31.E: Radioactivity and Nuclear Physics (Exercises)

Conceptual Questions

31.1: Nuclear Radioactivity

1. Suppose the range for $5.0 MeV \alpha$ ray is known to be 2.0 mm in a certain material. Does this mean that every $5.0 MeV \alpha$ a ray that strikes this material travels 2.0 mm, or does the range have an average value with some statistical fluctuations in the distances traveled? Explain.

2. What is the difference between γ rays and characteristic x rays? Is either necessarily more energetic than the other? Which can be the most energetic?

3. Ionizing radiation interacts with matter by scattering from electrons and nuclei in the substance. Based on the law of conservation of momentum and energy, explain why electrons tend to absorb more energy than nuclei in these interactions.

4. What characteristics of radioactivity show it to be nuclear in origin and not atomic?

5. What is the source of the energy emitted in radioactive decay? Identify an earlier conservation law, and describe how it was modified to take such processes into account.

6. Consider Figure. If an electric field is substituted for the magnetic field with positive charge instead of the north pole and negative charge instead of the south pole, in which directions will the α, β, and γ rays bend?

7. Explain how an α particle can have a larger range in air than a β particle with the same energy in lead.

8. Arrange the following according to their ability to act as radiation shields, with the best first and worst last. Explain your ordering in terms of how radiation loses its energy in matter.

(a) A solid material with low density composed of low-mass atoms.

(b) A gas composed of high-mass atoms.

(c) A gas composed of low-mass atoms.

(d) A solid with high density composed of high-mass atoms.

9. Often, when people have to work around radioactive materials spills, we see them wearing white coveralls (usually a plastic material). What types of radiation (if any) do you think these suits protect the worker from, and how?

31.2: Radiation Detection and Detectors

10. Is it possible for light emitted by a scintillator to be too low in frequency to be used in a photomultiplier tube? Explain.

31.3: Substructure of the Nucleus

11. The weak and strong nuclear forces are basic to the structure of matter. Why we do not experience them directly?

12. Define and make clear distinctions between the terms neutron, nucleon, nucleus, nuclide, and neutrino.

13. What are isotopes? Why do different isotopes of the same element have similar chemistries?

31.4: Nuclear Decay and Conservation Laws

14. Star Trek fans have often heard the term “antimatter drive.” Describe how you could use a magnetic field to trap antimatter, such as produced by nuclear decay, and later combine it with matter to produce energy. Be specific about the type of antimatter, the need for vacuum storage, and the fraction of matter converted into energy.

15. What conservation law requires an electron’s neutrino to be produced in electron capture? Note that the electron no longer exists after it is captured by the nucleus.

16. Neutrinos are experimentally determined to have an extremely small mass. Huge numbers of neutrinos are created in a supernova at the same time as massive amounts of light are first produced. When the 1987A supernova occurred in the Large Magellanic Cloud, visible primarily in the Southern Hemisphere and some 100,000 light-years away from Earth, neutrinos from the explosion were observed at about the same time as the light from the blast. How could the relative arrival times of neutrinos and light be used to place limits on the mass of neutrinos?

17. What do the three types of beta decay have in common that is distinctly different from alpha decay?

31.5: Half-Life and Activity

18. In a 3×10^9 -year-old rock that originally contained some ^{238}U, which has a half-life of 4.5×10^9 years, we expect to find some ^{238}U remaining in it. Why are ^{226}Ra, ^{222}Rn, and ^{210}Po also found in such a rock, even though they have much shorter half-lives (1600 years, 3.8 days, and 138 days, respectively)?

19. Does the number of radioactive nuclei in a sample decrease to exactly half its original value in one half-life? Explain in terms of the statistical nature of radioactive decay.

20. Radioactivity depends on the nucleus and not the atom or its chemical state. Why, then, is one kilogram of uranium more radioactive than one kilogram of uranium hexafluoride?

21. Explain how a bound system can have less mass than its components. Why is this not observed classically, say for a building made of bricks?

