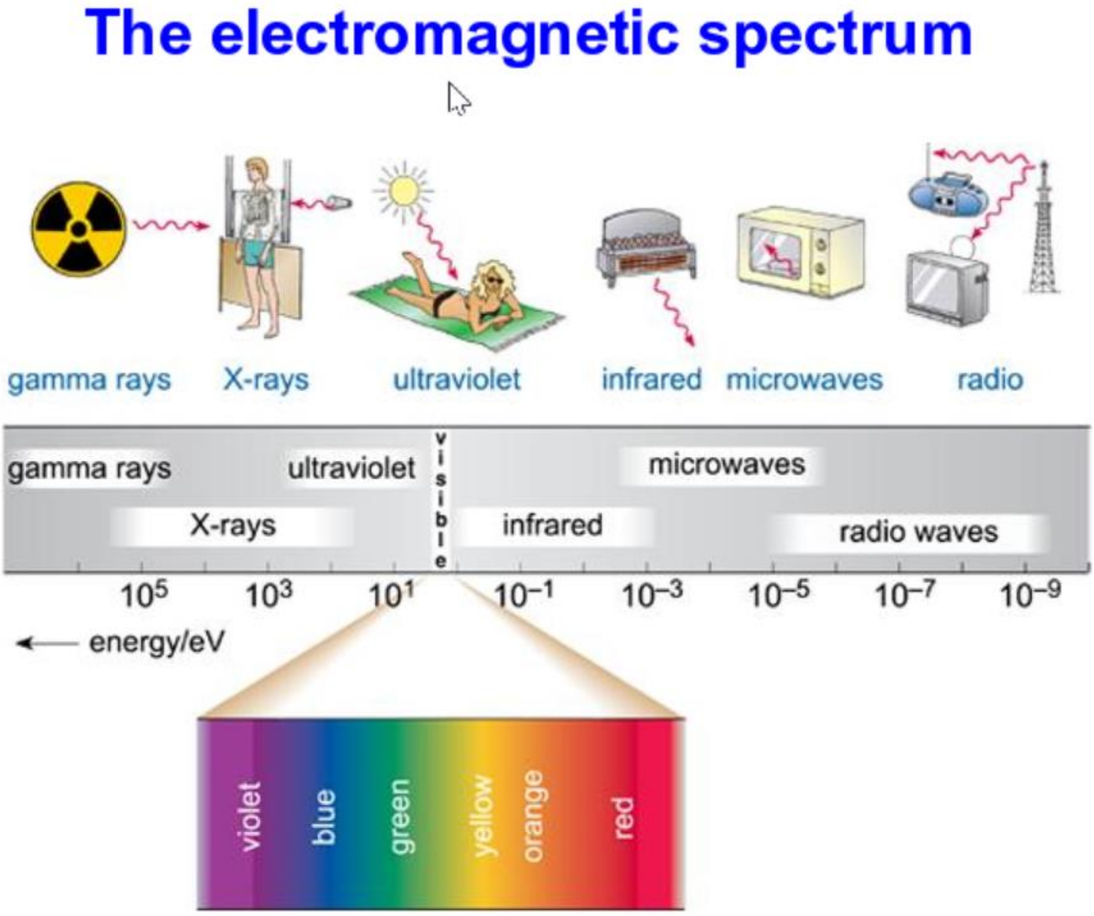
RADIATION PROTECTION NOTE 11:
X-RAY EMITTING DEVICES

This note concerns electrical devices that emit X-rays, such as diagnostic X-ray systems, electron microscopes, crystallography systems etc. Radioactive sources that emit characteristic X-ray radiation as a result of electron movement within the atom are covered in another note.

The use of such devices is governed by the Ionising Radiations Regulations 2017 (IRR17) and overseen by the Health and Safety Executive (HSE). Under IRR17 it may be necessary to apply for Notification/Consent/Registration from the HSE, however, for all devices sited in the Gilmorehill or Garscube Campus the University has the relevant documents.

Nature of X-rays

X-rays are a form of electromagnetic radiation similar to visible light and are part of the electromagnetic spectrum.



As can be seen from the diagram above the main difference between visible light and X-rays is the energy of the radiation. The energy of electromagnetic is given by the formula:

$E = hf \text{ or } E = \frac{h}{\lambda}$; where f = frequency, λ = wavelength, h = Planck’s constant

From the above formula we can see that since the energy of X-ray radiation is greater than that of visible light we can conclude that the frequency (wavelength) of X-rays are higher (shorter) than that of visible light. This combination of high energy and short wavelength gives X-rays their penetrating power and the ability to cause ionisation in matter.

