X-rays: uses and dangers

Introduction

Although X-rays have many uses people generally associate them with their use in medical *diagnostics*. X-rays can pass through soft body tissues relatively easily but are stopped to some extent by denser *tissues* such as bone. For many years after their discovery in the 1870s, scientists investigated their properties but were largely unaware of the dangers associated with them.

As with all sources of ionising radiation, their use results in a radiation dose and an increased risk of *cancer* later in life. Small doses from diagnostic X-rays carry a small risk, while larger doses or repeated use carry a higher risk.

Discovery

The German physicist Wilhelm Röntgen is usually credited with the discovery of X-rays in 1895; in fact others were aware of their existence about twenty years earlier but had not studied them to the same extent. Röntgen took an X-ray photograph of his wife's hand to demonstrate their possible medical use.

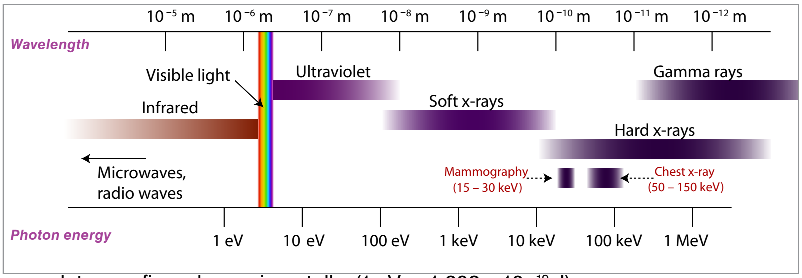
Röntgen's first X-ray photograph – of his wife's left hand

What are X-rays?

X-rays are *electromagnetic waves* having the same nature as visible light, *ultra violet*, *infrared*, radio waves and *microwaves*, etc. These types of electromagnetic radiation differ in their *wavelength*; those with shorter wavelength have greater energy. The energy of *photons* of ultraviolet and X-rays is sufficient to break *chemical bonds* and so these radiations are said to be *ionising*. *Gamma rays* are like high energy X-rays and are mainly produced in nuclear interactions such as radioactive decay. *Cosmic rays*, which are believed to come from exploding stars (*supernovae*), have even greater energy than gamma rays; they have been found to consist mainly of high energy *protons* and are largely blocked by the atmosphere. They generate gamma rays when they collide with molecules in the atmosphere or indeed in living things.

Energy and wavelength

Albert Einstein was awarded the Nobel Prize, not for his theory of *relativity* but for his explanation of the *photoelectric effect*. This effect was first noticed by Heinrich Hertz in 1887. A negatively charged *gold-leaf electroscope* can be discharged by shining short wavelength light on it; the minimum energy required depends on the metal used to make the cap of the electroscope. In 1905, in his explanation of this phenomenon, Einstein proposed that light behaved as a stream of particles, which he called photons. The energy of a photon was *directly proportional* to the frequency (or *inversely proportional* to the wavelength, since $f = c / \lambda$): $E = h.f$ or $E = h\,c / \lambda$, where E is the energy in *joules*, h is Planck's constant (6.626×10^{-34} J s), f is the frequency of the radiation in *hertz*, c is the speed of light in metres per second and λ is the wavelength in metres. Photons of sufficient energy (usually measured in electron-volts, eV) could eject electrons from the surface of a metal; any excess energy appeared as kinetic energy of the ejected electron. This was later confirmed experimentally. (1 eV = 1.602×10^{-19} J)



The electromagnetic spectrum

Wave-particle duality

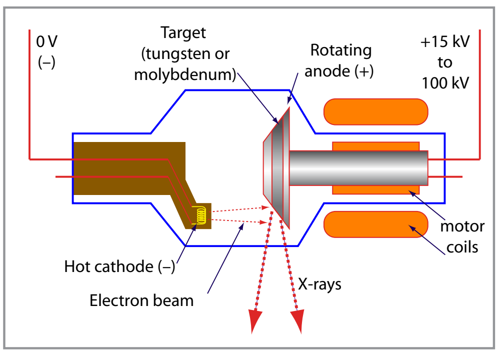
The fact that light could behave as a particle suggested that particles such as electrons, and even protons and *neutrons*, might behave as waves. This was proposed in 1924, by Louis-Victor de Broglie and was demonstrated, in the case of electrons, by George Thompson (in Aberdeen) and Clinton Davisson (in the USA). *Diffraction* of neutrons was first demonstrated in 1945. (In more recent decades the wave nature of molecules has been demonstrated.)

