32.E: Medical Applications of Nuclear Physics (Exercises)

Conceptual Questions

32.1: Medical Imaging and Diagnostics

1. In terms of radiation dose, what is the major difference between medical diagnostic uses of radiation and medical therapeutic uses?

2. One of the methods used to limit radiation dose to the patient in medical imaging is to employ isotopes with short half-lives. How would this limit the dose?

32.2: Biological Effects of Ionizing Radiation

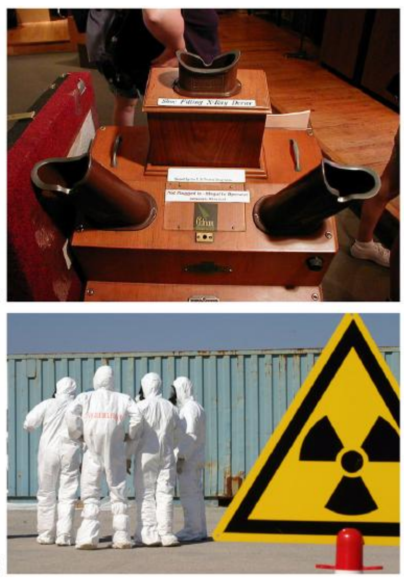
3. Isotopes that emit α radiation are relatively safe outside the body and exceptionally hazardous inside. Yet those that emit γ radiation are hazardous outside and inside. Explain why.

4. Why is radon more closely associated with inducing lung cancer than other types of cancer?

5. The RBE for low-energy βs is 1.7, whereas that for higher-energy βs is only 1. Explain why, considering how the range of radiation depends on its energy.

6. Which methods of radiation protection were used in the device shown in the first photo in Figure? Which were used in the situation shown in the second photo?

(a)
(b)



(a) This x-ray fluorescence machine is one of the thousands used in shoe stores to produce images of feet as a check on the fit of shoes. They are unshielded and remain on as long as the feet are in them, producing doses much greater than medical images. Children were fascinated with them. These machines were used in shoe stores until laws preventing such unwarranted radiation exposure were enacted in the 1950s. (credit: Andrew Kuchling) (b) Now that we know the effects of exposure to radioactive material, safety is a priority. (credit: U.S. Navy)

7. What radioisotope could be a problem in homes built of cinder blocks made from uranium mine tailings? (This is true of homes and schools in certain regions near uranium mines.)

8. Are some types of cancer more sensitive to radiation than others? If so, what makes them more sensitive?

9. Suppose a person swallows some radioactive material by accident. What information is needed to be able to assess possible damage?

32.3: Therapeutic Uses of Ionizing Radiation

10. Radiotherapy is more likely to be used to treat cancer in elderly patients than in young ones. Explain why. Why is radiotherapy used to treat young people at all?

32.4: Food Irradiation

11. Does food irradiation leave the food radioactive? To what extent is the food altered chemically for low and high doses in food irradiation?

12. Compare a low dose of radiation to a human with a low dose of radiation used in food treatment.

13. Suppose one food irradiation plant uses a ^{137}Cs source while another uses an equal activity of ^{60}Co. Assuming equal fractions of the γ rays from the sources are absorbed, why is more time needed to get the same dose using the ^{137}Cs source?

32.5: Fusion

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

15. Energy input is required to fuse medium-mass nuclei, such as iron or cobalt, into more massive nuclei. Explain why.

16. In considering potential fusion reactions, what is the advantage of the reaction $^2H+^3H\rightarrow^4He+n$ over the reaction $^2H+^2H\rightarrow^3He+n$?

17. Give reasons justifying the contention made in the text that energy from the fusion reaction $^2H+^2H\rightarrow^4He+\gamma$ is relatively difficult to capture and utilize.

32.6: Fission

19. Explain why the fission of heavy nuclei releases energy. Similarly, why is it that energy input is required to fission light nuclei?

20. Explain, in terms of conservation of momentum and energy, why collisions of neutrons with protons will thermalize neutrons better than collisions with oxygen.

21. The ruins of the Chernobyl reactor are enclosed in a huge concrete structure built around it after the accident. Some rain penetrates the building in winter, and radioactivity from the building increases. What does this imply is happening inside?

22. Since the uranium or plutonium nucleus fissions into several fission fragments whose mass distribution covers a wide range of pieces, would you expect more residual radioactivity from fission than fusion? Explain.

23. The core of a nuclear reactor generates a large amount of thermal energy from the decay of fission products, even when the power-producing fission chain reaction is turned off. Would this residual heat be greatest after the reactor has run for a long time or short time? What if the reactor has been shut down for months?

