PHYS 111
1ST semester 1439-1440

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Lecture 25

Chapter 44

Nuclear Structure

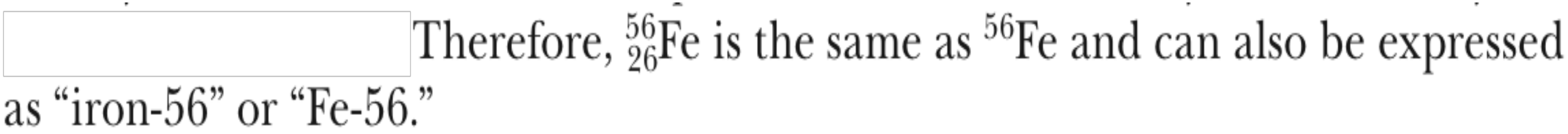
- **44.1** Some Properties of Nuclei
- **44.2** Nuclear Binding Energy
- **44.4** Radioactivity
- **44.5** The Decay Processes
- **44.6** Natural Radioactivity
- **44.7** Nuclear Reactions

44.1 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:
    - 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

44.1 Some Properties of Nuclei

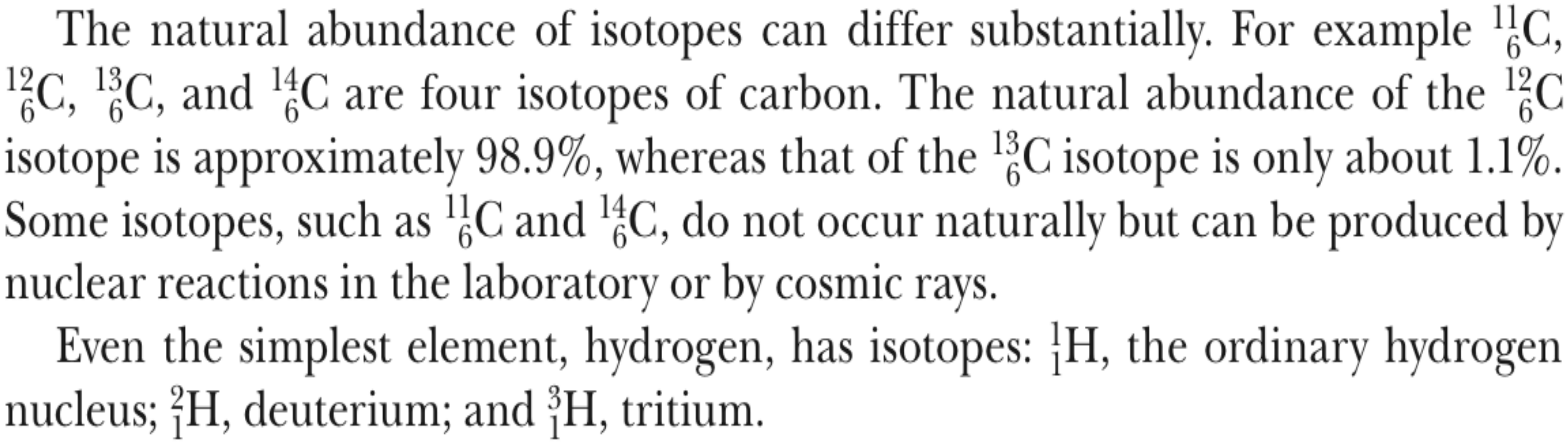
- A **nuclide** is a specific combination of atomic number and mass number that represents a nucleus.
- In representing nuclides, it is convenient to use the symbol $^{A}_{Z}\mathrm{X}$ to convey the numbers of protons and neutrons, where X represents the chemical symbol of the element.
- For example, $^{56}_{26}\mathrm{Fe}$ (iron) has mass number 56 and atomic number 26; therefore, it contains 26 protons and 30 neutrons.
- We omit the subscript *Z* because the chemical symbol can always be used to determine *Z*.



Therefore, $^{56}_{26}\mathrm{Fe}$ is the same as $^{56}\mathrm{Fe}$ and can also be expressed as “iron-56” or “Fe-56.”

