Chapter 12
Nuclear Physics, Subatomic Particles and Radiation

Radiation

Radiation consists of subatomic particles traveling with enough energy so they are not bound to atoms, molecules, crystals or any substances. These particles can include nuclei or photons. Electromagnetic radiation consists of photons. Alpha radiation consists of traveling helium nuclei which are called alpha particles. Beta radiation consists of electrons called beta particles. Alpha particles typically are stopped by a sheet of paper and beta particles can be stopped by sheets of aluminum. Gamma radiation penetrates deep into metals and is a useful probe into metal vessels. For example, gamma radiation has been used to probe inside the walls of jet engines or engine housings to search for defects.

Physicists and most engineers specify amounts of radiation in terms of physical quantities, but biologists and medical doctors prefer biophysical quantities. A purely physical quantity can be an energy, a number of particles or a flux of either energy or particles. A flux is a flow rate per area with a direction. Thus, flux can be considered a vector. Physical quantities are useful in physics and engineering, but biologists and medical doctors found such physical quantities specified by physicists to be difficult to apply when determining health hazards. Various physical quantities were suggested for use in determining health hazards. Some of these units were given names based loosely on the name of the physicist Wilhelm Röntgen (also called William Roentgen). The “gray” (Gy) was defined as one joule of ionizing radiation absorbed per kilogram of matter. The “rad” was defined as a hundredth of a gray. (100 rad = 1 Gy.) These units are still used by biophysicists. However, these physical units still present problems for medical doctors. Thus, biophysical quantities with biophysical units, quantities and units defined in terms of effects on living organisms, were introduced.

When biologists and medical doctors specify a dose of radiation, they specify the amount based on the damage to human-body tissue rather than in terms of purely physical quantities like energy or number of particles. The amount of damage depends on the type of radiation, the number of particles and the energy of the particles. Thus, the quantities, often called “equivalent doses” or “effective doses,”
desired by doctors would be part physical and part biological. Conversion tables help doctors convert from physical quantities, which a physicist may use, to equivalent doses preferred for specifying damage done to human tissue. Thus, if a physicist states that 0.25 joules of beta radiation were absorbed by 100 kg of human tissue, the doctor can look up beta radiation in a conversion table and use values given in the table to convert to desired biophysical units of radiation dose. The “roentgen equivalent man” (or equivalent mammal), abbreviated “rem” and occasionally as R, became an acceptable unit of radiation dose for medical work. Later, the sievert (Sv) was accepted as a unit of radiation dose. However, such biophysical units were found to have their shortcomings. The tables fail to give correct estimates of damage for high levels of radiation exposure, and doctors sometimes revert back to using physical quantities such as the gray.

Radioactivity

Radioactivity is the process of production of radiation by nuclear decay. Some nuclei are unstable and can decay spontaneously with little or no disturbance to initiate the decay. A nucleus is held together by a type of force called the “strong force.” This force, as its name suggests, is very strong in that much energy is needed to overcome it. However, this force has a very short range—much smaller than the radius of an atom. One feature of its short range is that it holds small nuclei together better. Large nuclei tend to be more unstable because the radius of a large nucleus is closer to the range of the strong force. This force is more complicated than mere dependence on range.

For example, a lone neutron is unstable and tends to decay into the combination of a proton and an electron (beta particle) despite the small size of a single neutron. Since the proton is much heavier than the electron, the combination of momentum conservation and energy conservation can be used to show that the electron gets more kinetic energy than the proton from the decay. Even the neutrons in radioactive (unstable) nuclei can undergo this transformation into a proton and electron. Thus, such a nucleus can emit a beta particle (the electron) and raise its atomic number (the number of protons) by one to become the nucleus of another chemical element.

A radioactive nucleus can also decay by emitting an alpha particle to lower its atomic number by two. Sometimes a nucleus will decay in steps, in one step emitting one type of radiation and maybe another type in the next step. For example, the uranium 238 nucleus, a uranium nucleus with an atomic mass number of 238 (the total number of protons and neutrons being 238), decays in several steps and emits beta particles and alpha particles as it continues and eventually becomes lead 206. The main point here
is that emitting a beta particle raises the atomic number by one and emitting an alpha particle lowers the atomic number by two. The atomic number determines the chemical element. Changing the atomic number changes the element. This process of changing one element into another is often called “transmutation.” Remember the different “isotopes” of an chemical element differ only in the number of neutrons in the nucleus. Thus, two isotopes of the same element have the same atomic number but different atomic mass numbers.

The half-life of a radioactive isotope is the time required for the number of nuclei to reduce to half the original number by radioactive decay. If \( t_{\text{1/2}} \) is the half life for an isotope, then every half-life \( t_{\text{1/2}} \) of time the number of nuclei is half of what it was before. One half-life later, half of that or one quarter of the original number of nuclei remain. In class, your instructor shows a graph showing the radioactive decay as a function of time. The decays is said to be an “exponential decay” because the mathematical description involves an exponential function.

