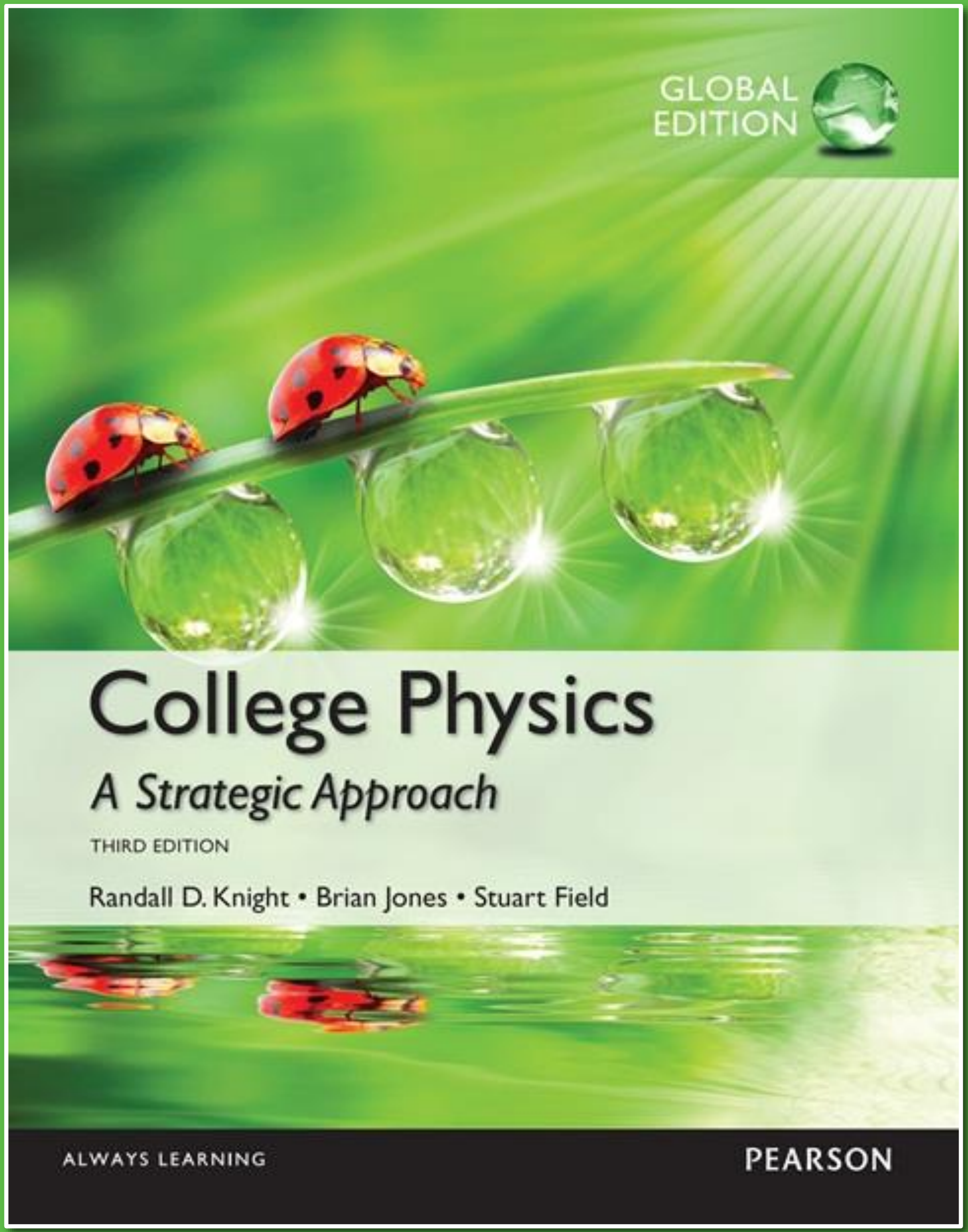


Lecture Presentation

Chapter 30

Nuclear Physics

Chapter 30 Nuclear Physics

Section 30.1 Nuclear Structure
Section 30.4 Radiation and Radioactivity
Section 30.5 Nuclear Decay and Half-Lives

Chapter 30 Preview
Looking Ahead

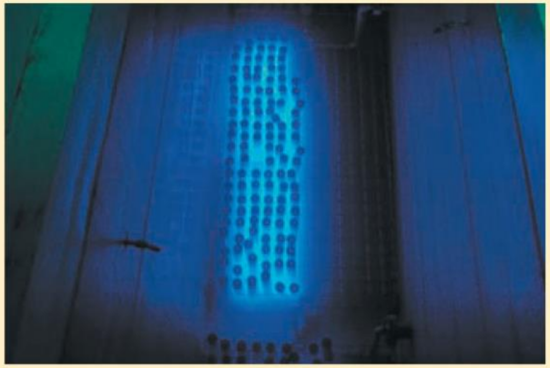
Nuclei and Isotopes

The ratio of two stable **isotopes** of oxygen in arctic ice gives us a record of past temperatures.