22. Spontaneous radioactive decay occurs only when the decay products have less mass than the parent, and it tends to produce a daughter that is more stable than the parent. Explain how this is related to the fact that more tightly bound nuclei are more stable. (Consider the binding energy per nucleon.)

23. To obtain the most precise value of BE from the equation $BE = [ZM(^1H) + Nm_n]c^2 - m(^AX)c^2$, we should take into account the binding energy of the electrons in the neutral atoms. Will doing this produce a larger or smaller value for BE? Why is this effect usually negligible?

24. How does the finite range of the nuclear force relate to the fact that BE/A is greatest for A near 60?

31.6: Binding Energy

25. Why is the number of neutrons greater than the number of protons in stable nuclei having A greater than about 40, and why is this effect more pronounced for the heaviest nuclei?

31.7: Tunneling

26. A physics student caught breaking conservation laws is imprisoned. She leans against the cell wall hoping to tunnel out quantum mechanically. Explain why her chances are negligible. (This is so in any classical situation.)

27. When a nucleus α decays, does the α particle move continuously from inside the nucleus to outside? That is, does it travel each point along an imaginary line from inside to out? Explain.

Problems & Exercises

31.2: Radiation Detection and Detectors

28. The energy of 30.0 eV is required to ionize a molecule of the gas inside a Geiger tube, thereby producing an ion pair. Suppose a particle of ionizing radiation deposits 0.500 MeV of energy in this Geiger tube. What maximum number of ion pairs can it create?

Solution
1.67×10^4

29. A particle of ionizing radiation creates 4000 ion pairs in the gas inside a Geiger tube as it passes through. What minimum energy was deposited, if 30.0 eV is required to create each ion pair?

30. (a) Repeat Exercise, and convert the energy to joules or calories.

(b) If all of this energy is converted to thermal energy in the gas, what is its temperature increase, assuming $50.0 cm^3$ of ideal gas at 0.250-atm pressure? (The small answer is consistent with the fact that the energy is large on a quantum mechanical scale but small on a macroscopic scale.)

31. Suppose a particle of ionizing radiation deposits 1.0 MeV in the gas of a Geiger tube, all of which goes to creating ion pairs. Each ion pair requires 30.0 eV of energy.

(a) The applied voltage sweeps the ions out of the gas in $1.00 \mu s$. What is the current?

(b) This current is smaller than the actual current since the applied voltage in the Geiger tube accelerates the separated ions, which then create other ion pairs in subsequent collisions. What is the current if this last effect multiplies the number of ion pairs by 900?

31.3: Substructure of the Nucleus

32. Verify that a $2.3 \times 10^{17} kg$ mass of water at normal density would make a cube 60 km on a side, as claimed in Example. (This mass at nuclear density would make a cube 1.0 m on a side.)

Solution

$$m = \rho V = \rho d^3 \Rightarrow = a = (\frac{m}{\rho})^{1/3} = (\frac{2.3 \times 10^{17} kg}{1000 kg/m^3})^{\frac{1}{3}} = 61 \times 10^3 m = 61 km$$

33. Find the length of a side of a cube having a mass of 1.0 kg and the density of nuclear matter, taking this to be $2.3 \times 10^{17} kg/m^3$.

34. What is the radius of an α particle?

Solution

1.9 fm

35. Find the radius of a ^{238}Pu nucleus. ^{238}Pu is a manufactured nuclide that is used as a power source on some space probes.

36. (a) Calculate the radius of ^{58}Ni, one of the most tightly bound stable nuclei.

(b) What is the ratio of the radius of ^{58}Ni to that of ^{258}Ha, one of the largest nuclei ever made? Note that the radius of the largest nucleus is still much smaller than the size of an atom.

Solution

(a) 4.6 fm

(b) 0.61 to 1

37. The unified atomic mass unit is defined to be $1u = 1.6605 \times 10^{-27} kg$. Verify that this amount of mass converted to energy yields 931.5 MeV. Note that you must use four-digit or better values for c and $|q_e|$.

38. What is the ratio of the velocity of a β particle to that of an α particle, if they have the same nonrelativistic kinetic energy?

