5CPP5000 Relativity and Subatomic Physics Mini Project

Coversheet

Project Title: Our Daily Dose of Radiation

Abstract:

Radiation refers simply to energy in the form of particles or electromagnetic waves. In this project our primary concern is with ionizing radiation, radiation of high enough energy to liberate orbital electrons from atomic nuclei. This is predominant in the discussion of radiation and human beings because of the effects of radiation on living tissue through cell damage, free radicals and the impairment of DNA to reliably replicate itself leading to cancer.

In this project we will explore the daily human experience of radiation from how we measure radiation empirically and theoretically where it comes from and in what quantities, its physiological effects on humans at the limits of our tolerance and how we protect ourselves from it.

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Individual contribution: Wrote/ researched the section called ‘Sources of The Radiation We Experience Daily’ (pages 8-12) and was responsible for administrative tasks in the group

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Abstract

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1. How do we measure radiation?

This chapter deals with methods of measuring radiation and more precisely with a specific group of nuclear detectors called **Gas filled detectors** or **Gas (ionization) chambers.** These instruments are capable of detecting nuclear particles like:

α particles coming from alpha decay, which can be presented as:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

β particles coming from beta -, beta + or electron capture decays which can be presented as:

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

γ radiation coming from gamma decay, which can be presented as:

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma$$

1.1 Gas filled detectors or Gas (ionization) chambers

Construction (Oak Ridge Associated Universities, "Ionisation Chambers")**:**

- Metallic cylinder filled with gaseous medium
- Negative terminal of voltage supply connected to the metallic surface
- Metallic electrode passing thru the centre of the tube connected to the low resistance that is then connected to the positive terminal of the power supply
- Insulating material installed to prevent a negatively charged metallic surface from touching positively charged metallic electrode
- Low resistor across which an amplifier or pulse counter (capable of detecting potential) drop is installed

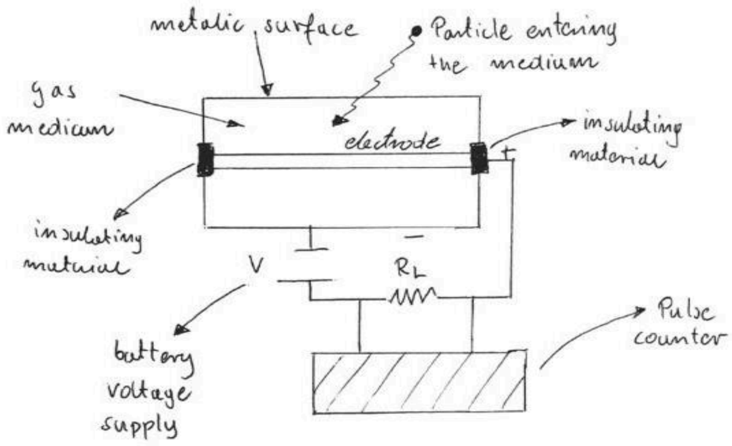


Figure 1 *(For the Love of Physics, "Nuclear Detectors - Ionization Chamber & Proportional Counter")*

Gas filled detectors or **Gas (ionization) chambers** are based on a principle of **ionization**.
Ionization is a physical process in which a given particle (atom or molecule) can enrich or lose energy thru gaining or losing the electron from its internal structure. This happens because of the collision between a given particle and some other energetic particle. This process is responsible for the creation of ions. If during the process a given particle gains an electron it becomes negatively charged and we call it an **anion**. If the case is reversed and the electron is lost, then the particle is positively charged and we call it a **cation**. (Afework, Hanania, Musgrove, Stenhouse, Donev, "Ionization")

Ionization in Gas filled detectors: Energetic particles coming from radioactive decays are capable of entering the metallic tube where they meet the particles of the medium. Once a radioactive particle with sufficient energy collides with the atoms of the medium it causes the ionization in which free electron and positive ion are created inside a **Gas filled detector.** (For the Love of Physics, "Nuclear Detectors - Ionization Chamber & Proportional Counter")

General mechanism behind **Gas filled detectors** or **Gas (ionization) chambers** (For the Love of Physics, "Nuclear Detectors - Ionization Chamber & Proportional Counter")**:**

- Inside the counter, we find a central electrode connected to the positive terminal of the battery acting as an anode. The outside of the counter is made of a metallic surface connected to the positive terminal acting as a cathode. Therefore there is an **Electric field** established inside the instrument that is directed from the electrode towards the metallic surface of the cylinder. The strength of the electric field is dependent on voltage inside the battery.

- If there is radioactive decay happening near the detector there is a high probability that: **α. β or γ** radiation will enter the detector.

- Once the radioactive particles enter the detector they are capable of ionizing the medium particles, causing the creation of free electrons and negatively charged anions

- Due to the direction of the electric field, the free electrons are accelerated in the direction of the electrode and anions in the direction of the surface. The electrons are accelerated with a force that can be presented as:

  $$F = eE \qquad \textbf{(1)}$$

  where:

  F-force acting on electron
  e- charge of electron
  E-strenght of electric field inside the tube

- Once electrons reach the electrode they accumulate on it and travel thru the circuit. During this process, a measuring device counts potential drops and current over a period of time. When electrons complete the circuit they accumulate on the metallic surface where they meet with positive ions and create neutral particles bringing the set up to its original state

Across the low resistance, we find an electronic setup that can: determine the potential drop and measure the current coming thru the setup. These events are counted over a period of time. However, this counts are dependent on amount of voltage supplied. The magnitude of the electric field depends on the supplied voltage and if the voltage is small then the acceleration of free electrons is also small. Furthermore, due to the thermal motion, the electrons and positive ions that are not accelerated enough can recombine and form neutral atoms, this process is referred to as **Recombination**. If free electrons and positive ions recombine they do not contribute to the potential drop and current measured by the electronic setup. For low voltage instruments, the process of recombination is dominant and hence small current can be observed.
Gas filled detectors or **Gas (ionization) chambers** can be divided into subgroups using the criterion of the amount of supplied voltage:

- Ionization chambers
- Proportional counters
- GM counters

1.2 Geiger-Müller counter

GM counter

Geiger Muller counter is a gas-filled radioactive decay detector most commonly used by scientists to measure background radiation coming from various materials surrounding the human body. It consists of a metallic tube filled with a mixture of noble gas like argon and alcohol. A metallic electrode is usually made of tungsten. What distinguished GM counters from other gas-filled detectors is the extremely high voltage supplied to the setup, usually in the range 1000V-3000V (For the Love of Physics, "What is a GM Counter? - Geiger Muller Counter").

Because of the high voltage, the electric field established inside the tube is also much higher than in other gas filled detectors. Therefore the free electrons that are created in the process of ionization are highly accelerated. This free electrons are traveling fast enough to induce more ionizations and create a process called **Townsend Avalanche**. This process refers to a chain reaction that starts with **primary ionization** (collision of a radioactive particle with medium particle) that causes further ionization of particles of the medium.

Mechanism of a GM counter can be presented in several steps:

1) Electrons from elements of the gaseous medium absorb energy from the particles like alpha, beta or gamma radiation, coming from radioactive decays

2) If electron absorbs enough energy it can become a free electron. Therefore in presence of radioactive decay, positive ions and negatively charged electrons are created inside a GM counter.

3) Due to the Electric field, established inside the tube the electrons accelerate towards electrode and positive ions are accelerated towards the surface of the tube

4) Single free electron created from the collision of radioactive decay particle with medium particle is capable of further ionisation. Once the electron is ejected from elements orbit it can collide with different particles of the medium and cause another ionisation thus creating another free electron. This creates a chain reaction in which many free electrons start to appear in the GM counter. This phenomenon is called **Townsend avalanche**.

5) Once electrons reach the electrode they accumulate on it and travel thru the circuit. During this process a measuring device counts potential drops and current over a period of time. When electrons complete the circuit they accumulate on metallic surface.

6) At the metallic surface electrons meet with positive ions and create neutral particles bringing the set up to original state

GM counters are more precise then low voltage gas filled detectors and hence they are commonly used to detect radiation that human body is exposed to.