You'll learn about nuclear structure. The number of protons determines the element; the number of neutrons, the isotope.

Radioactivity and Radiation

These **radioactive** nuclei in this tank are unstable. They decay, emitting high-energy particles—**radiation**—that ionize the water.



You'll learn about different nuclear decay modes (alpha, beta, and gamma) and the resulting radiation for each.

Decay and Half-Life

Measurements of carbon isotopes in these cave drawings show that they are 30,000 years old.

In any sample of ^{14}C, half the nuclei decay in 5700 years. You'll see how to use this half-life to calculate an object's age.

Chapter Goal: To understand the physics of the nucleus and some of the applications of nuclear physics.

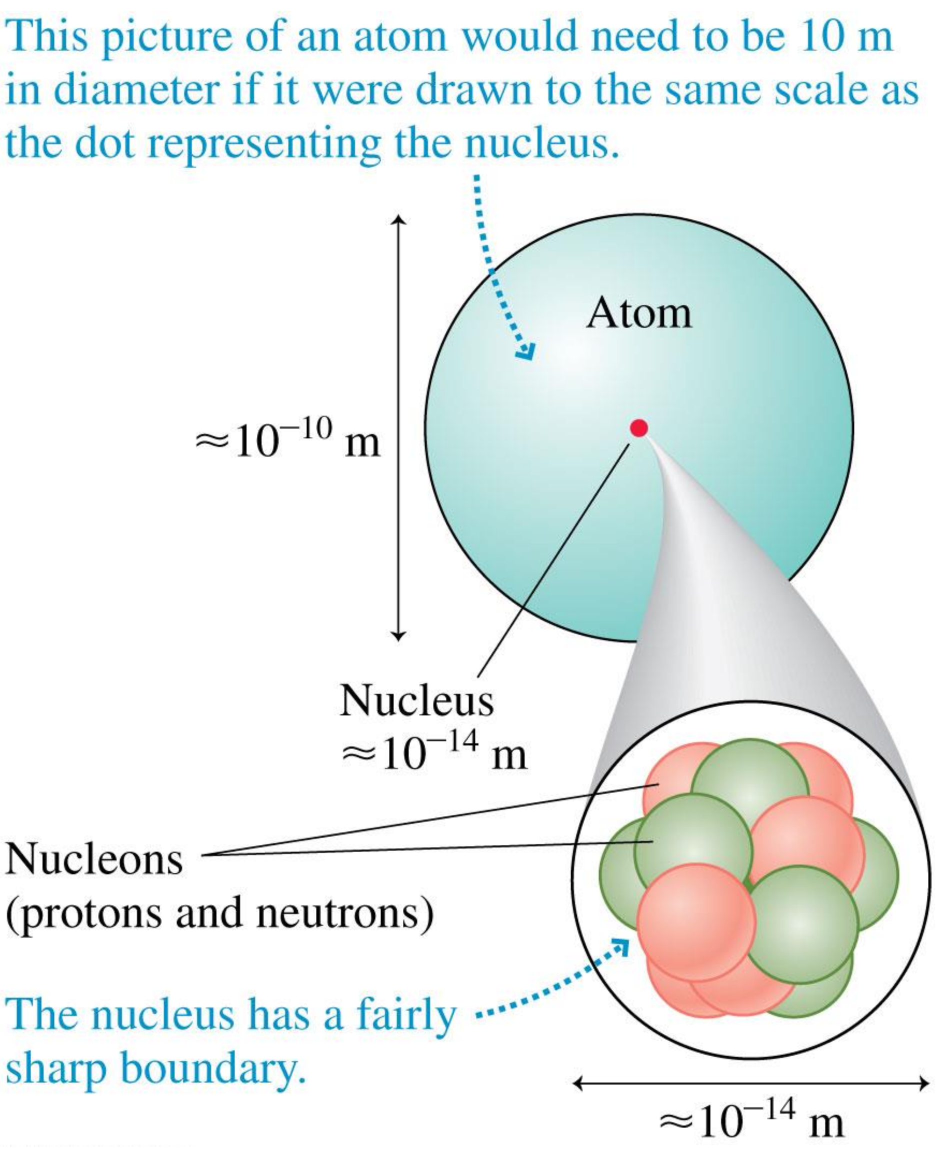
Section 30.1 Nuclear Structure

Nuclear Structure

- The nucleus is composed of protons and neutrons. Together they are referred to as nucleons.

