Accreditation course in radiation protection - Radiation Protection Officer – Dispersible radioactive substances level D (TMS-VRS D)

September 2025

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Lectures

Chapter 1

Lecture 1 - Physics 1

1.1 Structure of an atom

An atom of X element has Z number of protons, N number of neutrons [n(0)], and a mass (A) of Z+N. An element can be expressed as ${}^{A}_{Z}X$

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1.2 Radioactive decay

Decay may occur due to:

1. Too many protons
2. Too many neutrons
3. Too many neutrons and protons
4. Energetically excited state

The chart of nucleides expresses in black the stable nuclei and in white the unstable nuclei. Isobars have the same mass (A), and isotopes have the same number of P+ (Z).

1.3 Ionizing radiation

Radiation is energy released as electromagnetic waves or particles.
Ionisation means removing electrons from the electron cloud of the atom.
Ionising radiation can consist of:

1. Particle radiation (with high energy)
   (a) Alpha decay
   (b) Beta decay
   (c) Electron capture
   (d) Positron emission
2. Electromagnetic radiation (with high energy)
   (a) Isomeric transition (gamma emission)

The radiation type that occurs can be seen on the chart of nucleides (see slide 10).

Alpha decay (α)

Occurs when the nucleus is unstable, due to being too big.
The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}^{A-4}_{Z-2}Y$ and an alpha particle ${}^{4}_{2}a$.

Beta decay (β)

Occurs when the nucleus is unstable, due to having an excess of n.
The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}_{Z+1}{}^{A}Y$, a beta particle ${}_{-1}^{0}e^{-}$, and an anti-neutrino $\overline{v}_e$.

Electron capture (E.C. or ϵ)

Occurs when the nucleus is unstable, due to having an excess of p.
The parent atom ${}^{A}_{Z}X$ absorbs an electron ${}_{-1}^{0}e^{-}$, and gets split into a daughter atom ${}_{Z-1}{}^{A}Y$, and a neutrino v. If the hole is filled by an outer shell electron, X-rays are emmitted. [...]

Positron emission (β^+)

Occurs when the nucleus is unstable, due to having an excess of p.
The parent atom ${}^{A}_{Z}X$ gets split into a daughter atom ${}_{Z+1}{}^{A}Y$, a positron ${}_{+1}^{0}e^{+}$, and a neutrino v. After a number of interactions, the positron unites with an electron and converts its entire mass to energy. This annihilation produces 511 keV.

Gamma decay (γ)

Occurs when the atom is excited.
The parent atom ${}^{A}_{Z}X\cdot$ gets excited and produces a daughter particle ${}^{A}_{Z}X$ and a gamma ray γ^1.

1.4 Activity

1.4.1 Unit of activity (A)

The unit of activity is the Becquerel (Bq). 1 Bq = 1 disintegration per second. The specific activity is the activity per mass (Bq/g) The old unit was Curie (Ci), equivalent to $3.710^{10} Bq$

1.4.2 Decay law

Decay is a random process. Activity is proportional to the number of nuclei and the decay constant $\lambda(s^{-1})$:

$$A = -\frac{dN}{dt} = \lambda N$$

The half life is the number of seconds that it takes to decay half of all nuclei present:

$$t_{1/2} = -\frac{ln2}{\lambda} = \frac{0.693}{\lambda}$$

The activity (A_t) on time (t) can be approximated as:

$$A_t = A_0 * e^{-\frac{t}{t_{1/2}} * ln(2)}$$

$$A_t = A_0 * \frac{1}{2}^{-\frac{t}{t_{1/2}}}$$

1.5 Electromagnetic radiation

Electromagnetic radiation is non-material.
The smaller the wavelength, the higher the frequency, and the higher the energy.

$$\lambda = \frac{c}{v}$$

$$E = \frac{hc}{\lambda} = h * v$$

1.5.1 Generation of X-rays

X-rays happen when high energy atoms are slowed down by matter. An atom is bombarded by electrons. When an electron hits another electron, a hole is formed. This is then filled by an electron from the electron shell, which releases energy. Three situations can occur:

1. The electron can hit the nucleus, which produces the maximum energy.
2. The electron can have a close interaction, which produces moderate energy.
3. The electron can have a distant interaction, which prouces low energy.

