Objective 15. Identify radiation types and understand nuclear chemistry reactions.
radiation types, balance equation, rate and half life, fission, fusion
Key ideas: Many applications of particle radiation and nuclear reactions: nuclear power plant, nuclear medicine, radioactive dating.
Particle radiation includes alpha particles and beta particles. Describe particle radiation with nuclide symbol, e.g., alpha particle = $^{4}_{2}He^{2+}$.
Gamma radiation (ray) = $^{0}_{0}\gamma$
Radioactive isotopes undergo radioactive decay to produce particle radiation.
E.g., carbon-14 is a beta emitter.
Radioactive decay is a 1st order rate process. Relate rate constant to half-life.

Practice Problems solutions:
1. a. What is the difference between nuclear radiation and electromagnetic radiation? What is the source of each type of radiation? Which radiation type involves more energy?
b. Name each type of nuclear radiation and its nuclide symbol. (A nuclide symbol shows the mass number (superscript), atomic number (subscript), symbol, and charge if needed.)
c. (i) Describe how to protect yourself from each type of radiation.
(ii) Alpha particles have the highest relative biological effectiveness (RBE = 20) but is blocked by skin. Why are alpha particles so dangerous?
(iii) X rays and gamma radiation have the lowest relative biological effectiveness (RBE = 1) but is blocked by a lead shield or thick concrete. How is the wavelength of electromagnetic radiation related to the thickness of the shielding?
d. How can you tell whether a substance is radioactive? (Hint: see atomic number, number of neutrons and protons.)
Answers:
a. Nuclear radiation involves the nucleus of an atom. Electromagnetic radiation involves the electrons in an atom.
Nuclear radiation involves a nuclear reaction, e.g., radioactive decay. Electromagnetic radiation is emitted when an electron undergoes a transition from a higher energy electron state to lower energy electron state in an atom.
Nuclear radiation involves a lot of energy. Electromagnetic radiation involves a little energy.

2. Nuclear reactions.
a. Carbon-14 (^{14}C) is the radioactive isotope of carbon and is used to determine the age of fossils (carbon dating). When ^{14}C undergoes radioactive decay. It emits a beta particle. Below is a partial radioactive decay nuclear equation:

^{14}C ---> ^{0}e + ^{14}X

The superscripts represent ____.
The subscripts represent atomic number. Write in the atomic number in each reactant and product.
What element is X? How many protons and neutrons are in this isotope?
b. Potassium-40 is radioactive and is a beta emitter. Write a balanced nuclear equation that represents the radioactive decay of K-40. How many protons and neutrons are in K-40?
c. Americium-241 is used in smoke detectors and is an alpha emitter. Write a balanced nuclear equation that represents the radioactive decay of Am-241. How many protons and neutrons are in Am-241?
d. Uranium-235 undergoes induced nuclear fission by capturing (reacting with) a neutron to produce barium-141, krytpton-92, neutrons, gamma radiation, and a lot (200 MeV) of energy. Write a balanced nuclear equation that represents the induced fission of U-235. How many neutrons are produced? How many protons and neutrons are in U-235?
e. Boron neutron capture therapy is a cancer therapy. Boron-10 captures a neutron to form lithium-7, gamma radiation, 2.4 MeV of energy, and a type of particle radiation. Write a balanced nuclear equation that represents the boron neutron capture reaction. What type of particle radiation is produced?
Answers:
a. Superscripts represent mass number.
$^{14}_{6}C$ ---> $^{0}_{-1}e$ + $^{14}_{7}N$
X is nitrogen, which has 7 protons and 7 neutrons (mass number – atomic number = 14 – 7 = 7)
b. $^{40}_{19}K$ ---> $^{0}_{-1}e$ + $^{40}_{20}Ca$
K-40 has 19 protons and 21 neutrons (mass number – atomic number = 40 – 19 = 21)
c. $^{241}_{95}Am$ ---> $^{4}_{2}He$ + $^{237}_{93}Np$
Am-241 has 95 protons and 146 neutrons (mass number – atomic number = 241 – 95 = 146)