**Radiation Detectors**

Radiation is detected by its interaction with matter. The following are some types of radiation detector.

- A **Geiger counter** detects short pulses of current caused when radiation ionizes gas in an electronic tube.

- A **scintillation counter** detects flashes of light in a transparent material when charged particles or gamma rays pass through the material.

- In a **cloud chamber**, charged particles produce visible trails by ionizing supersaturated vapor. A supersaturated vapor is on the verge of condensing to the liquid phase and the passage of a charged particle can trigger the phase change. Each charged particle has a charge \( q \) and a mass \( m \). Cloud chambers are often placed in electric and magnetic fields to get information about the charge-to-mass ratio \( q/m \) of the particle making each track.

- In a **bubble chamber**, liquid hydrogen is heated under pressure till the liquid is close to the point of phase change to the vapor phase, but then the pressure is suddenly released. Particles passing through the hydrogen form tracks of bubbles which can be photographed. As for cloud chambers, electric and magnetic fields are used to study the charge-to-mass ratio \( q/m \) of each particle making each track.

- A **drift chamber** allows particles to form tracks of ions in a gas like a cloud chamber does, but rather than photograph or observe the tracks directly, an electric field causes the track of ions to...
drift down to a two-dimensional array of charge detectors that detect the ions when they reach the detectors. A three dimensional image of the tracks is obtained since the array provides two dimensions and the time of drift provides a third dimension for the three-dimensional image.

- A calorimeter is a detector that detects energy deposited by passing particles. An array of calorimeters can yield the velocities of the particles.

In recent decades, physicists have developed some new types of particle detectors. For example, an electronic device operating at a temperature near absolute zero (hundredths of a Kelvin from absolute zero) can detect the passage of a charged particle by monitoring the tiny magnetic field created by the passing charge through a tiny loop. An advanced detector detects the recoil of a nucleus when a particle collides with the nucleus. These modern detectors are used in various experiments for detecting subatomic particles and radiation from beyond our galaxy.

Radiometric Dating

Radiometric dating is the method of dating a sample by either the amount of isotopes present in the sample or evidence of past effects of radiation on the sample. Most methods of radiometric dating involve measuring ratios of radioactive isotopes in the sample to other isotopes in the sample. For example, neutrons incident on nitrogen 14 nuclei can replace one proton to cause the nitrogen to transmute to carbon 14. (The replaced proton is ejected from the nitrogen nucleus.) Carbon 14 is unstable and eventually emits a beta particle (causing a neutron to become a proton) to transmute back to nitrogen 14. The half-life of carbon 14 is 5730 years. Thus, carbon 14 remains in the atmosphere for significant time. The ratio of carbon 14 to carbon 12 is small. Plants absorb both isotopes of carbon from the air. Animals eating the plants get the roughly same ratio of carbon 14 to carbon 12 in their bodies. When an animal dies, the carbon 14 slowly decays and this decay slowly changes the ratio of carbon 14 to carbon 12. Carbon-14 dating measures this ratio to determine the age of the remains since the animal died. (The nitrogen 14 produced by the decay escapes and is not as useful for dating.)

Carbon-14 dating, like most types of dating, relies on some assumptions. The main assumption of carbon-14 dating is that the ratio of carbon 14 to carbon 12 has been fairly constant since the time the animal was alive and the carbon was being acquired. The ratio of carbon 14 to carbon 12 has been changing over years. Some Earth scientists suggest the changes in the ratio observed in recent decades may be due to human activities.
Mass Energy

In previous chapters, we have seen there are several types of energy. Another type of energy is due to mass itself. This energy is called mass energy and it is proportional to mass. With the modern (metric) units scientists use, this mass energy \( E \) is the product of the mass \( m \) and the square of the speed of light in vacuum \( c \). \( E=mc^2 \). This new form of energy was suggested by Einstein as a result of his Theory of Special Relativity (which will be introduced in a later chapter). In nuclear processes, mass energy can be converted to other forms of energy and other forms of energy can be converted to mass energy.

For example, the nucleus of the most common isotope of hydrogen is a single proton (without any neutrons). A proton and a neutron can be combined for form a “deuteron.” The deuteron is the nucleus of an isotope of hydrogen often called “deuterium.” We may expect the mass of the deuteron to be the sum of the masses of the proton and neutron. However, the deuteron has less mass than the sum of those masses because some of the mass energy (that is, in other words, some of the mass) is converted to “binding energy” which is potential energy due to the strong force. The binding energy is equal to the work that must be done (against the strong force) to separate the deuteron into a separate proton and neutron. The sum of the mass energy of the deuteron and the binding energy is equal to the sum of the masses of the proton and neutron. Some people say the proton and neutron have less mass when combined into a deuteron (or combined to form any nucleus) than when they are apart. That is okay to say but really the deuteron can be considered to be a new particle rather than a proton and neutron.