The X-ray tube produces X-rays. It depends on the electron energy (regulated by the tube voltage), and the anode material (usually tungsten). ¡1% of energy is converted to X-rays, and the rest is heat. The X-ray tube has a spectrum of emission, called the Spectrum Bremsstrahlung. In an X-ray spectrum there's always peaks. Those are called the characteristic X-rays, and they depend on the material. X-rays can be filtered or unfiltered. This reduces the amount of X-rays in the areas that aren't of interest. The filter affects the X-rays differently depending on the material it's made out of.

1.5.2 Interaction of radiation with matter

Gamma and X-rays can interact with matter in the following ways:

1. Classic scattering (mainly non-ionising radiation)
2. Photo effect
3. Compton effect
4. Pair production

Which method occurs depends on the photon energy and the atomic number (see slide 61)

Classic scattering

Also called elastic, coherent or Rayleigh scattering. Gamma energy remains unchanged, but the direction of the photon may change. It is important at low E_λ

Photo effect

The photon knocks an electron out of its orbit. The electron has binding energy, so the resulting energy is minimal. It goes up to 0.5MeV. The chance is roughly proportional to Z^4, and it produces characteristic X-rays.

Compton effect

The dominant effect at higher energies. Depends on the material. The photon is scattered at weakly bound electrons, transferring partly the energy to the electron. However, it continues and may hit another electron. It can go through the material, with less energy that it came in. The degree of energy transfer depends on the scatter angle. The maximal energy will be at 180ª, and the minimal energy at 0º. With a portable X-ray tube it's better to have it below the bed, as it's shielded, and most of the backscatter will go to the rear.

Pair production

Near the nucleus, the photon can create both an electron and a positron, if it has enough energy. This usually results in an annihilation, usually outside of the atom, creating 2 511keV photons, at 180º from each other. This can only occur at energies of over 1.022MeV (mass of the electron + positron).

Chapter 2

Lecture 2 - Physics 2

2.1 Interaction of charged particles with matter

Photons do not experience energy loss per distance. However, charged particles do. There is a certain amount of energy loss per cm (LET: Linear Energy Transfer), or Stopping Power. Alpha particles have a high stopping power, as they lose a lot of energy at a short distance.
The range is the maximum distance that charged particles can travel in matter. It depends on the type of charged particle, the energy of the charged particle, and the density of the material. Not every electron has the same speed, as the energy is distributed unequally and randomly between the electron and the neutrino. The mean energy is lower than the 50% of the range.
Rule of thumb (produces an overestimation) for β with E ¿ 0.6 MeV:

$$R(cm) * \rho(\frac{g}{cm}) = 0.5\ E_{\beta,max}(MeV)$$

Soft tissue is very equivalent to water, and thus can be approximated to a density of 1. Air is around 1000 times higher.

2.1.1 Interaction of α particles with matter

Due to the interaction with the electrons of atoms (ionizations and excitations), the energy of an α particle decreases. It disposes of its energy linearly along a straight path. The range/pathway depends on the energy of the radiation and the density of the material
Alpha particles have a high stopping power. They lose a lot of energy at a short distance (small range, thick track). They are unable to pass the epidermis, but they are very dangerous if ingested.

2.1.2 Interaction of protons with matter

Protons behave like α particles, but they can be directed to deposit most of their energy at a specific point (Bragg peak). The Bragg peak can be manipulated with the energy.

2.1.3

2.1.4 Shielding from ionizing radiation

Shielding for particles only needs to be as thick as the maximal range. However, for photons, you the shielding needs to be as thick as deemed reasonably safe.
The γ-photon pathway is much longer than the β-particle, which is longer than the α-particle pathway.

