Nuclear physics is the study of atomic nuclei. Nuclei contain **protons** and **neutrons**, which are collectively known as **nucleons**. The total number of nucleons, A, is the nucleus's **atomic mass number**. The number of protons, Z, is the **atomic number**. The number of neutrons equals $A - Z$. **Isotopes** are nuclei with the same Z, but with different numbers of neutrons. For an element X, an isotope of given Z and A is represented by

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

The nuclear radius is approximately proportional to $A^{\frac{1}{3}}$, indicating that all nuclei have about the same density. Nuclear masses are specified in **unified atomic mass units** (u), where the mass of $^{12}_{6}\mathrm{C}$ (including its 6 electrons) is defined as exactly 12.000000 u. In terms of the energy equivalent (because $E = mc^2$),

$$1\,\mathrm{u} = 931.5\,\mathrm{MeV}/c^2 = 1.66 \times 10^{-27}\,\mathrm{kg}.$$

The mass of a stable nucleus is less than the sum of the masses of its constituent nucleons. The difference in mass (times c^2) is the **total binding energy**. It represents the energy needed to break the nucleus into its constituent nucleons. The **binding energy per nucleon** averages about 8 MeV per nucleon, and is lowest for low mass and high mass nuclei.

Unstable nuclei undergo **radioactive decay**; they change into other nuclei with the emission of an α, β, or γ particle. An α particle is a $^{4}_{2}\mathrm{He}$ nucleus; a β particle is an electron or positron; and a γ ray is a high-energy photon. In β decay, a **neutrino** is also emitted. The transformation of **parent** nuclei into **daughter** nuclei is called **transmutation** of the elements. Radioactive decay occurs spontaneously only when the mass of the products is less than the mass of the parent nucleus. The loss in mass appears as kinetic energy of the products.

Nuclei are held together by the **strong nuclear force**. The **weak nuclear force** makes itself apparent in β decay. These two forces, plus the gravitational and electromagnetic forces, are the four known types of force.

Electric charge, linear and angular momentum, mass–energy, and **nucleon number** are **conserved** in all decays.

Radioactive decay is a statistical process. For a given type of radioactive nucleus, the number of nuclei that decay (ΔN) in a time Δt is proportional to the number N of parent nuclei present:

$$\Delta N = -\lambda N\,\Delta t; \tag{30–3a}$$

the minus sign means N *decreases* in time.

The proportionality constant λ is called the **decay constant** and is characteristic of the given nucleus. The number N of nuclei remaining after a time t decreases exponentially,

$$N = N_0 e^{-\lambda t}, \tag{30–4}$$

as does the **activity**, R = magnitude of $\Delta N/\Delta t$:

$$R = \left|\frac{\Delta N}{\Delta t}\right|_0 e^{-\lambda t}. \tag{30–5}$$

The **half-life**, $T_{\frac{1}{2}}$, is the time required for half the nuclei of a radioactive sample to decay. It is related to the decay constant by

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda}. \tag{30–6}$$

Radioactive dating is the use of radioactive decay to determine the age of certain objects, such as carbon dating.

[*Alpha decay occurs via a purely quantum-mechanical process called **tunneling** through a barrier.]

Particle **detectors** include **Geiger counters**, **scintillators** with attached **photomultiplier tubes**, and **semiconductor detectors**. Detectors that can image particle tracks include **semiconductors**, photographic **emulsions, bubble chambers**, and **multiwire chambers**.

