# 16.7: Nuclear Physics and Biology

The discovery of nuclear physics revolutionized the way we interact with the world. Radioactivity helps us to determine the ages of ancient artifacts, discover and treat cancers, and provides power to our electrical grid. At the same time, radioactive decay can cause damage to our cells and cause cancers. The same process that generates power also produces hazardous waste that threatens the environment if not properly contained. As with all discoveries made by humanity, with the potential for great rewards comes the potential for immense harm.

## Medical Benefits

### Radioimmunoassay

The difference in behaviors of radioactive and nonradioactive substances underpins all applications of nuclear medicine. An example of this is the technique of *radioimmunoassay* (RIA) which was developed to detect and measure the precise amount of some substance. Antibodies are special proteins that can bind to other proteins, and they can be designed to bind to a specific protein of interest. In order to test for the presence of some substance in a blood or urine sample, an antibody that binds to that substance is manufactured. Some of the antibody is made radioactive by including an isotope of a particular atom. Initially only the radioactive antibody is present, so the sample emits the largest amount of radiation possible.

Next, the antibodies drawn from the person to be tested are added to the sample. If the same antibody is present in the patient's sample, it will preferentially bind to the receptor sites and dislodge the radioactive antibodies. The sample is 'washed' and the unbound radioactive antibodies are flushed from the sample. This means the sample becomes less radioactive. The amount by which the radioactivity decreases is directly proportional to the amount of antibodies in the patient's sample. Using a standard reference curve, the precise amount of substance in the patient sample can be determined.

RIA is used to detect the presence of many hormones and drugs. It is extremely precise and highly sensitive, allowing the detection of nanograms of antibodies. RIA is also used in the detection of hepatitis and early stage cancers.

### Radiopharmaceuticals

Another application of radioactive substances in medicine is the use of *radiopharmaceuticals.* These are special drugs that contain an unstable isotope of one of the constituent atoms. The drug is administered and tends to concentrate in areas of the body showing signs of Inflammation. As the drug accumulates, detectors can pinpoint the location of radioactive activity. The act of adding an unstable isotope to a substance is called *radioactive tagging* and this allows doctors to track how drugs move around in a patient's body. This same technique allows for the detection of Alzheimer's disease, brain tumors and some bone cancers. Radioactive tagging can also monitor blood flow, the activity of the heart muscle and can identify a malfunctioning thyroid gland. It can be used to image the skeletal structure, the lungs and kidneys.

An idea radioactive tag will have a short half-life to minimize the radiation effect on the patient, and also have a unique 'fingerprint'. This fingerprint is most often a gamma ray with a well-defined energy, so it is clear where the isotope is concentrated. It is common to use an isotope of technetium $(^{90}_{43}\mathrm{Tc})$ because it has a six-hour half life and produces an easily identifiable gamma ray when it decays.

### Radiation Imaging

You 've probably had an x-ray at some point in your life. There, a high energy photon is used to image the interior of the body. X-ray images are two dimensional and face some technical challenges to achieving good image quality for diagnostic purposes. Positron Emission Tomography (PET) provides superior, three-dimensional imaging by taking advantage of matter-antimatter annihilation.

A radiopharmaceutical that decays by positron emission is administered to the patient, and the patient is placed inside a radiation detector. When the isotope decays and produces a positron, it will immediately encounter an electron and the two will annihilate each other. This process completely converts the masses of the electron and positron into identical gamma rays that travel in opposite directions. Detecting the gamma rays allows software to locate the point in the patient's body where the decay occurred.

This technique allows for resolution at a scale of one-half centimeter and is especially useful in identifying and studying areas of specific brain activity, such as speech, motor function and sight. It is also used to monitor how the brain utilizes oxygen and water. Regions of decreased brain metabolism are often linked to Alzheimer's disease, so this type of monitoring can identify areas of concern before symptoms manifest in the patient.

### Radioactive Seeds

One of the by-products of radioactive decay is energy. If energy is added to a region, the temperature of the region increases. The greater the rate of energy transfer, the faster the temperature rises. High temperatures tend to kill cells, so radioactive seeds are used to treat certain types of cancers, such as prostate, breat and lung cancer. A radioactive seed is a small, radioactive cylinder that resembles a tiny nail. The seeds is inserted into the cancerous region of the body and decays in place, releasing energy the entire time. Seeds are also inserted into tumors, effectively 'cooking' the tumor from the inside. The use of radioactive seeds in the treatment of tumors and cancers is called *brachytherapy*.

## Biological Risks

The same processes that aids in the treatment and cure of cancers can also be the source of biological harm, including cancer. The transfer of energy to the environment from radioactive decay processes is at the heart of all these effects. In particular, how the released energy is transferred to the environment is important. In a nuclear reactor, the decay energy is transferred to large volume of water, which transforms into steam and the steam is used to produce electrical energy. In brachytherapy the energy is released into the small volume of a tumor, thereby destroying it.

