Radiation Protection Training Manual

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Chapter 1: STRUCTURE OF MATTER

1.1 Introduction

For this course, we can use a simple model of matter. According to this model, the matter is made of substances and interactions.

Substances are made of atoms. The structure of atoms is presented below.

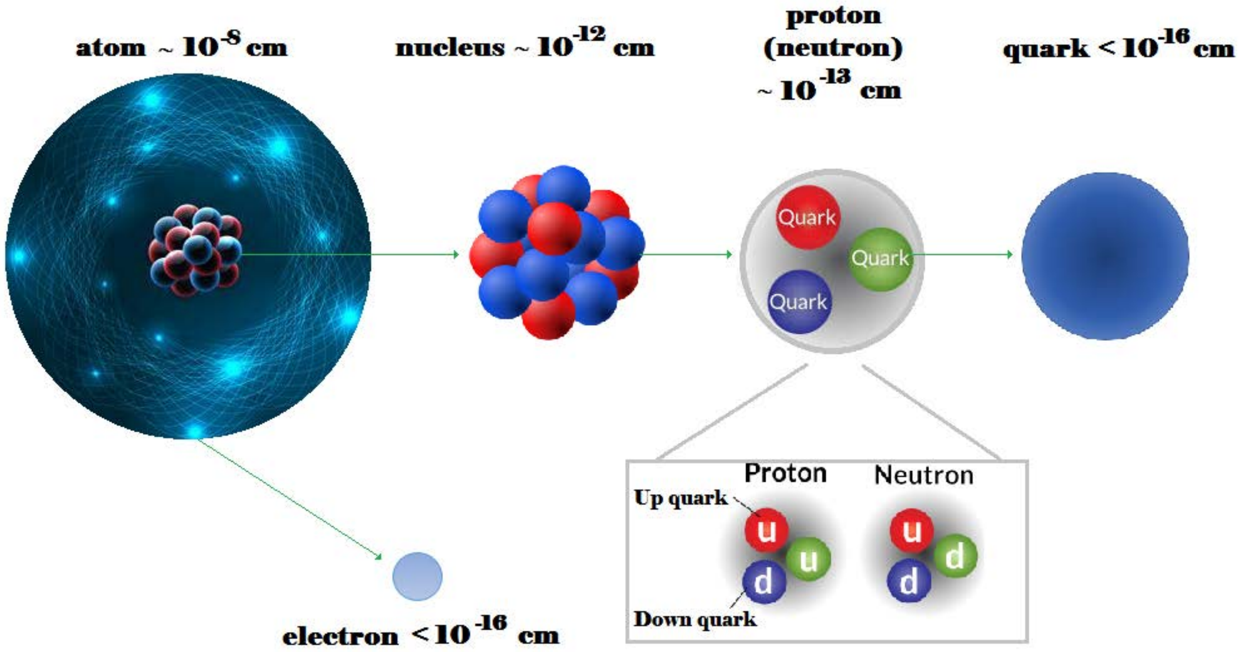


Fig. 1-1: Structure of the atom

According to quantum mechanics, the atoms have a positive nucleus and a cloud of a negative electrical charge made of electrons. The nucleus is made of positively charged particles, called protons, and electrically neutral particles called neutrons. The protons and neutrons are made of quarks.

There are four basic interactions between particles:

1. Gravitational
2. Electromagnetic
3. Nuclear strong
4. Nuclear weak

1.1.1 Gravitational

The gravitational field is responsible for the attraction between masses of matter. The gravitational force carrier particle is called the graviton. The gravitational interaction has an infinite range.

1.1.2 Electromagnetic

The electromagnetic field is responsible for electric and magnetic interactions. The electromagnetic force carrier particle is called the photon. The electromagnetic interaction range is also infinite.

X-rays and gamma rays are made of photons.

1.1.3 Nuclear strong

The nuclear strong interaction is responsible for holding particles together inside the nucleus. The nucleus is composed of protons and neutrons.

Very large forces are necessary to hold together such a structure. The gluon is an elementary particle that acts as the exchange particle (gauge boson) for the strong force between quarks, forming protons and neutrons. As a residual effect, it creates the nuclear force that binds these particles to form the atomic nuclei. The nuclear strong interaction has a range of 10^{-15} m (diameter of a proton).

1.1.4 Nuclear weak

The weak interaction is carried by particles called W and Z bosons, and acts on the nucleus of atoms, mediating beta radioactive decay. The weak force carrier particles are called weak gauge bosons. The nuclear weak interaction has a range of 10^{-17} m (1% of the diameter of a proton).

1.2 The Atom

The fundamental structural blocks of a substance are atoms. More than 3400 different atoms have been identified. They are grouped into 118 different elements assembled in a table called the "Periodic Table of Elements”.

Mendeleev discovered a periodicity of elements back in the 19th century. The periodicity is supported by the chemical properties characteristic of each element. These properties in turn stem from the arrangement of electrons around the nucleus.

The electrons are situated around the nucleus at large distances compared to nuclear dimensions. Electrons, which are much lighter than protons and neutrons, have a negative electric charge of 1.6×10^{-19} C. (C is the symbol for electric charge unit called coulomb in the "System International” - SI - unit system)

The electron mass is equal to 0.000549 amu, (one atomic mass unit - amu - is defined as 1/12 the mass of C-12 and is equal to 1.6604×10^{-27} kg).

Electrons move around the nucleus in shells, situated at different distances from the nucleus. Starting from the closest to the nucleus, the shells are named K, L, M, N, … These shells are further divided into sub-shells called s, p, d, f, …

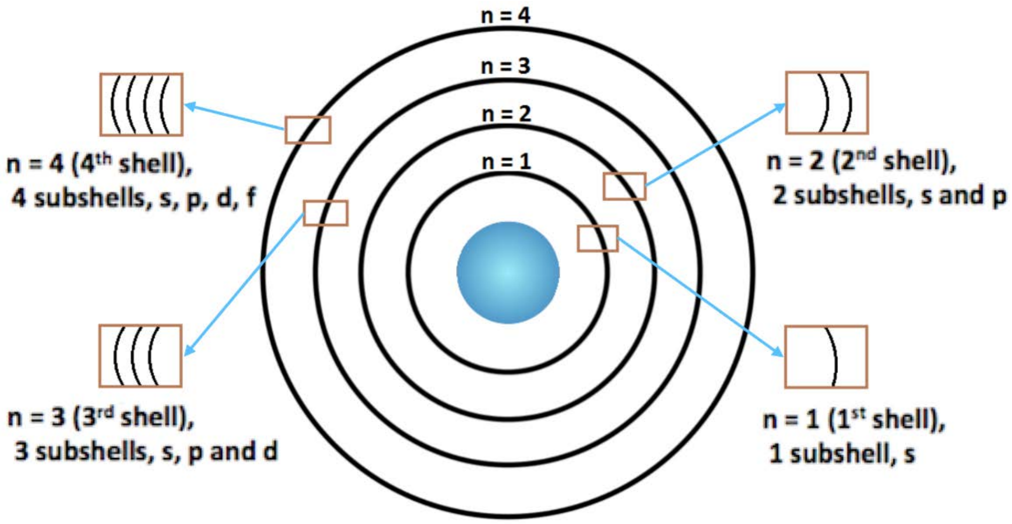


Fig. 1-2: Shells and subshells

The interaction between electrons and the nucleus is electromagnetic. Therefore, the carrier particle is the photon (quantum of light). When electrons jump from one shell to another or outside of the atom, a quantum of light is emitted or absorbed by the atom.

When the number of electrons around the nucleus equals the number of protons inside the nucleus, the atom is electrically neutral. Different types of interactions can remove one or more electrons from a shell and thus create a positive ion. However, when the number of electrons is greater than the number of protons in the nucleus, we have a negative ion. The energy required to remove an electron from an atom is called ionization energy. When a type of radiation carries enough energy to cause the ionization of an atom, it is called **ionizing radiation**.

1.3 The Nucleus

The nucleus of an atom is composed of heavy particles called protons and neutrons.

A proton is a stable particle with a positive electric charge of $1.6\text{x}10^{-19}$ C, and a mass of 1.007276 amu.

A neutron is an electrically neutral particle with a mass of 1.008665 amu. Outside the nucleus, the neutron is unstable. It disintegrates into a proton, an electron, and an electron antineutrino.

The atomic number (Z) represents the total number of protons inside the nucleus. It is the same as the number of electrons surrounding the nucleus in neutral atoms. It is also called the order number, referring to the position in the Periodic Table. All atoms having the same atomic number have the same position in the periodic table. Different atoms having the same number of protons, but a different number of neutrons are called **isotopes** ("iso" for the same, "top" for the position). In this case, the atomic number (Z) remains unchanged.

The number of neutrons is usually equal to or greater than the number of protons. The sum of the two is called the mass number (A) and gives the atomic weight of the atoms.

We recognize an atom by the name of the element (or atomic number) and by the mass number. For example, ${}^{3}_{1}\mathrm{H}$ means that this atom is an isotope of Hydrogen (atomic number 1, and it occupies the first position in the periodic table) with a mass number (A) of 3. Therefore, inside the nucleus, there are one proton (Z = 1) and two neutrons (A - Z, or 3 - 1 = 2) and around the nucleus is one electron in a neutral atom. ${}^{235}_{92}\mathrm{U}$ means that this atom has 92 protons (occupies the 92nd position in the periodic table) and a mass number of 235. Therefore, the number of neutrons is 143 (A - Z, or 235 - 92 = 143). The number of electrons is 92.

Although the SI notation for the naming of nuclides is the one shown above, in day-by-day life, their notation is simplified. For example, instead of ${}^{3}_{1}\mathrm{H}$ we simply use **H-3**, and instead of ${}^{235}_{92}\mathrm{U}$, we use **U-235**. In this course, we will adopt the simplified notation of nuclides.

Holding together two or more positively charged particles can only be accomplished by a very strong interaction.

Due to the infinite range of electromagnetic interaction, and the short-range of the strong force, neutrons are essential for the stability of the nucleus. For relatively small numbers of protons (at the beginning of the periodic table), an equal number of neutrons is sufficient to hold the nucleus together. As the atomic number increases, the number of neutrons required for stability also increases. Therefore, the mass number (A) for stable atoms is more than double that of the atomic number (Z) for the heavy elements.

For all atomic numbers below 92, there are one or more stable isotopes. They form a so-called "island of stability" for that particular atomic number. Currently, there are 254 stable isotopes.

If the number of neutrons is greater than the required number for nuclear stability, the isotope is unstable and considered a neutron-rich nucleus. Conversely, if the number of neutrons is less than the required number for nuclear stability, that isotope is also unstable but is now considered a proton-rich nucleus.

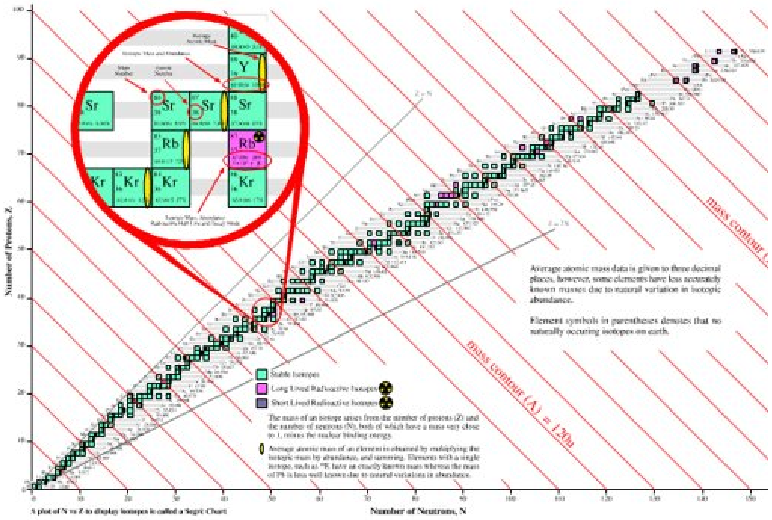


Fig. 1-3: Nuclear stability

There are no known stable atoms above Z = 92

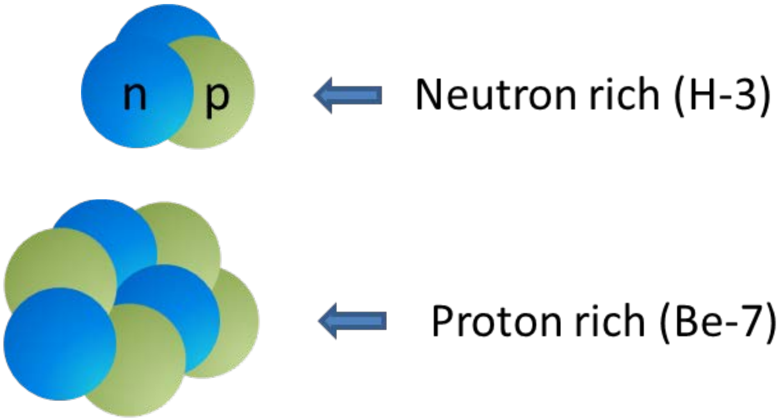


Fig. 1-4: Type of atoms

Unstable isotopes are called radioisotopes or radionuclides. They will keep disintegrating until they reach nuclear stability. This phenomenon is called **radioactivity**.

Chapter 2: RADIOACTIVITY AND RADIATION

As stated in Chapter 1, nuclei can be stable or unstable depending on the number of protons and neutrons. Unstable nuclei will go through one or more nuclear transformations until they reach stability.

There are certain numbers of protons and neutrons, called magic numbers, for which nuclei are more stable. The reason is that they are arranged into complete shells within the atomic nucleus. As a result, atomic nuclei with a “magic” number of protons or neutrons are much more stable than other nuclei. The seven most widely recognized magic numbers are **2, 8, 20, 28, 50, 82, and 126**. For protons, this corresponds to the elements helium, oxygen, calcium, nickel, tin, lead and one which is not yet discovered.

Radioactivity is the process of nuclear transformation resulting in a progeny nucleus and emission of particles and/or electromagnetic energy from the parent nucleus. We also call this nuclear transformation a disintegration (or radioactive decay).

Examples of the radioactive decay process are presented in the next sub-chapters.

2.1 Alpha radioactivity

Alpha radioactivity consists of emission from a heavy nucleus of a particle-containing 2 protons and 2 neutrons (a He-4 nucleus). This type of radioactivity often leaves the new (or progeny) nucleus in an excited state. In that case, de-excitation occurs through the emission of gamma rays. The new nucleus has two protons and two neutrons less than the initial (or parent) nucleus. Therefore, the progeny will be situated 2 places to the left of the parent in the Periodic Table, and its mass number will be 4 units less than that of the parent.

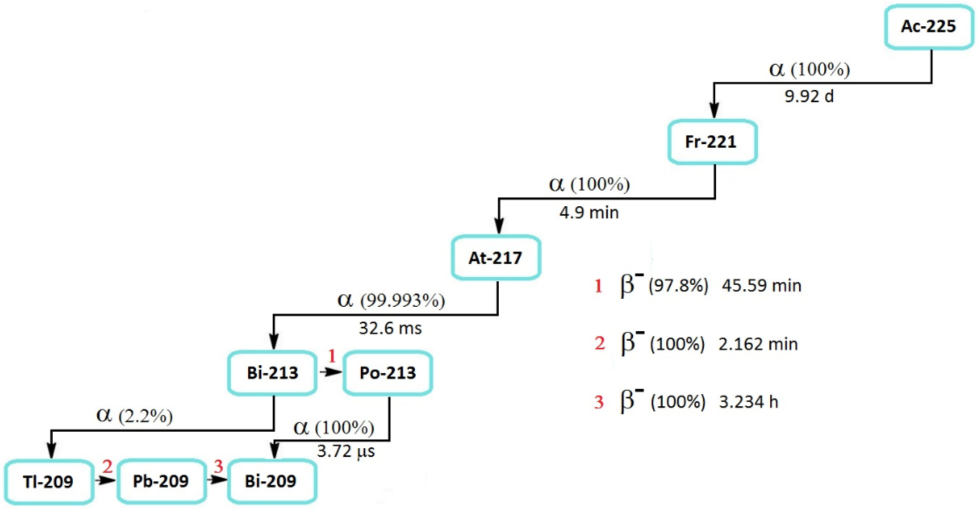


Fig. 2-1: Alpha disintegration

There are several radioactive sources containing alpha-emitting radionuclides at U of T. One example is the Am-Be neutron source. In this source, the Am-241 radionuclide emits an alpha particle through the following nuclear transformation:

$$\text{Am-241} \Rightarrow \text{Np-237} + \text{He-4} + \text{energy}$$

The energy is carried out mostly by the He-4 nucleus (alpha particle). The resulting nucleus (Np-237) is in an excited energy state.

In this type of sources, the alpha particle reacts with the beryllium according to the equation:

$$\text{Be-9} + \alpha \Rightarrow \text{C-12} + n + \gamma$$

giving, as a result, a flux of neutrons and gamma radiation.

The unit of energy used in radiation is the electro-volt (eV). One eV is the energy gained by an electron moving in electrical potential of 1 V.

In SI units: 1 eV = $1.6 * 10^{-19}$ J

The most used multiples of eV are kilo eV (1 keV = 10^3 eV) and mega eV (1 MeV = 10^6 eV). Alpha particles emitted during an alpha disintegration are mono-energetic, usually with energy around 5 or 6 MeV.

The energy of the alpha particle is particular to the specific nucleus. In the case of Am-241 disintegration, most (85%) of the alpha particles emitted have a kinetic energy of 5.5 MeV = $5.5 * 10^6$ eV = $8 * 10^{-13}$ J, around 14% have a kinetic energy of 5.4 MeV, and around 1% have a kinetic energy of 5.3 MeV. The distribution of energies and relative intensities of these particles are collectively referred to as the alpha spectrum of the Am-241 disintegration.

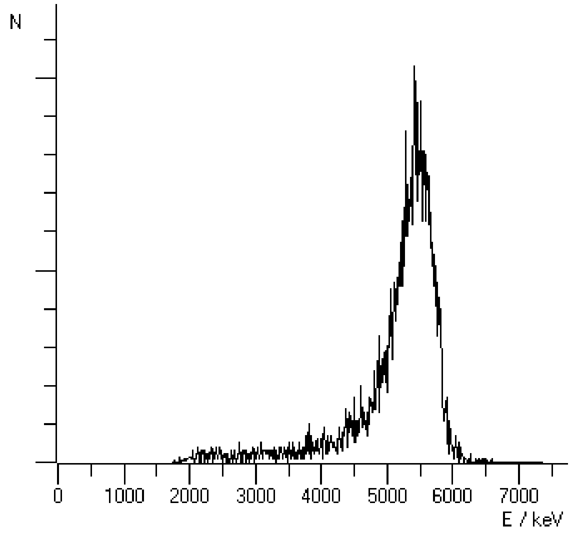


Fig. 2-2: Typical alpha spectrum of Am-241

An alpha spectrum is representative of each specific alpha decay. Therefore, it is used to identify the alpha-emitting radionuclide. This identification process is called alpha spectrometry. When multiple radionuclides are present in a sample the position and relative intensities of each peak are used to identify the radionuclides and the activities.

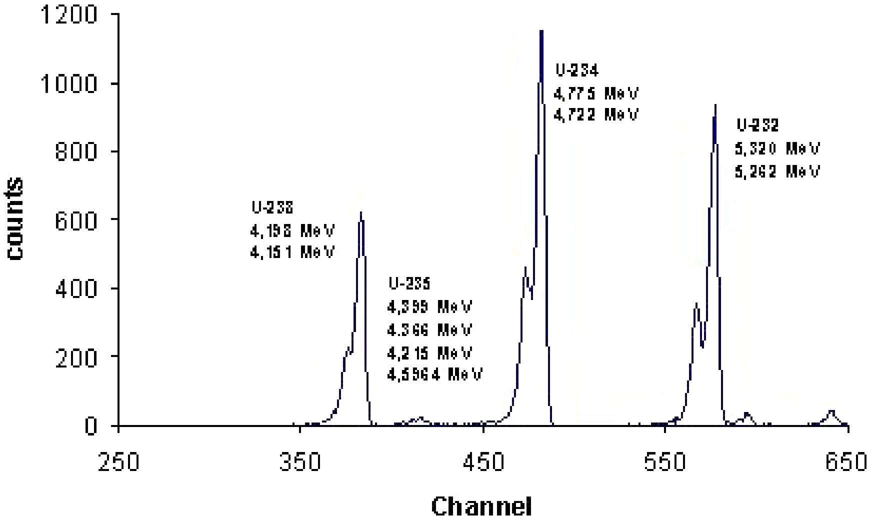
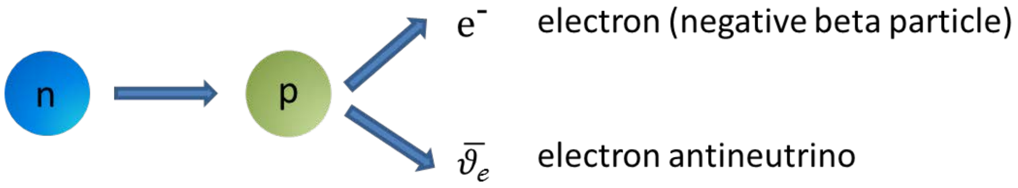


Fig. 2-3: Alpha spectrum

2.2 Beta radioactivity

Unlike alpha radioactivity, which is common only to heavy nuclei, beta radioactivity can be encountered at all nucleus sizes. It consists of emission from the nucleus of particles smaller than alpha particles. When a neutron-rich nucleus is unstable, it emits a negative beta particle (an electron) and an electron antineutrino (a particle without rest mass, similar to a quantum of light). When a proton-rich nucleus is unstable, it emits a positive beta particle (called a positron, having the same mass as an electron but a positive electric charge) and an electron neutrino (also a mass-less particle).

Sometimes the new nucleus (situated to the right in the periodic table for negative beta radioactivity and to the left for positive beta radioactivity) is in an excited energy state. De-excitation can be done through the emission of one or more gamma rays.

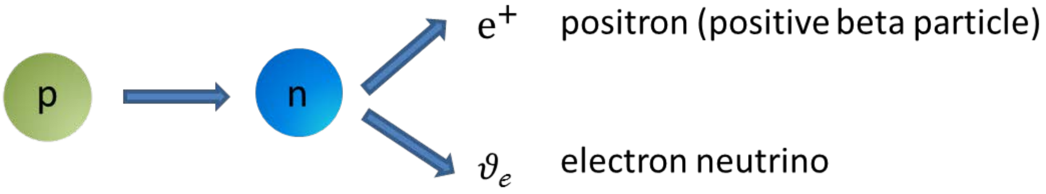


$$\boxed{n^0 \rightarrow p^+ + e^- + \bar{\vartheta}_e}$$

Fig. 2-4: Neutron disintegration

An example of negative beta radioactivity is the disintegration of P-32:

P-32 ➡ Si-32 + electron + electron antineutrino + energy



$$\boxed{p^+ \rightarrow n^0 + e^+ + \vartheta_e}$$

Fig. 2-5: Proton disintegration

An example of positive beta radioactivity is the disintegration of Na-22 (89% of the cases of disintegration):

Na-22 ➡ Ne-22 + positron + electron neutrino + energy

Because beta particles share their energy with an antineutrino or neutrino, the beta energy spectrum is continuous. The energy of the beta particle varies continuously between zero and a maximum value, which is specific to the beta-emitting radionuclide. At the maximum beta particle energy, the antineutrino or neutrino has zero kinetic energy and, in the other extreme, the energy of the beta particle will be zero when the neutrino carries all the energy.

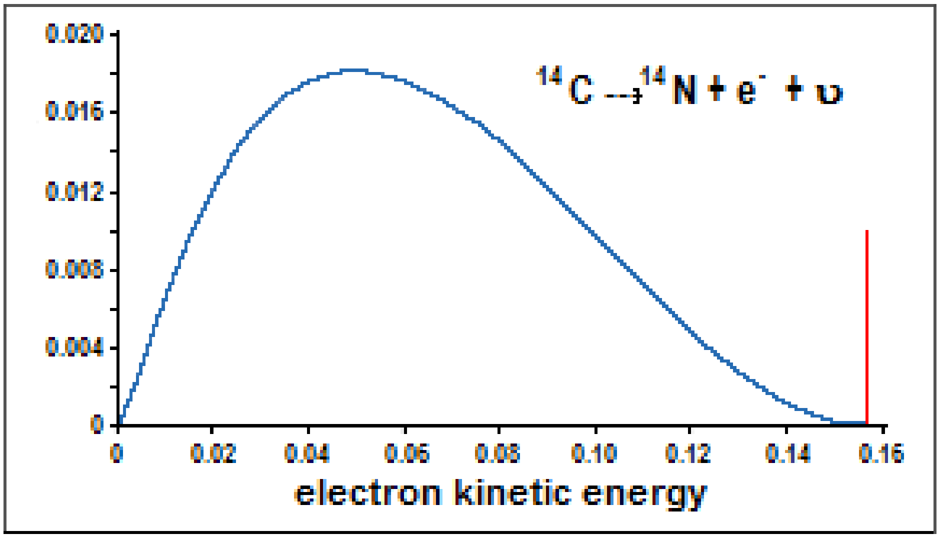


Fig. 2-6: C-14 beta energy spectrum

In a sample containing many radionuclides, qualitative and quantitative analysis is more difficult by using just beta spectrometry. Figure 2.7 presents the beta spectrum of a sample containing H-3 and C-14. The superposition of the spectra depends on the amount of C-14 present in the sample.