As protons and neutrons are combined to form nuclei, mass energy is converted to binding energy. The more stable the nucleus, the larger the ratio of binding energy to the total number of protons and neutrons is and the smaller is the ratio of the mass of the nucleus to the sum of the masses of the individual protons and neutrons before combination to form the nucleus. An isotope of iron has the most stable nucleus, the largest ratio of binding energy to number of nucleons (protons and neutrons), and the smallest ratio of nuclear mass to the sum of the masses of the individual nucleons before combining to form the nucleus.

Mass energies, such as nuclear binding energies, are usually much larger per atom than typical chemical energies per atom. Thus, nuclear processes usually involve energies much larger than energies involved in chemical reactions. A nuclear reaction may be initiated by a large energy but can actually produce even larger energies. This is one of the main reasons nuclear processes were considered for...
generating power.

**Nuclear Fission**

Nuclear fission is a nuclear process in which one nucleus splits into two (or more) nuclei. Other particles may be released in such a process. Smaller particles released have higher kinetic energies than the larger particles. Thus, the new nuclei resulting from the nuclear fission have much less kinetic energy than particles like lone protons, neutrons and beta particles released in the fission. However, the kinetic energies of the new nuclei are responsible for most of the macroscopic heat produced since their motion results in moving atoms.

The smaller particles with higher kinetic energy can cause additional nuclear fissions. Fission of nuclei with atomic mass numbers larger than those of iron nuclei tend to release more energy than required to start the fission. Thus, large radioactive nuclei tend to be used for fission chain reactions. If there is a significant concentration and mass of radioactive nuclei that can fission, a chain reaction can occur where some fissions cause more fissions. Typically this causes the material to heat, and the heat causes the material to expand, melt, boil, sublime or explode apart. Nuclear bombs involve causing a sudden concentration of radioactive material in a pressure vessel that resists the expansion for a short time—a short time that is long enough for the rate of chain reactions to increase to a level where energy is being produced at a very rapid rate.

**Nuclear Fission Reactors**

Nuclear fission reactors in electric power plants have four principal parts: radioactive fuel to produce the nuclear fission, a moderator to slow neutrons down so they can produce more nuclear fissions, control materials that absorb neutrons to control the rate of reaction, and a coolant that controls the temperature and carries heat to where it is converted to electrical energy. The reactor can be halted by

- removing the moderator or decreasing its efficiency,
- increasing the amount of the control materials present to absorb neutrons, or
- removing the fuel.

In electric power plants, increasing the presence of the control materials is the main way to halt a reactor quickly, but removing the fuel is needed to completely remove the reaction.
Nuclear Fusion

Nuclear fusion is a nuclear process in which two nuclei combine to form a single nucleus. Nuclei with atomic mass numbers smaller than those of iron nuclei tend to release more energy in nuclear fusion than is required to start the fusion. Thus, small nuclei are used in nuclear fusion. Thus, nuclear fission tends to transmute large nuclei toward iron and nuclear fusion tends to transmute small nuclei toward iron. In a nuclear process (including fission and fusion), the number of nucleons is conserved.

Because of this stability of a particular isotope of iron mentioned earlier, nuclear reactions in nature tend to change nuclei toward becoming that isotope. Heavy atoms tend to become lighter by fission and light atoms tend to become heavier by fusion with the end target of such nuclear reactions being the stable isotope of iron. Some people predicted that the universe would eventually be entirely made of iron.

Example Calculations

Example 01. Suppose a sample, either a chemical sample or a sample of a radioactive element, decays in 63 days to one eighth of the original amount. We can calculate the half-life of the sample.

\[
\frac{1}{8} = \left(\frac{1}{2}\right)^3
\]

Thus, the time of 63 days the sample decayed to 1/8 of the original amount is three half-lives. A single half-life will be

\[
\frac{63 \text{ days}}{3} = 21 \text{ days}
\]

The half-life is 21 days. Suppose we want to know how long a time is needed for the sample to decay from its full original amount to 1/64 of its original amount.

\[
\frac{1}{64} = \left(\frac{1}{2}\right)^6
\]

Thus, six half-lives are required.

\[
21 \text{ days} \times 6 = 126 \text{ days}
\]

Thus, in 126 days the sample to decay from its original amount to 1/64 of its original amount.
Example 02. The speed of light in vacuum is $c = 3.00 \times 10^8$ m/s. Suppose the mass of a body is $m = 1 \times 10^{-5}$ kg. We can calculate the mass energy of that mass.

$$E = mc^2 = 1 \times 10^{-5} \text{ kg} \times (3.00 \times 10^8 \text{ m/s})^2 = 9 \times 10^{11} \text{ J}$$

Thus, even 0.01 mg of mass has a large amount of mass energy. Large mass energies for even small amounts of mass is the reason the binding energy that holds nucleons (protons and neutrons) inside a nucleus is large enough that the strong force is very strong at short range.