Questions

1. What do different isotopes of a given element have in common? How are they different?
2. What are the elements represented by the X in the following: (*a*) $^{232}_{92}\mathrm{X}$; (*b*) $^{18}_{7}\mathrm{X}$; (*c*) $^{1}_{1}\mathrm{X}$; (*d*) $^{86}_{38}\mathrm{X}$; (*e*) $^{252}_{100}\mathrm{X}$?
3. How many protons and how many neutrons do each of the isotopes in Question 2 have?
4. Identify the element that has 87 nucleons and 50 neutrons.
5. Why are the atomic masses of many elements (see the Periodic Table) not close to whole numbers?
6. Why are atoms much more likely to emit an alpha particle than to emit separate neutrons and protons?
7. What are the similarities and the differences between the strong nuclear force and the electric force?
8. What is the experimental evidence in favor of radioactivity being a nuclear process?
9. The isotope $^{64}_{29}\mathrm{Cu}$ is unusual in that it can decay by γ, β^-, and β^+ emission. What is the resulting nuclide for each case?
10. A $^{238}_{92}\mathrm{U}$ nucleus decays via α decay to a nucleus containing how many neutrons?
11. Describe, in as many ways as you can, the difference between α, β, and γ rays.
12. Fill in the missing particle or nucleus:
    (*a*) $^{45}_{20}\mathrm{Ca} \rightarrow ? + e^- + \bar{\nu}$
    (*b*) $^{58}_{29}\mathrm{Cu}^* \rightarrow ? + \gamma$
    (*c*) $^{46}_{24}\mathrm{Cr} \rightarrow {}^{46}_{23}\mathrm{V} + ?$
    (*d*) $^{234}_{94}\mathrm{Pu} \rightarrow ? + \alpha$
    (*e*) $^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + ?$
13. Immediately after a $^{238}_{92}\mathrm{U}$ nucleus decays to $^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$, the daughter thorium nucleus may still have 92 electrons circling it. Since thorium normally holds only 90 electrons, what do you suppose happens to the two extra ones?
14. When a nucleus undergoes either β^- or β^+ decay, what happens to the energy levels of the atomic electrons? What is likely to happen to these electrons following the decay?
15. The alpha particles from a given alpha-emitting nuclide are generally monoenergetic; that is, they all have the same kinetic energy. But the beta particles from a beta-emitting nuclide have a spectrum of energies. Explain the difference between these two cases.

16. Do isotopes that undergo electron capture generally lie above or below the stable nuclides in Fig. 30–2?

17. Can hydrogen or deuterium emit an α particle? Explain.

18. Why are many artificially produced radioactive isotopes rare in nature?

19. An isotope has a half-life of one month. After two months, will a given sample of this isotope have completely decayed? If not, how much remains?

20. Why are none of the elements with $Z > 92$ stable?

21. A proton strikes a $^{6}_{3}\text{Li}$ nucleus. As a result, an α particle and another particle are released. What is the other particle?

22. Can $^{14}_{6}\text{C}$ dating be used to measure the age of stone walls and tablets of ancient civilizations? Explain.

23. Explain the absence of β^{+} emitters in the radioactive decay series of Fig. 30–11.

24. As $^{222}_{86}\text{Rn}$ decays into $^{206}_{82}\text{Pb}$, how many alpha and beta particles are emitted? Does it matter which path in the decay series is chosen? Why or why not?

25. A ^{238}U nucleus (initially at rest) decays into a ^{234}Th nucleus and an alpha particle. Which has the greater (i) momentum, (ii) velocity, (iii) kinetic energy? Explain.
    (*a*) The ^{234}Th nucleus.
    (*b*) The alpha particle.
    (*c*) Both the same.

MisConceptual Questions

1. Elements of the Periodic Table are distinguished by
    (*a*) the number of protons in the nucleus.
    (*b*) the number of neutrons in the nucleus.
    (*c*) the number of electrons in the atom.
    (*d*) Both (*a*) and (*b*).
    (*e*) (*a*), (*b*), and (*c*).

2. A nucleus has
    (*a*) more energy than its component neutrons and protons have.
    (*b*) less energy than its component neutrons and protons have.
    (*c*) the same energy as its component neutrons and protons have.
    (*d*) more energy than its component neutrons and protons have when the nucleus is at rest but less energy than when it is moving.

3. Which of the following will generally create a more stable nucleus?
    (*a*) Having more nucleons.
    (*b*) Having more protons than neutrons.
    (*c*) Having a larger binding energy per nucleon.
    (*d*) Having the same number of electrons as protons.
    (*e*) Having a larger total binding energy.

