Chapter 9: Ionizing Radiation

Goals of Period 9

Section 9.1: To describe the types of ionizing radiation
Section 9.2: To discuss detection of ionizing radiation
Section 9.3: To describe the sources of ionizing radiation
Section 9.4: To use conservation of electric charge and nucleon number to predict the products of radioactive decay

In Period 8 we saw that some nuclei are unstable. Unstable isotopes can decay into more stable nuclei by emitting radiation. Next we examine the types of this ionizing radiation, how it can be detected, and how nuclei decay. In a future period, we will consider the potential harmful effects of this radiation on living cells and some of the beneficial medical and scientific applications of ionizing radiation.

9.1 Types of Ionizing Radiation

In the early days of the study of radioactivity, around 1900, it was soon learned that there were at least three different types of radiation emerging from radioactive nuclei. This was inferred from the very different amounts of material through which the three kinds of radiation can penetrate. The three types of radiation were given the names alpha (α), beta (β), and gamma (γ), in order of increasing ability to penetrate through material. These were collectively called ***ionizing radiation*** because of their ability to strip one or more electrons away from atoms in whatever material they pass through. Recall that atoms that have lost one or more electrons are called ions.

Later, after many experiments, it became clear that alpha, beta and gamma radiation are really particles emitted by the radiating nucleus. Alpha particles were found to be helium nuclei ($^{4}_{2}He$). Alpha particles are expelled by very heavy unstable nuclei trying to make themselves smaller and thus more stable. Beta particles were found to be electrons (e^-). Electrons are emitted from unstable nuclei when a neutron changes into a proton. Finally, gamma radiation was identified as very energetic photons (particles of radiant energy), which are emitted when a nucleus falls from an excited state to its ground state.

Decades later, in the 1930's, it was discovered that neutrons can also be emitted when a nucleus decays. This happens when a very large nucleus such as uranium spontaneously ***fissions***, or splits apart into two pieces. It was also learned that radioactive nuclei are not the only natural source of ionizing radiation. Another source is very energetic protons from outer space, called ***cosmic rays.*** In addition to these natural sources of ionizing radiation, there are man-made sources of ionizing radiation, such as x-ray machines. X-ray are produced by a process that does not involve a change in an atomic nucleus.

9.2 Detection of Ionizing Radiation

In this period, you will see three examples of detectors that measure ionizing radiation: photographic film, Geiger counters, and a cloud chamber.

Film

The energy deposited by ionizing radiation in photographic film causes chemical changes in the film, much as light does. Natural radioactivity was accidentally discovered in this way. Film is also the primary way in which X-rays are used and detected.

Geiger counter

A Geiger counter is an example of a class of detectors that produce an electrical signal each time an ionizing particle passes through. Inside the metal tube of a Geiger counter, a thin wire is held at a high voltage in an insulating gas. This voltage is almost high enough for a spark to jump from the wire to the wall of the tube. When an ionizing particle passes through the gas in the tube, the ions and free electrons that are produced provide free (mobile) charges, and the gas suddenly becomes a conductor, producing a spark. A spark thus occurs each time an ionizing particle passes through the gas in the counter tube. The electrical signal from these sparks is amplified, and is heard as clicks from a loudspeaker.

Cloud chamber

A cloud chamber is one example of a detector that produces a visible track along the path of ions left by the passage of an ionizing particle. Inside the cloud chamber, a vapor is cooled slightly below the temperature at which it would normally condense into droplets; the vapor is said to be ***supercooled***. This supercooled condition occurs also in some high-altitude clouds. In that case, seeding the clouds with dry ice can cause raindrops to form. In a cloud chamber, the ions along a particle track have a similar effect; tiny raindrops form around these ions, making a visible track. Cloud chambers not only show you where the particles went, but also how much ionization they produce. As we will see, alpha particles leave dense trails (lots of ions per centimeter of path), while beta particles make thin trails (fewer ions per centimeter of path). Gamma particles leave no perceptible track.

