Activity 10 Solutions: Ionizing Radiation I

10.1 What is Ionizing Radiation?

1) Stable and Unstable Nuclei

a) Watch the demonstration of isotopes placed near a Geiger counter. Geiger counter clicks indicate unstable nuclei. Record the results of the experiment.

Isotope	Geiger counter clicks?	Stable or Unstable?
$^{238}_{92}U$ (uranium-238)	__**yes**__	__**unstable**__
$^{207}_{82}Pb$ (lead-207)	__**no**__	__**stable**__
$^{26}_{13}Al$ (aluminum-26)	__**no**__	__**stable**__
$^{226}_{88}Ra$ (radium-226)	__**yes**__	__**unstable**__

b) The Geiger counter clicks when it detects ionizing radiation. Which of these isotopes are radioactive? ___**Uranium and radium**___

c) Why are unstable nuclei radioactive?

Materials containing atoms with unstable nuclei are radioactive. As the nuclei decay, they give off some combination of types of ionizing radiation depending on the nuclear reaction.

2) Ionizing radiation

a) What is an alpha particle (α)? What is the electric charge of an alpha particle?

An alpha particle is made up of a helium nuclei – 2 protons and 2 neutrons ($^{4}_{2}He$). Since an alpha particle has two protons, it has a charge of +2.

b) What are the two types of beta particles (β)? What is the electric charge of each type of beta particle?

A beta particle can be an electron (β^-) and have an electric charge of –1. A beta particle can also be an antielectron (β^+), which is also called a positron. An antielectron has a charge of +1.

c) What is a gamma particle (γ)? Do gamma particles have an electric charge?

Gamma particles are photons of high energy electromagnetic radiation. Gamma particles have no electric charge.

d) Which type of ionizing radiation has the most ionizing ability? Why?

Alpha particles have the most ionizing ability. Because an alpha particle is much heavier than an electron (a beta particle), it moves more slowly. Also, each alpha particle has two electric charges. For both reasons, an alpha particle is more ionizing than a beta particle.

e) Which type of ionizing radiation has the least ionizing ability? Why?

Gamma particles have the least ionizing ability because they have no electric charge.

3) Summary of Ionizing Radiation

Fill in the table below, which summarizes the properties of the types of ionizing radiation.

Radiation	Particle emitted	A = # of nucleons	Z = # of protons	Electric Charge
alpha (α)	**helium nuclei ($^4_2$He)**	**4**	**2**	**+2**
beta (β^-)	**electron (e^-)**	**0**	**0**	**-1**
beta (β^+)	**antielectron (e^+)**	**0**	**0**	**+1**
gamma (γ)	**high energy photon**	**0**	**0**	**0**

4) Radioactive decay of large unstable nuclei

a) Why are large nuclei with more than 83 protons unstable?

The strong nuclear force that binds the nucleus operates over a very short distance. In large nuclei, the strong force cannot bind the nucleons tightly enough to overcome the long-range repulsive electromagnetic force between the positively charged protons.

b) Which type of radioactive decay (α, β, or γ) would reduce the size of a nucleus?

Alpha decay emits a helium nuclei ($^4_2$He). The nucleus is reduced in size by two protons and two neutrons.

c) What happens to the identity of the nucleus after this type of decay?

Since the nucleus loses two protons, we now have a nucleus of a different element – an element with two fewer protons than the original nucleus.

5) Radioactive decay of small unstable nuclei

a) Why are some isotopes of small nuclei unstable?

Most isotopes of small nuclei (20 or fewer protons) are unstable if they have unequal numbers of protons and neutrons.

b) Which type of radioactive decay (α, β, or γ) would make such isotopes more stable?

Beta decay makes an isotope more stable by changing the electric charge of the nucleus. The charge of the nucleus is increased by 1

when an electron (β^-) is emitted. In this case, one neutron is changed into a proton. The nucleus charge is decreased by 1 when an antielectron (β^+) is emitted. In this case, one proton is changed into a neutron.

c) Group Discussion Question: Which types of decay (alpha, beta plus, beta minus, or gamma) result in the formation of nuclei of a different element?

