University of Al-Anbar
College of Applied Sciences-Heet
Biophysics Department

Modern Physics-Fourth Stage

Nuclear Physics

Lecture Five

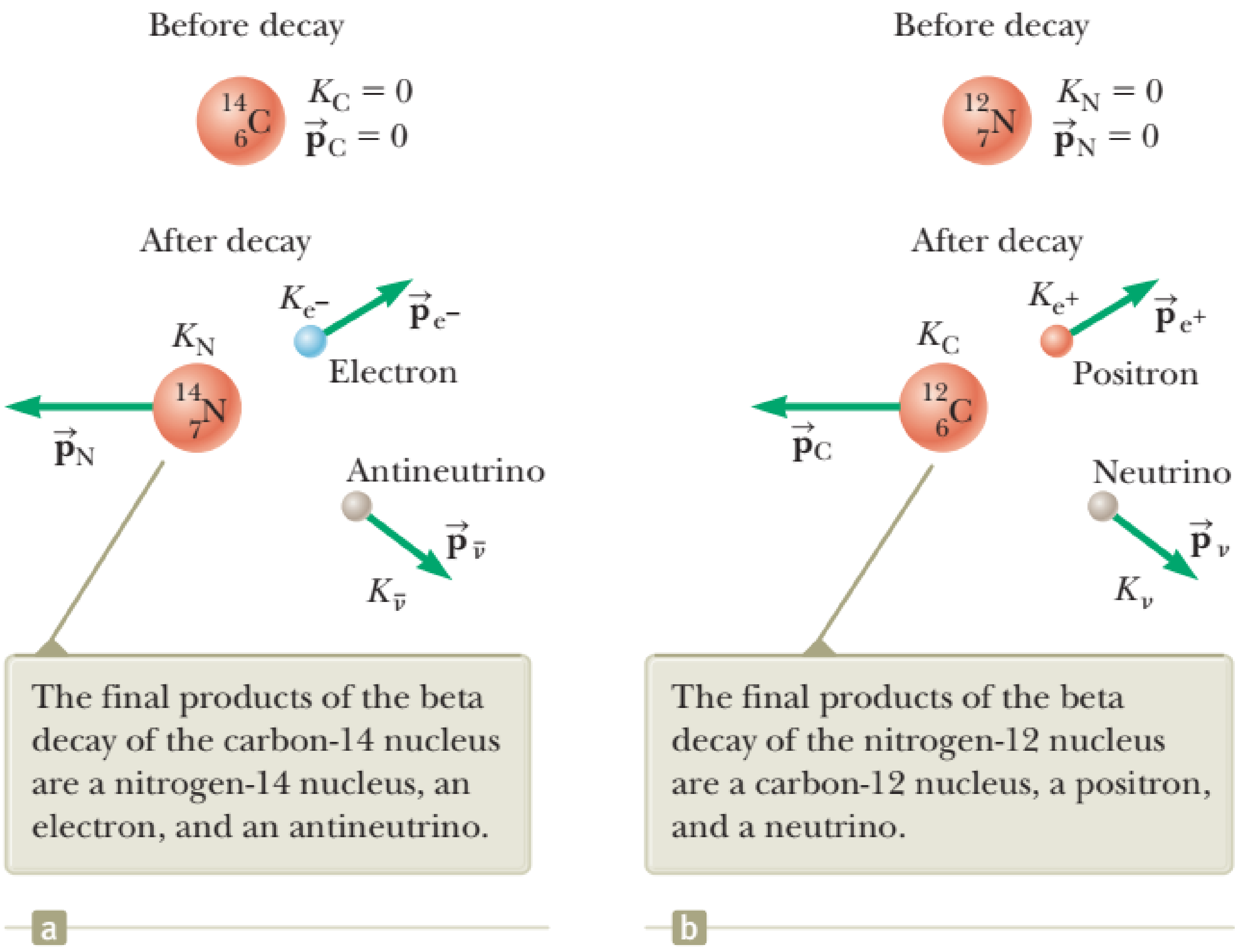
Dr. Nabeel F. Lattoofi

The Decay Processes

Alpha Decay

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu} $$

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



- The disintegration energy Q of the systen

$$ \boxed{Q = (M_X - M_Y - M_\alpha)c^2} $$

$$ \boxed{Q = (M_X - M_Y - M_\alpha) \times 931.494\ \mathrm{MeV/u}} $$

- A typical disintegration energy (Q≈5 MeV) which is the approximate kinetic energy of the alpha particle. In the view of quantum mechanics, there is always some probability that a particle can tunnel through a barrier. the alpha particle tunnels through the barrier.