24. How can a nuclear reactor contain many critical masses and not go supercritical? What methods are used to control the fission in the reactor?

25. Why can heavy nuclei with odd numbers of neutrons be induced to fission with thermal neutrons, whereas those with even numbers of neutrons require more energy input to induce fission?

26. Why is a conventional fission nuclear reactor not able to explode as a bomb?

32.7: Nuclear Weapons

27. What are some of the reasons that plutonium rather than uranium is used in all fission bombs and as the trigger in all fusion bombs?

28. Use the laws of conservation of momentum and energy to explain how a shape charge can direct most of the energy released in an explosion in a specific direction. (Note that this is similar to the situation in guns and cannons—most of the energy goes into the bullet.)

29. How does the lithium deuteride in the thermonuclear bomb shown in Figure supply tritium (^3H) as well as deuterium (^2H)?

30. Fallout from nuclear weapons tests in the atmosphere is mainly ^{90}Sr and ^{137}Cs, which have 28.6- and 32.2-y half-lives, respectively. Atmospheric tests were terminated in most countries in 1963, although China only did so in 1980. It has been found that environmental activities of these two isotopes are decreasing faster than their half-lives. Why might this be?

Problems & Exercises

32.1: Medical Imaging and Diagnostics

31. A neutron generator uses an α source, such as radium, to bombard beryllium, inducing the reaction ${}^{4}He+{}^{9}Be\rightarrow{}^{12}C+n$. Such neutron sources are called RaBe sources, or PuBe sources if they use plutonium to get the αs. Calculate the energy output of the reaction in MeV.

Solution
5.701 MeV

32. Neutrons from a source (perhaps the one discussed in the preceding problem) bombard natural molybdenum, which is 24 percent ${}^{98}Mo$. What is the energy output of the reaction ${}^{98}Mo+n\rightarrow{}^{99}Mo+\gamma$? The mass of ${}^{98}Mo$ is given in Appendix A: Atomic Masses, and that of \(\displaystyle ^{99}Mo_ is 98.907711 u.

33. The purpose of producing ${}^{99}Mo$ (usually by neutron activation of natural molybdenum, as in the preceding problem) is to produce ${}^{99m}Tc$. Using the rules, verify that the β^{-} decay of ${}^{99}Mo$ produces ${}^{99m}Tc$. (Most ${}^{99m}Tc$ nuclei produced in this decay are left in a metastable excited state denoted ${}^{99m}Tc$.)

Solution
${}^{99}_{42}Mo_{57}\rightarrow{}^{99}_{43}Tc_{56}+\beta^{-}+\bar{v}_e$

34. (a) Two annihilation γ rays in a PET scan originate at the same point and travel to detectors on either side of the patient. If the point of origin is 9.00 cm closer to one of the detectors, what is the difference in arrival times of the photons? (This could be used to give position information, but the time difference is small enough to make it difficult.)

(b) How accurately would you need to be able to measure arrival time differences to get a position resolution of 1.00 mm?

35. Table indicates that 7.50 mCi of ${}^{99m}Tc$ is used in a brain scan. What is the mass of technetium?

Solution
$1.43\times10^{-9}g$

36. The activities of ${}^{131}I$ and ${}^{123}I$ used in thyroid scans are given in Table to be 50 and $70\mu Ci$, respectively. Find and compare the masses of ${}^{131}I$ and ${}^{123}I$ in such scans, given their respective half-lives are 8.04 d and 13.2 h. The masses are so small that the radioiodine is usually mixed with stable iodine as a carrier to ensure normal chemistry and distribution in the body.

37. (a) Neutron activation of sodium, which is 100% ${}^{23}Na$, produces ${}^{24}Na$, which is used in some heart scans, as seen in Table. The equation for the reaction is ${}^{23}Na+n\rightarrow{}^{24}Na+\gamma$. Find its energy output, given the mass of ${}^{24}Na$ is 23.990962 u.

(b) What mass of ${}^{24}Na$ produces the needed 5.0-mCi activity, given its half-life is 15.0 h?

Solution
(a) 6.958 MeV
(b) $5.7\times10^{-10}g$

32.2: Biological Effects of Ionizing Radiation

38. 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) 1.5 mGy of α exposure?

Solution
(a) 100 mSv
(b) 80 mSv
(c) ~30 mSv

39. 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 β^- and γ rays from the ^{40}K in your body.

