Chapter 11: Ionizing Radiation and Health

Goals of Period 11

Section 11.1: To describe sources of natural radioactivity
Section 11.2: To discuss the effects of ionizing radiation on living matter
Section 11.3: To estimate our radiation exposure from various sources.

11.1 Natural Radioactivity

The material around us and even in our bodies contains radioactive isotopes at small levels of concentration. In student experiments you will detect ionizing radiation from several such natural sources.

The element potassium (K) is present in the food we eat and is essential for healthy operation of our bodies. However, one K nucleus in every 10,000 is the radioactive isotope $^{40}_{19}K$, a beta emitter with a half-life of 1.3 billion years. This radioactivity is impossible to avoid, since it is always present in our bodies. Beta emission from K-40 is present in dietary salt substitute sold in grocery stores.

All isotopes of uranium are unstable, as are most of the daughters of uranium decay, including radon. Alpha, beta and gamma radiation is produced in the series of decays of uranium and its radioactive daughters. It might appear possible to avoid this source of radiation by staying out of uranium mines. But there are smaller concentrations of uranium in other rock formations and soil scattered throughout the U.S. This mildly radioactive rock and soil can be used in bricks and other building materials and contributes to your natural background radiation exposure. In class, you will detect radiation from some uranium ore samples and look for radioactivity from samples of Ohio brick and stone.

Sometimes natural radioactivity appears in unexpected places. You will detect radioactivity from silk mantles intended for use in camp lanterns. These mantles have been impregnated with thorium salts, whose chemical (not nuclear) properties make the mantles glow when heated. But $^{232}_{40}Th$ (100% natural abundance) happens also to be radioactive, with a half-life of 14 billion years. It decays by alpha emission. Its decay products are also radioactive, and some of them are beta emitters.

Does this mean you shouldn't use camp lanterns? No, but carrying mantles in your pocket for long periods of time is not a good idea. More important, you should avoid eating or inhaling bits of lantern mantle or its ash, since radioactivity inside your body is generally more harmful than that which enters through the skin. Campers should wash their hands after handling lantern mantles.

Other avoidable sources of radiation in commercial products have been found and taken off the market in the last few decades. However, some may still be found in peoples' homes or attics. They include pottery with a pretty orange glaze made from uranium oxide and alarm clocks with bright luminous hands and dials whose source of energy was radium decay.

Ionization Density and Penetrating Ability

The chemical and biological damage done by radiation depends in part on how many atoms are ionized per centimeter of path length, called the ***ionization density***. The trails of ions left by ionizing radiation can be visible in a cloud chamber. Furthermore, the ionization density can also be observed visually. In class you will see tracks from alpha and beta emitters in a cloud chamber and compare the ionization density of their tracks.

Alpha particles from radioactive decays leave dense trails of ionized atoms. They also have low penetrating ability. These aspects are connected, because it requires energy to ionize atoms. Alpha particles spend their kinetic energy quickly by making many ions per centimeter of path, so that their energy is used up after traveling a short distance through matter. Beta particles, which have comparable kinetic energies, spend their energy more slowly by making fewer ions per centimeter of path, and so can go through more material before this energy is used up. Gamma rays (and x-rays) have an even lower ionization density, and thus are even more penetrating.

Why do alpha particles have a much larger ionization density than beta particles? Ionization of atoms in a material is caused by the electrical force between the ionizing particle (alpha or beta) and the electrons in the atoms through which it moves. Electrons are pulled out of these atoms by this electrical force. Recall that alpha particles are $^{4}_{2}\mathrm{He}$ nuclei, while beta particles are electrons or antielectrons. Alpha particles, with two protons (Z=2), carry twice as much electrical charge as beta particles, so the electrical force that alphas can exert is twice as strong. Also, alpha particles usually move much more slowly than beta particles, so that their electrical force has a longer time to act on the atomic electrons to pull them out. Alphas move much more slowly than betas of similar kinetic energy because alphas are about 8000 times heavier. Remember that kinetic energy $E_{kin} = ½ M v^2$. Alphas and betas from nuclear decay both have E_{kin} of approximately an MeV, but alphas have big M and small v, while betas have small M and big v to get a similar E_{kin}.

11.2 Biological Effects of Ionizing Radiation

When ionizing radiation passes through living tissue, it ionizes atoms in the tissue just as it does inside a Geiger tube or a cloud chamber. These ionized atoms can be part of the complex molecules that make up living cell. Ionizing the atoms breaks the chemical bonds in the molecule to which these atoms belong. Furthermore, the ions can do additional chemical damage to even more molecules.