$$ {}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \bar{\nu} $$

$$ {}^{12}_{7}N \rightarrow {}^{12}_{6}C + e^{+} + \nu $$

Example 44.7 The Energy Liberated When Radium Decays AM

The ^{226}Ra nucleus undergoes alpha decay according to Equation 44.12.

(A) Calculate the Q value for this process. From Table 44.2, the masses are 226.025 410 u for ^{226}Ra, 222.017 578 u for ^{222}Rn, and 4.002 603 u for $^{4}_{2}$He.

SOLUTION

Conceptualize Study Figure 44.12 to understand the process of alpha decay in this nucleus.

Categorize The parent nucleus is an *isolated system* that decays into an alpha particle and a daughter nucleus. The system is isolated in terms of both *energy* and *momentum*.

Analyze Evaluate Q using Equation 44.14:

$$Q = (M_X - M_Y - M_\alpha) \times 931.494 \text{ MeV/u}$$
$$= (226.025\,410 \text{ u} - 222.017\,578 \text{ u} - 4.002\,603 \text{ u}) \times 931.494 \text{ MeV/u}$$
$$= (0.005\,229 \text{ u}) \times 931.494 \text{ MeV/u} = \boxed{4.87 \text{ MeV}}$$

(B) What is the kinetic energy of the alpha particle after the decay?

Analyze The value of 4.87 MeV is the disintegration energy for the decay. It includes the kinetic energy of both the alpha particle and the daughter nucleus after the decay. Therefore, the kinetic energy of the alpha particle would be *less* than 4.87 MeV.

Set up a conservation of momentum equation, noting that the initial momentum of the system is zero:

$$(1)\quad 0 = M_Y v_Y - M_\alpha v_\alpha$$

Set the disintegration energy equal to the sum of the kinetic energies of the alpha particle and the daughter nucleus (assuming the daughter nucleus is left in the ground state):

$$(2)\quad Q = \tfrac{1}{2}M_\alpha {v_\alpha}^2 + \tfrac{1}{2}M_Y {v_Y}^2$$

Solve Equation (1) for v_Y and substitute into Equation (2):

$$Q = \tfrac{1}{2}M_\alpha v_\alpha^{2} + \tfrac{1}{2}M_Y\left(\frac{M_\alpha v_\alpha}{M_Y}\right)^2 = \tfrac{1}{2}M_\alpha v_\alpha^{2}\left(1 + \frac{M_\alpha}{M_Y}\right)$$

$$Q = K_\alpha\left(\frac{M_Y + M_\alpha}{M_Y}\right)$$

Solve for the kinetic energy of the alpha particle:

$$K_\alpha = Q\left(\frac{M_Y}{M_Y + M_\alpha}\right)$$

Evaluate this kinetic energy for the specific decay of ^{226}Ra that we are exploring in this example:

$$K_\alpha = (4.87\text{ MeV})\left(\frac{222}{222 + 4}\right) = \boxed{4.78\text{ MeV}}$$

Finalize The kinetic energy of the alpha particle is indeed less than the disintegration energy, but notice that the alpha particle carries away *most* of the energy available in the decay.

Beta Decay

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 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* is defined in such a way that the mass of one atom of the isotope ^{12}C is exactly 12*u*, where ($1\ u = 1.660539 \times 10^{-27}$ kg) which is equal to the proton or neutron mass.

How six protons and six neutrons, each having a mass larger than 1 u, can be combined with six electrons to form a carbon-12 atom having a mass of exactly 12 u?