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

Solution
~2 Gy

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

42. One half the γ 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?

Solution
1.69 mm

43. 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.

44. 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.

Solution
1.24 MeV

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

32.3: Therapeutic Uses of Ionizing Radiation

46. A beam of 168-MeV nitrogen nuclei is used for cancer therapy. If this beam is directed onto a 0.200-kg tumor and gives it a 2.00-Sv dose, how many nitrogen nuclei were stopped? (Use an RBE of 20 for heavy ions.)

Solution
7.44×10^8

47. (a) If the average molecular mass of compounds in food is 50.0 g, how many molecules are there in 1.00 kg of food?

(b) How many ion pairs are created in 1.00 kg of food, if it is exposed to 1000 Sv and it takes 32.0 eV to create an ion pair?

(c) Find the ratio of ion pairs to molecules.

(d) If these ion pairs recombine into a distribution of 2000 new compounds, how many parts per billion is each?

48. Calculate the dose in Sv to the chest of a patient given an x-ray under the following conditions. The x-ray beam intensity is $1.50 W/m^2$, the area of the chest exposed is $0.0750 m^2$, 35.0% of the x-rays are absorbed in 20.0 kg of tissue, and the exposure time is 0.250 s.

Solution
$4.92 \times 10^{-4} Sv$

49. (a) A cancer patient is exposed to γ rays from a 5000-Ci ^{60}Co transillumination unit for 32.0 s. The γ rays are collimated in such a manner that only 1.00% of them strike the patient. Of those, 20.0% are absorbed in a tumor having a mass of 1.50 kg. What is the dose in rem to the tumor, if the average γ energy per decay is 1.25 MeV? None of the β s from the decay reach the patient.

(b) Is the dose consistent with stated therapeutic doses?

50. What is the mass of 60Co in a cancer therapy transillumination unit containing 5.00 kCi of 60Co?

Solution
4.43 g

51. Large amounts of ^{65}Zn are produced in copper exposed to accelerator beams. While machining contaminated copper, a physicist ingests $50.0 \mu Ci$ of ^{65}Zn. Each ^{65}Zn decay emits an average γ-ray energy of 0.550 MeV, 40.0% of which is absorbed in the scientist's 75.0-kg body. What dose in mSv is caused by this in one day?

52. Naturally occurring ^{40}K is listed as responsible for 16 mrem/y of background radiation. Calculate the mass of ^{40}K that must be inside the 55-kg body of a woman to produce this dose. Each ^{40}K decay emits a 1.32-MeV β, and 50% of the energy is absorbed inside the body.

Solution

0.010 g

53. (a) Background radiation due to ^{226}Ra averages only 0.01 mSv/y, but it can range upward depending on where a person lives. Find the mass of ^{226}Ra in the 80.0-kg body of a man who receives a dose of 2.50-mSv/y from it, noting that each ^{226}Ra decay emits a 4.80-MeV α particle. You may neglect dose due to daughters and assume a constant amount, evenly distributed due to balanced ingestion and bodily elimination.

(b) Is it surprising that such a small mass could cause a measurable radiation dose? Explain.

54. The annual radiation dose from ^{14}C in our bodies is 0.01 mSv/y. Each ^{14}C decay emits a β^- averaging 0.0750 MeV. Taking the fraction of ^{14}C to be $1.3 \times 10^{-12} N$ of normal ^{12}C, and assuming the body is 13% carbon, estimate the fraction of the decay energy absorbed. (The rest escapes, exposing those close to you.)

Solution

95%

55. If everyone in Australia received an extra 0.05 mSv per year of radiation, what would be the increase in the number of cancer deaths per year? (Assume that time had elapsed for the effects to become apparent.) Assume that there are 200×10^{-4} deaths per Sv of radiation per year. What percent of the actual number of cancer deaths recorded is this?

32.5: Fusion

56. Verify that the total number of nucleons, total charge, and electron family number are conserved for each of the fusion reactions in the proton-proton cycle in

$$^1H + ^1H \rightarrow ^2H + e^+ + v_e \ ,$$

$$^1H + ^2H \rightarrow ^3He + \gamma \ ,$$

and

$$^3He + ^3He \rightarrow ^4He + ^1H + ^1H \ .$$

(List the value of each of the conserved quantities before and after each of the reactions.)

Solution

(a) $A = 1 + 1 = 2, Z = 1 + 1 = 1 + 1, efn = 0 = -1 + 1$

(b) $A = 1 + 2 = 3, Z = 1 + 1 = 2, efn = 0 = 0$

(c) $A = 3 + 3 = 4 + 1 + 1, Z = 2 + 2 = 2 + 1 + 1, efn = 0 = 0$

57. Calculate the energy output in each of the fusion reactions in the proton-proton cycle, and verify the values given in the above summary.