6) Ionizing radiation in a cloud chamber

Your instructor will show you radiation events in a cloud chamber.

a) How does a cloud chamber detect radiation? Why are alcohol and the dry ice needed?

The alcohol vapor in the cloud chamber is cooled (by the dry ice) slightly below the temperature at which it would normally condense into droplets; the vapor is said to be supercooled. Ions are produced along the paths of the particles that result from the decay of the radioactive sources. These ions seed the supercooled vapor and tiny raindrops form around the ions, leaving a visible tracks. The tracks also reveal the ionization density of the source, since some tracks appear thicker (more droplets) than others.

b) How do the trails of alpha particles compare with those of beta particles? Why?

Alpha particles are much heavier than beta particles and have twice the electric charge of beta particles, so the alpha particles will leave denser trails. For the same reason, the alpha particles lose energy faster and travel a shorter distance than the beta particles.

10.2 How do Unstable Nuclei Decay?

7) Conservation laws

a) What is conservation of charge? How does this conservation law apply to a nuclear reaction?

Conservation of charge tells us that electric charge cannot be created or destroyed. In a nuclear or a chemical reaction, the net electric charge of the products must equal the net charge of the decaying nucleus.

b) What is conservation of nucleon number? How does this conservation law apply to a nuclear reaction?

Conservation of nucleon number tells us that the total number of nucleons in a nuclear reaction does not change. While protons can be converted into neutrons, or neutrons into protons, the total number of neutrons plus protons does not change during a nuclear reaction.

c) The radioactive isotope thorium-232 ($^{232}_{90}Th$) decays into radon-228 ($^{228}_{88}Ra$) and emits a particle of ionizing radiation.

i) Write an equation that describes this nuclear reaction.

$$^{232}_{90}\mathbf{Th} \rightarrow {}^{228}_{88}\mathbf{Ra} + {}^{4}_{2}\mathbf{He}$$

ii) Which ionizing particle is emitted? __**an alpha particle**__

d) Uranium-238 decays by emitting an alpha particle.

i) Write an equation that describes this reaction.

$$^{238}_{92}\mathbf{U} \rightarrow {}^{4}_{2}\mathbf{He} + {}^{234}_{90}\mathbf{X}$$

ii) Which element is formed after this decay?

The periodic chart shows that the element with 90 protons (Z = 90) is thorium (Th).

$$^{238}_{92}\mathbf{U} \rightarrow {}^{4}_{2}\mathbf{He} + {}^{234}_{90}\mathbf{Th}$$

8) Neutrinos and Conservation of Energy and

a) What is conservation of energy?

Conservation of energy tells us that the energy of the products of a reaction must equal the energy of the reactants.

b) The electrons and antielectrons (β^- and β^+) emitted during beta decay of a particular isotope have varying amounts of energy. How does the cloud chamber image show this?

Different beta particles leave trails of different lengths. Thus, these beta particles must have different amounts of kinetic energy.

c) Beta particles from the decay of identical nuclei can have varying amounts of energy. To preserve conservation of energy, a beta decay reaction must emit another type of particle called a neutrino (ν).

What is a neutrino? Does a neutrino have an electric charge?

Neutrinos are very light particles emitted during beta decay. Since neutrinos are not seen in the cloud chamber, they are not ionizing and they must have no electric charge.