TABLE 30.1 Protons and neutrons

	Proton	Neutron
Number	Z	N
Charge q	$+e$	0
Mass, in u	1.00728	1.00866



To identify a nucleus, we need two of three numbers:

1.mass number, *A*, which corresponds to the number of nucleons in the nucleus.

2. atomic number, Z, which corresponds to the number of protons in the nucleus,

3. the number of neutrons, *N*.

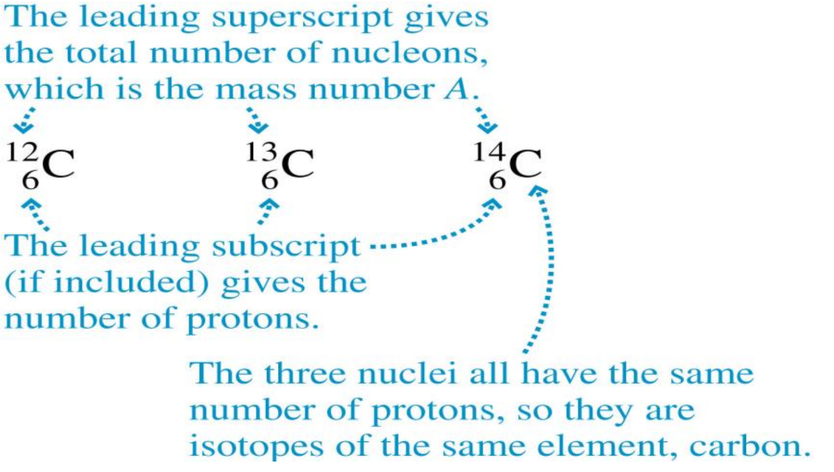
$$A = Z + N$$

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

chemical symbol X

Isotopes

- Atoms with the same number of protons in the nucleus can have different numbers of neutrons.
- Atoms with the same number of protons but different number of neutrons are <u>isotopes</u> of the same element.
- For example, the most common isotope of carbon is $^{12}_{6}C$, which has six protons and six neutrons.



- Most isotopes are radioactive, meaning that the nucleus is not stable and, after some period, will emit a subatomic particle to reach a more stable state.

QuickCheck 30.1

The isotope ${}^{3}_{2}\text{He}$ has ___ neutrons.

A. 0
B. 1
C. 2
D. 3
E. 4

QuickCheck 30.2

How many neutrons are in each of the following isotopes? (Some of these are uncommon or unstable.)

$$^{11}_{3}\text{Li},\ ^{11}_{4}\text{Be},\ ^{11}_{5}\text{B},\ ^{11}_{6}\text{C}$$

QuickCheck 30.2

How many neutrons are in each of the following isotopes? (Some of these are uncommon or unstable.)

$$^{11}_{3}\text{Li},\ ^{11}_{4}\text{Be},\ ^{11}_{5}\text{B},\ ^{11}_{6}\text{C}$$

The number of neutrons is given by A–Z, so:

$^{11}_{3}\text{Li}$: 8 neutrons

$^{11}_{4}\text{Be}$: 7 neutrons

$^{11}_{5}\text{B}$: 6 neutrons

$^{11}_{6}\text{C}$: 5 neutrons

Section 30.4 Radiation and Radioactivity

Alpha Decay

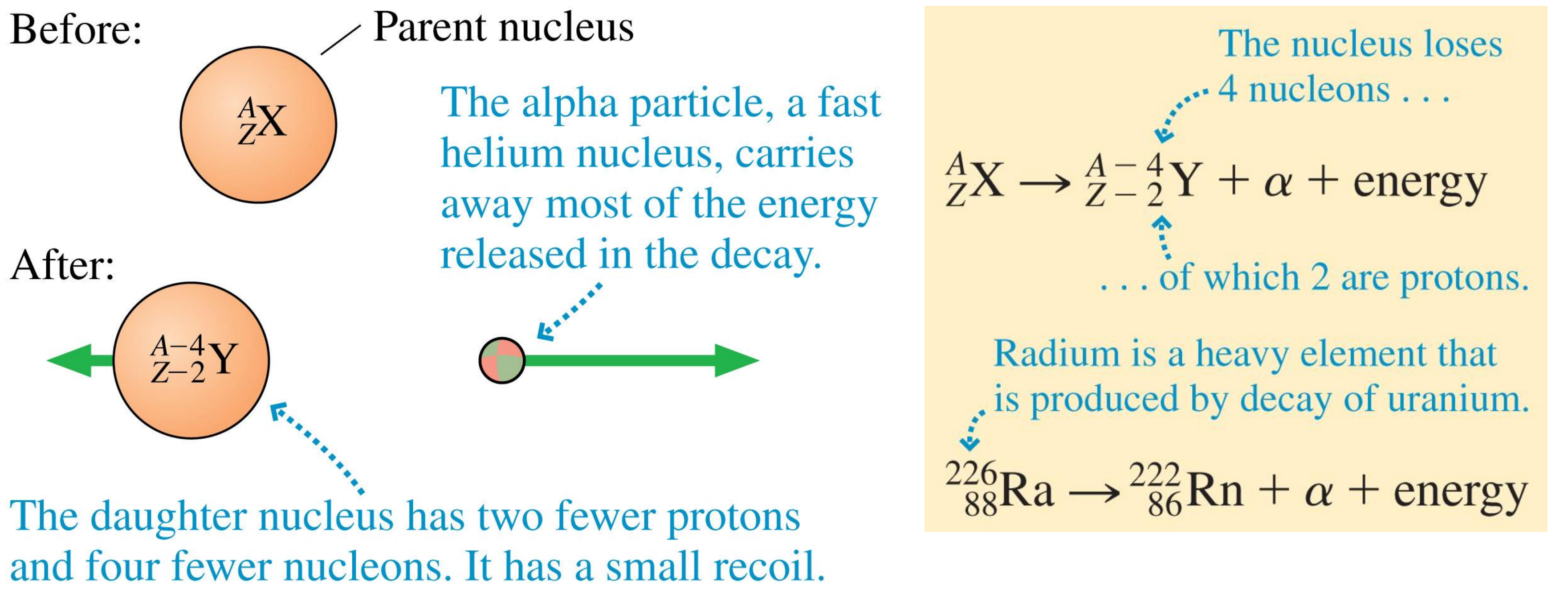
- When a **large nucleus** spontaneously decays by breaking into two smaller fragments, one of the fragments is almost always a stable ^{4}He nucleus—an alpha particle. An alpha particle is symbolized by α.
- An unstable nucleus that ejects an alpha particle loses two protons and two neutrons, so we write the decay as (Eq. 30.6)

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + \alpha + \text{energy}$$

Alpha decay of a nucleus

Alpha Decay

- The original nucleus X is called the **parent nucleus** and the decay-product nucleus Y is the **daughter nucleus.**



Beta Decay

- In beta decay, a nucleus decays by emitting an electron.
- The neutron changes itself into a proton by emitting an electron:

$$n \rightarrow p + e^-$$

- The electron is ejected from the nucleus but the proton is not. The beta-decay process is (Eq. 30.9)

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \text{energy}$$

Beta-minus decay of a nucleus

Beta Decay

- Some nuclei emit a positron. A positron, e^+, is identical to an electron except that it has a positive charge. It is the antiparticle of the electron.
- To distinguish between the two forms of beta decay, we call the emission of an electron beta-minus decay and the emission of a positron beta-plus decay.

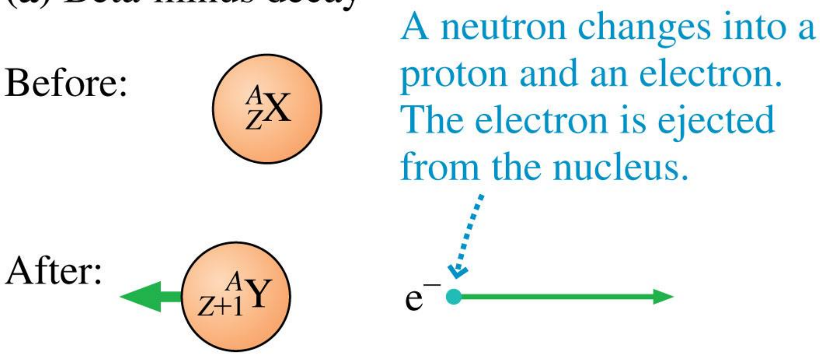
$$p^+ \rightarrow n + e^+$$

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \text{energy}$$

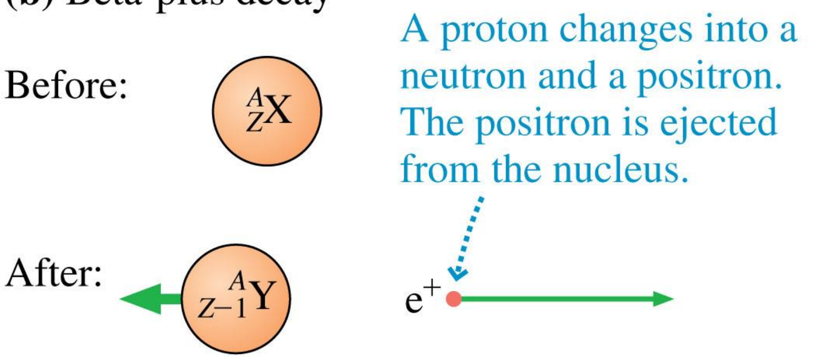
Beta-plus decay of a nucleus

Beta Decay

(a) Beta-minus decay



(b) Beta-plus decay



Beta-minus decay

A neutron turns into a proton, so:

The number of nucleons stays the same . . .