58. Show that the total energy released in the proton-proton cycle is 26.7 MeV, considering the overall effect in $^1H + ^1H \rightarrow ^2H + e^+ + v_e, ^1H + ^2H \rightarrow ^3He + \gamma$, and $^3He + ^3He \rightarrow ^4He + ^1H + ^1H$ and being certain to include the annihilation energy.

Solution

$E = (m_i - m_f)c^2 = [4m(^1H) - m(^4He)]c^2 = [4(1.007825) - 4.002603](931.5 MeV) = 26.73 MeV$

59. Verify by listing the number of nucleons, total charge, and electron family number before and after the cycle that these quantities are conserved in the overall proton-proton cycle in $2e^- + 4^1H \rightarrow ^4He + 2v_e + 6\gamma$.

60. The energy produced by the fusion of a 1.00-kg mixture of deuterium and tritium was found in Example Calculating Energy and Power from Fusion. Approximately how many kilograms would be required to supply the annual energy use in the United States?

Solution
$3.12 \times 10^5 kg$ (about 200 tons)

61. Tritium is naturally rare, but can be produced by the reaction $n + ^2H \rightarrow ^3H + \gamma$. How much energy in MeV is released in this neutron capture?

62. Two fusion reactions mentioned in the text are

$$n + ^3He \rightarrow ^4He + \gamma$$

and

$$n + ^1H \rightarrow ^2H + \gamma \ .$$

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, ^4He or ^2H.

Solution
$E = (m_i - m_f)c^2$
$E_1 = (1.008665 + 3.016030 - 4.002603)(931.5MeV) = 20.58MeV$
$E_2 = (1.008665 + 1.007825 - 2.014102)(931.5MeV) = 2.224MeV$
^4He is more tightly bound, since this reaction gives off more energy per nucleon.

63. (a) Calculate the number of grams of deuterium in an 80,000-L swimming pool, given deuterium is 0.0150% of natural hydrogen.

(b) Find the energy released in joules if this deuterium is fused via the reaction $^2H + ^2H \rightarrow ^3He + n$.

(c) Could the neutrons be used to create more energy?

(d) Discuss the amount of this type of energy in a swimming pool as compared to that in, say, a gallon of gasoline, also taking into consideration that water is far more abundant.

64. How many kilograms of water are needed to obtain the 198.8 mol of deuterium, assuming that deuterium is 0.01500% (by number) of natural hydrogen?

Solution
$1.19 \times 10^4 kg$

65. The power output of the Sun is $4 \times 10^{26} W$.

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

(b) How many neutrinos per second should there be per square meter at the Earth from this process? This huge number is indicative of how rarely a neutrino interacts, since large detectors observe very few per day.

66. Another set of reactions that result in the fusing of hydrogen into helium in the Sun and especially in hotter stars is called the carbon cycle. It is

$$\begin{gathered} ^{12}C + ^1H \rightarrow ^{13}N + \gamma \ , \\ ^{13}N \rightarrow ^{13}C + e^+ + v_e \ , \\ ^{13}C + ^1H \rightarrow ^{14}N + \gamma \ , \\ ^{14}N + ^1H \rightarrow ^{15}O + \gamma \ , \\ ^{15}O \rightarrow ^{15}N + e^+ + v_e \ , \\ ^{15}N + ^1H \rightarrow ^{12}C + ^4He \ . \end{gathered}$$

Write down the overall effect of the carbon cycle (as was done for the proton-proton cycle in $2e^- + 4^1H \rightarrow ^4He + 2v_e + 6\gamma$). Note the number of protons (^1H) required and assume that the positrons (e^+) annihilate electrons to form more γ rays.

Solution
$2e^- + 4^1H \rightarrow ^4He + 7\gamma + 2v_e$

67. (a) Find the total energy released in MeV in each carbon cycle (elaborated in the above problem) including the annihilation energy.

(b) How does this compare with the proton-proton cycle output?

68. Verify that the total number of nucleons, total charge, and electron family number are conserved for each of the fusion reactions in the carbon cycle given in the above problem. (List the value of each of the conserved quantities before and after each of the reactions.)

