Part I
Radiation Protection Fundamentals

Basic Health Physics. Problems and Solutions. Second Ed. Joseph John Bevelacqua

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Introduction

A basic course in health physics is by its very nature a broad endeavor. Relevant topics necessarily include basic physical science (atomic and nuclear physics, radioactivity, and interactions of radiation with matter), basic radiation protection (standards, regulations, biological effects, instrumentation, internal and external dosimetry, and statistics), applications, and the specialty areas of health physics.

A number of excellent health physics and introductory physics texts treat basic science in hundreds of pages. This book builds on these basic physical science topics, so we will not repeat a basic science discussion here. Instead, we will refer the reader to the texts listed in the References to this chapter for a discussion of underlying concepts. We will, however, provide a set of problems with worked examples and several appendixes to illustrate the basic concepts. A thorough review of this material will permit the reader to assess his or her knowledge of the basic science that underlies the health physics principles and practices that will be presented in this book.

1.1
Questions

1-001. The number of states available in a shell with principal quantum number n is
- **a.** $n + 2$
- **b.** $2\,n$
- **c.** $2\,n + 2$
- **d.** n^2
- **e.** $2\,n^2$

1-002. The radius of a superheavy nucleus of mass 1000 is about
- **a.** 0.01 fm
- **b.** 0.1 fm
- **c.** 1.0 fm
- **d.** 10 fm
- **e.** 100 fm

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1-003. The wavelength (λ) of an electron as a function of its mass (m), kinetic energy (E), and Planck's constant (h) is
a. $h/E^{1/2}$
b. $h/(m\ E)^{1/2}$
c. $h/(2\ m\ E)^{1/2}$
d. $(h/2\ m\ E)^{1/2}$
e. $(2\ h/m\ E)^{1/2}$

1-004. In which of the following nuclides does spontaneous fission occur more often than alpha decay?
a. Pu-238
b. Cm-242
c. Cm-244
d. Cf-252
e. Cf-254

1-005. A nuclear energy level has a width of 2.5 MeV. What is its lifetime?
a. 2.6×10^{-23} s
b. 5.2×10^{-23} s
c. 2.6×10^{-22} s
d. 5.3×10^{-22} s
e. 1.7×10^{-21} s

1-006. If the radius of the lowest Bohr orbit in hydrogen is a_o, what is the radius of the $n = 1$ level in lead ($Z = 82$)?
a. $1.5 \times 10^{-4}\ a_o$
b. $1.2 \times 10^{-2}\ a_o$
c. a_o
d. $82\ a_o$
e. $6724\ a_o$

1-007. Which of the following nuclei has the largest binding energy per nucleon?
a. He-4
b. C-12
c. O-16
d. Fe-56
e. Pb-208

1-008. Which of the following materials is commonly found in photoneutron sources?
a. Beryllium
b. Carbon
c. Aluminum
d. Cobalt
e. Polonium

1-009. What is the rest mass of an electron?
a. 0.511 MeV
b. 1.022 MeV
c. 0.511 keV

d. 1.022 keV
e. 2.2 MeV

1-010. What is the binding energy of the electron in a hydrogen atom?
a. 0.014 eV
b. 2.06 eV
c. 5.11 eV
d. 13.6 eV
e. 33.0 eV

1-011. In an elastic collision between a 1.0-MeV neutron and a room temperature hydrogen atom, what is the maximum energy that can be transferred to the hydrogen atom?
a. 0.25 MeV
b. 0.50 MeV
c. 0.75 MeV
d. 0.95 MeV
e. 1.00 MeV

1-012. If an electron travels at a velocity of 0.99 c, what is its relativistic mass?
a. 0.511 MeV
b. 1.022 MeV
c. 3.62 MeV
d. 25.6 MeV
e. 51.1 MeV

1-013. The binding energy of a K-shell electron in a Bohr hydrogen atom is 13.6 eV. What is the predicted Bohr binding energy of an L-shell electron in an element with $Z = 147$?
a. 41.3 eV
b. 0.5 keV
c. 6.1 keV
d. 73.5 keV
e. 0.5 MeV