2. Sources of The Radiation We Experience Daily

2.1 An Overview of Radiation Sources

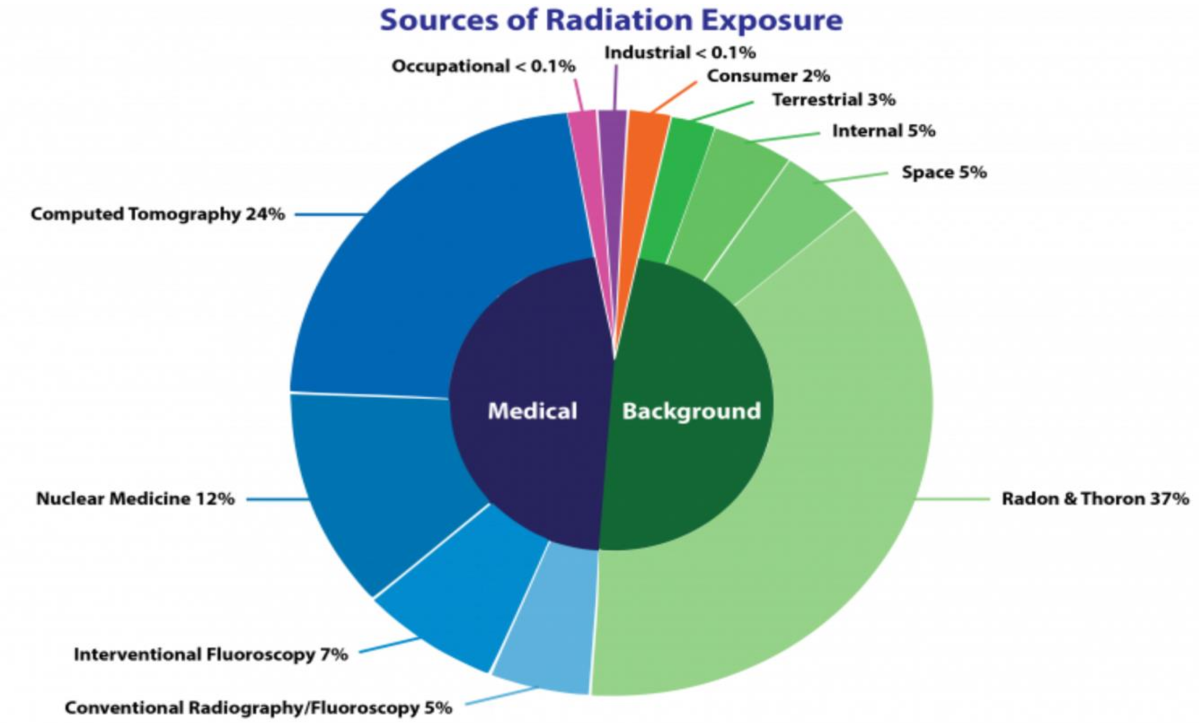


Figure 2: *Pie chart showing sources of average annual radiation dose of US citizens (Radiation Sources and Doses, 2019)*

A source of radiation is the origin at which the radiation was produced. A man-made source is one which produces radiation intended for a specific purpose. Whereas a natural source is one which produces background radiation. A natural source is said to be terrestrial if it originates from the Earth.

Sources of average annual radiation dose of US citizens are summarised in Figure 1. The natural sources this includes which we will explore are radon and thoron gas. The main man-made source it includes is 'Computed Tomography,' a form of medical imaging. This section discusses Computerised Axial Tomography (CAT) and Positron Emission Tomography (PET).

This section also discusses the Sun as a natural source. Of the radiation produced by the Sun is cosmic rays and electromagnetic radiation. Radiation in cosmic rays includes ions which become trapped in Earth's magnetic field, and weakly interacting neutrinos. The effects of these are experienced less commonly and therefore have been neglected. However, electromagnetic radiation includes non-ionizing radiation neglected by Figure 1 and is discussed since its effects are experienced daily.

2.2 Radon and Thoron Gases

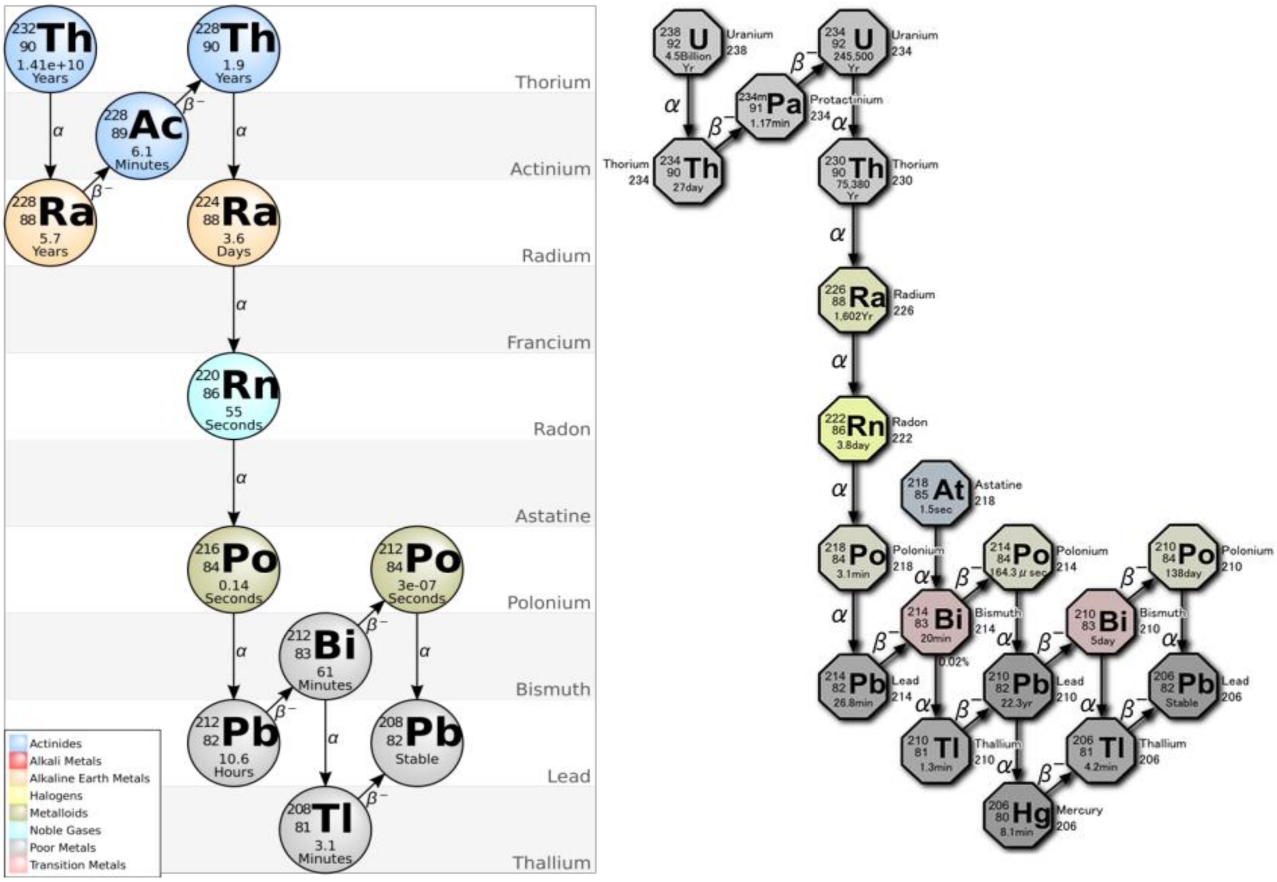


Figure 3 Left: *decay chain of Thorium producing thoron gas shown in cyan. Right: decay chain of Uranium producing Radon gas shown in yellow (Wang, 2020)*

Radon (^{222}Rd) and Thoron (^{220}Rd) gases are the sources responsible for the largest contributions to our daily dose of radiation. Both are isotopes of Radon (Radiat., 2020) and are produced as by-products from radioactive decay chains in rocks and fossils. Since both gases have atomic masses greater than that of Iron, they fission once in the atmosphere in order to increase binding energy per nucleon and become more stable.

Thoron gas is produced from the decay chain of Thorium, whereas Radon gas is produced from the decay chain of Uranium (Gregersen, 2020). These decay chains are shown in Figure 2 left and right respectively. This shows Radon gas is produced with a half-life of 3.8 days, whereas Thoron gas is produced with a half-life of 55 seconds. These gases are considered radioactive sources because their resulting decays directly produce alpha and gamma radiation, which their progeny continue to release as they decay (Marshall, 2000).