Solution
(a) $A=12+1=13, Z=6+1=7, efn=0=0$
(b) $A=13=13, Z=7=6+1, efn=0=-1+1$
(c) $A=13+1=14, Z=6+1=7, efn=0=0$
(d) $A=14+1=15, Z=7+1=8, efn=0=0$
(e) $A=15=15, Z=8=7+1, efn=0=-1+1$
(f) $A=15+1=12+4, Z=7+1=6+2, efn=0=0$

69. *Integrated Concepts*

The laser system tested for inertial confinement can produce a 100-kJ pulse only 1.00 ns in duration.

(a) What is the power output of the laser system during the brief pulse?

(b) How many photons are in the pulse, given their wavelength is $1.06\mu m$?

(c) What is the total momentum of all these photons?

(d) How does the total photon momentum compare with that of a single 1.00 MeV deuterium nucleus?

70. *Integrated Concepts*

Find the amount of energy given to the ^4He nucleus and to the γ ray in the reaction $n+^3He\rightarrow^4He+\gamma$, using the conservation of momentum principle and taking the reactants to be initially at rest. This should confirm the contention that most of the energy goes to the γ ray.

Solution
$E_\gamma=20.6MeV$
$E_{^4He}=5.68\times10^{-2}MeV$

71. *Integrated Concepts*

(a) What temperature gas would have atoms moving fast enough to bring two ^3He nuclei into contact? Note that, because both are moving, the average kinetic energy only needs to be half the electric potential energy of these doubly charged nuclei when just in contact with one another.

(b) Does this high temperature imply practical difficulties for doing this in controlled fusion?

72. *Integrated Concepts*

(a) Estimate the years that the deuterium fuel in the oceans could supply the energy needs of the world. Assume world energy consumption to be ten times that of the United States which is $8\times10^{19}J/y$ and that the deuterium in the oceans could be converted to energy with an efficiency of 32%. You must estimate or look up the amount of water in the oceans and take the deuterium content to be 0.015% of natural hydrogen to find the mass of deuterium available. Note that approximate energy yield of deuterium is $3.37\times10^{14}J/kg$.

(b) Comment on how much time this is by any human measure. (It is not an unreasonable result, only an impressive one.)

Solution
(a) 3×10^9y
(b) This is approximately half the lifetime of the Earth.

73. (a) Calculate the energy released in the neutron-induced fission (similar to the spontaneous fission in Example)

$$n+^{238}U\rightarrow^{96}Sr+^{140}Xe+3n,$$

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.

Solution

(a) 177.1 MeV

(b) Because the gain of an external neutron yields about 6 MeV, which is the average BE/A for heavy nuclei.

(c) $A=1+238=96+140+1+1+1, Z=92=38+53, efn=0=0$

74. (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.

75. (a) Calculate the energy released in the neutron-induced fission reaction

$$n+^{239}Pu\rightarrow^{96}Sr+^{140}Ba+4n,$$

given $m(^{96}Sr)=95.921750u$and $m(^{140}Ba)=139.910581u$.

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

Solution

(a) 180.6 MeV

(b) $A=1+239=96+140+1+1+1+1, Z=94=38+56, efn=0=0$

76. Confirm that each of the reactions listed for plutonium breeding just following Example conserves the total number of nucleons, the total charge, and electron family number.

77. Breeding plutonium produces energy even before any plutonium is fissioned. (The primary purpose of the four nuclear reactors at Chernobyl was breeding plutonium for weapons. Electrical power was a by-product used by the civilian population.) Calculate the energy produced in each of the reactions listed for plutonium breeding just following Example. The pertinent masses are $m(^{239}U)=239.054289u$, $m(^{239}Np)=239.052932u$, and $m(^{239}Pu)=239.052157u$.

Solution

$^{238}U+n\rightarrow^{239}U+\gamma 4.81MeV$

$^{239}U\rightarrow^{239}Np+\beta^-+v_e 0.753MeV$

$^{239}Np\rightarrow^{239}Pu+\beta^-+v_e 0.211MeV$

78. The naturally occurring radioactive isotope ^{232}Th does not make good fission fuel, because it has an even number of neutrons; however, it can be bred into a suitable fuel (much as ^{238}U is bred into ^{239}P).

(a) What are Z and N for ^{232}Th?

(b) Write the reaction equation for neutron captured by ^{232}Th and identify the nuclide ^AX produced in $n+^{232}Th\rightarrow^{A}X+\gamma$.

(c) The product nucleus β− decays, as does its daughter. Write the decay equations for each, and identify the final nucleus.

(d) Confirm that the final nucleus has an odd number of neutrons, making it a better fission fuel.

(e) Look up the half-life of the final nucleus to see if it lives long enough to be a useful fuel.

