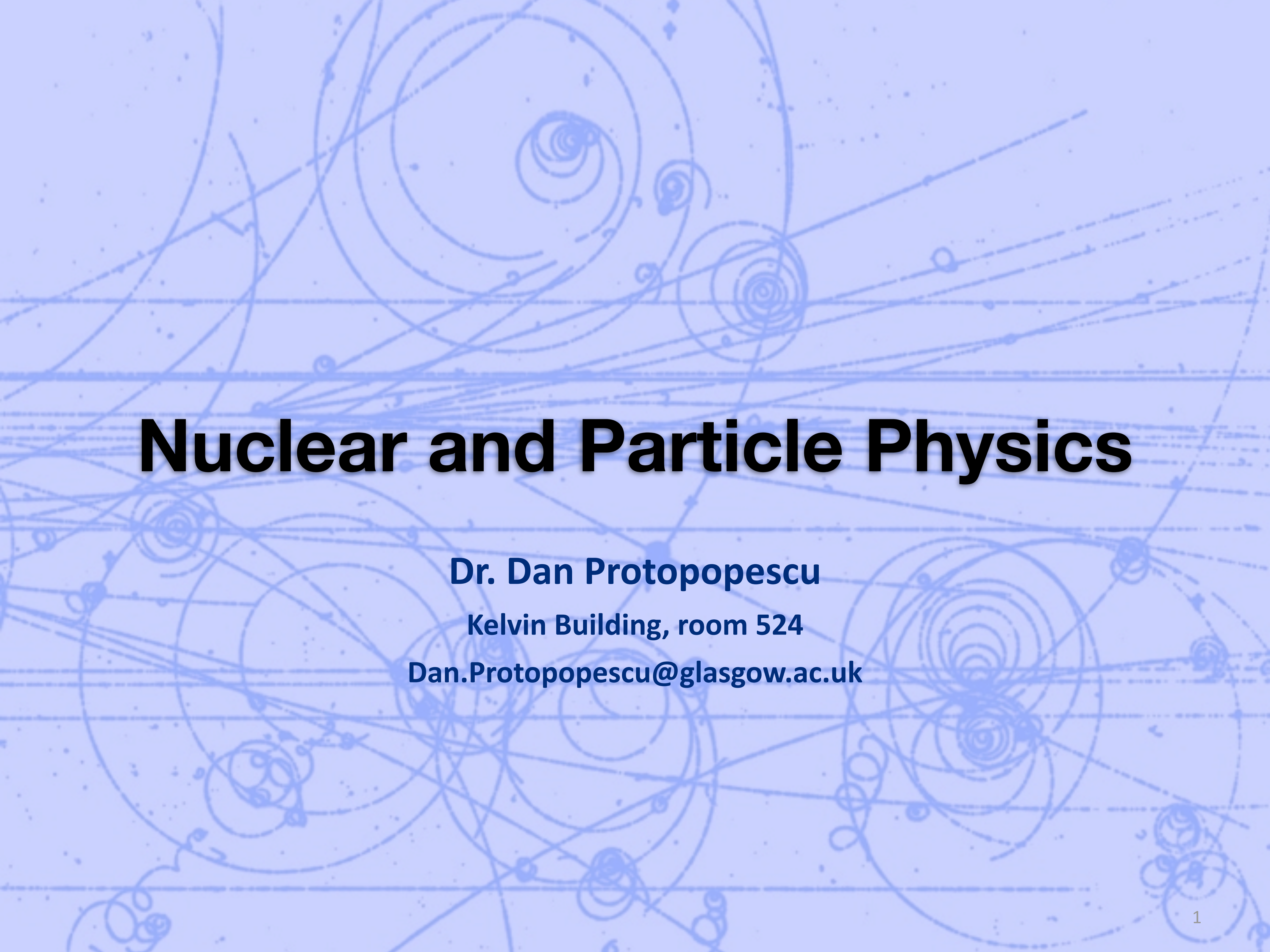

Nuclear and Particle Physics

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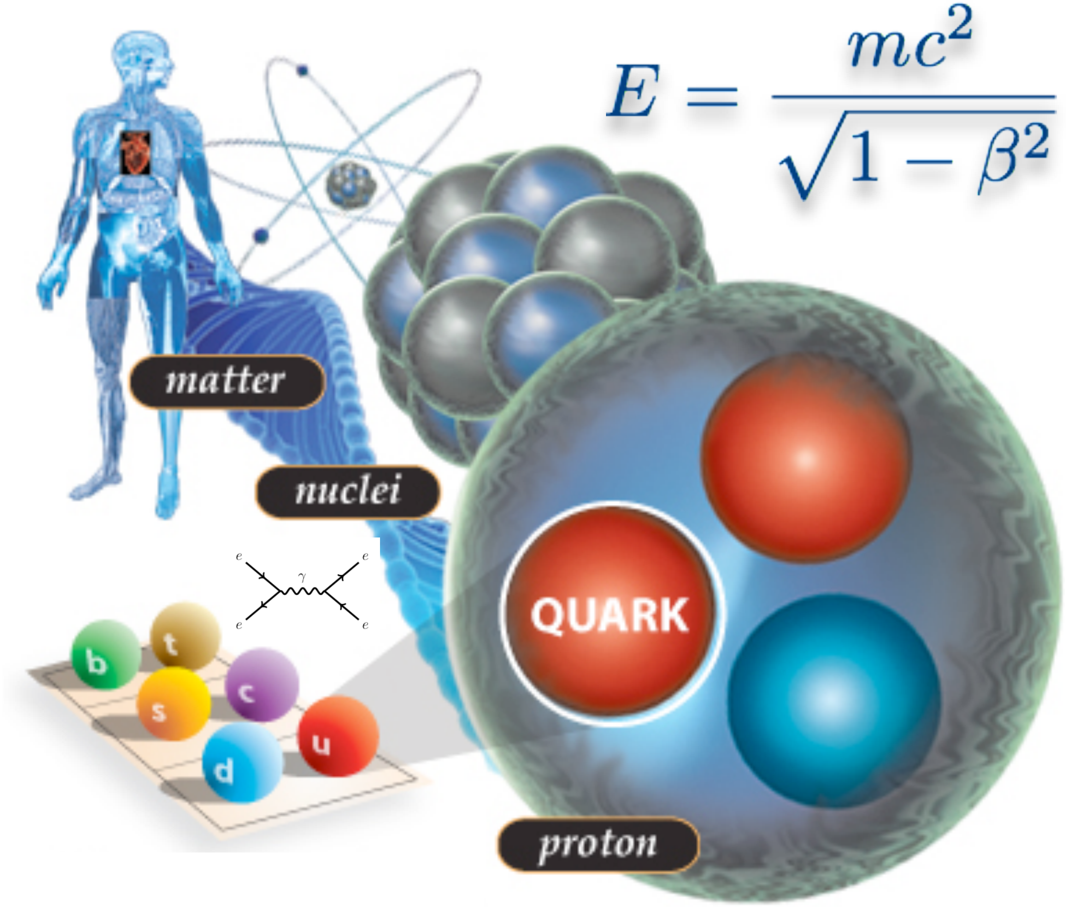
Topics covered in this course