1-014. What is the maximum recoil kinetic energy of an O-16 nucleus if it is hit head-on by a 20-MeV proton?
a. 0.221 MeV
b. 1.22 MeV
c. 2.21 MeV
d. 4.43 MeV
e. 9.41 MeV

1-015. The most common mechanism for neutron interaction with matter is:
a. Capture
b. (n, γ) photoproduction
c. (n, e) electroproduction
d. Elastic scattering
e. Inelastic scattering

1-016. U-238 decays to stable Pb-206 through a series of alpha and beta decay mechanisms. What is the total energy released during this decay series?

The following rest masses of electrically neutral atoms are provided:

U-238	238.050819 amu
Pb-206	205.974468 amu
He-4	4.002603 amu

a. 51.7 MeV
b. 57.7 MeV
c. 627.3 MeV
d. 29.8 GeV
e. 59.8 GeV

1-017. The reaction Li-7 (α, n) B-10 has a Q-value of –2.79 MeV.
What is the minimum energy of an alpha particle required to initiate this reaction?
a. 2.79 MeV
b. 3.19 MeV
c. 3.97 MeV
d. 4.38 MeV
e. 7.67 MeV

1-018. For pair production to occur in the vicinity of an O-16 nucleus, the incident photon must have an energy of at least
a. 0.511 keV
b. 1.022 keV
c. 0.511 MeV
d. 1.022 MeV
e. 2.04 MeV

1-019. The threshold energy for pion production during proton scattering on light nuclei is approximately
a. 40 MeV
b. 75 MeV
c. 140 MeV
d. 220 MeV
e. 1080 MeV

1-020. If each of the following particles has the same kinetic energy, which particle has the largest momentum?
a. Electron
b. Photon
c. Proton
d. Alpha particle
e. Li-6 nucleus

1-021. What is the maximum recoil kinetic energy of a Ra-226 nucleus after it emits a 4.785-MeV alpha particle?
a. 0.070 MeV
b. 0.075 MeV
c. 0.080 MeV
d. 0.085 MeV
e. 0.090 MeV

1-022. What is the *Q*-value for the emission of a 4.602-MeV alpha particle in Ra-226?
a. 4.60 MeV
b. 4.62 MeV
c. 4.64 MeV
d. 4.66 MeV
e. 4.68 MeV

1-023. In calculating atomic energy levels which force does the Bohr model assume binds the orbiting electron to the nucleus?
a. Gravitational
b. Coulomb
c. One-pion exchange
d. van der Waals
e. Effective Bohr

1-024. A radionuclide has a half-life of 1.0 hour. What is its mean lifetime?
a. 0.693 h
b. 1.443 h
c. 0.980 h
d. 2.041 h
e. 1.000 h

1-025. Radioactive P-32 decays to S-32 via beta decay. If the atomic mass of P-32 is 31.98403 amu and the atomic mass of S-32 is 31.98224 amu, what is the maximum beta energy from this decay?
a. 0.7 MeV
b. 1.2 MeV
c. 1.7 MeV
d. 2.2 MeV
e. 2.7 MeV

1-026. Given the following atomic mass data:
M(Po-210) = 210.04850 amu
M(Pb-206) = 206.03883 amu
M(He-4)$^{+2}$ = 4.00277 amu
1 amu = 931.48 MeV
what is the total energy released in the decay of Po-210?
a. 0.0047 amu
b. 0.0053 amu
c. 0.0058 amu
d. 0.0064 amu
e. 0.0069 amu

1-027. Which of the following nuclides is not a pure beta emitter?
a. H-3
b. C-14
c. P-32
d. Co-62
e. Y-90

1-028. As a general rule, photoelectric absorption below 100 keV:
- **a.** Is independent of the photon energy
- **b.** Becomes less probable as the photon energy decreases
- **c.** Becomes less probable as the photon energy increases
- **d.** Is proportional to the square of the atomic number of the absorber
- **e.** Is inversely proportional to the atomic number of the absorber