Alpha

For α particles, barely any shielding is necessary.

Beta

For β particles, the rule of thumb can be applied. Shielding materials with a low Z-value cause less Bremsstrahlung. Such materials are Perspex or aluminum (mostly Perspex, as it's see-through, and has an even lower Z-value). Bremsstrahlung causes a loss of energy, which is released as a photon, usually in the X-ray range. β emmitters are usually stored in a perspex container in a lead container. Perspex is often used a a mimic for tissue.

Gamma

For γ and X-rays, the material cannot stop them entirely but rather attenuate them. It depends on the energy of the radiation, and the density of the material (or rather Z value, the highest Z-value attenuates the most). The attenuation can be calculated with:

$$I_d = I_0\ e^{-\mu d}$$

Where d is the thickness of the material and μ is the attenuation coefficient. After $d_{1/2}$, the photon intensity is halved:

$$d_{1/2} = \frac{ln2}{\mu}$$

Transmission is the ratio between the original intensity and the dampened intensity.

$$T = \frac{I_d}{I_0}$$

2.1.5 Inverse square law

Electromagnetic radiation is a Newtonian form of radiation, which means that it decreases in intensity by the square of the distance. This is because the intensity is the number of photons/sm$^{\mathbf{2}}$, and the surface of a sphere increases with the square of the radius.

2.2 Dose

2.2.1 Definition of dose

An absorbed dose (D) is the absorbed energy per mass of matter. We use the Gray (Gy), equivalent to 1 Joule/kg.

2.2.2 Calculation of a γ dose rate

$$H = \frac{h(10)A}{r^2}$$

Where h(10) is the ambience dose equivalent rate/source constant, H is the dose rate, A is the activity, and r is the distance.
The h(10) is exclusive for nucleides with gamma emission. There's tables that can be used.

2.2.3 Rules of thumb

β radiation

The source of an A MBq source that emits a β particle of E MeV per decay event at 10 cm is

$$H_{skin} = 1000A(\frac{\mu Sv}{h}$$

γ radiation

The source of an A MBq source that emits a γ photon of E MeV per decay event at 30 cm is

$$H = 2A(\frac{\mu Sv}{h}$$

2.2.4 Dose reduction

1. Time $\rightarrow$ Work fast
2. Distance $\rightarrow$ Stay away
3. Shielding $\rightarrow$ Use shielding
4. Activity $\rightarrow$ Use the minimum needed

2.2.5 Buildup factor

The attenuation law assumes a narrow beam. However, that's not correct. Depending on the shielding material, there may be a lot of backscatter, which amplifies the radiation after the shielding. The build-up factor depends on the energy and the material, and it may need additional shielding to compensate. The buildup factor can be considerable, commonly factor 2-4, but even goes higher than 100.

Quantity	Symbol	Unit	Type
Absorbed dose	D	Gray (Gy)	Physical
Equivalent dose	H_T	Sievert (Sv)	Biological (Specific part)
Effective dose	E	Sievert (Sv)	Biological (Whole body)

Type of radiation	W_R
β	1
γ	1
X-ray	1
n	5-20
p	1.1-10
α	20

2.2.6 Dose and biology

Equivalent dose

The seriousness of biological tissue damage is also determined by the way that energy is disposed. It depends on the kind of radiation. α radiation has more ionizations per path length, so it does more damage than β or γ.

$$H_T = D * W_R$$

Where W_R is the radiation weighting factor, and D is the absorbed dose in Gray

Effective dose

It is a quantity used for comparison of risks. The effective dose is the radiation dose needed in homogenous total body irradiation to obtain the same risk.

$$\sum_T H_T \cdot W_T$$

Where H_T is the equivalent dose and W_T is the tissue weighting factor (See Table 5.2 in the book). W_T depends on the rate of division of the cells in each organ.