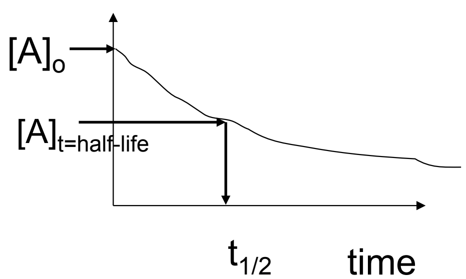
3. Of these two isotopes of gallium, $^{71}_{31}Ga$ and $^{76}_{31}Ga$, one is stable and the other is radioactive.
a. Determine the number of protons, neutrons, and electrons in each isotope.

b. Predict which one is radioactive. Give reasons. (Hint: elements with an atomic number > 83 are radioactive. Isotopes with an odd number of protons and odd number of neutrons are almost always radioactive.)
c. For the radioactive isotope, predict whether it is an alpha emitter or beta emitter. Write a balanced nuclear equation that shows its decay. (Hint: In general, heavy elements are alpha emitters and light elements are beta emitters.)
Answers:

a. $^{71}_{31}Ga$ has 31 protons, 31 electrons, and 40 neutrons. $^{76}_{31}Ga$ has 31 protons, 31 electrons, and 45 neutrons.

b. Predict: Ga-76 is radioactive because this isotope has an odd number of protons and neutrons.
Ga-71 is stable.
c. Predict: Ga-76 is a beta emitter because it is a light element.
$^{76}{}_{31}\text{Ga} \longrightarrow {}^{0}{}_{-1}\text{e} + {}^{76}{}_{32}\text{Ge}$

4. We studied reaction rates earlier in Chem 1B.
The rate (speed) of a radioactive decay reaction is first order in the radioactive isotope. E.g., ^{14}C decay is 1st order:
$^{14}C \longrightarrow {}^{0}e + {}^{14}N$ rate = k N^1 where N = number of ^{14}C nuclei in sample, k = rate constant
The half-life of a first order reaction is $t_{1/2} = 0.693/k$.
For ^{14}C, $t_{1/2}$ = 5,730 years. This means half of the original sample has undergone radioactive decay after 5,730 years. After another 5,730 years, half of the remaining sample (or ½ x ½ = ¼ of original sample) has decayed.
a. Draw a graph of N vs. time for the radioactive decay of ^{14}C.
b. If the original amount of ^{14}C is 2 g, how many g are left after 4 half-lives? How many years have elapsed?
c. Your analysis of a fossil sample shows 0.1 g of ^{14}C. How many g of ^{14}C was in the sample about 17,000 years ago?
d. The Earth is believed to be about 5 billion years old. The half life of U-238 is 4.5 billion years. How much U-238 remains from the birth of the Earth?
e. (i) The rate of radioactive decay of a radioactive isotope is _____. (Hint: See order.)
(ii) Would you rather be exposed to a radioisotope with a long half-life or short half-life? Give reasons. (Hint: how is half-life related to rate?)
Answers:
a. This graph is from the Objective 13 Lecture slide 39.
For the radioactive decay of ^{14}C, substitute N (the number of radioactive ^{14}C nuclei) for A.
A_o is the initial amount of ^{14}C nuclei in the sample.



b. after 1 half-life (5730 years), 1 g of ^{14}C remains.
after 2 half-lives (2 x 5730 years), 0.5 g of ^{14}C remains.
after 3 half-lives (3 x 5730 years), 0.25 g of ^{14}C remains.
after 4 half-lives (4 x 5730 years = 22920 years), 0.125 g of ^{14}C remains.
c. 0.1 g of ^{14}C
1 half-life (5730 years) ago, 0.2 g of ^{14}C.
2 half-lives (2 x 5730 years = 11460 years), 0.4 g of ^{14}C.
3 half-lives (3 x 5730 years = 17190 years), 0.8 g of ^{14}C.
d. about half of the original amount of U-238 remains from 5 billion years ago.
e. (i) 1st order. So $k = 0.693/t_{1/2}$.
(ii) long half-life so slower rate (smaller k) and less exposure to radiation.