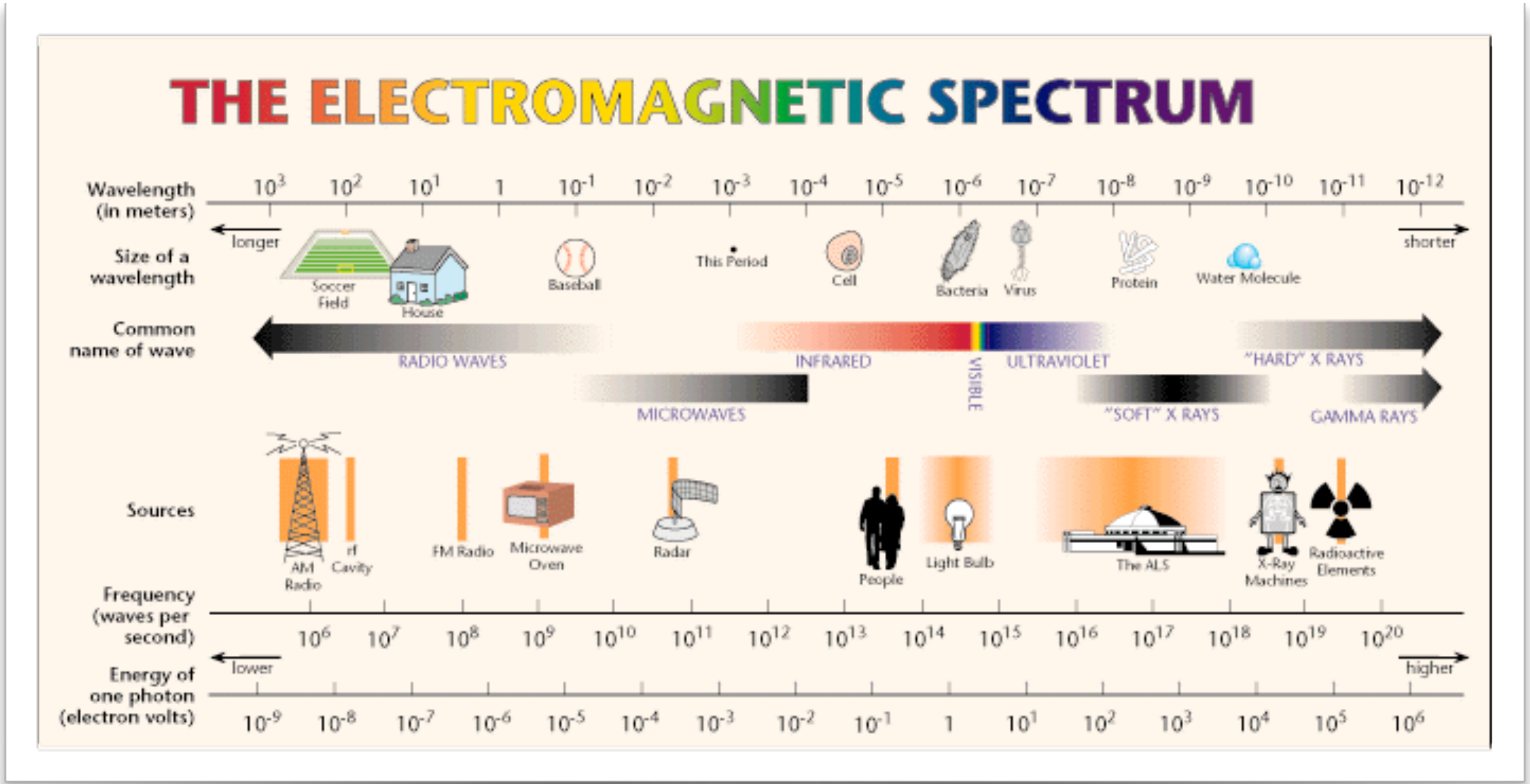
I. Radiation
II. Atomic nuclei
III. Radioactivity and radioactive decay
IV. Nuclear reactions
V. Fundamental forces and particles
VI. Quark model of hadrons
VII. Special relativity theory



Radiation

What is radiation ?

- Radiation is defined as energy travelling in the form of particles or waves
- *Ionising* and non-ionising radiation
- *Alpha (α) radiation*
- *Beta (β) radiation*
- Electromagnetic spectrum: X and gamma (γ) rays



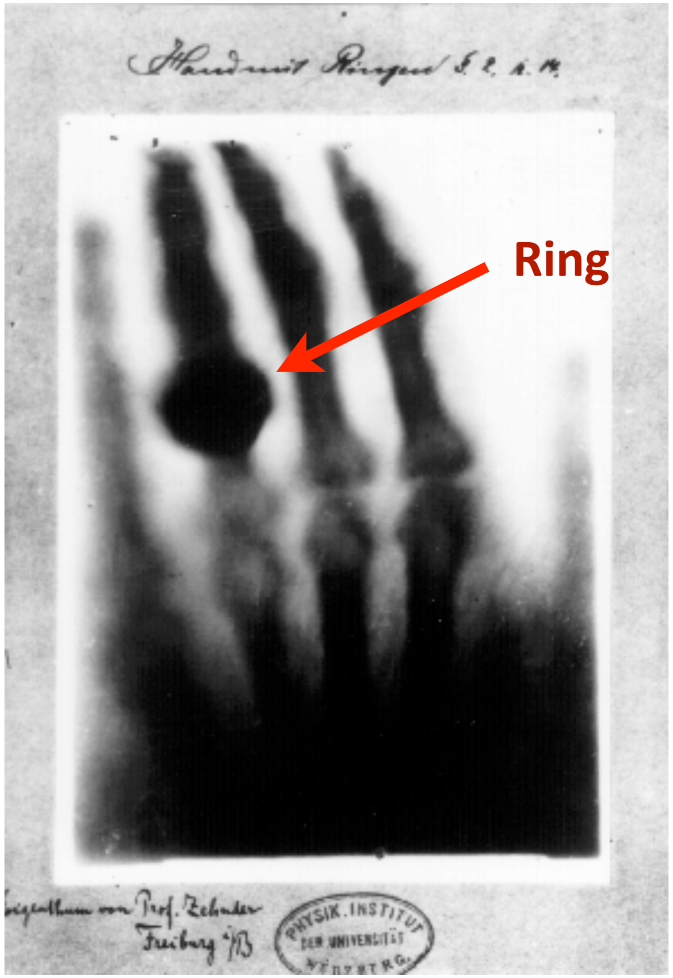
A word about units

- Typically in nuclear and particle physics, energies are measured as electron volts: eV
  - 1eV = energy gained by an electron when it moves through a potential difference of 1V
  - 1eV = $1.602\text{x}10^{-19}$ C x 1V = $1.602\text{x}10^{-19}$ J

