21.E: Nuclear Chemistry (Exercises)

21.E.1: 21.2: Nuclear Structure and Stability

21.E.1.1: Q21.2.1

Write the following isotopes in hyphenated form (e.g., “carbon-14”)

a. ${}^{24}_{11}\text{Na}$
b. ${}^{29}_{13}\text{Al}$
c. ${}^{73}_{36}\text{Kr}$
d. ${}^{194}_{77}\text{Ir}$

21.E.1.2: Q21.2.2

Write the following isotopes in nuclide notation (e.g., " ${}^{14}_{6}\text{C}$ ")

a. oxygen-14
b. copper-70
c. tantalum-175
d. francium-217

21.E.1.3: Q21.2.3

For the following isotopes that have missing information, fill in the missing information to complete the notation

a. ${}^{34}_{14}\text{X}$
b. ${}^{36}\text{P}$
c. ${}^{57}_{\text{X}}\text{Mn}$
d. ${}^{121}_{56}\text{X}$

21.E.1.4: Q21.2.4

For each of the isotopes in Question 21.2.3, determine the numbers of protons, neutrons, and electrons in a neutral atom of the isotope.

21.E.1.5: Q21.2.5

Write the nuclide notation, including charge if applicable, for atoms with the following characteristics:

a. 25 protons, 20 neutrons, 24 electrons
b. 45 protons, 24 neutrons, 43 electrons
c. 53 protons, 89 neutrons, 54 electrons
d. 97 protons, 146 neutrons, 97 electrons

21.E.1.6: Q21.2.6

Calculate the density of the ${}^{24}_{12}\text{Mg}$ nucleus in g/mL, assuming that it has the typical nuclear diameter of 1×10^{-13} cm and is spherical in shape.

21.E.1.7: Q21.2.7

What are the two principal differences between nuclear reactions and ordinary chemical changes?

21.E.1.8: Q21.2.8

The mass of the atom ${}^{23}_{11}\text{Na}$ is 22.9898 amu.

a. Calculate its binding energy per atom in millions of electron volts.
b. Calculate its binding energy per nucleon.

21.E.1.9: Q21.2.9

Which of the following nuclei lie within the band of stability?

a. chlorine-37
b. calcium-40
c. ^{204}Bi
d. ^{56}Fe
e. ^{206}Pb
f. ^{211}Pb
g. ^{222}Rn
h. carbon-14

21.E.1.10: Q21.2.10

Which of the following nuclei lie within the band of stability?

a. argon-40
b. oxygen-16
c. ^{122}Ba
d. ^{58}Ni
e. ^{205}Tl
f. ^{210}Tl
g. ^{226}Ra
h. magnesium-24

21.E.2: 21.3: Nuclear Equations

21.E.2.1: Q21.3.1

Write a brief description or definition of each of the following:

a. nucleon
b. α particle
c. β particle
d. positron
e. γ ray
f. nuclide
g. mass number
h. atomic number

21.E.2.2: Q21.3.2

Which of the various particles (α particles, β particles, and so on) that may be produced in a nuclear reaction are actually nuclei?

21.E.2.3: Q21.3.3

Complete each of the following equations by adding the missing species:

a. ${}^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow ? + {}^{1}_{0}\mathrm{n}$
b. ${}^{239}_{94}\mathrm{Pu} + ? \longrightarrow {}^{242}_{96}\mathrm{Cm} + {}^{1}_{0}\mathrm{n}$
c. ${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \longrightarrow ? + {}^{1}_{1}\mathrm{H}$
d. ${}^{235}_{92}\mathrm{U} \longrightarrow ? + {}^{135}_{55}\mathrm{Cs} + 4\,{}^{1}_{0}\mathrm{n}$

21.E.2.4: Q21.3.4

Complete each of the following equations:

a. ${}^{7}_{3}\mathrm{Li} + ? \longrightarrow 2\,{}^{4}_{2}\mathrm{He}$
b. ${}^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + ?$
c. ${}^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow ? + {}^{1}_{0}\mathrm{n}$
d. ${}^{250}_{96}\mathrm{Cm} \longrightarrow ? + {}^{98}_{38}\mathrm{Sr} + 4\,{}^{1}_{0}\mathrm{n}$