Solution

85.4 to 1

39. If a 1.50-cm-thick piece of lead can absorb 90.0% of the γ rays from a radioactive source, how many centimeters of lead are needed to absorb all but 0.100% of the γ rays?

40. The detail observable using a probe is limited by its wavelength. Calculate the energy of a γ-ray photon that has a wavelength of $1 \times 10^{-16} m$, small enough to detect details about one-tenth the size of a nucleon. Note that a photon having this energy is difficult to produce and interacts poorly with the nucleus, limiting the practicability of this probe.

Solution

12.4 GeV

41. (a) Show that if you assume the average nucleus is spherical with a radius $r = r_0 A^{1/3}$, and with a mass of A u, then its density is independent of A.

(b) Calculate that density in u/fm^3 and kg/m^3, and compare your results with those found in Example for ^{56}Fe.

42. What is the ratio of the velocity of a 5.00-MeV β ray to that of an α particle with the same kinetic energy? This should confirm that βs travel much faster than αs even when relativity is taken into consideration. (See also Exercise.)

Solution

19.3 to 1

43. (a) What is the kinetic energy in MeV of a β ray that is traveling at $0.998c$? This gives some idea of how energetic a β ray must be to travel at nearly the same speed as a γ ray.

(b) What is the velocity of the γ ray relative to the β ray?

31.4: Nuclear Decay and Conservation Laws

In the following eight problems, write the complete decay equation for the given nuclide in the complete ${}^A_ZX_N$ notation. Refer to the periodic table for values of Z.

44. β^- decay of ${}^3H$ (tritium), a manufactured isotope of hydrogen used in some digital watch displays, and manufactured primarily for use in hydrogen bombs.

Solution
${}^3_1H_2 \rightarrow^3_2 He_1 + \beta^- + \bar{\nu_e}$

45. β^- decay of ${}^{40}K$, a naturally occurring rare isotope of potassium responsible for some of our exposure to background radiation.

46. β^+ decay of ${}^{50}Mn$.

Solution
${}^{50}_{25}M_{25} \rightarrow^{50}_{24} Cr_{26} + \beta^+ + \nu_e$

47. β^+ decay of ${}^{52}Fe$.

48. Electron capture by ${}^7Be$.

Solution
${}^7_4Be_3 + e^- \rightarrow^7_3 Li_4 + \nu_e$

48. Electron capture by ${}^{106}In$.

49. \(\displaystyle α\) decay of ${}^{210}Po$, the isotope of polonium in the decay series of ${}^{238}U$ that was discovered by the Curies. A favorite isotope in physics labs, since it has a short half-life and decays to a stable nuclide.

Solution
${}^{210}_{84}Po_{126} \rightarrow^{206}_{82} Pb_{124} +^4_2 He_2$

50. α decay of ${}^{226}Ra$, another isotope in the decay series of ${}^{238}U$, first recognized as a new element by the Curies. Poses special problems because its daughter is a radioactive noble gas.

In the following four problems, identify the parent nuclide and write the complete decay equation in the ${}^A_ZX_N$ notation. Refer to the periodic table for values of Z.

51. β^- decay producing ${}^{137}Ba$. The parent nuclide is a major waste product of reactors and has chemistry similar to potassium and sodium, resulting in its concentration in your cells if ingested.

Solution
${}^{137}_{55}Cs_{82} \rightarrow^{137}_{56} Ba_{81} + \beta^- + \bar{\nu_e}$

52. β^- decay producing ${}^{90}Y$. The parent nuclide is a major waste product of reactors and has chemistry similar to calcium, so that it is concentrated in bones if ingested (${}^{90}Y$ is also radioactive.)

53. α decay producing ${}^{228}Ra$. The parent nuclide is nearly 100% of the natural element and is found in gas lantern mantles and in metal alloys used in jets (${}^{228}Ra$ is also radioactive).

Solution
${}^{232}_{90}Th_{142} \rightarrow^{228}_{88} Ra_{140} +^4_2 He_2$

54. α decay producing ${}^{208}Pb$. The parent nuclide is in the decay series produced by ${}^{232}Th$, the only naturally occurring isotope of thorium.