5. In a 70 kg human, there is 1.6×10^4 g of carbon. A very small amount of this carbon is radioactive carbon-14. The relative abundance of radioactive carbon-14 is 1 carbon-14 in 10^{12} C. Carbon-14 is a beta emitter with a half-life of 5730 years. The mass destroyed per disintegration is 7.85×10^{-32} kg.
a. Write a balanced nuclear equation that shows the radioactive decay of carbon-14. What is the order of this reaction and any radioactive decay reaction?
b. Calculate the number of carbon-14 nuclei in a 70 kg human.
c. Calculate the radiation exposure in mrem/year from carbon-14.

d. How is carbon-14 used to date fossils? (Hint: compare the ratio of carbon-12 to carbon-14 in a living organism vs. a dead one.)

Answers:

a. ${}^{14}_{6}C$ ---> ${}^{0}_{-1}e$ + ${}^{14}_{7}N$

1^{st} order reaction: rate = k N, where N = number of radioactive nuclei in sample

b. 1600 g C (1 mole/12 g)(1 ${}^{14}_{6}C$/1x10^{12} total C)(6.02x10^{23} nuclei/mole) = 8.03x10^{14} nuclei of ${}^{14}_{6}C$ in 70 kg human

c. rate = k N

k = 0.693/ $t_{1/2}$ = 0.693/5730 yr = 0.000121 yr^{-1}.

N = 8.03x10^{14} nuclei of ${}^{14}_{6}C$ in 70 kg human

So rate = (9.71x10^{10} yr^{-1})(8.03x10^{14} nuclei) = 9.71x10^{10} yr^{-1}.

Mass destroyed per nuclei = 7.85x10^{-32} kg

Energy produced from mass destruction of one ${}^{14}_{6}C$ nucleus: E = mc^2 = (7.85x10^{-32} kg)(3.00x10^{8} m/sec)^2 = 7.06x10^{-15} J/nucleus

E from number of ${}^{14}_{6}C$ that disintegrate in 1 year =

(Energy produced from mass destruction of one ${}^{14}_{6}C$ nucleus)(rate of ${}^{14}_{6}C$ decay)

= (7.06x10^{-15} J/nucleus)(9.71x10^{10} yr^{-1}) = 0.000686 J/yr

1 rad = 10^{-2} J/kg of tissue

Do a conversion: (0.000686 J/yr)(1 rad/10^{-2} J/kg of tissue)(1/70 kg) = 0.00098 rad

1 rem = 1 rad x RBE

RBE of beta particle = 1

Do a conversion: 0.00098 rad (1 rem/1 rad x 1 RBE) = 0.00098 rem

So radiation exposure = 0.98 mrem per yr.

d. From https://en.wikipedia.org/wiki/Radiocarbon_dating: "During its life, a plant or animal is in equilibrium with its surroundings by exchanging carbon either with the atmosphere or through its diet. It will, therefore, have the same proportion of ^{14}C as the atmosphere, or in the case of marine animals or plants, with the ocean. Once it dies, it ceases to acquire ^{14}C, but the ^{14}C within its biological material at that time will continue to decay, and so the ratio of ^{14}C to ^{12}C in its remains will gradually decrease. Because ^{14}C decays at a known rate, the proportion of radiocarbon can be used to determine how long it has been since a given sample stopped exchanging carbon – the older the sample, the less ^{14}C will be left."