4. There are 82 protons in a lead nucleus. Why doesn't the lead nucleus burst apart?
    (*a*) Coulomb repulsive force doesn't act inside the nucleus.
    (*b*) Gravity overpowers the Coulomb repulsive force inside the nucleus.
    (*c*) The negatively charged neutrons balance the positively charged protons.
    (*d*) Protons lose their positive charge inside the nucleus.
    (*e*) The strong nuclear force holds the nucleus together.

5. The half-life of a radioactive nucleus is
    (*a*) half the time it takes for the entire substance to decay.
    (*b*) the time it takes for half of the substance to decay.
    (*c*) the same as the decay constant.
    (*d*) Both (*a*) and (*b*) (they are the same).
    (*e*) All of the above.

6. As a radioactive sample decays,
    (*a*) the half-life increases.
    (*b*) the half-life decreases.
    (*c*) the activity remains the same.
    (*d*) the number of radioactive nuclei increases.
    (*e*) None of the above.

7. If the half-life of a radioactive sample is 10 years, then it should take _____ years for the sample to decay completely.
    (*a*) 10. (*b*) 20. (*c*) 40.
    (*d*) Cannot be determined.

8. A sample's half-life is 1 day. What fraction of the original sample will have decayed after 3 days?
    (*a*) $\frac{1}{8}$. (*b*) $\frac{1}{4}$. (*c*) $\frac{1}{2}$. (*d*) $\frac{3}{4}$. (*e*) $\frac{7}{8}$. (*f*) All of it.

9. After three half-lives, what fraction of the original radioactive material is left?
    (*a*) None. (*b*) $\frac{1}{16}$. (*c*) $\frac{1}{8}$. (*d*) $\frac{1}{4}$. (*e*) $\frac{3}{4}$. (*f*) $\frac{7}{8}$.

10. Technetium $^{98}_{43}\text{Tc}$ has a half-life of 4.2×10^{6} yr. Strontium $^{90}_{38}\text{Sr}$ has a half-life of 28.79 yr. Which statements are true?
    (*a*) The decay constant of Sr is greater than the decay constant of Tc.
    (*b*) The activity of 100 g of Sr is less than the activity of 100 g of Tc.
    (*c*) The long half-life of Tc means that it decays by alpha decay.
    (*d*) A Tc atom has a higher probability of decaying in 1 yr than a Sr atom.
    (*e*) 28.79 g of Sr has the same activity as 4.2×10^{6} g of Tc.

11. A material having which decay constant would have the shortest half-life?
    (*a*) 100/second.
    (*b*) 5/year.
    (*c*) 8/century.
    (*d*) 10^{9}/day.

12. Uranium-238 decays to lead-206 through a series of
    (*a*) alpha decays.
    (*b*) beta decays.
    (*c*) gamma decays.
    (*d*) some combination of alpha, beta, and gamma decays.

13. Carbon dating is useful only for determining the age of objects less than about _____ years old.
(*a*) 4.5 million.
(*b*) 1.2 million.
(*c*) 600,000.
(*d*) 60,000.
(*e*) 6000.

14. Radon has a half-life of about 1600 years. The Earth is several billion years old, so why do we still find radon on this planet?
(*a*) Ice-age temperatures preserved some of it.
(*b*) Heavier unstable isotopes decay into it.
(*c*) It is created in lightning strikes.
(*d*) It is replenished by cosmic rays.
(*e*) Its half-life has increased over time.
(*f*) Its half-life has decreased over time.

15. How does an atom's nucleus stay together and remain stable?
(*a*) The attractive gravitational force between the protons and neutrons overcomes the repulsive electrostatic force between the protons.
(*b*) Having just the right number of neutrons overcomes the electrostatic force between the protons.
(*c*) A strong covalent bond develops between the neutrons and protons, because they are so close to each other.
(*d*) None of the above.

16. What has greater mass?
(*a*) A neutron and a proton that are far from each other (unbound).
(*b*) A neutron and a proton that are bound together in a hydrogen (deuterium) nucleus.
(*c*) Both the same.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

[See Appendix B for masses]

30–1 Nuclear Properties

1. (I) A pi meson has a mass of 139 MeV/c^2. What is this in atomic mass units?

