Nuclear Physics

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Contents

1. Atoms

Planetary model of atom

- Rutherford proposed the planetary model of the atom.
- The planetary model of the atom pictures low-mass electrons orbiting a large-mass nucleus.
- The sizes of the electron orbits are large compared with the size of the nucleus, with mostly vacuum inside the atom.
- This picture is analogous to how low-mass planets in our solar system orbit the large-mass Sun at distances large compared with the size of the sun.
- In the atom, the attractive Coulomb force is analogous to gravitation in the planetary system.

Substructure of the atom

- The atom being neutral is supposed to have as many protons inside the nucleus as there are electrons revolving around the nucleus.
- It was later discovered that the nucleus contains neutral particles called neutrons apart from protons. Neutrons have a mass almost identical to protons.
- The number of protons in a nucleus is the atomic number Z.
- The total number of protons and neutrons is called the mass number A. This is because the mass of the atom is nearly equal to the mass of protons and neutrons. Hence the mass of the atom is propotional to A.
- The total mass of an atom or the atomic weight is defined as the total mass of all the constituent particles of the atom which are the protons, neutrons and the electrons. It is mostly expressed in the non-SI unit u(atomic mass unit).
- The number of neutrons, N can be obtained as $N = A - Z$.
- The simple notation for nuclides is

$$^{A}X$$

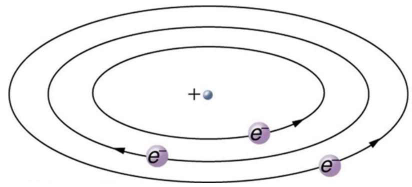

Figure 1.1: Rutherford's planetary model of the atom

Isotopes

- All of the chemical properties of an element is determined by the number of electrons and hence the atomic number Z. This is the reason for the existence of the periodic table.
- Isotopes are atoms of the same element that have different number of neutrons.
- Thus isotopes of an element has the same chemical properties but different physical properties like mass.
- The three isotopes of hydrogen are ^1H,^2H, and ^3H.

2. Radioisotopes

- A substance or object that emits nuclear radiation is said to be radioactive.
- Nuclear radiation is the emission of rays that originate in the nuclei of atoms and have other unique characterisitics.
- It consists of three types of radiation. Alpha, beta and gamma rays.
- All three types of nuclear radiation produce ionization in materials, but they penetrate different distances in materials—that is, they have different ranges.
- Radioisotopes are radio active isotopes of an element.

Ionizing radiation

Ionizing radiation is defined as any form of radiation that produces ionization whether nuclear in origin or not, since the effects and detection of the radiation are related to ionization.

3. Biomedical application of radioisotopes

- A host of medical imaging techniques employ nuclear radiation.

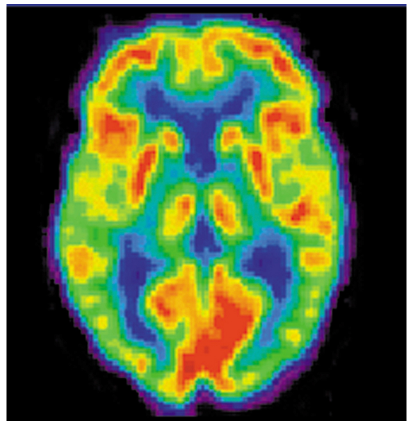

Figure 3.1: A radiopharmaceutical is used to produce this brain image of a patient with Alzheimer's disease. Certain features are computer enhanced.

- Nuclear radiation can easily penetrate tissue; hence, it is a useful probe to monitor conditions inside the body.
- Nuclear radiation depends on the nuclide and not on the chemical compound it is in, so that a radioactive nuclide can be put into a compound designed for specific purposes. The compound is said to be tagged. A tagged compound used for medical purposes is called a radiopharmaceutical.
- Radiation detectors external to the body can determine the location and concentration of a radiopharmaceutical to yield medically useful information.
- For example, certain drugs are concentrated in inflamed regions of the body, and this information can aid diagnosis and treatment.
- Another application utilizes a radiopharmaceutical which the body sends to bone cells, particularly those that are most active, to detect cancerous tumors or healing points. Images can then be produced of such bone scans.
- Radioisotopes are also used to determine the functioning of body organs, such as blood flow, heart muscle activity, and iodine uptake in the thyroid gland.