Interaction with matter

X-rays are ionising radiation, that is interaction with X-rays can remove an electron from an atom to leave behind an ion. The mechanisms for this interaction are through the *Photoelectric Effect* and *Compton Scattering*.

The Photoelectric Effect

The photoelectric effect (figure 1) is an absorption process and usually occurs for low energy photons (<0.1 MeV) such as X-rays. The energy E_X of the X-ray is transferred (absorbed) to an inner electron, normally a K-shell electron, and this gives the electron sufficient energy to escape from the atom. The atom is left positively charged (i.e., an ion) and in an excited state due to the vacancy left in the inner shell. This vacancy is quickly filled by another electron dropping down from a higher shell with the subsequent release of a photon of frequency determined by the two shells involved.

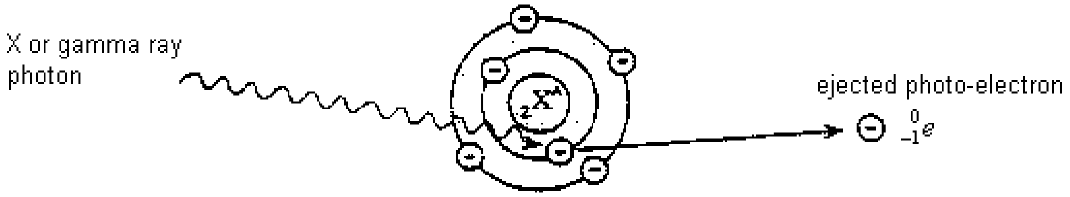


Fig 1: The Photoelectric Effect.

The energy of the ejected electron is given by the simple formula; $E_e = E_X - BE$, where:

E_e = energy of ejected electron
E_X = energy of incoming X or γ ray photon
BE = binding energy of ejected electron.

The ejected electron will then travel through the surrounding medium creating ion pairs in the same way as a beta particle of equivalent energy.

The Compton Effect

The Compton Effect (figure 2) is essentially an inelastic collision process and generally occurs for high-energy photons (>0.1 MeV) such as gamma rays. An incoming photon of high energy (γ - ray) collides with an electron in the valence band, ejecting the electron from the atom. A photon of lower energy (and hence different frequency) than the original is produced that travels at an angle to the direction of the incident photon, determined by conservation of momentum. The energy of the ejected or Compton electron can be determined by knowledge of the energies of the incoming and scattered photons.

As in the Photoelectric Effect, the ejected electron will then travel through the surrounding medium creating ion pairs in the same way as a beta particle of equivalent energy.

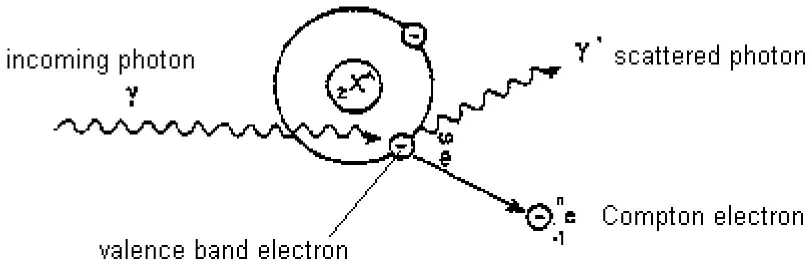


Fig 2: The Compton Effect

Effects on Biological Material

Since X-rays are a form of ionising radiation we need a way to quantify any possible damage to exposed biological material. There is a direct relationship between the amount of energy received to tissue and the subsequent damage to the tissue, we call this relationship the *Absorbed* dose (D_T), defined as

D_T = Energy dissipated per unit mass = J/kg; and is given the symbol Gy (Gray).

Therefore, the dissipation of one joule of energy in one kilogram of tissue is equal to 1 Gy. The Gray is a large unit and normal doses received in working life are generally in the range of microGray (µGy) or milliGray (mGy).

It also turns out that biological tissue responds differently to different types of radiation, this led to the formulation of the 'equivalent dose' (H_T) as follows:

$H_T = W_R D_T$; where W_R is called the 'radiation weighting factor', for X-rays the factor is one. The unit of equivalent dose is called the Sievert (Sv). For X-rays 1 Sv = 1 Gy

A further complication arises as different tissues in the body have different susceptibilities to radiation damage and this led to the formation of the 'effective dose' (E) as follows:

$E = H_T W_T$; where W_T is the 'tissue weighting factor'. Note, if more than one organ is irradiated the effective dose must be summed over all organs affected, as follows:

$$E = \sum_T W_T \; H_T$$

We now have a method for quantifying the damage to biological systems, there are two ways in which damage from ionising radiation manifests itself, these are called 'deterministic' and 'stochastic' effects.