2. (I) What is the approximate radius of an α particle ($^4_2$He)?

3. (I) By what % is the radius of $^{238}_{92}$U greater than the radius of $^{232}_{92}$U?

4. (II) (*a*) What is the approximate radius of a $^{112}_{48}$Cd nucleus? (*b*) Approximately what is the value of A for a nucleus whose radius is 3.7×10^{-15} m?

5. (II) What is the mass of a bare α particle (without electrons) in MeV/c^2?

6. (II) Suppose two alpha particles were held together so they were just "touching" (use Eq. 30–1). Estimate the electrostatic repulsive force each would exert on the other. What would be the acceleration of an alpha particle subjected to this force?

7. (II) (*a*) What would be the radius of the Earth if it had its actual mass but had the density of nuclei? (*b*) By what factor would the radius of a $^{238}_{92}$U nucleus increase if it had the Earth's density?

8. (II) What stable nucleus has approximately half the radius of a uranium nucleus? [*Hint*: Find A and use Appendix B to get Z.]

9. (II) If an alpha particle were released from rest near the surface of a $^{257}_{100}$Fm nucleus, what would its kinetic energy be when far away?

10. (II) (*a*) What is the fraction of the hydrogen atom's mass ($^1_1$H) that is in the nucleus? (*b*) What is the fraction of the hydrogen atom's volume that is occupied by the nucleus?

11. (II) Approximately how many nucleons are there in a 1.0-kg object? Does it matter what the object is made of? Why or why not?

12. (III) How much kinetic energy, in MeV, must an α particle have to just "touch" the surface of a $^{232}_{92}$U nucleus?

30–2 Binding Energy

13. (I) Estimate the total binding energy for $^{63}_{29}$Cu, using Fig. 30–1.

14. (I) Use Fig. 30–1 to estimate the total binding energy of (*a*) $^{238}_{92}$U, and (*b*) $^{84}_{36}$Kr.

15. (II) Calculate the binding energy per nucleon for a $^{15}_{7}$N nucleus, using Appendix B.

16. (II) Use Appendix B to calculate the binding energy of $^2_1$H (deuterium).

17. (II) Determine the binding energy of the last neutron in a $^{23}_{11}$Na nucleus.

18. (II) Calculate the total binding energy, and the binding energy per nucleon, for (*a*) $^7_3$Li, (*b*) $^{195}_{78}$Pt. Use Appendix B.

19. (II) Compare the average binding energy of a nucleon in $^{23}_{11}$Na to that in $^{24}_{11}$Na, using Appendix B.

20. (III) How much energy is required to remove (*a*) a proton, (*b*) a neutron, from $^{15}_{7}$N? Explain the difference in your answers.

21. (III) (*a*) Show that the nucleus $^8_4$Be (mass = 8.005305 u) is unstable and will decay into two α particles. (*b*) Is $^{12}_{6}$C stable against decay into three α particles? Show why or why not.

30–3 to 30–7 Radioactive Decay

22. (I) The $^7_3$Li nucleus has an excited state 0.48 MeV above the ground state. What wavelength gamma photon is emitted when the nucleus decays from the excited state to the ground state?

23. (II) Show that the decay $^{11}_{6}\text{C} \rightarrow {}^{10}_{5}\text{B} + \text{p}$ is not possible because energy would not be conserved.

24. (II) Calculate the energy released when tritium, $^3_1$H, decays by β^- emission.

25. (II) What is the maximum kinetic energy of an electron emitted in the β decay of a free neutron?

26. (II) Give the result of a calculation that shows whether or not the following decays are possible:
(*a*) $^{233}_{92}\text{U} \rightarrow {}^{232}_{92}\text{U} + \text{n}$;
(*b*) $^{14}_{7}\text{N} \rightarrow {}^{13}_{7}\text{N} + \text{n}$;
(*c*) $^{40}_{19}\text{K} \rightarrow {}^{39}_{19}\text{K} + \text{n}$.

