nuclei that decay in the time interval between $t1 = 10.0$ h and $t2 = 12.0$ h.

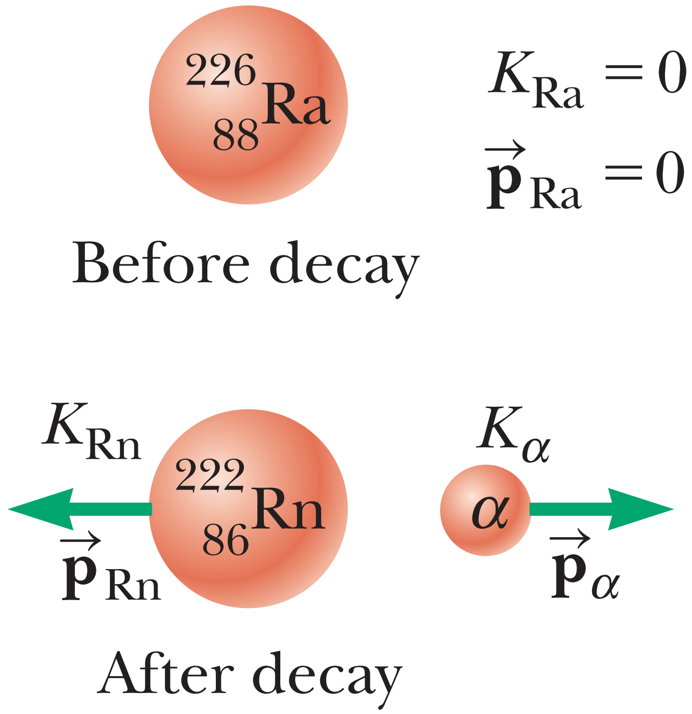
Exercise

The half-life of I-131 is 8.04 days,

(a) Find the decay constant for this nuclide.
(b) Find the number of nuclei necessary to produce a sample with an activity of 6.40 mCi.
(c) A sample of I-131 with this initial activity decays for 40.2 d. What is the activity at the end of that period?

The decay processes: alpha decay

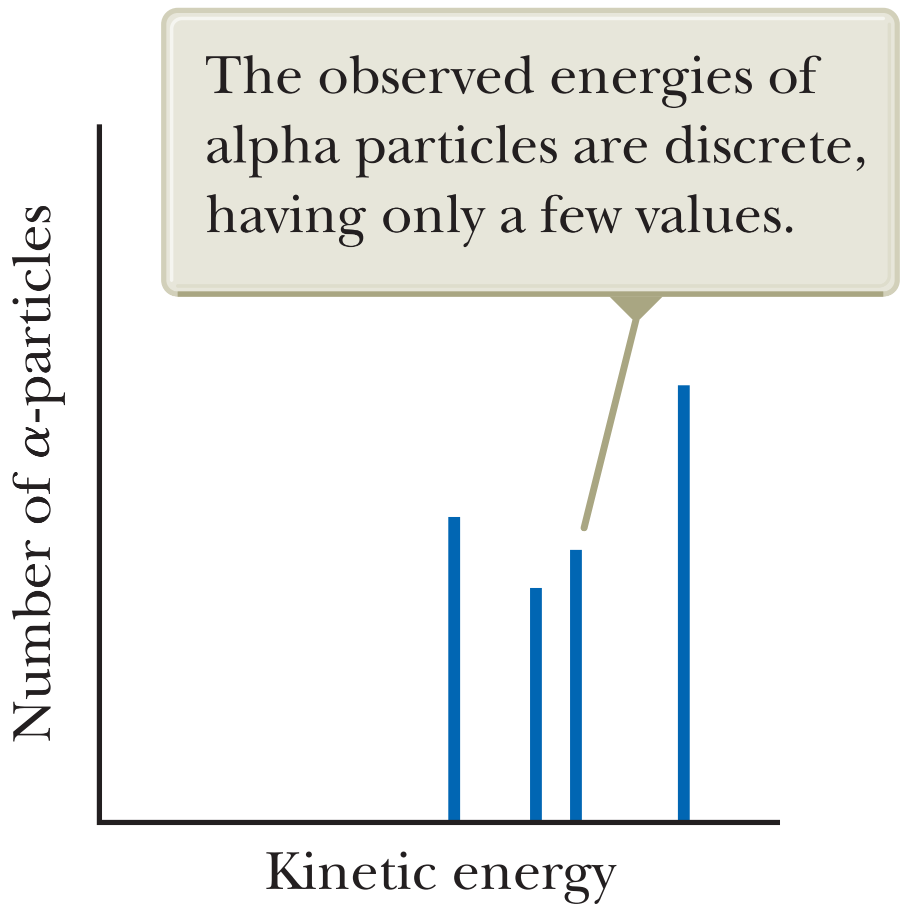
Alpha decay or α-decay is a type of radioactive decay in which an atomic nucleus emits an alpha particle (helium nucleus) and thereby transforms or 'decays' into a different atomic nucleus, with a mass number that is reduced by four and an atomic number that is reduced by two.