On the large scale, exposure to radioactive decay can lead to skin burns and the death of hair follicles with subsequent hair loss. Nausea and vomiting can result from radiation exposure as the cells lining the digestive system die. Blindness may also result if the energy release happens quickly, as in a nuclear explosion. On the smaller scale, if energy is transferred to a molecule there are different possible outcomes. If the energy transfer is small, the one or more of the atoms making up that molecule may become excited, but can then dissipate that energy without ill effect. If the energy transfer is larger, one or more of the atoms may become ionized. This can have dramatic effects on the molecule. It may change its shape or break apart, both of which change the way it functions. One benchmark for whether or not a particular radiation is dangerous to biological organisms at the cellular level is its ability to ionize atoms and change the way molecules function.

The helical DNA molecules that regulate the behavior of cells can become damaged by *ionizing radiation*. DNA normally can repair itself, and does so on a regular and ongoing basis. Of particular concern is when the ionizing radiation inhibits the DNA repair ability. In these cases, the damaged cell can become senescent - a sort of cellular coma where it ceases to do anything. Or, the cell can undergo programmed cell death - analagous to cellular suicide. Finally, the cell may begin dividing in an uncontrolled fashion. This third outcome can result in cancers and tumors.

## Radiation Dose

The heart of determining *radiation dose* is measuring the amount of energy delivered to (absorbed by) each kilogram of body tissue. The *radiation dose unit*, also known as a *rad*, is defined to be:

$$1 \text{ rad} = \frac{1 \text{ Joule}}{100 \text{ kilogram}} = 0.01 \ \frac{\text{Joule}}{\text{kilogram}}$$

This is also referred to as the "whole body radiation dose".

As seen earlier, there are different types of radioactive decay products and each poses a different risk to cells even if the decay energy is the same. In general, alpha particles are extremely damaging, but only at very small distances. Beta decays are less damaging, but can deliver energy over larger distances. Gamma rays have the greatest range, but are also generally less damaging than alpha particles. This leads to the concept of *relative biological effectiveness* (RBE). RBE takes into account both the energy and the type of radiation to estimate the 'harm multiplier'. Typical RBE values are shown in the table:

A table of RBE values to determine relative health hazard.

| Type of Radiation and Decay Energy | Body RBE (approximate values) |
|---|---|
| $\gamma$ rays, $\beta$ decay > 32 keV | 1 |
| $\beta$ decay < 32 keV, neutrons < 20 keV | 2 |
| neutrons and protons from 1 to 10 MeV | 10 |
| $\alpha$, heavy ions from particle accelerators | 10 to 20 |

Table of RBE taken from OpenStax *University Physics vol. 3* and is licensed under CC-BY

Note that the mass and charge of the decay product both play a role in determining biological damage. Highly charged and massive particles, such as alphas are very damaging. Uncharged, yet massive particles are also damaging because they produce secondary ionization. The determination of RBE values are approximations determined from an understanding of radiation and its effects on living tissue. Data was collected

## Rads, Rems and Sieverts

A more meaningful unit of radiation exposure takes into account the type of radiation, so the *roentgen equivalent man* (rem) is used:

$$\text{rem} = \text{rad}(\text{RBE})$$

Since the rad - and therefore the rem - are defined to be a tiny amount of energy per unit of mass, the *sievert* (Sv) is then defined:

$$1\ \text{Sv} = 100\ \text{rem}$$

A low dose is anything less than 10 rem, while a dose of 10 to 100 rem is called a moderate dose. Doses above 100 rem are considered high. A dose of about 4.5 Sv will kill 50% of the people thus exposed within about a month. A dose of over 20 Sv will prove fatal in a matter of hours as the entire central nervous system collapses.

Exposure to low levels of radiation is common and ongoing, no matter where you are on the planet. The earth emits radiation due to the presence of uranium, thorium and potassium isotopes in the soil. As a matter of fact, bananas are radioactive though in negligible amounts, due to the presence of naturally occurring potassium isotopes. Fertilizers also contain radioactive isotopes and these are taken up by plants, making them radioactive as well. The wood used for buildings and the granite used for countertops also contain unstable isotopes. We are also constantly being bombarded by gamma rays originating high in the atmosphere. Additionally, medical visits can increase radiation doses through nuclear medicine or even routine dental x-rays. There are no places on earth that are devoid of radiation, so it is a good thing our DNA has a robust repair mechanism.

The average person will absorb between 250 to 400 millirem per year, an incredibly small dose overall. Still, any ionizing radiation exposure has the possibility of damaging DNA. As a result, there is a roughly 20% chance that a person will develop some form of cancer during their lifetime, typically in their later years. There are regional differences in both frequency of cancers and health outcomes. For example, Australians are statistically more likely to develop cancer, but Mongolians are more likely to die from the disease. Diet and lifestyles can contribute significantly to the chances of developing cancer, and The World Cancer Research Fund International estimates that 40% of global cancer cases could be prevented by addressing diet, nutrition and physical activity.

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