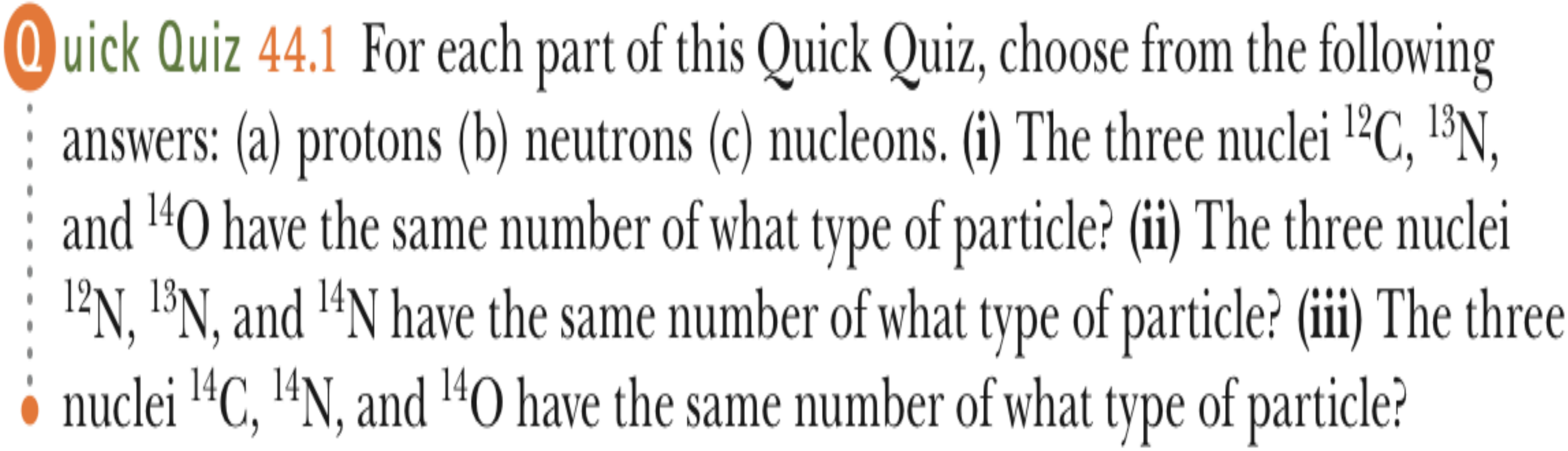
Isotopes

- The nuclei of all atoms of a particular element contain the same number of pro- tons but often contain different numbers of neutrons. Nuclei related in this way are called **isotopes.** The isotopes of an element have the same *Z* value but different *N* and *A* values.



The natural abundance of isotopes can differ substantially. For example $^{11}_{6}\mathrm{C}$, $^{12}_{6}\mathrm{C}$, $^{13}_{6}\mathrm{C}$, and $^{14}_{6}\mathrm{C}$ are four isotopes of carbon. The natural abundance of the $^{12}_{6}\mathrm{C}$ isotope is approximately 98.9%, whereas that of the $^{13}_{6}\mathrm{C}$ isotope is only about 1.1%. Some isotopes, such as $^{11}_{6}\mathrm{C}$ and $^{14}_{6}\mathrm{C}$, do not occur naturally but can be produced by nuclear reactions in the laboratory or by cosmic rays.

Even the simplest element, hydrogen, has isotopes: $^{1}_{1}\mathrm{H}$, the ordinary hydrogen nucleus; $^{2}_{1}\mathrm{H}$, deuterium; and $^{3}_{1}\mathrm{H}$, tritium.



Quick Quiz 44.1 For each part of this Quick Quiz, choose from the following answers: (a) protons (b) neutrons (c) nucleons. **(i)** The three nuclei $^{12}\mathrm{C}$, $^{13}\mathrm{N}$, and $^{14}\mathrm{O}$ have the same number of what type of particle? **(ii)** The three nuclei $^{12}\mathrm{N}$, $^{13}\mathrm{N}$, and $^{14}\mathrm{N}$ have the same number of what type of particle? **(iii)** The three nuclei $^{14}\mathrm{C}$, $^{14}\mathrm{N}$, and $^{14}\mathrm{O}$ have the same number of what type of particle?

Charge and Mass

- The proton carries a single **positive** charge *e*, equal in magnitude to the charge -*e* on the electron ($e = 1.6 \times 10^{-19}$ C).
- The neutron is electrically **neutral**.
- The proton is approximately 1 836 times as massive as the electron, and the masses of the proton and the neutron are almost equal.
- The **atomic mass unit** u

$$1 \text{ u} = 1.660\ 539 \times 10^{-27} \text{ kg}$$

- The proton and neutron each have a mass of approximately 1 u.

Charge and Mass

- It is often convenient to express the atomic mass unit in terms of its *rest-energy equivalent.* For one atomic mass unit,

$$E_R = mc^2 = (1.660\,539 \times 10^{-27}\,\mathrm{kg})(2.997\,92 \times 10^8\,\mathrm{m/s})^2 = 931.494\,\mathrm{MeV}$$

- where we have used the conversion 1 eV = 1.602 176 x 10^{-19} J.

- Based on the rest-energy expression, nuclear physicists often express mass in terms of the unit MeV/c^2.