The bound system of 12C has a lower rest energy than that of six separate protons and six separate neutrons. According to Equation ($E = mc^2$), this lower rest energy corresponds to a smaller mass for the bound system. The difference in mass accounts for the binding energy when the particles are combined to form the nucleus.

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

Example 44.1 The Atomic Mass Unit

Use Avogadro's number to show that $1\text{ u} = 1.66 \times 10^{-27}$ kg.

SOLUTION

Conceptualize From the definition of the mole given in Section 19.5, we know that exactly 12 g (= 1 mol) of ^{12}C contains Avogadro's number of atoms.

Categorize We evaluate the atomic mass unit that was introduced in this section, so we categorize this example as a substitution problem.

Find the mass m of one ^{12}C atom:

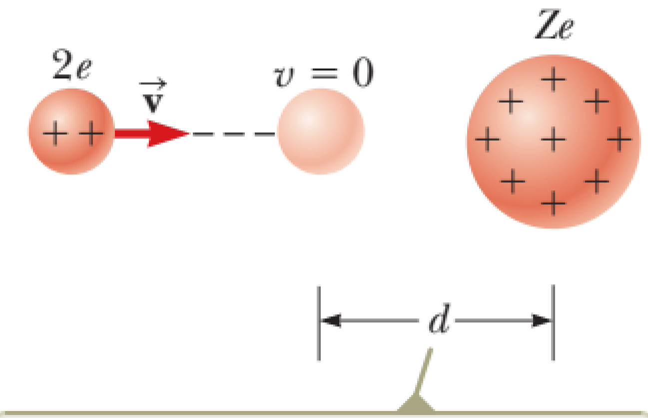
$$m = \frac{0.012\text{ kg}}{6.02 \times 10^{23}\text{ atoms}} = 1.99 \times 10^{-26}\text{ kg}$$

Because one atom of ^{12}C is defined to have a mass of 12.0 u, divide by 12.0 to find the mass equivalent to 1 u:

$$1\text{ u} = \frac{1.99 \times 10^{-26}\text{ kg}}{12.0} = 1.66 \times 10^{-27}\text{ kg}$$

2- The Size and Structure of Nuclei

Rutherford used, in scattering experiment, 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.



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.

$$\Delta K + \Delta U = 0$$

$$\left(0 - \tfrac{1}{2}mv^2\right) + \left(k_e \frac{q_1 q_2}{d} - 0\right) = 0$$

$$d = 2k_e \frac{q_1 q_2}{mv^2} = 2k_e \frac{(2e)(Ze)}{mv^2} = 4k_e \frac{Ze^2}{mv^2}$$

Rutherford found that the alpha particles approached nuclei to within 3.2×10^{-14} m. 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 ($1\ \mathrm{fm} \equiv 10^{-15}\ \mathrm{m}$)

3- the volume and density

In the early 1920s, it was known that the nucleus of an atom contains Z protons and has a mass nearly equivalent to that of A protons, where on average A ~ 2Z for lighter nuclei ($Z \leq 20$) and $A > 2Z$ for heavier nuclei.

To account for the nuclear mass, Rutherford proposed that each nucleus must also contain N-Z neutral particles that he called neutrons. In 1932, British physicist James Chadwick discovered the neutron.

- Other experiments have shown that most nuclei are approximately spherical and have an average radius given by

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

where $a = 1.2\times10^{-15}$ fm

Because the volume of a sphere is proportional to the cube of its radius, it follows that the volume of a nucleus (assumed to be spherical) is directly proportional to A, the total number of nucleons. This proportionality suggests that all nuclei have nearly the same density. When nucleons combine to form a nucleus, they combine as though they were tightly packed spheres.

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

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 $\boxed{Am}$.

(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:

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

(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:

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

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

WHAT IF? What if the Earth could be compressed until it had this density? How large would it be?

Answer Because this density is so large, we predict that an Earth of this density would be very small.

