10.E: Nuclear Physics (Exercises)

Conceptual Questions

10.1 Properties of Nuclei

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

2. What are isotopes? Why do isotopes of the same atom share the same chemical properties?

10.2 Nuclear Binding Energy

3. Explain why a bound system should have less mass than its components. Why is this not observed traditionally, say, for a building made of bricks?

4. Why is the number of neutrons greater than the number of protons in stable nuclei that have an A greater than about 40? Why is this effect more pronounced for the heaviest nuclei?

5. To obtain the most precise value of the binding energy per nucleon, it is important to take into account forces between nucleons at the surface of the nucleus. Will surface effects increase or decrease estimates of BEN?

10.3 Radioactive Decay

6. How is the initial activity rate of a radioactive substance related to its half-life?

7. For the carbon dating described in this chapter, what important assumption is made about the time variation in the intensity of cosmic rays?

10.4 Nuclear Reactions

8. What is the key difference and the key similarity between beta ($\beta-$) decay and alpha decay?

9. What is the difference between γ rays and characteristic X-rays and visible light?

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

11. Consider Figure 10.12. If the magnetic field is replaced by an electric field pointed in toward the page, in which directions will the $\alpha-$, β^+-, and γ rays bend?

12. Why is Earth's core molten?

10.5 Fission

13. Should an atomic bomb really be called nuclear bomb?

14. Why does a chain reaction occur during a fission reaction?

15. In what way is an atomic nucleus like a liquid drop?

10.6 Nuclear Fusion

16. Explain the difference between nuclear fission and nuclear fusion.

17. Why does the fusion of light nuclei into heavier nuclei release energy?

10.7 Medical Applications and Biological Effects of Nuclear Radiation

18. Why is a PET scan more accurate than a SPECT scan?

19. Isotopes that emit α radiation are relatively safe outside the body and exceptionally hazardous inside. Explain why.

20. Ionizing radiation can impair the ability of a cell to repair DNA. What are the three ways the cell can respond?

Problems

10.1 Properties of Nuclei

21. Find the atomic numbers, mass numbers, and neutron numbers for

(a) $^{58}_{29}Cu$,

(b) ${}^{24}_{11}Na$,

(c) ${}^{210}_{84}Po$,

(d) ${}^{45}_{20}Ca$, and

(e) ${}^{206}_{82}Pb$.

22. Silver has two stable isotopes. The nucleus, ${}^{107}_{47}Ag$, has atomic mass 106.905095 g/mol with an abundance of 51.83; whereas ${}^{109}_{47}Ag$ has atomic mass 108.904754 g/mol with an abundance of $48.17$48.17%. Find the atomic mass of the element silver.

23. The mass (**M**) and the radius (**r**) of a nucleus can be expressed in terms of the mass number, **A**.

(a) Show that the density of a nucleus is independent of **A**.

(b) Calculate the density of a gold (Au) nucleus. Compare your answer to that for iron (Fe).

24. A particle has a mass equal to 10 u. If this mass is converted completely into energy, how much energy is released? Express your answer in mega-electron volts (MeV). (Recall that $1eV = 1.6 \times 10^{-19} J$.)

25. Find the length of a side of a cube having a mass of 1.0 kg and the density of nuclear matter.

26. The detail that you can observe using a probe is limited by its wavelength. Calculate the energy of a particle that has a wavelength of $1 \times 10^{-16} m$, small enough to detect details about one-tenth the size of a nucleon.

10.2 Nuclear Binding Energy

27. How much energy would be released if six hydrogen atoms and six neutrons were combined to form ${}^{12}_{6}C$?

28. Find the mass defect and the binding energy for the helium-4 nucleus.

29. ${}^{56}Fe$ is among the most tightly bound of all nuclides. It makes up more than 90 of natural iron. Note that ${}^{56}Fe$ has even numbers of protons and neutrons. Calculate the binding energy per nucleon for ${}^{56}Fe$ and compare it with the approximate value obtained from the graph in Figure 10.7.

30. ${}^{209}Bi$ is the heaviest stable nuclide, and its BEN is low compared with medium-mass nuclides. Calculate BEN for this nucleus and compare it with the approximate value obtained from the graph in Figure 10.7.