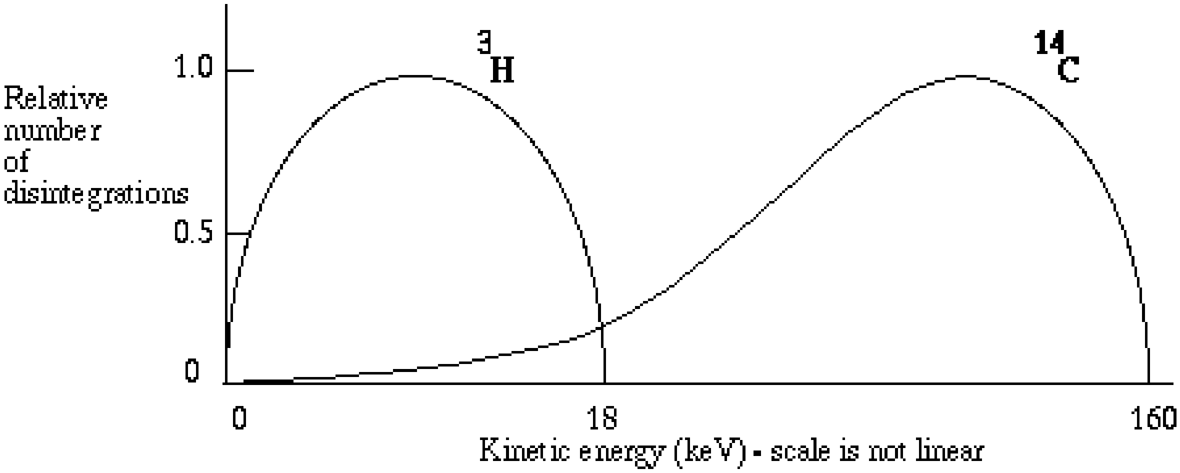


Fig. 2-7: Beta spectrum for H-3 and C-14

2.3 Electron Capture

An alternative way of solving the instability of proton-rich nuclei is through electron capture (EC) radioactivity. In this kind of process, an electron from the closest shell (usually K-shell) is absorbed into the nucleus and reacts with a proton. This causes the formation of a new nucleus situated in one place to the left in the periodic table and the emission of an electron neutrino. The new nucleus may be left in an excited state. The de-excitation is then done through the emission of gamma rays, while the re-arrangement of electrons in the atom (i.e., electrons moving from upper shells into the lower shell) results in the emission of X-rays.

An example of EC radioactivity is:

I-125 + electron (from K-shell) ➡ Te-125 + electron neutrino + energy

De-excitation of Te-125 can happen through gamma emission or internal conversion (see 2.5).

2.4 Gamma rays

Gamma rays are mono-energetic electromagnetic rays emitted from an excited progeny nucleus. Gamma rays originate from a re-arrangement of neutrons and protons inside the excited nucleus.

The energy and relative intensities of the gamma rays are characteristic of each particular nucleus. Therefore, the measure of energies and relative intensities emitted by a nucleus can be used to identify the radionuclides. For example, Co-60 emits two gamma rays, one at 1.1732 MeV (intensity = 100%), and one at 1.3325 MeV (both are emitted at 100% because it is a cascade emission). This identification process is called gamma spectroscopy or gamma spectrometry.

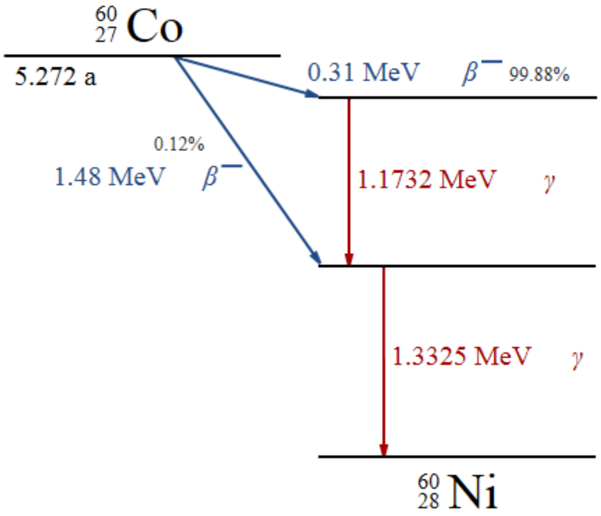


Fig. 2-8: Co-60 gamma emission scheme

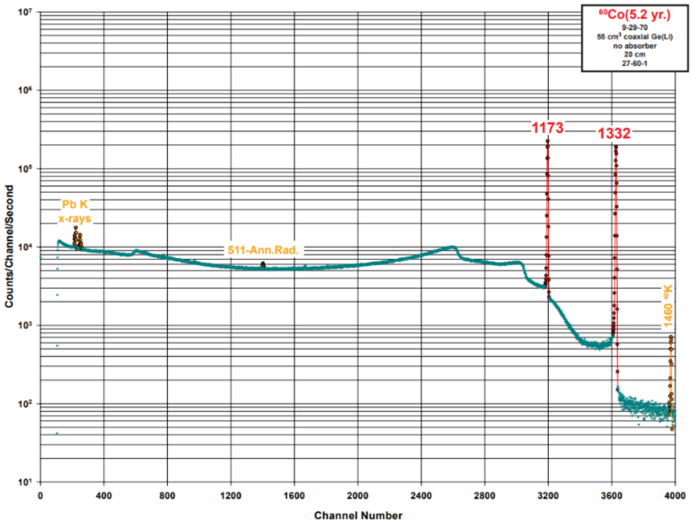


Fig. 2-9: Co-60 gamma spectrum

Gamma-ray energies of different nuclei vary between tens of keV (this is also the range of X-rays) and tens of MeV.

It is important to understand that gamma rays with low energy (in the range of tens of keV) are indistinguishable from characteristic X-rays (with monochromatic energy) emitted by an atom due to the re-arrangement of electrons between shells. In this case, they only differ concerning their origin and appear identical in the measuring process (called gamma or X-ray spectrometry).

Another type of gamma emission occurs when a positron is emitted from a nucleus (i.e. positive beta radioactivity). The positron will react with an electron and generate two gamma rays. This process is called annihilation of radiation.

electron + positron ➡ 2 gamma rays (annihilation radiation)

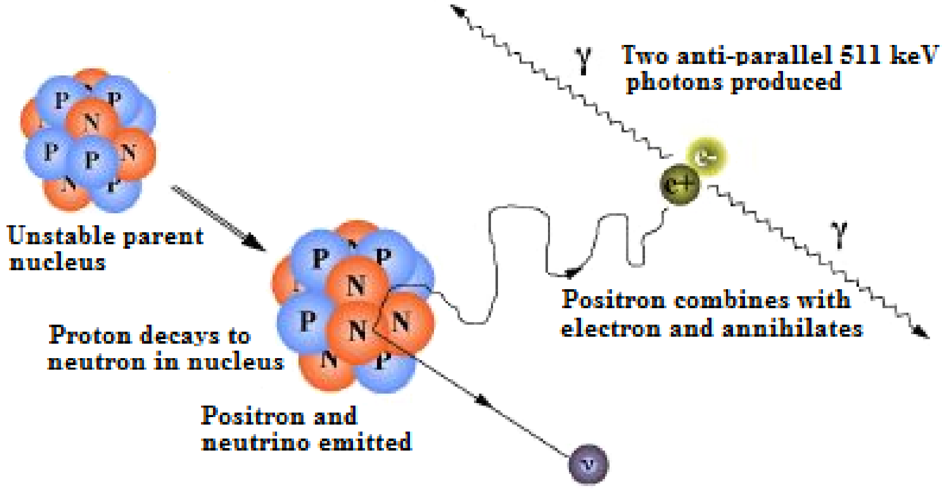


Fig. 2-10: Annihilation radiation

Therefore, every time a positive beta radionuclide is used, the gamma radiation should be taken into account when selecting the proper shielding, dosimetry and radiation hazard evaluation.

2.5 <u>Internal conversion</u>

Internal conversion (IC) is an alternative de-excitation mechanism. The excited nucleus, instead of emitting a gamma-ray, interacts with a tightly bound electron (usually from K or L shell). As a result, the electron is ejected from the atom.

The emitted electrons are mono-energetic, therefore their spectrum resembles that of an alpha or gamma spectrum. Thus, electrons emitted through internal conversion differ from beta electrons due to both their origins and spectra type.

As a result of the internal conversion process, the atom is in an excited state. The atom de-excitation is achieved by emitting x-rays as a result of re-arrangements of electrons on the shells. The atom's de-excitation can also be achieved by ejecting another electron from the atoms. This latter process is called the Auger transition, and the ejected electron is called the Auger electron.

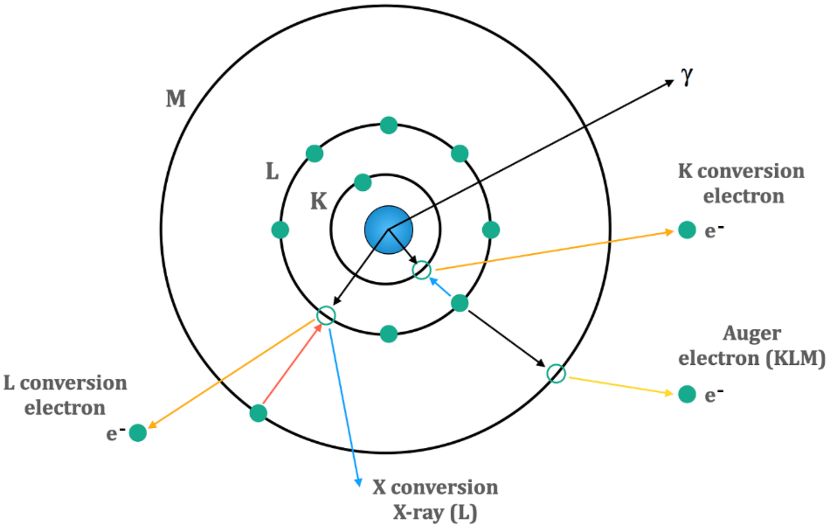


Fig. 2-11: Internal conversion

2.6 <u>Neutron emission</u>

Neutrons are produced through nuclear reactions. A reaction in which a heavy nucleus splits into 2 separate parts is called fission. Some heavy nuclei (like uranium) can do this spontaneously. During the fission reaction, 2 or 3 neutrons are produced.

When the conditions for neutron absorption are present, a chain-induced fission reaction may take place. A chain reaction takes place when the reaction sustains itself by emitting and absorbing enough neutrons. A controlled chain reaction is obtained inside a nuclear reactor.

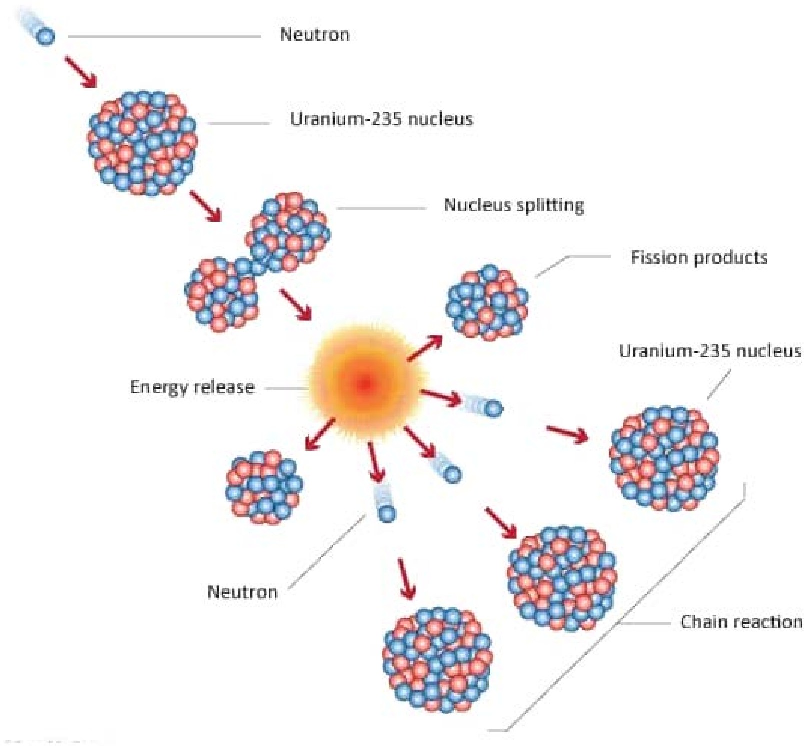


Fig. 2-12: Nuclear chain reaction

Other nuclear reactions can be used to generate neutrons. For example, the reaction between alpha particles (He nuclei) and Be is the most frequently used method:

He-4 + Be-9 ➡ C-12 + neutron + energy

Alpha sources such as Ra, Po, Am or Pu can be used. In each case, the neutron source is named Ra-Be, Po-Be, Am-Be or Pu-Be.

2.7 Activity

The disintegration of an unstable nucleus, at any moment, is a random physical phenomenon. The number of nuclei that have disintegrated after a certain interval is random.

Radioactive decay is a probabilistic event. According to its definition, probability is the ratio between the number of favourable events that occur over the number of all possible events. For rolling a two with a dice we will have one event, and the total number of possible events is 6, therefore the probability is 1/6. For rolling an even number with dice, there are 3 favourable events (a two, a four or a six), and since the total number of possible events is still 6, the probability is 3/6 or ½.

For the decay process, the favourable number is the number of nuclei that disintegrate, and the number of possible events is the total number of unstable nuclei.

The probability of radioactive decay depends on the radionuclide and is proportional to the time.

$$\mathrm{p} = \frac{\mathrm{dN(t)}}{\mathrm{N(t)}} = -\lambda \mathrm{dt}$$

Where “p” is the probability, N(t) is the number of unstable nuclei at the moment “t”, 'λ' is the disintegration constant that depends on the particular unstable species, dN(t) represents the variation of the number of unstable nuclei in the interval dt. The negative sign indicates that the number of unstable nuclei decreases with time.

The number of decays per second (the rate of disintegration at the time “t”) is defined as the activity of the source at the time “t”.

$$\mathrm{A(t)} = \frac{\mathrm{dN(t)}}{\mathrm{dt}} \qquad \text{Disintegration rate}$$

Experiments show that the activity of a source decreases exponentially in time. The activity of a radioactive source at each moment is proportional to the number of unstable nuclei present in the source at that moment:

$$\mathrm{A(t)} = -\lambda * \mathrm{N(t)} \qquad \text{Activity}$$

From these equations, it can be deduced that the number of unstable nuclei in a sample also decreases exponentially with time.

The laws of radioactive decay are:

$$\mathrm{N(t)} = \mathrm{N(0)} * \mathrm{e}^{-\lambda \mathrm{t}}$$

and

$$\mathrm{A(t)} = \mathrm{A(0)} * \mathrm{e}^{-\lambda \mathrm{t}}$$

where “e” is the base of the natural logarithm, N(0) is the number of unstable nuclei at the initial moment, and A(0) is the activity at the initial moment.

The unit of measure for activity is disintegration per second. To honour the discoverer of radioactivity (Henri Becquerel, 1896), the unit of activity (disintegration per second) was named “**becquerel”** and the symbol used is **Bq**.

Fig. 2-13: Henri Becquerel

Historically, another unit was used - the **curie** - noted **Ci**. It was named after Marie and Pierre Curie, the discoverers of Radium and Polonium. One curie (or 1 Ci) is the activity of 1 gram of pure Radium-226. This activity is equal to 3.7 x $10^{\mathbf{10}}$ disintegration per second or 3.7 x $10^{\mathbf{10}}$ Bq.

Fig. 2-14: Marie Curie

Fig. 2-15: Pierre Curie

$$1\ \mathrm{Ci} = 3.7 * 10^{10}\ \mathrm{Bq}$$

The curie is a rather large activity for typical usage at U of T, and the becquerel is rather small. Therefore, Bq multiples and Ci sub-multiples are used. Examples of the transformation between the two are given below:

$$1\ \mathrm{mCi} = 37\ \mathrm{MBq} \qquad 500\ \mathrm{kBq} = 13.5\ \mu\mathrm{Ci}$$

2.8 Half-life

An important characteristic of each unstable nuclear species is the time it takes for the number of unstable nuclei to decrease to one-half. This is called the "half-life" of the radionuclide. The half-life ($T_{1/2}$) and the disintegration constant (λ) are connected by the following relationship:

$$T_{1/2} = \frac{\ln(2)}{\lambda}$$ Half-life

where **ln** is the natural logarithm.

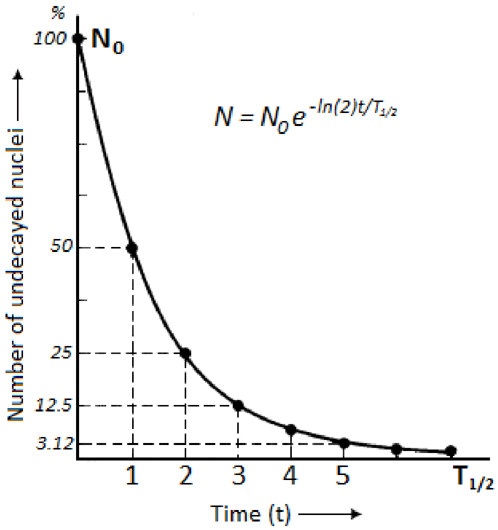


Fig. 2-16: Decay curve

With the half-life, the equation for radioactive decay (decrease in activity) became:

$$A_t = A_0 * e^{-\ln(2)*t/T_{1/2}}$$ Activity calculation using the half-life

Usually, radionuclide tables give the value for $T_{1/2}$.

Example 2.8a:

The half-life of P-32 is 14.3 days. If 250 µCi (9.25 MBq) are bought and used after approximately 6 weeks (more precisely, after 43 days) the activity will be only:

$$A\ (43\ \text{days}) = 250\ \mu\text{Ci} * e^{-\ln(2)*43/14.3} = 31.25\ \mu\text{Ci}$$

**** This is 8 times less than was initially bought. Therefore, it is better to order the radionuclide as close as possible to the date of use.***

Example 2.8b:

The half-life of C-14 is 5730 years. Therefore, in the same interval as in **example 2.9a** (6 weeks), the activity of 1 mCi (37 MBq) of C-14 will practically not change at all:

$$A\ (43\ \text{days}) = 1\ \text{mCi} * e^{-\ln(2)*43/(5730*365.25)} = 0.999986\ \text{mCi}$$

*Go to the Periodic Table and click on the links to a few elements to get information on the most common radioisotopes, their half-lives, decay modes, and the energy (in MeV) of the most important emitted radiation.

Chapter 3: INTERACTION OF RADIATION WITH MATTER

During the radioactive decay process, a particle and/or a photon are emitted from the parent atom. The emitted particle carries energy proportional to their mass and speed. The photons carry energy proportional to their frequency. The photons and the particles interact with the surrounding matter. This interaction depends on their type (alpha, beta, gamma, neutrons, etc.), mass, electrical charge, energy, and the composition of the surrounding materials.

3.1 Alpha Radiation

Since the alpha particle is a He nucleus (2 protons & 2 neutrons), it is the largest and most massive type of radiation (except for fission fragments). Additionally, the interaction of alpha particles with matter is very strong due to the alpha particle's electrical charge of 2 units. Alpha trajectories can be deviated by both electric and magnetic fields. The major energy loss mechanism for alpha particles is electronic excitation and ionization of the atoms of the material. The air-specific ionization of an alpha particle is very high, in the order of thousands of ion pairs per centimetre of air.

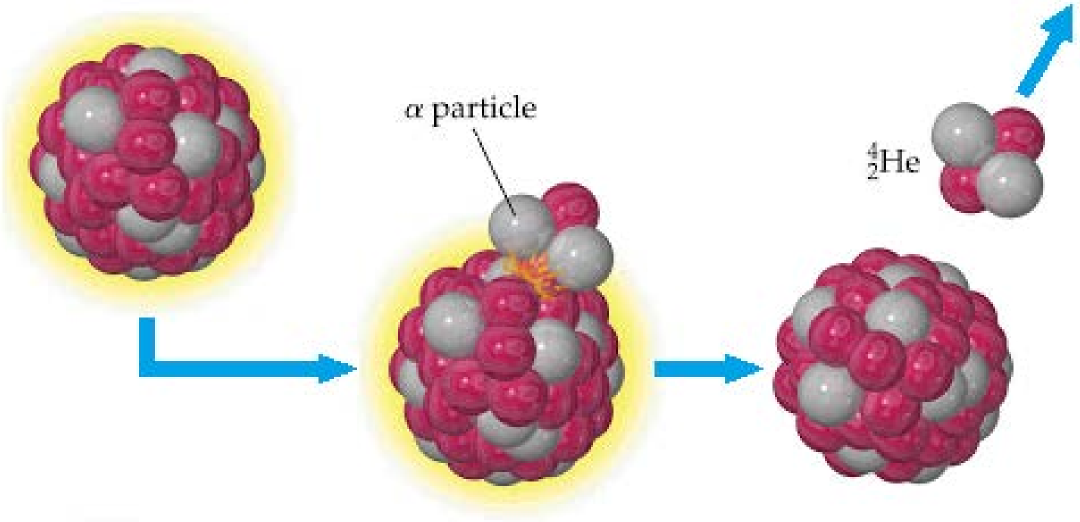


Fig. 3-1: Alpha emission

Because of the strong interaction of alpha particles with matter, they have a short-range; a sheet of paper, the surface layer of dead skin (epidermis), or a few centimetres of air can easily stop them. Consequently, there is no concern for the external irradiation of people. However, when gamma radiation is emitted together with alpha particles, precautions against external irradiation caused by gamma rays should be taken into account.

When inhalation or ingestion of an alpha-emitting radioactive material occurs, internal irradiation becomes a major concern. The alpha particles interact strongly with the surrounding internal tissues (live tissue). All of their energy is absorbed inside the body, potentially causing damage to the cells. Therefore, special precautions are taken when handling open, volatile sources of alpha-emitting radionuclides.

3.2 Beta Radiation

Positrons, positively charged beta particles, interact with electrons from surrounding matter through the process called annihilation of radiation, producing 2 gamma rays (see chapter 2.4).

Electrons are negative beta particles with relatively light mass. Their interaction with matter can be characterized as average. There are 2 main mechanisms of electrons' interaction that are important from the point of view of radiation protection.

3.2.1 Excitation and Ionization

The interaction between the beta minus particles (that are electrons) and the orbital electrons of the absorbing medium leads to inelastic collisions that generate electronic excitation and ionization. The specific ionization (the number of ion pairs created per cm of air) decreases from approximately 200 ion pairs (at low beta energy) to approximately 60 ion pairs at beta energy of 1 MeV. For beta energies above 1 MeV, there is a slight increase in the specific ionization with energy.

3.2.2 Bremsstrahlung

The second important mechanism of reducing the energy of beta particles is called "bremsstrahlung". When a high-speed charged particle passes through a medium, it occasionally undergoes a substantial nuclear scattering created by the electric field of the nuclei. The result of this process is the slowing down of the charged-particles and the emission of continuous electromagnetic energy. The process was called by Wilhelm Roentgen, bremsstrahlung or "braking of radiation". The electromagnetic energy emitted during bremsstrahlung is dependent on the atomic number Z of the stopping material. For example, heavy metals are more likely to create higher energy photons. The use of light materials reduces the bremsstrahlung effect. This is why light materials such as plexiglass or Al are used to absorb beta radiation.

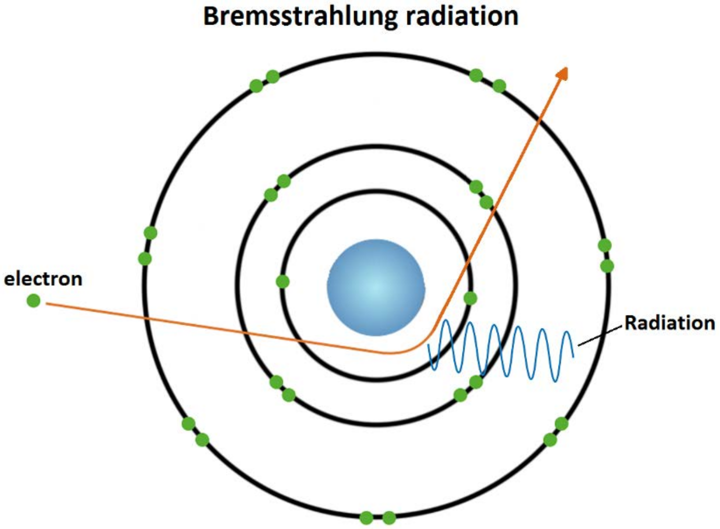


Fig. 3-2: Bremsstrahlung radiation

When gamma emission follows beta disintegration, protection against gamma rays is also required. In this situation, we need to stop the beta particles first with light materials and then gamma and bremsstrahlung radiation with heavy materials made of lead or other metals.

Because of the continuous energy distribution, the absorption of beta particles in a material is also continuous. The range, however, has a maximum value for different materials and is related to the maximum energy of the beta particles. For example, tritium (H-3) has low maximum beta energy (0.018 MeV) and a maximum range in air of 6 mm. On the other hand, P-32 has higher maximum beta energy (1.71 MeV) and a maximum range in air of 7.9 m.

3.3 <u>Gamma Radiation</u>

Gamma rays are photons (quanta of light) and have no electric charge and no rest mass. Therefore, the interaction of gamma rays with matter is weak. Three interaction mechanisms are important from the point of view of radiation protection.

3.3.1 Photoelectric Effect

During this process, the incoming gamma-ray transfers all its energy to an electron from the atom. The electron is then ejected from the atom and moves through matter losing its energy as described for beta interactions. The photoelectric effect is predominant at low gamma energies.

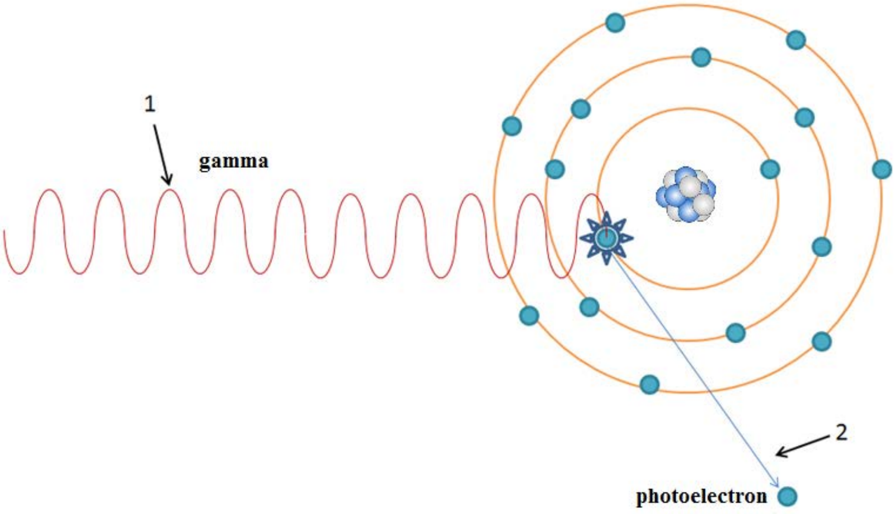


Fig: 3-3: Photoelectric effect

3.3.2 Compton Scattering

During this process, the incoming gamma-ray also interacts with an electron from the atom. However, during the Compton scattering, only partial gamma-ray energy is transferred to the electron. The electron is ejected from the atom together with a new gamma-ray. The sum of the energies of the recoil electron and gamma-ray is equal to the energy of the initial gamma-ray minus the atom's binding energy. The recoil electron interacts as explained earlier. The new gamma-ray can escape from the material or can be absorbed through the photoelectric effect. The Compton Effect is the predominant effect at intermediate gamma energies.