- Masses can also be quoted in terms of eV
- Use $E=mc^2$
- Then we can relate masses to energy with $m=E/c^2$
  - For example the mass of a *proton*: $m_p = 1.672621637(83)\times10^{-27}$ kg, but this is somewhat unwieldy
  - Instead convert to eV:
    $E = 1.673\times10^{-27}\text{kg x }(3\text{x}10^8\text{ms}^{-1})^2 = 1.505\text{x}10^{-10}\text{J}$
    $= 1.505\text{x}10^{-10}\text{J}/1.602\text{x}10^{-19}\text{J/eV}$
    $= 939.45\text{MeV}/c^2\ \ (\simeq 1\text{GeV}/c^2)$

Discovery of X-rays

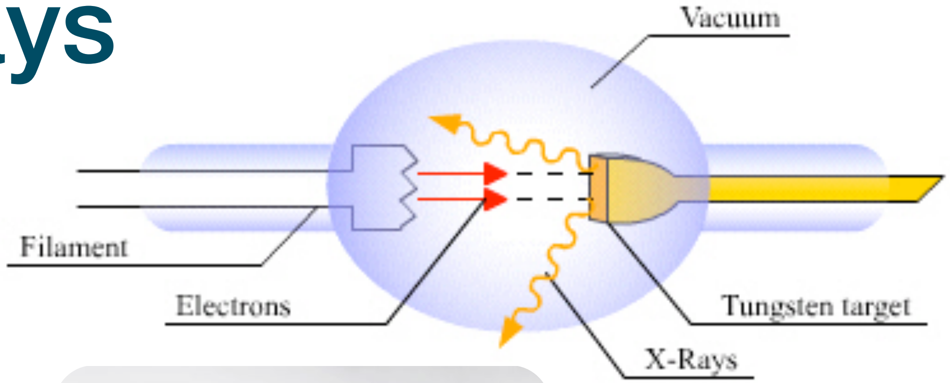
- X-rays were discovered by *Wilhelm C. Roentgen.* While he was studying cathode rays using a Hittorf-Crookes tube, he observed a glow from a fluorescent screen on a nearby table
- He determined that the fluorescence was due to penetrating rays that were being emitted from the tube
- Two weeks later, Roentgen took a picture of his wife's hand and demonstrated that X-rays could be used as a medical diagnostic tool

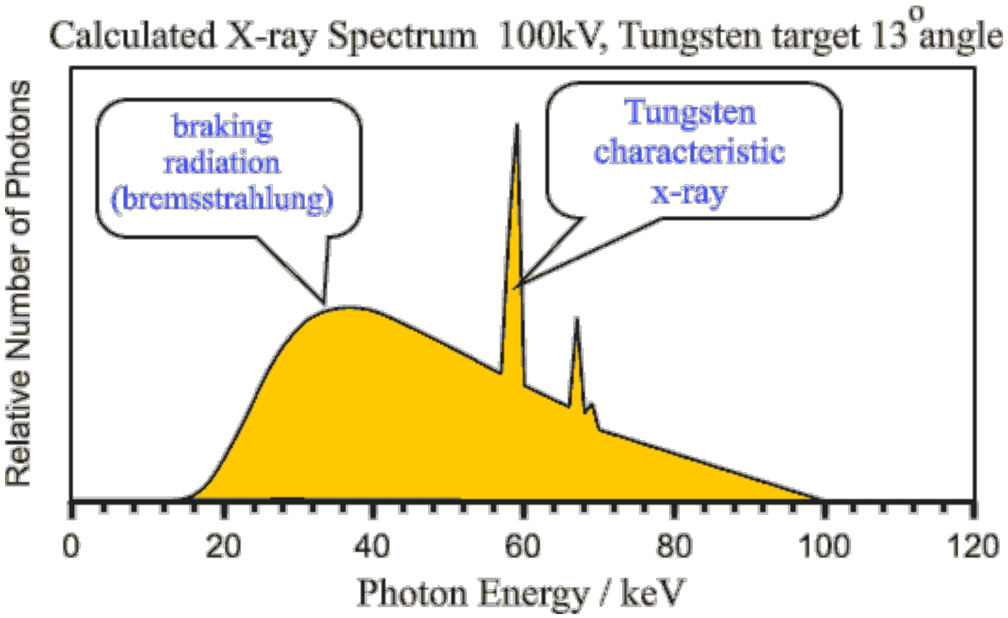


X-ray image of Anna Roentgen's hand

X-rays

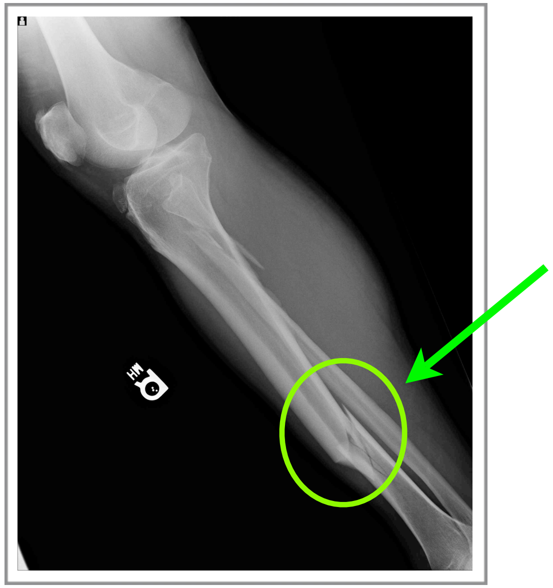
- X-rays are generated by:
  - ***Fluorescence***
    an electron knocks out a inner orbital electron and a high energy photon is emitted when the vacant energy level is filled by an electron moving from an outer orbital level.
    This process produces X-rays of specific energies.
  - ***Bremmstrahlung***
    Breaking radiation due to electrons decelerating in the electric field of nuclei.
    This produces a *continuous* spectrum of X-rays.
- Typical X-ray energies are in the keV range