Use Equation 1.1 and the mass of the Earth to find the volume of the compressed Earth:

$$V = \frac{M_E}{\rho} = \frac{5.97 \times 10^{24}\ \text{kg}}{2.3 \times 10^{17}\ \text{kg/m}^3} = 2.6 \times 10^7\ \text{m}^3$$

From this volume, find the radius:

$$V = \tfrac{4}{3}\pi r^3 \rightarrow r = \left(\frac{3V}{4\pi}\right)^{1/3} = \left[\frac{3(2.6 \times 10^7\ \text{m}^3)}{4\pi}\right]^{1/3}$$

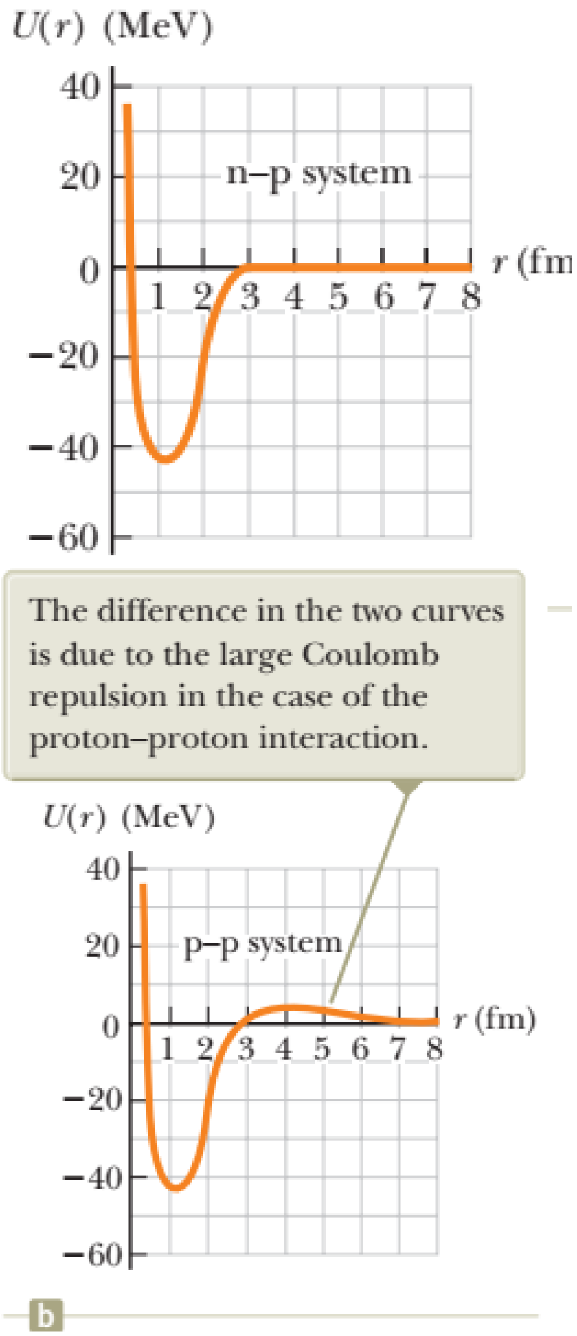
$$r = 1.8 \times 10^2\ \text{m}$$

An Earth of this radius is indeed a small Earth!