Deterministic Effects (see also Note 4)

Deterministic effects are those that are certain to occur after a 'threshold dose' of radiation is reached. An example of this is an erythema (skin burn) which will occur if skin is exposed to a radiation dose in excess of 250 mSv, the severity of the effect increases with increasing dose. The following table (taken from note 4) indicates the correlation between dose received and various clinical effects, note below approximately 250 mSv there is no obvious effects.

Dose (Sv)	**Clinical Effect**
0 → 0.25	No obvious injury
0.25 → 0.50	Possible blood changes
0.50 → 1.00	Blood cell changes, some injury, no disability
1.00 → 2.00	Injury, possible disability, nausea/vomiting within 24 hrs
2.00 → 4.00	Injury and disability certain, death possible
> 4.00	50% probability of death

Table 1: Clinical Effects of Acute Radiation Exposure (ICRP 60)

Stochastic Effects (see also note 4)

Stochastic effects are those that have a probability of occurrence but are not certain. Analogous to this is the probability of a smoker developing lung cancer from the smoking of cigarettes. In the case of ionising radiation, the probability of an adverse effect is determined by a risk factor (ICRP 26 and 103) given as;

Fatal cancer –	4% per Sv
Non-fatal cancer –	1.2% per Sv
Hereditary effects -	0.6% per Sv

Note the Sievert is a very large unit. The current dose limit (IRR17) for stochastic effects is 20 mSv effective dose per year, within the University we have a target effective dose limit of < 1 mSv per year.

Generation of X-rays

It is known, that, an accelerating (or decelerating) electric charge will emit electromagnetic radiation. This effect is generally called *Bremsstrahlung* and is the basis for the generation of X-rays in electrical devices.

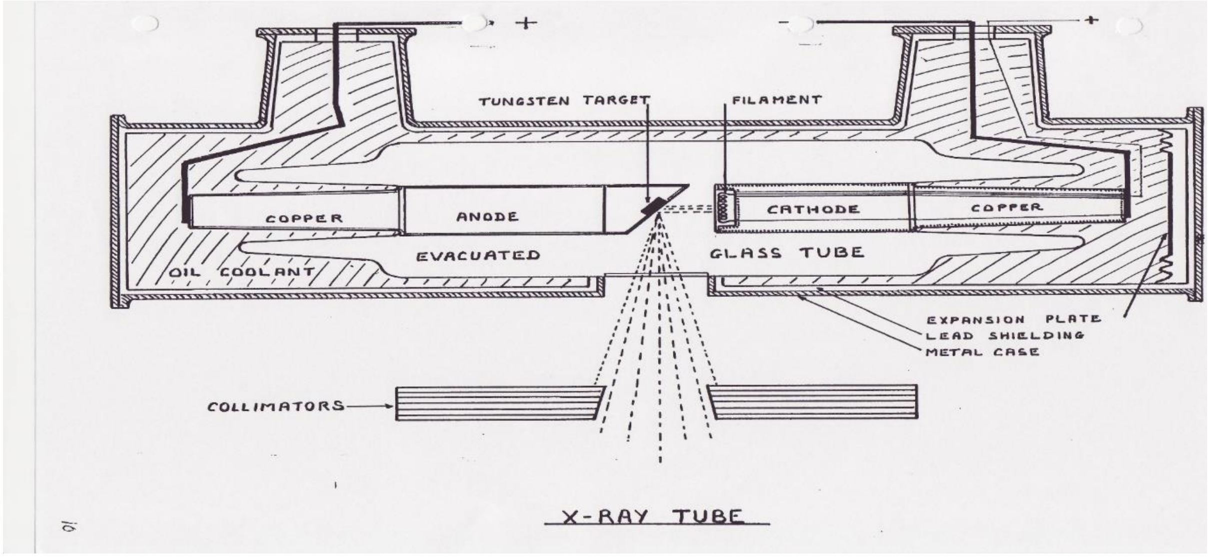


Fig. 3

The above diagram shows a simple X-ray device. A heated filament at the cathode provides a source of electrons, a high voltage is applied between the anode and cathode causing the electrons to accelerate towards the anode. A high density material, such as tungsten, is attached to the anode in the path of the incoming electrons, resulting in the rapid deceleration of the electrons and in the generation of electromagnetic radiation in the form of X-rays (the conversion rate of the energy of the electrons to X-ray radiation is of the order 1%, with the rest of the energy dissipated as heat). The tube is shielded apart from a small window to allow the primary beam to exit, collimators are used to further reduce the dimension of the primary beam to suit the required purpose.