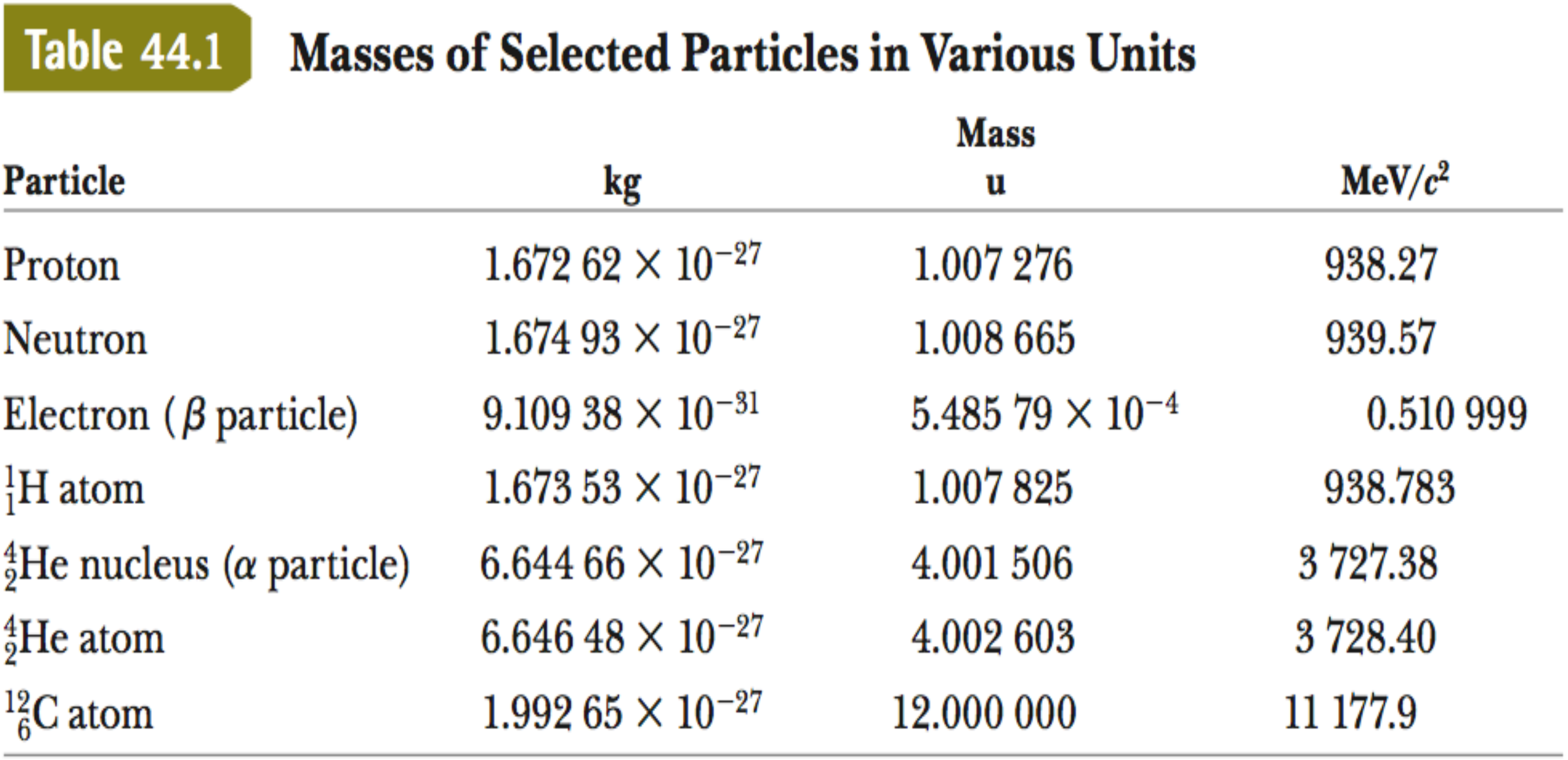


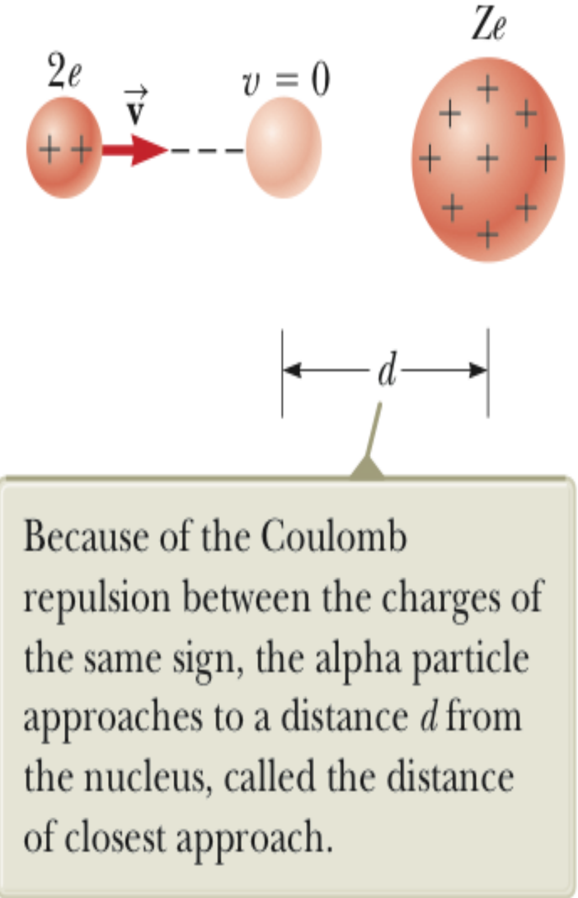
Table 44.1 **Masses of Selected Particles in Various Units**

Particle	Mass 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

The Size and Structure of Nuclei

- In Rutherford’s scattering experiments, positively charged nuclei of helium atoms (alpha particles) were directed at a thin piece of metallic foil.
- As the alpha particles moved through the foil, they often passed near a metal nucleus. Because of the positive charge on both the incident particles and the nuclei, the particles were deflected from their straight-line paths by the Coulomb repulsive force.
- Rutherford concluded that the positive charge in an atom is concentrated in a small **sphere**, which he called the **nucleus**, whose **radius** is no greater than approximately 10^{-14} m.
- Because such small lengths are common in nuclear physics, an often-used convenient length unit is the femtometer (fm), which is sometimes called the **fermi** and is defined as

$$1 \text{ fm} = 10^{-15} \text{ m}$$



Because of the Coulomb repulsion between the charges of the same sign, the alpha particle approaches to a distance *d* from the nucleus, called the distance of closest approach.

Figure 44.1 An alpha particle on a head-on collision course with a nucleus of charge Ze.

The Size and Structure of Nuclei

- 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

$$r = aA^{1/3}$$

- where *a* is a constant equal to 1.2 x 10^{-15} m and *A* is the mass number.