31. (a) Calculate BEN for ${}^{235}U$, the rarer of the two most common uranium isotopes;

(b) Calculate BEN for ${}^{238}U$. (Most of uranium is ${}^{238}U$.)

32. The fact that BEN peaks at roughly $A = 60$ implies that the range of the strong nuclear force is about the diameter of this nucleus.

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

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

10.3 Radioactive Decay

33. A sample of radioactive material is obtained from a very old rock. A plot ln**A** verses t yields a slope value of $-10^{-9} s^{-1}$ (see Figure 10.10(b)). What is the half-life of this material?

34. Show that: $\bar{T} = \dfrac{1}{\lambda}$.

35. The half-life of strontium-91, ${}^{91}_{38}Sr$ is 9.70 h. Find

(a) its decay constant and

(b) for an initial 1.00-g sample, the activity after 15 hours.

36. A sample of pure carbon-14 ($T_{1/2} = 5730y$ has an activity of $1.0\mu Ci$. What is the mass of the sample?

37. A radioactive sample initially contains 2.40×10^{-2} mol of a radioactive material whose half-life is 6.00 h. How many moles of the radioactive material remain after 6.00 h? After 12.0 h? After 36.0 h?

38. 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 $2^{10}=1024$.

39. Calculate the activity R, in curies of 1.00 g of ^{226}Ra.

(b) Explain 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.

40. Natural uranium consists of ^{235}U (**percent abundance=0.7200%**, $\lambda=3.12\times10^{-17}/s$) and ^{238}U (**percent abundance=99.27%**, $\lambda=4.92\times10^{-18}/s$). What were the values for percent abundance of ^{235}U and ^{238}U when Earth formed 4.5×1094.5×109 years ago?

41. World War II aircraft had instruments with glowing radium-painted dials. The activity of one such instrument was 1.0×10^{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?

42. 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?

43. 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 nonradioactive. 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.

10.4 Nuclear Reactions

44. ^{249}Cf undergoes alpha decay.

(a) Write the reaction equation.

(b) Find the energy released in the decay.

45. (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?

46. The $\beta-$ 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?

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

(b) Find the energy released in the decay.

48. Write a nuclear $\beta-$ decay reaction that produces the ^{90}Y nucleus. (**Hint:** 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.)

49. Write the complete decay equation in the complete $^{A}_{Z}X_{N}$ notation for the beta ($\beta-$) decay of ^{3}H (tritium), a manufactured isotope of hydrogen used in some digital watch displays, and manufactured primarily for use in hydrogen bombs.

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

51. An electron can interact with a nucleus through the beta-decay process: ${}_{Z}^{A}X+e^{-}\rightarrow Y+v_{e}$.

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

(b) Calculate the energy released.

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

(b) Calculate the energy released.

53. 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.

10.5 Fission

54. A large power reactor that has been in operation for some months is turned off, but residual activity in the core still produces 150 MW of power. If the average energy per decay of the fission products is 1.00 MeV, what is the core activity?

55. (a) Calculate the energy released in this rare neutron-induced fission $n+^{238}U\rightarrow^{96}Sr+^{140}Xe+3n$, given $m(^{96}Sr)=95.921750u$and $m(^{140}Xe)=139.92164$.

(b) This result is about 6 MeV greater than the result for spontaneous fission. Why? (c) Confirm that the total number of nucleons and total charge are conserved in this reaction.

56. (a) Calculate the energy released in the neutron-induced fission reaction $n+^{235}U\rightarrow^{92}Kr+^{142}Ba+2n$, given $m(^{92}Kr)=91.926269u$and $m(^{142}Ba)=141.916361u$

(b) Confirm that the total number of nucleons and total charge are conserved in this reaction.

57. The electrical power output of a large nuclear reactor facility is 900 MW. It has a 35.0 efficiency in converting nuclear power to electrical power.

(a) What is the thermal nuclear power output in megawatts?

(b) How many ${}^{235}U$ nuclei fission each second, assuming the average fission produces 200 MeV?

(c) What mass of ${}^{235}U$ is fissioned in 1 year of full-power operation?

58. Find the total energy released if 1.00 kg of ${}_{92}^{235}U$ were to undergo fission.

10.6 Nuclear Fusion

59. Verify that the total number of nucleons, and total charge are conserved for each of the following fusion reactions in the proton-proton chain.