The output from the X-ray tube is a continuous spectrum as shown below:

Features of the spectrum include:

- Low energy cut off – due to heavy attenuation from the components of the X-ray tube
- High energy cut off – due to occasional 100% conversion
- Characteristic peaks – due to characteristic emission from the target material

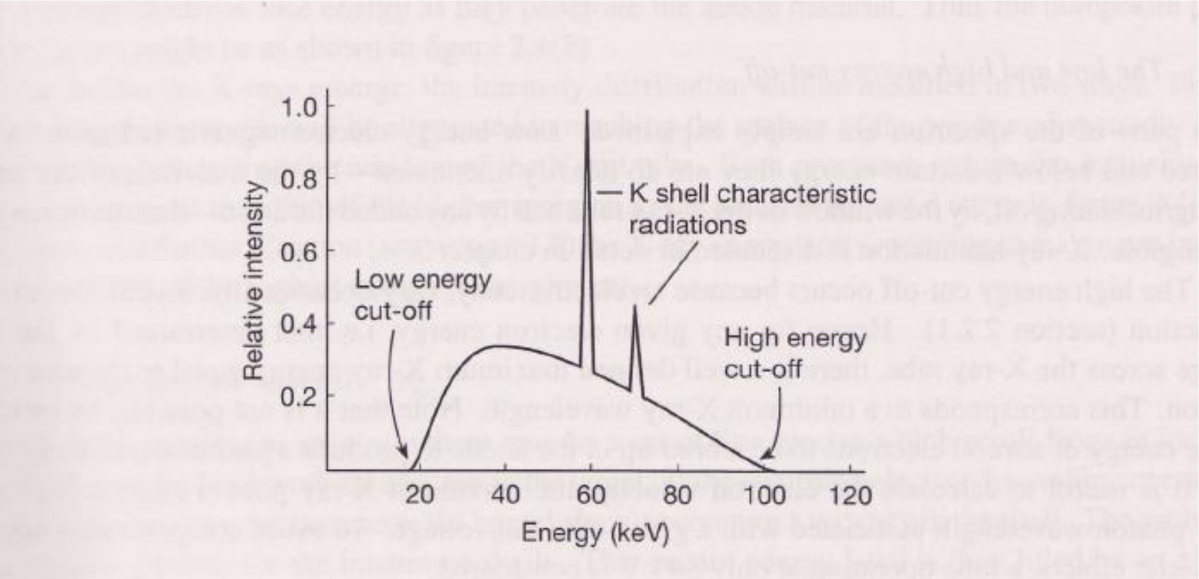


Fig. 4

Factors affecting the spectrum include:

- Tube current – affects the intensity of the output and therefore the resulting dose rate
- Exposure time – as above for tube current
- Tube voltage – affects the 'quality' of the spectrum, shifts the peak voltage higher/lower
- Filtering – affects the 'quality' of the beam by narrowing the spectrum to a desired range of energies
- Target – the shape of the spectrum depends greatly on the target material

Note: Manufacturers normally express tube voltage as kV_p*, this is the maximum voltage applied across the tube and not the peak of the voltage spectrum, e.g. from fig 4* kV_p *= 100 keV, the 'peak' of the spectrum @ 40 keV is called the 'effective energy'.*

Safe use of X-ray generating equipment

Engineering Controls

It is a requirement, in law, for manufacturers of devices that are intended to emit X-ray radiation to incorporate built-in engineering safeguards. These may include;

- Variable collimators to adjust the size of the beam
- Positioning systems for targeting without X-ray emission
- Filters to remove unnecessary energies
- Triggering mechanism to limit exposure time
- Tube voltage and/or tube current adjustments
- Remote triggering systems
- Proximity cut-off systems for hand held devices
- Warning lights when X-rays are being emitted

Additional to built-in controls

- Mobile shields and PPE
- Interlock systems for unauthorized entry to the X-ray area
- Fully enclosed and shielded cabinets
- Shielded bunkers and mazes

When operating an X-ray emitting device you must be trained in the use and operation of all engineering controls and safety systems.

When operating or designing home made systems you should try to incorporate as many of the above systems into your device as possible.