27. (II) $^{24}_{11}$Na is radioactive. (*a*) Is it a β^- or β^+ emitter? (*b*) Write down the decay reaction, and estimate the maximum kinetic energy of the emitted β.

8. (II) A $^{238}_{92}$U nucleus emits an α particle with kinetic energy = 4.20 MeV. (*a*) What is the daughter nucleus, and (*b*) what is the approximate atomic mass (in u) of the daughter atom? Ignore recoil of the daughter nucleus.

29. (II) Calculate the maximum kinetic energy of the β particle emitted during the decay of $^{60}_{27}$Co.

30. (II) How much energy is released in electron capture by beryllium: $^{7}_{4}\mathrm{Be} + e^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu$?

31. (II) The isotope $^{218}_{84}$Po can decay by either α or β^{-} emission. What is the energy release in each case? The mass of $^{218}_{84}$Po is 218.008973 u.

32. (II) A photon with a wavelength of 1.15×10^{-13} m is ejected from an atom. Calculate its energy and explain why it is a γ ray from the nucleus or a photon from the atom.

33. (II) How much recoil energy does a $^{40}_{19}$K nucleus get when it emits a 1.46-MeV gamma ray?

34. (II) Determine the maximum kinetic energy of β^{+} particles released when $^{11}_{6}$C decays to $^{11}_{5}$B. What is the maximum energy the neutrino can have? What is the minimum energy of each?

35. (III) Show that when a nucleus decays by β^{+} decay, the total energy released is equal to

$$(M_{\mathrm{P}} - M_{\mathrm{D}} - 2m_{\mathrm{e}})c^{2},$$

where M_{P} and M_{D} are the masses of the parent and daughter atoms (neutral), and m_{e} is the mass of an electron or positron.

36. (III) When $^{238}_{92}$U decays, the α particle emitted has 4.20 MeV of kinetic energy. Calculate the recoil kinetic energy of the daughter nucleus and the Q-value of the decay.

30–8 to 30–11 Half-Life, Decay Rates, Decay Series, Dating

37. (I) (*a*) What is the decay constant of $^{238}_{92}$U whose half-life is 4.5×10^{9} yr? (*b*) The decay constant of a given nucleus is $3.2 \times 10^{-5}\,\mathrm{s}^{-1}$. What is its half-life?

38. (I) A radioactive material produces 1120 decays per minute at one time, and 3.6 h later produces 140 decays per minute. What is its half-life?

39. (I) What fraction of a sample of $^{68}_{32}$Ge, whose half-life is about 9 months, will remain after 2.5 yr?

40. (I) What is the activity of a sample of $^{14}_{6}$C that contains 6.5×10^{20} nuclei?

41. (I) What fraction of a radioactive sample is left after exactly 5 half-lives?

42. (II) The iodine isotope $^{131}_{53}$I is used in hospitals for diagnosis of thyroid function. If 782 μg are ingested by a patient, determine the activity (*a*) immediately, (*b*) 1.50 h later when the thyroid is being tested, and (*c*) 3.0 months later. Use Appendix B.

43. (II) How many nuclei of $^{238}_{92}$U remain in a rock if the activity registers 420 decays per second?

44. (II) In a series of decays, the nuclide $^{235}_{92}$U becomes $^{207}_{82}$Pb. How many α and β^{-} particles are emitted in this series?

45. (II) $^{124}_{55}$Cs has a half-life of 30.8 s. (*a*) If we have 8.7 μg initially, how many Cs nuclei are present? (*b*) How many are present 2.6 min later? (*c*) What is the activity at this time? (*d*) After how much time will the activity drop to less than about 1 per second?

46. (II) Calculate the mass of a sample of pure $^{40}_{19}$K with an initial decay rate of $2.4 \times 10^{5}\,\mathrm{s}^{-1}$. The half-life of $^{40}_{19}$K is 1.248×10^{9} yr.

47. (II) Calculate the activity of a pure 6.7-μg sample of $^{32}_{15}$P ($T_{\frac{1}{2}} = 1.23 \times 10^{6}$ s).