Dose Conversion Coefficients

To calculate the effective (committed = internal) dose after contamination (ingestion) with radionucleides, the following formula is used:

$$E_{committed} = A * e_{50}$$

E(50) is the effective dose received over 50 years after intake, and it depends on the chemical form, way of intake, and sometimes disease of the patient. The e(50) or DCC or $e_{inh/ing}$ is a coefficient that can be looked up on tables.

To calculate the effective dose after skin contamination, e(50) (Sv/Bq) and DCC_{skin} (mSv/s per kBq/cm^2) are used for contamination, h(10) is used for irradiation (μ Sv/h per MBq/m^2)

Chapter 3

Lecture 3 - Measuring methods

Principle of operation	Detector material	Detector type
Electrical charge	Gas	Gas-filled
	Solid state	Semiconductor
Luminescence	Solid/liquid state	Scintillation
	Solid state	Thermoluminescence
Chemical reaction	Photographic emulsion	Densitometer
Warmth	Solid/liquid state	Calorimeter
Activation	Solid state	Activation dose meter

The purpose of measuring is to determine the type of radiation, the activity, the energy of the radiation, or the (effective) dose or dose rate.

3.1 Principles of radiation detection

3.2 Ionization/Electric charge

3.2.1 Gas-filled detectors

Gas-filled detectors have a closed tube that contain air or another gas. When radiation enters the tube, ionization occurs. The walls of the detector have a voltage between them, which separates the ions, and this can be measured through the current. The current is proportional to the primary electron-ion pairs, which is proportional to the absorbed amount of energy. However, these detectors have a a recombination region (Applied voltage ¡ Saturation voltage), in which they can work. Above the saturation voltage, there's the saturation region, in which the detector can't detect more because all formed ion pairs can reach the electrodes, and cannot recombinate. They consist of a tube with very thin membranes at the end (protected by a mesh or bars).

Ionization chamber

They produce very small electrical signals. They aren't used in pulse mode to detect indiviual counts, but rather used for radiation intensity. They are most suited to detect radiation with high energy deposition (α or β), or with high energy, but it's not efficient for γ rays. It can be used as a dose calibrator to determine the amount of radioactivity of a known radioisotope.

Proportional counter region

At sufficiently high voltage, the accelerated primary electrons have enough energy to cause ionization themselves and form secondary electron pairs (cascade).
The proportional counter uses the proportional counter region. It produces larger electrical signals than the ionization chamber, so it is used in pulse mode to detect individual counts. The electrical signal is proportional to the amount of deposited energy, so it can be used for energy selective counting. It's most suited to detect radiation with high energy deposition (α and β), and though it can detect γ, it's not as efficient. It can be used as a contamination monitor.

Geiger-Müller region

Similar to the proportional counter region, but even more. This is called the avalanche. At high voltage, emission photons are created, which can interact with gas, creating even more electron-ion pairs. The avalanche is stopped when a large number of 'slow' positive ions reduces the effective voltage, and the electrical charge becomes independent of absorbed energy.
The Geiger-Müller counter uses the Geiger-Müller region. It produces larger electrical signals that can be easily measured with low cost electronics, so they are used in pulse mode. The electrical signal is independent of absorbed energy, so it's not used for energy-selective counting. It's inefficient for γ rays, but it's more sensitive than the ionization chamber and the proportional counters. They are used as survey monitors.

3.2.2 Semiconductors

They work in a similar way to the gas-filled detectors, but they're more efficient for X- and γ-rays, given their higher stopping power. The energy needed to create a single electron-ion pair is much lower than for air, so a larger electrical signal is produced.
Individual counts can be measured with a very high energy resolution, which produces an energy spectrum, which is a 'fingerprint' that is used to identify radio-isotopes.
In order to suppress noise they must be cooled, so they are immovile and very heavy.