10.3 Examples of Radioactive Decay

9) Beta Plus Decay (β^+) Using plastic chips, make up a nucleus of protons and neutrons. The white sides of the chips represent neutrons and the orange sides represent protons. Turn a chip from its orange side to its white side to represent a proton changing into a neutron. Then open the box marked "beta plus decay" to see the products of this reaction.

a) Write the equation for the nuclear reaction that occurs when a when a proton in a nucleus emits an antielectron and becomes a neutron.

$$^{1}_{1}\mathbf{p} \rightarrow \, ^{1}_{0}\mathbf{n} + \, ^{0}_{1}\mathbf{e}^{+} + \, ^{0}_{0}\nu \ \textbf{+ energy}$$

b) Why is an antielectron, rather than an electron, emitted in this reaction?

To satisfy conservation of electric charge, the right side of the reaction must have one positive charge.

c) What does the spring represent?

The springs represent the energy emitted in the reaction.

10) *Conservation of Leptons and Antineutrinos*

a) Leptons are light-weight particles, such as electrons and neutrinos. What is conservation of leptons?

Whenever a lepton is emitted, an antilepton must also be emitted.

i) When an antielectron is emitted, is a neutrino (ν) or an antineutrino ($\overline{\nu}$) emitted?

To satisfy conservation of leptons, a neutrino is emitted.

ii) When an electron is emitted, is a neutrino or an antineutrino emitted?

an antineutrino

11) *Beta Minus Decay* (β^{-}) Turn a chip in your nucleus from its white side to its orange side to represent a neutron changing into a proton. Then open the box marked "beta minus decay" to see the products of this reaction.

a) Write the reaction that occurs when a neutron emits an electron and becomes a proton.

$$^{1}_{0}\mathbf{n} \rightarrow \, ^{1}_{+1}\mathbf{p} + \, ^{0}_{-1}\mathbf{e} + \, ^{0}_{0}\overline{\nu} + \ \textbf{energy}$$

b) Why is an electron, rather than an antielectron, emitted in this reaction?

Since a neutron is electrically neutral, the left side of the reaction has zero electric charge. To satisfy conservation of charge, the right side of the reaction must also have zero charge.

c) Why is an antineutrino, rather than a neutrino, emitted?

To satisfy conservation of leptons, leptons are emitted in pairs of matter and antimatter. Since an electron is a lepton, the light weight particle emitted with the electron must be an antilepton (an antineutrino).

12) Gamma Decay (γ) Some unstable nuclei emit gamma particles. Open the box marked "gamma decay" to see what a gamma particle is.

a) What is a gamma particle?

A high energy photon of radiant energy.

b) What is the charge of a gamma particle? What is its mass?

Like all photons, the gamma photon has zero electric charge and zero rest mass.

c) Why do nuclei emit gamma particles?

Just like the electrons in an atom can be in an excited state, the protons and neutrons that make up a nucleus can be in an excited state. This is often the case after a nucleus has emitted an alpha or beta particle. When the nucleus decays to a lower energy state, keeping its number of neutrons constant and its number of protons constant, the nucleus emits a gamma particle.

13) Examples of Nuclear Reactions

a) Oxygen-14 ($^{14}_{8}\mathbf{O}$) is an unstable isotope of oxygen. Arrange orange and white plastic chips to represent this isotope. Draw a diagram of your arrangement.

8 orange chips (for 8 protons) and 6 white chips (for 6 neutrons)

b) Why is this isotope unstable?

This nucleus has more protons than neutrons. Small stable nuclei have equal numbers of protons and neutrons.

c) How would $^{14}_{8}\mathbf{O}$ decay to become stable? Change the plastic chips and open the appropriate box to illustrate this decay. What change to the chips did you make? Which box did you open?

To make a stable nucleus, one proton must change into a neutron. Turning over one orange chip to its white side illustrates this change. To satisfy conservation of charge, a positive antielectron must be emitted, which is represented by the contents of the "beta plus" box.

d) Is the decay product an isotope of oxygen? If not, what element has the nucleus become?

Because the nucleus now has 7 protons, it is nitrogen.

e) In part c), you turned over an orange chip to its white side to represent a proton changing into a neutron. Rearrange these chips so that the orange chips (protons) are separated from one another as much as possible by white chips (neutrons). Rearranging the chips (nucleons) is a transition accompanied by the emission of which type of ionizing radiation – alpha, beta, or gamma?