2.3 Tomography

2.3.1 Tomography & Medical Imaging

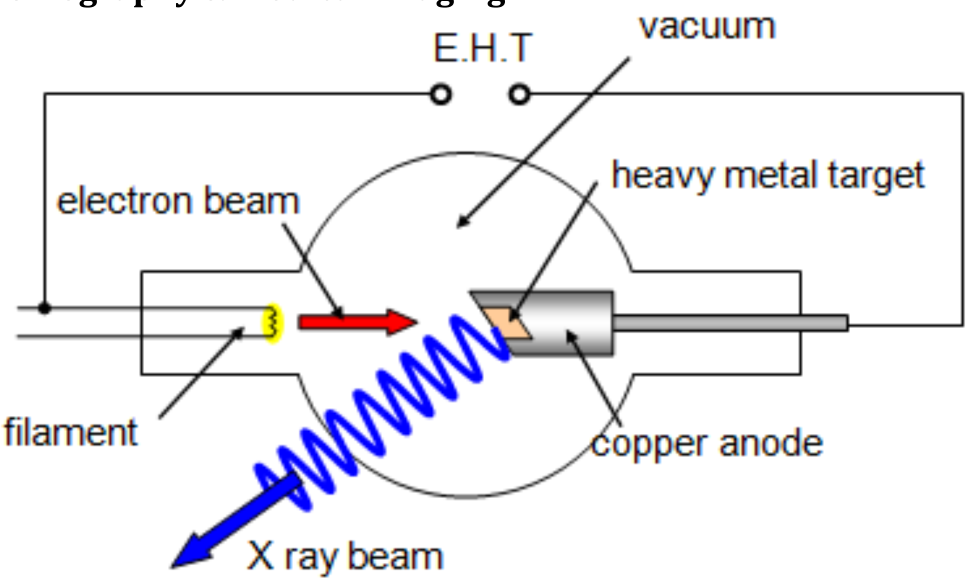


Figure 4: *diagram of an X-ray tube producing X-rays used in CAT scanning (Stockford, 2014)*

Tomography refers to the 3D medical imaging of a patient. Software is typically used to combine multiple 2D images or 'slices' of a patient into the 3D image (Harmonay, 2015). This Computed Tomography (CT) is commonly used to identify tumours and the spreading or 'metastasis' of cancers (Wyant, 2020). CT exists in two main forms, CAT (Computerised Axial Tomography) and PET (Positron Emission Tomography).

2.3.2 Computerised Axial Tomography

In CAT scanning, the source of radiation is X-rays. A fan shaped beam of these X-rays is spiralled around a patient in a helical path (Tikkanen, 2012). The radiation not absorbed by the patient is recorded by a fan of detectors placed opposite to the X-ray source on the other side of the patient (Stockford, 2014). The CAT machine combines these signals to form the 3D image of the patient. The source of these X-rays used are produced by an X-ray tube (Plas, 2016).

A diagram of an X-ray tube is shown in Figure 3. A voltage is applied, which increases the temperature of the cathode. This gives electrons on its surface enough potential energy to form an electron cloud and dissociate from their bonds (Plas, 2016). An external electric field is then applied, which 'boils' the electrons off of the cathode in a process called thermionic emission (Hibler, 2009) and accelerates them towards the oppositely charged anode. As they decelerate upon collision with the anode, their kinetic energies are transferred into the form of the X-rays produced to then be used in the CAT scan.

2.3.3 Positron Emission Tomography

In PET scanning, the source of radiation is a radiotracer. These are radioactive materials consumed in low doses by patients (Promeet, 2018). This is such that the positrons produced by their decay inside the body annihilate with electrons inside the tissue. This produces pairs of gamma photons travelling in opposite directions (as momentum is conserved). These pairs of gamma photons penetrate the body and are recorded and processed by the PET machine (Webb, 2011), producing the 3D image.

The most common form of radiotracer is Fluorodeoxyglucose (FDG), which is the radioactive isotope of Fluorine - ^{18}F bonded to glucose (Webb, 2011). Glucose is used since cancers metabolise it at a higher rate than surrounding tissues and therefore produce more gamma rays. This means that areas of higher activity on the scan indicate cancerous tissues or areas of higher metabolism in the body (Alley, 2017).

^{18}F used in radiotracers has a half-life of 110 minutes (Webb, 2011) and is produced in an on-site particle accelerator (cyclotron). These use electromagnetic fields to accelerate charged particles and magnetic fields to control their direction. In the case of ^{18}F used in FDG, the particle produced by the cyclotron is a high velocity proton which is aimed at and absorbed by a sample containing ^{18}O. In this process a neutron is then emitted to produce the ^{18}F (Alauddin, 2011). This is such that the ^{18}F and ^{18}O are isobars, although ^{18}F contains one more proton and one less neutron.

2.3.3 A Summary of Radiation Sources in Tomography

The sources of radiation used in tomography we have explored are X-rays used in CAT scanning and radiotracers used in PET scanning. The X-rays used in the former case are produced by decelerating electrons produced by thermionic emission inside an X-ray tube. Whereas the radioactive elements in radiotracers used in the latter case are produced by aiming charged particles accelerated in a cyclotron at a source containing enriched nuclei, depending on which radiotracer is used.

2.4 The Sun

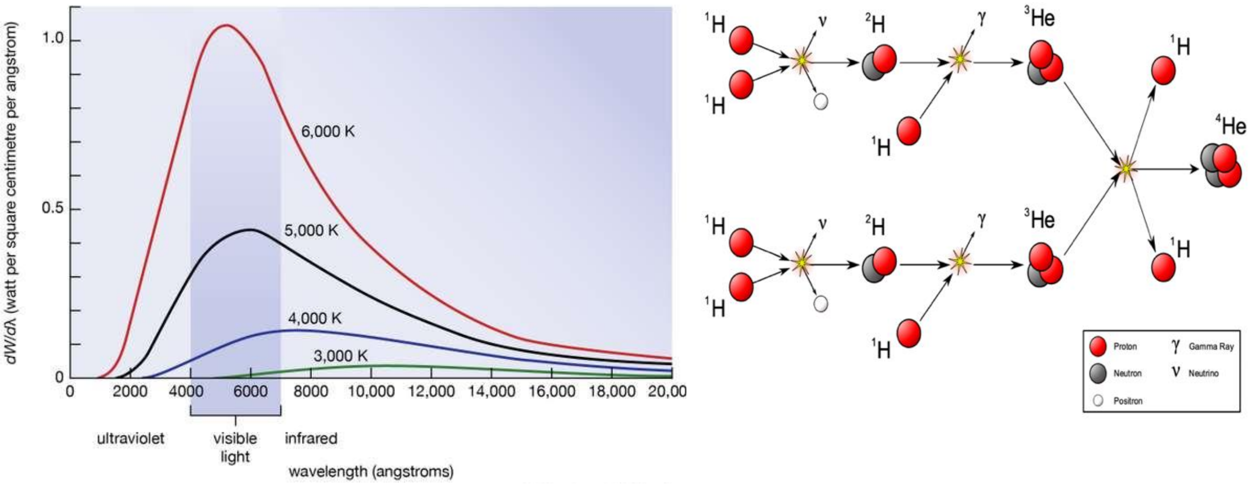


Figure 5 Left: *continuous blackbody spectrum (Lotha, 2020). Right: proton-proton chain showing production of gamma photons from fusion of H to He (Garrett, 2017)*

The Sun is the main natural source responsible for electromagnetic radiation. This exists in a continuous blackbody spectrum shown in Figure 4 (left) and varies for different temperatures. This begins with the production of gamma photons as by-products of fusion in the proton-proton cycle shown in Figure 4, right (Garrett, 2017). In the Sun, these gamma photons are only produced in the core.

In order to reach the surface of the Sun (the photosphere), photons must propagate through the Sun's layers (Dhavala, 2018). In this process, ions in the plasma that the Sun is composed of absorb and re-emit the photons, causing them to lose energy. Simulations predict this random walk of the photons to the photosphere takes 170, 000 years when considering variations of densities in the layers of the Sun, and that higher energy photons are less likely to be arbored those of lower energies (Odenwald, 2015). This random absorption of energy from the gamma photons as they reach the photosphere produces the continuous blackbody spectrum of natural electromagnetic radiation which is experienced daily.

2.5 A Summary of The Sources of Radiations Experienced Daily

Sources have been described either as *natural* or *man-made*. A source of *man-made* radiation dose is medical imaging (tomography). Radiation here comes from X-ray tubes for CAT scanning and from radiotracers in PET scanning. The main *natural* source of *electromagnetic radiation* experienced is fusion in the Sun, emitting photons experienced as a continuous black body spectrum. The main *natural* source of *ionising* radiation is from Radon and Thoron gases emitted from the decay of radioactive elements in rocks. All of these sources are ideally summarised by the nuclear interactions occurring at the quantum scale which cause them.