3.3 Luminescence

3.3.1 Scintillation

They work through scintillations. This means that a photon is released in the UV or visible-light range when an excited electron returns to its ground state. The produced amount of light is proportional to the amount of energy. But this energy can be very small, so a photomultiplier tube is used by converting scintillation light to pulses of electrical current. The most common cathode is sodium iodide, or not as commonly, another salt. Radiation enters the crystal, and photons are released as a result.
Solid materials can be used, such as NaI or CsI (for γ radiation), or anthracene or stilbene (plastics, used for α and β radiation). Organic liquid materials can also be used to detect α or β radiation (a small amount of sample is put in the liquid), and it's best used for low-energy sources, as it's often the only way to check for contamination (with swipe or smear tests).
Scintillation can also be used to identify materiials, although they have a lower resolution than semiconductors.

3.3.2 Thermoluminescence

It is often used in personal dosimeters. The thermoluminescent detector is made from a material that can emit photons upon heating after exposure to ionizing radiation. Therefore, it 'captures' radiation, and releases it when it's heated.

3.4 Efficiency

No detector is 100% efficient. This is because even if the detector was perfect, you'd only be measuring by one side. The measurement efficiency depends on detector efficiency, geometric efficiency, the source, and the absorption between the source and the detector. The efficiency can be determined by measuring a source with known activity.

$$\epsilon = \frac{R_{net}}{A} = \frac{R_{gross} - R_{background}}{A}$$

Where R¡A, R being the count rate, and A being the actual activity.

3.5 Counting statistics

Chapter 4

Lecture 4 - Biological Effects

4.1 Effects of radiation on cells

Everything in the cell is a possible target. However, the biggest risk is the nucleus, and its DNA. This is because it can create DNA damage, such as base damage, cross-links, single/double strand breaks. In oncology, double strand breaks are needed to treat cancer. 1Gy of LET X-rays produces 1000 single-strand breaks, 40 double-strand breaks and 1000 altered bases.

4.1.1 DNA repair

Cells have a lot of repair mechanisms. Double-stranded breaks can cause many errors due to non-homologous end-joining. NHEJ cuts corners for the sake of speed. Single-strand breaks are easily repaired, in a couple of minutes after irradiation, 80% of breaks are repaired. Double-strand breaks take much longer, taking hours for the same 80% of breaks being repaired.

4.1.2 Stochastic effects

Chance is proportionally related to the dose. There's no threshold, any exposure is any damage. It can cause cancer or congenital defects. There may be a latency period. This is based on the multiple hit theory (multiple 'hits' are needed to cause cancer). The multiple hit theory says that multiple genetic changes are necessary. Oncogenes (such as Ras) are needed to quickly proliferate cells. Tumour supressor genes (such as p53 or RB1) are needed to prevent mutated cells from dividing. DNA-repair genes (such as HNPCC or BRCA) are needed to to repair the DNA. Leukemia is a more immediate form of cancer (around 10-20 years), but most other forms of cancer take at least 15 years.
However, electromagnetic radiation usually only makes around 5-7% of the carcinogenic factors. This also includes the sun's radiation, radon gas from working inside (radon is formed in the same rocks that are used to make buildings). Cancer is a multi-factorial risk, so it's difficult to tell the cause of the cancer. However, risks can be estimated by having large groups of exposed and non-exposed individuals, knowing the exact dose everyone received, and having a big difference with background radiation. One example of research was the one done after Hiroshima and Nagasaki. They had over 85k subjects in the cohort, and it has been running since the atomic bombs. The subjects get questionnaires, medical checkups, etc. yearly. Using the position where everyone was in the city when the bombs hit, the dose was estimated, which ranged from 0.01 to 6 Gy. By this life span study, they found that stomach cancer had an excess risk. There was also an increased chance of lung cancer, due to inhaling fallout. In general, per whole-body 1Gy dose, cancer risk increased by 47%. For those who received over 2 Gy, 56% of cancers were caused by that dose. The age also increases the effect of the cancer. The younger at which you're exposed, the higher the chance of cancer.
The risk of malignancy was set to 5%/Sv for 'civilians', and for workers 4%/Sv. This is because in 'civilians' it's usually because of accidents, with a high dose at once; while in workers it's a lower dose spread through many years, which is more repairable.
Cancer is not the only type of stochastic effect. There's also genetic effects, which are hereditary. This damage is induced before conception, and may skip several generations. It is therefore difficult to study these effects in humans, so we only have animal studies. The studies also only use high doses (¿0.5 Gy). A linear dose-effect relation without threshold is assumed. Only the damage in live births is accounted for. One such research was the MegaMouse project (¿7000 mice). They looked at 6 types of hair colour and stunted ears. They found that not all the mice were equally sensitive, that repair time before procreation decreased the mutation frequency, and that there was a dose rate effect (high dose rate causes more damage than a low dose rate). From those experiments, there was a risk number of 1%/Sv and a high spontaneous incidence of 10-20% of genetic effects. The individual genetic effects are low.
Radiation during pregnancy is quite risky. The later the fetus is, the lower the risk to it is. During the preimplantation period (0-10 d), cells are pluripotent, so they can replace each other. Any damage results in apoptosis. It's an all-or-nothing effect, if the fetus survives, the child will not have effects. If not, the period will occur normally. During the organogenesis period (3-8 w), congenital malformations may occur. The effects are deterministic, with a threshold dose of 100 mSv. During the fetal period (8-25w) there's a growth delay, which may cause mantal retardation with a threshold dose of 100mSv, and after that a 10-40% chance per Sv, with about 30 IQ points loss per Sv. The childhood malignancy is at 6%/Sv. There's an increased risk of adult malignancy in life (2-3x). The fetal sensitivity is highest during the 1st trimester. With a dose below 100 mSv, the stochastic effects are unlikely, and there's no