(i) ${}^{1}H+^{1}H\rightarrow^{2}H+e^{+}+v_{e}$,

(ii) ${}^{1}H+^{2}H\rightarrow^{3}He+\gamma$, and

(iii) ${}^{3}He+^{3}He\rightarrow^{4}He+^{1}H+^{1}H$. (List the value of each of the conserved quantities before and after each of the reactions.)

60. Calculate the energy output in each of the fusion reactions in the proton-proton chain, and verify the values determined in the preceding problem.

61. Show that the total energy released in the proton-proton chain is 26.7 MeV, considering the overall effect in ${}^{1}H+^{1}H\rightarrow^{2}H+e^{+}+v_{e},^{1}H+^{2}H\rightarrow^{3}He+\gamma$, and ${}^{3}He+^{3}He\rightarrow^{4}He+^{1}H+^{1}H$. Be sure to include the annihilation energy.

62. Two fusion reactions mentioned in the text are $n+^{3}He\rightarrow^{4}He+\gamma$ and $n+^{1}H\rightarrow^{2}H+\gamma$. Both reactions release energy, but the second also creates more fuel. Confirm that the energies produced in the reactions are 20.58 and 2.22 MeV, respectively. Comment on which product nuclide is most tightly bound, ${}^{4}He$ or ${}^{2}H$.

63. The power output of the Sun is $4\times10^{26}W$.

(a) If 90 of this energy is supplied by the proton-proton chain, how many protons are consumed per second?

(b) How many neutrinos per second should there be per square meter at the surface of Earth from this process?

64. Another set of reactions that fuses hydrogen into helium in the Sun and especially in hotter stars is called the CNO cycle:
$^{12}C+^{1}H\rightarrow^{13}N+\gamma^{13}N\rightarrow 13C+e^{+}+v_{e}^{13}C+^{1}H+\gamma^{14}N+^{1}H\rightarrow^{15}O+^{15}N+e^{+}+v_{e}15N+^{1}H\rightarrow 12C$
$+^{4}He$
This process is a "cycle" because ^{12}C appears at the beginning and end of these reactions. Write down the overall effect of this cycle (as done for the proton-proton chain in $2e^{-}+4^{1}H\rightarrow^{4}He+2v_{e}+6\gamma$). Assume that the positrons annihilate electrons to form more γ rays.

65. (a) Calculate the energy released by the fusion of a 1.00-kg mixture of deuterium and tritium, which produces helium. There are equal numbers of deuterium and tritium nuclei in the mixture.

(b) If this process takes place continuously over a period of a year, what is the average power output?

10.7 Medical Applications and Biological Effects of Nuclear Radiation

66. What is the dose in mSv for:

(a) a 0.1-Gy X-ray?

(b) 2.5 mGy of neutron exposure to the eye?

(c) 1.5m Gy of α exposure?

67. Find the radiation dose in Gy for:

(a) A 10-mSv fluoroscopic X-ray series.

(b) 50 mSv of skin exposure by an α emitter.

(c) 160 mSv of $\beta-$ and γ rays from the ^{40}K in your body.

68. Find the mass of ^{239}Pu that has an activity of $1.00\mu Ci$.

69. In the 1980s, the term picowave was used to describe food irradiation in order to overcome public resistance by playing on the well-known safety of microwave radiation. Find the energy in MeV of a photon having a wavelength of a picometer.

70. What is the dose in Sv in a cancer treatment that exposes the patient to 200 Gy of γ rays?

71. One half the γγ rays from ^{99m}Tc are absorbed by a 0.170-mm-thick lead shielding. Half of the γ rays that pass through the first layer of lead are absorbed in a second layer of equal thickness. What thickness of lead will absorb all but one in 1000 of these γ rays?

72. How many Gy of exposure is needed to give a cancerous tumor a dose of 40 Sv if it is exposed to α activity?

73. A plumber at a nuclear power plant receives a whole-body dose of 30 mSv in 15 minutes while repairing a crucial valve. Find the radiation-induced yearly risk of death from cancer and the chance of genetic defect from this maximum allowable exposure.