3. How Much is the Dose from the Different Radiation Sources?

When talking about radiation, the three main types released are: alpha, beta and gamma. Alpha particles are helium nuclei, they are the least penetrative but the most ionising therefore are quickly absorbed over short distances (2-10cm in air). Beta particles are moderately ionising and can travel further than alpha before they are absorbed (~1m). The most penetrating radiation is gamma. As gamma rays are a high energy form of electromagnetic radiation rather than particles, they are the least ionising and therefore are not slowed down through colliding with other particles, giving them a very large range and making gamma the most biologically hazardous to living organisms.

The main source of radiation felt on Earth comes from that of background radiation. Background radiation can be split into two main sections: Natural sources; and artificial, man-made sources. The current split of natural to man-made radiation is approximately 88% natural, to 12% artificial (Association, n.d.).

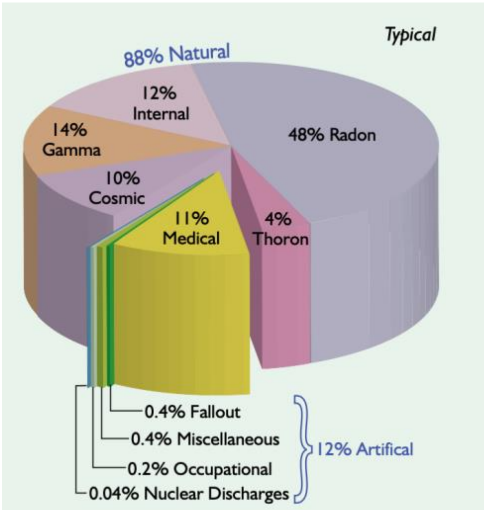


Figure 6: *A pie-chart showing the approximate break-down of background radiation.*

3.1 Natural Background Radiation
3.1.1 Radon
The largest source of natural background radiation is from airborne radon, a radioactive gas that is emitted from the ground and accounts for approximately 48% of all background radiation. Radon inhalation is the second highest cause of lung cancer in the world, therefore determining the exposure in different areas is of high importance to public health. Radon and its isotopes and decay products contribute to an average inhaled dose of 1.26 millisieverts per year (mSv/yr) (Anon., n.d.). The distribution throughout the Earth is scattered and uneven, varying with several external factors such as weather. This therefore results in higher doses of radon emission in different areas of the world, for example the increased average inhaled dose of 1.45 mSv/yr in Shiraz, Iran (Yarahmadi, et al., 2016). Radon is a decay product of uranium, an element which is found in abundance in the crust of the Earth, but most concentrated in ore-bearing rocks. Although a natural source, exposure can be enhanced through human activity, such as construction work.

3.1.2 Cosmic Radiation

Another contributor to the 88% of natural background radiation is cosmic radiation. This is the radiation from cosmic rays bombarding the Earth from outside the solar system. These rays are made up of atom fragments such as protons, electrons and muons, with their dose on the Earth varying in dependence to geomagnetic field and altitude (Howell, 2018). Cities at a higher altitude receive a higher dose of yearly cosmic radiation, with the most intense radiation being received to the upper troposphere. This becomes a concern for airline personnel and frequent flyers as, at this altitude, there is less atmosphere to shield the cosmic rays, exposing flight personnel to an average of 2.19mSv/yr (Anon., n.d.). Outside the atmosphere, where minimal shielding is offered, radiation from cosmic rays is much more intense and therefore astronauts, e.g on the ISS, are exposed to much higher levels of radiation each year. This is demonstrated in the International Commission on Radiological Protection's (ICRP) recommended radiation limit of 25,000 millirems per Space Shuttle mission. (Anon., 1994). Other areas of natural background radiation include food and water, naturally high radiation areas and neutron background radiation.

3.2 Artificial Background Radiation

3.2.1 Medical

As discussed, artificial background radiation accounts for approximately 12% of the total background radiation. The main source of artificial background radiation comes from medical processes and equipment, specifically X-rays, accounting for 11% of total background radiation. Looking into more specific examples of medical procedures using radiation, we must investigate the effects of high doses applied in small areas. For example, looking at those suffering from a hyperthyroid problem, most notably experienced by former President George Bush, a radioactive drink of iodine-131 is often used. This is designed to deliver about 10,000,000 millirems of the radioactive iodine to the thyroid, consequently also delivering about 20,000 millirems to the rest of the body in the process (a slightly lower dose of 6,000,000 millirems is used to kill cancerous tumours). The reason this is done is because the thyroid gland absorbs nearly all the iodine in the body, so focusing the Iodine-131 at this area allows the radiation to destroy the thyroid gland and any other thyroid cells (including cancer cells) with little effect on the rest of the body (team, 2019). Iodine-131 is used in medical procedures such as this due to its relatively short half-life, 8.06 days, and the fact that it decays by beta-particle emission to a stable ^{131}Xe (Mettler & Guiberteau, 2012).

3.2.2 Nuclear Accidents

Another source of artificial radiation is from nuclear accidents. Nuclear reactors, under normal running conditions, release small amounts of radioactive gases into the atmosphere. However, it is very rare for large releases of radioactivity from reactors, with there being only two major civilian incidents so far – Chernobyl, and the Fukushima accident. The 1986 Chernobyl accident caused the largest ever recorded uncontrolled radioactive release into the environment for any civilian operation. It is estimated that the radiation in the worst-hit areas of the disaster were around the 300Sv/hr mark, a dose enough to prove fatal in just over one minute. As of 2020, due to the construction of the new safe confinement sarcophagus, a €2.1billion steel structure encasing the original sarcophagus, radiation levels are much lower. The average radiation around the powerplant is now in the range of 1.2μSv/hr (Welcome, n.d.), showing that the new structure is working well at trapping the majority of dangerous radiation in close proximity of the reactor. This has allowed for the government to relax some of the health guidelines around Chernobyl, allowing for the tourism industry to begin to 'boom'.

Figure 7: *The famous photograph of the Chernobyl 'elephant's foot'. It is a radioactive sludge of melted nuclear fuel mixed with concrete and sand known as corium, which leaked from the reactor. In 1986 the radiation level was measured to be over 100Sv/hr.*

3.2.3 Nuclear Weapons Testing

There is also artificial background radiation from atmospheric nuclear testing and explosive nuclear devices. On August 6, 1945 the US dropped the first ever atomic bomb, a 9000-pound uranium-235 bomb, over the Japanese city of Hiroshima, followed by a second atomic device over the city of Nagasaki. These devices killed an estimated 120,000 people immediately, with radiation accounting for a following, estimated, 70,000 to 135,000 people in Hiroshima, and 60,000 – 80,000 people in Nagasaki (Editors, 2009).
According to studies made after these explosions, half of the people who were exposed to 450 rems of radiation died. Whereas all of the people who were exposed to 600 rems of radiation were killed (Anon., 1994).

Following the second world war there was frequent testing of above-ground nuclear weaponry, between the 1950's and 1960's, spreading large amounts of radioactive material. This testing was mainly between the USA and the Soviet Union trying to make and perfect their thermonuclear weapons, in competition with one another to make the larger device. In the end, the largest test carried out by the US was the 'Ivy Mike' hydrogen bomb in 1951. This device had an explosive yield of 10.4 megatons, equivalent to 10.4 million tons of TNT, at that moment in time making it the most powerful nuclear weapon ever created. The device featured a plutonium core in a chamber of tritium gas, allowing for a 'sparkplug' fission reaction, providing outward pressure to increase the conditions for the following fusion reaction. It had around 700 times the explosive power of the weapon dropped on Hiroshima seven years earlier, a weapon which itself killed 160,000 people (CTBTO, n.d.).

All of the atomic weapons tests that took place through the 1950's and 1960's, are estimated to have put approximately 100 to 1000 times more radioactive material into the atmosphere than the Chernobyl accident (Agency, 1996).

4. What are the dose limits on human bodies?

4.1.1 Human Exposure to Radiation in Our Natural Background

Radiation has always known to exist naturally as part of our environment. Some natural radioactive sources on Earth originate in soil, water and air which contribute to the human exposure of ionising radiation. Man-made sources also enhance the amount of radiation in our environment as a result of mining and power generation, nuclear medicine and military usage. Humans are also exposed to naturally occurring radiation from outside of the earth, this is known as cosmic radiation. Ionising radiation include alpha and beta radiation, gamma rays and neutrons. Radiation produces electrical ions which can affect standard biological processes in living tissue.

