The Language of Physics

Atomic number Z
The number of protons or electrons in an atom (p. 1004).

Mass number A
The number of protons plus neutrons in the nucleus (p. 1004).

Neutron number N
The number of neutrons in the nucleus. It is equal to the difference between the mass number and the atomic number (p. 1004).

Isotope
An isotope of a chemical element has the same number of protons as the element but a different number of neutrons. An isotope reacts chemically in the same way as the parent element. Its observable difference is its different atomic mass, which comes from the excess or deficiency of neutrons in the nucleus (p. 1004).

Atomic mass
The mass of a chemical element that is listed in the periodic table of the elements. That atomic mass is an average of the masses of its different isotopes (p. 1005).

Strong nuclear force
The force that binds protons and neutrons together in the nucleus. Whenever the nuclear force is less than the electrostatic force, the nucleus breaks up or decays, and emits radioactive particles (p. 1005).

Mass defect
The difference in mass between the sum of the masses of the constituents of a nucleus and the mass of the nucleus (p. 1006).

Binding energy
The energy that binds the nucleus together. It is the mass defect expressed as an energy (p. 1006).

Radioactivity
The spontaneous disintegration of the nuclei of an atom with the emission of α, β, or γ particles (p. 1007).

Activity
The rate at which nuclei decay with time (p. 1007).

Half-life
The time it takes for half the original radioactive nuclei to decay (p. 1008).

Alpha decay
A disintegration of an atomic nucleus whereby an α particle is emitted. The original element of atomic number Z is transmuted into a new chemical element of atomic number $Z - 2$ (p. 1012).

Beta decay, β^-
A nuclear decay whereby a neutron within the nucleus decays into a proton, an electron, and an antineutrino. The proton stays in the nucleus, but the electron and antineutrino are emitted. Thus, the atomic number Z increases by 1, but the mass number A stays the same. Hence, a chemical element Z is transmuted into the element $Z + 1$ (p. 1013).

Beta decay, β^+
A nuclear decay whereby a proton within the nucleus decays into a neutron, a positron, and a neutrino. The positron and neutrino are emitted but the neutron stays behind in the nucleus. The atomic number Z of the element decreases by one because of the loss of the proton. Hence, an element of atomic number Z is converted into the element $Z - 1$ (p. 1014).

Q value of a nuclear reaction
The energy available in a reaction caused by the difference in mass between the reactants and the products (p. 1020).

Exoergic reaction
A nuclear reaction in which energy is released. It is sometimes called an exothermic reaction (p. 1020).

Endoergic reaction
A nuclear reaction in which energy must be added to the system to make the reaction proceed. It is sometimes called an endothermic reaction (p. 1020).

Nuclear fission
The process of splitting a heavy atom into two lighter atoms (p. 1022).

Nuclear fusion
The process in which lighter nuclei are joined together to produce a heavier nucleus with a large amount of energy released (p. 1027).

Nucleosynthesis
The formation of the nuclei of all the chemical elements by the process of fusion within the stars (p. 1029).

Radioactive dating
A technique in which the age of very old objects can be determined by the amount of unstable isotopes still contained in them (p. 1030).

Summary of Important Equations

Neutron number
$$N = A - Z \quad (33.1)$$

Representation of a nucleus
$$^{A}_{Z}X \quad (33.2)$$

Mass defect
$$\Delta m = Zm_p + (A - Z)m_n - m_{\text{nucleus}} \quad (33.3)$$

Binding energy
$$\text{BE} = (\Delta m)c^2 \quad (33.5)$$

Rate of nuclear decay
$$\frac{\Delta N}{\Delta t} = -\lambda N \quad (33.6)$$

Activity
$$A = -\frac{\Delta N}{\Delta t} = \lambda N \quad (33.7)$$

Radioactive decay law
$$N = N_0 e^{-\lambda t} \quad (33.8)$$

Decay constant
$$\lambda = \frac{0.693}{T_{1/2}} \quad (33.11)$$

Alpha decay
$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}\text{He} \quad (33.16)$$

Neutron decay
$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\text{e} + \bar{\nu} \quad (33.19)$$

Beta$^-$ decay
$$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}X + {}^{0}_{-1}\text{e} + \bar{\nu} \quad (33.20)$$

Proton decay
$$^{1}_{1}\text{p} \rightarrow {}^{1}_{0}\text{n} + {}^{0}_{+1}\text{e} + \nu \quad (33.21)$$

Beta$^+$ decay
$$^{A}_{Z}X \rightarrow {}_{Z-1}^{A}X + {}^{0}_{+1}\text{e} + \nu \quad (33.22)$$

Electron capture
$$^{0}_{-1}\text{e} + {}^{1}_{1}\text{p} \rightarrow {}^{1}_{0}\text{n} + \nu \quad (33.23)$$