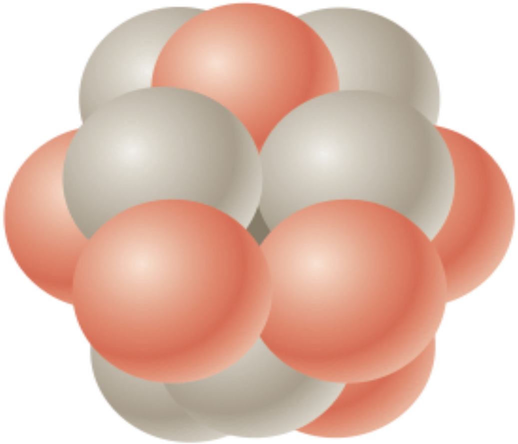


Figure 44.2 A nucleus can be modeled as a cluster of tightly packed spheres, where each sphere is a nucleon.

Example 44.2 The Volume and Density of a Nucleus

Consider a nucleus of mass number A.

(A) Find an approximate expression for the mass of the nucleus.

continued

SOLUTION

Conceptualize Imagine the nucleus to be a collection of protons and neutrons as shown in Figure 44.2. The mass number A counts *both* protons and neutrons.

Categorize Let's assume A is large enough that we can imagine the nucleus to be spherical.

Analyze The mass of the proton is approximately equal to that of the neutron. Therefore, if the mass of one of these particles is m, the mass of the nucleus is approximately Am.

(B) Find an expression for the volume of this nucleus in terms of A.

SOLUTION

Assume the nucleus is spherical and use Equation 44.1:

$$(1)\quad V_{\text{nucleus}} = \tfrac{4}{3}\pi r^3 = \tfrac{4}{3}\pi a^3 A$$

(C) Find a numerical value for the density of this nucleus.

SOLUTION

Use Equation 1.1 and substitute Equation (1):

$$\rho = \frac{m_{\text{nucleus}}}{V_{\text{nucleus}}} = \frac{Am}{\frac{4}{3}\pi a^3 A} = \frac{3m}{4\pi a^3}$$

Substitute numerical values:

$$\rho = \frac{3(1.67 \times 10^{-27}\ \text{kg})}{4\pi(1.2 \times 10^{-15}\ \text{m})^3} = 2.3 \times 10^{17}\ \text{kg/m}^3$$

Finalize The nuclear density is approximately 2.3×10^{14} times the density of water ($\rho_{\text{water}} = 1.0 \times 10^3\ \text{kg/m}^3$).