4.1.2 Radioactivity in Humans

Some natural elements in our environment are unstable therefore their when their nuclei decay, they release energy in the form of radiation. This radioactive decay is measured in units of Becquerels. The radionuclides decay at a rate that typically is constant despite changes in temperature and pressure. Usually, radionuclides decay in terms of half-life which is the time it takes for half of the radionuclide to disintegrate. Potassium, which is the main source of radioactivity in our bodies, has a half-life of 1.42 billion years whereas, Uranium which is present globally, has a half-life of 4.5 billion years. **(***International Atomic Energy Agency, (1998)***)**

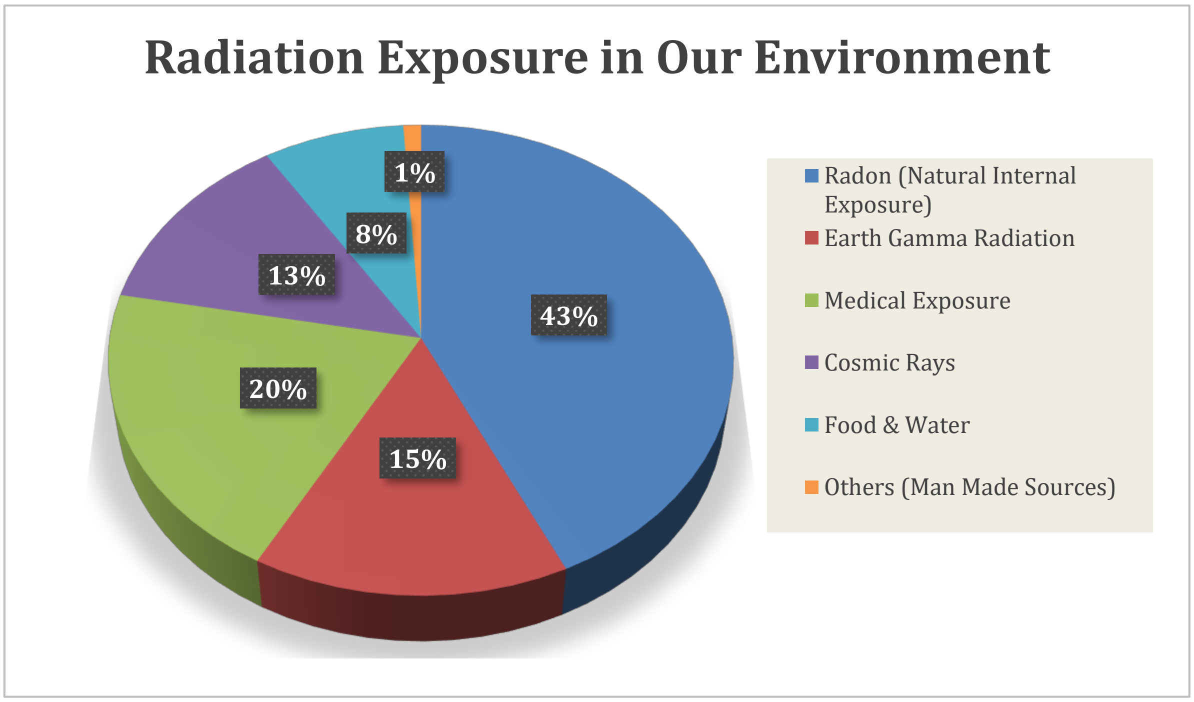


Figure 8. *Distribution of average radiation exposure to the global human population (statistics provided by World Health Organisation, 2020)*

4.2 Radiation Dose

Light from the Sun usually feels warm because a human body absorbs the infra-red rays which are emitted, however, these rays do not produce ionisation in human body tissue. In comparison, ionising radiation can in fact harm functioning cells or possibly destroy them. The required energy to significantly affect a human's biology as a result of ionisation is very miniscule, therefore, a human body cannot feel the energy of infra-red rays which lead to heat transfer.
Ionising radiation varies in type and energy when considering biological effects. The risk of radiation harming a human biologically is the dose of radiation that the tissues receive. The unit for absorbed radiation is Sievert (Sv).
For example, one chest X-ray will exhibit 0.2 mSv of radiation. Average radiation exposure is approximately 2.4mSv every year. People are also exposed internally from radioactive elements such as Potassium, Carbon and Radium in food, in the air and in the human body.
People are generally exposed to several man-made radiation sources such as medical X-rays, industrial uses of consumer products, smoke detectors and nuclear testing.

Radiation exposure due to cosmic rays is dependent on altitude therefore, people who travel by air very often increase their exposure to radiation.

These radioactive elements are mainly Radon, Thoron and by-products formed as a result of decay of Radium 226 which are present in rocks, building materials and soil. The largest source of natural radiation originates from Uranium and Thorium in soil.

The effects of radiation doses vary incredibly and are recorded as such. A very large dose of radiation to a human body over a short time will ultimately become the catalyst for death of a person within a few days. The opportunity to learn about some of the health effects due to exposure was by studying the health records of individuals who survived the Hiroshima bombing. Many other effects like cancers are visible to detect in those who have received more than moderate doses. At low does, recovery is possible in body tissue. There is still some uncertainty about low doses having little effect as studies have shown that there may be risks of cancer even at the levels of natural exposure.

According to USNRC Technical Training Centre, below 5 rad, there are no observable effects but between 5 and 50 rad, blood changes can be detected. Beyond 150 rad, an exposed body is at its most likely to die.

Based on the ICRP recommendations, an individual's total does should not exceed 5mSv per year and any radiation to an individual organ should not exceed 500 mSv per year which excludes the eye lens, which has a limit of 150 mSv. For anyone under the age of 18, their dose limits should be 10% of the annual dose limits for adults. For an embryo/foetus, this should not exceed 5 mSv. **(***Cherry R. Simon, Phelps E. Michael, (2012)***)**

Radiation in several industries such as medicine, agriculture and energy has been beneficial for societies for example, using radiation in medicine for diagnosis and treatment of patients has essentially aided to save human lives.

4.3. Radiation for Astronauts

Radiation can also be expressed in units of rem. The recommendation for astronauts is typically a limit of 25,000 millirems per Space Shuttle mission as their exposure to cosmic rays increases with altitude. The amount that astronauts are exposed to is highly above the average of 300 millirems of radiation from natural sources or medicine. **(***MIT News, (1994)***)**

4.4.1 Individual Doses

An Adult: The current limit for radiation exposure per year for an adult is recommended not to exceed 5000 millirems. The lifetime exposure can be limited to the age of an individual multiplied by 1000 millirems (for example, for a 35 year old person, their limit should be 35000 millirems).

Children: The maximum exposure for a person under the age of 18 is 10% of the adult limit hence children should not exceed 500 millirems per year above the 300 millirems from natural sources of radiation, as well as medical.

Fetus: 500 millirems or 50 per month.

4.4.2 Weight Variables

Similar to levels of alcohol intoxication, levels of radioactivity exposure depends on the individual's weight. If one microcurie of a diagnostic tracer of radioactive Calcium is given orally, this would result in an exposure of 3.7 millirems for a person weighing 45kg and 1.85 millirems for a 90kg person.

4.5.1 Medical Exposure

Man-made radiation such as X-rays, are used in medicine and dentistry to diagnose disease or bone abnormalities.

Exposure to radiation of these levels do not cause long-term health effects but there is still a small increase in the risk of cancer. Studies have shown from groups of different people who have been exposed to radiation, from atomic bomb survivors and radiation industry workers, that more radiation exposure increases the chance of getting cancer and therefore, the risk increases as the dosage does and vice versa.

One dose can be determined from radiation exposure in one incident or from accumulated exposures over a certain amount of time. According to the EPA, about 99% of people would not get cancer as a result of a one-time uniform whole-body exposure of 100 mSv. At this dose, it would be difficult to identify cancers caused by radiation when currently, 40% of men and women in the US or 1 in 5 in the UK will be diagnosed with cancer at any point during their lifetime. Therefore, in order to protect the population, limits are set from excess exposure. **(***US EPA,OAR, (2019)***)**

4.5.2 Therapeutic Doses of Radiation

In order to undergo therapeutic radioactive iodine treatment of the thyroid gland, 20000 millirems are usually required. A local dose delivers 10 million millirems to the thyroid and approximately 20000 millirems to the whole body.

Radiation to kill a cancerous tumour often delivers 6 million millirems to the cancerous tissue but amount delivered to the body is around 6000 millirems, much less than that of the thyroid. **(***US NRC Technical Training Center, (2009)***)**

4.6 Conclusion

It is certain that it is inevitable to be associated with risks of radiation as humans are naturally exposed to radiation anyways, however, the above exemplifies that there are some benefits from the use of radiation and radiation should be viewed as less harmful in comparison to other agents.