Diagnosis

- Many organs can be imaged with a variety of nuclear isotopes replacing a stable element by a radioactive isotope.

- One common diagnostic employs iodine to image the thyroid, since iodine is concentrated in that organ. The most active thyroid cells, including cancerous cells, concentrate the most iodine and, therefore, emit the most radiation. Conversely, hypothyroidism is indicated by lack of iodine uptake.

- Note that there is more than one isotope that can be used for several types of scans.

- Another common nuclear diagnostic is the thallium scan for the cardiovascular system, particularly used to evaluate blockages in the coronary arteries and examine heart activity. The salt TlCl can be used, because it acts like NaCl and follows the blood.

- Gallium-67 accumulates where there is rapid cell growth, such as in tumors and sites of infection. Hence, it is useful in cancer imaging. Usually, the patient receives the injection one day and has a whole body scan 3 or 4 days later because it can take several days for the gallium to build up.

Single-photon-emission computed tomography(SPECT)

- Imaging techniques much like those in x-ray computed tomography (CT) scans use nuclear activity in patients to form three-dimensional images.

  Figure 3.2 shows a patient in a circular array of detectors that may be stationary or rotated, with detector output used by a computer to construct a detailed image.

- This technique is called single-photon-emission computed tomography(SPECT) or sometimes simply SPET.

- The spatial resolution of this technique is poor, about 1 cm, but the contrast (i.e. the difference in visual properties that makes an object distinguishable from other objects and the background) is good.

PET

- Images produced by $\beta+$ emitters have become important in recent years. When the emitted positron encounters an electron, mutual annihilation occurs, producing two gamma rays. These gamma rays have identical energies (0.511-MeV) and they move directly away from one another, allowing detectors to determine their point of origin accurately.

- The system is called positron emission tomography (PET). It requires detectors on opposite sides to simultaneously detect photons and utilizes computer imaging techniques similar to those in SPECT and CT scans.

Figure 3.2: SPECT uses a geometry similar to a CT scanner to form an image of the concentration of a radiopharmaceutical compound. (credit: Woldo, Wikimedia Commons)

- Examples of $\beta+$ emitting isotopes used in PET are $^{11}C,^{13}N,^{15}O,$ and ^{18}F . This list includes C, N, and O, and so they have the advantage of being able to function as tags for natural body compounds.

- Its resolution of 0.5 cm is better than that of SPECT; the accuracy and sensitivity of PET scans make them useful for examining the brain's anatomy and function.

- The brain's use of oxygen and water can be monitored with ^{15}O. PET is used extensively for diagnosing brain disorders. It can note decreased metabolism in certain regions prior to a confirmation of Alzheimer's disease. PET can locate regions in the brain that become active when a person carries out specific activities, such as speaking, closing their eyes, and so on.

Figure 3.3: This image of the concentration of a radioactive tracer in a patient's body reveals where the most active bone cells are, an indication of bone cancer. A short-lived radioactive substance that locates itself selectively is given to the patient, and the radiation is measured with an external detector. The emitted gamma radiation has a sufficient range to leave the body—the range of alpha and beta is too small for them to be observed outside the patient.

Figure 3.4: This is an image of the gamma rays emitted by nuclei in a compound that is concentrated in the bones and eliminated through the kidneys. Bone cancer is evidenced by nonuniform concentration in similar structures. For example, some ribs are darker than others.

Use of radioisotopes in medicine

Refer to text.

4. Detecting Radiation

- Ionizing radiation, such as X-rays, alpha rays, beta rays, and gamma rays, remains undetectable by the senses, and the damage it causes to the body is cumulative, related to the total dose received.

- Therefore, workers who are exposed to radiation, such as radiographers, nuclear power plant workers, doctors using radiotherapy, workers in laboratories using radionuclides are required to wear instrument which can keep a record of their exposure, to verify that it is below legally prescribed limits.

- Ionizing radiations can be measures or monitored by dosimeters, Geiger counters and scintillation counters.

5. Radiation Hazards

- All the effects of ionizing radiation on biological tissue can be understood by knowing that ionizing radiation affects molecules within cells, particularly DNA molecules.

- DNA contains codes that check whether the DNA is damaged or can repair itself. It is like an auto check and repair mechanism. This repair ability of DNA is vital for maintaining the integrity of the genetic code and for the normal functioning of the entire organism.