9.3 Sources of Ionizing Radiation: Radioactive Decay

What governs the way in which a given unstable nucleus might decay? Why do some decay by alpha emission, and some by beta emission? Why aren't there many other ways to decay? As is the case with chemical reactions, nature places restrictions on which nuclear reactions and radioactive decays can occur. These restrictions are in the form of conservation laws. We have studied two of these laws: the laws of conservation of energy and of conservation of electric charge. In the nuclear domain, the law of conservation of charge is found to remain valid, as is the law of conservation of energy. (However, a new kind of energy must be added to the list of forms of energy, and we must introduce beta particles that have a positive charge.)

In addition to these conservation laws, a new conservation law was discovered in nuclear experiments, the law of conservation of nucleon number. This law says that in all nuclear reactions, including nuclear decays, the number of nucleons is conserved. The number of protons and the number of neutrons may change in such a reaction, as long as the total number of protons plus neutrons does not change. Further discussion and examples of these conservation laws is given below.

Among decays allowed by conservation laws, a given unstable isotope will choose decays that result in increased binding energy. These decays bring the nucleus closer to equilibrium. In the previous period, we discussed two reasons why a nucleus might be unstable. These were: a) electrical repulsion from a very large number of protons; b) a ratio of neutrons to protons which is not optimal. Alpha and beta decays are ways, consistent with conservation laws, to cure these causes of instability.

Alpha Decay

Very heavy (large Z) isotopes are unstable because of the electrical repulsion among the large number of protons. Only one isotope with a Z higher than that of lead (Z = 82) is stable. Very heavy unstable nuclei decay mainly by alpha emission, in which a helium nucleus containing two protons and two neutrons is expelled from the heavy decaying nucleus. This is a way for the nucleus to reduce its number of protons and, at the same time, to reduce its number of neutrons in such a way as to preserve about the right ratio of protons to neutrons.

Beta Decay

Beta decays occur because of the weak nuclear force, the fourth of the four fundamental forces in nature. The study of beta decay uncovered some new physical phenomena that no one had expected, including antielectrons, which have a positive charge, neutrinos, and antineutrinos. Beta decay is a way for an unstable nucleus to adjust its ratio of neutrons to protons by changing a neutron into a proton (or vice versa). Neutrons and protons are very much alike except for electric charge. The law of conservation of nucleon number allows one to change into the other, provided that all other conservation laws are satisfied. In order to conserve electric charge, an electron must also be emitted when a neutron changes into a proton.

Isotopes also exist that are unstable because they have too many protons for their number of neutrons. These proton-rich isotopes can also decay by giving off a beta particle. In this case, a proton in the nucleus can turn into a neutron, ejecting an antielectron and a neutrino. The antielectron is the ***antiparticle***, or antimatter twin, of the electron. An antielectron has the same mass as an electron, but has positive charge rather than negative charge. An antielectron is also known as a positron. All known subatomic particles, including the proton and the neutron, have now been found experimentally to have antimatter twins. It is a striking and still unexplained experimental fact that we live in a universe where stars and planets are made of matter and antimatter is extremely rare.

It was discovered experimentally that a new, very light neutral particle was also emitted in beta decay. This new particle came as a complete surprise to everyone. It was named the ***neutrino***, denoted by the Greek letter ν (nu). It turns out that the additional particle should have been recognized as an antineutrino $\overline{\nu}$, since production of a new particle (the electron) has been found to require the simultaneous production of an antiparticle. Thus, the beta decay reaction in which a neutron turns into a proton is $n \rightarrow p + e^- + \bar{\nu}$, where $\bar{\nu}$ denotes an antineutrino. The beta decay reaction in which a proton turns into a neutron is $p \rightarrow n + e^+ + \nu$. Because the e^+ is an antiparticle, a neutrino, rather than an antineutrino, is required in this case.