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \text{energy}$$

. . . and the nucleus gains a proton.

This chlorine isotope is present at low levels in the environment.

$$^{36}_{17}Cl \rightarrow {}^{36}_{18}Ar + e^- + \text{energy}$$

Beta-plus decay

A proton turns into a neutron, so:

The number of nucleons stays the same . . .

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^+ + \text{energy}$$

. . . and the nucleus loses a proton.

This carbon isotope is produced in cyclotrons.

$$^{11}_{6}C \rightarrow {}^{11}_{5}B + e^+ + \text{energy}$$

Gamma Decay

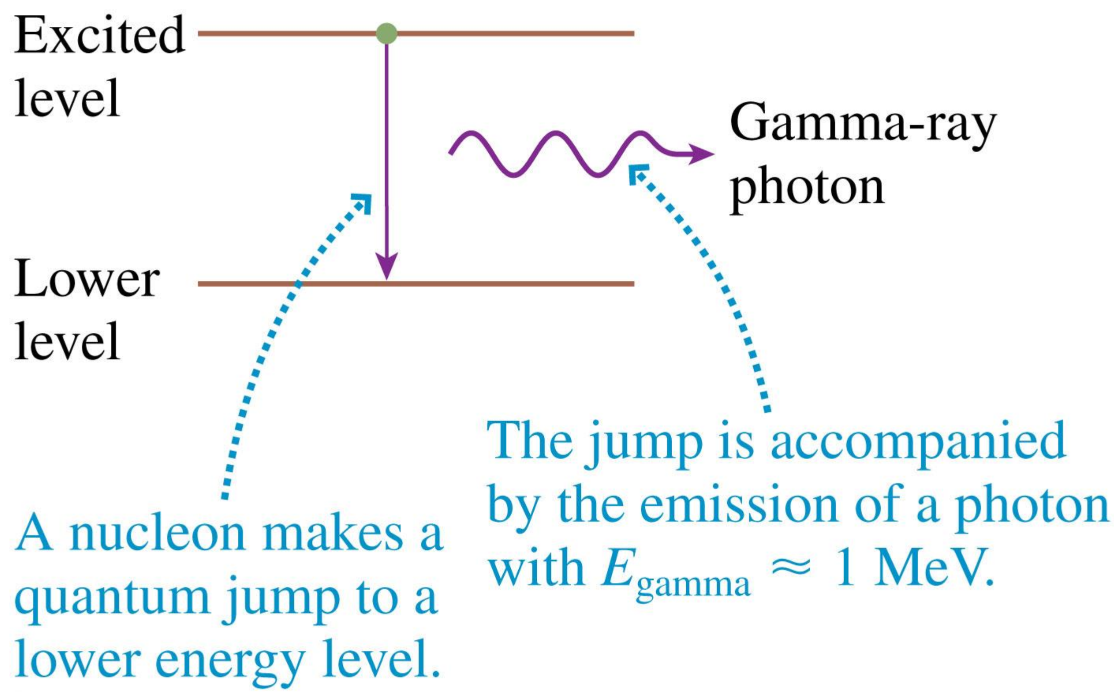
- Gamma decay occurs when a proton or neutron undergoes a quantum jump.

No change in the number of neutrons or protons means no change of element or isotope.

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

This excited form of nickel is produced in the beta-minus decay of ${}^{60}\mathrm{Co}$.

$${}^{60}_{28}\mathrm{Ni}^{*} \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma$$



QuickCheck 30.6

Is $^{238}_{94}\text{Pu} \rightarrow {}^{236}_{92}U + \alpha$ a possible decay mode?

A. Yes

B. No

C. It depends on the energy of the alpha particle.

QuickCheck 30.8

What is the daughter nucleus for the following decay?

$$^{90}_{38}Sr \rightarrow {}^{?}\mathrm{X} + \mathrm{e}^{-}$$

A. $^{90}_{39}Y$
B. $^{89}_{39}Y$
C. $^{90}_{37}Rb$
D. $^{89}_{37}Rb$

QuickCheck 30.11

What is the decay mode of the following decay?

$$^{137}_{55}Cs \rightarrow {}^{137}_{56}\mathrm{Ba} + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay

QuickCheck 30.13

What is the decay mode of the following decay?