The amount of biological damage that is done depends on how many particles of ionizing radiation passes through the living tissue and on how densely ionizing it is: high ionization density causes more damage than low ionization density. Thus, for example, inhaling or ingesting an alpha-emitting isotope can do lots of damage, because the densely-ionizing alphas are already inside the body and are not stopped by the skin.

Biological damage also depends on the length of time over which the exposure occurred, because living tissue can repair itself from limited damage if given the time. Thus the same amount of radiation is more damaging if delivered in a short time.

There are three adverse effects of significant radiation exposure: killing of cells, genetic damage, and increased risk of cancer.

Killing of cells

Because the body can repair itself, killing of a limited number of cells is generally not serious. Very large radiation exposures, such as those received by some of the people working at the Chernobyl reactor during and immediately after the major accident there, can kill enough cells to depress the blood count and impair immunity to disease. Very large exposures resulted in death for some of the Chernobyl workers.

Genetic damage

If DNA molecules, which carry the genetic instructions, are altered by ionizing radiation, the instructions can become scrambled and mutations can occur when the cell divides. This can lead to inherited defects. It is estimated that the natural radiation background is responsible for only about 2% of all cases of human genetically related diseases. However, there is evidence that developing embryos may be more susceptible to damage, and extra precautions should be taken to minimize radiation exposure to pregnant women.

Increased cancer risk

Cell mutations produced by damaged DNA can result in cancer. This is known to happen for large doses, but the small-dose effects on cancer are very difficult to either establish or refute. This is because cancer takes years or decades to develop and because people are exposed to many other cancer-causing agents during their lifetimes. Increased cancer incidences from additional doses of radiation that are small compared to the natural background level are probably not detectable even with sophisticated statistical methods. Most cancers are not caused by radiation.

Because of the uncertainties in estimating the small-dose effects of radiation, the common-sense approach, which is also public policy, is to keep each person's radiation exposure as low as reasonably achievable. Increased exposure from sources such as medical X-rays must be weighed against their beneficial effects.

11.3 Radiation Exposure from Natural and Medical Sources

How much radiation does the average person receive in a year? How much is avoidable? The major sources of natural and manmade radiation exposure are cosmic rays from outer space, decays of radioactive isotopes that have been incorporated chemically into your body, decays of radioactive isotopes from rocks, soil and building materials, and exposure from medical diagnostics, mostly x-rays. The amount of radiation you actually get in a year depends on where you live and work, how many x-rays you get, and even on how much flying you do.

A common unit of radiation exposure or dose is the ***millirem***, abbreviated mrem. This unit takes into account the different biological damage done by different types of radiation. The average dose for a person living in the U.S. is about 200 mrem per year.

Radioactive decays inside your body

If your home is radon-free, the largest source of radioactive decays inside your body is potassium-40, which accounts for about 8% of the average person's total annual exposure. However, if your home has a serious radon problem, radioactive isotopes from radon decay (radon daughters) can accumulate in your lungs, and increase this internal dose by a factor of 100 or more. Radon is discussed in more detail below.

Cosmic rays

Very high energy protons from outer space are constantly bombarding the atmosphere, producing showers of ionizing radiation. Most of this cosmic ray radiation is absorbed by the atmosphere, just as lead absorbs gamma rays from a radioactive source. However, the higher you go, the thinner the atmosphere protecting you, and the larger your radiation exposure from cosmic rays. A person living at a level of 10,000 feet (typical Rocky Mountain pass) gets 4 times the cosmic ray exposure of a person living at sea level. Commercial jets fly at about 35,000 feet, where the exposure rate is even higher. A 5-hour flight to Europe gives you the equivalent of about one month's worth of sea-level cosmic ray radiation exposure. Flight crews are officially designated radiation workers, just as are nuclear plant employees.

External exposure from rocks, soil and building materials

External exposure means that the ionizing radiation (mainly gamma rays) enters your body from outside sources, as opposed to inhaling something that decays inside your body. This source of radiation exposure also depends on where you live; whether you live on top of a uranium deposit, for example. It is about 4 times larger in the Rocky Mountains than it is in most places along the eastern seaboard.

Exposure from medical diagnostic x-rays

X-rays are the equivalent of low-energy gamma rays. They are photons with typical energies around 0.1 MeV, and their biological effects are similar to those of gamma rays. However, lead shielding for protection against x-rays need not be as thick as that for gamma rays because of their lower energy. The radiation exposure you get from an x-ray depends on the technology used. Old-fashioned fluoroscopes, in which the x-ray image appeared on a glowing screen, gave huge doses of thousands of mrem, many times the yearly exposure of a typical person. Improved technology (sensitive film, for example) has decreased the exposure needed to get the same information. The best procedures give doses of about 6 mrems, but the average is about 200 mrem per x-ray. One such x-ray is about twice the average annual radiation dose from natural sources.