55. When an electron and positron annihilate, both their masses are destroyed, creating two equal energy photons to preserve momentum.

(a) Confirm that the annihilation equation $e^+ + e^- \rightarrow \gamma + \gamma$ conserves charge, electron family number, and total number of nucleons. To do this, identify the values of each before and after the annihilation.

(b) Find the energy of each γ ray, assuming the electron and positron are initially nearly at rest.

(c) Explain why the two γ rays travel in exactly opposite directions if the center of mass of the electron-positron system is initially at rest.

Solution

(a) $charge: (+1)+(-1)=0$;electron family number: $(+1)+(-1)=0$; $A: 0+0=0$

(b) 0.511 MeV

(c) The two γ rays must travel in exactly opposite directions in order to conserve momentum, since initially there is zero momentum if the center of mass is initially at rest.

56. Confirm that charge, electron family number, and the total number of nucleons are all conserved by the rule for α decay given in the equation ${}^{A}_{Z}X_N \rightarrow^{A-4}_{Z-2} Y_{N-2} +^{4}_{2} He_2$. To do this, identify the values of each before and after the decay.

57. Confirm that charge, electron family number, and the total number of nucleons are all conserved by the rule for β^- decay given in the equation ${}^{A}_{Z}X_N$ →^A_{Z+1}Y_{N−1}+β^−+\bat{v_e}\). To do this, identify the values of each before and after the decay.

Solution

$Z=(Z+1)-1; A=A; efn: 0=(+1)+(-1)$

58. Confirm that charge, electron family number, and the total number of nucleons are all conserved by the rule for β^- decay given in the equation ${}^{A}_{Z}X_N \rightarrow^{A}_{Z-1} Y_{N-1} + \beta^- + \nu_e$. To do this, identify the values of each before and after the decay.

59. Confirm that charge, electron family number, and the total number of nucleons are all conserved by the rule for electron capture given in the equation ${}^{A}_{Z}X_N + e^- \rightarrow^{A}_{Z-1} Y_{N+1} + \nu_e$. To do this, identify the values of each before and after the capture.

Solution

$Z-1=Z-1; A=A; efn: (+1)=(+1)$

60. A rare decay mode has been observed in which ${}^{222}Ra$ emits a ${}^{14}C$ nucleus.

(a) The decay equation is ${}^{222}Ra \rightarrow^{A} X +^{14} C$. Identify the nuclide ${}^{A}X$.

(b) Find the energy emitted in the decay. The mass of ${}^{222}Ra$ is 222.015353 u.

61. (a) Write the complete α decay equation for ${}^{226}Ra$.

(b) Find the energy released in the decay.

Solution

(a) ${}^{226}_{88}Ra_{138} \rightarrow^{222}_{86} Rn_{136} +^{4}_{2} He_2$

(b) 4.87 MeV

62. (a) Write the complete α decay equation for ${}^{249}Cf$.

(b) Find the energy released in the decay.

63. (a) Write the complete β^- decay equation for the neutron.

(b) Find the energy released in the decay.

Solution

(a) $n \rightarrow p + \beta^- + \bar{\nu}_e$

(b)) 0.783 MeV

64. (a) Write the complete β^- decay equation for ${}^{90}Sr$, a major waste product of nuclear reactors.

(b) Find the energy released in the decay.

65. Calculate the energy released in the β^+ decay of ${}^{22}Na$, the equation for which is given in the text. The masses of ${}^{22}Na$ and ${}^{22}Ne$ are 21.994434 and 21.991383 u, respectively.

Solution

1.82 MeV

66. (a) Write the complete β^+ decay equation for ${}^{11}C$.

(b) Calculate the energy released in the decay. The masses of ^{11}C and ^{11}B are 11.011433 and 11.009305 u, respectively.

67. (a) Calculate the energy released in the α decay of ^{238}U.

(b) What fraction of the mass of a single ^{238}U is destroyed in the decay? The mass of ^{234}Th is 234.043593 u.