The higher the energy of a photon the more it appears as a particle; the lower its energy the more it appears as a wave.

The diagram above lists the different types of electromagnetic radiation and the wavelength and energy associated with each. Those with wavelengths somewhat less than that of visible light can break chemical bonds and so ionise atoms or molecules. The upper boundary wavelength of ionising radiation is variously set at 250 nm (*nanometre*), 100 nm, 50 nm and 10 nm, all of which are in the ultraviolet region of the electromagnetic spectrum. A 250 nm photon can break a carbon-carbon bond and so is capable of damaging bio-molecules. X-rays have even shorter wavelengths than UV and so are more hazardous. High energy X-rays (those with wavelengths less than about 0.2 nm) are called *hard X-rays* and are more penetrating; those with lower energy are called *soft X-rays*.

How are X-rays produced?

In a typical X-ray tube a beam of electrons is accelerated by a high voltage (15 kV to 150 kV) and strikes a metal *anode*, causing some electrons in the metal atoms to move to higher *energy levels*. When the electrons return to their normal state they emit the excess energy as electromagnetic radiation. If the energy difference is relatively small visible light might be emitted; this happens in the screens of *oscilloscopes* and older television sets. If the energy difference is sufficiently large then X-rays may be emitted. In practice the process is quite inefficient and about 99% of the energy used just heats the metal target.



X-rays: uses and dangers

In order to dissipate the heat the target is usually cooled and rotated. Different metals emit different characteristic X-rays.

Tungsten and *molybdenum* are commonly used as target metals.

X-rays are also emitted by the beam of electrons as they are decelerated by heavy nuclei (i.e. those with large positive charge). This 'braking radiation' (the so-called '*bremsstrahlung*' radiation) has a wide spectrum, in contrast to the characteristic emissions from the electrons of the target atoms.

X-ray applications

Common applications of X-rays include medical imaging and airport security scanning. Denser materials require higher energy X-rays; for this reason hard X-rays are used for examining welds in metal. Softer X-rays are used in mammography and intermediate energy X-rays are used for whole body imaging.

Radiation dose

The average radiation received by people in Ireland is about 4000 μSv (*microsievert*) per annum. About 86% comes from natural sources and about 14% from artificial sources. By far the largest source of natural radiation that people in Ireland are exposed to is *radon* in the home; the average dose per person from radon is about 2000 μSv, but some people receive many times this dose.

Radiation Source	**Natural Dose (μSv)**	**Artificial Dose (μSv)**
Cosmic Radiation	9%	
Gamma Radiation from Soils	8%	0%
Radon in Homes	52%	
Thoron in Homes	7%	
Radioactivity in Food	6%	0%
Occupational Exposures	5%	0%
Patient Exposures		
Diagnostic X-ray examinations		13%
Nuclear medicine (e.g. Bone Scan)		1%
TOTAL (3950)	**86%**	**14%**

Most of the artificial radiation we receive is from medical X-rays. Again, the actual dose received varies greatly from person to person. Since all ionising radiation is hazardous, the use of X-rays should be limited to necessary procedures.

Licensing

In Ireland a licence must be obtained from the Radiological Protection Institute of Ireland (RPII) for the custody or use of sources of ionising radiation whether for educational, industrial or medical purposes. Records must be kept of all uses of ionising radiation and authorisation must be obtained for disposal of radioactive materials.

Radiological Protection Institute of Ireland
An Institiúid Éireannach um Chosaint Raideolaíoch

Radiological Protection Institute of Ireland

The Radiological Protection Institute of Ireland (RPII) is an independent scientific organisation under the aegis of the Department of Environment, Heritage and Local Government.

Since its establishment in 1992, the RPII has played a vital role in:

- Educating the public on the risks of ionising radiation
- Contributing to Government policy on radiation protection matters
- Licensing and regulating the possession and use of ionising radiation in medicine, industry, research and education
- Maintaining a national laboratory for the measurement of radioactivity levels in the environment
- Providing an instrument calibration service
- Assisting in the development of national plans to deal with nuclear accidents and incidents
- Conducting and promoting research on a range of areas relevant to radiation protection
- Drawing up national radon maps indicating the geographic areas most likely to be affected by high indoor radon concentrations
- Driving forward programmes of radon measurement and remediation in homes, workplaces and schools
- Representing Ireland on international bodies dealing with radiation protection and nuclear matters
- Cooperating with radiation protection authorities and other relevant organisations overseas.