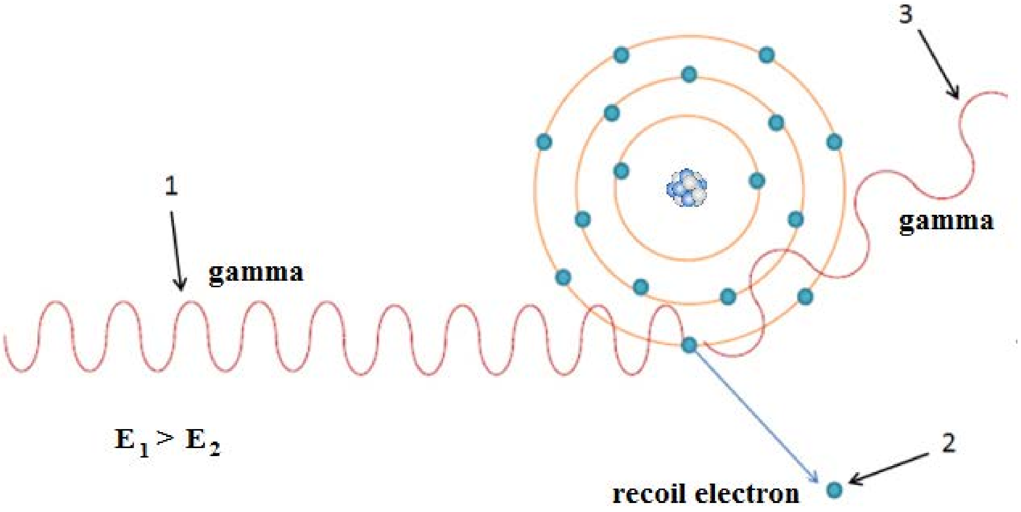


Fig. 3-4: Compton scattering

3.3.3 Pair Production

During this process, a high-energy gamma-ray interacts with the nucleus and two particles are created (an electron and a positron). The electron and the positron share the energy of the gamma-ray. The electron and positron lose their energy through ionization or excitation. The electron is absorbed in the material, and the positron interacts with an electron creating two gamma rays with energies of 511 keV each (annihilation of radiation. These two gamma rays can escape or interact with the material through the Compton scattering or Photoelectric effect.

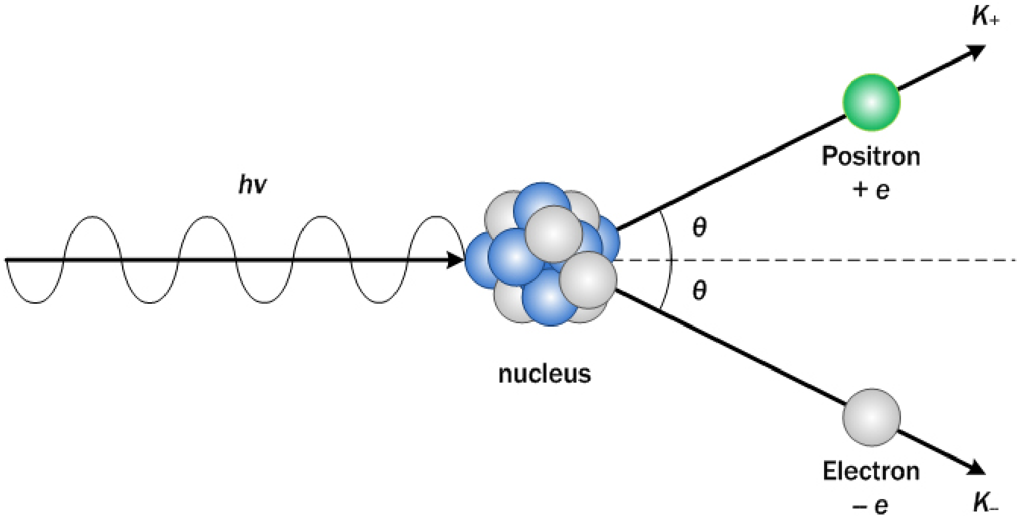


Fig. 3-5: Pair production

The absorption of gamma rays obeys an exponential law. There is no definite range of absorption for gamma rays in the matter. Protection against gamma rays (as well as against X-rays) is best obtained with heavy materials made of lead or other metals.

Any material if thick enough will also offer protection against gamma-rays. For example, the earth's atmosphere protects us against high-energy gamma rays coming from outer space.

3.4 Neutrons

Neutrons have a rest mass similar to protons but are electrically neutral. They have weak interactions with matter. For high-energy neutrons, the main interaction is through elastic collisions. In an elastic collision, the maximum loss of energy happens when the collision is between particles of similar masses (like billiard balls colliding with each other). For that reason, a material with a large number of Hydrogen atoms is the most efficient shielding against neutrons. Examples of these materials are water, wax and concrete.

After several collisions, the neutron's energy decreases. This process is called thermalization or moderation of neutrons. Low-energy neutrons (also called thermal) interact with matter mainly by absorption processes.

Due to the high content of water in human tissue, neutrons are considered more hazardous than beta or gamma radiation. High-energy neutrons are considered to harm the human body as much as alpha radiation.

Most of the time, the detection of neutrons is an indirect process. The absorption of neutrons by boron nuclei is usually the mechanism used for neutron detection:

B-10 + neutron → Li-7 + alpha + energy

As a result of this nuclear reaction, alpha particles and gamma rays are emitted. Both gamma and alpha radiations are much easier to detect than neutrons.

Chapter 4: RADIATION DOSIMETRY

4.1 Exposure

As explained in the previous chapter, when radiation interacts with matter, electrons are removed from atoms through the process called ionization. When the energy carried by each particle or photon of the incoming radiation is under the ionization energy, electron excitation (jumps from lower shells to upper shells) may occur. The excitation of molecules or breaking of molecular bonds can also occur, causing damage to living cells. When the energy of particles or photons of the incoming radiation is above the ionization energy, the radiation is called ionizing radiation. Otherwise, it is called non-ionizing radiation.

When dealing with the interaction of gamma and X-rays in the air, the term radiation exposure is used. Exposure measures the electric charge (positive or negative) produced by electromagnetic radiation in a unit mass of air, at normal atmospheric conditions.

In the SI system of units, exposure is measured in the X unit

$$1\ \mathrm{X} = 1\ \mathrm{C/kg\ air}$$

where C is the coulomb, the SI unit for electric charge.

The old unit for exposure was the roentgen (R). This unit was named in honour of Wilhelm Roentgen, the discoverer of X-rays. The new and old unit are connected by the relations:

$$1\ \mathrm{X} = 3881\ \mathrm{R} \qquad\qquad 1\ \mathrm{R} = 2.58 * 10^{-4}\ \mathrm{X} = 2.58 * 10^{-4}\ \mathrm{C/kg}$$

Exposure is a very useful physical quantity because it can easily be measured. One just needs to measure the charge produced by the radiation in the air (or the electrical current, multiplied by time) to find out the strength of the electromagnetic field. The instruments used for this purpose are ionization chambers. Measurement results are usually expressed in R or mR.

At a distance "d" from a point source of radiation, exposure follows an inverse square law (see chapter 7.2.2), that is, when the distance increases by a factor "k", exposure decreases by a factor "k^2").

Example:

Exposure from a Cs-137 point-source at 10 cm is 10 R.

Find the exposure at 1 m.

Answer:

The distance between the Cs-137 source and the point at which exposure is determined to have increased 10 times. Therefore, the exposure at 1 m will be 100 (10^2) times less, i.e. 0.1R = 100 mR.

4.2 Absorbed Dose

Although exposure from gamma or X-rays can be easily quantified by measuring the electrical charge produced in air, we also deal with other types of radiation, like alpha, beta, or neutron. Additionally, we are also interested in the effects of radiation in other materials (like human tissue) not only in dry air.

The absorbed dose is the physical quantity used to measure the interaction of all types of radiation with any kind of material. The unit of measure for absorbed dose in the SI system is J/kg. This unit is named gray (Gy), in honour of Louis Harold Gray. A radiation field that deposits 1 joule of energy in 1 kg of material has an absorbed dose of 1 Gy.

Fig. 4-1: Louis Harold Gray

The old unit of measure for the absorbed dose is named rad (short for "radiation absorbed dose"). The relationship between the SI unit and the old unit is:

$$1\ \mathrm{Gy} = 100\ \mathrm{rad} \qquad \text{or} \qquad 1\ \mathrm{rad} = 0.01\ \mathrm{Gy}$$

The radiation absorbed dose (measured in Gy or rad) is used to quantify the acute effects of radiation on the human body, organs and tissues.

4.3 Equivalent Dose (H)

The term "dose" is used in connection with many other terms. But the most important meaning of dose is connected with radiation stochastic effects. The equivalent and effective doses are used for radiation protection purposes, engineering design criteria, and legal and administrative purposes. Because of this, equivalent and effective doses in day-by-day life are often simply called "dose".

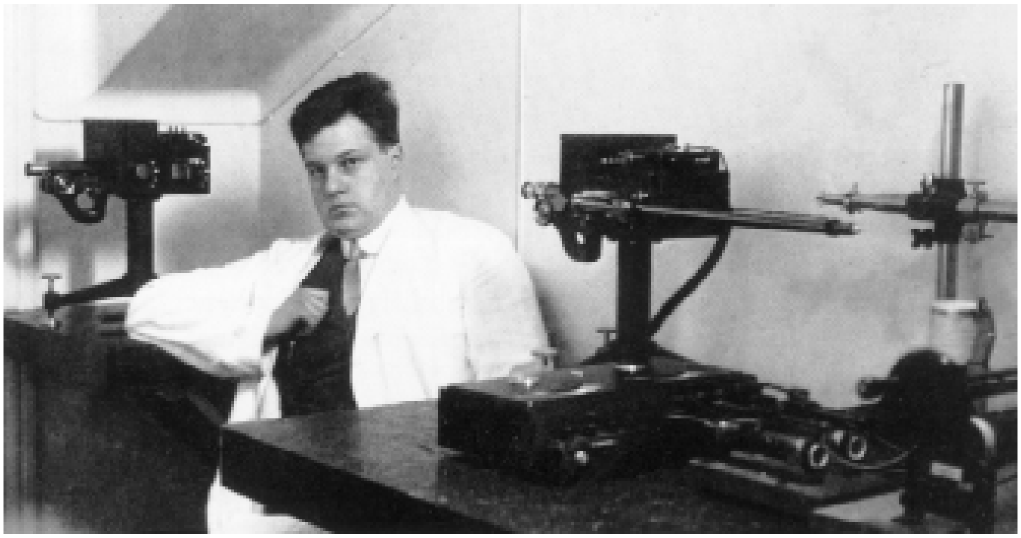


Fig. 4-2: Rolf Sievert in his laboratory 1929.

The equivalent dose is defined as:

$$\mathrm{H}\ (\mathrm{in\ Sv}) = \sum_{i} \left(\mathrm{D_i} * \mathrm{W_{R,i}}\right)$$

Where **D_i** is the absorbed dose for the radiation type “i” (alpha, beta, gamma, x-ray, neutrons, protons, etc.), and $W_{R,i}$ is the **radiation weighting factor** for the “i” type of radiation. $W_{R,i}$ varies from 1 (for gamma, X-ray and beta radiation) to 20 (for alpha radiation or fission fragments).

The old unit for measuring radiation equivalent dose is the rem (short for roentgen equivalent man).

The relationship between the old and the new unit is:

1 rem = 0.01 Sv; 1 Sv = 100 rem

4.4 Effective Dose

The stochastic effects of ionizing radiation on the whole body are measured with a physical quantity called the effective dose. When different organs and tissues have been irradiated, the effect on the whole body is calculated with the formula:

$$\mathrm{E\ (in\ Sv)} = \sum_{\mathrm{i}} \left(\mathrm{H_i} * \mathrm{W_{T,i}} \right)$$

Where E is the **effective dose**, H_i is the equivalent dose of organ or tissue “i” and $W_{T,i}$ is the tissue weighting factor. The tissue weighting factor varies between 12% and 1% depending on the sensibility of each organ to ionizing radiation. The effective dose is also measured in Sv**.**

4.5 External Dose

When the source of radiation is situated outside of the body, the irradiated person will receive what is referred to as an external dose. The calculation of external dose can be performed for the whole body, for extremities, and superficial skin dose (0.07 cm depth) or shallow dose (1 cm depth). The type of radiation also plays an important role in assessing the external dose.

For gamma and X-rays, the "inverse square law" can be applied for point-sources and absorption in the air can be neglected for relatively short distances. For beta radiation, the absorption in the air can be very important (depending on the beta energy). For alpha radiation, the external dose is zero since alpha particles cannot penetrate the layer of dead skin (see Chapter 3).

Pocket dosimeters, thermoluminescent dosimeters and electronic dosimeters are examples of devices used to measure the external dose.

4.6 Internal Dose

Internally deposited radionuclides will irradiate a person's tissues and organs from the inside. This type of radiation exposure is called internal dose.

Typical routes of radioisotopes entry in the body are inhalation, ingestion or skin penetration. Radioisotopes entering into the body are referred to as intakes. Radioisotopes that enter the body are not completely retained by the body. The amount that is retained after an intake is called the uptake.

Radionuclides can be retained for varying amounts of time inside the human body. Some are partially fixed for a longer time (like Sr-90 inside the bones or I-131 and I-125 inside the thyroid) but the majority of the radioactive materials entering the body are eliminated after a much shorter time. Each radionuclide is characterized by a "biological half-life", which is the time after which the uptake decays to half of its original value.

When calculating the internal dose, the biological half-life and the physical disintegration half-life of the radionuclide must be considered. The combination of the two half-lives is called effective half-life.

4.7 Committed Dose

The time that each radioisotope is present in the body depends on the physical and biological half-life, the organ, the chemical composition, etc. The equivalent dose resulted from the exposure of a certain organ for the next 50 years (or to age 70 for children) is called the **committed equivalent dose**. Similarly, the effect of exposure to the whole body for the next 50 years is called the **committed effective dose**. In a practical application for radioisotopes with a short half-life, the calculation extends up to a maximum of 10 effective half-lives.

4.8 Annual Limit of Intake (ALI)

In Canada, the ALI is defined as the activity (measured in Bq) of a radionuclide that will deliver a committed effective dose of 20 mSv. The ALI values vary with the radionuclide, the chemical composition, the route of entry in the body, the effective half-live, etc. The ALI values are also used in the classification of radioisotope laboratories.

4.9 Natural dose

Due to the presence of numerous sources of ionizing radiation in the natural environment (i.e. around us and inside us), the dose received from these types of sources has been named the natural dose, or background.

The natural dose varies around the world by more than a factor of ten. This variation arises from differences in soil composition, type of materials used for building, food and water, to the altitude (the higher the altitude, the larger the irradiation from cosmic sources), etc. Nevertheless, the main contribution (over 50%) comes from the inhalation of radioactive Radon gas products found in the air we breathe. Another important contributor to the natural dose is from K-40 inside our bodies. In North America, the natural dose varies between 2 and 3 mSv (200 and 300 mrem) per year.

4.10 Artificial dose

The total dose received by an average person in North America is bigger than the amount shown above. This is due to artificially produced radiation and is referred to as the artificial dose. The main contribution to the artificial dose in North America comes from X-ray machines used in medical diagnoses and treatments.

Canadian federal regulations impose a limit for artificial doses received from sources other than medical purposes. This value was established for members of the general public at 1 mSv (100 mrem) per year. The artificial dose received by a patient is decided by the medical doctor.

4.11 <u>Dose rates</u>

Each of the terms used above (Exposure, Absorbed Dose, Equivalent Dose, etc.) can also be described as a function of time. When doing so, the terms are called: Exposure rate, Absorbed Dose rate, Equivalent Dose rate, etc. The units of measure remain the same, but the values are divided by the time interval. For example, we can have the absorbed dose rate received in a minute measured in mGy/min, effective dose received in the year in mSv/year, etc.

Chapter 5: BIOLOGICAL EFFECTS OF RADIATION

Radiation is one of the best-investigated hazardous agents. Because of the vast accumulation of quantitative dose-response data, specialists can set radiation levels so that applications of nuclear technologies may continue at a level of risk that is better known than with many other technologies.

5.1 Acute and Delayed Effects

A single accidental exposure to a high dose of radiation during a short period is referred to as an acute exposure and may produce biological effects within a short period after exposure. These effects include:

- Skin damage
- Nausea and vomiting
- Malaise and fatigue
- Increased temperature
- Blood changes
- Bone marrow damage
- Damage to cells lining the small intestine
- Damage to blood vessels in the brain

The above list is given for information purposes only. The doses that can produce such effects are orders of magnitude higher than the radiation exposures received when working with radioactive materials at the U of T.

The delayed effects of radiation are due to both acute exposure and continuous exposure (chronic exposure). In this case, the negative effects may not be apparent for years. Chronic exposure is likely to be the result of improper or inadequate protective measures.

In the case of inhalation or ingestion of radioactive materials, a single "acute" event may cause a long period of "chronic" internal body exposure due to irradiation of tissue where radioactive material has been fixed.

The most common delayed effects are various forms of cancer (leukemia, bone cancer, thyroid cancer, lung cancer) and genetic defects (malformations in children born to parents exposed to radiation). In any radiological situation involving the induction of cancer, there is a certain period between the exposure to radiation and the onset of disease. This is known as the "latency period" and is an interval in which no symptoms of the disease are present. The minimum latency period for leukemia produced by radiation is 2 years and can be up to 10 years or more for other types of cancer.

5.2 Dose-Effect Relationship

Based on the dose-response relationship, the effects of radiation are classified into two categories: non-stochastic, and stochastic.

The non-stochastic effects, also referred to as deterministic or tissues and organs effects, are specific to each exposed individual. They are characterized by:

a) A certain minimum dose must be exceeded before the particular effect is observed. Because of this minimum dose, the non-stochastic effects are also called Threshold Effects. The threshold may differ from individual to individual
b) The magnitude of the effect increases with the size of the dose received by the individual
c) There is a clear relationship between exposure to radiation and the observed effect on the individual

Stochastic effects are those that occur by chance. They are more difficult to identify since the same type of effects may appear among individuals not working with radioactive materials. The main stochastic effects are cancer and genetic defects. According to current knowledge of molecular biology, cancer is initiated by damaging chromosomes in a somatic cell. Genetic defects are caused by damage to the chromosomes in a germ cell (sperm or ovum). There is no known existing threshold for stochastic effects. One single-photon or electron can produce the effect. The number of individuals affected is proportional to the dose.

Stochastic effects can also be caused by many other factors, not only by artificial radioactivity. Since everybody is exposed to natural radiation, chemicals, viruses, etc., stochastic effects can arise in all of us regardless of the type of work (working with radiation or not). Whether or not an individual develops the effect is a question of chance.

There is a stochastic correlation between the number of cases of cancers and the dose received by the population at relatively high levels of radiation exposure. Attempts have been made to extrapolate the data from high levels, to low doses (close to the levels received from background radiation). Several mathematical models were being developed to support these extrapolations.

Since there is no evidence of a lower threshold for the appearance of stochastic effects, the prudent course of action is to ensure that all radiation exposures follow a principle known as **ALARA (As Low As Reasonably Achievable)**. We will be referring to the application of this principle at U of T in subsequent chapters.

5.3 Effects of Radiation on Foetus

It is well known that the fetus is more sensitive to the effects of radiation than an adult human. If irradiation occurs in the first 30 weeks of pregnancy, delayed effects may appear in the child. These include mental and behaviour retardation, with a delay period of approximately 4 years.

Table 5-1: Delayed effects in the fetus

Preimplantation	**Organogenesis**	**Fetal**
0-9 days	10 days – 12 weeks	6 weeks - term
From fertilization to the time at which the embryo attaches to the wall of the uterus	Organs are formed	Growth of formed structures
		11 – 16 weeks
		eyes, skeletal, genital organs (stunt microcephaly, mental retardation)
		16 – 20 weeks
		a mild degree of microcephaly, mental retardation
Miscarriage	Abnormalities to many organs	After 30 weeks does NOT produce structural abnormalities but may produce functional disabilities

Because of these possible effects, dosimetry during pregnancy differs from the usual protocol. Special attention is paid to both external and internal irradiation. A Radiation Safety Officer of the U of T must review procedures for handling radioactive materials when a pregnant worker performs such work.

It is not possible to accurately measure the dose to the fetus and so it must be inferred from the exposure to the mother. Radiation protection principles limit exposure to the mother to achieve a minimum risk to the fetus.

5.4 <u>Effects of very Low Radiation Levels</u>

As was explained earlier, everybody is exposed to a level of radiation called natural radiation or background radiation. Also, it was proved that the background levels vary on Earth by a factor greater than 10. There are not enough data to support extrapolations of the effects of high levels of radiation exposures (like the survivors of the Hiroshima and Nagasaki bombing, uranium miners, medical exposures, etc.) to the levels of radiation exposure close to the background.

Exposure to very low levels of radiation is a controversial issue. The scientific community did not reach an agreement. Several mathematical models are used.

In Fig. 5-1, four mathematical models used to describe the effects of low levels of radiation exposure, are presented. All are supported (more or less) by controversial epidemiological studies, or by extrapolation of the findings obtained from studies with other mammals, to humans.

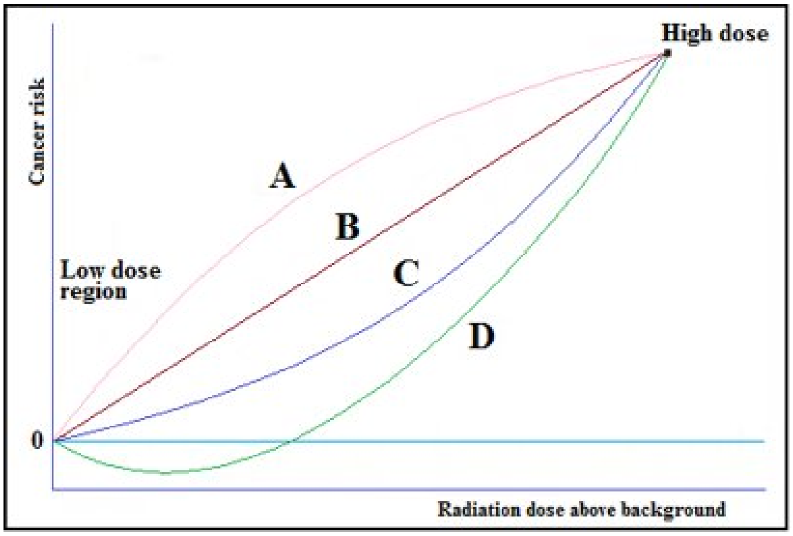


Fig. 5-1: Models for the low level of radiation exposures

Model B (also called the Linear Non-Threshold, or LNT, model) considers that there is a linear proportionality between the effect and the dose. The stochastic effects can appear at any dose (there is no threshold) and any increase in dose results in a proportional increase in cancer risk. According to this model, we can decrease the chances of having radiation-caused cancer by decreasing the dose, or if we put it differently, any photon absorbed in a human body can be the cause of cancer.

Model A considers also that there is no threshold dose for stochastic effects, but at a low level, there is an increased cancer risk (more than results from the proportionality). Model C considers that at low doses there is no threshold, but the risk of cancer is lower than the one obtained by simple proportionality with the risk at high doses.

Model D (also called the Hormesis model), considers that a low dose of radiation exposure has a positive effect and decreases the overall risk of cancer. The scientific argument presented by the promoters of this model is that we evolved in a natural environment where radiation was present, therefore we are used to, and adapted to, a certain level of radiation exposure.

In the absence of clear scientific evidence, the regulators adopted a conservative approach and consider all levels of radiation as being potentially damaging to the human body. Because of this, any procedure that involves radioactive materials must abide by the ALARA principle.

Chapter 6: RADIATION DETECTION AND MEASUREMENTS

Radiation cannot be perceived by human senses so, we rely upon the use of physical effects of radiation to create an instrument to detect and measuring it. There are two basic types of instruments used for its detection:

- Particle counting instruments
- Dose measuring instruments

The particle counting instruments measure the number of particles (electrons, alphas, protons, neutrons, etc.) or photons that give a signal in the detector and the result is expressed in counts per minute (cpm) or counts per second (cps). The dose-measuring instruments also measure the number of particles or photons, but the result is given in units of dose (R, rem, Gy, Sv, etc.), or dose rate (R/s, mSv/h, Gy/min, etc.). Sometimes the same instrument is capable of both types of readings.

The internal dose can be estimated from bioassay measurements performed with particle counting instruments.

6.1 Particle counting instruments

Particle counting instruments are used to determine the activity of a sample taken from the environment, to measure the activity of body fluids and can be used as portable survey instruments for contamination monitoring.

The detector in particle counting instruments can either be a gas, a solid or liquid. When ionizing particles pass through the detector, energy dissipation through a burst of ionization occurs. This burst of ionization is converted into an electrical pulse that actuates a readout device, such as a scaler or a ratemeter, to register a count.

6.1.1 Gas-Filled Detectors

The gas-filled detectors resemble a cylindrical condenser, with a central anode for collecting electrons and an outer cathode for collecting positive ions. The ionizing particle passes through the gas that fills the condenser, creating positive ions and electrons.

Depending on the value of the electrical field applied to the detector, the electrons initially created can acquire enough kinetic energy to produce secondary ionizations.