48. (II) A sample of $^{233}_{92}$U ($T_{\frac{1}{2}} = 1.59 \times 10^{5}$ yr) contains 4.50×10^{18} nuclei. (*a*) What is the decay constant? (*b*) Approximately how many disintegrations will occur per minute?

49. (II) The activity of a sample drops by a factor of 6.0 in 9.4 minutes. What is its half-life?

50. (II) **Rubidium–strontium dating.** The rubidium isotope $^{87}_{37}$Rb, a β emitter with a half-life of 4.75×10^{10} yr, is used to determine the age of rocks and fossils. Rocks containing fossils of ancient animals contain a ratio of $^{87}_{38}$Sr to $^{87}_{37}$Rb of 0.0260. Assuming that there was no $^{87}_{38}$Sr present when the rocks were formed, estimate the age of these fossils.

51. (II) Two of the naturally occurring radioactive decay sequences start with $^{232}_{90}$Th and with $^{235}_{92}$U. The first five decays of these two sequences are:

$$\alpha,\ \beta,\ \beta,\ \alpha,\ \alpha$$

and

$$\alpha,\ \beta,\ \alpha,\ \beta,\ \alpha.$$

Determine the resulting intermediate daughter nuclei in each case.

52. (II) An ancient wooden club is found that contains 73 g of carbon and has an activity of 7.0 decays per second. Determine its age assuming that in living trees the ratio of $^{14}\mathrm{C}/^{12}\mathrm{C}$ atoms is about 1.3×10^{-12}.

53. (II) Use Fig. 30–11 and calculate the relative decay rates for α decay of $^{218}_{84}$Po and $^{214}_{84}$Po.

54. (III) The activity of a radioactive source decreases by 5.5% in 31.0 hours. What is the half-life of this source?

55. (III) $^{7}_{4}$Be decays with a half-life of about 53 d. It is produced in the upper atmosphere, and filters down onto the Earth's surface. If a plant leaf is detected to have 350 decays/s of $^{7}_{4}$Be, (*a*) how long do we have to wait for the decay rate to drop to 25 per second? (*b*) Estimate the initial mass of $^{7}_{4}$Be on the leaf.

56. (III) At $t = 0$, a pure sample of radioactive nuclei contains N_0 nuclei whose decay constant is λ. Determine a formula for the number of daughter nuclei, N_{D}, as a function of time; assume the daughter is stable and that $N_{\mathrm{D}} = 0$ at $t = 0$.

General Problems

57. Which radioactive isotope of lead is being produced if the measured activity of a sample drops to 1.050% of its original activity in 4.00 h?

58. An old wooden tool is found to contain only 4.5% of the $^{14}_{6}\text{C}$ that an equal mass of fresh wood would. How old is the tool?

59. A neutron star consists of neutrons at approximately nuclear density. Estimate, for a 10-km-diameter neutron star, (*a*) its mass number, (*b*) its mass (kg), and (*c*) the acceleration of gravity at its surface.

60. **Tritium dating**. The $^{3}_{1}\text{H}$ isotope of hydrogen, which is called *tritium* (because it contains three nucleons), has a half-life of 12.3 yr. It can be used to measure the age of objects up to about 100 yr. It is produced in the upper atmosphere by cosmic rays and brought to Earth by rain. As an application, determine approximately the age of a bottle of wine whose $^{3}_{1}\text{H}$ radiation is about $\frac{1}{10}$ that present in new wine.

61. Some elementary particle theories (Section 32–11) suggest that the proton may be unstable, with a half-life $\geq 10^{33}$ yr. (*a*) How long would you expect to wait for one proton in your body to decay (approximate your body as all water)? (*b*) Of the roughly 7 billion people on Earth, about how many would have a proton in their body decay in a 70 yr lifetime?

62. How long must you wait (in half-lives) for a radioactive sample to drop to 2.00% of its original activity?

63. If the potassium isotope $^{40}_{19}\text{K}$ gives 42 decays/s in a liter of milk, estimate how much $^{40}_{19}\text{K}$ and regular $^{39}_{19}\text{K}$ are in a liter of milk. Use Appendix B.