Find out more about the work of Radiological Protection Institute of Ireland at **www.rpii.ie**

Find this and other lessons on **www.sta.ie**

Syllabus References

The relevant syllabus references are:

Leaving Certificate Physics (p. 27, 29, 41; pp 33, 39, 41)

- Potential energy and kinetic energy. Mass as a form of energy.
- Conversions from one form of energy to another. Principle of conservation of energy.
- Mass transformed to other forms of energy in the Sun.
- Radiation from the Sun. Solar constant (solar irradiance).
- Principles of fission and fusion. Mass-energy conservation in nuclear reactions, $E = mc^2$.
- Fusion: source of Sun's energy. Ultraviolet and ozone layer.
- Electromagnetic spectrum. Relative positions of radiations in terms of wavelength and frequency. Detection of UV and IR radiation.
- X-rays produced when high-energy electrons collide with target.
- X-ray tube. X-ray production as inverse of photoelectric effect.
- Mention of properties of X-rays: electromagnetic waves, ionisation, penetration. Uses of X-rays in medicine and industry. Hazards.

Science and Technology in Action is widely used for project work in **Transition Year**.

Learning Outcomes

On completion of this lesson, students should be able to:

- Distinguish between the different kinds of electromagnetic waves
- Distinguish between ionising and non-ionising radiation
- Explain why ionising radiation is dangerous
- Describe what is meant by the photoelectric effect and outline its implications
- Outline what is meant by wave-particle duality
- Outline how X-rays are produced
- State the approximate contribution of medical X-rays to the average dose of ionising radiation received by people in Ireland.

General Learning Points

The following points can be used to enhance the lesson content and to inform discussion.

- There are many kinds of electromagnetic radiation; some are ionising (UV, X-rays, gamma rays) and some are not (visible light, infrared, microwaves and radio waves).
- Ionising radiation can break chemical bonds and so can interfere with biological systems.
- Most (over 80%) of the ionising radiation we receive is from natural sources.
- Hard X-rays have shorter wavelength and are more penetrating. They are used in examining welds in metal.

Student Activities

1. Research the history of the development of medical X-rays and summarise your findings on a poster. (This may be done as a group exercise.)
2. Investigate developments in the use of multiple frequency medical X-rays for detection of abnormal tissue growth.
3. Explore the section called "Your Health" on the RPII website. Study the subsection called "Health risk" and summarise your findings in a poster.
4. **Mammography**: Scans for breast cancer generally employ X-rays. However they do not always clearly distinguish between dense tissue and tumours. If 10% of the 'positive' results are doubtful which of the following options should doctors take:
   a) ignore all doubtful results (and risk missing some positive results)
   b) regard all doubtful results as 'positive' and offer further tests (and risk some 'false positives')
   c) make a 'best guess'.
5. **New techniques**: New scanning techniques employing 'near infrared' (NIR) are being developed to complement X-ray mammography. Because this 'optical mammography' does not use ionising radiation, multiple scans have no cumulative effect. The technique can distinguish between water, fat tissue, oxygen-rich tissue and oxygen-poor tissue. Find out more about this development and summarise your findings in a suitable format (e.g. poster, article, PowerPoint, drama etc.)

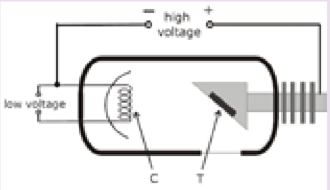
True/False Questions

a)	X-rays are non-ionising.	T	F
b)	The typical energy of medical X-rays is hundreds of times greater than that of visible light.	T	F
c)	The typical energy of microwaves is hundreds of times less than that of visible light.	T	F
d)	X-rays were discovered by Marie Curie.	T	F
e)	The X-rays used in examining welds in metal are more penetrating than medical X-rays.	T	F
f)	The maximum energy of X-rays is directly proportional to the voltage used to generate them.	T	F
g)	There is no danger associated with medical X-rays.	T	F
h)	Most of the ionising radiation we receive is artificial.	T	F
i)	Mobile phones emit ionising radiation.	T	F
j)	The average dose of ionising radiation that people in Ireland receive is about 4000 microsievert per annum.	T	F
k)	Hard X-rays have shorter wavelength than soft X-rays.	T	F

Check your answers to these questions on www.sta.ie.