(c) Although the fractional mass loss is large for a single nucleus, it is difficult to observe for an entire macroscopic sample of uranium. Why is this?

Solution
(a) 4.274 MeV
(b) 1.927×10^{-5}
(c) Since U-238 is a slowly decaying substance, only a very small number of nuclei decay on human timescales; therefore, although those nuclei that decay lose a noticeable fraction of their mass, the change in the total mass of the sample is not detectable for a macroscopic sample.

68. (a) Write the complete reaction equation for electron capture by ^{7}Be.

(b) Calculate the energy released.

69. (a) Write the complete reaction equation for electron capture by ^{15}O.

(b) Calculate the energy released.

Solution
(a) $^{15}_{8}O_7 + e^- \rightarrow ^{15}_{7} N_8 + \nu_e$
(b) 2.754 MeV

31.5: Half-Life and Activity

Data from the appendices and the periodic table may be needed for these problems.

70. An old campfire is uncovered during an archaeological dig. Its charcoal is found to contain less than 1/1000 the normal amount of ^{14}C. Estimate the minimum age of the charcoal, noting that $2^{10} = 1024$.

Solution
57,300 y

71. A ^{60}Co source is labeled 4.00 mCi, but its present activity is found to be 1.85×10^7 Bq.

(a) What is the present activity in mCi?

(b) How long ago did it actually have a 4.00-mCi activity?

72. (a) Calculate the activity R in curies of 1.00 g of ^{226}Ra.

(b) Discuss why your answer is not exactly 1.00 Ci, given that the curie was originally supposed to be exactly the activity of a gram of radium.

Solution
(a) 0.988 Ci
(b) The half-life of ^{226}Ra is now better known.

73. Show that the activity of the ^{14}C in 1.00 g of ^{12}C found in living tissue is 0.250 Bq.

74. Mantles for gas lanterns contain thorium, because it forms an oxide that can survive being heated to incandescence for long periods of time. Natural thorium is almost 100% ^{232}Th, with a half-life of $1.405 \times 10^{10} y$. If an average lantern mantle contains 300 mg of thorium, what is its activity?

Solution
$1.22 \times 10^3 Bq$

75. Cow's milk produced near nuclear reactors can be tested for as little as 1.00 pCi of ^{131}I per liter, to check for possible reactor leakage. What mass of ^{131}I has this activity?

76. (a) Natural potassium contains ^{40}K, which has a half-life of $1.277 \times 10^{9} y$. What mass of ^{40}K in a person would have a decay rate of 4140 Bq?

(b) What is the fraction of ^{40}K in natural potassium, given that the person has 140 g in his body? (These numbers are typical for a 70-kg adult.)

Solution
(a) 16.0 mg
(b) 0.0114%

77. There is more than one isotope of natural uranium. If a researcher isolates 1.00 mg of the relatively scarce 235U and finds this mass to have an activity of 80.0 Bq, what is its half-life in years?

78. ^{50}V has one of the longest known radioactive half-lives. In a difficult experiment, a researcher found that the activity of 1.00 kg of ^{50}V is 1.75 Bq. What is the half-life in years?

Solution
$1.48 \times 10^{17} y$

79. You can sometimes find deep red crystal vases in antique stores, called uranium glass because their color was produced by doping the glass with uranium. Look up the natural isotopes of uranium and their half-lives, and calculate the activity of such a vase assuming it has 2.00 g of uranium in it. Neglect the activity of any daughter nuclides.

80. A tree falls in a forest. How many years must pass before the ^{14}C activity in 1.00 g of the tree's carbon drops to 1.00 decay per hour?

Solution
$5.6 \times 10^{4} y$

81. What fraction of the ^{40}K that was on Earth when it formed 4.5×10^{9} years ago is left today?

82. A 5000-Ci ^{60}Co source used for cancer therapy is considered too weak to be useful when its activity falls to 3500 Ci. How long after its manufacture does this happen?

Solution
2.71 y

83. Natural uranium is 0.7200% ^{235}U and 99.27% ^{238}U. What were the percentages of ^{235}U and ^{238}U in natural uranium when Earth formed 4.5×10^{9} years ago?