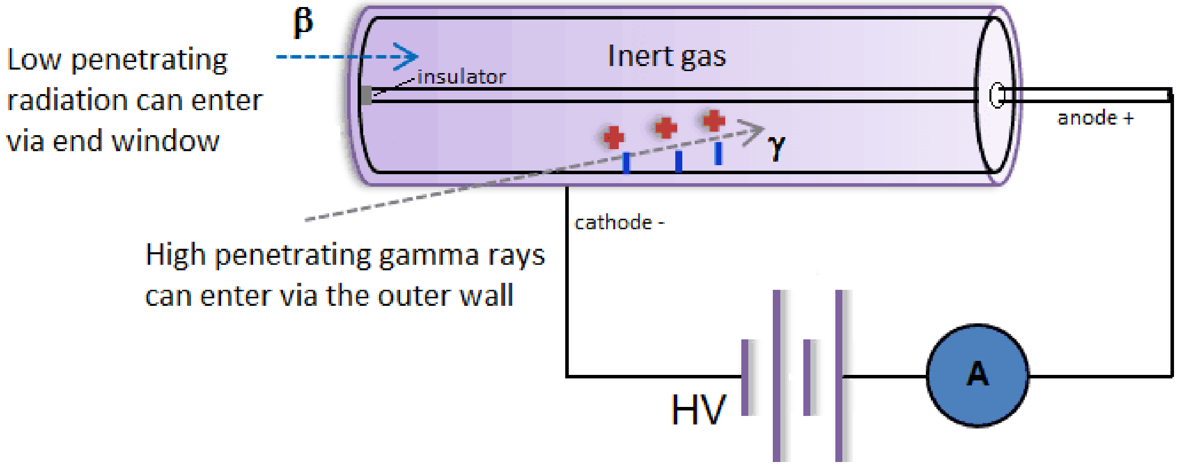


Fig. 6-1: Schematic design of a gas-filled detector

Depending on its energy, gamma radiation can enter through both the end window and outer wall.

There are various types of particle counting instruments filled with gas:

a) Ionization chamber counters (no secondary ions are produced)
b) Proportional counters (secondary ions are produced but the number is proportional to the initial energy of the radiation)
c) Geiger-Müller counters (secondary ions are produced in large numbers and the number of ions is no longer proportional to the energy of the radiation)

The main difference between these 3 types of counters is the voltage used for charging the condenser.

6.1.2 Solid and Liquid Scintillation Detectors

A scintillation counter is a transducer that changes the kinetic energy of an ionizing particle into a flash of light. The flashes of light are detected by photomultiplier tubes. The output pulses may be amplified, sorted by peak intensity, and counted.

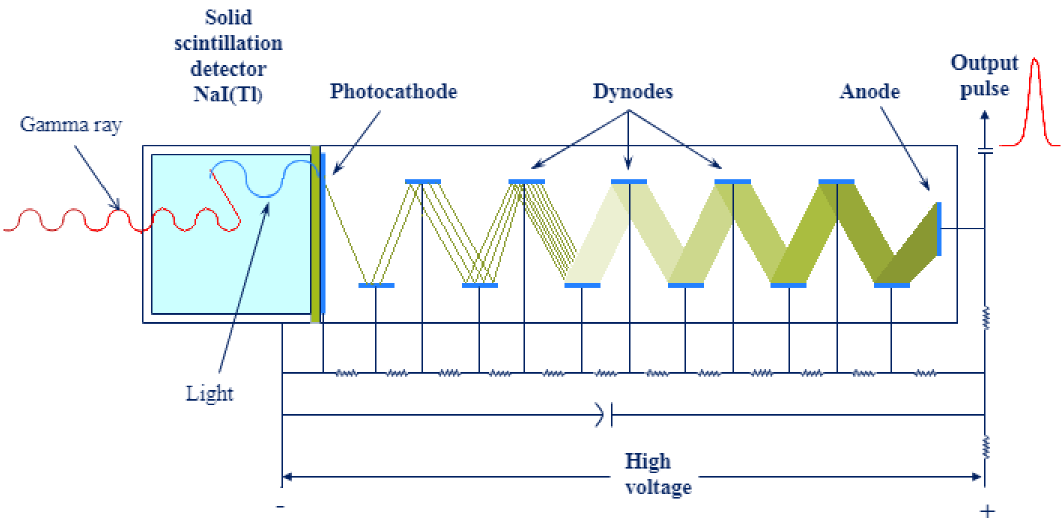


Fig. 6-2: Solid scintillation counter

Different scintillation materials (NaI (Tl), CsI (Tl) crystals, plastics, or liquids) are used to detect different types of radiation.

Scintillation counters are widely used in our radiation protection program for bioassays, swipes, and laboratory experiment samples. Liquid scintillation counters have a very good detection threshold since the scintillation liquid and sample are practically mixed.

6.1.3 The measurement process

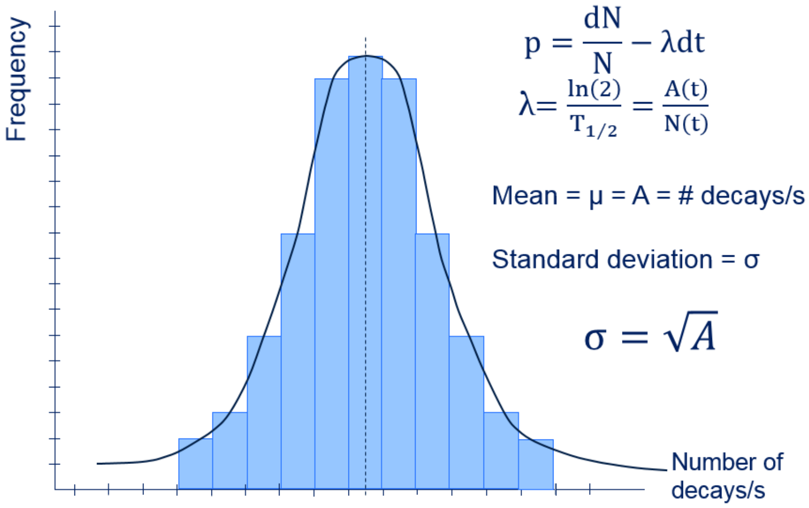


Fig. 6-3: Counting statistic

As was discussed in chapter 2.7 dedicated to the definition of radioactivity and the laws of radioactive disintegration, radioactive decay is a statistical process. The probability “p”, of the decay, is proportional to time. The constant of proportionality indicates the dependency on the radionuclide and is called the decay constant, noted as “λ” lambda.

If the time dt is chosen as 1 s, and if 1 s is much smaller than the half-life of the radionuclide, we can represent on a diagram the frequency of the number of decays per second, as a random event. The histogram represents on the x-axis the number of decays per second and on the y-axis the frequency of each number of decays per second likely to happen. For radionuclides used in our university, which have the half-life of the order of days or more, the number of unstable nuclei is very large, and the number of decays per second larger than 20, the distribution of the number of decays per second can be approximated to a gaussian distribution.

The mean of this distribution is the activity of the sample, and the standard deviation is the square root of the activity. A measurement (counts per a certain time interval called the counting time) is a number proportional to the number of decays per second. The proportionality constant is the detector’s efficiency. If a sample is measured many times with a counting time much smaller than the half-life, a similar histogram to the one presented in figure 6.3 will be obtained, but on the x-axis, the number of counts per counting time will appear.

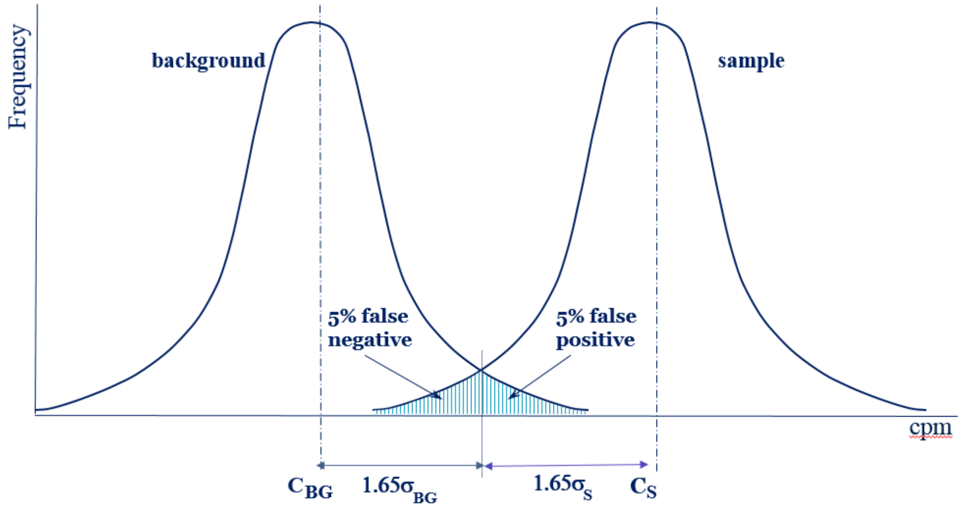


Fig. 6-4: Sample and background

When measuring a sample we always measure both the activity of the sample and the background. By keeping the detector at a large distance from the sample we can measure the background only. To determine the activity of the sample we need to subtract the background. Both measurements, the sample and the background are statistical events. The two Gaussian distributions will always overlap. The overlap is greater if the measured count rates are close to each other (for example when the sample measurement is for example 60 counts per minute – cpm - and the background is 50 cpm). When interpreting the result of the subtraction of two Gaussian distributions, there are two types of errors: false positive (when we assume that the result belongs to the sample distribution, but is part of the background) or false negative (when we assume that the result belongs to the background distribution but belongs to the sample). In figure 6-4, the superposition takes place at 1.65 standard deviations for both distributions. For this situation, the false-negative and the false-positive are each 5%.

Usually, in the theory of radiation measurements, the 5% errors for both false negative and false positive are considered acceptable. Under this assumption, the lowest number of counts considered statistically significant above the background is called the detection limit (DL) and is given by the formula:

$$\mathrm{DL\ (cpm)} = \frac{3 + 4.65 * \sqrt{\mathrm{Background\ counts}}}{\mathrm{Counting\ time\ (min)}}$$

By reducing the background, the detection limit can be decreased. The background can be reduced if the detector is enclosed in a shielding (e.g. a lead castle).

When the difference between sample measurement and background (net counting rate) is bigger than the detection limit, the measurement is considered statistically significant and the result is expressed as:

$$\mathrm{A\ (Bq/sample)} = \frac{\mathrm{Net\ count\ rate\ (cpm)}}{\mathrm{Detector\ efficiency} * 60\ \mathrm{(s/min)} * \mathrm{Sample\ size}}$$

The detection efficiency is determined by measuring samples of known activity (calibrated sources) under similar conditions. That is why it's very important to have the detection system properly calibrated.

If a swipe sample is measured, the detection efficiency includes two terms:

1. The efficiency of the detector
2. The efficiency of the swiping process (to be on the conservative side at U of T, we consider a swiping efficiency of 10%)

The uncertainty of measurement is calculated with the formula:

$$\mathrm{UN}\left({}^{\mathrm{Bq}}/_{\mathrm{sample}}\right) = \frac{\sqrt{\mathrm{Sample\ counts} + \mathrm{BG\ counts}}}{\mathrm{Detector\ efficiency} * 60\ \mathrm{(s/min)} * \mathrm{Sample\ size} * \mathrm{CT\ (min)}}$$

Where CT is the counting time in minutes. When using an instrument set for measuring counting rates in cpm (the majority of the handheld instruments), the sample counts represents the reading of the sample, the BG counts represents the reading of the background, and CT is 1 min.

The final result should be expressed as activity ± uncertainty, in Bq/sample.

When the activity is expressed as Bq per volume of sample or per cm^2, as is the case with the swipes, the volume of the sample (or the swiping surface) must also be accounted for in the denominator.

When the difference between sample measurement and background (net counting rate) is smaller than DL, the result of the measurement is NOT considered statistically significant and the result should be expressed as a minimum detectable activity (MDA).

$$\text{MDA (Bq/sample)} = \frac{\text{DL (cpm)}}{\text{Detector efficiency} * 60\ (\text{s/min}) * \text{Sample size}}$$

MDA is not a characteristic of the sample measured but it is a characteristic of the instrument's limit in detecting radioactivity. That is why results should be expressed as "less than MDA (Bq)". Such a result indicates that the radioactivity of the sample is less than the capability of the instrument for detecting radioactivity.

Nevertheless, this kind of result can be quite informative. It will indicate whether an instrument is appropriate for specific applications. For example, an instrument's MDA might be equal to or smaller than the release criteria for contaminated surfaces. Thus, any contaminated surface measured using this instrument cannot be considered “clean”.

Example:

Tritium contamination occurred in a laboratory. A swipe of 100 cm^2 was taken and measured with a liquid scintillation counter for 1 minute.

a) Considering a swipe efficiency of 10% and a detection efficiency of 55%. Determine the result of a measurement when the number of counts for the sample is 750 with a background of 41.
b) Decide to clean the area and swipe again. In the same conditions, determine the result of the measurement if the new reading is now 60 counts and the new background is 39 counts in one minute.

Answer:

a) The detection limit DL is:

$$\text{DL (cpm)} = \frac{3 + 4.65 * \sqrt{\left(41\ (\text{cpm}) * 1\ (\text{min})\right)}}{1\ (\text{min})} = 32.8\ (\text{cpm})$$

The difference between the sample (750 cpm) and the background (41 cpm) is 709 cpm, which is more than 32.8 cpm. Therefore, the result is statistically significant. The activity and the uncertainty can now be calculated as:

$$\mathrm{A\ (Bq/sample)} = \frac{709\ \mathrm{(cpm)}}{0.55 * 100 * 0.1 * 60\ \mathrm{(s/min)}} = 2.15\ \mathrm{(Bq/cm^2)}$$

$$\mathrm{UN}\ \left({}^{\mathrm{Bq}}/_{\mathrm{sample}}\right) = \frac{\sqrt{41(counts) + 750\ \mathrm{(counts)}}}{0.55 * 60\ \mathrm{(s/min)} * (0.10 * 100)\ (\mathrm{cm^2}) * 1(min)} = 0.09\ \mathrm{(Bq/cm^2)}$$

Therefore, the result is (2.15 ± 0.09) Bq/cm^2

b) The new detection limit is:

$$\mathrm{DL\ (cpm)} = \frac{3 + 4.65 * \sqrt{39\ \mathrm{(cpm)} * 1\ \mathrm{(min)}}}{1\ \mathrm{(min)}} = 32.0\ \mathrm{(cpm)}$$

The difference between the new sample (60 cpm) and the background (39 cpm) is now 21 cpm. Because 21 is smaller than 32, the measurement is not statistically significant. In this case, the MDA is:

$$\mathrm{MDA\ (Bq/cm^2)} = \frac{32.0\ \mathrm{(cpm)}}{0.55 * 100 * 0.1\mathrm{(cm2)} * 60\ \mathrm{(s/min)}} = 0.10\ \ \mathrm{Bq/cm^2}$$

Therefore, the result is expressed as "less than 0.10 Bq/cm^2" (< 0.10 Bq/cm^2) and indicates that the surface is not contaminated with an activity of 0.10 or more Bq/cm^2.

6.2 Dose measuring instruments

To measure the radiation dose, the instrument's response must be proportional to the energy absorbed from radiation. A "radiation flux" measuring instrument does not necessarily measure the dose. To effectively measure dose, efficiency for different types of radiation and energy must be taken into account. Pocket dosimeters, film badges, and personal thermoluminescent dosimeters are all used to measure a personal dose. They are based on the effects of the accumulated energy of radiation in the detector. Changes in the detector's material structure can be stored until the reading process takes place. With appropriate calibration, the personal dose can be determined.

Thermoluminescence is a property of some crystals (i.e. LiF, CaF_2:Mn, etc) that when high energy radiation creates electronically excited states, these states are trapped by localized defects or imperfections in the crystal’s lattice.

According to the quantum mechanic, these states are stationary and they do not have time dependence, however, they are not energetically stable. Heating the material enables the trapped states to rapidly decay into lower-energy states, causing the emission of photons in the process.

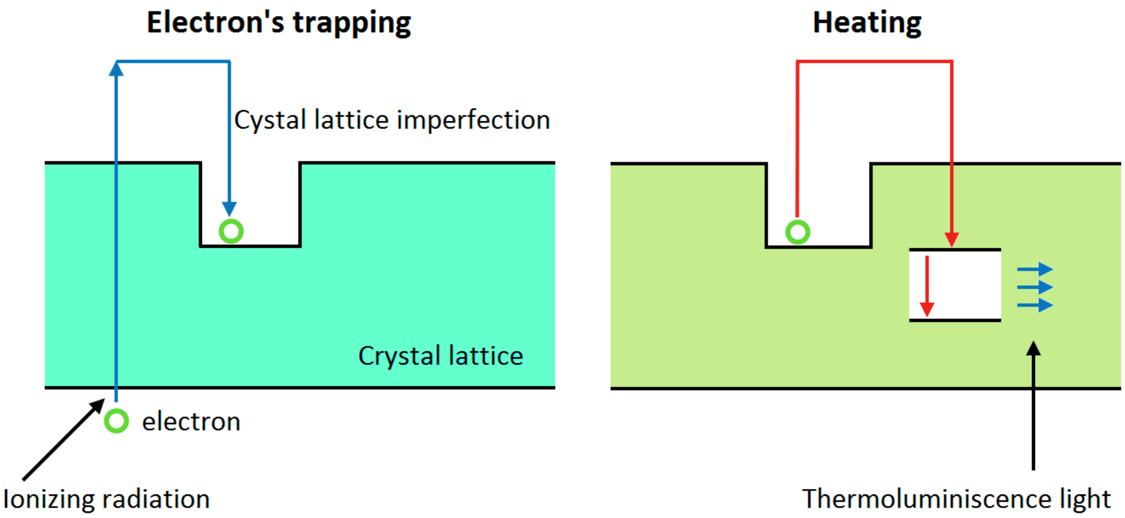


Fig. 6-5: Thermoluminiscence principle

Radiation badges are used at U of T for measuring doses received by people working with radiation and for area dosimetry. A certified (by the federal regulatory agency) company provides this service to the university. There are two kinds of radiation badges used in U of T:

1. Whole-body dosimeter. This dosimeter should be worn somewhere on the person's trunk.
2. Extremity dosimeter (a ring dosimeter). This special dosimeter should be worn on the hand that is used the most during radioactive work.

Area dosimeters are identical to whole-body dosimeters and are used to measure the exposure in the area around the workplace.

All radiation badges (whole body, ring or area dosimeters) are limited to measuring high energy beta radiation and gamma/x-ray exposure. These dosimeters cannot measure exposure received from low-level energy beta emitters like H-3, C-14, S-35 or Ni-63.

Fig. 6-6: Radiation badges

Electronic dosimeters are also used for direct reading of dose. They are very useful for work in high radiation fields because of the alarm system they are equipped with. Alarms can be set for total dose, dose rate, and superficial or deep dose.

Survey meters are particle counting instruments that have been calibrated to measure the dose. They are highly specialized and can only be used for the type of radiation (X-ray, gamma-ray or neutrons) for which they have been calibrated. These instruments should never be used to measure doses outside the energy range or type of radiation for which they were calibrated. The calibration of these instruments must be done according to a procedure approved by the federal regulator.

6.3 <u>Internal dosimetry</u>

As was mentioned before, inhalation and ingestion are the main paths for internal irradiation of those working with radioactive materials. Therefore, special methods are required for measuring the internal irradiation of personnel. At U of T, there are two internal dosimetry programs: thyroid bioassays and urinalysis.

6.3.1 Iodine measurement

The iodine bioassay program is based on the well-known fact that iodine radionuclides used in our laboratories (I-125 and I-131) tend to accumulate inside the thyroid. Both radionuclides are gamma emitters. Therefore, a gamma detector can be used to measure the iodine content of the person's thyroid. Proper calibration of the instrument is done using 'phantoms' that mimic human body composition. After gathering information about thyroid activity (in Bq) and the moment of iodine use, it is possible to estimate iodine intake and uptake. Since the level of radioiodine in the thyroid decreases after 5 days, the measurement must be done between 1 and 4 days after usage. The amount of radioiodine in the thyroid is compared with the annual limit on intake (ALI) and the dose received by the contaminated person can be estimated.

6.3.2 Urinalysis

The scientific basis for this type of analysis is the fact that most radionuclides tend to be eliminated in body fluids. By measuring activity content in urine, it is possible to estimate the intake and uptake of a specific radionuclide. The dose is estimated by comparing the intake with the ALI for that particular radionuclide.

Example:

a) During an iodine bioassay of a person using I-125, the result of a 2-minute measurement is 1200 counts (or 600 cpm). The background for a 2-minute measurement performed immediately before was 950 counts (or 475 cpm). Knowing the detection efficiency of the instrument for I-125 to be 1.42 % for a person without fat tissue, determine the content of I-125 in the person's thyroid.

b) What is the content of I-125 for a different person measured immediately after the first one, if the measured value is now 980 counts (or 490 cpm)?

Answer:

a) The detection limit for a 475 (cpm) background measurement is:

$$\mathrm{DL\ (cpm)} = \frac{3 + 4.65 * \sqrt{950\ \mathrm{(counts)}}}{2\ \mathrm{(min)}} = 75\ \mathrm{(cpm)}$$

The difference between the person's measurement (600 cpm) and the background (475 cpm) is 125 cpm. This is more than 75 cpm. Therefore, measurement is statistically significant. The activity of I-125 in the thyroid is:

$$\mathrm{A\ (Bq)} = \frac{125\ \mathrm{(cpm)}}{0.0142 * 60\ \mathrm{(s/min)}} = 147\ \mathrm{Bq}$$

The uncertainty is:

$$\mathrm{UN\ (Bq)} = \frac{\sqrt{1200\ \mathrm{(counts)} + 950\mathrm{(counts)}}}{0.0142 * 60\ \mathrm{(s/min)} * 2\ (min)} = 27\ \mathrm{(Bq)}$$

The result is: (147 ± 27) Bq

b) The second measurement is taken immediately after the first one. The assumption is made that the background of the instrument remains the same.

Therefore, the detection limit is the same DL = 150 counts for a 2-minute measurement.

The difference between the person's measurement (490 cpm) and background (475 cpm) is now 15 cpm. This number is less than 75 cpm. Therefore, the result is NOT statistically significant. The MDA of the instrument is:

$$\mathrm{MDA\ (Bq)} = \frac{75\ \mathrm{(cpm)}}{0{,}0142 * 60\ \mathrm{(s/min)}} = 88\ \mathrm{(Bq)}$$

The result is expressed as "less than 88 Bq" (< 88 Bq), and the person's thyroid is 'clean'.

Chapter 7: RADIATION SAFETY

In recent years, extensive efforts have been made to reduce the risk of irradiation from radioactive sources at work by controlling the permitted levels of radioactivity. This was achieved by applying the three principles of radiation protection:

Justification

Any decision that alters the radiation exposure should do more good than harm.

Optimization of Protection

The number of people exposed, and the magnitude of their doses should be kept as low as reasonably achievable **(ALARA**), taking into account economic and social factors.

Application of Dose limits

The total dose to any individual from regulated sources in planned exposure situations, other than the medical exposure of patients, should not exceed the appropriate limits.

Note that the optimization principle requires actual operational dose limits for any work with radiation sources to be more restrictive than the maximum regulated dose limits.

7.1 Reduction of dose to personnel

Once radioactive materials are being considered as part of one's research, an application for a radioisotope permit must be completed. During the process of obtaining the permit, the radioisotope work procedures will be examined. Other considerations include the applicant's training, previous work experience with radioactive materials, adequacy of workplace preparation and equipment, types of dosimeters used, protective equipment, etc.

No radioactive material can be ordered until the radioactive permit has been approved. Subsequently, only those isotopes listed on the permit can be ordered within the prescribed limits. However, new isotopes can be added and/or their limits changed, provided a written request by the permit holder is sent to the Radiation Protection Service (RPS) for approval.

It is better to order radioactive materials as close as possible to the date of the experiment, from both experimental and ALARA perspectives. This will reduce the risks associated with the long-term storage of labelled materials, as well as reducing the possibility of source leakage, external irradiation, etc.

7.2 Protection against external exposure

Protection against external exposure can be done by following three fundamental methods:

- Time
- Distance
- Shielding

7.2.1 Time

Because radiation is roughly emitted at a constant rate from its source, the radiation dose will be proportional to the amount of time spent in proximity to the source. Therefore, the worker should try to reduce the time spent working with radioactive materials as much as possible.

Good work practice is to run a mock experiment first, without any radioactive material, to get used to the procedures. Then, perform the first experiment with the smallest amount of radioactive material that will provide a readable result. After becoming familiar with the procedures and safe handling of these materials, the quantities can be increased if necessary.

Store the bulk of the radioactive material away from the work area or keep behind shielding. Only take the necessary amount of radioactive material for the experiment on the bench, returning the stock solution to the storage area. All radioactive waste should also be kept away from the work area or stored behind shielding.

Example:

a) Radiation is used in ferrokinetic studies of blood plasma. An injection of ferric chloride containing 18.5 MBq (0.5 mCi) of Fe-59 is to be administrated to a calf. The dose rate at the surface of the syringe is 0.40 mSv/minute. The syringe is handled for 1.5 minutes. Estimate the dose to the fingers.
b) If the procedure can be performed in half the time noted above, then the radiation dose received will be reduced. Estimate the new dose to the fingers.

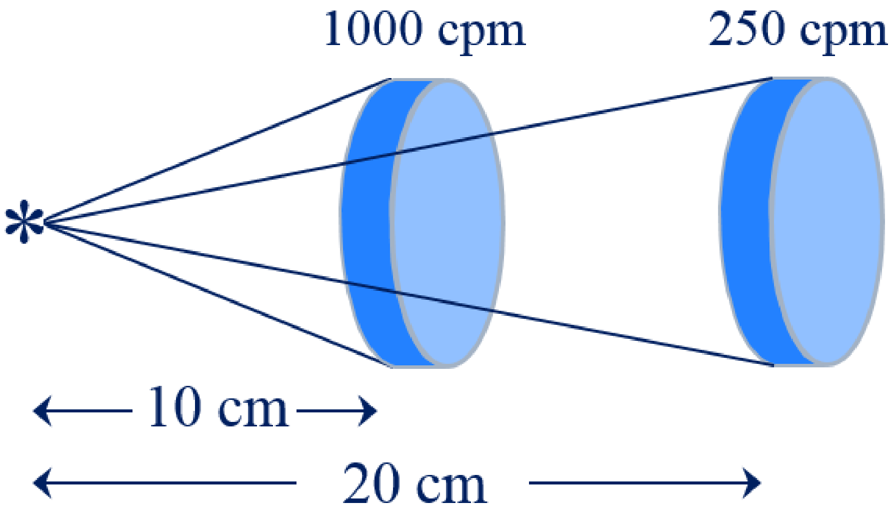
Answers:

a) Dose = 0.40 mSv/min * 1.5 min = 0.60 mSv
b) Dose = 0.40 mSv/min * 0.75 min = 0.30 mSv

7.2.2 Distance

As described in Chapter 4, gamma and X-ray exposure decreases with distance from the source, according to the inverse square law (for point-source). As the potential for exposure decreases, so does the potential dose.