Electron capture
$$^{0}_{-1}\text{e} + {}^{A}_{Z}X \rightarrow {}_{Z-1}^{A}X + \nu \quad (33.24)$$

Gamma decay
$${}^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma \quad (33.25)$$

Q value of a nuclear reaction
$$Q = (m_x + M_X)c^2 - (m_y + M_Y)c^2 \quad (33.31)$$
$$Q = [(\text{Input mass}) - (\text{Output mass})]c^2 \quad (33.32)$$
$$Q = E_{in} - E_{out} \quad (33.33)$$

General form of equation for nuclear reaction
$$x + X = y + Y + Q \quad (33.34)$$

Nuclear fission of ${}^{235}_{92}U$
$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow y + Y + {}^{1}_{0}n + Q \quad (33.35)$$

Proton-proton cycle of nuclear fusion
$${}^{1}_{1}p + {}^{1}_{1}p \rightarrow {}^{2}_{1}H + {}^{0}_{+1}e + \nu \quad (33.40)$$
$${}^{2}_{1}H + {}^{1}_{1}p \rightarrow {}^{3}_{2}He + \gamma \quad (33.41)$$
$${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2{}^{1}_{1}p \quad (33.42)$$

Radioactive age
$$t = \frac{-\ln(A/A_0)}{\lambda} \quad (33H.2)$$

Questions for Chapter 33

1. What are isotopes? What do they have in common and what are their differences?
2. What is the difference between fast neutrons and slow neutrons, and how do they have an effect on nuclear reactions?
3. What do we mean by the term critical mass?
4. Discuss the advantages and disadvantages of nuclear power compared to the use of fossil-fuel-generated power.
†5. What is a radioactive tracer and how is it used in medicine?
6. Explain the difference between nuclear fission and nuclear fusion.
7. Should an atomic bomb really be called a nuclear bomb?
8. How is the half-life of a radioactive substance related to its activity?
†9. Was the Chernobyl Nuclear Reactor explosion in the Soviet Union a nuclear explosion? Does the fact that the reactor was a breeder reactor, rather than a commercial electricity generator, have anything to do with the severity of the disaster?

Problems for Chapter 33

Section 33.2 Nuclear Structure

1. Find the atomic number, the mass number, and the neutron number for (a) ${}^{58}_{29}Cu$, (b) ${}^{24}_{11}Na$, (c) ${}^{210}_{84}Po$, (d) ${}^{45}_{20}Ca$, and (e) ${}^{206}_{82}Pb$.
2. Determine the number of protons and neutrons in one atom of (a) ${}^{87}_{37}Rb$, (b) ${}^{40}_{19}K$, (c) ${}^{137}_{55}Cs$, (d) ${}^{60}_{27}Co$, and (e) ${}^{131}_{53}I$.
3. Find the number of protons in 1 g of ${}^{40}_{19}K$.
4. ${}^{63}_{29}Cu$ has an atomic mass of 62.929595 u and an abundance of 69.09%, whereas ${}^{65}_{29}Cu$ has an atomic mass of 64.927786 u and an abundance of 30.91%. Find the atomic mass of the element copper.
5. ${}^{107}_{47}Ag$ has an atomic mass of 106.905095 u and an abundance of 51.83%, whereas ${}^{109}_{47}Ag$ has an atomic mass of 108.904754 u and an abundance of 48.17%. Find the atomic mass of the element silver.
6. Find the mass defect and the binding energy for the helium nucleus if the atomic mass of the helium nucleus is 4.0026 u.
7. Find the mass defect and the binding energy for tritium if the atomic mass of tritium is 3.016049 u.
8. How much energy would be released if six hydrogen atoms and six neutrons were combined to form ${}^{12}_{6}C$?

Section 33.3 Radioactive Decay Law

9. ${}^{63}_{28}Ni$ has a half-life of 92 yr. Find its decay constant.
10. ${}^{235}_{92}U$ has a half-life of 7.038×10^8 yr. Find its decay constant.
11. An unknown sample has a decay constant of 2.83×10^{-6} 1/s. Find the half-life of the sample.
12. The decay constant of ${}^{14}_{6}C$ is $\lambda = 3.86 \times 10^{-12}$ s^{-1}. If there are 7.35×10^{90} atoms of carbon fourteen at $t = 0$, how many of them will decay in a time of $t = 2.00 \times 10^{12}$ s?
13. A sample contains 0.200 moles of ${}^{65}_{30}Zn$. If ${}^{65}_{30}Zn$ has a decay constant of 3.27×10^{-8} /s, find the number of ${}^{65}_{30}Zn$ nuclei present at the end of 1 day.
14. One gram of ${}^{87}_{36}Kr$ has a half-life of 78.0 min. How many of these nuclei are still present at the end of 15.0 min?
15. ${}^{60}_{27}Co$ has a half-life of 5.27 yr. How long will it take for 90.0% of the original sample to disintegrate?
16. ${}^{90}_{38}Sr$ has a half-life of 28.8 yr. How long will it take for it to decay to 10.0% of its original value?
17. A dose of 1.85×10^6 Bq of radioactive iodine, ${}^{131}_{53}I$, is used in the treatment of a disorder of the thyroid gland. If its half-life is 8 days, find the activity after (a) 8 days, (b) 16 days, and (c) 32 days.
18. In a given sample of radioactive material, the number of original nuclei drops from 6.00×10^{50} to 1.50×10^{50} in 4.50 s. Find (a) the half-life and (b) the mean lifetime (τ_{avg}) of the material.