21.E.2.5: Q21.3.5

Write a balanced equation for each of the following nuclear reactions:

a. the production of ^{17}O from ^{14}N by α particle bombardment
b. the production of ^{14}C from ^{14}N by neutron bombardment
c. the production of ^{233}Th from ^{232}Th by neutron bombardment
d. the production of ^{239}U from ^{238}U by $^{2}_{1}\mathrm{H}$ bombardment

21.E.2.6: Q21.3.6

Technetium-99 is prepared from ^{98}Mo. Molybdenum-98 combines with a neutron to give molybdenum-99, an unstable isotope that emits a β particle to yield an excited form of technetium-99, represented as $^{99}Tc^{*}$. This excited nucleus relaxes to the ground state, represented as ^{99}Tc, by emitting a γ ray. The ground state of ^{99}Tc then emits a β particle. Write the equations for each of these nuclear reactions.

21.E.2.7: Q21.3.7

The mass of the atom $^{19}_{9}\mathrm{F}$ is 18.99840 amu.

a. Calculate its binding energy per atom in millions of electron volts.
b. Calculate its binding energy per nucleon.

21.E.2.8: Q21.3.8

For the reaction $^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + ?$, if 100.0 g of carbon reacts, what volume of nitrogen gas (N_2) is produced at 273 K and 1 atm?

21.E.3: 21.4: Radioactive Decay

21.E.3.1: Q21.4.1

What are the types of radiation emitted by the nuclei of radioactive elements?

21.E.3.2: Q21.4.2

What changes occur to the atomic number and mass of a nucleus during each of the following decay scenarios?

a. an α particle is emitted
b. a β particle is emitted
c. γ radiation is emitted
d. a positron is emitted
e. an electron is captured

21.E.3.3: Q21.4.3

What is the change in the nucleus that results from the following decay scenarios?

a. emission of a β particle
b. emission of a β^{+} particle
c. capture of an electron

21.E.3.4: Q21.4.4

Many nuclides with atomic numbers greater than 83 decay by processes such as electron emission. Explain the observation that the emissions from these unstable nuclides also normally include α particles.

21.E.3.5: Q21.4.5

Why is electron capture accompanied by the emission of an X-ray?

21.E.3.6: Q21.4.6

Explain how unstable heavy nuclides (atomic number > 83) may decompose to form nuclides of greater stability (a) if they are below the band of stability and (b) if they are above the band of stability.

21.E.3.7: Q21.4.7

Which of the following nuclei is most likely to decay by positron emission? Explain your choice.

a. chromium-53
b. manganese-51
c. iron-59

21.E.3.8: Q21.4.8

The following nuclei do not lie in the band of stability. How would they be expected to decay? Explain your answer.

a. $^{34}_{15}\mathrm{P}$
b. $^{239}_{92}\mathrm{U}$
c. $^{38}_{20}\mathrm{Ca}$
d. $^{3}_{1}\mathrm{H}$
e. $^{245}_{94}\mathrm{Pu}$

21.E.3.9: Q21.4.9

The following nuclei do not lie in the band of stability. How would they be expected to decay?

a. $^{28}_{15}\mathrm{P}$
b. $^{235}_{92}\mathrm{U}$
c. $^{37}20\,\mathrm{Ca}$
d. $^{9}_{3}\mathrm{Li}$
e. $^{245}_{96}\mathrm{Cm}$

21.E.3.10: Q21.4.10

Predict by what mode(s) of spontaneous radioactive decay each of the following unstable isotopes might proceed:

a. $^{6}_{2}\mathrm{He}$
b. $^{60}_{30}\mathrm{Zn}$
c. $^{235}_{91}\mathrm{Pa}$
d. $^{241}_{94}\mathrm{Np}$
e. $^{18}\mathrm{F}$
f. $^{129}\mathrm{Ba}$
g. $^{237}\mathrm{Pu}$

21.E.3.11: Q21.4.11

Write a nuclear reaction for each step in the formation of $^{218}_{84}\mathrm{Po}$ from $^{238}_{92}\mathrm{U}$, which proceeds by a series of decay reactions involving the step-wise emission of α, β, β, α, α, α, α particles, in that order.

21.E.3.12: Q21.4.12

Write a nuclear reaction for each step in the formation of $^{208}_{82}\mathrm{Pb}$ from $^{228}_{90}\mathrm{Th}$, which proceeds by a series of decay reactions involving the step-wise emission of α, α, α, α, β, β, α particles, in that order.

21.E.3.13: Q21.4.13

Define the term half-life and illustrate it with an example.