1-029. In tissue, fast neutrons lose 80% to 95% of their energy by interacting with:
- **a.** Hydrogen
- **b.** Carbon
- **c.** Nitrogen
- **d.** Oxygen
- **e.** Calcium

1-030. What is the specific activity of C-14 ($T_{1/2}$, = 5730 years)?
- **a.** 2.5 Ci/g
- **b.** 4.5 Ci/g
- **c.** 6.4 Ci/g
- **d.** 62.4 Ci/g
- **e.** 90.0 Ci/g

1-031. A wood sample from an old vase has a C-14 specific activity of 10 dis/min per gram. If samples from a nearby growing tree yield 15 dis/min per gram, what is the age of the vase?
- **a.** 2300 years
- **b.** 3400 years
- **c.** 4800 years
- **d.** 5000 years
- **e.** 5700 years

1-032. Thermal neutron capture by hydrogen nuclei results in:
- **a.** 0.511 MeV gamma rays
- **b.** Bremsstrahlung photons
- **c.** 2.2 MeV gamma rays
- **d.** 150 keV X-rays
- **e.** 1.17 and 1.33 MeV gamma rays

1-033. Which of the following nuclides has the shortest half-life?
- **a.** H-3
- **b.** O-15
- **c.** P-32
- **d.** K-40
- **e.** Mo-99

1-034. Carbon dating is possible because:
- **a.** The specific activity of carbon-14 in living organisms has changed over time, and one can identify the era of time in which the organism lived based on its current specific activity
- **b.** Carbon-14 is in secular equilibrium with its daughter
- **c.** The specific activity of carbon-14 in living organisms is relatively constant through time, but decays after the death of the organism

d. The specific activity of carbon-14 in wood increases over time due to shrinkage of the wood
e. The rate of C-14 generation due to cosmic ray sources plus nuclear weapons testing has increased C-14 levels by a factor of 1.02 (1 + cos θ) where θ is the longitude

1-035. Consider a parent radioisotope A ($T_{1/2}$ = 10 h) that decays to a daughter radioisotope B ($T_{1/2}$ = 1 h). Which of the following statements is true concerning these radioisotopes?
a. Because $\lambda_A > \lambda_B$, the parent and daughter will eventually reach the condition of transient equilibrium
b. Because $\lambda_A \gg \lambda_B$, the parent and daughter will eventually reach the condition of secular equilibrium
c. Because $\lambda_A = \lambda_B$, no state of equilibrium can ever exist between the parent and daughter
d. Because $\lambda_B > \lambda_A$, the parent and daughter will eventually reach the condition of transient equilibrium
e. Because $\lambda_B \gg \lambda_A$, the parent and daughter will eventually reach the condition of secular equilibrium

1-036. A nuclide that undergoes orbital electron capture
a. Emits an electron, a neutrino and the characteristic X-rays of the daughter
b. Emits a neutrino and the characteristic X-rays of the daughter
c. Also decays by positron emission
d. Also emits internal conversion electrons
e. Makes an isomeric transition

1-037. I-126 (Z = 53) can decay into stable Te-126 (Z = 52) by orbital electron capture (EC) (55%) or by positron emission (1%). It can, alternatively, decay by negative beta emission (44%) into stable Xe-126 (Z = 54). The binding energy of the K-shell electron in I-126 is 32 keV.