Sources used in Physics 104

The weakness of the sources, the short time you use them, and the arm's length rule for working with sources, result in a dose of less than 0.001 mrem per student, which is miniscule compared to the average person's 200 mrem annual dose.

Monitoring radiation exposure: film badges

The yearly exposure to a radiation worker (such as a nuclear plant employee or an x-ray technician) is limited by law to 5000 mrem/year, about 25 times the typical exposure of the general public. To measure this exposure, radiation workers wear film badges consisting of small pieces of photographic film in light-tight plastic holders. These badges are checked at intervals of one month or less to measure the darkening of the film, from which the radiation exposure can be deduced.

Radon: An Avoidable Hazard

Radon gas (radon-222) comes from uranium-238 decay. Because it is a gas, it can move through the soil from uranium deposits into homes through cracks in the basement floor and walls. The half-life of radon-222 is only 3.8 days, but its decay products are radioactive alpha and beta emitters that adhere to dust particles. These radioactive dust particles can be inhaled and lodge in the lungs. Some of these isotopes are alpha emitters and deposit heavy ionization directly in the lung tissue. Inhalation of radon and radon daughters may account for 20% of the lung cancer rate in nonsmokers. (If you smoke, you don't have to worry too much about radon!)

Although the geographical areas where radon is likely to be found are approximately known, the seepage of radon gas can vary enormously from one house to the next. The only way to be certain is to test your home. To test for radon, you need a detector that traps gas like your lungs, and averages over several days of exposure. Such test kits are available in many hardware stores. If significant radon is found, the home can be made safe by installing specially-designed ventilation devices in the basement.

Period 11 Summary

11.1 Ionizing radiation strips electrons from atoms, turning the atoms into charged ions. Three types of ionizing radiation exist.

Alpha particles = helium nuclei $^{4}_{2}\text{He}$ (2 neutrons and 2 protons)

Beta particles = electrons $^{0}_{-1}\text{e}$ or antielectrons $^{0}_{+1}\text{e}$

Gamma rays = very high energy photons from nuclear changes

11.2 Health damage from ionizing radiation

a) Killing cells: Exposure to large amounts of radiation can destroy enough body cells to cause death. Lesser amounts of radiation can impair the immune system and lower blood count, making you more susceptible to disease.

b) Genetic damage: Ionizing radiation can damage DNA molecules in the body resulting in genetic mutations and birth defects.

c) Increased risk of cancer: Damage to DNA molecules can result in cell mutations, which cause cancer.

Period 11 Summary, Continued

11.3 Sources of ionizing radiation

a) Radon decay: U-238 in the ground decays into Radon gas, which can seep into buildings. Radon quickly decays into daughter elements, which emit alpha and beta particles. When these particles are inhaled, they cause lung damage.

b) Cosmic rays: High energy protons from outer space ionize molecules in the atmosphere. Exposure to cosmic rays increases with altitude – people living at high altitudes or flying in planes have greater exposure than those at sea level. (Don't confuse cosmic rays with gamma rays. Gamma rays are high energy photons.)

c) Rocks, soil, and building materials: Naturally occurring radioactive materials decay and emit ionizing radiation (mostly high energy gamma rays).

d) Medical X-rays: Lile gamma rays, but of lower energy. The amount of exposure varies between 6 mrem and 200 mrem per X-ray.

e) Radioactive decay inside your body: Potassium-40 from foods decays to produce some ionizing radiation. However, potassium is essential for metabolism.

Detecting ionizing radiation: Geiger counters, cloud chambers, and film badges can detect ionizing radiation.

Period 11 Exercises

E.1 Ionizing radiation

a) can cause cancer.
b) can be used to diagnose cancer.
c) can be used to treat cancer.
d) Answers a) and c) are both true.
e) All of the above answers are true.

E.2 Which of the following is **NOT** a source of ionizing radiation?

a) cosmic rays
b) some types of rocks
c) dental X-rays
d) potassium in the body
e) photographic film

E.3 Which of the following statements is **FALSE**?

a) Radioactivity occurs naturally in nature.
b) Radiation can cause biological damage.
c) Distance from a radioactive source is important in determining the dose of radiation received.
d) The exposure to background radiation from cosmic rays decreases with increasing altitude.
e) The presence of radioactive substances can be detected by using a cloud chamber.

Period 11 Review Questions

R.1 Why is it so difficult to determine how many cases of cancer are caused by a small increase in a population's radiation exposure?

R.2 How does radon-222 increase the risk of lung cancer?

R.3 How can radon-222 be detected?

R.4 Can you decrease your natural radiation exposure significantly by avoiding foods containing potassium? Why or why not?

R.5 Should you avoid medical x-rays as a health hazard? Explain your answer.