21.E.3.14: Q21.4.14

A 1.00×10^{-6}-g sample of nobelium, $^{254}_{102}\mathrm{No}$, has a half-life of 55 seconds after it is formed. What is the percentage of $^{254}_{102}\mathrm{No}$ remaining at the following times?

a. 5.0 min after it forms
b. 1.0 h after it forms

21.E.3.15: Q21.4.15

^{239}Pu is a nuclear waste byproduct with a half-life of 24,000 y. What fraction of the ^{239}Pu present today will be present in 1000 y?

21.E.3.16: Q21.4.16

The isotope ^{208}Tl undergoes β decay with a half-life of 3.1 min.

a. What isotope is produced by the decay?
b. How long will it take for 99.0% of a sample of pure ^{208}Tl to decay?
c. What percentage of a sample of pure ^{208}Tl remains un-decayed after 1.0 h?

21.E.3.17: Q21.4.17

If 1.000 g of $^{226}_{88}\text{Ra}$ produces 0.0001 mL of the gas $^{222}_{86}\text{Rn}$ at STP (standard temperature and pressure) in 24 h, what is the half-life of ^{226}Ra in years?

21.E.3.18: Q21.4.18

The isotope $^{90}_{38}Sr$ is one of the extremely hazardous species in the residues from nuclear power generation. The strontium in a 0.500-g sample diminishes to 0.393 g in 10.0 y. Calculate the half-life.

21.E.3.19: Q21.4.19

Technetium-99 is often used for assessing heart, liver, and lung damage because certain technetium compounds are absorbed by damaged tissues. It has a half-life of 6.0 h. Calculate the rate constant for the decay of $^{99}_{43}\text{Tc}$.

21.E.3.20: Q21.4.20

What is the age of mummified primate skin that contains 8.25% of the original quantity of ^{14}C?

21.E.3.21: Q21.4.21

A sample of rock was found to contain 8.23 mg of rubidium-87 and 0.47 mg of strontium-87.

a. Calculate the age of the rock if the half-life of the decay of rubidium by β emission is 4.7×10^{10} y.
b. If some $^{87}_{38}Sr$ was initially present in the rock, would the rock be younger, older, or the same age as the age calculated in (a)? Explain your answer.

21.E.3.22: Q21.4.22

A laboratory investigation shows that a sample of uranium ore contains 5.37 mg of $^{238}_{92}U$ and 2.52 mg of $^{206}_{82}Pb$. Calculate the age of the ore. The half-life of $^{238}_{92}U$ is 4.5×10^9 yr.

21.E.3.23: Q21.4.23

Plutonium was detected in trace amounts in natural uranium deposits by Glenn Seaborg and his associates in 1941. They proposed that the source of this ^{239}Pu was the capture of neutrons by ^{238}U nuclei. Why is this plutonium not likely to have been trapped at the time the solar system formed 4.7×10^9 years ago?

21.E.3.24: Q21.4.24

A $^{7}_{4}Be$ atom (mass = 7.0169 amu) decays into a $^{7}_{3}Li$ atom (mass = 7.0160 amu) by electron capture. How much energy (in millions of electron volts, MeV) is produced by this reaction?

21.E.3.25: Q21.4.25

A $^{8}_{5}B$ atom (mass = 8.0246 amu) decays into a $^{8}_{4}Be$ atom (mass = 8.0053 amu) by loss of a β^+ particle (mass = 0.00055 amu) or by electron capture. How much energy (in millions of electron volts) is produced by this reaction?

21.E.3.26: Q21.4.26

Isotopes such as ^{26}Al (half-life: 7.2×10^5 years) are believed to have been present in our solar system as it formed, but have since decayed and are now called extinct nuclides.

a. ^{26}Al decays by β^+ emission or electron capture. Write the equations for these two nuclear transformations.

b. The earth was formed about 4.7 × 10^9 (4.7 billion) years ago. How old was the earth when 99.999999% of the ^{26}Al originally present had decayed?