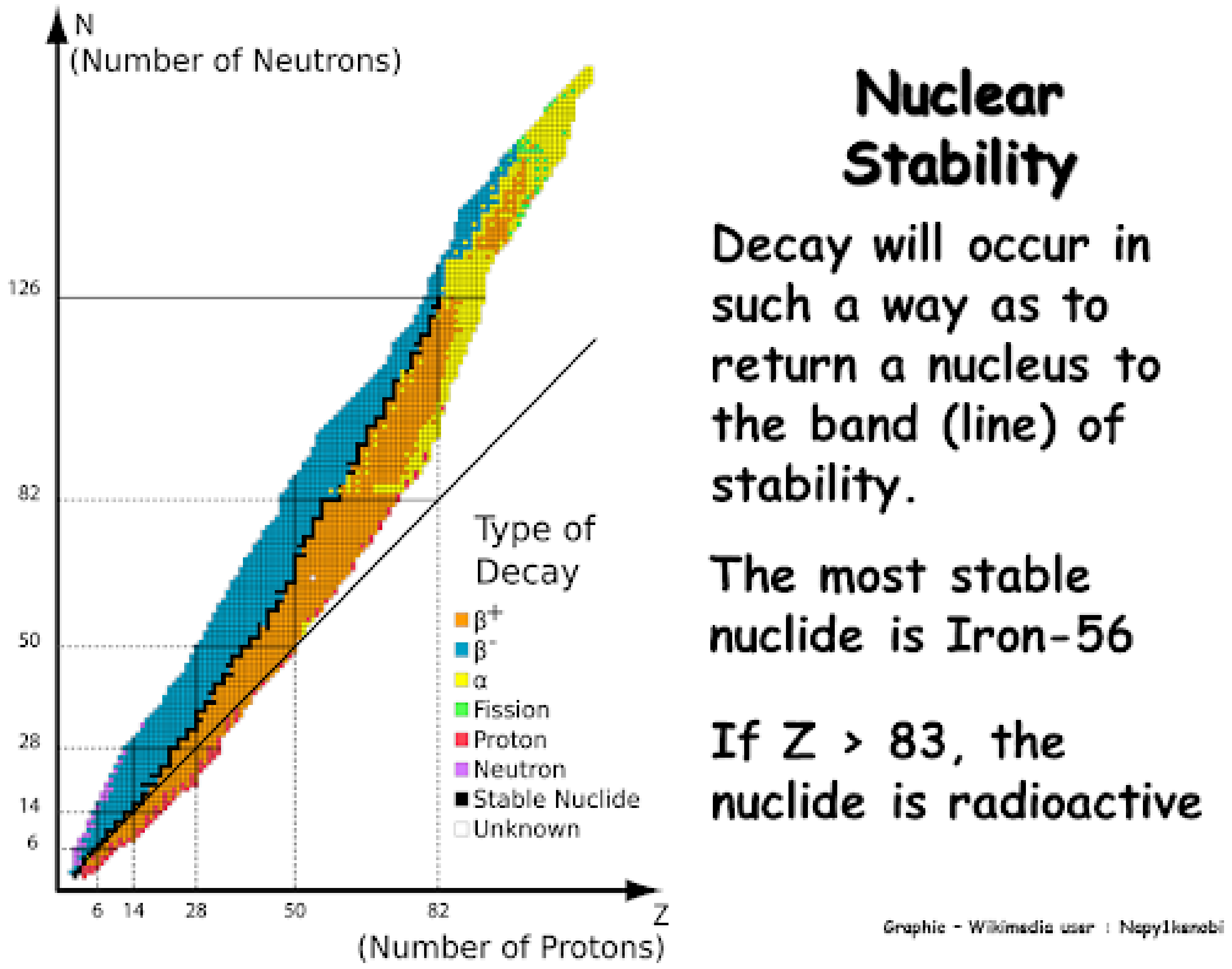
4-Nuclear Stability

- The nuclear force is a very short range (about 2 fm) attractive force that acts between all nuclear particles. The protons attract each other by means of the nuclear force, and, at the same time, they repel each other through the Coulomb force.

The nuclear force is independent of charge. The depth of the n–p potential energy well is 40 to 50 MeV, and there is a strong repulsive component that prevents the nucleons from approaching much closer than 0.4 fm