9.4 Conservation of Charge and of Nucleon Number

Conservation of electric charge, as applied to nuclear reactions and decays, requires that the total electric charge of the reactants must be the same before and after the reaction. Conservation of charge can also be stated as requiring that the sum of the atomic numbers Z of the reactants be the same before and after the reaction. This is because Z measures the charge of a nucleus in units of the proton charge. Conservation of nucleon number, as applied to nuclear reactions and decays, can be stated as requiring that the sum of the atomic mass numbers A of the reactants be the same before and after the reaction. This is because A is by definition the number of nucleons in a nucleus. In many cases, we can predict the decay of unstable isotopes by applying the principles of conservation of electric charge and nucleon number. Table 9.1 summarizes the types of ionizing radiation and their charge and nucleon numbers. Neutrinos and antineutrinos do no appear on this list because, although they always accompany the production of the ionizing particles e^- and e^+, they do not themselves produce ionization.

Table 9.1 Summary of Ionizing Radiation

Radiation	Emission product	A = # of nucleons	Z = # of protons	Electric Charge
alpha (α)	helium nuclei (^4_2He)	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

(Example 9.1)

Thorium-232 ($^{232}_{90}Th$) decays into radon-228 ($^{228}_{88}Ra$). Use conservation of charge and nucleon number to determine the type of ionizing radiation emitted.

The question can be written as the equation: $^{232}_{90}Th \rightarrow {}^{228}_{88}Ra + {}^{A}_{Z}X$ where X is the unknown decay product. Conservation of nucleon number requires that each side of the equation have equal numbers of nucleons. Therefore, A = 232 – 228 = 4 nucleons. Conservation of charge requires both sides to have equal charge. Therefore, Z = 90 – 88 = 2 protons. The unknown particle has ^4_2X and is a helium nuclei (^4_2He). Thorium-232 decays by alpha emission according to the equation,

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

(Example 9.2)

In a nuclear reaction, one neutron decays into one proton. What type of radiation is emitted?

A neutron can be written as ${}_{0}^{1}\text{n}$ (one nucleon, no charge) and a proton as ${}_{1}^{1}\text{p}$ (one nucleon, one positive charge). The equation for this decay is: ${}_{0}^{1}\text{n} \rightarrow {}_{1}^{1}\text{p} + {}_{Z}^{A}\text{X}$
From conservation of nucleon number, 1 – 1 = 0 nucleons for the decay product. From conservation of charge, 0 – 1 = -1, so the decay product must have a charge of negative 1. The unknown particle has ${}_{-1}^{0}\text{X}$ and is an electron (${}_{-1}^{0}\text{e}$). A neutron decays as

$${}_{0}^{1}\text{n} \rightarrow {}_{1}^{1}\text{p} + {}_{-1}^{0}\text{e} + {}_{0}^{0}\overline{\nu}$$

Recall that when an electron is emitted, an antineutrino ${}_{0}^{0}\overline{\nu}$ is also given off. The antineutrino has zero values of both Z and A because it is not electrically charged and it is not a nucleon.

(Example 9.3)

In a nuclear reaction, potassium-40 (${}_{19}^{40}\text{K}$) decays by emitting one electron. What is the nuclear decay product?

The equation for the reaction is ${}_{19}^{40}\text{K} \rightarrow {}_{-1}^{0}\text{e} + {}_{0}^{0}\overline{\nu} + {}_{Z}^{A}\text{X}$

From conservation of nucleon number, 40 – 0 – 0 = 40 nucleons for the decay product. From conservation of charge, 19 – (-1) - 0 = 20, so the decay product must have a charge of 20, or Z = 20. The unknown decay product has ${}_{20}^{40}\text{X}$. To find the identity of this nucleus, we consult a periodic chart as shown in Figure 9.1 on the next page. The element with Z = 20 is calcium (Ca). Thus potassium-40 decays into calcium-40 according to the equation

$${}_{19}^{40}\text{K} \rightarrow {}_{20}^{40}\text{Ca} + {}_{-1}^{0}\text{e} + {}_{0}^{0}\overline{\nu}$$

(Check for yourself that this equation obeys the laws of conservation of nucleon number and electric charge.)

Concept Check 9.1

a) Use conservation of nucleon number and electric charge to determine A and Z in the reaction ${}_{92}^{238}\text{U} \rightarrow {}_{2}^{4}\text{He} + {}_{Z}^{A}\text{X}$

b) The unknown decay product in the reaction above is a nucleus of which element?