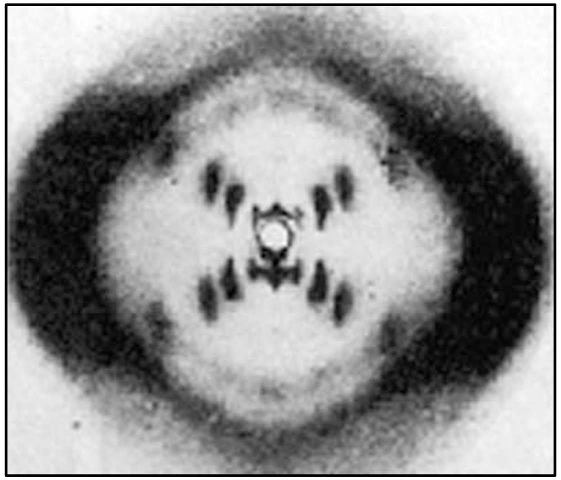

Calculated X-ray Spectrum 100kV, Tungsten target 13°angle

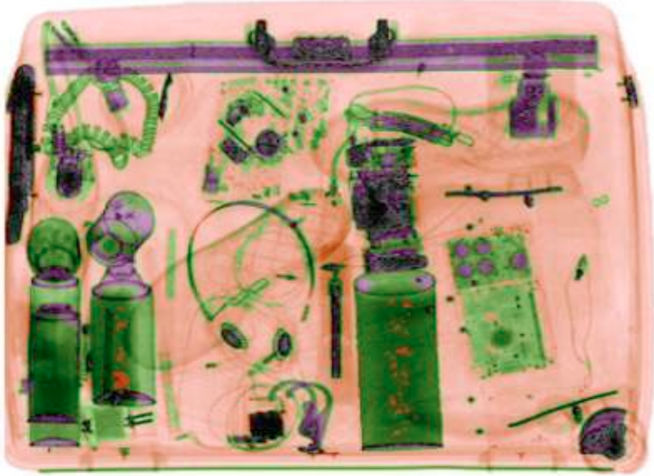
X-rays everywhere

- Medical applications
  - Diagnosis via imaging
  - Cancer treatment via radiotherapy
- X-ray crystallography
  - Discovery of DNA (W. Ashbury, 1937)
- X-ray astronomy
  - Complementary to visible light astronomy
- Airport security
  - baggage scan
  - backscatter X-ray systems (banned by EU)



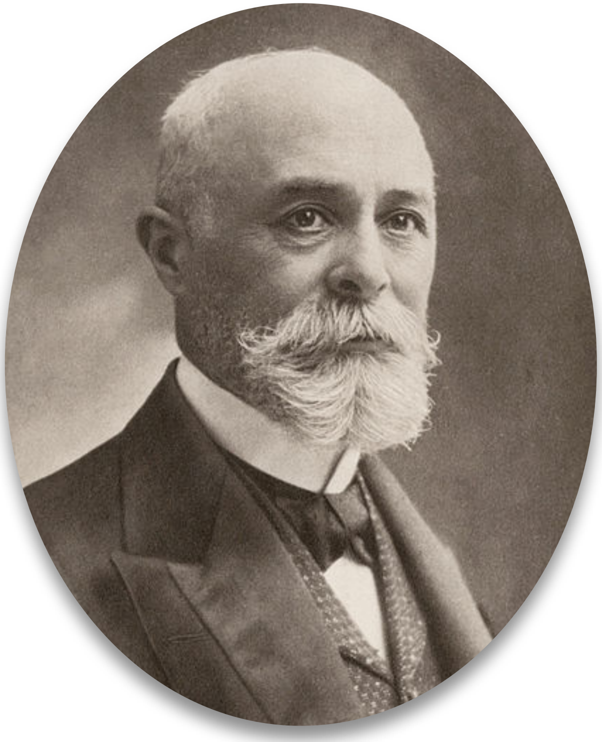
Bone fracture





Discovery of radioactivity

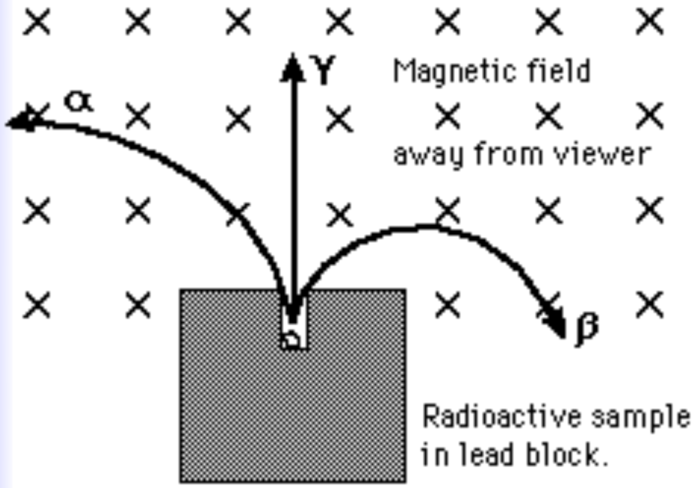
Feb 26, 1896

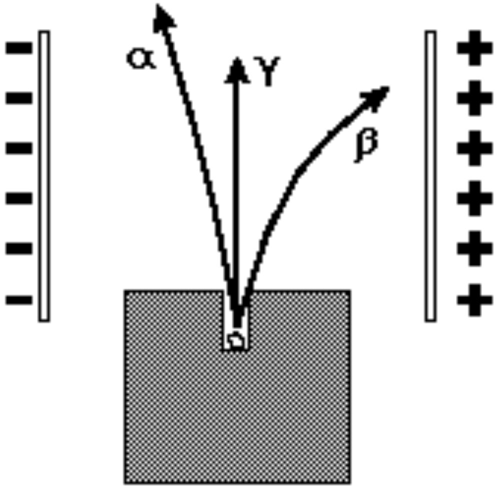


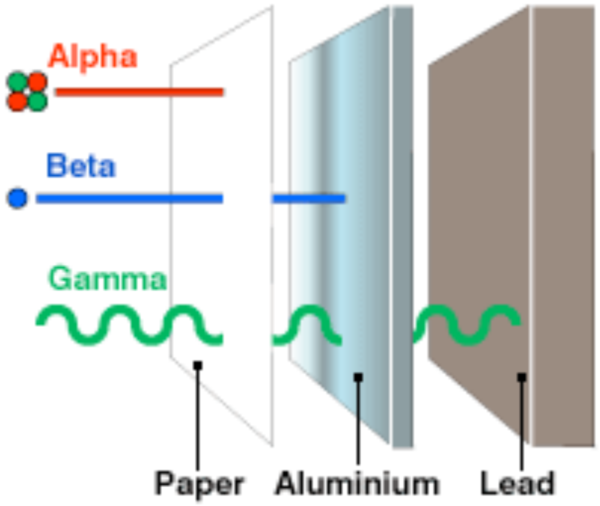
Antoine Henri Becquerel
(1852 – 1908)

- Photographic plates were accidentally placed on top of Uranyl Sulphate salts (UO_2SO_4) in a drawer.
- *Henri Becquerel* noticed that although the photographic plates had not been exposed they were still cloudy.
- The Uranyl Sulphate salts had not been exposed to the Sun.
- This indicated that an ***internal source*** in the Uranyl Sulphate was producing radiation that exposed the plates!