Section 33.4 Forms of Radioactivity

19. ${}^{220}_{86}Rn$ decays by alpha emission. What isotope is formed?
20. ${}^{230}_{90}Th$ decays by alpha emission. What isotope is formed?
21. If ${}^{223}U$ decays twice by alpha emission, what is the resulting isotope?
22. ${}^{214}_{84}Po$ decays by β^- decay. What isotope is formed?
23. ${}^{210}_{82}Pb$ decays by β^- decay. What isotope is formed?
24. ${}^{33}_{17}Cl$ decays by β^+ decay. What isotope is formed?
25. ${}^{49}_{24}Cr$ decays by β^+ decay. What isotope is formed?
26. ${}^{41}_{20}Ca$ decays by electron capture. What isotope is formed?
27. ${}^{52}_{25}Mn$ decays by electron capture. What isotope is formed?

Section 33.6 Energy in Nuclear Reactions

28. How much energy is released or absorbed in the following reaction?

$$^{216}_{84}Po \rightarrow ^{212}_{82}Pb + ^{4}_{2}He$$

The atomic mass of $^{216}_{84}Po$ is 216.0019 u, $^{4}_{2}He$ is 4.002603 u, and $^{212}_{82}Pb$ is 211.9919 u.

29. Determine the energy associated with the reactions

$$^{1}_{0}n + ^{1}_{1}p \rightarrow ^{0}_{-1}e + \bar{\nu}$$
$$^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{+1}e + \nu$$

30. Find the Q value associated with the reaction

$$^{1}_{1}H + ^{14}_{7}N \rightarrow ^{15}_{8}O + \nu$$

The atomic mass of $^{14}_{7}N$ is 14.003074 and $^{15}_{8}O$ is 15.003072 u.

31. Find the Q value associated with the reaction

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e + \bar{\nu} + Q$$

32. Find the Q value associated with the nuclear fission reaction

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{132}_{50}Sn + ^{101}_{42}Mo + 3^{1}_{0}n + Q$$

The atomic mass of $^{235}_{92}U$ is 235.043933 u, $^{132}_{50}Sn$ is 49.917756 u, and $^{101}_{42}Mo$ is 41.910346 u.

33. Find the Q value of the fusion reaction

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + Q$$

Additional Problems

†34. A 5.00-g sample of $^{60}_{27}Co$ has a half-life of 5.27 yr. Find (a) the decay constant, (b) the activity of the material when $t = 0$, (c) the activity when $t = 1.00$ yr, and (d) the number of nuclei present after 1.00 yr.

†35. A 5.00-g sample of $^{230}_{90}Th$ has a half-life of 80.0 yr, and a 5.00-g sample of $^{222}_{86}Rn$ has a half-life of 3.82 days. For each sample find (a) the decay constant, (b) the activity of the material when $t = 0$, (c) the activity when $t = 100$ days, (d) the number of nuclei present after 100 days. (e) Comparing the activities and the number of radioactive nuclei remaining at 100 days for the two samples, what can you conclude?

36. If ^{231}Pa decays first by beta decay, and then by alpha emission, what is the resulting isotope?

37. A bone from an animal is found in a very old cave. It is tested in the laboratory and it is found that it has a carbon-14 activity of 13.0 disintegrations per minute. A similar bone from a new animal is tested and found to have an activity of 25.0 disintegrations per minute. What is the age of the bone?

38. A wooden statue is observed to have a carbon fourteen activity of 7.0 disintegrations per minute. How old is the statue? (New wood was found to have an activity of 15.0 disintegrations/min.)

Interactive Tutorials

39. Radioactive decay. A mass of 8.55 g of the isotope $^{90}Sr_{38}$ has a half-life $T_{1/2} = 28.8$ yr. Find (a) the decay constant λ, (b) the number of nuclei N_0 present at the start, (c) the activity A_0 at the start, (d) the number of nuclei N present for $t = T_{1/2}$, (e) the rate of decay of the nuclei at $t = T_{1/2}$, (f) the number of nuclei present for any time t, and (g) the activity at any time t.