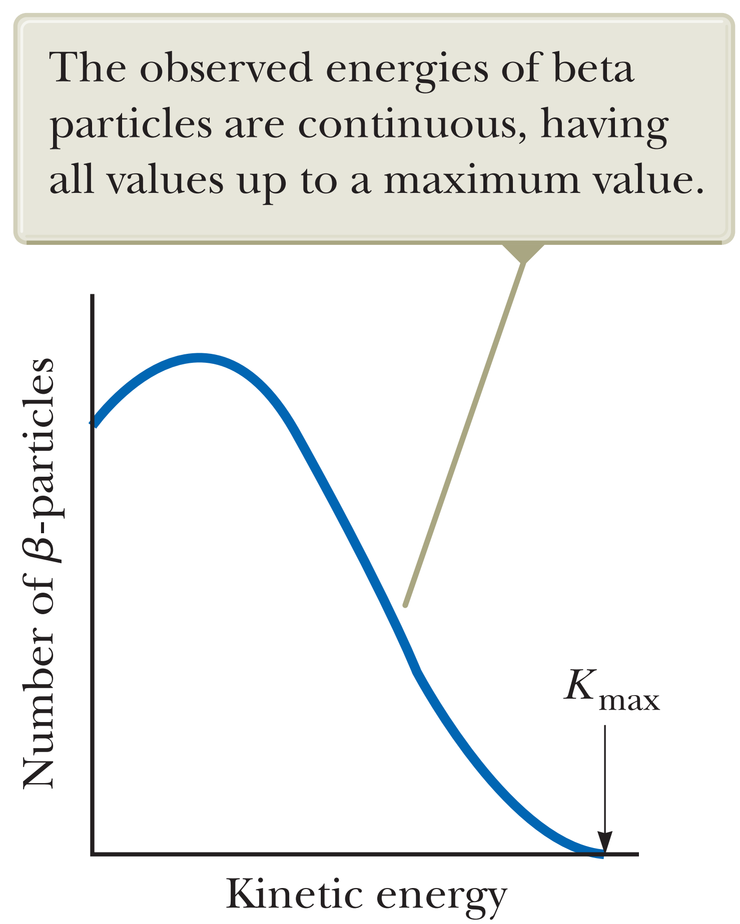


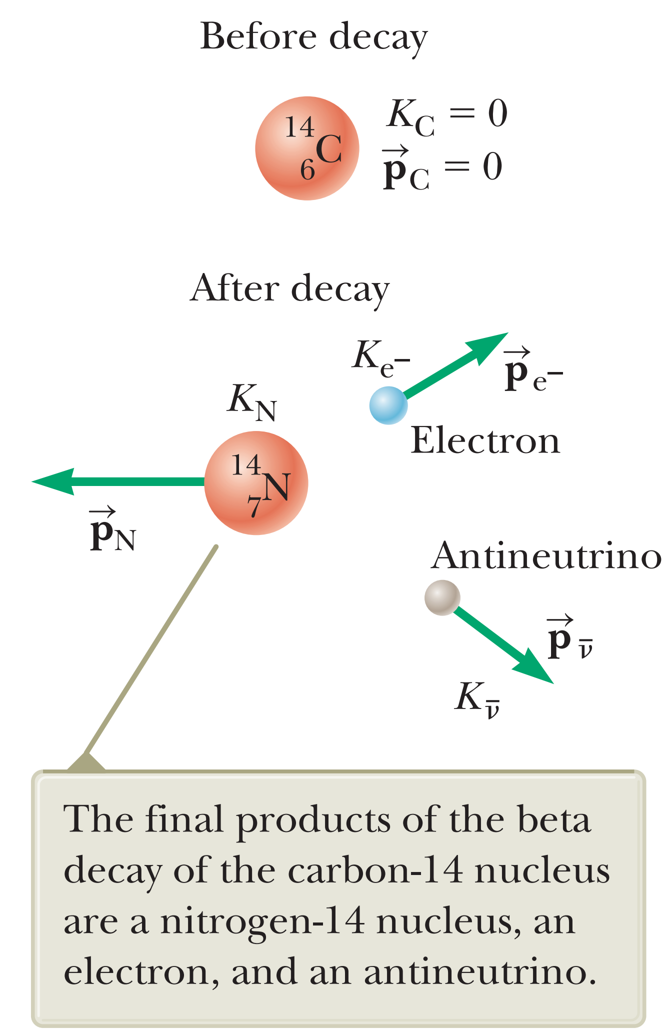
The decay processes: beta decay

beta decay (β-decay) is a type of radioactive decay in which a beta particle (fast energetic electron or positron) is emitted from an atomic nucleus, transforming the original nuclide to an isobar of that nuclide.