84. The β^{-} particles emitted in the decay of ^{3}H (tritium) interact with matter to create light in a glow-in-the-dark exit sign. At the time of manufacture, such a sign contains 15.0 Ci of ^{3}H.

(a) What is the mass of the tritium?

(b) What is its activity 5.00 y after manufacture?

Solution
(a) 1.56 mg
(b) 11.3 Ci

85. World War II aircraft had instruments with glowing radium-painted dials (see [link]). The activity of one such instrument was $1.0 \times 10^{5} Bq$ when new.

(a) What mass of ^{226}Ra was present?

(b) After some years, the phosphors on the dials deteriorated chemically, but the radium did not escape. What is the activity of this instrument 57.0 years after it was made?

86. (a) The ^{210}Po source used in a physics laboratory is labeled as having an activity of $1.0 \mu Ci$ on the date it was prepared. A student measures the radioactivity of this source with a Geiger counter and observes 1500 counts per minute. She notices that the source was prepared 120 days before her lab. What fraction of the decays is she observing with her apparatus?

(b) Identify some of the reasons that only a fraction of the α s emitted are observed by the detector.

Solution
(a) 1.23×10^{-3}
(b) Only part of the emitted radiation goes in the direction of the detector. Only a fraction of that causes a response in the detector. Some of the emitted radiation (mostly α particles) is observed within the source. Some is absorbed within the source, some is absorbed by the detector, and some does not penetrate the detector.

87. Armor-piercing shells with depleted uranium cores are fired by aircraft at tanks. (The high density of the uranium makes them effective.) The uranium is called depleted because it has had its ^{235}U removed for reactor use and is nearly pure ^{238}U. Depleted uranium has been erroneously called non-radioactive. To demonstrate that this is wrong:

(a) Calculate the activity of 60.0 g of pure ^{238}U.

(b) Calculate the activity of 60.0 g of natural uranium, neglecting the ^{234}U and all daughter nuclides.

88. The ceramic glaze on a red-orange Fiestaware plate is U_2O_3 and contains 50.0 grams of ^{238}U , but very little ^{235}U.

(a) What is the activity of the plate?

(b) Calculate the total energy that will be released by the ^{238}U decay.

(c) If energy is worth 12.0 cents per $kW \cdot h$, what is the monetary value of the energy emitted? (These plates went out of production some 30 years ago, but are still available as collectibles.)

Solution
(a) $1.68 \times 10^{-5} Ci$
(b) $8.65 \times 10^{10} J$
(c) $\$2.9 \times 10^3$

89. Large amounts of depleted uranium (^{238}U) are available as a by-product of uranium processing for reactor fuel and weapons. Uranium is very dense and makes good counter weights for aircraft. Suppose you have a 4000-kg block of ^{238}U.

(a) Find its activity.

(b) How many calories per day are generated by thermalization of the decay energy?

(c) Do you think you could detect this as heat? Explain.

90. The *Galileo* space probe was launched on its long journey past several planets in 1989, with an ultimate goal of Jupiter. Its power source is 11.0 kg of ^{238}Pu, a by-product of nuclear weapons plutonium production. Electrical energy is generated thermoelectrically from the heat produced when the 5.59-MeV α particles emitted in each decay crash to a halt inside the plutonium and its shielding. The half-life of ^{238}Pu is 87.7 years.

(a) What was the original activity of the ^{238}Pu in becquerel?

(b) What power was emitted in kilowatts?

(c) What power was emitted 12.0 y after launch? You may neglect any extra energy from daughter nuclides and any losses from escaping γ rays.

Solution
(a) $6.97 \times 10^{15} Bq$
(b) 6.24 kW
(c) 5.67 kW

91. *Construct Your Own Problem*

Consider the generation of electricity by a radioactive isotope in a space probe, such as described in Exercise. Construct a problem in which you calculate the mass of a radioactive isotope you need in order to supply power for a long space flight. Among the things to consider are the isotope chosen, its half-life and decay energy, the power needs of the probe and the length of the flight.