64. Strontium-90 is produced as a nuclear fission product of uranium in both reactors and atomic bombs. Look at its location in the Periodic Table to see what other elements it might be similar to chemically, and tell why you think it might be dangerous to ingest. It has too many neutrons to be stable, and it decays with a half-life of about 29 yr. How long will we have to wait for the amount of $^{90}_{38}\text{Sr}$ on the Earth's surface to reach 1% of its current level, assuming no new material is scattered about? Write down the decay reaction, including the daughter nucleus. The daughter is radioactive: write down its decay.

65. The activity of a sample of $^{35}_{16}\text{S}$ $\left(T_{\frac{1}{2}} = 87.37\text{ days}\right)$ is 4.28×10^{4} decays per second. What is the mass of the sample?

66. The nuclide $^{191}_{76}\text{Os}$ decays with β^{-} energy of 0.14 MeV accompanied by γ rays of energy 0.042 MeV and 0.129 MeV. (*a*) What is the daughter nucleus? (*b*) Draw an energy-level diagram showing the ground states of the parent and daughter and excited states of the daughter. (*c*) To which of the daughter states does β^{-} decay of $^{191}_{76}\text{Os}$ occur?

67. Determine the activities of (*a*) 1.0 g of $^{131}_{53}\text{I}$ $\left(T_{\frac{1}{2}} = 8.02\text{ days}\right)$ and (*b*) 1.0 g of $^{238}_{92}\text{U}$ $\left(T_{\frac{1}{2}} = 4.47 \times 10^{9}\text{ yr}\right)$.

68. Use Fig. 30–1 to estimate the total binding energy for copper and then estimate the energy, in joules, needed to break a 3.0-g copper penny into its constituent nucleons.

69. Instead of giving atomic masses for nuclides as in Appendix B, some Tables give the **mass excess**, Δ, defined as $\Delta = M - A$, where A is the atomic mass number and M is the mass in u. Determine the mass excess, in u and in MeV/c^{2}, for: (*a*) $^{4}_{2}\text{He}$; (*b*) $^{12}_{6}\text{C}$; (*c*) $^{86}_{38}\text{Sr}$; (*d*) $^{235}_{92}\text{U}$. (*e*) From a glance at Appendix B, can you make a generalization about the sign of Δ as a function of Z or A?

70. When water is placed near an intense neutron source, the neutrons can be slowed down to almost zero speed by collisions with the water molecules, and are eventually captured by a hydrogen nucleus to form the stable isotope called **deuterium**, $^{2}_{1}\text{H}$, giving off a gamma ray. What is the energy of the gamma ray?

71. The practical limit for carbon-14 dating is about 60,000 years. If a bone contains 1.0 kg of carbon, and the animal died 60,000 years ago, what is the activity today?

72. Using Section 30–2 and Appendix B, determine the energy required to remove one neutron from $^{4}_{2}\text{He}$. How many times greater is this energy than the binding energy of the last neutron in $^{13}_{6}\text{C}$?

73. (*a*) If all of the atoms of the Earth were to collapse and simply become nuclei, what would be the Earth's new radius? (*b*) If all of the atoms of the Sun were to collapse and simply become nuclei, what would be the Sun's new radius?

74. (*a*) A 72-gram sample of natural carbon contains the usual fraction of $^{14}_{6}\text{C}$. Estimate roughly how long it will take before there is only one $^{14}_{6}\text{C}$ nucleus left. (*b*) How does the answer in (*a*) change if the sample is 340 grams? What does this tell you about the limits of carbon dating?

75. If the mass of the proton were just a little closer to the mass of the neutron, the following reaction would be possible even at low collision energies:

$$e^{-} + p \rightarrow n + \nu.$$

(*a*) Why would this situation be catastrophic? (See last paragraph of Chapter 33.) (*b*) By what percentage would the proton's mass have to be increased to make this reaction possible?

76. What is the ratio of the kinetic energies for an alpha particle and a beta particle if both make tracks with the same radius of curvature in a magnetic field, oriented perpendicular to the paths of the particles?