Types of radiation: α,β,γ





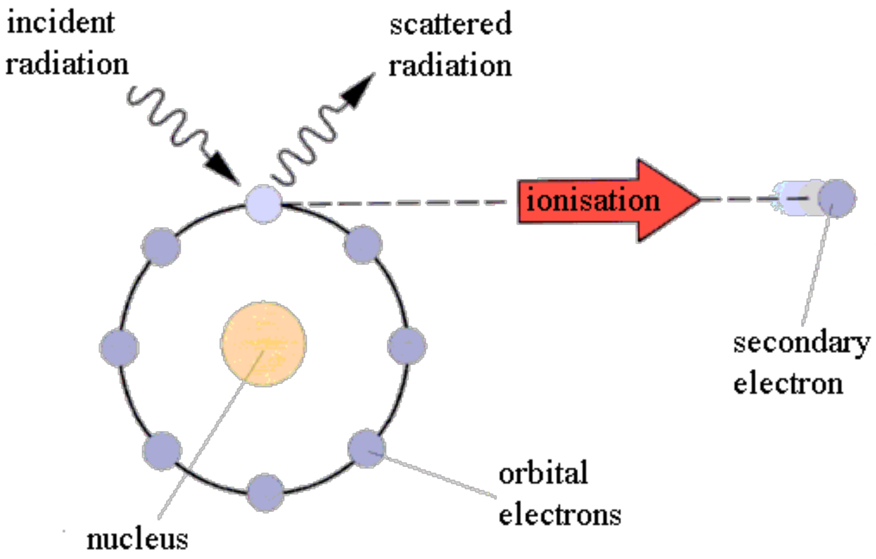


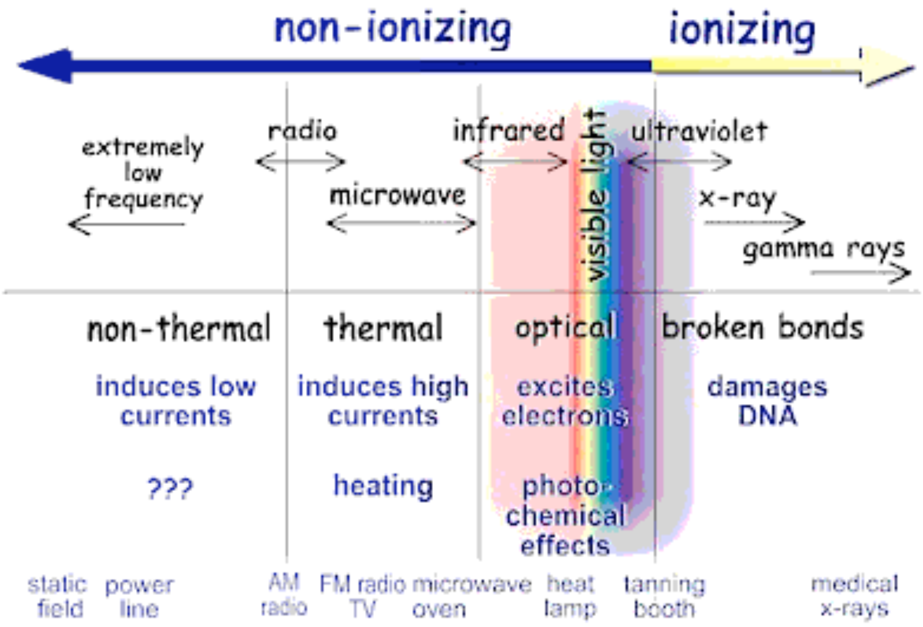
Different radiations were observed and characterised by their range and motion in electric and magnetic fields:

- Alpha, α, bends in electric and magnetic field demonstrating it has positive electric charge.
  The trajectory does not bend as much as β particles indicating it is heavier.
  Alpha radiation does not penetrate paper.
- Beta, β, also bends in an electric and magnetic field, demonstrating it has negative electric charge.
  Able to penetrate paper but not Al; it is more penetrating than α but less penetrating that gamma
- Gamma, γ, does not bend in an electric or a magnetic field and is therefore composed of neutral particles.
  They are very penetrating, able to penetrate Al and thin layers of Pb.

Ionising radiation

- Ionising radiation removes electrons from atoms resulting in ions and free electrons.
- This requires energies of a few keV or greater



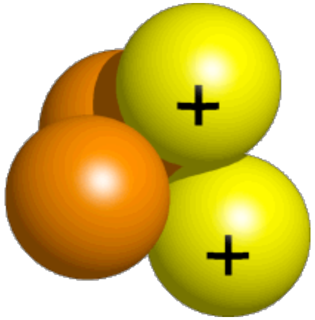


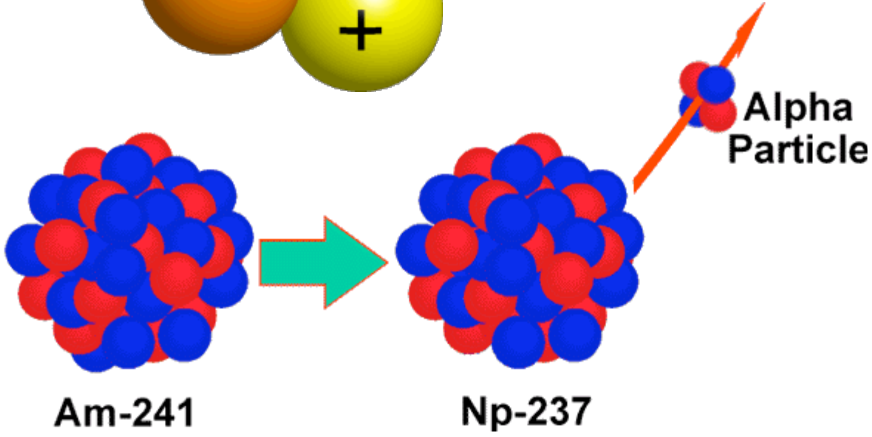
Alpha particles

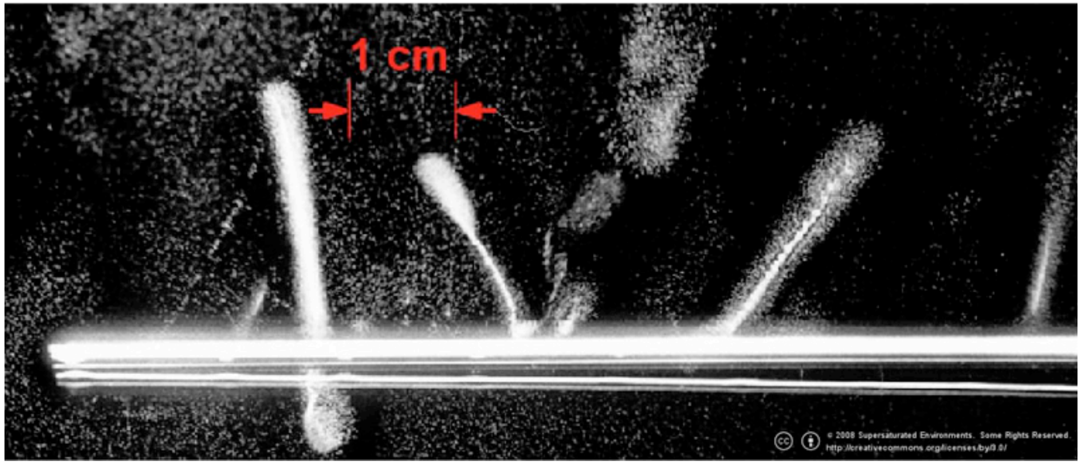
- Alpha particle is a bound state of 2 protons and 2 neutrons, essentially a He^{2+} ion

$$\alpha = {}^{4}_{2}He^{2+}$$

- Alpha particles are emitted from the nuclei
- Typical energies are 3-7 MeV
- They have a range of a few cm in air