The energy equivalents (Δ) of the mass excesses of the atoms involved in these transformations are (Δ = atomic mass – atomic mass number) Δ(Te-126) = –90.05 MeV, Δ(I-126) = –87.90 MeV, and Δ(Xe-126) = –89.15 MeV. The energy released (Q-value) by the decay of I-126 via K-shell capture going directly to the ground state of Te-126 is
a. 0.03 MeV
b. 1.13 MeV
c. 2.12 MeV
d. 2.15 MeV
e. 2.18 MeV

1-038. The energy released by the positron decay of I-126 to the ground state of Te-126 (see Question 1-037) is
a. 0.51 MeV
b. 1.02 MeV
c. 1.13 MeV

d. 1.64 MeV
e. 2.15 MeV

1-039. The energy released in the beta decay of I-126 to the ground state of Xe-126 (see Question 1-037) is
a. 0.20 MeV
b. 0.23 MeV
c. 0.74 MeV
d. 0.90 MeV
e. 1.25 MeV

1-040. Of the following kinds of radiation emitted from I-126, which is the single least significant potential contributor to internal dose?
a. Annihilation photons
b. Bremsstrahlung
c. Internal-conversion electrons
d. Auger electrons
e. Antineutrinos

1-041. Of the following kinds of radiation emitted from I-126, which is the single least significant potential contributor to external dose?
a. Annihilation photons
b. Bremsstrahlung
c. Internal-conversion electrons
d. Auger electrons
e. Antineutrinos

1-042. Why are the 32-keV Te X-rays present in an I-126 source (see Question 1-037)?
a. The nucleus of Te-126 has excess energy after the EC event. This excess energy is released by Te-126 as X-rays.
b. Stable Te-126 has excess energy after positron emission. This excess energy is released by Te-126 as X-rays.
c. Electrons rearranging between the L- and M-shells produce X-rays.
d. Te X-rays are released when the EC event creates a vacancy in the inner shells and electrons from outer shells fill the vacancy.
e. Te X-rays are equivalent to the bremsstrahlung radiation emitted by I-126.

1-043. Sr-90 (27.7 y) decays by beta emission into Y-90 (64.2 hours), which then decays by beta emission into Zr-90. What is the mean, or average, life of a Y-90 atom?
a. 31.1 h
b. 44.5 h
c. 77.04 h
d. 92.6 h
e. 128.4 h

1-044. What is the specific activity of Y-90 (see Question 1-043)?
a. 5.42×10^{15} Bq/kg
b. 7.22×10^{16} Bq/kg

c. 2.01×10^{19} Bq/kg
d. 7.22×10^{19} Bq/kg
e. 6.49×10^{21} Bq/kg

1-045. Starting with a pure Sr-90 sample (see Question 1-043) at time, $t = 0$, a researcher finds that the Y-90 activity is 3.4 mCi at $t = 72.0$ h. What was the activity of the Sr-90 at $t = 0$?
a. 1.84 mCi
b. 3.40 mCi
c. 4.37 mCi
d. 6.29 mCi
e. 7.39 mCi

1-046. The radius of an Al-27 nucleus is approximately
a. 4.0×10^{-6} m
b. 4.0×10^{-9} m
c. 4.0×10^{-12} m
d. 4.0×10^{-15} m
e. 4.0×10^{-18} m

1-047. Deuterium and tritium are isotopes of hydrogen. The relative abundance of deuterium and tritium is one atom of deuterium for every ___ hydrogen atoms and one atom of tritium for every ___ hydrogen atoms.
a. 50, 1.0×10^{10}
b. 1000, 1.0×10^{9}
c. 2500, 1.0×10^{15}
d. 7000, 1.0×10^{17}
e. 25 000, 1.0×10^{14}

1-048. Which of the following radionuclides has the smallest specific activity? The radionuclide's half-life is in parenthesis.
a. Al-28 (2.2 min)
b. I-131 (8.1 d)
c. Mn-54 (313 d)
d. Cs-137 (30 y)
e. Ra-226 (1600 y)

1-049. Fission of U-238 mostly produces which radiation types?
a. Neutrons, gamma rays, and positrons
b. Neutrons, gamma rays, and beta particles
c. Neutrons, gamma rays, and alpha particles
d. Gamma rays, positrons, and alpha particles
e. Gamma rays, beta particles, and alpha particles