$$^{60}_{28}Ni^* \rightarrow {}^{60}_{28}Ni + ?$$

A. Alpha decay
B. Beta-minus decay
C. Beta-plus decay
D. Gamma decay

Section 30.5 Nuclear Decay and Half-Lives

Nuclear Decay and Half-Lives

- If you start with N_0 unstable nuclei, after an interval of time called the *half-life*, you'll have ½ N_0 nuclei remaining.
- The **half-life** $t_{1/2}$ is the average time required for one-half the nuclei to decay.
- The number of nuclei N remaining at time t is (Eq. 30.12):

$$N = N_0 \left(\frac{1}{2}\right)^{t/t_{1/2}}$$

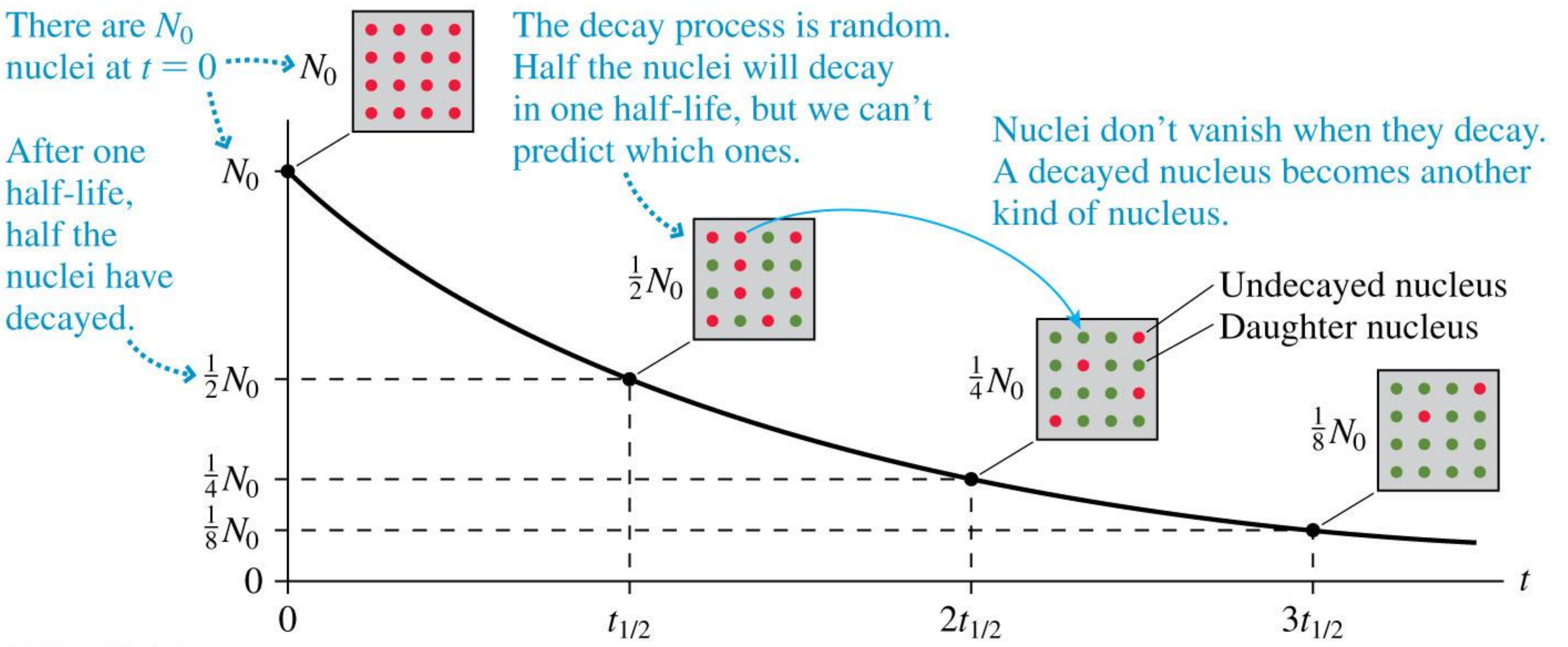
Number of atoms remaining after time t → N

Number of atoms at the start, $t = 0$ → N_0

The units for t and $t_{1/2}$ must be the same.

Nuclear Decay and Half-Lives

- The figure shows the decay of a sample of radioactive nuclei.



Nuclear Decay and Half-Lives

- The decay of radioactive nuclei is an exponential decay.
- The equation for the number of atoms after a half-life can be written in terms of a time constant τ that is related to the half-life :

$$N = N_0 e^{-t/\tau}$$

The time constant τ is proportional to the half-life $t_{1/2}$

$$\tau = \frac{t_{1/2}}{\ln 2} = (1.44)t_{1/2}$$

Nuclear Decay and Half-Lives

- The relationship between the time constant and the half life can be demonstrated by applying $N = N_0/2$ at $t = t_{1/2}$ to the equation for exponential decay:

$$\frac{N_0}{2} = N_0 e^{-t_{1/2}/\tau}$$

$$\ln\left(\frac{1}{2}\right) = -\ln 2 = -\frac{t_{1/2}}{\tau}$$

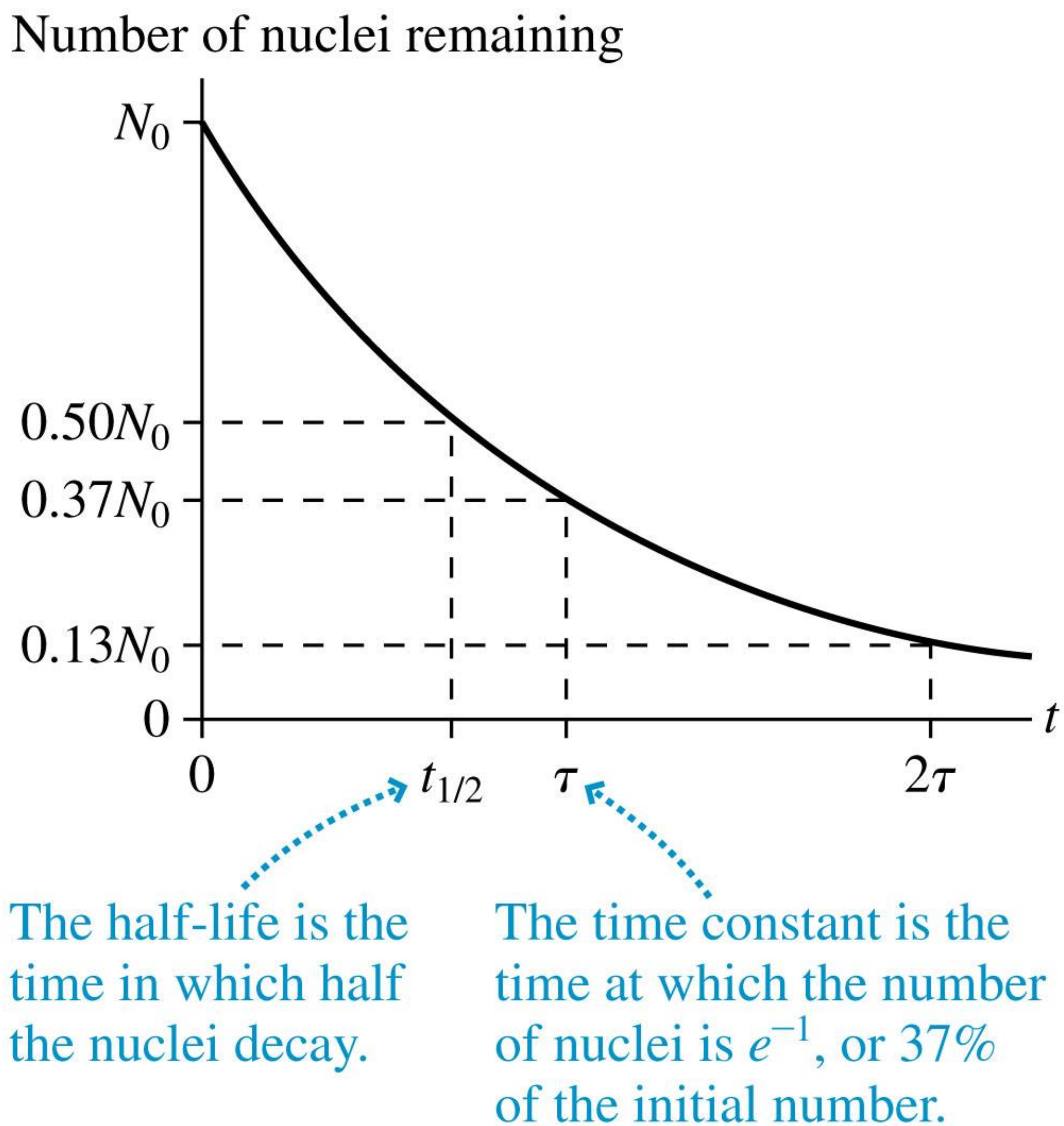
- We find that the time constant in terms of the half-life and the half-life in terms of the time constant are

$$\tau = \frac{t_{1/2}}{\ln 2} = 1.44 t_{1/2}$$

$$t_{1/2} = \tau \ln 2 = 0.693\tau$$

Nuclear Decay and Half-Lives

- The number of radioactive atoms decreases exponentially with time.



QuickCheck 30.5

100 g of radioactive element X are placed in a sealed box. The half-life of this isotope of X is 2 days. After 4 days have passed, what is the mass of element X in the box?