$\text{Dose} \approx 1/r^2$



An effective method of protection from gamma radiation is to maintain a distance as great as possible from the source. It is good practice to work with radioactive materials at arm's length, minimizing the radiation field to the trunk of the body. When handling sources of high activity, the use of long-handled tools is required. This will reduce exposure to the hands and fingers. For high activity sources such as greater than 50 MBq (1.35 mCi) of P-32 in the research laboratory, whole-body and ring radiation badges are required.

Example:

The gamma field from a particular Co-60 source is 0.10 mSv/hr at 0.5 meters.

What is the dose at 3 meters?

Answer:

According to the inverse square law:

Dose (3 m) = Dose (0.5 m) * $0.5^2 / 3^2$ = 0.10 * 0.25 / 9 = 0.0028 mSv/hr

Distance is also very effective in reducing the dose received from alpha and beta radioisotopes. The resulting decrease in dose is even greater than in the case of gamma and X-ray sources due to the absorption of alpha and beta radiation in the air.

When maintaining a sufficient distance from beta and gamma radiation is not feasible, shielding becomes necessary.

7.2.3 Shielding

As explained previously, no shielding is required for alpha radiation unless beta and/or gamma emission is also associated with the alpha emission.

When working with beta radiation sources, X-rays also appear in the shielding material due to bremsstrahlung. It is recommended to use low atomic mass number (Z) materials such as plastics (e.g. plexiglass) or Aluminium, for shielding against beta radiation. If the radionuclide has gamma emissions associated with beta radiation (e.g., I-131), protection against gamma and X-rays is also required.

Due to their weak interaction with matter, shielding against gamma and X-rays is the most difficult. High atomic mass number (Z) materials (lead, steel, or even high-density concrete) are used. The thickness of the material depends on the intensity and energy of the X- and gamma radiation (for high energies, a thicker layer is necessary).

Interaction of gamma and X-rays with the shielding material usually produces secondary radiation. A build-up factor, specific to each type of material and radiation, estimates the resulting increases in the radiation field.

A simple approach to selecting shielding against gamma and X-ray is by using the HVT (Half Value Thickness) of a specific material. This is the thickness of the material required to reduce X- and gamma radiation to half intensity. Another important value is the TVT (Tenth Value Thickness). It's the thickness of the material that reduces the intensity of the gamma field to one-tenth of its initial value. The most commonly used material for gamma and X-ray shielding is lead. The following table lists lead HVT and TVT values for different radioisotopes used at U of T.

Lead HVT and TVT values (in cm) for different radionuclides

	Tc-99m	**I-131**	**Cs-137**	**Ir-192**	**Co-60**
HVT (cm)	0.03	0.72	0.65	0.55	1.10
TVT (cm)	0.09	2.40	2.20	1.90	4.00

Example:

A Co-60 radiation source creates a gamma field of 20 Sv/hr. Find the lead thickness that will reduce the gamma field to 2 mSv/hr?

Answer:

TVT value for Co-60 lead is 4.0 cm.

To reduce the gamma field from 20 Sv/hr to 0.002 Sv/hr (four orders of magnitude), a layer of lead with thickness 4*TVT= 4*4.0 cm = 16.0 cm is necessary.

The best value of the thickness of the shielding material needed can be calculated using computer codes. The Radiation Protection Services offers a web application to make these calculations that can be accessed at:

https://ehs.utoronto.ca/our-services/radiation-safety/useful-calculations/gamma-radiation-shielding-calculations/

The best shielding against neutron radiation is a material with abundant Hydrogen content such as water, paraffin, wax, or concrete.

A large enough quantity of any material can shield all types of radiation.

Always remember to check the effectiveness of your shielding first. The shielding used for one experiment may not be appropriate for the next experiment, especially when larger quantities of radioactive material or different radioisotopes are used.

7.3 Protection against internal radiation

As discussed previously, all types of radiation become more hazardous once inside the human body. The greatest internal hazard is alpha radiation, which is the least dangerous when outside the body.

Protection against internal radiation is the same as with other biological or chemical hazardous materials. Suitable handling precautions, good working procedures and protective equipment are necessary.

Eating or drinking, and even storage of food or drinks, are not permitted inside any designated radioactive laboratory. Lab coats and the use of disposable gloves are required when handling radioactive materials. Eyes or face protection (goggles or plastic face shield) is also recommended when using open sources of radioactive materials.

7.4 Radionuclides used at U of T

The Periodic Table links to some of the most commonly used radionuclides at U of T along with their half-life, disintegration mode, type and the energy of emitted radiation, necessary protective equipment, etc.

Chapter 8: REGULATORY REQUIREMENTS

8.1 Introduction

The possession, storage, use and disposal of radioactive materials is highly regulated at the international, federal, provincial, municipal and local (U of T) levels.

The United Nations established the International Atomic Energy Agency (IAEA) in 1956, with headquarters in Vienna (Austria). An important IAEA activity is to establish rules for international transport, use, and disposal of radioactive materials. However, their publications serve mostly as guidelines for each country. The agency has the power to control the enforcement of international treaties banning the use of nuclear technology for military purposes. Their safeguard inspectors also have the right to visit U of T and ask questions about the use, storage, and disposal of strategic radioactive materials (like compounds containing Pu, U and Th).

In 1928, an international committee was formed to recommend radiation protection measures and to propose limits on radiation exposure. In 1950, the committee was reorganized and named the International Commission on Radiological Protection (ICRP). Recommendations from the ICRP are used as the basis for radiation protection programs in countries all over the world.

In Canada, the federal body with regulatory powers on all aspects of radiation safety is the Canadian Nuclear Safety Commission (CNSC). It exercises control over radioactive materials through the tenets of the Nuclear Safety and Control Act and enforces its mandate through license report submissions and regular inspections and audits. The CNSC also establishes dose exposure standards for the public and nuclear energy workers all across Canada.

Other federal and provincial agencies are involved in the control of radioactive materials. These include Transport Canada, Health Canada, Environment Canada, Ontario Ministry of Health, and Ontario Ministry of Labour.

8.2 Licensing and Permits

The main method for controlling the use of radioactive materials employed by the CNSC is the licencing system. The University of Toronto possesses a Nuclear Substances and Radiation Devices Licence. This type of licence allows considerable flexibility, which is required in a dynamic research centre such as U of T. It requires the University to maintain a well-managed and documented radiation protection program to ensure that radioactive materials are used safely.

The licence contains information about the federal and provincial acts and regulations for the use of radioactive materials. The Radiation Protection Service maintains copies of the licence. Any company that delivers radioisotopes to the U of T must have a copy of this licence.

8.3 University of Toronto Radiation Protection Authority - UTRPA

The University of Toronto Radiation Protection Authority (UTRPA) is a committee composed of academics and administrators who are appointed by the U of T Governing Council. The UTRPA oversees the radiation protection program at U of T. It is the responsibility of the UTRPA to establish policies and procedures to ensure the safe use of radioactive materials following federal and provincial legislation.

Under the terms of the Nuclear Substances and Radiation Devices Licence, the UTRPA is responsible for authorizing qualified individuals to use radioactive materials and has the power to issue internal Radioisotope Permits.

8.3.1 UTRPA responsibilities and duties

The UTRPA oversees all aspects of the radiation protection program at the U of T. Their control of the program is complete and all-embracing. The UTRPA has all necessary executive power delegated to it by the Governing Council to enforce and maintain the required standards of radiation protection necessary for a complex teaching and research institution.

The responsibility of the UTRPA includes all sources of ionizing and non-ionizing radiation (from both materials and machines) on all properties owned or controlled by the U of T.

The UTRPA has the power to enforce and set standards through policies, inspections and disciplinary action, if necessary. It issues, administers, reviews, and amends Radioisotope Permits.

Membership consists of academic personnel (including active permit holders) and administrative staff (see current membership). It meets regularly to discuss and implement new radiation protection initiatives in the interest of improving the overall radiation safety program.

The UTRPA maintains the radiation safety-training program to ensure that all users of radioactive materials receive appropriate training.

The UTRPA considers and advises on, the establishment of radiation emergency measures within the university, as well as co-operation and integration with other authorities (CNSC, Health Canada, etc.).

8.3.2 RPS responsibilities and duties

The UTRPA executes its mandate through the University of Toronto Radiation Protection Service (RPS). The RPS resides administratively within the Office of Environmental Health and Safety. The function of the RPS is to carry out the daily operation of the radiation safety program, as directed by the UTRPA.

Duties of the Radiation Protection Service include:

- Functioning as a link between the UTRPA and radioisotope users at the University of Toronto;
- Reviewing the radiation safety manual, at least every two years;
- Having major input in matters of:
  - facility and equipment design
  - work practices and procedures
  - waste storage and disposal management
  - evaluation, issuance and enforcement of internal Permits
  - disciplinary actions;
- Organizing radiation safety training;
- Preparing an Annual Report to the CNSC, as required by Regulatory Guide R-80 (or update);
- Acting as the contact for the institution concerning licencing matters with the CNSC;
- Being available for advice to radioisotope users on a full-time basis;
- Establishing, implementing and maintaining a radiation safety control and assessment program in conjunction with the UTRPA;
- Systematically and periodically reviewing survey programs for radiation and contamination levels in all areas where radioactive materials are found;
- Ensuring the proper operation of the personnel monitoring program, including the bioassay program;
- Ensuring that radiation safety instruments are available to the RPS in sufficient number and are calibrated and serviced as required;
- Conducting a quarterly review of occupational radiation exposures and recommend ways of reducing exposures in the interest of the ALARA principle;
- Supervising decontamination procedures, as necessary;
- Ensuring that waste disposal procedures are under the conditions of the radioisotope license;
- Ensuring that the necessary leak testing of sealed sources is performed;
- Controlling the purchasing, use and disposal of radioactive materials through the issuance of internal Permits and the enforcement of Permit conditions;
- Ensuring that appropriate radiation protection training is provided regularly for all users and for those who regularly come into contact with radioactive materials;
- Maintaining required records;

- Ensuring that each internal Permit is amended when needed by changes to facilities, equipment, policies, isotopes, conditions of use or procedures;
- Co-ordinating the development of plans to be used in the case of an emergency involving radioactive materials;
- Investigating all overexposures, accidents and losses of radioactive materials and reporting them to the CNSC, when necessary;
- Liaising with radioisotope users to ensure that doses of radiation are consistent with the ALARA principle.

8.4 Responsibilities and duties of the Permit Holders

The Internal Permit Holders are responsible at all times for all aspects of radiation safety in areas under their supervision. They must provide adequate training of persons under their supervision in the proper use, handling, and storage of radioactive materials.

An applicant for a radioisotope permit must be a person experienced in working with radioactive materials. He/she must be a U of T faculty member, or otherwise acceptable to the UTRPA. Work with radioactive materials must be performed on the University properties or other premises under the control and authority of the U of T. A chart listing the criteria necessary to become a permit holder, along with an application form and other necessary information for obtaining a radioisotope permit can be found at https://ehs.utoronto.ca/our-services/radiation-safety/guide-completion-radioisotope-permit-application/

After completing the form, supporting documents establishing previous work experience with radioisotopes should be attached to the form. Both the applicant and Chair of the department under which the work will be performed must sign the form, and the signed form forwarded to the RPS. The Radiation Protection Officer in charge of new radioisotope permit approval and commissioning will visit the applicant and discuss the application. After all additional information (if any) is clarified, the application is sent to the Chair of the UTRPA. After approval of the permit, purchasing of radioactive materials under that permit will be approved and work with radioactive materials can begin. At the next UTRPA meeting, all applications for new radioisotope permits will be analyzed. If more information is necessary, it will be obtained from the applicant and the permit will be amended, if necessary.

Permit Holders must:

- Be responsible for the safe use of radioactive materials being stored and handled in radioisotope laboratories under their supervision;
- Comply with all CNSC and UTRPA policies, procedures and permit conditions;
- Ensure that staff and students are familiar with all relevant aspects of radiation safety, procedure and policy;
- Provide specific training as required;

- Be available to supervise students and oversee the daily operation of their radioisotope laboratories;
- Establish specific work and storage areas for radioactive materials;
- Provide personal protective equipment and dose surveillance, including Thermoluminescent Dosimeters where required, functional survey meter(s), appropriate shielding, laboratory coats, gloves and other personal safety supplies;
- Keep an inventory of all radioactive materials and maintain a contamination monitoring program;
- Report incidents.

8.5 Responsibilities and duties of the radioisotope users

Students, research associates, research assistants, technicians, etc. must:

- Work in compliance with all CNSC and UTRPA policies and procedures;
- Understand and implement all relevant aspects of radiation safety, procedure and policy;
- Ensure that work with radioactive materials does not create a hazard to themselves or others;
- Use personal protective equipment such as laboratory coats and gloves;
- Wear thermoluminescent dosimeters, when required;
- Participate in the bioassay program, where required;
- Perform contamination monitoring: Survey work areas and equipment for contamination after work, or at maximum within 7 days after use.
- Record contamination survey results;
- Record daily use of radioactive materials;
- Follow all waste disposal procedures, ensuring that there are no releases of radioactive materials to the environment;
- Record date of disposal;
- Report any defective equipment or situations that may endanger themselves or others.

Chapter 9: U of T POLICIES, STANDARDS, AND PROCEDURES FOR RADIATION SAFETY

9.1 U of T Radiation Safety Policies

The ALARA concept has been adopted by the UTRPA as the basic philosophy governing the use of radioactive materials at the U of T.

The UTRPA radiation safety policies are presented in the "University of Toronto Ionizing Radiation Safety Procedures and Policies Manual”. It is the responsibility of all persons who supervise work with radioactive materials to become familiar with the information presented in this manual.

In addition to the information and requirements set out in the "Manual", the UTRPA may require additional compliance as necessary. Each policy will be approved by the UTRPA and notification sent to each permit holder. The policies are effective upon approval by the UTRPA.

The main policies are:

- Disciplinary action (4-step policy)
- Security of radioisotope laboratories
- Decommissioning
- Laboratory decontamination
- Foodstuff in radioactive laboratories
- Counting facilities
- Interrupted laboratories

9.2 U of T Radiation Internal Standards

According to ICRP recommendations, the CNSC has established the following limits for effective dose levels in Canada:

- Nuclear energy worker (NEW)
    - for a one-year dosimetry period: 50 mSv
    - for a five-year dosimetry period: 100 mSv
- Pregnant NEW (for the balance of the pregnancy): 4 mSv
- A person who is not a nuclear energy worker (one calendar year): 1 mSv

Equivalent dose levels have also been established for various organs:

- The lens of the eye, NEW, one-year dosimetry period: 150 mSv
- The lens of an eye, any other person, one calendar year: 15 mSv
- Skin, NEW, one-year dosimetry period: 500 mSv
- Skin, any other person, one calendar year: 50 mSv

- Hands and feet, NEW, one-year dosimetry period: 500 mSv
- Hands and feet, any other person, one calendar year: 50 mSv

The UTRPA established administrative investigation levels for the dose received by a person working with radioactive materials at U of T. The role of the investigation level is to allow for intervention in preventing further exposure. Each time the radiation badge reading results are received by the RPS, they are checked against the investigation levels. Action is taken if these investigation levels are exceeded.

The investigation levels at U of T are:

- 0.4 mSv for effective whole-body dose
- 10 mSv for extremity dose

The bioassay program enables the RPS to immediately detect the possible intake of radioactive materials. For radio-iodine, the reporting limit set by the CNSC is 10,000 Bq from a person's thyroid. However, at U of T, the internal administrative investigation level is set at 1,000 Bq.

Loose contamination limits, determined by swipes, are established by the CNSC for each radionuclide in controlled and public areas. These limits vary from 3 Bq/cm^2 to 30 Bq/cm^2 for the radioisotopes used as open sources in U of T labs. Under the ALARA principle, in U of T, any detectable loose contamination must be removed whenever possible. The minimum detectable activity (MDA) for the method used to determine the contamination must be 0.05 Bq/cm^2 for alpha-emitting radionuclides, and 0.5 Bq/cm^2 for all other radionuclides. If the removal is not possible, the surface should be covered to prevent the spread of radioactive contamination.

CNSC regulations require that signs indicating the presence of radioactive materials must be posted when there is a reasonable probability that a person in the area, room or vehicle, will be exposed to an effective dose rate greater than 25 μSv/h. According to ALARA, U of T standard requires that the signs should be posted at a level 10 times lower: 2.5 μSv/h (0.25 mrem/h).

9.3 U of T Radiation Procedures

9.3.1 Procedures for Ordering, Receiving and Transferring Radioactive Materials

9.3.1.1 Procedure for Obtaining Radioactive Materials

The Radiation Protection Service must be notified of all radioisotope orders, transfers, and gifts before receipt. Permit holders, authorized staff and students can obtain radioactive materials for storage and use in their designated radioisotope laboratories only.

Currently, all radioisotope orders must be processed using one of the following options:

1. the computerized Financial Information System/Administrative Management System (AMS), which is accessed by either the departmental business officer or the permit holder;
2. the U-source, which is accessed by the permit holder/lab member.

All orders for radioactive materials submitted via the AMS and U-source systems are automatically routed to Radiation Protection Service for approval. The purchaser must provide ALL of the following information for approval of the order:

- permit number;
- permit holder's name;
- radioisotope (e.g., P-32);
- chemical form (e.g., dCTP);
- total activity per vial ordered (e.g., 250 microCi);
- number of vials ordered (e.g., 2 vials);
- supplier;
- date of request;
- delivery location;
- name of lab member/authorized user requesting;
- laboratory telephone number.

The link to the purchase request form is: Purchase request

N.B.: Since the AMS and U-source systems are designed specifically for the processing of new purchases, the Radiation Protection Service must be notified of any gifts, donations, exchanges and transfers of radioactive materials by email to sandu.sonoc@utoronto.ca before receipt or transfer. All radioactive materials must be received, used, and disposed of in designated radioisotope laboratories under the same permit.

The Radiation Protection Service must be contacted for assistance whenever radioactive materials need to be transported between buildings or to external institutions. The transport of radioactive materials between buildings is strictly prohibited without prior permission from the RPS.

9.3.1.2 Receiving Radioactive Materials

Caution must be exercised when receiving and opening radioisotope shipments. The packing slip and label information should be compared with the original order to ensure that the correct compound has been delivered. A dose rate meter should be used to check the dose rate being emitted by the package and compare the reading with the value identified on the radiation warning labels (if applicable). The following table describes the dose rate limits for each type of radiation warning label:

Label	Maximum radiation field	
	In contact	At 1m
White I	< 0.005 mSv/hr	
Yellow II	> 0.005 mSv/hr but < 0.05 mSv/hr	< 0.01 mSv/hr
Yellow III	> 0.05 mSv/hr but <2 mSv/hr	< 0.1 mSv/hr

9.3.1.3 Radiation Warning Labels: (what they mean)

- White I: maximum radiation level < 0.005 mSv/hr at any location on the external surface of the package;
- Yellow II: maximum radiation level > 0.005 mSv/hr but < 0.5 mSv/hr on surface of the package and maximum radiation level < 0.01 mSv/hr at 1 m away from the package;
- Yellow III: maximum radiation level > 0.50 mSv/hr but < 2 mSv/hr on the surface of the package and maximum radiation level < 0.1 mSv/hr at 1 m away from the package.

9.3.1.4 Procedure for Receiving Radioisotope Packages

- Receive radioisotope packages in a designated radioisotope laboratory;
- Wear laboratory coat and gloves;
- **If the package shows evidence of leaking, (decolouration), tampering, or if it is damaged:**
  - Inform RPS and your PH immediately;
  - Store package in a fume-hood in a secure place;
  - Control the spread of contamination;
  - Identify any contaminated areas;
  - Mark the contaminated area;
  - Inform all lab personal about the possible area being contaminated;
  - Clean the contaminated area;
  - Check the effectiveness;
  - Record the results.
- Check radiation dose rates (if applicable) and compare the result with the type of warning label, as well as the written value. Dose rates exceeding the described limits may suggest an incorrect shipment or leakage from the internal container;
- Open the package in a fume hood, if contents are volatile;
- Wipe test the package and radioisotope container - contact RPS if contamination is found;
- Avoid direct contact with the radioactive material; shield it if necessary;
- Compare the information on the packing slip with the container label - contact RPS if there are any inconsistencies;
- Confirm the receipt of the package on the web application of the EHS database;
- File a copy of the packing slip in the lab (inventory binder);

- Deface or remove radiation labels from packaging and check for contamination before disposing of. Non-contaminated packaging should be disposed of as regular waste, while contaminated packaging must be disposed of in the solid radioactive waste container. Do not put non-radioactive materials in radioactive waste containers.

9.3.2 Procedures for Working with Radioactive Materials

General work procedures with radioactive materials are presented during the regular training delivered by the RPS to all workers before they start working with radioactive materials in U of T.

9.3.2.1 Specific Work Procedures

Each Permit Holder develops a specific set of working procedures. This is a condition of obtaining and keeping a radioisotope permit. The Permit Holder is responsible for training students and staff under his/her supervision in these working procedures. Any change in the procedures and/or radioisotopes (or any increase in the amount used) should be reported in writing to the RPS, with a formal request to amend the permit.

9.3.2.2 Wearing Radiation Badges

Persons handling radioisotopes other than H-3, C-14 and S-35, of activity of more than 1.35 mCi per vial/container, must wear whole body and ring radiation badges. The radiation badges are the primary source of information for personal exposure, as it measures the accumulated personal dose. The radiation badges are replaced and analyzed quarterly for the open-source workers and Nuclear Energy Workers (NEWs). All personal dose reports are sent to the NEWs.

A whole-body radiation badge records the dose to the skin and body, while an extremity radiation badge records the superficial dose to the hands and extremities. The radiation badges should be stored away from sources of ionizing and UV radiation when not in use.

9.3.2.3 Bioassay Requirements

Bioassays are performed on individuals to determine whether there has been an uptake of radioisotopes in the body. Users of radio-iodine (I-125 or I-131) working with activities greater than 2 MBq without containment, or greater than 200 MBq in a fume hood during 24 hours, must register for the thyroid bioassay. The bioassay measurement determines the amount of radio-iodine in the person's thyroid. Other radionuclides are monitored for uptake by urinalysis. This type of bioassay is necessary for all users of unbound, volatile radionuclides (e.g. tritiated water).

The radioisotope and it's biological half-life determine the frequency of bioassay monitoring:

- Within four days of usage of I-131 and I-125
- Within four days of usage for tritium users

Since the bioassay requirements for tritium depends on the chemical form of the labelled material, users of large quantities of H-3 (0.96 GBq or 26 mCi at a time) must consult with Radiation Protection Service to determine whether registration in the tritium bioassay program is necessary. All recorded uptakes are investigated to verify if safe work procedures are being followed and that the fume hood and experimental apparatus are working properly.

9.3.2.4 Actions Taken to Protect a Pregnant Worker

To protect the fetus, pregnant women working with radioactive materials should inform their supervisors in writing, indicating the expected date of birth. The supervisor will contact the university RPS and the following actions will be taken:

- An RSO will contact the pregnant worker and analyze the working procedures;
- An estimate of the dose for the remaining period of the pregnancy will be performed, with special attention to the possible internal and external irradiation of the abdomen;
- If a dose above 0.4 mSv is expected, a change in procedures will be recommended;
- If a change in procedures is not possible, it will be suggested that non-radioactive work be assigned to the worker until completion of the pregnancy;
- An electronic dosimeter may be issued to the worker who decides to continue to work with radioactive materials. The electronic dosimeter allows for direct reading (at any moment) of external dose;
- An action level is established for each specific case and communicated to the worker. In the event of reading above this action level, the worker must notify the RPS immediately.

9.3.3 Procedure for Disposal of Radioactive Materials

Radioactive waste can be characterized into different categories (described in further detail below). All radioactive waste must be segregated and disposed of into the proper containers. All material that is determined to be contaminated should be treated and disposed of as radioactive waste.

All efforts must be made to prevent the disposal of non-radioactive waste, such as paper and packaging, into the radioactive waste stream. The Environmental Protection Services technicians provide labs with radioactive waste supplies including jars, bags, and waste tags. Any request for waste supplies should be directed to the technicians by e-mail or by phone:

hazwaste.ehs@utoronto.ca Phone: 416 978-2050

9.3.3.1 Dry / Solid Radioactive Waste:

- Dispose of materials such as contaminated gloves, filter and auto-radiography paper, gels, and lead-free radioisotope source containers into the yellow solid radioactive waste container;
- Do not dispose of counting vials or free liquids in the solid waste container;
- Place broken glass and sharps into a durable box or securely wrap before disposing into the solid waste container to prevent puncture and potential injury to the Environmental Protection Services technicians;
- Complete the required information on the waste tag when disposing of solid waste.

9.3.3.2 Liquid Waste:

- Dispose of all liquids and buffers into the appropriate liquid waste containers;
- Complete the required information on the waste tag when disposing of liquid waste;
- Liquid radioactive waste is segregated into three categories (see below) to facilitate the "decay-in-storage" of shorter-lived radioisotope species;
- Dispose of mixed radioisotope liquid waste into the container designated for the longer-lived species.

9.3.3.3 Three Liquid Waste Categories / Containers:

1. **GREEN LABEL CONTAINERS**

   for isotopes with half-life < 30 days (i.e., P-32, P-33, I-131, Cr-51)

2. **BLUE LABEL CONTAINERS**

   for isotopes with half-lives > 30 days but < 90 days (i.e., S-35, Fe-59, I-125)

3. **YELLOW LABEL CONTAINERS**

   for isotopes with half-lives > 90 days (i.e., H-3, C-14, Ca-45)

9.3.3.4 Liquid Scintillation Vials:

- Collect used counting vials into a durable, leak-proof cardboard box, durable bags or lined buckets;

- Separate plastic and glass vials;
- Label with radiation tape, mark as "waste vials", and place beside the solid waste container;
- Vial waste does not need to be characterized for documentation purposes.