Examination Questions

Leaving Certificate Physics (HL) 2004, Q. 12 d



The diagram shows an X-ray tube.

What are X-rays?

How are electrons emitted from the cathode C?

What is the function of the high voltage across the X-ray tube?

Name a suitable material for the target T in the X-ray tube.

Give one use of X-rays.

Leaving Certificate Physics (HL) 2010, Q. 9

What is thermionic emission?

X-rays are produced when high-energy electrons collide with a target. Draw a labelled diagram of an X-ray tube.

What are X-rays and how do they differ from light rays?

Give two uses of X-rays.

When electrons hit the target in an X-ray tube, only a small percentage of their energy is converted into X-rays. What happens to the rest of their energy and how does this influence the type of target used?

A potential difference (voltage) of 40 kV is applied across an X-ray tube.

Calculate:

(i) the maximum energy of an electron as it hits the target

(ii) the frequency of the most energetic X-ray produced.

(Plank constant = 6.6×10^{-34} J s ; charge on electron = 1.6×10^{-19} C)

Leaving Certificate Physics (HL) 2001, Q. 3

(i) Give two differences between X-rays and cathode rays.

(ii) Name the scientist who discovered X-rays

(iii) How might cathode rays be detected?

(iv) What is thermionic emission?

(v) Give two ways by which a beam of electrons may be deflected.

(vi) The work function of zinc is 6.9×10^{-19} J. What is the minimum frequency of ultraviolet radiation that will cause the photoelectric effect to occur in zinc? (Planck constant, $h = 6.6 \times 10^{-34}$ J s.)

Leaving Certificate Physics (HL) 2006, Q. 12 (part)

The first Nobel Prize in Physics was awarded in 1901 for the discovery of X-rays. What are X-rays? Who discovered them?

In an X-ray tube electrons are emitted from a metal cathode and accelerated across the tube to hit a metal anode. How are the electrons

(i) emitted from the cathode; (ii) accelerated?

Calculate the kinetic energy gained by an electron when it is accelerated through a potential difference of 50 kV in an X-ray tube. Calculate the minimum wavelength of an X-ray emitted from

Did You Know?

- X-ray images were formerly captured on photographic film which then had to be developed. This was expensive (because of the amount of silver used in the film) and slow (because the film had to be developed, which would take several minutes).
- In recent years digital sensors have largely replaced film. Images are produced quickly or in real time and because they are already digitised they can be transmitted electronically to consultants elsewhere.
- Since 1999 the use of silver in the production of photographic film (including X-ray film) has declined from about 26% of total annual silver consumption to about 5% (in 2013), mainly due to developments in digital photography

Biographical Notes

Marie Curie (1867 –1934)

Maria Skłodowska was born in Warsaw, Poland in 1867. At the time Poland was occupied by Russia and the Polish language was suppressed. However, she received a good education in a Polish 'university' that operated in secret. In 1891 she moved to Paris and became a distinguished student at the Sorbonne and later became its first female professor. She married Pierre Curie in 1895. They cooperated in tediously isolating and identifying radioactive materials and for their efforts they, along with Henri Becquerel, were awarded the Nobel Prize in Physics in 1903. She won the Nobel Prize in Chemistry in 1911. She was the first woman to win a Nobel Prize.

When war broke out in 1914 she campaigned and raised funds to set up about twenty mobile X-ray units for use at the front. She and her daughter Iréne operated one of these in difficult circumstances. It is likely that the high X-ray doses she received in this work caused the cancer which eventually killed her.

"I am resolved to put all my strength at the service of my adopted country, since I cannot do anything for my unfortunate native country just now..." *letter from Marie Curie to Paul Langevin, January 1, 1915*

Revise The Terms

Can you recall the meaning of the following terms? Revising terminology is a powerful aid to recall and retention.

anode, cancer, chemical bond, cosmic rays, cumulative, diagnostics, diffraction, directly proportional, electromagnetic waves, energy levels, frequency, gamma rays, gold-leaf electroscope, hard X-rays, hertz, inversely proportional, ionising, joule, mammography, microsievert, molybdenum, nanometre, neutron oscilloscope, photoelectric effect, photon, radon, relativity, soft X-rays, supernova, tissue, tungsten, wavelength.

Check the Glossary of terms for this lesson on www.sta.ie