1-050. An excited state in a radionuclide has a width of 6.0 MeV. What is its lifetime?
a. 1.0×10^{-25} s
b. 1.0×10^{-22} s
c. 1.0×10^{-19} s
d. 1.0×10^{-16} s
e. 1.0×10^{-13} s

1-051. A radionuclide has a disintegration constant of 1.0/min. What fraction of atoms has decayed after 2.0 min?
a. 0.135
b. 0.25
c. 0.50
d. 0.75
e. 0.865

1-052. The alpha decay of Ra-226 has a *Q*-value of 4.88 MeV. What is the energy of the emitted alpha particle?
a. 0.05 MeV
b. 0.09 MeV
c. 2.44 MeV
d. 4.79 MeV
e. 9.58 MeV

1-053. The energy deposited by an acute dose of 500 rad will raise the temperature of one gram of tissue by about:
a. 0.001 °C
b. 0.01 °C
c. 0.1 °C
d. 1.0 °C
e. 10.0 °C

1-054. Which of the following radionuclides emits the highest energy beta particle?
a. C-14
b. P-32
c. Co-60
d. Y-90
e. Cs-137

1-055. Which of the following radionuclides is a pure beta emitter?
a. P-32
b. Co-57
c. Kr-85
d. I-131
e. Po-214

1-056. 100 mCi of which of the following radionuclides would decay to *de minimus* levels after two years?
a. H-3
b. C-14
c. P-32
d. Co-60
e. Sr-90

1-057. An investigator receives Co-60 (5.27 y half-life) for use in a research study. Unfortunately, the Co-60 is contaminated with Cs-137 (30.0 y half-life). The initial Co-60 activity is 400 times the initial Cs-137 activity. How long after the initial assay will the Cs-137 activity be 0.02 times the Co-60 activity?

a. 13 y
b. 16 y
c. 19 y
d. 27 y
e. 34 y

1-058. What are the binding energies of S-32 and P-32? The following mass excess values are provided: $\Delta(p) = 7.289$ MeV, $\Delta(n) = 8.071$ MeV, Δ(S-32) = –26.016 MeV, and Δ(P-32) = –24.305 MeV.
a. 219.75 MeV and 222.24 MeV, respectively
b. 219.75 MeV and 270.85 MeV, respectively
c. 271.78 MeV and 222.24 MeV, respectively
d. 270.85 MeV and 271.78 MeV, respectively
e. 271.78 MeV and 270.85 MeV, respectively

1-059. The dominant decay modes for fission product nuclei are
a. Photon emission and beta decay
b. Neutron emission and alpha decay
c. Beta decay and electron capture
d. Positron decay and photon emission
e. Alpha decay and beta decay

1-060. The dominant decay mode for the U-238 nucleus is
a. Photon emission
b. Neutron emission
c. Beta decay
d. Positron decay
e. Alpha decay

1-061. The dominant decay mode for N-13 is
a. Photon emission
b. Neutron emission
c. Beta decay
d. Positron decay
e. Alpha decay

1-062. A radionuclide has a beta particle whose maximum energy is 5.0 MeV. What is the range of this beta particle in air at STP?
a. 3.0 m
b. 7.0 m
c. 15.0 m
d. 20.0 m
e. 35.0 m

1-063. What is the range of a 7.0-MeV alpha particle in air at STP?
a. 2 cm
b. 4 cm
c. 6 cm
d. 8 cm
e. 10 cm

1-064. What is the range of a 7.0-MeV alpha particle in aluminum having a density of 2.7 g/cm^3?

a. 25 μm
b. 38 μm
c. 65 μm
d. 80 μm
e. 100 μm

1-065. What fraction of the energy of a 1.0-MeV photon is lost if it scatters through an angle of 90°?

a. 0.338
b. 0.662
c. 0.204
d. 0.796
e. 0.500

1-066. Within the activation equation $A = N \sigma \phi \, [1 - \exp(-\lambda \, t)]$, what does $N \sigma \phi$ represent?

a. Reaction rate
b. Mean activity
c. Cumulative activity
d. Saturation activity
e. Weighted fluence rate