9.3.3.5 Animal Carcasses and Bedding:

- Identify a freezer or storage bin in a designated location that can be used for the storage of animal carcasses and bedding;
- Place waste materials into durable, leak-proof plastic bags;
- Complete the required information on the waste tags and notify the radiation service technicians of the storage location.

9.3.3.6 Lead Radioisotope Shipping Pots:

- Check lead shipping pots for contamination and deface radiation labels;
- Collect lead shipping pots into a durable box and label box with radiation tape - place beside solid waste container for pickup by the waste technicians;
- Clean the contaminated lead shipping pots and proceed like above;
- Lead shipping pots should be disposed of as radioactive waste only if they are contaminated and could not be cleaned.

9.3.3.7 Shipping Boxes:

- Check shipping boxes and packaging for contamination and deface radiation labels;
- Dispose of non-contaminated packaging as regular waste.

9.4 <u>Laboratory Compliance Checklist</u>

9.4.1 Signs, Labels and Housekeeping

- Make certain that the current radioisotope permit is posted in all designated radiation laboratories;
- All benches, equipment, containers and storage areas used for radioactive materials must be labelled with radiation tape or stickers;
- CNSC rule card must also be posted, along with the radioisotope permit, in all designated labs;
- The laboratory must be kept neat and tidy. Active areas for the use of radioactive materials must be free of extraneous equipment and supplies.

9.4.2 Lab Classification and Supervision

- All locations being used for handling or storing radioactive materials must be indicated on the permit;

- All radioisotopes in storage, and use, must be within delivery rate limits as indicated on the permit;
- The activity of isotopes handled on the bench and/or fume hood must be within laboratory designation limits;
- The permit holder or designate must be available to supervise. For any absence of more than a month, the permit holder must notify the RPS before leaving and inform the name of another permit holder who will be responsible during his/her absence.

9.4.3 Training and Knowledge

- All staff and students must have completed the U of T Radiation Safety Course before handling radioactive materials;
- Radioisotope users must demonstrate adequate knowledge of safe work practices and have a clear understanding of all regulatory requirements.

9.4.4 Security

- Laboratories must be locked when unattended;
- Storage areas must be secured or locked when unattended.

9.4.5 Food Prohibition

- Do not eat, drink, store food, smoke, or apply make-up in radioactive laboratories;
- There must be no evidence of food consumption or storage of food utensils or containers in designated radioisotope laboratories;
- There must be no disposal of food or food containers in laboratory waste receptacles.

9.4.6 Inventory

- All open sources of radioactive materials in use and storage must have corresponding inventory records. All new orders have an inventory record automatic generated by the EHS database;
- A separate inventory form must be prepared and maintained whenever an open-source is diluted, processed or separated into different products that are subsequently utilized;
- The radioisotope storage location and a unique identification number must be recorded on all inventory records;
- Daily usage, remaining quantities and final disposal dates must be recorded on the inventory forms;
- The Radiation Protection Service must be notified of any relocation of sealed sources or planned disposal;

- Inventory records must be kept for a minimum of three years.

9.4.7 Contamination Control and Detection Criteria

- Documented contamination surveys must be done within seven days of work with radioactive materials;
- Survey locations must be identified in contamination records and include all active benches, equipment and floors;
- A contamination results binder must be maintained in all permitted rooms;
- A copy of the contamination survey results must also be kept in shared radioisotope laboratories whenever open sources of radioisotope are used in these locations;
- Contaminated areas must be cleaned and re-monitored. Results from contamination clean-up must be recorded both before and after decontamination;
- The radiation survey technique must be appropriate and adequate for the type of isotopes used (meets the threshold criteria of 0.5 Bq/cm² for beta and gamma contamination and 0.05 Bq/cm² for alpha contamination)
- Survey meters must be calibrated annually and must be in good working condition. Instruments should be given pre-operational checks before each use (e.g., checking the battery)(link to operational checks)
- Liquid scintillation counters and well-crystal gamma counters should be routinely serviced and calibrated according to the manufacturer's specifications;
- Count and record a blank and standard (e.g. H-3, C-14) with each set of wipes;
- Monitoring records from LSC must be kept for a minimum of three years.

Dose rates due to fixed contamination that exceeds 2.5 μSv/h (0.25 mrem/h) must be posted (post the reading, the unit and the date and time of the reading)

9.4.8 Personnel Dosimetry

- Persons handling radioisotopes other than H-3, C-14 and S-35 of activity more than 50 MBq (1.35 mCi) must wear whole-body and ring dosimeters;
- The radiation badges must be stored away from any source of radiation;
- Radiation badges must be returned to the supplier for analysis on time.

9.4.9 Lab and Personnel Safety

- Areas used for work with radioactive materials must be properly identified, contained, prepared, and sequestered whenever possible;
- Appropriate shielding must be available and used properly when needed;
- Laboratory coats, gloves and other appropriate protective equipment must be worn by radioisotope users;

- Dose rates from any source exceeding 2.5 μSv/h (0.25 mrem/h) must be posted;
- The fume hood must be functioning properly;
- Laboratory necessities must be readily available (absorbent pads, wipe test paper, decontamination solution, etc.)

9.4.9.1 Bioassays

- Persons working with radio-iodine in quantities greater than 50 MBq (1.35 mCi) must participate in the thyroid bioassay program;
- Persons working with more than twice ALI quantities of radionuclides at a time without containment must participate in the urinalysis bioassay program (criteria is case specific)

9.4.9.2 Radioactive Waste Disposal

- All radioactive materials must be deposited into appropriate waste containers and the required information must be recorded on the waste tags;
- Radioactive waste containers must be adequately shielded or stored in a location that minimizes potential exposures to all personnel;
- Proper procedures for waste disposal must be followed at all times (i.e., sharps boxed or wrapped before being disposed of into solid waste container, liquid waste disposed of into appropriate liquid waste containers);
- Radiation symbols on lead/plastic pots or radioisotope containers must be defaced when re-used for non-radioactive work;
- Containers re-used to store radioisotope must be re-labelled with a description of the current contents.

9.4.10 Room Commissioning and Decommissioning

- A formal written request should be sent to the RPS for the addition of a new room to the radioisotope permit;
- An RSO will visit the room, fill in the commissioning form and submit it for review by the building manager or equivalent, to ultimately be approved by the Senior Radiation Safety Officer;
- After approval, the Permit Holder will be notified and a change to the permit will be implemented before work with radioactive materials commences in the new room;
- A formal written request must also be submitted to the RPS for room decommissioning;
- An RSO will visit the room to make certain that all radioactive materials have been disposed of, confirm contamination control by swipes and direct radiation monitoring, and remove all radioactive signs;

- A room decommissioning form will then be filled out by the RSO and approved by the Senior Radiation Safety Officer;
- After approval, the Permit Holder will be notified and a change to the permit will be implemented.

9.4.11 Inventory and Leak Testing of Sealed Sources

- A detailed inventory of all sealed sources is kept for each permit by the Permit Holder as well as by the RSO in charge of sealed sources;
- Any sealed source over 50 MBq (1.35 mCi) must be tested for leakage every year. It must be tested every two years when in storage and immediately before used again.

9.4.12 Decommissioning of Devices with Radioactive Sources

- A formal written request must be sent to the RPS;
- The RPS will arrange to remove and dispose of any radioactive source from the device;
- An RSO will conduct a contamination check of the device;
- A formal report will be sent to the Permit Holder and records of the device decommissioning will be kept in the RPS files;
- The permit will then be amended.

9.4.13 Decommissioning of Instruments and Furniture used for Radioactive Work

- A formal written request must be sent to the RPS;
- An RSO will conduct a contamination check of the object;
- A formal report will be sent to the Permit Holder and records of the decommissioning will be kept in the RPS files.

Chapter 10: RADIATION SAFETY FOR X-RAY UNITS

10.1 Nature of Analytical X-rays

Analytical X-ray instruments produce intense beams of ionizing radiation that are used for diffraction and fluorescence studies. At U of T, there are also numerous X-ray producing machines for medical and/or dental applications.

The part of the beam that corresponds to the shell (K, L, M, etc.) emission of the target material is called characteristic x-ray radiation. In addition to the characteristic radiation, a continuous radiation spectrum is produced, ranging from very low energy to the maximum setting. Undesirable parts of the x-ray may be filtered out using cones, diaphragms and collimators.

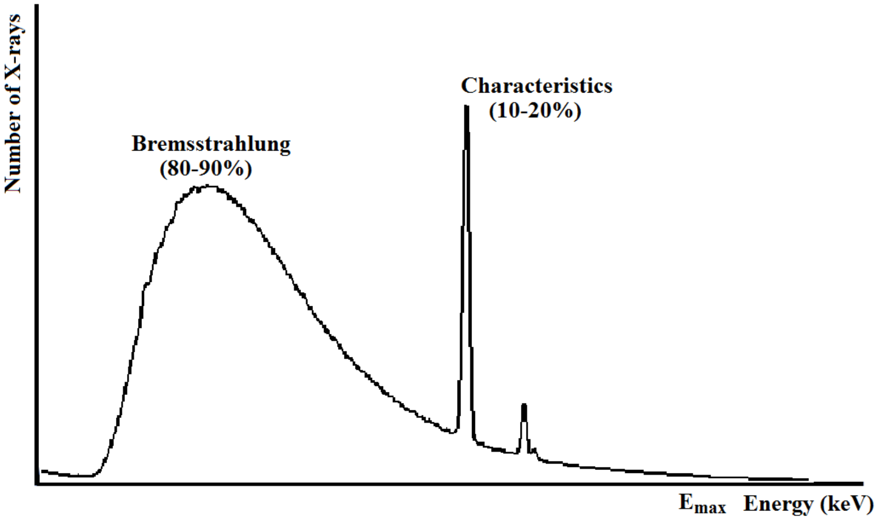


Fig. 10-1: Typical X-ray spectrum

The primary beam of the x-ray machine is not the only source of ionizing radiation. Any high voltage discharge is a potential source of X-rays. Faulty high-voltage vacuum-tube rectifiers may emit X-rays of twice the voltage applied to the X-ray tube. Other sources of ionizing radiation are:

- Secondary emissions and scattering from the sample, shielding material, and fluorescent screens
- Leakage of primary or scattered X-rays through gaps and cracks in shielding
- Penetration of the primary beam through or scattering from faulty shutters, beam traps, or collimator couplings

X-rays emitted from an open, un-collimated port form a cone of about 30 degrees. A collimator can reduce the beam size to about a 1-millimetre diameter.

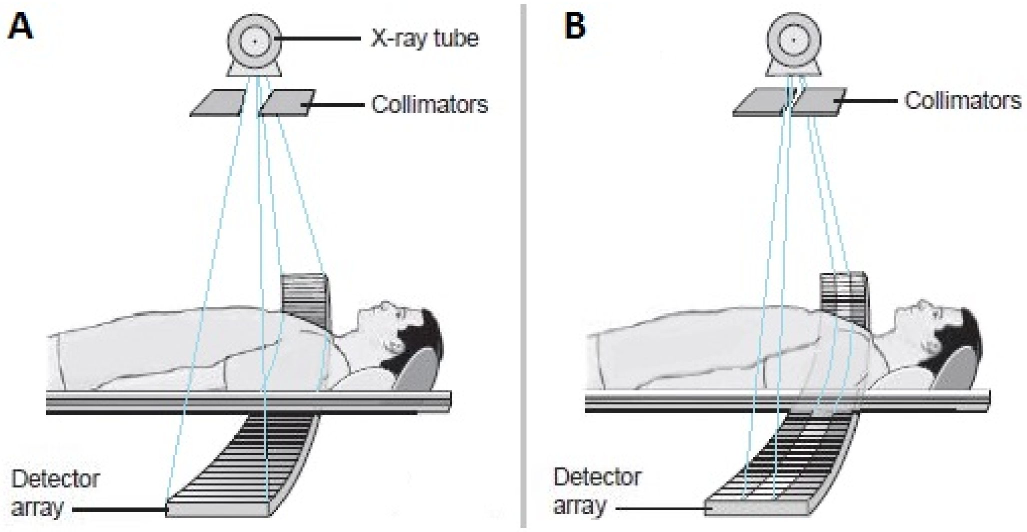


Fig. 10-2: Collimator

10.2 <u>X-ray Hazards and Biological Effects</u>

X-rays produced by diffraction machines are readily absorbed in the first millimetres of tissue, and therefore do not contribute any dose to the internal organs of the body. However, the lens of the eye can receive a significant dose from X-rays of this energy. Overexposure of lens tissue can lead to the development of lens opacities and cataracts.

An absorbed dose of a few grays may produce a reddening of the skin (erythema) which is transitory. Higher doses to the skin - 100 Gy and greater - may produce significant cellular damage resulting in pigment changes and chronic radiation dermatitis. Exposure to erythema doses may not result in immediate skin reddening. The latent period may be from several hours to several days.

X-rays used for medical purposes are about one order of magnitude shorter in wavelength. Diagnostic rays are designated for tissue penetration and are carefully filtered to avoid X-ray damage to the skin caused by the longer, more readily absorbed wavelengths.

10.3 <u>Safety Precautions, Shielding</u>

A calculation code for the shielding of X-ray beams (primary and secondary barriers) for controlled and non-controlled areas for open-beams equipment can be found at

https://ehs.utoronto.ca/our-services/x-ray-safety/x-ray-barriers/

Precautions are necessary when working with X-ray machines.

Before the removal of shielding or before beginning work in the sample area, the operator must check both the warning lights and current meter on the console or computer. The best way to avoid accidental exposure is to turn the machine off before working in the sample area.

Normally, the new cabinet enclosed equipment has interlocks installed so, when the door is opened, the X-ray production is immediately turn off.

Never put any part of the body in the primary beam. Exposure of any part of the body to the collimated beam for even a fraction of a second may result in damage to the exposed tissue.

If an instrument malfunction is suspected, the machine should be turned off and unplugged. A notice should be placed on the control panel until the instrument is repaired. A qualified person must perform all repairs. Alignment procedures also require special training and knowledge. Such service to X-ray emitting devices must be reported to the Radiation Protection Service.

10.4 Eye Protection

The use of safety glasses is encouraged when working with analytical X-rays. While glasses cannot provide complete protection to the eyes, they can reduce X-ray exposure. Glass provides about 10 times the protection of plastic but neither one will adequately protect the eye from direct exposure to the primary beam.

10.5 Tube Status Indicators

There must be a visual indication located on or near the tube head to indicate when X-rays are being produced. This is usually an assembly consisting of two red bulbs, wired in parallel and labelled X-RAYS ON. If one of the bulbs is burned out, the operator should either replace it before leaving the room or leave a note on the light assembly indicating that the bulb is burned out. An unlit warning bulb does not necessarily mean that X-rays are not produced. Never trust a bulb, unless it is illuminated **ON**! Always check the control panel or the computer when the bulb is off.

Fig. 10-3: A warning light

10.6 Safety Devices - Interlocks

Interlock switches are used to prevent inadvertent access to the beam. They should not be bypassed. Interlocks should be checked periodically to ensure that they are functioning properly.

Interlocks and other safety devices, including warning systems, are not foolproof or fail-safe. A safety device should be used as a backup to minimize the risk of radiation exposure, never as a substitute for proper procedures and good judgement.

10.7 Registration of X-ray Instruments

Users of X-ray-producing devices on U of T campuses (or in areas that are controlled by the U of T) must register their instrument with the University RPS. Registration is necessary for the reporting requirements of the Ontario Ministry of Labour (MOL) and the Ministry of Health.

The following information is required for registration:

- Type of device (dental, crystallography, fluorescent, medical, etc.)
- Name of Manufacturer
- Model of the device
- Serial number
- Maximum voltage
- Maximum current
- Building and room number where the instrument is located
- Department to which the instrument belongs
- Name and telephone number of the person in charge of the instrument

More information about the U of T X-ray safety program can be found at https://ehs.utoronto.ca/x-ray-safety-program

Chapter 11: U of T EMERGENCY PROCEDURES

11.1 Emergency Response Procedure for Radioactive Material Spill

The most common radiation emergency when working with open sources is a spill. When a spill of radioactive material occurs, an important consideration must be given to the prevention of the spread of the material. All spills of radioactive material must be cleaned up immediately.

11.1.1 Spill on objects

When a spill of radioactive material on objects occurs, the following steps must be taken:

a. **Injuries first**

First aid to the injured persons takes precedence over the spill cleaning. When emergency personnel arrives, advise them about the radioactive materials involved.

b. **Alert Everyone in the Area**

Ensure that everyone near the accident has been alerted. Mark the area and post a sign if necessary, to prevent anyone from walking on the spilt material.

c. **Confine the Spill**

Take action to prevent the spread of the material. If the material is dry, lightly dampen it. If it is wet, cover it with dry absorbent.

d. **Clear the Area**

Remove all persons from the vicinity of the spilt material. Minimize movement in the area.

e. Decontaminate

Apply decontamination procedures in this order: personnel, laboratory, and equipment

f. **Summon Aid**

If there is any doubt about cleaning up the spill, the spill involves more than 100 Exemption Quantities (EQ) of radioactive material, contamination of personnel, or release of volatile material, contact the Radiation Protection Service.

During normal working hours:	**416 978-2028**
Nights & Weekends:	
St. George Campus	**416-978-2222**
The University of Toronto at Mississauga	**905-569-4333**
The University of Toronto at Scarborough	**416-978-2222**
Aerospace (UTIAS) campus	**416-978-2222**

State:

- your name, phone number, location (building & room)
- that the accident involves radioactive material

- if there are any injuries

Wait for assistance to arrive.

11.1.2 Spill on a person

If a person is suspected of being contaminated with radioactive material, complete the following:

- immediately assess the location and extent of the contamination
- use appropriate monitoring procedure, to locate the material and provide an assessment of the amount
- remove any contaminated clothing, place in a plastic bag, labelled as to contents, tape shut
- monitor to determine if any skin contamination has occurred, its location and the extent
- if contamination involves I-123, I-124, I-125 or I-131 contact RPS for a thyroid screening

If contamination of the skin is identified, notify the permit holder and RPS immediately. If necessary, the SRSO or his/her delegate will inform the CNSC immediately and will prepare and send a report to the CNSC within 21 days.

If the skin is intact proceed as follows:

- flush contaminated area with copious amounts of warm water
- wet hands and apply mild soap or detergent, lather well with plenty of water
- wash for 2 to 3 minutes and rinse thoroughly, keeping rinse water confined to the contaminated area as much as possible
- monitor the effectiveness of removal by use of appropriate survey techniques
- repeat wash/rinse procedure if necessary
- if further washing does not remove the contamination, contact the RPS.

11.2 Emergency Response in Case of an Intake of Radioactive Material

As described in item 4.6 an internal irradiation of a person occurs in case of an intake of radioactive material. There are 3 major principal pathways for radioactive materials to enter the body: ingestion, inhalation and through the skin.

Ingestion can be the result of not following the rules regarding the food and drinks in the radioactive laboratories. In this case, food or drinks may be contaminated with radioactive materials. Ingestion can also result when the gloves are not removed and the hands are not washed when finishing the radioactive work. In this case, contamination of the hands or gloves can be transmitted to the food or drink.

Inhalation can be the result of producing aerosols, vapours or fumes during radioactive work. When this is possible, the work must be performed in a fumehood or glove-box. It is also possible in case of a spill of a material with high volatility.

Penetration through the skin can happen as a result of a spill on a person or a cut.

If the radioactive material involved in the intake is chemically toxic as well as radioactive, treat for chemical toxicity first. Prompt medical attention is the best procedure. Personnel working with radioactive material should understand its chemical and radioactive properties to ensure that a prompt response to a suspected intake of material can be carried out.

If an intake of radioactive material is suspected contact RPS immediately and follow the instructions given by the Health and Safety Officer.

11.3 Emergency Response in Case of External Exposure to Radiation

External exposure to radiation may occur when working with high activity radiation sources or with open beam X-ray machines. The open sources used in the U of T laboratories are not high enough to cause significant external exposure. However, high activity sealed sources are present in some laboratories and especially in the irradiators. These sources are surrounded by large amounts of lead, iron and other high Z materials, diminishing the risk of radiation exposures.

In case of known exposure to external radiation coming from a radioactive source or an X-ray machine, the person must leave the area without crossing the radiation field, and contact the RPS immediately.

Chapter 12: GLOSSARY

A	B	C	D	E	F	G	H	I	J	L
M	N	O	P	Q	R	S	T	U	W	X

A

Absorption

The process by which radiation transfers some, or all, of its energy to the medium through which it is passing.

Absorbed Dose

Absorbed dose is a measure of the energy deposited by radiation in a certain material. The SI unit for absorbed dose is the gray (Gy). One gray is an absorbed radiation dose of 1 joule per kilogram. 1 Gy = 1 J/kg.

Absorption Coefficient, Linear (m)

The fractional decrease in the intensity of a beam of gamma or X-radiation as it passes through an absorbing medium. It is expressed per unit thickness of medium (usually cm^{-1}). The specific value of the linear absorption coefficient depends on the type of absorbing material, the energy of the gamma or X-ray, and the density of the absorbing medium. The value of m is used in the equation $I = I_0{*}e^{-mx}$; where I is the intensity of the radiation after passing through the material, I_0 is the intensity of incident radiation and x is the thickness of the absorber in the same base units as m (e.g.: when m is measured in cm^{-1}, x is measured in cm).

Absorption Coefficient, Mass (cm^2/g)

The mass absorption coefficient is obtained by dividing the linear absorption coefficient of a material by the density of the absorbing material. It is expressed in units of cm^2/g. The mass absorption coefficient is independent of the density of the material, while the linear absorption coefficient depends on the density of the material. For example, the mass absorption coefficient of water for 1.0 MeV gamma rays is 0.0707 cm^2/g. The linear absorption coefficient of water as liquid (at 20°C) is (0.0707 x 0.998234) = 0.0706 cm^{-1}; and for water as ice (at -20°C) is (0.0707 x 0.99349) = 0.0702 cm^{-1}.

Activation

The process of making a material radioactive by the absorption of neutrons, protons, photons, etc. in a material. Activation is used in a nuclear reactor to allow the analysis of very small amounts of material using the radiation given off during the decay process.

Activity

The rate of nuclear transformations or transitions occurring in a radioactive source. The SI unit of activity is the becquerel (Bq), which equals one disintegration per second.

Acute Effects

These effects usually appear shortly after exposure to high levels of radiation. Among these effects are inflammations of the skin, nausea and vomiting, blood changes, bone marrow damage, etc.

Alpha Particle (α)

A charged particle consisting of two neutrons and two protons. It is sometimes emitted from the nucleus of high atomic number elements during radioactive decay. The alpha particle is the nucleus of a Helium-4 atom. Due to the +2 charge, it causes ionizations along its path length. An alpha particle will travel a few centimetres in air and is stopped by a sheet of paper or the skin's layer of dead cells.

Annihilation Radiation

The radiation is emitted as a result of the interaction of a positron (positively charged beta particle) and an electron (negatively charged beta particle). The annihilation of these particles results in the disappearance of the two particles and the formation of two gamma photons each of 0.511 MeV, moving in opposite directions.

Annual Limit on Intake (ALI)

An ALI is the amount of activity of a radioisotope, measured in becquerel (Bq), which if ingested or inhaled, will result in a maximum committed dose of 20 mSv in a "reference person" for the next 50 years.

Anti-neutrino, Electron

Elementary particle without rest mass accompanies beta minus (electron) particles during disintegration. The electron anti-neutrino shares energy with the electron, which is why the beta energy spectrum is continuous.

As Low As Reasonably Achievable (ALARA)

It is the principle of radiation protection demanding that the number of people exposed, and the magnitude of their doses should be kept as low as reasonably achievable (ALARA), taking into account economic and social factors (optimization of protection)

Atom

Greek origin (atomos = indivisible), the atoms are the fundamental building blocks of matter. Contrary to their names, atoms have structure. The heavy nucleus is surrounded by lighter electrons moving around in shells.

Atomic Number (Z)

The number of protons in the nucleus of an atom. The atomic number determines the chemical properties of the element. Atoms with the same atomic number but with different numbers of neutrons are called isotopes.

Atomic Mass Number (A)

The total number of neutrons and protons in the nucleus of an atom.

Attenuation

The reduction in the intensity of radiation when is absorbed in a medium as it passes through it

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B

Background Radiation

Radiation arising from natural sources in the environment. The main sources of ionizing radiation in the environment are radon gas in the air, radiation from rocks and soil, radiation from ingestion (food and water) and cosmic radiation. The annual effective dose from all-natural radiation sources in Toronto, Ontario, is approximately 1.59 mSv.

Becquerel (Bq)

The SI unit of radioactivity. 1 Bq is equivalent to 1 disintegration per second.

Beta Particle (β)

A charged particle is emitted during a beta disintegration. It has a mass equal to 1/1837 of the mass of the proton and an electrical charge equal in value. When its electrical charge is negative, it is called an electron. When the electrical charge is positive, it is called a positron.

Bioassay

The assessment of the uptake of radioactive materials into the body. Two methods are available, in vitro and in vivo. The former involves taking a specimen, usually a fluid such as urine, and measuring the radioactivity in it by use of a suitable counter. The material is assessed externally to the body. In vivo techniques involve placing a radiation monitor near the body and measuring the radioactivity being emitted from radioactive material within the body. An example of this is the use of a detector placed near the thyroid to measure uptake of I-125 by counting the gamma radiation emanating directly from the gland.

Bremsstrahlung

A phrase derived from the German language means "braking radiation". When a charged particle (generally referring to beta particles) passes close to a nucleus, a change in the velocity of the particle will cause a loss of the particle’s energy by electromagnetic radiation. The bremsstrahlung photons have a continuous spectrum of energy distribution below the maximum kinetic energy of the charged particle. The likelihood of bremsstrahlung production increases with the atomic number of the absorbing material. Therefore, it is better to use low Z materials for protection against beta radiation.

C

Calibration

The process of determining the efficiency of equipment used for radiation monitoring. The response of the instrument to a source of known activity is measured. The resulting efficiency is used to determine unknown activities.

Carcinogenic

The ability of a material to cause cancer, whether it is chemical, biological or physical. β-naphthylamine is an example of a carcinogenic chemical and ionizing radiation is an example of a carcinogenic physical agent.

CNSC

Acronym for the Canadian Nuclear Safety Commission, the federal agency regulating the possession and use of radioactive materials in Canada.