21.E.3.27: Q21.4.27

Write a balanced equation for each of the following nuclear reactions:

a. bismuth-212 decays into polonium-212
b. beryllium-8 and a positron are produced by the decay of an unstable nucleus
c. neptunium-239 forms from the reaction of uranium-238 with a neutron and then spontaneously converts into plutonium-239
d. strontium-90 decays into yttrium-90

21.E.3.28: Q21.4.28

Write a balanced equation for each of the following nuclear reactions:

a. mercury-180 decays into platinum-176
b. zirconium-90 and an electron are produced by the decay of an unstable nucleus
c. thorium-232 decays and produces an alpha particle and a radium-228 nucleus, which decays into actinium-228 by beta decay
d. neon-19 decays into fluorine-19

21.E.4: 21.5: Transmutation and Nuclear Energy

21.E.4.1: Q21.5.1

Write the balanced nuclear equation for the production of the following transuranium elements:

a. berkelium-244, made by the reaction of Am-241 and He-4
b. fermium-254, made by the reaction of Pu-239 with a large number of neutrons
c. lawrencium-257, made by the reaction of Cf-250 and B-11
d. dubnium-260, made by the reaction of Cf-249 and N-15

21.E.4.2: Q21.5.2

How does nuclear fission differ from nuclear fusion? Why are both of these processes exothermic?

21.E.4.3: Q21.5.3

Both fusion and fission are nuclear reactions. Why is a very high temperature required for fusion, but not for fission?

21.E.4.4: Q21.5.4

Cite the conditions necessary for a nuclear chain reaction to take place. Explain how it can be controlled to produce energy, but not produce an explosion.

21.E.4.5: Q21.5.5

Describe the components of a nuclear reactor.

21.E.4.6: Q21.5.6

In usual practice, both a moderator and control rods are necessary to operate a nuclear chain reaction safely for the purpose of energy production. Cite the function of each and explain why both are necessary.

21.E.4.7: Q21.5.7

Describe how the potential energy of uranium is converted into electrical energy in a nuclear power plant.

21.E.4.8: Q21.5.8

The mass of a hydrogen atom $\left(^1_1\mathrm{H}\right)$ is 1.007825 amu; that of a tritium atom $\left(^3_1\mathrm{H}\right)$ is 3.01605 amu; and that of an α particle is 4.00150 amu. How much energy in kilojoules per mole of $^4_2\mathrm{He}$ produced is released by the following fusion reaction: $^1_1\mathrm{H} + ^3_1\mathrm{H} \longrightarrow ^4_2\mathrm{He}$.

21.E.5: 21.6: Uses of Radioisotopes

21.E.5.1: Q21.6.1

How can a radioactive nuclide be used to show that the equilibrium:

$$\mathrm{AgCl}(s) \rightleftharpoons \mathrm{Ag}^{+}(aq) + \mathrm{Cl}^{-}(aq) \tag{21.E.1}$$

is a dynamic equilibrium?

21.E.5.2: Q21.6.2

Technetium-99m has a half-life of 6.01 hours. If a patient injected with technetium-99m is safe to leave the hospital once 75% of the dose has decayed, when is the patient allowed to leave?

21.E.5.3: Q21.6.3

Iodine that enters the body is stored in the thyroid gland from which it is released to control growth and metabolism. The thyroid can be imaged if iodine-131 is injected into the body. In larger doses, I-131 is also used as a means of treating cancer of the thyroid. I-131 has a half-life of 8.70 days and decays by β^{-} emission.

a. Write a nuclear equation for the decay.
b. How long will it take for 95.0% of a dose of I-131 to decay?

21.E.6: 21.7: Biological Effects of Radiation

21.E.6.1: Q21.7.1

If a hospital were storing radioisotopes, what is the minimum containment needed to protect against:

a. cobalt-60 (a strong γ emitter used for irradiation)
b. molybdenum-99 (a beta emitter used to produce technetium-99 for imaging)

21.E.6.2: Q21.7.2

Based on what is known about Radon-222's primary decay method, why is inhalation so dangerous?

21.E.6.3: Q21.7.3

Given specimens uranium-232 ($t_{1/2} = 68.9\ \mathrm{y}$) and uranium-233 ($t_{1/2} = 159,200\ \mathrm{y}$) of equal mass, which one would have greater activity and why?

21.E.6.4: Q21.7.4

A scientist is studying a 2.234 g sample of thorium-229 ($t_{1/2}$ = 7340 y) in a laboratory.

a. What is its activity in Bq?
b. What is its activity in Ci?

21.E.6.5: Q21.7.5

Given specimens neon-24 ($t_{1/2} = 3.38\ \mathrm{min}$) and bismuth-211 ($t_{1/2} = 2.14\ \mathrm{min}$) of equal mass, which one would have greater activity and why?