92. *Unreasonable Results*

A nuclear physicist finds $1.0 \mu g$ of ^{236}U in a piece of uranium ore and assumes it is primordial since its half-life is $2.3 \times 10^7 y$.

(a) Calculate the amount of ^{236}U that would had to have been on Earth when it formed $4.5 \times 10^9 y$ ago for $1.0 \mu g$ to be left today.

(b) What is unreasonable about this result?

(c) What assumption is responsible?

93. *Unreasonable Results*

(a) Repeat Exercise but include the 0.0055% natural abundance of ^{234}U with its $2.45 \times 10^5 y$ half-life.

(b) What is unreasonable about this result?

(c) What assumption is responsible?

(d) Where does the ^{234}U come from if it is not primordial?

94. *Unreasonable Results*

The manufacturer of a smoke alarm decides that the smallest current of α radiation he can detect is $1.00 \mu A$.

(a) Find the activity in curies of an α emitter that produces a $1.00 \mu A$ current of α particles.

(b) What is unreasonable about this result?

(c) What assumption is responsible?

Solution
(a) 84.5 Ci
(b) An extremely large activity, many orders of magnitude greater than permitted for home use.
(c) The assumption of $1.00 \mu A$ is unreasonably large. Other methods can detect much smaller decay rates.

31.6: Binding Energy

95. ^2H is a loosely bound isotope of hydrogen. Called deuterium or heavy hydrogen, it is stable but relatively rare—it is 0.015% of natural hydrogen. Note that deuterium has $Z = N$, which should tend to make it more tightly bound, but both are odd numbers. Calculate BE/A, the binding energy per nucleon, for ^2H and compare it with the approximate value obtained from the graph in Figure.

Solution
1.112 MeV, consistent with graph

96. ^{56}Fe is among the most tightly bound of all nuclides. It is more than 90% of natural iron. Note that ^{56}Fe has even numbers of both protons and neutrons. Calculate BE/A, the binding energy per nucleon, for ^{56}Fe and compare it with the approximate value obtained from the graph in Figure.

97. ^{209}Bi is the heaviest stable nuclide, and its BE/A is low compared with medium-mass nuclides. Calculate BE/A, the binding energy per nucleon, for ^{209}Bi and compare it with the approximate value obtained from the graph in Figure.

Solution
7.848 MeV, consistent with graph

98. (a) Calculate BE/A for ^{235}U, the rarer of the two most common uranium isotopes.

(b) Calculate BE/A for ^{238}U. (Most of uranium is ^{238}U.) Note that ^{238}U has even numbers of both protons and neutrons. Is the BE/A of ^{238}U significantly different from that of ^{235}U?

99. (a) Calculate BE/A for ^{12}C. Stable and relatively tightly bound, this nuclide is most of natural carbon.

(b) Calculate BE/A for ^{14}C. Is the difference in BE/A between ^{12}C and ^{14}C significant? One is stable and common, and the other is unstable and rare.

Solution
(a) 7.680 MeV, consistent with graph
(b) 7.520 MeV, consistent with graph. Not significantly different from value for ^{12}C, but sufficiently lower to allow decay into another nuclide that is more tightly bound.

100. The fact that BE/A is greatest for A near 60 implies that the range of the nuclear force is about the diameter of such nuclides.

(a) Calculate the diameter of an $A = 60$ nucleus.

(b) Compare BE/A for ^{58}Ni and ^{90}Sr. The first is one of the most tightly bound nuclides, while the second is larger and less tightly bound.

101. The purpose of this problem is to show in three ways that the binding energy of the electron in a hydrogen atom is negligible compared with the masses of the proton and electron.

(a) Calculate the mass equivalent in u of the 13.6-eV binding energy of an electron in a hydrogen atom, and compare this with the mass of the hydrogen atom obtained from Appendix A.

(b) Subtract the mass of the proton given in [link] from the mass of the hydrogen atom given in Appendix A. You will find the difference is equal to the electron's mass to three digits, implying the binding energy is small in comparison.