Committed Dose

The total equivalent and effective radiation dose received from a radioactive substance in the body during the 50 years following the intake of that substance for adults, or to the age of 70 for children.

Contamination (Radioactive)

Radioactive material is deposited on a surface or in a medium where it is not wanted. Surface contamination is monitored directly with portable instruments or indirectly through the use of the swipe test.

Counter, Scintillation (also Liquid Scintillation Counter or LSC)

An instrument designed to measure very small amounts of radioactivity, generally from negative beta decay. It involves placing the radioactive material in a vial containing a scintillation fluid. As the radiation is given off, it interacts with the fluid and causes excitation of the molecules. Organic compounds in the mixture convert the excitation energy to fluorescence. The light emitted during the fluorescence is detected by photomultiplier tubes positioned outside of the vial. The signal from the photomultiplier tubes is processed and then converted into counts per minute. Because the radioactive material is intimately mixed with the primary detector – the scintillation fluid, detection efficiency for low energy beta emitters is much higher than with other means of detection.

Curie (Ci)

The former unit for expressing activity. The curie was originally based on the decay of 1 gram of radium and is equivalent to 37 billion disintegrations per second. More common units are the millicurie (mCi) and the microcurie (μCi). This unit is being replaced by the SI unit known as the becquerel (Bq). One mCi is equivalent to 37 MBq.

D

Daughter nucleus (Progeny)

The resulting nucleus of the radioactive decay. Sometimes an unstable nucleus, itself a daughter nucleus, can suffer radioactive decay becoming a parent nucleus for this new radioactive process. In these cases, parent and daughter nuclei form a radioactive decay series.

Decay Constant (λ)

The fraction of the number of atoms of a radioisotope that decay in a unit of time. It is expressed as the reciprocal of time (e.g. seconds^{-1}) and is related to the half-life by the following equation:

$$\lambda = \frac{\ln 2}{t_{1/2}} \quad \text{or} \quad \frac{0.693}{t_{1/2}}$$

Decay, Radioactive

The nuclear transformation of a parent nucleus resulting in a progeny nucleus. During this process, the emission of particles and/or electromagnetic energy can occur. This is also called disintegration.

Decision Limit

A statistical tool is applied to identify whether a radiation measurement is within the background or not. It is also used to calculate the minimum detectable activity (MDA) for the method/instrument used to perform the measurement.

Decommissioning

Actions which are taken in the interest of health, safety, security and protection of the environment, to retire a nuclear facility permanently from service. May also be used to refer to the cleaning of a radioisotope laboratory, equipment, furniture, etc., so that it may be removed from a radioisotope permit.

Delay and Decay

The storage of radioactive waste containing radionuclides with short half-lives for a sufficient time to enable their unrestricted discharge to the environment when their final activity level is below regulatory limits.

Delayed Effects

These effects appear much later after exposure. They can arise from repeated exposures to relatively low levels of radiation, or single exposure to higher levels of radiation. For example different forms of cancer, life-shortening, cataracts, genetic effects, etc.

Deterministic Effects

See Non-stochastic Effects.

De-excitation

The process by which an excited system releases energy to achieve a more stable state.

Disintegration

See Decay, Radioactive.

Disposal, Waste

The permanent and secure containment of radioactive wastes, with no intention to retrieve them.

Dose, Absorbed (see Absorbed Dose)

Dose, Artificial

The dose is received by a person from artificial sources. In Canada, the CNSC imposes a limit of 1 mSv/yr for the public from artificial sources other than for medical purposes. The main contributor to artificial dose for the average Canadian is medical exposure.

Dose, Effective

The tissue weighted sum of the equivalent doses in all specified tissues and organs of the body, given by expressions: E = $\sum_T W_T \sum_R W_R D_{T,R}$ or E = $\sum_T W_T H_T$ where H_T is the equivalent dose in a tissue or organ, and W_T is the tissue weighting factor. The unit for the effective dose is the same as for the unit for absorbed dose, J*kg^{-1}, and its special name is the sievert (Sv)

Dose, Equivalent

The dose in a tissue or organ T given by $H_T = \sum_R W_R D_{T,R}$, where D_{TR} is the mean absorbed dose from radiation type R (alpha, beta, gamma, neutrons, etc.) in a tissue or organ T, and W_R is the radiation weighting factor. Since W_R is dimensionless, the unit for equivalent dose is the same as the unit for absorbed dose, $J*kg^{-1}$, and its special name is the sievert (Sv)

Dose, External

The dose received by a person when the radiation source is situated outside his/her body. Radiation badges are used to measure the external dose. Protection against external exposure is achieved by applying the principle of time, distance and shielding.

Dose, Internal

The dose received by a person from a radioactive material that entered the body. Bioassays are used to measure internal exposure. Inhalation and ingestion of radioactive materials can be prevented by following laboratory rules and good work practices.

Dose Limits

It is the principle of radiation protection demanding that the total dose to any individual from regulated sources in planned exposure situations, other than medical exposure of patients, should not exceed the appropriate limits established by the government.

Dose, Natural

The dose received by a person from natural sources. Natural irradiation is both internal and external. The natural dose from background radiation in Canada is around 2 mSv/yr. The natural dose can vary by a factor of more than 10.

Dose Rate

The dose received by an individual per unit of time $Jkg^{-1}s^{-1}$. When referring to the effective dose, the unit of measure can be Sv/hr, mSv/day, etc.

Dosimeter

A device used to measure and record the dose of radiation to which a person has been exposed. There are whole body, extremity, skin dosimeters, etc.

Dosimetry

The process of finding the radiation dose. Carried out by either practical measurements or theoretical evaluation.

DPM

Acronym for disintegrations per minute.

E

Efficiency (Counter)

The ratio between the number of counts registered by the instrument and the number of disintegrations of the radioactive source. Efficiency is usually expressed as a percentage. It is a function of the geometry and design of the detector, as well as the internal electronics. It also depends on the type and energy of radiation being monitored.

Electron Capture (EC), Orbital

An unstable proton-rich nucleus may capture an orbital electron (as an alternative to beta plus disintegration) to solve the instability. The electron from the inner shell will react with a proton, changing the nucleus into one with a lower Z number (decreased by 1) in an excited state. During the process, a neutrino is also emitted. From the rearrangement of electrons in the new atom, X-rays will be emitted. The excited daughter/progeny nucleus can get rid of the energy by gamma emission or by internal conversion.

Electron Volt (eV)

A unit of energy. It is commonly used for expressing the energy of particles and/or electromagnetic radiation emitted during radioactive decay. It is the amount of energy gained by an electron travelling through a potential difference of one volt. Common multiples include the kilo electron volt (keV) and the Megaelectron volt (MeV).

Element, Chemical

All atoms belonging to a chemical element have the same atomic number Z (the same number of protons) and the same number of electrons. They all have the same chemical properties and occupy the same position in the periodic table of elements. All atoms forming a chemical element are called isotopes of that element. There are more than 105 different chemical elements.

Equivalent Dose

See Dose, Equivalent

Erythema

Reddening of the skin caused by exposure to radiation. The skin erythema dose (SED) was a unit of radiation exposure in the early part of the 1900s. It is due to the dilation of the capillaries in the skin and occurs with exposure to ionizing radiation doses of about 10 Sv to the skin.

Excitation

The unstable state of an atom or a nucleus caused by external agents or by radioactive decay. When caused by external agents, the system (atom or nucleus) absorbs energy from the surroundings. An excited system, sooner or later, undergoes the process called de-excitation.

Exposure Dose

The measure of ionization produced in air by gamma or X-radiation. Originally measured in röntgens (R), the current SI equivalent is coulomb per kilogram of air. 1C/kg = 3876 R.

Exposure, Acute

Exposure to a high dose during a short time may produce biological effects within a short period after exposure.

Exposure, Chronic

Continuous exposure to radiation for long periods may cause delayed effects.

F

Fission Reaction

The nuclear reaction resulting in the splitting of a heavy nucleus into two or more nuclei. Accompanied by particles (usually 2 or 3 neutrons) and gamma-ray emissions. The resulting nuclei and accompanying radiation carry large amounts of energy (approximately 200 MeV at the fission of a U-235 nucleus). Can be spontaneous or provoked by neutron absorption. Under certain conditions, neutron production and consumption can sustain the reaction (chain fission reaction). It is used in energy production (in nuclear reactors) or for military purposes (atomic bombs).

Fusion Reaction

The nuclear reaction resulting in the unification of two light nuclei to obtain a new nucleus. Accompanied by particles and energy emission. It is the reaction that produces energy in stars. Still, at the experimental stage for energy production, it is used for military applications (so-called "hydrogen bomb").

G

Gamma Ray (γ)

An energetic photon emitted from the nucleus during radioactive decay. The energy spectrum of gamma rays is discrete. Protection from gamma radiation requires lead or concrete shielding. Gamma radiation usually accompanies other types of decay.

Geiger Müller Tube (G-M tube)

The main component of most commonly available radiation detection instruments. It consists of a hollow tube filled with a gas and contains a central electrode running parallel to the length of the tube. The shell of the tube forms the other electrode. The tube is held at a high potential voltage, approximately 800-1200 volts and radiation passing through the gas will cause it to become ionized. The ionization is amplified and detected by the supporting circuitry. The G-M tube may also have a small amount of material wrapped around it to improve its response over a wide range of radiation energies and is known as an energy compensated detector. If the end of the tube is made of a thin material such as mylar, it is called a thin end window detector and the G-M tube can be more sensitive to some alpha and beta radiation.

Genetic Damage

Damage caused to genes in cells that are part of the reproductive organs. Genetic damage does not affect the current generation but may be passed on to future generations.

Gray (Gy)

The SI unit of absorbed dose. It is equivalent to one joule per kilogram. Used to measure deterministic (organ or tissue) effects of radiation.

H

Half-life, Physical

The characteristic time taken for the activity of a particular radioactive material to decay to half of its original value; that is, for half the unstable atoms initially present to disintegrate.

Half-life, Biological

The characteristic time required for the amount of a substance to be reduced to one-half of its initial value from metabolism alone. The biological half-life of a radionuclide does not depend on the radioisotope but on the organ or body system in which the material is deposited, as well as the chemical properties of the radioactive material.

Half-life, Effective

The characteristic time required for radioactive material to be eliminated from a biological system through a combination of the physical and biological removal processes. The effective half-life is a mathematical combination of the physical and biological half-lives of the particular radioisotope.

Half-Value Thickness (HVT)

The thickness of shielding material that is required to reduce the intensity of a given type of radiation to one-half of the original amount. Related to the tenth value thickness (TVT).

Health Physics

The branch of science dealing with radiation protection. It arose as a result of the development of the atomic bomb in the Manhattan Project. There is some suggestion that the phrase arose as a result of the need for secrecy surrounding the development of the bomb. Supposedly, words associated with radiation could not be used and so it was decided to call the field health physics. Persons working in the field of radiation protection may also be referred to as health physicists.

I

IAEA

Acronym for the International Atomic Energy Agency. It is an international body within the United Nations that provides advice and assistance to the member nations on the use of radioactive materials.

ICRP

Acronym for the International Commission on Radiological Protection. Originally known as the International X-ray and Radium Protection Committee founded in 1928, it was reorganized in 1950 to become the ICRP. It is composed of a Chair and not more than 12 members chosen based on their expertise in specific areas without regard to nationality. The ICRP publishes recommendations on radiation protection that are usually the basis of legislation for radiation protection.

Inverse Square Law

The relationship between distance and intensity for gamma and X-radiation. The intensity from a point source is inversely proportional to the square of the distance from the source.

Internal Conversion (IC)

An excited nucleus transmits its energy to an electron from an inner electronic shell (usually K or L). The electron is ejected from the atom carrying the de-excitation energy. The IC electrons are mono-energetic, therefore, they differ from beta minus electrons by both origin and energy spectrum. The IC process is always accompanied by X-ray emissions. IC is an alternative mechanism for gamma emission.

Ion

An atomic particle, atom or chemical radical that carries a net electrical charge, either positive or negative.

Ionization

The process by which electrons are removed or added to atoms to create ions. Radiation that possesses enough energy to remove orbital electrons is called ionizing radiation.

Ionization Chamber

A chamber used for the measurement of radiation exposure. Similar to a Geiger Müller tube, it is operated at much lower electrical potentials. The fundamental principle of gas ionization by radiation still applies but since the potential voltage is not as high, the amount of amplification in the tube is small. Generally used for personal dosimeters and standardization instruments.

Irradiation

The exposure of a material to radiation.

Isotopes

Atoms with the same atomic number (number of protons in the nucleus) but having different atomic mass numbers (because of different numbers of neutrons in the nucleus). Chemically, isotopes of a given element all behave the same although some may be radioactive.

J

Justification

It is the principle of radiation protection demanding that any decision that alters the radiation exposure should do more good than harm.

L

Labelled Compound, Radioactive

A molecule that has had one of its atoms replaced by a radioactive isotope. Once labelled, the path of the molecule can be traced through a biological system.

Latent Period

The period between the exposure to radiation and the expression of radiation injury. Generally applied to cancer induction from chronic radiation exposure, the latent period can be anywhere from 5-10 years for leukemia, to 20-30 years for other types of cancers.

Linear Energy Transfer (LET)

A measure of the rate at which an energetic particle transfers energy to the surrounding medium. Alpha particles have a high LET, while beta particles have a lower LET. The unit for LET is $J*m^{-1}$ or $keV*\mu m^{-1}$.

Linear-non-threshold (LNT) model

A dose-response model which is based on the assumption that, in the low dose range, radiation doses greater than zero will increase the risk of excess cancers and/or heritable disease in a simple proportional manner.

M

Minimum Detectable Activity (MDA)

MDA is a characteristic of the instrument or measurement method. It indicates the instrument's (or method) limitation to detect radioactive material.

N

Neutron

A nuclear particle having a mass similar to a proton but having no electrical charge. During negative beta decay (β^-), a neutron disintegrates into a proton, an electron and an anti-neutrino which are then ejected from the nucleus. Neutrons can exist outside of the nucleus and have a high potential for radiation damage since they lose energy in biological materials through scattering. Shielding for neutron sources involves using materials containing large amounts of hydrogen.

Neutron Emission

Accompanies a fission reaction or other type of nuclear reaction. Depending on the type of reaction, the energy spectrum can be discrete or continuous.

Neutrino

Elementary particle without rest mass which accompanies beta plus (positron) particles during disintegration. The neutrino shares energy with the positron giving a continuous beta energy spectrum. It is also emitted during electron capture.

Non-Stochastic Effects (Deterministic Effects)

Injury in a population of cells, characterized by a threshold dose and an increase in the severity of the reaction as the dose is increased. Also termed tissue or organ reaction. An example of a non-stochastic effect is cataract formation in the lens of the eye.

Nuclear Energy Worker (NEW)

A person who, during occupational work, is likely to receive a dose of ionizing radiation above the exposure limit allowed for members of the general public.

Nuclear Reaction

A reaction involving one or more nuclei resulting in the creation of one or more new nuclei. Usually accompanied by particles (electrons, protons, neutrons, alpha, etc.) and /or gamma-ray emissions.

Nuclide

A general term referring to all isotopes of an element.

O

Optimization of Protection

It is the principle of radiation protection demanding that the number of people exposed, and the magnitude of their doses should be kept as low as reasonably achievable (ALARA), taking into account economic and social factors

P

Parent Nucleus

The original nucleus in a radioactive decay.

Permit Holder

A person who is issued a permit under the university's licence. Must be approved by the UTRPA. Permit Holders are held responsible at all times for all aspects of radiation safety in areas under their supervision.

Photon

A quantum of energy emitted in the form of electromagnetic radiation. Gamma photons originate in the nucleus and X-ray photons originate in electronic shells and from the bremsstrahlung process.

Point Source

A source of radiation, the physical size of which is small by comparison with the distance at which the radiation is monitored. The radiation can be considered to arise from a single point.

Positron (β+)

A positively charged electron, emitted from the nucleus during some forms of radioactive decay. A positron will combine with an electron (β-) and result in the production of annihilation radiation. See also Beta Particle.

Principles of Radiation Protection

The current philosophy in radiation protection is covered by three principles: justification, optimization (ALARA) and dose limits.

R

Radiation

The emission and propagation of particles and electromagnetic rays. Generally used to refer to ionizing radiation.

Radiation Badge

A personal dosimeter that uses solid crystals to monitor radiation absorbed dose. Typically, these crystals are composed of lithium fluoride (LiF) and exhibit radiation absorption characteristics similar to that of human tissue. The ionizing radiation produces small local crystal defects which are stable until the crystal is heated. When the crystal is heated to temperatures of approximately 200°C, the defects are removed and the associated energy is released in the form of light. The amount of light produced is proportional to the number of induced crystal defects which in turn is related to the amount of absorbed radiation.

Radiation, Ionizing

Radiation which removes orbital electrons from atoms, or breaking the molecular bonds, thus creating ion pairs. Alpha and beta particles are more densely ionizing than gamma rays or X-rays of equivalent energy.

Radiation Protection Service (RPS), U of T

It is an administrative service within the U of T Office of Environmental Health and Safety which carries out the daily operation of the radiation safety program, as directed by the UTRPA.

Radiation Weighting Factor, W_R

A dimensionless factor by which the organ or tissue absorbed dose is multiplied to reflect the higher biological effectiveness or high-LET radiation compared with low-LET radiation. It is used to derive the equivalent dose from the absorbed dose averaged over a tissue or organ.

Radioactive Decay Series

Two or more radioactive decay processes in which the daughter nucleus serves as a parent nucleus for the next process. There are four natural radioactive decay series and large numbers of artificial ones.

Radioactive Isotope

An unstable nucleus which undergoes a nuclear transformation.

Radioactive Material

A substance containing unstable nuclei exceeding a certain concentration limit. It is also called a **prescribed radioactive substance**, **radioactive nuclear substance** or **nuclear substance**.

Radioactivity

The property of a certain nuclide to spontaneously emit particles or gamma or X-radiation following a nuclear transformation.

Radioisotope (Radionuclide)

A radioactive isotope.

Radioisotope User

A person using radioactive materials. He/she has specific responsibilities under different acts and regulations to ensure that work with radiation does not create a hazard to themselves, to others and the environment.

Radiosensitive

Sensitive to the effects of irradiation, principally applied to biological systems. Cells of the body which are easily damaged by exposure to ionizing radiation are termed radiosensitive.

Radiotoxicity

The term referring to the potential of a radioisotope to cause damage to living tissue by the absorption of energy from the disintegration of the radioactive material that is within the body.

Reference Man

A standard model of a human being, developed by the ICRP and detailed in ICRP Report #23. The characteristics of standard man are used when specific body information is not available for dosimetry purposes.

Regulatory Dose Limit

A legal limit on radiation dose specified in the Canadian Nuclear Safety Regulations.

Röntgen Equivalent Man (rem)

The older term used to describe equivalent and effective dose. The SI unit is the Sievert (Sv). 1 Sv = 100 rem.

Röntgen, also spelled Rœntgen or Roentgen (R)

Named after Wilhelm Röntgen, it is a unit of radiation exposure. Useful submultiples include the milliröntgen (mR) and the microröntgen (μR). This is gradually being replaced by the SI equivalent which is *coulomb per kilogram of air*.

S

Sealed Source

A radioactive source sealed in a container or having a bonded cover, the container or cover being strong enough to prevent contact with and dispersion of the radioactive material under the conditions of use and wear for which it is designed.

Shielding

The use of absorbing material between a source of radiation and the detector or recipient. Shielding absorbs radiation and reduces the intensity of the incident radiation. Shielding is chosen based on its effectiveness for a given type of radiation, its cost and other physical attributes.

SI

Acronym for Système International is the international system of units of measurement.

Sievert (Sv)

The SI unit for equivalent and effective dose. It is gradually replacing the rem. **1 rem = 0.01 Sv**. Used to measure stochastic effects – radiation-related cancer and heritable effects.

Somatic Injury

Injury to tissues of the body other than the reproductive organs. The somatic injury affects the current generation but is not passed on to future generations.

Specific Activity (Specific Radioactivity)

The activity of a radioactive material divided by its mass, volume, surface, etc.

Spectrometry (Spectroscopy)

The process of identifying an unknown nucleus, atom, or substance by measuring the energy absorbed during excitation or emitted during de-excitation.

Spectrum, Energy

The distribution of the number of particles or electromagnetic rays counted by an instrument over a certain energy range. The spectrum contains the "signature" of the system (nucleus, atom or substance) and is used in spectrometry. For beta disintegration and bremsstrahlung X-rays, the energy spectrum is continuous, whereas for alpha, gamma and characteristic X-rays the spectrum is discrete.

Stochastic Effects

Malignant disease and heritable effects for which the probability of an effect occurring, but not its severity, is regarded as a function of dose without threshold

Survey Meter

An instrument used to measure radiation, typically radiation exposure dose. The instrument usually consists of an energy compensated Geiger Müller tube and associated circuitry which causes a meter's needle deflection or another readout in the presence of ionizing radiation.

Swipe Test

The process of measuring contamination by wiping a certain area (approx. 100 cm^2) of a surface with a filter paper and placing it in a vial with scintillation fluid for counting in a scintillation counter. The efficiency for the removal of non-fixed contamination with the filter paper is considered 10%.

T

Tenth-value Layer

This is the amount of shielding required to reduce the intensity of gamma or X-radiation to one-tenth of its initial value.

Tissue Weighting Factor, W_T

The factor by which the equivalent dose in a tissue or organ T is weighted to represent the relative contribution of that tissue or organ to the total health detriment resulting from uniform irradiation of the body. It is weighted such that: $\sum_T W_T = 1$

U

Uncertainty

The degree of accuracy of the measuring method and/or instrument. For radioactive measurements, the uncertainty is a sum of the uncertainty in the measurement of the sample, measurement of the background, and other possible sources.

University of Toronto Radiation Protection Authority (UTRPA)

A committee composed of academics and administrators appointed by the U of T Governing Council to exercise complete and all-embracing control of the radiation protection program within U of T jurisdiction.

W

Waste, Radioactive

Any material containing or contaminated with radionuclides in concentrations greater a certain value than would be considered acceptable for uncontrolled use or release, and for which there is no foreseen purpose.

X

X-ray

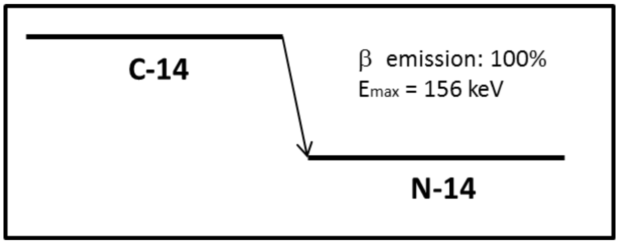
A form of electromagnetic energy that is produced external to the nucleus of an atom. Typically, X-rays may be produced when orbital electrons are rearranged (characteristic X-rays) or when accelerated electrons are slowed in the presence of a nucleus, such as during the production of bremsstrahlung. X-rays are similar to gamma-rays in the manner by which they are absorbed and shielded. However, whereas gamma rays have discrete energies and originate from the nucleus, X-rays can be emitted with both discrete and a broad spectrum of energies and originate outside of the nucleus.

Chapter 13: MOST COMMONS RADIOISOTOPES USED at U of T

13.1: Carbon-14

$^{14}_{6}\mathrm{C}$

Carbon-14



Radioactive Half-life: 5730 years

Decay mode: beta – 100%

Principal emissions: beta

Maximum beta energy: 156 keV

ALI:

a) Ingestion: 34 MBq/y

b) Inhalation: 1000 MBq/y

Max. beta range in the air: 240 mm

The appropriate method for contamination monitoring:

Liquid scintillation counter

Shielding material: Total absorption in 0.2 mm glass or 0.3 mm plastic

Dosimetry: Urine analysis for those that use 68 MBq (1.84 mCi) or more volatile liquids or gases at a time, without containment

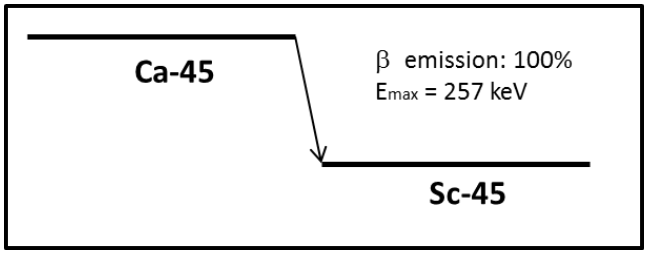
Special precautions:

1. Recommended protective clothing:
    - Disposable lab coat, gloves (select gloves appropriate for chemicals handled) and wrist guards.
    - Some organic compounds can be absorbed through gloves therefore wear two pairs of gloves and change the outer layer frequently.
2. Use disposable absorbent liners on trays.
3. Be careful not to generate carbon dioxide and handle potentially volatile or dusty compounds in a fume hood.

13.2: Calcium-45

$^{45}_{20}\mathrm{Ca}$

Calcium-45



Radioactive Half-life: 162.61 days

Decay mode: beta – 100%

Principal emissions: beta

Maximum beta energy: 257 keV

ALI:

a) Ingestion: 26 MBq/y

b) Inhalation: 8.7 MBq/y

Max. beta range in the air: 520 mm

The appropriate method for contamination monitoring:

a) Geiger-Muller

b) Liquid scintillation counter

Shielding material: Total absorption: 0.3 mm glass or 0.6 mm plastic

Dosimetry: Urine analysis for those that use 17.2 MBq (0.46 mCi) or more volatile liquids or gases at a time without containment. Contact the U of T radiation protection Services if you use larger quantities.

Special precautions:

1. Calcium-45 is considered highly radiotoxic because of its affinity for the bone. Radiocalcium has a long biological half-life and can cause damage to the blood-forming organs. Calcium reacts with water, producing hydrogen. If concentrated, the gas becomes a fire and explosion hazard. Calcium also poses a fire and explosion hazard when heated or when in contact with strong oxidizing agents.
2. Recommended protective clothing:
    - When working with unsealed sources wear appropriate protective clothing, such as laboratory coats, coveralls, gloves, and safety glasses/goggles.
    - Laboratory coats must be monitored before leaving the laboratory.
    - Use a suitable mask if the radioactive material is in the form of dust, powder or if it is volatile.
3. The metabolism of Calcium is complex. The majority is deposited in the bone and is retained with a long biological half-life (18000 days/50 years). A smaller

fraction is eliminated immediately via the urine but eventually, half of the radionuclide is eliminated via the feces.