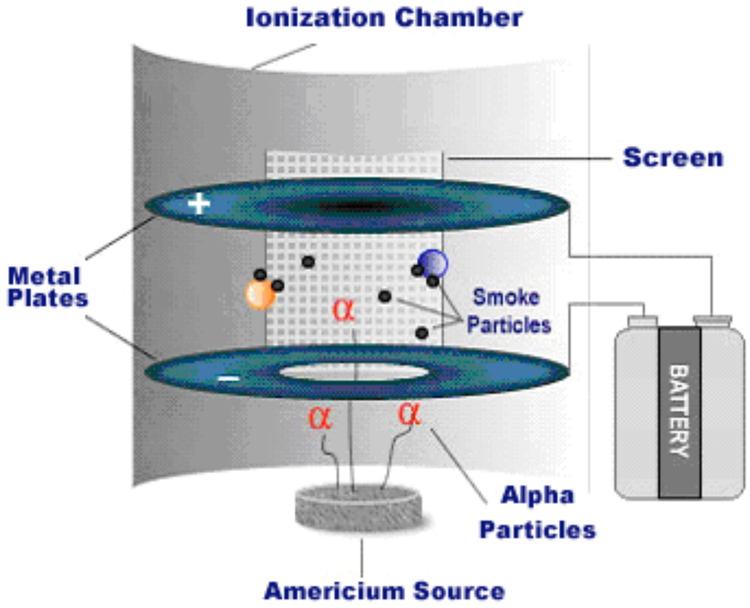


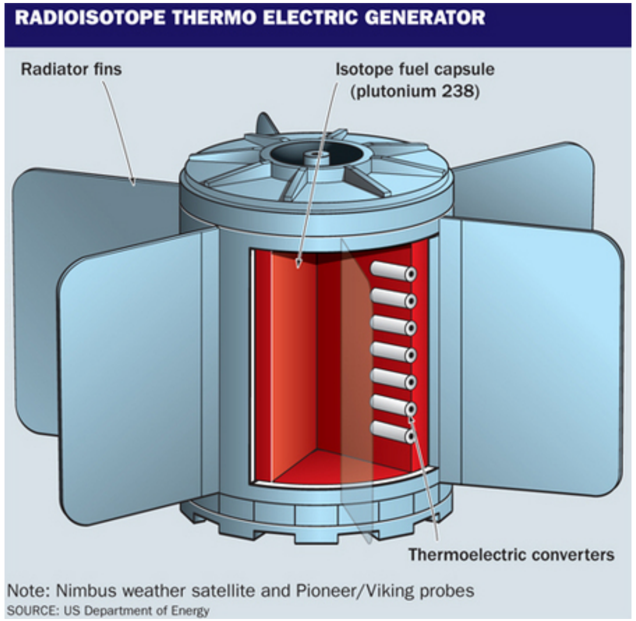




Alpha particles everywhere

- Smoke detector
  - Operate as an ionisation chamber, smoke absorbs alpha particles cutting the current and causing an alarm
- Single event upsets
  - Random switching of electronic circuits due to alpha (or other radiation) generating charge in the circuit
- Radioisotope thermoelectric generators
  - Heat from radioactive decay is converted to electricity via thermoelectric (Seebeck) effect.
    Used in satellites, space probes, etc.
- Earthquakes
  - Radioactivity results in molten core of Earth → plate tectonics and earthquakes
- Radiotherapy
  - Targeted deposits of energy – see discussion later



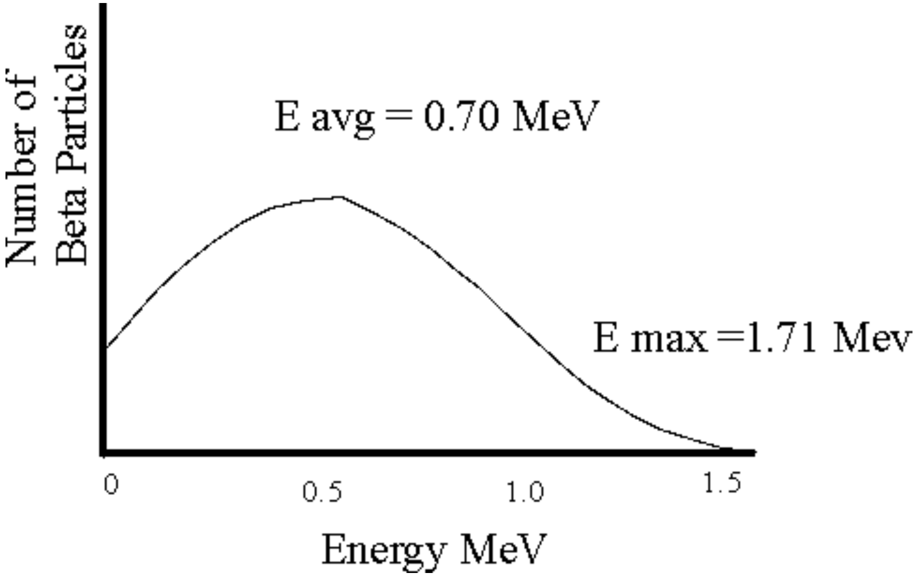


Note: Nimbus weather satellite and Pioneer/Viking probes
SOURCE: US Department of Energy

Beta radiation

- Beta radiation consists of electrons e^- or positrons e^+
- Beta particles are emitted by nucleons undergoing beta decay (more later)
- Beta particles from a source have typical energies up to a few keV
- They are moderately penetrating, able to travel several metres in air but stopped by thin layers of Al