Kinetic energy of alpha and beta decays:

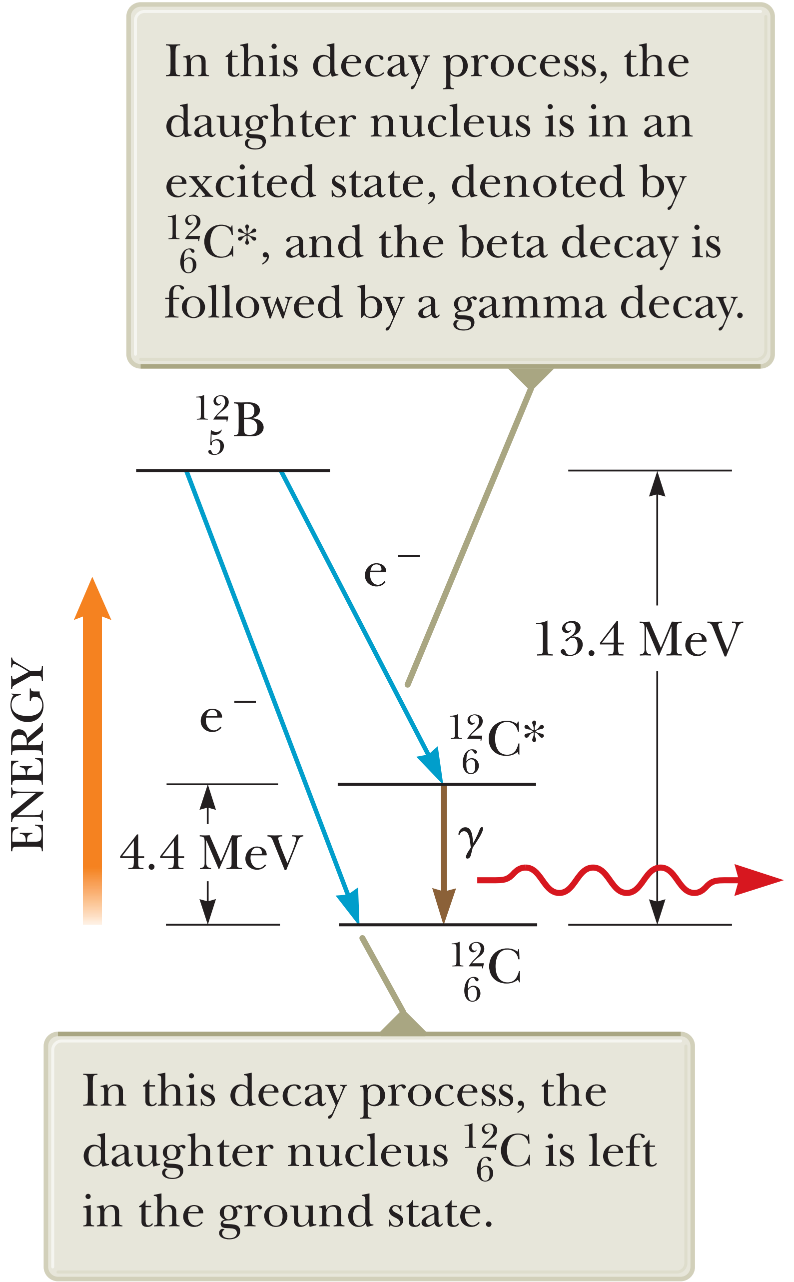






The decay processes: gamma decay

Gamma decay is a type of radioactivity in which some unstable atomic nuclei dissipate excess energy by a spontaneous electromagnetic process. In the most common form of gamma decay, known as gamma emission, gamma rays (photons, or packets of electromagnetic energy, of extremely short wavelength) are radiated.



Nuclear reactions

It is also possible to stimulate changes in the structure of nuclei by bombarding them with energetic particles. Such collisions, which change the identity of the target nuclei, are called **nuclear reactions**.

Reactions energy Q is the difference between the initial and final rest energies resulting from the reaction.

- **Exothermic**:

- **Endothermic**:

Exercise

The nucleus O-15 decays by electron capture. The nuclear reaction is written

$$O_8^{15} + e^- \rightarrow N_7^{15} + \nu$$

(a) Write the process going on for a single particle within the nucleus.

(b) Disregarding the daughter's recoil, determine the energy of the neutrino.

Note: Atomic mass of O_8^{15} is 15.0030656 u. Atomic mass of N_7^{15} is 15.000108 u.