It is evident however that increasing dosage, increases the risk of biological effects, the higher the dose, the higher the risk of cancer therefore, it is vital to recognise the limits in dosage and exposure.

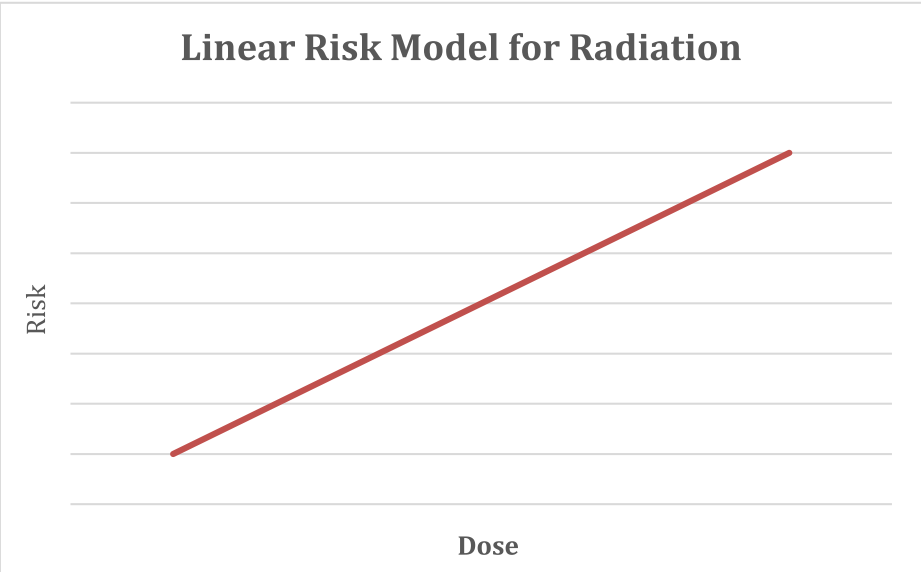


Figure 9: *A graph to represent how dosage and risk are associated.*

This model shows a linear relationship between dosage and risk and therefore implies a change in dosage affects the level of risk e.g. a decrease in dosage of radiation means a smaller risk of biological harm.

5. Can we protect ourselves?
5.1 A Brief Recapitulation of the Radiation Sources we're exposed to.

In spite of always existing, as our society evolves Radiation has become a more increasingly present part of our lives. *Background Radiation*, coming primarily from *natural minerals*, is around us all the time. Fortunately, there are very few situations where an average person is exposed to uncontrolled sources of radiation above *background*. Nevertheless, it is well-worth knowing the measures we should take in order to limit our exposure to the more common ones.

In *Part 2* (look back to *2.4* and *Figure 1.* for more details) we categorized the possible sources of radiation we might be exposed to into 2 different sections: *natural* or *man-made*. We then, divided the *natural* ones into 2 further categories: *ionising* radiation and *electromagnetic* radiation.

Having clarified and reminded ourselves of these main sources, in this section we'll delve into the ways we can protect ourselves from each certain type of radiation thus minimising its negative side-effects on us.

5.2 General Advice on Radioactive Protection: *Time*, *Distance*, *Shielding* (TDS)

As general advice to ensure better protection against all types of radiation there are 3 factors that have the biggest effect on how much we're exposed to these harmful sources: Time, distance, and shielding. These actions when taken appropriately minimize your exposure to radiation in much the same way as they would to protect you against overexposure to the sun:

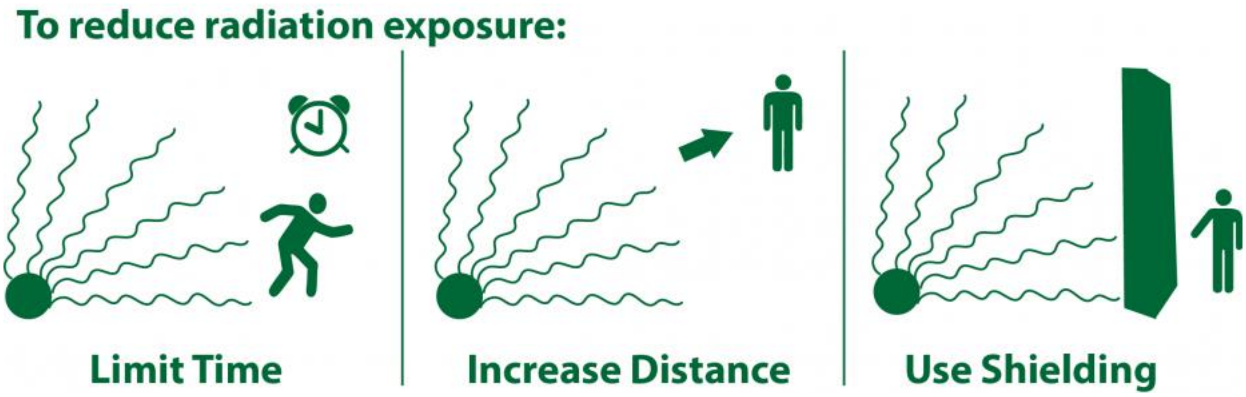


Figure 10*. on how to reduce Radiation Exposure*

- **<u>TIME</u>**: It might seem obvious but nevertheless crucial. For any individual who is exposed to any type of source of radiation in addition to *background* radiation, the more he limits the exposure time the better.
- **<u>DISTANCE:</u>** The same way the heat from a fire reduces as you get further away, the dose of radiation decreases dramatically as you increase your distance from the source. The paramount important distance has in protecting you is due to the *Inverse Square Law* the relationship distance-radiation follows. This means that for example, doubling the distance from a point source of radiation reduces the exposure rate to ¼ the original exposure rate. And inversely, halving the distance

from said point source would mean you would increase your exposure by a factor of 4.

- **<u>SHIELDING:</u>** As ionizing radiation passes through matter; the intensity of the radiation is diminished. What is meant by *Shielding* is the placement of an "absorber" between the radiation source and a person thus greatly reducing, or ideally eliminating, their exposure to it. An absorber is a material that reduces radiation from the radiation source to you. Alpha, beta, or gamma radiation can all be stopped by different thicknesses of absorbers. Alpha is absorbed by skin, paper or a few centimetres of air. Beta radiation is absorbed by a few millimetres of aluminium and Gamma radiation is absorbed by many centimetres of lead or several metres of concrete.

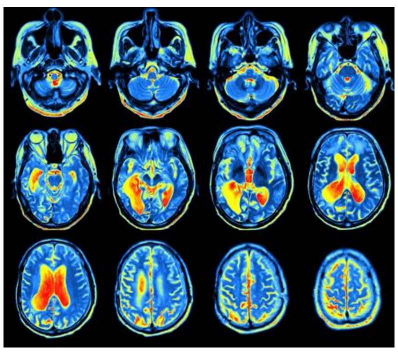
5.3 Protection against *Man-Made* Radiation.
5.3.1 X-Ray Tubes for CAT

As we mentioned in *Part 2.3.2*, in CAT Scanning X-Rays are used in order to detect for example bone and joint problems, like complex bone fractures and tumors. It can also allow doctors to spot or follow the development of for example cancer, heart disease or liver masses. *X-rays* resemble *gamma radiation*, with one main difference which is that they originate from an electron cloud. The main way doctors and nurses in hospitals help the patient minimize its exposure to this radiation, or at least to make sure it doesn't reach more areas than the absolutely necessary ones, is by giving him/her leaded aprons or leaded plaques. This makes sure that the X-Rays (or Gamma Rays) are absorbed by the lead and don't even reach the patient's skin.

Figure 11. *showing a Leaded Apron*

Although this has, in recent years, been criticised by some experts. For example, The American Association of Physicists in Medicine no longer supports shielding patient's reproductive organs when exposed to Medical X-Ray Imaging and CT Scans. They argue that most of the time, these aprons or plaques are misplaced therefore forcing the doctor to repeat the process and thus exposing the patient to more radiation than the strictly necessary. Furthermore, the way doctors protect themselves is by shielding themselves from the source of radiation.

5.3.2 Radiotracers for PET Scanning



As mentioned in *Part 2.3.3* Positron Emission Tomography (PET) is another source of *man-made* radiation but in this case the radiation comes in the form of a *radiotracer*.
The radioactive substance most commonly used in PET scanning is a simple sugar (like glucose) called FDG, which stands for "fluorodeoxyglucose". It is injected into the bloodstream and accumulates in the body where it gives off energy in the form of gamma rays. This is a very safe procedure from the *radioactive safety* point of view. This is

Figure 12*. showing a PET scan*

because there is no significant risk to the staff taking care of these patients nor to the patients.