74. Calculate the dose in rem/y for the lungs of a weapons plant employee who inhales and retains an activity of $1.00\mu Ci$ ^{239}Pu in an accident. The mass of affected lung tissue is 2.00 kg and the plutonium decays by emission of a 5.23-MeV α particle. Assume a RBE value of 20.

Additional Problems

75. The wiki-phony site states that the atomic mass of chlorine is 40 g/mol. Check this result. **Hint:** The two, most common stable isotopes of chlorine are: $^{35}_{17}Cl$ and $^{37}_{17}Cl$. (The abundance of Cl-35 is 75.8, and the abundance of Cl-37 is 24.2.)

76. 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?

77. A nuclear physicist finds $1.0\mu g$ of ^{236}U in a piece of uranium ore ($T_{1/2}=2.348\times 10^{7}y$.

(a) Use the decay law to determine how much ^{236}U would had to have been on Earth when it formed $4.543\times 10^{9}y$ago for 1.0μg1.0μg to be left today.

(b) What is unreasonable about this result?

(c) How is this unreasonable result resolved?

78. A group of scientists use carbon dating to date a piece of wood to be 3 billion years old. Why doesn't this make sense?

79. According to your lab partner, a 2.00-cm-thick sodium-iodide crystal absorbs all but 10 of rays from a radioactive source and a 4.00-cm piece of the same material absorbs all but 5? Is this result reasonable?

80. In the science section of the newspaper, an article reports the efforts of a group of scientists to create a new nuclear reactor based on the fission of iron (Fe). Is this a good idea?

81. 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 brightly-colored ceramic plates went out of production some 30 years ago, but are still available as collectibles.)

82. 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.

83. A piece of wood from an ancient Egyptian tomb is tested for its carbon-14 activity. It is found to have an activity per gram of carbon of $A = 10 decay/min \cdot g$. What is the age of the wood?

Challenge Problems

84. This problem demonstrates that the binding energy of the electron in the ground state of a hydrogen atom is much smaller than the rest mass energies 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 known mass of the hydrogen atom.

(b) Subtract the known mass of the proton from the known mass of the hydrogen atom.

(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.

85. The **Galileo** space probe was launched on its long journey past Venus and Earth 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 becquerels?

(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.

86. Find the energy emitted in the $\beta-$ decay of ^{60}Co.

87. Engineers are frequently called on to inspect and, if necessary, repair equipment in nuclear power plants. Suppose that the city lights go out. After inspecting the nuclear reactor, you find a leaky pipe that leads from the steam generator to turbine chamber.

(a) How do the pressure readings for the turbine chamber and steam condenser compare?

(b) Why is the nuclear reactor not generating electricity?

88. If two nuclei are to fuse in a nuclear reaction, they must be moving fast enough so that the repulsive Coulomb force between them does not prevent them for getting within $R \approx 10^{-14} m$ of one another. At this distance or nearer, the attractive nuclear force can overcome the Coulomb force, and the nuclei are able to fuse.

(a) Find a simple formula that can be used to estimate the minimum kinetic energy the nuclei must have if they are to fuse. To keep the calculation simple, assume the two nuclei are identical and moving toward one another with the same speed **v**.

(b) Use this minimum kinetic energy to estimate the minimum temperature a gas of the nuclei must have before a significant number of them will undergo fusion. Calculate this minimum temperature first for hydrogen and then for helium. (**Hint**: For fusion to occur, the minimum kinetic energy when the nuclei are far apart must be equal to the Coulomb potential energy when they are a distance R apart.)

89. For the reaction, $n + ^3 He \rightarrow ^4 He + \gamma$, find the amount of energy transfers to ^4He and γ (on the right side of the equation). Assume the reactants are initially at rest. (**Hint:** Use conservation of momentum principle.)

90. Engineers are frequently called on to inspect and, if necessary, repair equipment in medical hospitals. Suppose that the PET system malfunctions. After inspecting the unit, you suspect that one of the PET photon detectors is misaligned. To test your theory you position one detector at the location $(r, \theta, \varphi) = (1.5, 45, 30)$ relative to a radioactive test sample at the center of the patient bed.

(a) If the second photon detector is properly aligned where should it be located?

(b) What energy reading is expected?