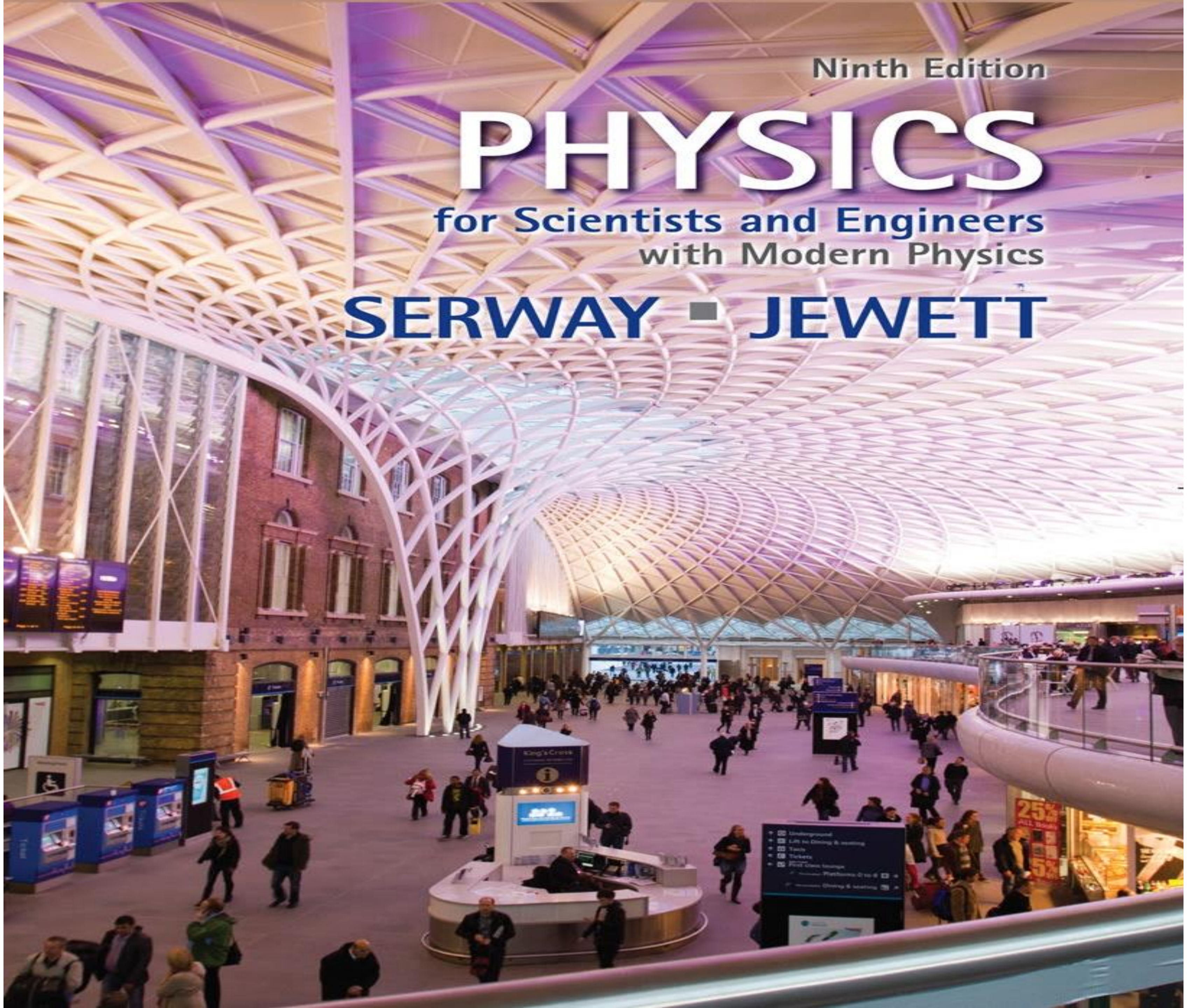


- The existence of the nuclear force results in approximately 270 stable nuclei; hundreds of other nuclei have been observed, but they are unstable. N= Z for light nuclei. Also notice that in heavy stable nuclei, the number of neutrons exceeds the number of protons: above Z=20, the line of stability deviates upward from the line representing N =Z?
- Eventually, the repulsive Coulomb forces between protons cannot be compensated by the addition of more neutrons. This point occurs at Z=83, meaning that elements that contain more than 83 protons do not have stable nuclei.



Thank you
For your Attention

Reference


Ninth Edition
PHYSICS
for Scientists and Engineers
with Modern Physics
SERWAY ▪ JEWETT