77. Almost all of naturally occurring uranium is $^{238}_{92}\text{U}$ with a half-life of 4.468×10^{9} yr. Most of the rest of natural uranium is $^{235}_{92}\text{U}$ with a half-life of 7.04×10^{8} yr. Today a sample contains 0.720% $^{235}_{92}\text{U}$. (*a*) What was this percentage 1.0 billion years ago? (*b*) What percentage of uranium will be $^{235}_{92}\text{U}$ 100 million years from now?

78. A banana contains about 420 mg of potassium, of which a small fraction is the radioactive isotope ${}^{40}_{19}\mathrm{K}$ (Appendix B). Estimate the activity of an average banana due to ${}^{40}_{19}\mathrm{K}$.

79. When ${}^{23}_{10}\mathrm{Ne}$ (mass = 22.9947 u) decays to ${}^{23}_{11}\mathrm{Na}$ (mass = 22.9898 u), what is the maximum kinetic energy of the emitted electron? What is its minimum energy? What is the energy of the neutrino in each case? Ignore recoil of the daughter nucleus.

80. (*a*) In α decay of, say, a ${}^{226}_{88}\mathrm{Ra}$ nucleus, show that the nucleus carries away a fraction $1/(1 + \frac{1}{4}A_\mathrm{D})$ of the total energy available, where A_D is the mass number of the daughter nucleus. [*Hint*: Use conservation of momentum as well as conservation of energy.] (*b*) Approximately what percentage of the energy available is thus carried off by the α particle when ${}^{226}_{88}\mathrm{Ra}$ decays?

Search and Learn

1. Describe in detail why we think there is a strong nuclear force.

2. (*a*) Under what circumstances could a fermium nucleus decay into an einsteinium nucleus? (*b*) What about the reverse, an Es nucleus decaying into Fm?

3. Using the uncertainty principle and the radius of a nucleus, estimate the minimum possible kinetic energy of a nucleon in, say, iron. Ignore relativistic corrections. [*Hint*: A particle can have a momentum at least as large as its momentum uncertainty.]

4. In Fig. 30–17, a nucleus decays and emits a particle that enters a region with a uniform magnetic field of 0.012 T directed into the page. The path of the detected particle is shown. (*a*) What type of radioactive decay is this? (*b*) If the radius of the circular arc is 4.7 mm, what is the velocity of the particle?

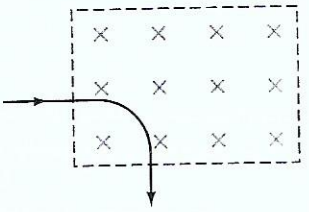

FIGURE 30–17
Search and Learn 4.

5. In both internal conversion and β decay, an electron is emitted. How could you determine which decay process occurred?

6. In 1991, the frozen remains of a Neolithic-age man, nicknamed Otzi, were found in the Italian Alps by hikers. The body was well preserved, as were his bow, arrows, knife, axe, other tools, and clothing. The date of his death can be determined using carbon-14 dating. (*a*) What is the decay constant for ${}^{14}_{6}\mathrm{C}$? (*b*) How many ${}^{14}_{6}\mathrm{C}$ atoms per gram of ${}^{12}_{6}\mathrm{C}$ are there in a living organism? (*c*) What is the activity per gram in naturally occurring carbon for a living organism? (*d*) For Otzi, the activity per gram of carbon was measured to be 0.121. How long ago did he live?

7. Some radioactive isotopes have half-lives that are greater than the age of the universe (like gadolinium or samarium). The only way to determine these half-lives is to monitor the decay rate of a sample that contains these isotopes. For example, suppose we find an asteroid that currently contains about 15,000 kg of ${}^{152}_{64}\mathrm{Gd}$ (gadolinium) and we detect an activity of 1 decay/s. Estimate the half-life of gadolinium (in years).

ANSWERS TO EXERCISES

A: 0.042130 u.
B: 7.98 MeV/nucleon.
C: (*b*) Gd.
D: (*b*) $\frac{1}{8}\,\mu\mathrm{g}$.
E: (*b*) 20 μg.