β-spectrum of ^{32}P



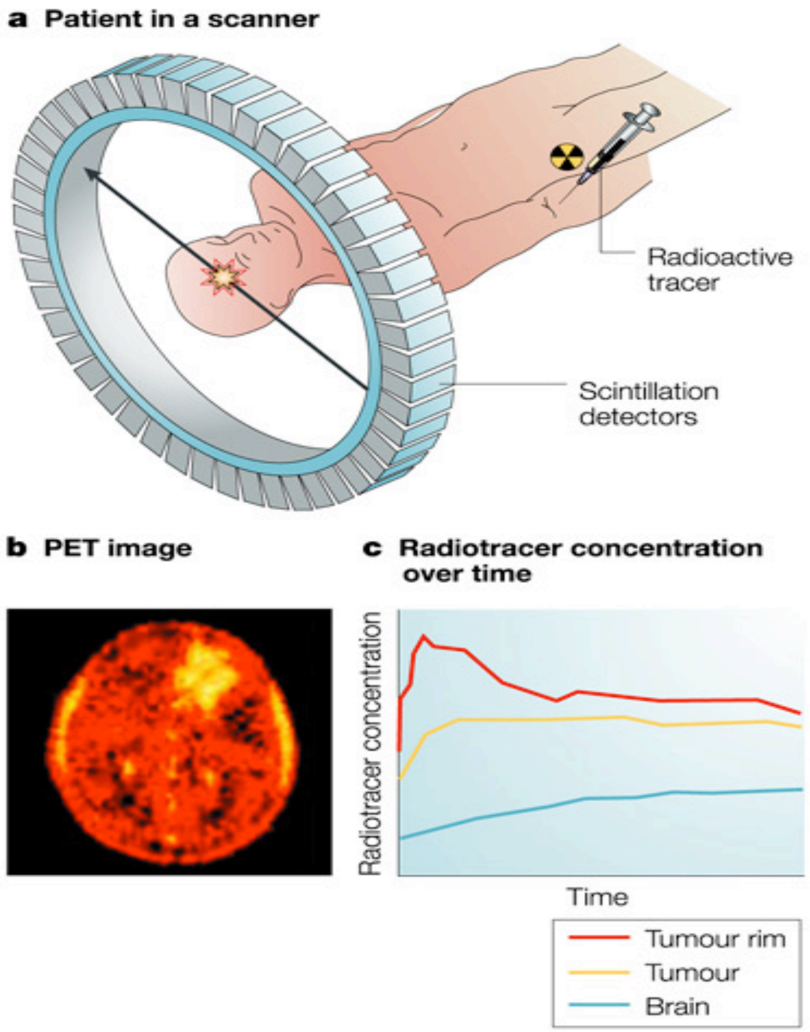
$n \rightarrow p + e^- + \nu$ β⁻-decay

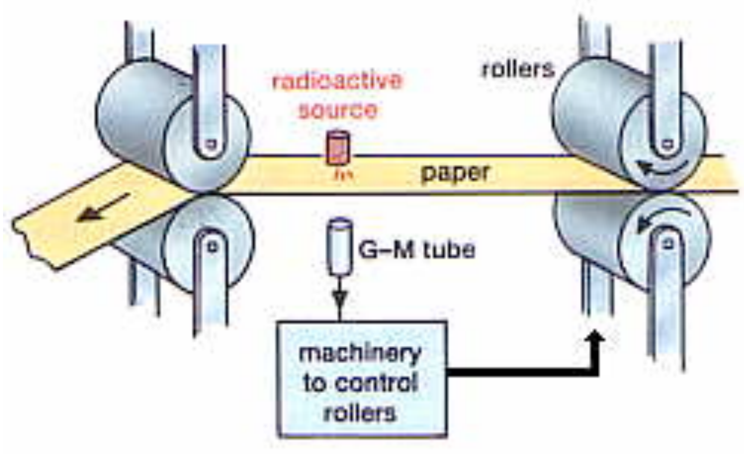
$p \rightarrow n + e^+ + \nu$ β⁺-decay

$e + p \rightarrow n + \nu$ electron capture

Beta radiation all around

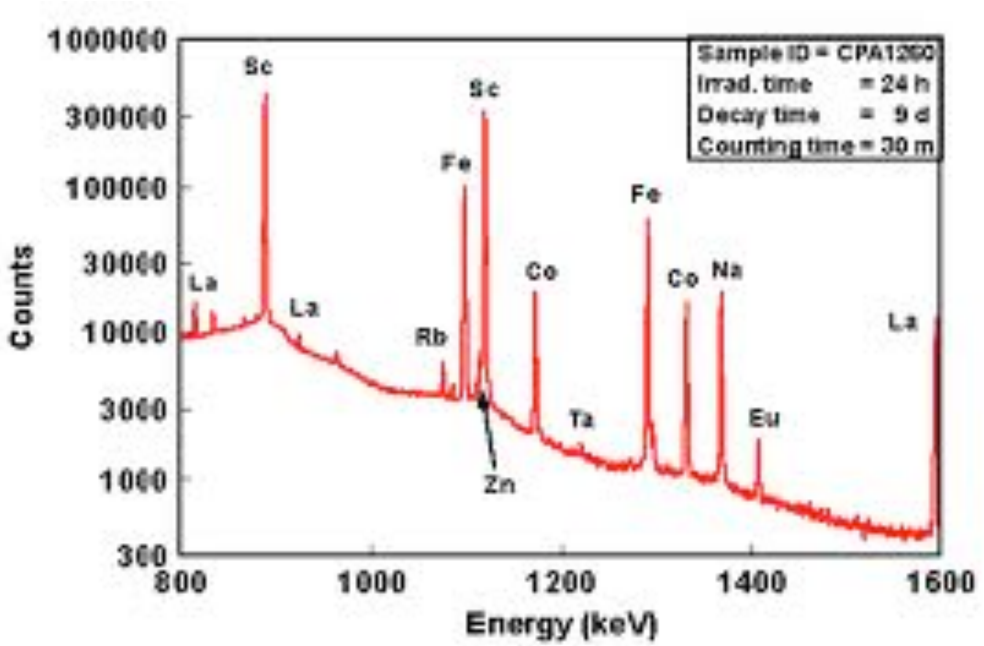
- PET: Positron Emission Tomography
  - $\beta^+ + e^- \rightarrow \gamma + \gamma$
- Thickness monitoring in manufacturing
  - Thickness of paper of thin metal





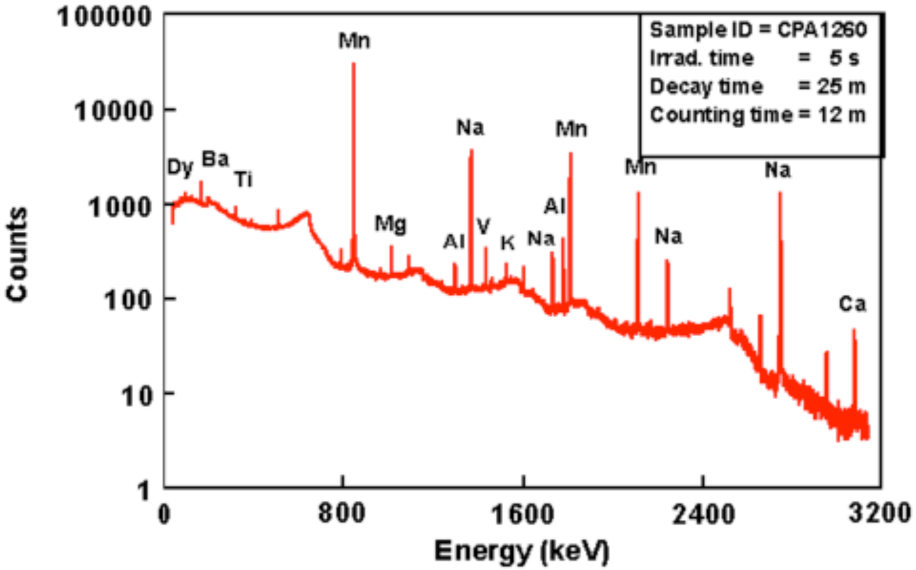
Gamma radiation

- Gamma radiation is high energy photons with energies in the MeV range
- Gamma rays are emitted from nuclei when nucleons change their energy state – a similar radiation (visible, UV, X-ray) to the one originating from electron transitions in atoms
- Gamma rays are highly penetrating and are only ‘stopped’ by several cm of heavy materials such as Pb