A. 100 g
B. 50 g
C. 37 g
D. 25 g
E. 0 g

Activity

- The **activity** R of a radioactive sample is the number of decays per second. Each decay corresponds to an alpha, beta, or gamma emission.
- The activity of a sample N nuclei with a time constant τ or half-life $t_{1/2}$ is (Eq. 30.15)

$$R = \frac{N}{\tau} = \frac{0.693N}{t_{1/2}}$$

- **The activity is inversely proportional to the half-life.**

Activity

- We can find the variation of activity with time:

$$R = \frac{N}{\tau} = \frac{N_0}{\tau}\left(\frac{1}{2}\right)^{t/t_{1/2}} = \frac{N_0}{\tau}e^{-t/\tau}$$

- N_0/τ is the initial activity R_0 so the decay of activity is (Eq. 30.16)

Activity after time t

Activity at the start, $t = 0$

$$R = R_0\left(\frac{1}{2}\right)^{t/t_{1/2}} = R_0 e^{-t/\tau}$$

- The SI unit of activity is the **becquerel**:

1 becquerel = 1 Bq = 1 decay/second or 1 s^{-1}

- The **curie** is also used:

1 curie = 1 Ci = 3.7×10^{10} Bq

Example

We consider a sample that contains 3×10^{16} nuclei Of radium-226 ,which has a half-life of 1600 years. What is the activity of the sample at $t = t_{1/2}$?

$$t_{1/2} = 1600\ years = 5 \times 10^{10} s$$

$$\frac{1}{\tau} = \frac{\ln 2}{t_{1/2}} = 1.4 \times 10^{-11} s^{-1}$$

$$R = \frac{N_0}{\tau}\left(\frac{1}{2}\right)^{t/t_{1/2}}$$

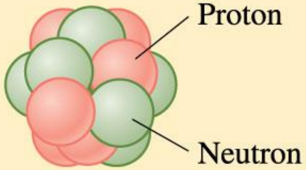
$$\mathrm{R} = 3 \times 10^{16} \times 1.4 \times 10^{-11} \times \left(\frac{1}{2}\right)^{1} = 2.1 \times 10^{5} Bq$$

Summary: General Principles

The Nucleus

The nucleus is a small, dense, positive core at the center of an atom.

Z protons, charge $+e$, spin $\frac{1}{2}$
N neutrons, charge 0, spin $\frac{1}{2}$



The **mass number** is

$$A = Z + N$$

Isotopes of an element have the same value of Z but different values of N.

The strong force holds nuclei together:

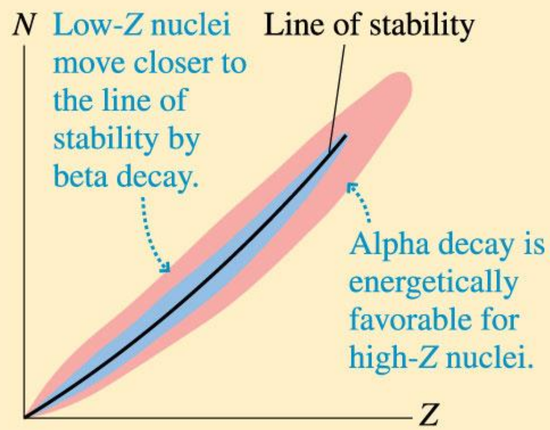
- It acts between any two nucleons.
- It is short range.

Adding neutrons to a nucleus allows the strong force to overcome the repulsive Coulomb force between protons.

Summary: General Principles

Nuclear Stability

Most nuclei are not **stable.** Unstable nuclei undergo **radioactive decay.** Stable nuclei cluster along the **line of stability** in a plot of the isotopes.



Mechanisms by which unstable nuclei decay:

Decay	Particle
alpha	^{4}He nucleus
beta-minus	e^-
beta-plus	e^+
gamma	photon

Alpha and beta decays change the nucleus; the daughter nucleus is a different element.

Alpha decay:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + \alpha + \text{energy}$$

Beta-minus decay:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta + \text{energy}$$

Summary

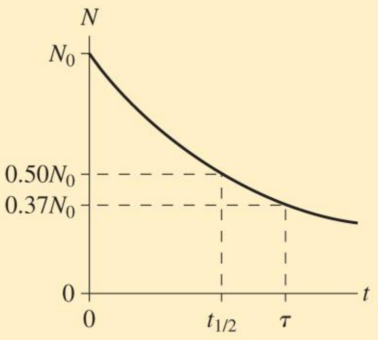
APPLICATIONS

Radioactive decay

The number of undecayed nuclei decreases exponentially with time t:

$$N = N_0 e^{-t/\tau}$$

$$N = N_0\left(\frac{1}{2}\right)^{t/t_{1/2}}$$



The **half-life**

$$t_{1/2} = \tau \ln 2 = 0.693\tau$$

is the time in which half of any sample decays.

Measuring radiation

The **activity** of a radioactive sample is the number of decays per second. Activity is related to the half-life as

$$R = \frac{0.693N}{t_{1/2}} = \frac{N}{\tau}$$