13.3: Chromium-51

$^{51}_{24}\mathrm{Cr}$

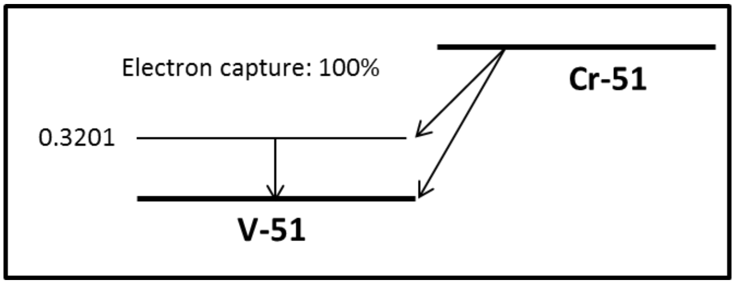
Chromium-51

Radioactive Half-life: 27.70 days

Decay mode: e capture

Principal emissions: a) gamma

b) X-rays



Gamma energy: 320 keV

X-ray energy: 5 keV

ALI:

a) Ingestion: 530 MBq/y

b) Inhalation: 560 MBq/y

The appropriate method for contamination monitoring:

a) Geiger-Muller

b) Gamma counter / Solid scintillation detector

c) Liquid scintillation counter

Shielding material: Lead; half-value layer = 0.17 cm

Dosimetry: Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

Special precautions:

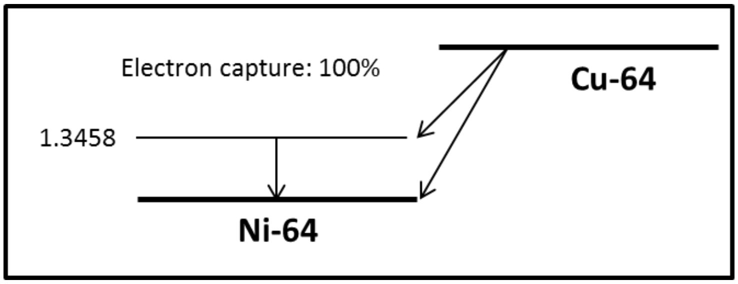
1. Chromium and chromate salts are suspected carcinogens of the lungs, nasal cavity and paranasal sinus, also experimental carcinogen of the stomach and larynx. Skin exposure to chromate salts may result in dermatitis. Sodium chromate (Cr-51) solution may emit radioactive fumes containing Cr-51 when heated to decomposition.
2. Recommended protective clothing:
    - Use disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Wear safety glasses.
3. Minimize handling time.
4. Use syringe shields and tongs to handle unshielded sources and potentially contaminated vessels.

5. Use disposable absorbent liners on trays.

13.4: Copper-64

$^{64}_{29}\mathrm{Cu}$

Copper-64



Radioactive Half-life:	12.7 hours
Decay mode:	e capture
Principal emissions:	a) gamma
	b) X-rays
Gamma energy:	511 keV (36%); 1345.8 keV
X-ray energy:	8 keV
ALI:	
a) Ingestion:	170 MBq/y
b) Inhalation:	130 MBq/y

The appropriate method for contamination monitoring:

a) Geiger-Muller

b) Gamma counter / Solid scintillation detector

c) Liquid scintillation counter

Shielding material:	Lead; half-value layer = 0.41 cm
Dosimetry:	Radiation badge whole-body and extremities for those using 50 MBq (1.35 mCi) or more at a time

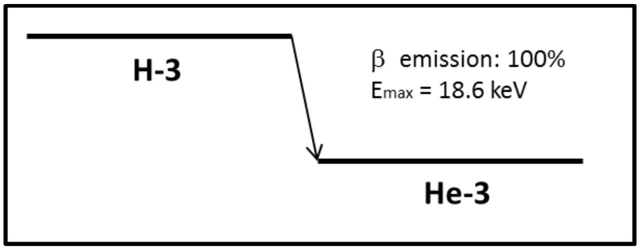
Special precautions:

1. Always use the principles of time, distance and shielding to minimize dose.
2. Recommended protective clothing:
    - Use disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Wear safety glasses.
3. Minimize handling time.
4. Use syringe shields and tongs to handle unshielded sources and potentially contaminated vessels.
5. Use disposable absorbent liners on trays.

13.5: Tritium

$^{3}_{1}\mathrm{H}$

Tritium



Radioactive Half-life: 12.35 years

Decay mode: beta – 100%

Principal emissions: beta

Maximum beta energy: 18.6 keV

ALI:

a) Ingestion: 480 MBq/y

b) Inhalation: 490 MBq/y

Max. beta range in the air: 6 mm

The appropriate method for contamination monitoring:

Liquid scintillation counter

Shielding material: Total absorption in <0.1 mm glass or plastic

Dosimetry: Urine analysis for those that use 0.96 GBq (26 mCi) or more volatile liquids or gases at a time without containment

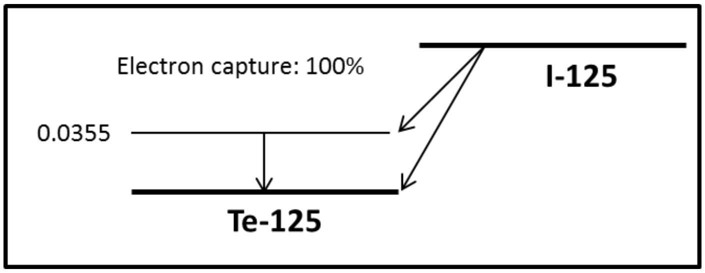
Special precautions:

1. Tritium is not a radiation hazard unless it enters the body. Once in the body, tritiated water is uniformly distributed in the body water and can then expose tissues. Tritiated water can be absorbed through the surface of the skin, leading to internal exposure.
2. Recommended protective clothing:
   - Lab coat and PVC gloves (0.5 mm thick) are preferred because of this material's low permeability to tritiated water.
   - Many tritium compounds readily penetrate gloves and skin. Handle these compounds remotely, wear two pairs of gloves and change the outer layer at least every twenty minutes.
3. Handle tritiated water, gases and volatile liquids in ventilated enclosures.
4. Use glass containers to store tritium compounds because tritiated water and tritiated organic solvents will pass through plastic.
5. Use disposable absorbent liners on trays.

13.6: Iodine-125

$^{125}_{53}\mathrm{I}$

Iodine-125



Radioactive Half-life:	60.14 days
Decay mode:	e capture
Principal emissions:	a) gamma b) X-rays
Gamma energy:	35.5 keV
X-ray energy:	27 keV
ALI:	
a) Ingestion:	1.3 MBq/y
b) Inhalation:	1.4 MBq/y

The appropriate method for contamination monitoring:

a) Gamma counter / Solid scintillation detector

b) Liquid scintillation counter

Shielding material: Lead; half-value layer = 0.1 mm

Dosimetry: Thyroid scan for those who use in 24 hours more than 2 MBq (54 microCi) without containment or more than 200 MBq (5.4 mCi) in a fume hood. Radiation badge (whole body and ring) for those who use more than 50 MBq (1.35 mCi) at a time

Special precautions:

1. Iodine compounds can become volatile. Handle and store in ventilated areas. Exposure to significant amounts of radioiodine increases the risk of developing thyroid cancer. Iodine is toxic by ingestion and inhalation and a strong irritant of eyes and skin. Iodine can be absorbed through the skin. When iodinated (I -125) albumin injection is heated to decomposition, radioactive fumes containing I-125 may be emitted.
2. Recommended protective clothing:
    - Disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Also wear safety glasses.

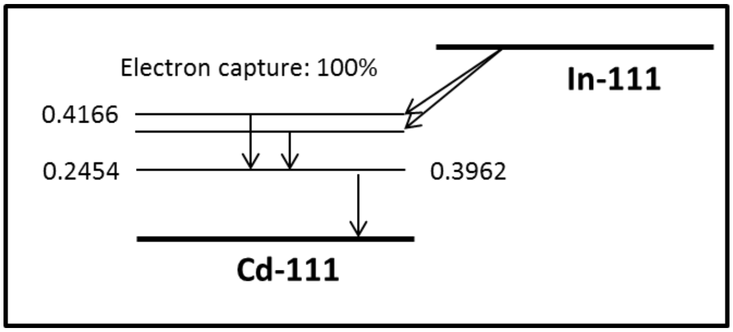
    - Some iodine compounds can penetrate surgical rubber gloves. Wear two pairs of polyethene gloves over the rubber.

3. Store NaI-125 solutions at room temperature because freezing may result in subsequent volatilization of radioiodine.
4. The critical organ for I-125 uptake is the thyroid. The thyroid may be assumed to accumulate 30% of the soluble iodine and retain it with a biological half-life of 138 days. The elimination takes place via urine.

13.7: Indium-111

$^{111}_{49}\mathrm{In}$

Indium-111



Radioactive Half-life:	2.83 days
Decay mode:	e capture
Principal emissions:	a) gamma
	b) X-rays
Gamma energy:	245.5 keV
(100%); 171.3 (96%)	
ALI:	
a) Ingestion:	69 MBq/y
b) Inhalation:	65 MBq/y

The appropriate method for contamination monitoring:

a) Gamma counter / Solid scintillation detector

b) Liquid scintillation counter

c) Geiger-Muller

Shielding material:	Lead; half-value layer < 2 mm
Dosimetry:	Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

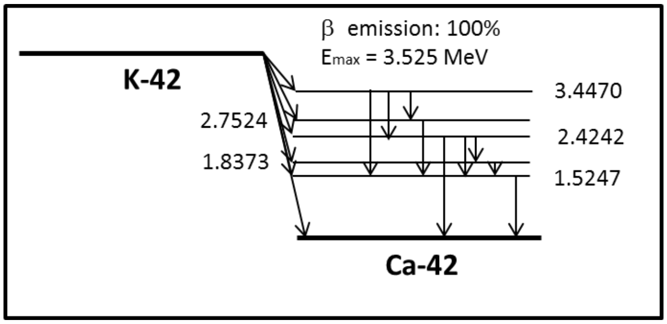
Special precautions:
1. Indium metal and its compounds are toxic by inhalation, causing cumulative organ damage. Suspected teratogen. When Indium 111 chloride is heated to decomposition, radioactive fumes may be emitted.
2. Recommended protective clothing:
    - Disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Also wear safety glasses.
3. Keep handling time to a minimum. Always use the principles of time, distance and shielding to minimize dose.
4. Use syringe shields and tongs.

5. Use disposable absorbent liners on trays.

13.8: Potassium-42

$^{42}_{19}K$

Potassium-42



Radioactive Half-life:	12.36 hours
Decay mode:	beta – 100%
Principal emissions:	a) beta b) gamma
Maximum beta energy:	3.525 MeV
Gamma energies:	1.524 MeV (100%), 1.922 MeV (22%), 2.424 MeV (16%)
ALI:	
a) Ingestion:	47 MBq/y
b) Inhalation:	100 MBq/y
Max. beta range in the air:	13 m

The appropriate method for contamination monitoring:

a) Geiger-Muller

b) Gamma counter / Solid scintillation detector

c) Liquid scintillation counter

Shielding material:	Lead; half-value layer = 1.18 cm
Dosimetry:	Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

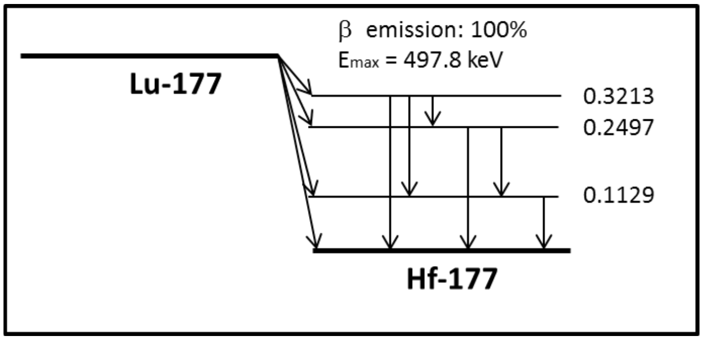
Special precautions:

1. Always use the principles of time, distance and shielding to minimize dose.
2. Recommended protective clothing:
    - Use disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Wear safety glasses.
3. Minimize handling time.
4. Use syringe shields and tongs to handle unshielded sources and potentially contaminated vessels. Use disposable absorbent liners on trays.
5. Always handle hundreds of MBq quantities behind lead shielding.

13.9: Lutetium-177

$^{177}_{71}\mathrm{Lu}$

Lutetium-177



Radioactive Half-life: 6.73 days

Decay mode: beta – 100%

Principal emissions: a) beta

a) gamma

Maximum beta energy: 498 keV

Gamma energies: 208.3 keV (11%), 113 keV (6.4%)

ALI:

a) Ingestion: 29.6 MBq/y

b) Inhalation: 29.6 MBq/y

Max. beta range in the air: 93 cm

The appropriate method for contamination monitoring:

a) Solid scintillation detector

b) Geiger-Muller

c) Liquid scintillation counter

Shielding material: Lead; Half-value layer = 0.2 cm

Dosimetry: Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

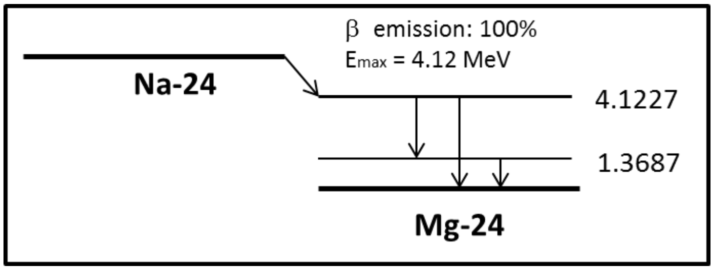
Special precautions:

1. Always use the principles of time, distance and shielding to minimize dose.
2. Recommended protective clothing:
    - Use disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Wear safety glasses.
3. Minimize handling time. Use syringe shields and tongs to handle unshielded sources and potentially contaminated vessels.
4. Use disposable absorbent liners on trays.

13.10: Sodium-24

$^{24}_{11}\mathrm{Na}$

Sodium-24



Radioactive Half-life: 14.96 hours

Decay mode: beta – 100%

Principal emissions: a) beta

b) gamma

Maximum beta energy: 1.39 MeV

Gamma energies: 1.368 Mev (100%), 2.754 Mev (99.9%)

ALI:

a) Ingestion: 47 MBq/y

b) Inhalation: 38 MBq/y

Max. beta range in the air: 600 cm

The appropriate method for contamination monitoring:

a) Geiger-Muller

b) Gamma counter / Solid scintillation

c) Liquid scintillation counter

Shielding material: Lead; half-value layer = 1.32 cm

Dosimetry: Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

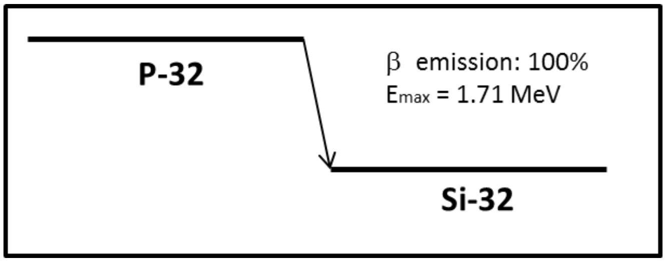
Special precautions:

1. Always use the principles of time, distance and shielding to minimize dose.
2. Recommended protective clothing:
    - Use disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Wear safety glasses.
3. Minimize handling time.
4. Use syringe shields and tongs to handle unshielded sources and potentially contaminated vessels.
5. Use disposable absorbent liners on trays.

13.11: Phosphorus-32

$^{32}_{15}\mathrm{P}$

Phosphorus-32



Radioactive Half-life: 14.26 days

Decay mode: beta – 100%

Principal emissions: beta

Maximum beta energy: 1.71 MeV

ALI:

a) Ingestion: 8.3 MBq/y

b) Inhalation: 6.9 MBq/y

Max. beta range in the air: 7.9 m

The appropriate method for contamination monitoring:

a) Geiger-Muller

b) Liquid scintillation counter

Shielding material: Total absorption: 3.4 mm glass or 6.3 mm Plexiglas

Dosimetry: Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

Special precautions:

1. Recommended protective clothing:
    - Disposable plastic, latex or rubber gloves, safety glasses.
2. Keep handling time to a minimum.
3. Use plastic syringe shields and tongs to avoid direct skin contact.
4. When possible work behind a plastic screen.
5. Use disposable absorbent liners on trays.
6. Always use the principles of time, distance and shielding to minimize dose.
7. Near an unshielded 37 MBq (1 mCi) P-32 source, dose rates due to beta radiation can be 260 mSv/hr. Never work over an open container with P-32.
8. Hundreds of MBq quantities can produce significant secondary radiation (x-rays) due to the bremsstrahlung effect. In this case, 3-6 mm of lead needs to be added to the Lucite shield. Avoid local high-dose exposure by remote handling of large quantities and prompt removal of contaminated clothing or gloves.

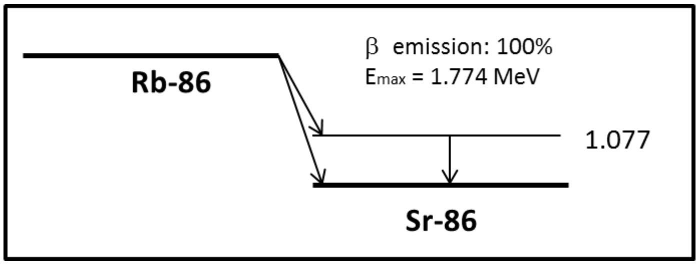
The bone is the critical organ for the uptake of transportable compounds of P-32. The lung and the lower intestine are the critical organs for inhalation and ingestion of insoluble P-32 compounds respectively.

13.12: Rubidium-86

$^{86}_{37}\mathrm{Rb}$

Rubidium-86

Radioactive Half-life:	18.63 days
Decay mode:	beta – 100%
Principal emissions:	a) beta b) gamma
Maximum beta energy:	1.774 MeV
Gamma energy:	1.077 MeV (100%)
ALI:	
a) Ingestion:	7.1 MBq/y
b) Inhalation:	15 MBq/y
Max. beta range in the air:	790 cm



The appropriate method for contamination monitoring:

a) Geiger-Muller

b) Gamma counter / Solid scintillation detector

c) Liquid scintillation counter

Shielding material:	Plexiglas +Lead; half-value layer (lead) = 0.87 cm
Dosimetry:	Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

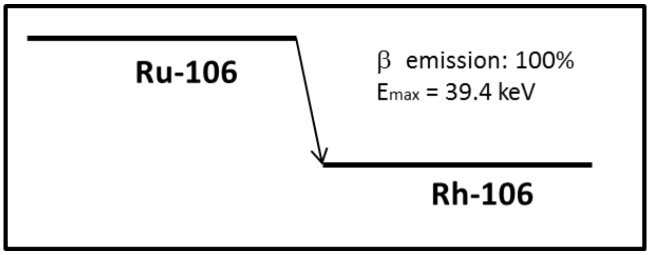
Special precautions:

1. Always use the principles of time, distance and shielding to minimize dose.
2. Recommended protective clothing:
    - Use disposable plastic, latex or rubber gloves.
    - Wear a lab coat, which must be monitored before leaving the laboratory.
    - Wear safety glasses.
3. Minimize handling time.
4. Use syringe shields and tongs to handle unshielded sources and potentially contaminated vessels.
5. Use disposable absorbent liners on trays.

13.13: Ruthenium-106

$^{106}_{44}\mathrm{Ru}$

Ruthenium-106



Radioactive Half-life: 373.6 days

Decay mode: beta – 100%

Principal emissions: beta

Maximum beta energy: 39.4 keV

ALI:

a) Ingestion: 2.96 MBq/y

b) Inhalation: 1.33 MBq/y

Max. beta range in the air: 8 mm

The appropriate method for contamination monitoring:

b) Liquid scintillation counter

Shielding material: None

Dosimetry: Radiation badge whole body and extremities for those using 50 MBq (1.35 mCi) or more at a time

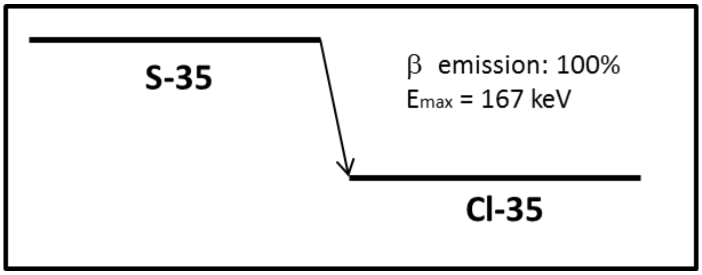
Special precautions:

1. Recommended protective clothing:
    - When working with unsealed sources wear appropriate protective clothing, such as laboratory coats, coveralls, gloves, and safety glasses/goggles.
    - Laboratory coats must be monitored before leaving the laboratory.
    - Use a suitable mask if the radioactive material is in the form of dust, powder or if it is volatile.

13.14: Sulphur-35

$^{35}_{16}\mathrm{S}$

Sulphur-35



Radioactive Half-life: 87.44 days

Decay mode: beta – 100%

Principal emissions: beta

Maximum beta energy: 167.5 keV

ALI:

- a) Ingestion: 26 MBq/y
- b) Inhalation: 170 MBq/y

Max. beta range in the air: 260 mm

The appropriate method for contamination monitoring:

- a) Liquid scintillation counter

Shielding material: Total absorption: 0.2 mm glass or 0.3 mm plastic

Dosimetry: Urine analysis for those that use 52 MBq (1.41 mCi) or more volatile liquids or gases at a time without containment

Special precautions:

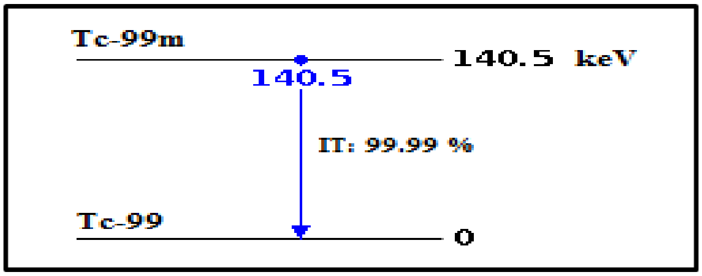
1. Sulphur dioxide: irritant to eye, nose, throat, lungs; bronchoconstriction; mutagen, suspect reproductive effects. Hydrogen sulphide: moderate irritant to the eye (conjunctivitis), lung; acute systemic toxicity; Central Nervous System may be affected. Sulphur is combustible.
2. Recommended protective clothing:
    - Wear a disposable lab coat, gloves and wrist guards for secondary protection.
    - Select appropriate gloves for chemicals handled.
    - Lab coat must be monitored before leaving the laboratory.
3. S-35 is volatile and should be handled in ventilated enclosures. Take care not to generate sulphur dioxide or hydrogen sulphide which could be inhaled.
4. Use disposable absorbent liners on trays.
5. Radiolysis of S-35 amino acids during storage and use may lead to the release of S-35 labelled volatile impurities. Therefore, all vials should be opened and used in a fume hood.

13.15: Technetium-99m

$^{99m}_{43}\mathrm{Tc}$

Technetium-99m

Radioactive Half-life:	6.01 hours
Decay mode:	IT – 99.99 %
	beta – 0.01 %
Principal emissions:	a) beta
	b) gamma
Maximum beta energy:	0.142 MeV
Gamma energy:	0.140 MeV (89 %)
ALI:	
a) Ingestion:	910 MBq/y
b) Inhalation:	690 MBq/y



The appropriate method for contamination monitoring:

b) Liquid scintillation counter

Chapter 14: PERIODIC TABLE

Periodic Table of Elements **For information about some commonly used radionuclides at UofT, just click on the hyperlink (coloured) elements**																	
H 1																	**He** **2**
Li **3**	**Be** **4**											**B** **5**	C 6	**N** **7**	**O** **8**	**F** **9**	**Ne** **10**
Na 11	**Mg** **12**											**Al** **13**	**Si** **14**	P 15	S 16	**Cl** **17**	**Ar** **18**
K 19	Ca 20	**Sc** **21**	**Ti** **22**	**V** **23**	Cr 24	**Mn** **25**	**Fe** **26**	**Co** **27**	**Ni** **28**	Cu 29	**Zn** **30**	**Ga** **31**	**Ge** **32**	**As** **33**	**Se** **34**	**Br** **35**	**Kr** **36**
Rb 37	**Sr** **38**	**Y** **39**	**Zr** **40**	**Nb** **41**	**Mo** **42**	**Tc** **43**	Ru 44	**Rh** **45**	**Pd** **46**	**Ag** **47**	**Cd** **48**	In 49	**Sn** **50**	**Sb** **51**	**Te** **52**	I 53	**Xe** **54**
Cs **55**	**Ba** **56**	*	**Hf** **72**	**Ta** **73**	**W** **74**	**Re** **75**	**Os** **76**	**Ir** **77**	**Pt** **78**	**Au** **79**	**Hg** **80**	**Tl** **81**	**Pb** **82**	**Bi** **83**	**Po** **84**	**At** **85**	**Rn** **86**
Fr **87**	**Ra** **88**	**	**Rf** **104**	**Db** **105**	**Sg** **106**	**Bh** **107**	**Hs** **108**	**Mt** **109**	**Ds** **110**	**Rg** **111**	**Cn** **112**	**Nh** **113**	**Fl** **114**	**Mc** **115**	**Lv** **116**	**Ts** **117**	**Og** **118**
Lanthanides Series																	
*	**La** **57**	**Ce** **58**	**Pr** **59**	**Nd** **60**	**Pm** **61**	**Sm** **62**	**Eu** **63**	**Gd** **64**	**Tb** **65**	**Dy** **66**	**Ho** **67**	**Er** **68**	**Tm** **69**	**Yb** **70**	Lu 71		
Actinides Series																	
**	**Ac** **89**	**Th** **90**	**Pa** **91**	**U** **92**	**Np** **93**	**Pu** **94**	**Am** **95**	**Cm** **96**	**Bk** **97**	**Cf** **98**	**Es** **99**	**Fm** **100**	**Md** **101**	**No** **102**	**Lr** **103**		

The information presented is considered adequate for the amounts usually used in the U of T laboratories. More information can be obtained at

https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html