The measures/precautions that have to be taken in order to practically eradicate the risk of radioactive exposure are simple. For nurses and doctors, reducing contact time and increasing the distance from the patient suffice to limit radiation exposure. For patients the radioactive exposure is practically harmless, but for those with urinary catheters or incontinence, standard precautions for dealing with biohazardous waste would be sufficient to prevent unwanted radiation exposure and contamination.

5.4 Protection Against *Natural* Radiation

When we talk about *Natural* sources of radiation, the main 2 are: *ionising* radiation and *electromagnetic* radiation. Ionising radiation mainly comes from, as we mentioned in *Part 2.2*, Radon and Thoron Gases. These gases are so called by-products from radioactive decay chains in rocks and fossils and are present in the air we breathe. This means that protection against them is practically impossible, this is not worrying nevertheless since this type of radiation is almost completely harmless.

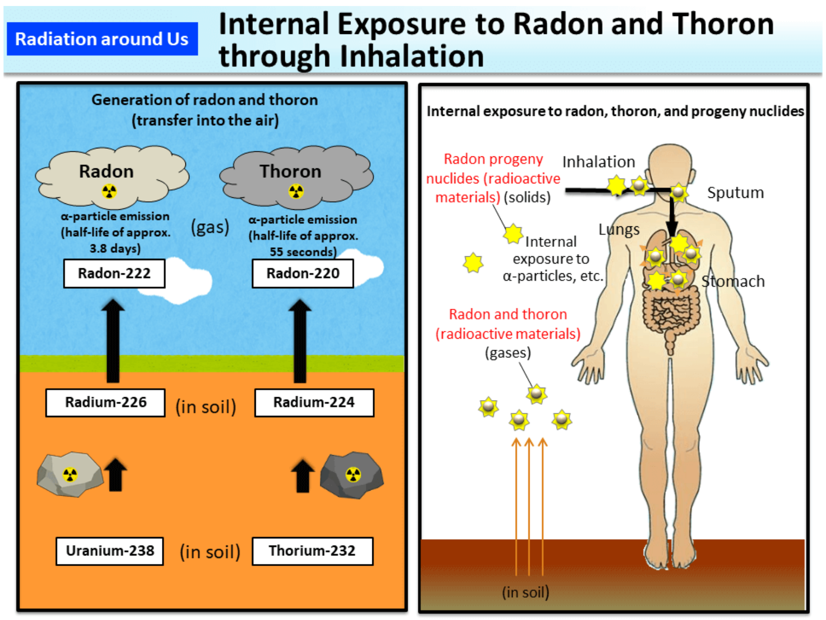


Figure 13*. showing Radiation by Radon and Thoron Gases*

The other type of *natural* radiation is electromagnetic coming from the Sun. Electromagnetic solar radiation is a phenomenon by which energy escapes from the Sun at the speed of light in the form of a wave. This type of radiation provides the light and warmth we need to survive, but also consists of invisible radiation some of which can be harmful such as ultraviolet that could even cause skin cancer. The way every one of us can protect ourselves from the harmful effects of over-exposure to UV Light is by using limiting the exposure to the sun especially during midday hours, by wearing clothes that cover our arms and legs or by wearing a hat and glasses. Sunscreen is also very helpful, but we must remember it is just a filter, it does not block *all* UV Rays.

Conclusion

Radiation is measured in Geiger-Muller Counters via the potential difference induced on a circuit by the ionization of inert gasses inside the gas chamber interacting with Alpha, Beta and Gamma radiation.

Sources of radiation we experience daily breaks down in to man-made and natural sources. The largest contributor to man-made sources, comprising 11% of the 12% of background radiation attributable to artificial sources is in the field of medical imaging. The penetrative property of high energy electromagnetic radiation is exploited to produce images. X-Rays are used in Computerised Axial Tomography (or CAT) scans where a continuous, broad beam of X-Rays opposite an array of detectors is spun around a patient in a helical path to produce a 3D image. Positron Emission Tomography (PET) involves the patient ingesting a radioactive tracer bonded to glucose that will be metabolised by most efficiently by cancer cells, the tracer emitting Gamma radiation most prevalently at these locations. The emitted radiation can then be recorded by PET machines to produce an image.

Other sources of Artificial background radiation include nuclear accidents, while not common, the local effects are devastating. the Chernobyl accident causing the largest ever recorded uncontrolled radioactive release into the environment for any civilian operation. Radiation in the worst hit areas would induce a dose high enough to kill a human in under a minute at 300Sv/hr. Similarly, in contributing proportionality little to normal background radiation but having devastating local effects is nuclear weapons. Radiation from the combined attacks on Hiroshima and Nagasaki killed between 1.08X and 1.8X the number of people killed in the initial detonation. Nuclear weapons tests that took place through the 1950's and 1960's, are estimated to have put approximately 100 to 1000 times more radioactive material into the atmosphere than the Chernobyl accident.

88% of background radiation comes from natural sources, the largest constituent of this category being airborne Radon Gas. Radon is a decay product of Uranium, a relatively abundant element in the earth's crust. Thoron is a radioactive isotope of Radon, also on the decay chain of an abundant element, Thorium. Radon inhalation is the second highest cause of lung cancer due to the alpha and gamma radiation emitted as biproducts of their decay, which their progeny continues to release. Although a natural source, exposure can be enhanced through human activity, such as construction work.

The other large contributor to background radiation is cosmic radiation and solar radiation.

Cosmic rays bombard the Earth from outside the solar system. These rays are made up of atom fragments such as protons, electrons and muons. On the surface of the sun, the photosphere, random absorption of energy from gamma photons produces the continuous blackbody spectrum of natural electromagnetic radiation which is experienced daily. The effective dose on the Earth from these sources varies with respect to geomagnetic field and altitude. Variation in exposure with respect to altitude is due to the shielding effect of the atmosphere. This is important to airline pilots and frequent flyers who spend a lot of time above the troposphere. Flight personnel are exposed on average to 2.19mSv/yr. The most extreme example of this is astronauts, the International Commission on Radiological Protection's (ICRP) recommended radiation limit is 250 mSv per space shuttle mission.

The average normal radiation dose in Americans is roughly 620 millirems. This dose comes primarily from background radiation contributing half the daily dose. Background radiation breaks down to natural sources of Radon in the air and cosmic rays. The other half, 310 millirems, comes from man-made sources of radiation, including medical (primarily), commercial, and industrial sources. The doses safe for humans is considered to be below 5000 millirems per year. Humans are naturally exposed to radiation doses from light emission from the Sun. However, the infra-red rays being emitted do not produce ionisation in human body tissue to harm functioning biological cells. Astronauts are exposed to radiation doses from cosmic rays and are limited to a dose of 25000 millirems per Space shuttle mission – this is because radiation increases as altitude increases. Hence, it can be concluded that an increase in dosage increases the risk of biological harm.

The principle tenets of radiation safety refer to time, distance and shielding (TDS). Minimize exposure time, attain maximum distance from source and use shielding between you and the source proportionate to the penetrating power of the specific radiation. Natural sources of radiation are hard to protect against. Limiting exposure time to intense sunlight protects against UV radiation. Protection against radon gas is practically impossible.

Man-made sources of radiation used in medical imaging is to limit exposure to absolutely necessary areas of the body, one technique is the use of lead aprons which absorb radiation, however this has been criticised in the medical community where it is argued that the complications introduced mean otherwise unnecessary repeat scans have to be made increasing overall dose .

Fluorodeoxyglucose is a commonly used radiotracer in PET scans because it limits medical staff and patients exposure to the most harmful radiation due to its emission of only Gamma radiation and its short half-life of 110 minutes, due to this low half-life it is produced on site in an accelerator known as a cyclotron.

References

Agency, I. A. E., 1996. Ten Years After Chernobyl: What do we really know?. Vienna, s.n.