79. 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.

(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 one year of full-power operation?

Solution
(a) $2.57 \times 10^3 MW$
(b) 8.03×10^{19} fission/s
(c) 991 kg

80. 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 in curies?

32.7: Nuclear Weapons

81. Find the mass converted into energy by a 12.0-kT bomb.

Solution
0.56 g

82. What mass is converted into energy by a 1.00-MT bomb?

83. Fusion bombs use neutrons from their fission trigger to create tritium fuel in the reaction $n +^6 Li \rightarrow^3 H +^4 He$. What is the energy released by this reaction in MeV?

Solution
4.781 MeV

84. It is estimated that the total explosive yield of all the nuclear bombs in existence currently is about 4,000 MT.

(a) Convert this amount of energy to kilowatt-hours, noting that $1kW \cdot h = 3.60 \times 10^6 J$.

(b) What would the monetary value of this energy be if it could be converted to electricity costing 10 cents per kW·h?

85. A radiation-enhanced nuclear weapon (or neutron bomb) can have a smaller total yield and still produce more prompt radiation than a conventional nuclear bomb. This allows the use of neutron bombs to kill nearby advancing enemy forces with radiation without blowing up your own forces with the blast. For a 0.500-kT radiation-enhanced weapon and a 1.00-kT conventional nuclear bomb: (a) Compare the blast yields. (b) Compare the prompt radiation yields.

Solution
(a) Blast yields $2.1 \times 10^{12} J$ to $8.4 \times 10^{11} J$, or 2.5 to 1, conventional to radiation enhanced.
(b) Prompt radiation yields $6.3 \times 10^{11} J$ to $2.1 \times 10^{11} J$, or 3 to 1, radiation enhanced to conventional.

86. (a) How many ^{239}Pu nuclei must fission to produce a 20.0-kT yield, assuming 200 MeV per fission?

(b) What is the mass of this much ^{239}Pu?

87. Assume one-fourth of the yield of a typical 320-kT strategic bomb comes from fission reactions averaging 200 MeV and the remainder from fusion reactions averaging 20 MeV.

(a) Calculate the number of fissions and the approximate mass of uranium and plutonium fissioned, taking the average atomic mass to be 238.

(b) Find the number of fusions and calculate the approximate mass of fusion fuel, assuming an average total atomic mass of the two nuclei in each reaction to be 5.

(c) Considering the masses found, does it seem reasonable that some missiles could carry 10 warheads? Discuss, noting that the nuclear fuel is only a part of the mass of a warhead.

Solution
(a) 1.1×10^{25} fissions , 4.4 kg
(b) 3.2×10^{26} fusions , 2.7 kg
(c) The nuclear fuel totals only 6 kg, so it is quite reasonable that some missiles carry 10 overheads. The mass of the fuel would only be 60 kg and therefore the mass of the 10 warheads, weighing about 10 times the nuclear fuel, would

be only 1500 lbs. If the fuel for the missiles weighs 5 times the total weight of the warheads, the missile would weigh about 9000 lbs or 4.5 tons. This is not an unreasonable weight for a missile.

88. This problem gives some idea of the magnitude of the energy yield of a small tactical bomb. Assume that half the energy of a 1.00-kT nuclear depth charge set off under an aircraft carrier goes into lifting it out of the water—that is, into gravitational potential energy. How high is the carrier lifted if its mass is 90,000 tons?

89. It is estimated that weapons tests in the atmosphere have deposited approximately 9 MCi of ^{90}Sr on the surface of the earth. Find the mass of this amount of ^{90}Sr.

Solution

$7 \times 10^4 g$

90. A 1.00-MT bomb exploded a few kilometers above the ground deposits 25.0% of its energy into radiant heat.

(a) Find the calories per cm^2 at a distance of 10.0 km by assuming a uniform distribution over a spherical surface of that radius.

(b) If this heat falls on a person's body, what temperature increase does it cause in the affected tissue, assuming it is absorbed in a layer 1.00-cm deep?

91. *Integrated Concepts*

One scheme to put nuclear weapons to nonmilitary use is to explode them underground in a geologically stable region and extract the geothermal energy for electricity production. There was a total yield of about 4,000 MT in the combined arsenals in 2006. If 1.00 MT per day could be converted to electricity with an efficiency of 10.0%:

(a) What would the average electrical power output be?

(b) How many years would the arsenal last at this rate?

Solution

(a) $4.86 \times 10^9 W$

(b) 11.0 y

Contributors and Attributions

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