Since the number of white chips (neutrons) and the number of orange chips (protons) remains the same, this is a transition in which a gamma particle is emitted.

10.4 What Is the Composition of a Nucleon?

Your instructor will discuss the composition of nucleons, which consist of quark trios held together by gluon clouds.

14) Quarks

a) What is a quark?

Quarks are the fundamental particles that make up neutrons and protons.

i) What is the electric charge of an "up" quark? $+\frac{\mathbf{2}}{\mathbf{3}}$

ii) What is the electric charge of a "down" quark? $-\frac{\mathbf{1}}{\mathbf{3}}$

b) What is the spin of a quark?

Like almost all particles, quarks have a rotation about their axes called intrinsic spin. The intrinsic spin of quarks (and leptons) = ½.

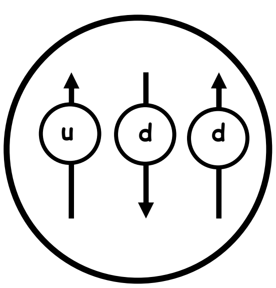
c) Place two of the green model "down" quarks side by side. In which directions do the spins of two quarks point?

The spins of two quarks of the same type must point in opposite directions. If the spin of one of the down quarks points in one direction, the other down quark must be placed so that its spin points in the opposite direction.

15) Formation of Neutrons

Place orange or green "quarks" into the metal "gluon cloud" to represent a neutron. (Hint: what is the electric charge of a neutron?)

a) Draw a diagram showing the quarks in the neutron.



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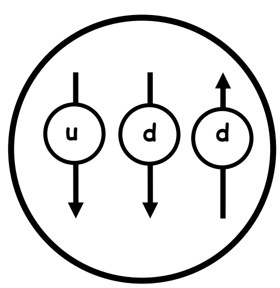


b) Each quark has a spin of ½. What is the total spin of a neutron? __**1/2**__

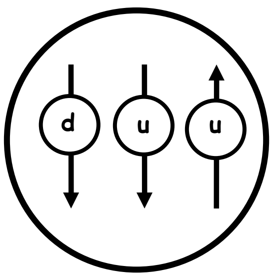
c) Why does this arrangement of the 3 quarks result in a spin of ½ for the neutron?

Since each quark has a spin of ½, the spins of two of the quarks will point in the same direction (spin = ½ + ½ = 1), and the spin of the third quark must point in the opposite direction. Two quarks of the same type cannot have the same spin direction, therefore, the spins of the two down quarks must point in opposite directions.

16) Formation of Protons

Place orange or green "quarks" into the metal "gluon cloud" to represent a proton. Make sure the spin of the proton points in the same direction as the spin of the neutron in part a). (You may need to rotate the metal gluon cloud.)

a) Draw a diagram showing the quarks in the proton.



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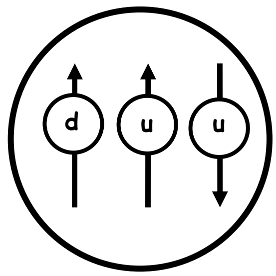

b) What is the total spin of a proton? __**1/2**__

c) Why does this arrangement of the 3 quarks result in a spin of ½ for the proton?

Similar to the neutron, the spins of two of the quarks will point in the same direction (spin = ½ + ½ = 1), and the spin of the third quark must point in the opposite direction. Since two quarks of the same type cannot have the same spin direction, the spins of the two up quarks must point in opposite directions.

d) Which of the four fundamental forces is involved in binding quarks into nucleons? **the strong nuclear force**

e) The exchange of which type of gauge boson is responsible for binding quarks into nucleons? **the gluon**

f) Group Discussion Question: How is the gluon cloud model of a nucleon related to flipping an orange or a white chip?