harmful tissue reactions. A dose above 500 mSv justifies abortion, as the risks are too high. The law sets an absolute limit from notification until birth of 1 mSv.

4.1.3 Deterministic effects

Deterministic/harmful tissue reactions depend on the dose. It takes a certain dose (threshold dose) to see effects in a certain amount of people (5% of people see the effect). Below the threshold dose, the effects are unlikely. However, the sensitivity depends on the person, based on how fast their cells repair DNA. It seems like this resistance does not always transmit to the cancer.
With stochastic effects, even with a very low dose, there is a possibility of cancer, even if very small. It is a very cautious approach. That's why the dose given to the general population should be as low as reasonably achievable. The higher the cumulative lifetime dose, the higher the chance of getting effects (cancer or hereditary effects). However, it is a binary effect: you get cancer or you don't, regardless of dose.
DNA damage can cause cell death (resulting in the loss of organ function or sterility - harmful tissue reactions/deterministic effects), mutations (resulting in cancer or hereditary defects - stochastic effects), or repair.
Acute harmful tissue reactions can be seen immediately or delayed. Immediate reactions are mainly cell loss, followed by an inflammatory response. Cell loss can result in anaemia, neutropenia, thrombopenia, epidermolysis, hair loss, ulceration... The following inflammatory response can result in mucositis, cystitis, enteritis, encephalitis, erythema, periostitis, keratitis... Late harmful tissue reactions can include atrophy, damage to blood vessels, chronic inflammatory reactions, fibrosis, sclerosis, necrosis... The effects vary by organ, as they have different sensitivities.
One famous case of carelessness is that of two interventional radiologists, and two nurses in 2 hospitals in Spain. They all developed cataract in both eyes, within two years. They were completely unknowledgeable about radiation protection. They didn't wear enough protection. There was no overhead shielding. They reached 0.45-0.9 Sv/y for several years.

4.1.4 Dose limits

In normal work, no harmful tissue reaction will be seen. There's dose limits which are set well below the damage threshold. The responsability of protection falls on the institution, not the worker. For 'civilians', the limit is 1 mSv/y. For radiation workers, the limit is 20 mSv/y. The damage is first seen at 2000 mSv.

Part III

Book