Alauddin, M. M. (2011, December 15). Positron emission tomography (PET) imaging with 18F-based radiotracers. Retrieved from National Center for Biotechnology Information: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3478111/

Alley, R. (2017, April 24). What Are Radioactive Tracers? Retrieved from Sciencing: https://sciencing.com/radioactive-tracers-8330110.html

*American Cancer Society (2020), UV Protection (Online)
Available at: https://www.cancer.org/healthy/be-safe-in-sun/uv-protection.html [date accessed: 16/12/2020]*

*Anon., 1994. MIT News. [Online]
Available at: https://news.mit.edu/1994/safe-0105
[Accessed 3 December 2020].*

*Anon., n.d. Background Radiation. [Online]
Available at: https://en.wikipedia.org/wiki/Background_radiation
[Accessed 12 12 2020].*

*Anon., n.d. Radiation Exposure During Commercial Airline Flights. [Online]
Available at: https://www.space.com/32644-cosmic-rays.html
[Accessed 13 December 2020].*

*ANS Center for Nuclear Science and Technology Information. (2018), Protecting Against Exposure (Online)
Available at: http://nuclearconnect.org/know-nuclear/science/protecting#:~:text=Distance%20can%20be%20used%20to,by%20a%20factor%20of%20four [date accessed: 08/12/2020]*

*Association, W. N., n.d. What is Background Radiation. [Online]
Available at: http://www.world-nuclear.org/uploadedFiles/org/Features/Radiation/4_Background_Radiation%281%29.pdf
[Accessed 15 December 2020].*

*Cherry R. Simon, Phelps E. Michael. (2012), Radiation Safety and Health Physics
Available at: https://www.sciencedirect.com/topics/pharmacology-toxicology-and-pharmaceutical-science/dose-limit, [date accessed: 14/12/2020]*

*CTBTO, n.d. 1 November 1952- Ivy Mike. [Online]
Available at: https://www.ctbto.org/specials/testing-times/1-november-1952-ivy-mike
[Accessed 12 12 2020].*

Dhavala, Y. (2018, October 1). Voyage of Photons. Retrieved from YouTube: https://www.youtube.com/watch?v=or3TPxq7Cew

*Editors, H., 2009. Bombing of Hiroshima and Nagasaki. [Online]
Available at: https://www.history.com/topics/world-war-ii/bombing-of-hiroshima-and-nagasaki
[Accessed 13 December 2020].*

Garrett, E. (2017, October 31). The Proton-Proton Chain. Retrieved from Science At Your Doorstep: https://scienceatyourdoorstep.com/2017/10/31/the-proton-proton-chain/

Gregersen, E. (2020, July 21). Radon. Retrieved from Britannica: https://www.britannica.com/science/radon

Harmonay, V. (2015, May 11). CT Scanner Slice: Handy Guide. Retrieved from Atlantis Worldwide: https://info.atlantisworldwide.com/blog/ct-scanner-slice

Hibler, J. (2009, March 23). Thermionic emission. Retrieved from Britannica: https://www.britannica.com/science/thermionic-emission

*Howell, E., 2018. What are Cosmic Rays. [Online]
Available at: https://www.space.com/32644-cosmic-rays.html
[Accessed 13 December 2020].*

*International Atomic Energy Agency. (1998) Radiation in Everyday Life (Online)
Available at: https://www.iaea.org/Publications/Factsheets/English/radlife, [date accessed: 12/12/2020]*

Iop.org, "Deflection in electric fields", Accessed at: December 12 2020, https://spark.iop.org/deflection-electric-fields#gref

J.M.K.C. Donev, Energy Education.Ca, "Ionization", 2018, Accessed: December 9 2020, https://libanswers.snhu.edu/faq/48009

Lotha, G. (2020, June 15). Blackbody radiation. Retrieved from Britannica: https://www.britannica.com/science/blackbody-radiation

*Love of Physics, "Ionization Chamber & Proportional Counter", YouTube video, 15:16, 03.04.2019, Accessed at: December 12 2020,
https://www.youtube.com/watch?v=avvXftiyBEs*

Love of Physics, "What is a GM Counter? - Geiger Muller Counter", YouTube video, 12:34, 03.04.2019, Accessed at: December 9 2020 https://www.youtube.com/watch?v=jxY6RC52Cf0

Marshall, B. (2000, October 4). How Stuff Works. Retrieved from How Radon Works: https://home.howstuffworks.com/home-improvement/household-safety/radon1.html

Mettler, F. & Guiberteau, M., 2012. Essentials of Nuclear Medicine Imaging. 6th Edition ed. s.l.:Saunders.

Michał A. Gryziński, Natalia Golnik, Mieczysław Zielczyńsk, "Initial recombination of ions in ionization chambers filled with hydrocarbon gases", NUKLEONIKA 2007;52(1):7–12, Accessed at: December 8 2020 http://www.ichtj.waw.pl/ichtj/nukleon/back/full/vol52_2007/v52n1p007f.pdf

*MIT News. (1994, Janaury 5), Radiation how much is safe for humans? (Article)
Available at: https://news.mit.edu/1994/safe-0105, [date accessed: 13/12/2020]*

Nuclear-power.net, "Townsend Avalanche", Accessed: December 14 2020, https://www.nuclear-power.net/nuclear-engineering/radiation-detection/gaseous-ionization-detector/operating-regions-of-ionizing-detectors-detector-voltage/townsend-avalanche/

Odenwald, S. (2015, May 12). Sunlight Is Way Older Than You Think. Retrieved from YouTube (TED-Ed): https://www.youtube.com/watch?v=Z-UO-RZBQ3U

Orau.org, 1999, Oak Ridge Associated Universities, "Ionization Chambers" Last updated: 07.31.09, Accessed: December 10 2020, https://www.orau.org/ptp/collection/ionchamber/introionizationchamberr.htm

*Pearson, E. (2020, May 12), Lead Aprons Little Protection (Online)
Available at: https://www.statnews.com/2020/05/12/lead-aprons-little-protection-xrays-clinician-use/ [date accessed: 14/12/2020]*

Plas, A. v. (2016, August 23). X-ray/CT technique. Retrieved from Start Radiology: https://www.startradiology.com/the-basics/x-rayct-technique/index.html

Promeet, D. (2018, April 11). Isotopic tracer. Retrieved from Britannica: https://www.britannica.com/science/isotopic-tracer

Radiat., I. J. (2020, November 19). Environmental thoron (220Rn) : A review. Retrieved from International Journal of Radiation Research: http://ijrr.com/article-1-644-en.pdf

Radiation Sources and Doses. (2019, August 6). Retrieved from United States Environmental Protection Agency: https://www.epa.gov/radiation/radiation-sources-and-doses#averagedoses

*Royal Belgian Institute for Space. (2020), Electromagnetic Solar Radiation (Online)
Available at: https://www.aeronomie.be/en/encyclopedia/electromagnetic-solar-radiation-energy-escaping-sun [date accessed: 16/12/2020]*

Stockford, L. (2014, November 20). Electromagnetic Waves. Retrieved from Slide Player: https://slideplayer.com/slide/2497209/

*Team, T. A. C. S. m. a. e. c., 2019. Treating Thyroid Cancer. [Online]
Available at: https://www.cancer.org/cancer/thyroid-cancer/treating/radioactive-iodine.html#written_by
[Accessed 4 December 2020].*

Tikkanen, A. (2012, January 26). Computed tomography. Retrieved from Britannica: https://www.britannica.com/topic/computed-tomography

*US EPA,OAR. (2019, December 5), Protecting Yourself Against Radiation (Online)
Available at: https://www.epa.gov/radiation/protecting-yourself-radiation [date accessed: 08/12/2020]*

*US EPA,OAR. (2019, August 2), Radiation Health Effects (Online)
Available at: https://www.epa.gov/radiation/radiation-health-effects [date accessed: 08/12/2020]*

*US NRC Technical Training Center. (2009), Biological Effects of Radiation (PDF Online)
Available at: https://www.nrc.gov/reading-rm/basic-ref/students/for-educators/09.pdf [date accessed: 14/12/2020]*

Wang, C. (2020, November 19). Decay Chains. Retrieved from Nuclear Forensic Search Project: https://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html

Webb, A. (2011). Introduction to Medical Imaging Physics, Engineering and Clinical Applications. Cambridge University Press.

*Welcome, C., n.d. Radiation in Chernobyl Now and Then. [Online]
Available at: https://www.chernobylwel.com/safety
[Accessed 13 December 2020].*

*Wikipedia. (2020, November 17), Inverse Law (Online)
Available at: https://en.wikipedia.org/wiki/Inverse-square_law [date accessed: 10/12/2020]*

Wyant, T. (2020, September 10). Understanding Advanced and Metastatic Cancer. Retrieved from American Cancer Society: https://www.cancer.org/treatment/understanding-your-diagnosis/advanced-cancer/what-is.html#written_b

Yarahmadi, M. et al., 2016. Estimation of the residential radon levels and the annual effective dose in dwellings of Shiraz, Iran, in 2015, s.l.: s.n.