Answer to Essential Question 29.8: Beta-minus decay increases the number of protons by 1, without changing the number of nucleons. Thus, beta-minus decay always takes the element one step up the periodic table. In addition to an electron and an anti-neutrino, krypton-85 decays into rubidium-85.

Chapter Summary

Essential Idea: The Nucleus.

Atomic nuclei are almost unimaginably tiny, yet the energy associated with nuclei is orders of magnitude larger than that associated with the electrons in an atom. Nuclear reactions, tapping into the energy of the nucleus, power the Sun (and other stars) as well as nuclear reactors (as well as nuclear bombs).

Holding the nucleus together

To hold a nucleus together, the mutual repulsion between protons in the nucleus is balanced by the nuclear force, which is associated with the interaction between nucleons (neutrons and protons). The nuclear force is a short-range force that is generally attractive.

To find the binding energy for an atom, we first find the mass defect, which is the difference between the total mass of the individual constituents of the atom and the mass of the atom itself. The mass defect is converted to energy via Einstein's famous equation, $E = mc^2$. This results in the mass to energy conversion factor:

1 u is equivalent to 931.5 MeV.

Radioactive decay processes

All radioactive decay processes conserve nucleon number and charge. The general equations describing specific processes are:

$${}^{A}_{Z}X_1 \Rightarrow {}^{A-4}_{Z-2}X_2 + {}^{4}_{2}\text{He}.$$ (Equation 29.3: **General equation for alpha decay**)

$${}^{A}_{Z}X_1 \Rightarrow {}^{A}_{Z+1}X_2 + {}^{0}_{-1}\text{e}^- + \overline{\nu}_e.$$ (Eq. 29.5: **General equation for beta-minus decay**)

$${}^{A}_{Z}X_1 \Rightarrow {}^{A}_{Z-1}X_2 + {}^{0}_{+1}\text{e}^+ + \nu_e.$$ (Eq. 29.7: **General equation for beta-plus decay**)

$${}^{A}_{Z}X_1^* \Rightarrow {}^{A}_{Z}X_1 + \gamma.$$ (Equation 29.9: **General equation for gamma decay**)

In the alpha and beta decay processes, the nucleus becomes a nucleus of a different element. In gamma decay, the nucleus simply drops from a higher-energy state to a lower-energy state, in a manner analogous to that of an electron making a transition from one electron energy level to a lower level. An alpha particle is a helium atom; a beta-minus particle is an electron; and a beta-plus particle is a positron.

Radioactivity

The rate at which N radioactive nuclei decay is:

$$\frac{\Delta N}{\Delta t} = -\lambda N .$$ (Equation 29.10: **Decay rate for radioactive nuclei**)

The equation that describes the exponential decay in the number of nuclei of a particular radioactive isotope as a function of time t is

$N = N_i e^{-\lambda t}$, (Equation 29.12: **The exponential decay of radioactive nuclei**)

where N_i is a measure of the initial number of radioactive nuclei (the number at $t = 0$).

The decay constant, λ, is related to the half-life, $T_{1/2}$, (the time for half of the nuclei to decay) by

$\lambda = \frac{\ln(2)}{T_{1/2}} = \frac{0.693}{T_{1/2}}$. (Eq. 29.11: **The connection between decay constant and half-life**)

Nuclear fusion and nuclear fission

The most stable nuclei (those with the highest average binding energy per nuclei) are nickel-62, iron-58 and iron-56. Nuclei that are lighter than these most stable nuclei can generally become more stable (increasing the average binding energy per nuclei) by joining together with other light nuclei – this process is known as nuclear fusion.

Very heavy nuclei, in contrast, can generally become more stable by splitting apart, usually into two medium-sized nuclei and a few neutrons. This process is known as nuclear fission. The fission of uranium-235, driven by the bombardment of the uranium-235 atoms with neutrons, is exploited in a nuclear reactor to produce nuclear energy, while the fission of plutonium-239 is what drives the explosion of a nuclear bomb.

End-of-Chapter Exercises

Exercises 1 – 12 are mainly conceptual questions that are designed to see if you have understood the main concepts of the chapter.

1. The symbol for the isotope iron-56 is ${}^{56}_{26}\mathrm{Fe}$. A neutral iron-56 atom has how many (a) protons? (b) neutrons? (c) nucleons?

2. Which of these numbers is larger, the mass of an iron-56 atom, or the total mass of the individual constituents (neutrons, protons, and electrons) of an iron-56 atom? Briefly explain your answer.

3. If you could convert 1 kg of matter entirely to energy, how much energy would you get?

4. (a) Fill in the blank to complete this decay process: ${}^{226}_{88}\mathrm{Ra} \Rightarrow \_\_\_ + {}^{4}_{2}\mathrm{He}$. (b) What kind of decay is this? (c) Based on the fact that this decay process happens spontaneously, which side of the equation do you expect to have more mass? Why?

5. (a) What kind of radioactive decay process gives rise to a positron? (b) What is the electric charge of a positron? (c) Complete this sentence: The mass of a positron is the same as the mass of ________________ .

6. Fill in the blanks to complete the following decay processes:
(a) $\_\_\_ \Rightarrow {}^{15}_{7}\mathrm{N} + {}^{0}_{+1}\mathrm{e}^{+} + \nu_e$. (b) ${}^{46}_{21}\mathrm{Sc} \Rightarrow \_\_\_ + {}^{0}_{-1}\mathrm{e}^{-} + \bar{\nu}_e$. (c) ${}^{60}_{28}\mathrm{Ni}^{*} \Rightarrow \_\_\_ + \gamma$.