Figure 9.1 The Periodic Chart of Elements

Period 9 Summary

9.1 Ionizing radiation strips electrons from atoms, turning the atoms into charged ions.

Unstable nuclei decay by giving off alpha particles α, beta particles (β^- or β^+) or gamma particles γ.

9.2 Ionizing radiation can be detected by

Film because the energy deposited by ionizing radiation in photographic film causes chemical changes in the film, much as light does.

A Geiger counter because an electrical signal is produced each time an ionizing particle passes through the counter tube. The electrical signal is amplified and heard as clicks from a loudspeaker.

A cloud chamber produces a visible track along the path of ions left by the passage of an ionizing particle.

9.3 Alpha particles (α) are helium nuclei $^{4}_{2}He$ (2 neutrons and 2 protons)

Beta particles are β^- (electrons $^{0}_{-1}e$) or β^+ (antielectrons $^{0}_{+1}e$)

Gamma particles γ are very high energy photons from outer space.

In a beta decay, a neutrino is also emitted. Neutrinos have no charge and very little, if any, mass. An antineutrino is emitted with an electron, and a neutrino is emitted with an electron

A protons can change into a neutron by emitting an antielectron and an neutrino.

$$p \rightarrow n + e^+ + \nu$$

A neutron can change into a proton by emitting an electron and an antineutrino.

$$n \rightarrow p + e^- + \bar{\nu}$$

9.4 Apply conservation of charge and conservation of nucleon number to determine the decay products of a nuclear reaction:

Charge must be conserved so that the number of positive or negative charges (Z) on each side of the reaction is equal.

Mass must be conserved so that the number of nucleons (A) on each side of the reaction is equal.

Period 9 Exercises

E.1 Alpha particle radiation is

a) emission of electrons from radioactive material.
b) high energy photons from outer space.
c) made up of neutrinos and antineutrinos.
d) emission of helium nuclei from radioactive material.
e) made up of two protons and four neutrons.

E.2 Comparing alpha and beta radiation of the same energy,

a) alpha is more ionizing and more penetrating.
b) alpha is more ionizing and less penetrating.
c) alpha is less ionizing and more penetrating.
d) alpha is less ionizing and less penetrating.
e) alpha and beta have the same ionizing and penetrating ability.

E.3 In a nuclear reaction, which of the following quantities are conserved?

a) neutron number, charge, and entropy
b) proton number, charge, and entropy
c) nucleon number, energy, and entropy
d) energy, charge, and nucleon number
e) energy, entropy, and charge

E.4 What are the values of Z and A for the isotope X produced in the decay of plutonium-234 shown below? Which type of ionizing radiation is given off?

$$_{94}\text{Pu} \rightarrow {}^{A}_{Z}\text{X} + {}^{4}\text{He}$$

a) A = 232, Z = 90; β^-
b) A = 234; Z = 90; α
c) A = 234; Z = 92; β^+
d) A = 234; Z = 92; α
e) **NONE** of the answers is correct.

E.5 The isotopes listed below are unstable. For each isotope, indicate whether you would expect the isotope to decay by α, β^- , or β^+. Why?

a) $^{14}_{8}O$ (Oxygen-14)

b) $^{238}_{92}U$ (Uranium-238)

c) $^{23}_{10}Ne$ (Neon-23)

Period 9 Review Questions

R.1 From your experiments in class, roughly what thickness of lead is needed to absorb most of the 1.2 MeV gamma rays from the Cobalt-60 source, $^{60}_{27}Co$?

R.2 How does a cloud chamber work? How can you tell the difference between the tracks of alpha and beta particles in a cloud chamber?

R.3 What is the difference between β^- and β^+ radiation? Why are β^+ particles sometimes called positrons?

R.4 What are neutrinos and antineutrinos? When are they produced?

R.5 Fill in the chart with the characteristics of ionizing radiation.

Particle	**What is it?**	**Charge**	**Ionizing density**	**Penetrating ability**
alpha α				
beta β^-				
beta β^+				
gamma γ				