To determine the age of a fossil,

Rate = ΔN/Δt = k N

Rearrange: ΔN/N = k Δt

Use calculus, take integral of each side of equation and solve: ln (N_f/N_o) = -k t

k = 0.693/ $t_{1/2}$ for a 1^{st} order radioactive decay reaction so substitute k into above equation: ln (N_f/N_o) = -(0.693/ $t_{1/2}$) t

Solve for t = (ln (N_f/N_o))($t_{1/2}$/ 0.693)

$t_{1/2}$ for C-14 = 5730 yr

N_f/N_o = % of C-14 in sample compared to the amount in living tissue

Reference: https://science.howstuffworks.com/environmental/earth/geology/carbon-142.htm

6. Radon is a source of concern for homeowners.

a. Where does radon come from? See Nuclear Radiation Lecture Slide 24 on the U-238 decay series. Write the nuclear equations that show how radon is produced.

b. See Nuclear Radiation Lecture Slide 24 on the U-238 decay series.

(i) Which isotope has the largest k? Give reasons.

(ii) After one month, which isotope is present is the highest amount? Give reasons.

(iii) Which isotope limits the amount of other isotopes produced?

c. In the U-238 decay series, radon is the only isotope that is a gas. Why does radon being a gas make radon so dangerous?

d. Is radon more or less dangerous than carbon-14? Give reasons. Consider state of matter, radioactive decay type, half-life and other.

e. Radon gas was detected in the chemistry stockroom. Since a very small amount of radon was detected, you calculate the approximate time required for 90% of the radon to decay. How much lab time will you miss? (Hint: see half-life and number of half-lives for 90% of a sample to decay.)

Answers:

a. Radon comes from radioactive decay of U-238.

${}^{238}_{92}U$ ---> ${}^{4}_{2}He$ + ${}^{234}_{90}Th$

${}^{234}_{90}Th$ ----> ${}^{0}_{-1}e$ + ${}^{234}_{91}Pa$

${}^{234}_{91}Pa$ ----> ${}^{0}_{-1}e$ + ${}^{234}_{92}U$

${}^{234}_{92}U$ ---> ${}^{4}_{2}He$ + ${}^{230}_{90}Th$

$^{230}_{90}Th \text{ ---> } ^{4}_{2}He + ^{226}_{88}Ra$
$^{226}_{88}Ra \text{ ---> } ^{4}_{2}He + ^{222}_{86}Rn$
b. (i) largest k should have shortest half life ($k = 0.693/ t_{1/2}$) so Po-214.
(ii) Isotope with longest half life is present in the highest amount so U-238.
(iii) Isotope with longest half life limits the amount of other isotopes present so U-238.
This is like the rate determining step (slowest step) in a reaction mechanism.
c. Radon gas can be inhaled into our lungs where the alpha particles can do a lot of damage.
d. Rn-222 is an alpha emitter with a half-life of 3.8 days. Radon is a gas.
C-14 is a beta emitter with a half-life of 5730 years. The state of matter of C-14 depends. Elemental carbon is graphite or coal, which are solids. Many compounds contain carbon, which have different states of matter, e.g., CO_2 is a gas, C_2H_5OH (ethanol) is a liquid, $C_6H_{12}O_6$ (glucose) is a solid.
Alpha particles are blocked by paper and skin but ionizes living tissue (RBE = 30) so as long as radon is outside of your body, you are safe. But if radon is inhaled and gets in your body, then it is very dangerous.
Beta particles are blocked by Al foil and lab coats (RBE = 1) so as long as you are covered (keep your clothes on!), you are safe.
e. Rn-222 has a half-life of 3.8 days.
If initial mass of Rn = 1 g,
after 1 half-life (3.8 days), 0.5 g of Rn remains = 50% decay.
after 2 half-lives (2 x 3.8 days = 7.6 days), 0.25 g of Rn remains = 75% decay.
after 3 half-lives (3 x 3.8 days = 11.4 days), 0.125 g of Rn remains = 87.5% decay.
after 4 half-lives (4 x 3.8 days = 15.2 days), 0.0625 g of Rn remains = 93.75% decay.
You will miss two weeks of lab.