1-067. A radionuclide emits only beta radiation with a maximum energy of 2.0 MeV. What is the ratio of shielding thicknesses of polyethylene required to shield a 10-Ci source versus a 1.0-Ci source of this radionuclide?

a. 1/100
b. 1/10
c. 1
d. 10
e. 100

1-068. You have lead and polyethylene shielding materials available. In shielding a pure 2.5-MeV beta emitter, how would you arrange the available materials to minimize worker exposure? List the materials as a function of distance from the radiation source, and determine the optimum shielding configuration.

a. Lead only
b. Polyethylene only
c. Lead followed by polyethylene
d. Polyethylene followed by lead
e. Lead, polyethylene, and lead

1-069. The mass attenuation coefficient (u/ρ) of molybdenum as a function of photon energy decreases between 10 and 20 keV, has a step increase at 20 keV, then decreases between 20 and 30 keV. The step increase at 20 keV is attributed to:

a. Compton scattering
b. Pair production

c. Photon energy exceeding the K-shell binding energy
d. Rayleigh scattering
e. Rainbow scattering

1-070. The average number of ion pairs produced by a 100-keV beta particle that stops in a germanium semiconductor is:
a. 30 000
b. 30
c. 300
d. 3000
e. 300 000

1-071. The average number of ion pairs produced by a 100-keV beta particle that stops in air is approximately:
a. 300
b. 30
c. 30 000
d. 3000
e. 300 000

1-072. The Compton scattering by air of photon radiation from open-topped radioactive waste storage cells explains the phenomenon of:
a. Bremsstrahlung
b. Straggling
c. Skyshine
d. Buildup
e. Pair production

1-073. The threshold energies for pair production near a nucleus and near an electron are ___ $m_e c^2$ and ___ $m_e c^2$, respectively.
a. 2, 2
b. 2, 3
c. 2, 4
d. 4, 2
e. 4, 3

1-074. At 10-MeV photon energy, pair production will have the largest cross-section in which of the following nuclides?
a. Hydrogen
b. Carbon
c. Iron
d. Zirconium
e. Uranium

1-075. Which of the following sequences represents the dominant photon interaction mechanism in tissue as the photon energy increases from 10 keV to 100 MeV?
a. Photoelectric effect, Compton scattering, and pair production, respectively
b. Compton scattering, photoelectric effect, and pair production, respectively

- **c.** Pair production, Compton scattering, and photoelectric effect, respectively
- **d.** Pair production, photoelectric effect, and Compton scattering, respectively
- **e.** Photoelectric effect, pair production, and Compton scattering, respectively

1-076. The energy distribution of fission neutrons is characterized by:

- **a.** Two to six distinct energy peaks whose magnitude and location depend on the nucleus being fissioned
- **b.** A distribution of energies that peaks at a most probable value and then decreases as the energy increases
- **c.** A distribution of energies with several peaks that occur between 1.0 and 4.0 MeV
- **d.** A relatively flat energy distribution up to about 7.0 MeV which then decreases as the energy increases
- **e.** A distribution of energies that peaks at a most probable value, decreases as the energy increases up to 5.0 MeV, and then slowly increases up to the giant resonance energy region

1-077. The most probable energy and the average energy of neutrons characterized by a Maxwell–Boltzmann distribution are

- **a.** 0.5 kT and kT, respectively
- **b.** 0.5 kT and 1.5 kT, respectively
- **c.** kT and 1.5 kT, respectively
- **d.** kT and 2.0 kT, respectively
- **e.** 2.0 kT and 3.0 kT, respectively

1-078. What is the relationship of the mass stopping power (S/ρ) of steam (s), water (w), and ice (i)? In the following relationships, the stopping power is denoted by S and the density by ρ:

- **a.** $(S/\rho)_S > (S/\rho)_w > (S/\rho)_i$
- **b.** $(S/\rho)_S < (S/\rho)_w < (S/\rho)_i$
- **c.** $(S/\rho)_S > (S/\rho)_w \geq (S/\rho)_i$
- **d.** $(S/\rho)_S < (S/\rho)_w \leq (S/\rho)_i$
- **e.** $(S/\rho)_S = (S/\rho)_w = (S/\rho)_i$

1-079. At 500 MeV, the dominant photon interaction(s) with tissue is (are):

- **a.** The photoelectric effect
- **b.** Compton scattering
- **c.** Pair production
- **d.** About equal contributions from the photoelectric effect and Compton scattering
- **e.** About equal contributions from Compton scattering and pair production

1-080. For photon energies between 100 keV and 2.5 MeV, the dominant contribution to the mass absorption coefficient in tissue is:

- **a.** The photoelectric effect
- **b.** Compton scattering

- **c.** Pair production
- **d.** Rayleigh scattering
- **e.** Coulomb scattering

1-081. At 10 keV, the dominant photon interaction(s) with tissue is (are):
- **a.** The photoelectric effect
- **b.** Compton scattering
- **c.** Pair production
- **d.** About equal contributions from the photoelectric effect and Compton scattering
- **e.** About equal contributions from Compton scattering and pair production

1-082. At 25 keV, the dominant photon interaction(s) with tissue is (are):
- **a.** The photoelectric effect
- **b.** Compton scattering
- **c.** Pair production
- **d.** About equal contributions from the photoelectric effect and Compton scattering
- **e.** About equal contributions from Compton scattering and pair production

1-083. At 1 MeV, the dominant photon interaction(s) with tissue is (are):
- **a.** The photoelectric effect
- **b.** Compton scattering
- **c.** Pair production
- **d.** About equal contributions from the photoelectric effect and Compton scattering
- **e.** About equal contributions from Compton scattering and pair production

1-084. At 20 MeV, the dominant photon interaction(s) with tissue is (are):
- **a.** The photoelectric effect
- **b.** Compton scattering
- **c.** Pair production
- **d.** About equal contributions from the photoelectric effect and Compton scattering
- **e.** About equal contributions from Compton scattering and pair production

1-085. What is the rest mass of a charged pion?
- **a.** 0.511 MeV
- **b.** 105 MeV
- **c.** 139.6 MeV
- **d.** 938.3 MeV
- **e.** 1150 MeV

1-086. Which of the following neutron energies is considered to lie within the thermal region?
- **a.** 0.025 eV
- **b.** 0.25 eV

c. 2.5 eV
d. 25 eV
e. 250 eV

1-087. Between mass number 20 and 100, the average binding energy per nucleon is approximately:
a. 6.0 MeV/nucleon
b. 6.5 MeV/nucleon
c. 7.0 MeV/nucleon
d. 7.5 MeV/nucleon
e. 8.5 MeV/nucleon

1-088. Which of the following radiation types are emitted during the decay of N-16?
a. High-energy photons, high-energy beta particles, and a neutron
b. High-energy photons, high-energy beta particles, and an alpha particle
c. Low-energy photons, high-energy beta particles, and a neutron
d. High-energy photons, low-energy beta particles, and an alpha particle
e. High-energy photons, alpha particles, and neutrons

1-089. A thick, dense object is to be radiographed. Which of the following sources would be used?
a. 250 keV X-ray machine
b. 0.32 MeV Ir-192 source
c. 0.66 MeV Cs-137 source
d. 1.25 MeV Co-60 source
e. 7.0 MeV N-16 source

1-090. Moisture/density gauges most commonly use which of the following isotopes?
a. Cs-137 and Am-241
b. Cs-137 and P-32
c. Co-60 and Pu-239
d. Co-60 and S-35
e. P-32 and Pu-239

1-091. According to the World Health Organization, what is the absorbed dose range required for industrial sterilization?
a. 0.001–0.01 kGy
b. 0.01–0.05 kGy
c. 0.05–1 kGy
d. 1–10 kGy
e. 10–50 kGy

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