Administration Controls

All areas where X-ray systems are in operation must have well designed administration controls in place. Including;

- Warning lights, these are in addition to any warning lights built-in to the system. The lights should be placed on the entry way to the X-ray area and should be of the 'fail to safe' type ideally integrated to the X-ray unit itself. If it is not possible to integrate the warning lights to the unit then multiple redundant warning lights should be considered, the operation of such to be detailed in the local rules.

- Warning signs, if the X-ray area is considered a permanent arrangement then warning signs should be affixed to the entry way. If the X-ray system is mobile then a method of displaying warning signs must be predetermined.

- Demarcation of area, if the X-ray unit is fixed then the boundary walls of the X-ray room are used to demark the area. If the unit is mobile then the common method is to demark an area no less then 2 m radius around the unit using X-ray warning tape and appropriate signage.

- Area classification, if the boundary walls are 2 m or less from the X-ray unit then the entire area is a 'Controlled Radiation Area[1]' when the unit is energised. If the unit is within a much larger area with boundary walls > 2 m from the unit then it is possible to make the area a 'Supervised Radiation Area' provided an area of 2 m surrounding the X-ray unit is demarcated.

- Local rules, this is a requirement under IRR17. Local rules must specify the detailed procedures in place for the safe operation of the X-ray system, the name and contact details of the local radiation supervisor, emergency procedures etc

- Risk assessment, this is a requirement under IRR17. The risk assessment must identify all foreseeable risks of using the equipment and the local rules document the procedures for minimising these potential risks.

- Staff training, all users must be trained in the safe use of any X-ray emitting devices, training logs must be kept.

- Worker registration, all persons working with ionising radiations (all types) must be prior registered with the University Radiation Protection Service. The URPS will determine if the worker is 'classified' or 'unclassified' radiation worker.

- Dosimeters, the URPS will determine if a worker is to receive a dosimeter. This depends on the workload of the individual and a prior dose assessment of the equipment.

Further Information

The use of X-ray generating equipment can be hazardous, typical output from an X-ray tube is summarised below;

Location	Dose Rate
Primary Beam at X-ray Tube Port	Several hundred Sv per second
Primary Beam at end of 10cm Collimator	Several hundred Sv per minute
Scattered Radiation	<1 μSv/h – Several Hundred mSv/h, depending on distance

Because of this skin burns from the primary beam can occur in a very short time (< 1 s), care must be taken to avoid exposure to the primary beam. Scattered radiation, in general, will not lead to a deterministic effect but we have to be cognisant of potential stochastic effects and limit exposure to As Low As Reasonably Practicable (ALARP). Use of leaded PPE, typically 0.25 to 0.3 mm lead equivalent, is recommended.

Shielding

X-rays, unlike beta or alpha radiation, cannot be physically stopped by shielding, the best we can manage is to attenuate the incoming radiation. The formula for attenuation is given by;

- $I = I_0 e^{-\mu x}$; where μ is linear absorption coefficient, x is thickness of absorber
- HVL (half value layer) = $0.693/\mu$

The linear absorption coefficient (μ) is a measure of the density of material, with units in reciprocal length. High density materials, like lead, are better for shielding X-rays than low density materials.

The half value layer (HVL) is a useful concept in easily determining the correct thickness of shielding required for a specific task. The HVL for X-rays is dependent on the energy of the beam as follows:

	Half-Value Layer, mm (inch)	
Peak Voltage (kVp)	**Lead**	**Concrete**
50	0.06 (0.002)	4.32 (0.170)
100	0.27 (0.010)	15.10 (0.595)
150	0.30 (0.012)	22.32 (0.879)
200	0.52 (0.021)	25.0 (0.984)
250	0.88 (0.035)	28.0 (1.102)
300	1.47 (0.055)	31.21 (1.229)
400	2.50 (0.098)	33.0 (1.299)
1000	7.90 (0.311)	44.45 (1.75)

Summary

Before working with X-ray equipment, you should be familiar with:

- The radiation hazards associated with the system
- The significance of the warning signs, safety devices and interlocks
- The safe operating procedures (SOP) for the equipment
- The Local Rules
- Equipment Risk Assessment
- Generic Authorization - HSE
- How to recognize the symptoms of an acute localized exposure
- Procedures for reporting accidental exposures
- When was the equipment last serviced/leak tested
- Log of usage

For further information on radiation protection within the University of Glasgow, visit our website @ https://www.gla.ac.uk/myglasgow/radiationprotection/