7. Uranium-235 undergoes induced fission and is used in nuclear power plants or weapons. In induced fission, a U-235 nucleus captures a neutron to form U-236. The unstable U-236 decays to form Ba-144, Kr-89, neutrons, gamma rays, and energy. The neutrons initiate a chain reaction.
a. How many neutrons are formed in the U-235 induced fission reaction? Write a balanced nuclear reaction to support your answer.
b. How is the chain reaction different in a nuclear power plant and in a nuclear bomb?
c. Describe how a light water nuclear power plant works. Include the substance(s) used in the fuel rods, control rods, moderator, and coolant.
d. How does the plant work to produce electricity?
e. What type(s) of radiation would you encounter if you worked in a nuclear power plant? Identify the specific source of each type of radiation. For one radiation type, write a nuclear equation that shows the source of radiation.
f. What is one advantage of nuclear power? What is one disadvantage of nuclear power?
g. The scientific community believes the earth's climate is changing due to global warming. Global warming is caused by the burning of fossil fuels. Which fuel, fossil fuels or nuclear fuel, is cleaner? Give reasons. (See The World's Foremost Environmentalist Weighs In On Nuclear Power, SOURCE: http://www.washingtonpost.com/wp-dyn/content/article/2006/04/14/AR2006041401209.html)
h. Would you want a nuclear power plant in your backyard? Give reasons.
Answers:
a. $^{235}_{92}U + ^{1}_{0}n \text{ ---> } ^{236}_{92}U \text{ ---> } ^{141}_{56}Ba + ^{92}_{36}Kr + 3\ ^{1}_{0}n + \; + 200$ MeV
$^{35}_{92}U$ is unstable
Other fission products (called "daughters") besides $^{141}_{56}Ba + ^{92}_{36}Kr$ can form.
3 neutrons are formed. Each neutron collides with another U-235 nucleus to induce another fission reaction ==> chain reaction.
b. Chain reaction in a nuclear power plant is controlled (by limiting the number of neutrons to induce fission).
Chain reaction in a nuclear bomb is uncontrolled so many neutrons cause many fission reactions ==> explosion.
c and d. Nuclear nuclear power plant:
fuel rods = U-235 enriched to 2-3% (natural % abundance = 0.7%).
control rods = substance that absorbs neutrons without fissioning itself. Control rods control reaction rate by limiting the number of neutrons that react with U-235. Control rods are made of B, Cd, Ag, In, and are inserted in the reactor core between the fuel rods.
moderator = water of a substance that reduces the velocity of fast neutrons. The fast neutrons become thermal neutrons that can sustain a nuclear chain reaction involving U-235.
coolant = water to keep reactor cool.
The fission reaction produces heat. The heat is transferred to the coolant (water), which circulates past the reactor core. The water turns to steam that is pressurized to drive turbines. The work produced by the turbine is used to generate electricity (physics: spin a magnet around a coil or coil around a magnet).

e. With U-235 fuel, would encounter alpha particles, neutrons, gamma radiation, and beta particles if fission products form beta emitters.

f. Nuclear power advantage: clean energy (no green house gas emissions), U is very energy dense fuel, safe (a person living within 50 miles of a nuclear plant receives less radiation from it in a year than you get from eating one banana). Nuclear power disadvantage: politics (the term “nuclear” does not inspire confidence), nuclear waste disposal (the retired fuel from 50 years of U.S. reactor operation could fit in a single football field; it amounts to 77,000 tons. A large coal-fired plant produces ten times as much solid waste in one day, much of it hazardous to health. We discard 179,000 tons of batteries annually-- they contain toxic heavy metals), limited life span (around 15-30 years), expensive to decommission old plants.

g. Nuclear fuel is cleaner than fossil fuels: nuclear energy is clean energy with no green house gas emissions, U is very energy dense fuel (a lot of energy is produced per g compared to other fuels). If you got all of your electricity for your lifetime solely from nuclear power, your share of the waste would fit in a single soda can. If you got all your electricity from coal, your share would come to 146 tons: 69 tons of solid waste that would fit into six rail cars and 77 tons of carbon dioxide.

h. Although a person living within 50 miles of a nuclear plant receives less radiation from it in a year than you get from eating one banana), it does not look as nice as a tree in my backyard because I’ve been socialized to believe trees are more aesthetically pleasing than a nuclear power plant.