(c) Take the ratio of the binding energy of the electron (13.6 eV) to the energy equivalent of the electron's mass (0.511 MeV).

(d) Discuss how your answers confirm the stated purpose of this problem.

Solution
(a) $1.46 \times 10^{-8} u$ vs. 1.007825 u for ^{1}H
(b) 0.000549 u
(c) 2.66×10^{-5}

102. *Unreasonable Results*

A particle physicist discovers a neutral particle with a mass of 2.02733 u that he assumes is two neutrons bound together.

(a) Find the binding energy.

(b) What is unreasonable about this result?

(c) What assumptions are unreasonable or inconsistent?

Solution
(a) $-9.315 MeV$
(b) The negative binding energy implies an unbound system.
(c) This assumption that it is two bound neutrons is incorrect.

31.7: Tunneling

103. Derive an approximate relationship between the energy of α decay and half-life using the following data. It may be useful to graph the log of $t_{1/2}$ against E_α to find some straight-line relationship.

Energy and Half-Life for α Decay

Nuclide	$E_\alpha (MeV)$	$t_{1/2}$
^{216}Ra	**9.5**	$0.18 \mu s$
^{194}Po	**7.0**	**0.7s**
^{240}Cm	**6.4**	**27 d**
^{226}Ra	**4.91**	**1600 y**
^{232}Th	**4.1**	$1.4 \times 10^{10} y$

104. *Integrated Concepts*

A 2.00-T magnetic field is applied perpendicular to the path of charged particles in a bubble chamber. What is the radius of curvature of the path of a 10 MeV proton in this field? Neglect any slowing along its path.

Solution
22.8 cm

105. (a) Write the decay equation for the α decay of ^{235}U.

(b) What energy is released in this decay? The mass of the daughter nuclide is 231.036298 u.

(c) Assuming the residual nucleus is formed in its ground state, how much energy goes to the α particle?

Solution
(a) $^{235}_{92}U_{143} \rightarrow ^{231}_{90}Th_{141} + ^{4}_{2}He_{2}$
(b) 4.679 MeV
(c) 4.599 MeV

106. *Unreasonable Results*

The relatively scarce naturally occurring calcium isotope ^{48}Ca has a half-life of about $2 \times 10^{16} y$.

(a) A small sample of this isotope is labeled as having an activity of 1.0 Ci. What is the mass of the 48Ca in the sample?

(b) What is unreasonable about this result?

(c) What assumption is responsible?

107. *Unreasonable Results*

A physicist scatters γ rays from a substance and sees evidence of a nucleus $7.5 \times 10^{-13} m$ in radius.

(a) Find the atomic mass of such a nucleus.

(b) What is unreasonable about this result?

(c) What is unreasonable about the assumption?

Solution
(a) $2.4 \times 10^{8} u$
(b) The greatest known atomic masses are about 260. This result found in (a) is extremely large.
(c) The assumed radius is much too large to be reasonable.

108. *Unreasonable Results*

A frazzled theoretical physicist reckons that all conservation laws are obeyed in the decay of a proton into a neutron, positron, and neutrino (as in β^{+} decay of a nucleus) and sends a paper to a journal to announce the reaction as a possible end of the universe due to the spontaneous decay of protons.

(a) What energy is released in this decay?

(b) What is unreasonable about this result?

(c) What assumption is responsible?

Solution
(a) $-1.805 MeV$
(b) Negative energy implies energy input is necessary and the reaction cannot be spontaneous.
(c) Although all conversation laws are obeyed, energy must be supplied, so the assumption of spontaneous decay is incorrect.

109. *Construct Your Own Problem*

Consider the decay of radioactive substances in the Earth's interior. The energy emitted is converted to thermal energy that reaches the earth's surface and is radiated away into cold dark space. Construct a problem in which you estimate the activity in a cubic meter of earth rock? And then calculate the power generated. Calculate how much power must cross each square meter of the Earth's surface if the power is dissipated at the same rate as it is generated. Among the things to consider are the activity per cubic meter, the energy per decay, and the size of the Earth.

Contributors and Attributions

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