- Ionizing radiation can induce damage to the ability of cells to repair DNA. As a result of this,

  - The cell can go into an irreversible state of dormancy, known as senescence.
  - The cell can commit suicide, known as programmed cell death.
  - The cell can go into unregulated cell division leading to tumors and cancers.

- Since ionizing radiation damages the DNA, which is critical in cell reproduction, it has its greatest effect on cells that rapidly reproduce, including most types of cancer. Thus, cancer cells are more sensitive to radiation than normal cells and can be killed by it easily.

- Cancer is characterized by a malfunction of cell reproduction, and can also be caused by ionizing radiation. Without contradiction, ionizing radiation can be both a cure and a cause.

- The large-scale effects of radiation on humans can be divided into two categories: immediate effects and long-term effects.
  - Immediate effects are explained by the effects of radiation on cells and the sensitivity of rapidly reproducing cells to radiation.
  - The first clue that a person has been exposed to radiation is a change in blood count, which is not surprising since blood cells are the most rapidly reproducing cells in the body.
  - At higher doses, nausea and hair loss are observed, which may be due to interference with cell reproduction. Cells in the lining of the digestive system also rapidly reproduce, and their destruction causes nausea. When the growth of hair cells slows, the hair follicles become thin and break off.
  - The two known long-term effects of radiation are cancer and genetic defects. Both are directly attributable to the interference of radiation with cell reproduction.
- High doses cause significant cell death in all systems, but the lowest doses that cause fatalities do so by weakening the immune system through the loss of white blood cells.

6. Radiation Units

- All effects of radiation are assumed to be directly proportional to the amount of ionization produced in the biological organism.
- The amount of ionization is in turn proportional to the amount of deposited energy. Therefore, we define a radiation dose unit called the rad, as 1/100 of a joule of ionizing energy deposited per kilogram of tissue,

  $1\ rad = 0.01 J/kg$.
- While calculating radiation doses, you divide the energy absorbed by the mass of affected tissue. You must specify the affected region, such as the whole body or forearm in addition to giving the numerical dose in rads. The SI unit for radiation dose is the gray (Gy), which is defined to be

  $1\ Gy = 1 J/kg = 100\ rad$.
- The effects of ionizing radiation may be directly proportional to the dose in rads, but they also depend on the type of radiation and the type of tissue. That is, for a given dose in rads, the effects depend on whether the radiation is α, β, γ, x-ray, or some other type of ionizing radiation.
- If the range of the radiation is small, as it is for alpha rays, then the ionization and the damage created is more concentrated and harder for the organism to repair, so short-range particles have greater biological effects.

- The relative biological effectiveness (RBE) or quality factor (QF) is different for different types of ionizing radiation—the effect of the radiation is directly proportional to the RBE.
- A dose unit more closely related to effects in biological tissue is called the roentgen equivalent man or rem and is defined to be the dose in rads multiplied by the relative biological effectiveness.

  $rem = rad \times RBE$

  The SI equivalent of the rem is the sievert (Sv), defined to be

  $Sv = \ Gy \times RBE$

7. Radiation protection

- Laws regulate radiation doses to which people can be exposed.
- The greatest occupational whole-body dose that is allowed depends upon the country and is about 20 to 50 mSv/y and is rarely reached by medical and nuclear power workers.
- Higher doses are allowed for the hands. Much lower doses are permitted for the reproductive organs and the fetuses of pregnant women.
- Inadvertent doses to the public are limited to 1/10 of occupational doses, except for those caused by nuclear power, which cannot legally expose the public to more than 1/1000 of the occupational limit or 0.05 mSv/y (5 mrem/y).
- Extensive monitoring with a variety of radiation detectors is performed to assure radiation safety. Increased ventilation in uranium mines has lowered the dose there to about 1 mSv/y.
- To physically limit radiation doses, we use shielding, increase the distance from a source, and limit the time of exposure.
  - Shielding absorbs radiation and can be provided by any material, including sufficient air.
  - The greater the distance from the source, the more the radiation spreads out.
  - The less time a person is exposed to a given source, the smaller is the dose received by the person.
- Doses from most medical diagnostics have decreased in recent years due to faster films that require less exposure time.