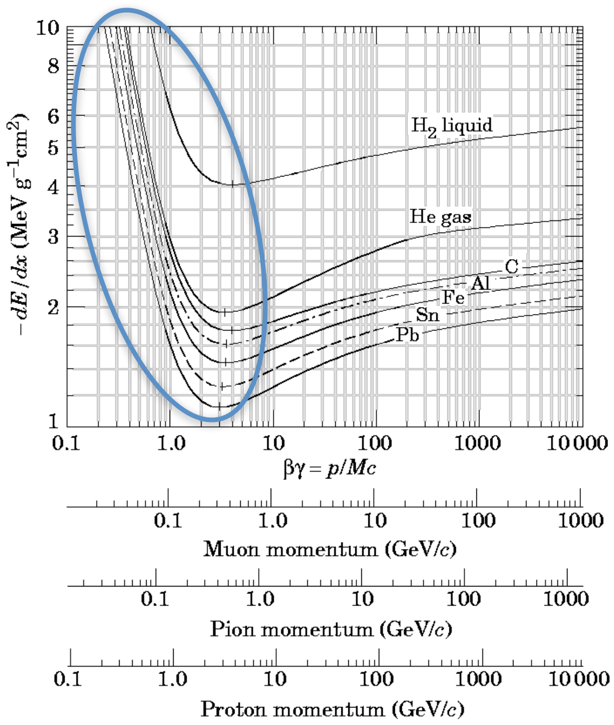
Gamma rays all around

- Radiotherapy
  - Cancer treatment
- Neutron activation analysis
  - Excite nuclei by firing neutrons at them and look at resulting γ-ray spectrum, similar to atomic spectra
  - Sensitive from micro- to picograms of elements
- Gamma ray bursts
  - are flashes of γ-rays associated with extremely energetic explosions in distant galaxies
  - the most luminous electromagnetic events known

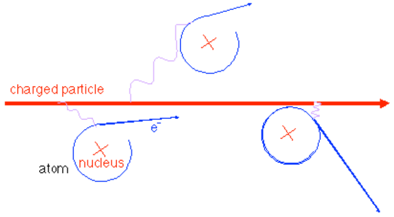


Interaction of radiation with matter

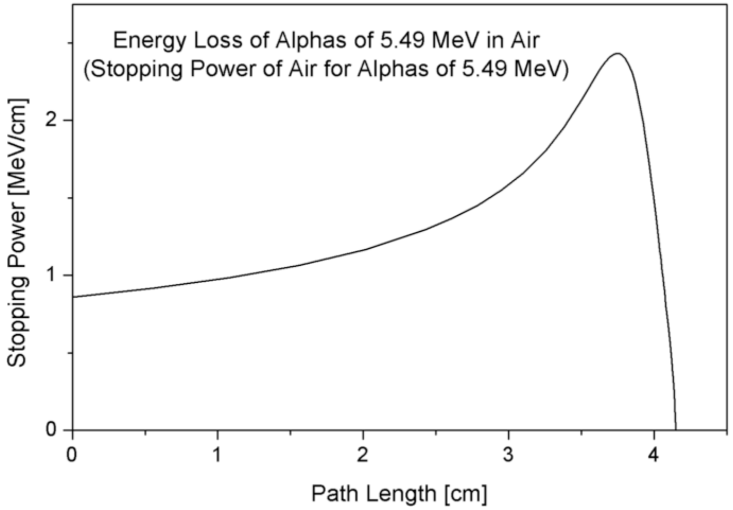
- Energy loss of heavy charged particles ($m>m_e$) is due to electromagnetic interactions between charged particle and atomic electrons



$$-\frac{dE}{dx} \propto \frac{Z^2}{v^2}$$

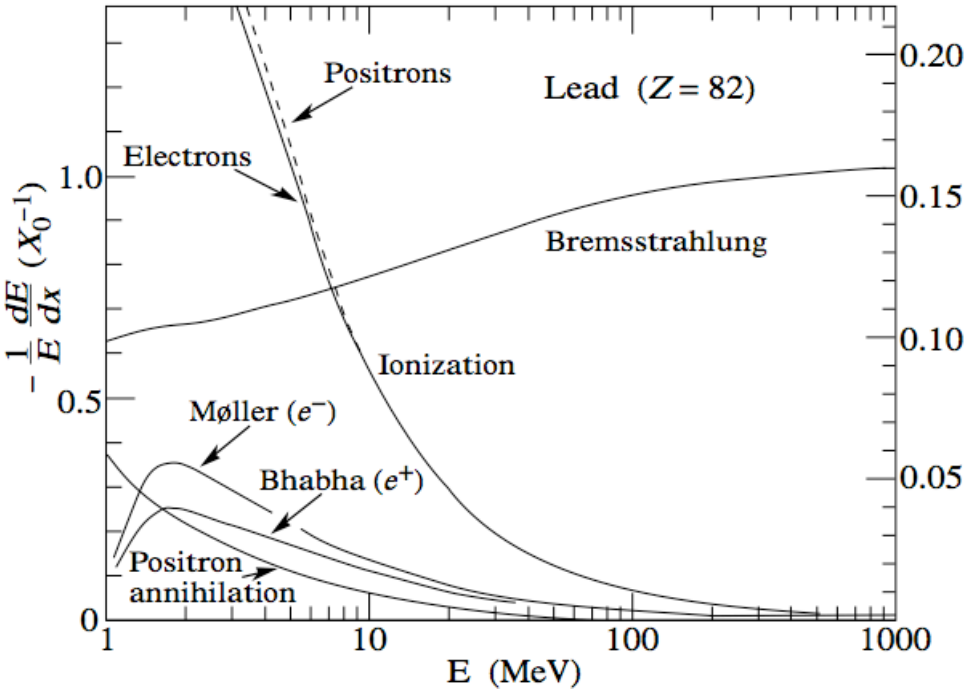


- Slow moving heavy charged particles ionise more
- Alpha particle exhibit a Bragg peak and a well defined range



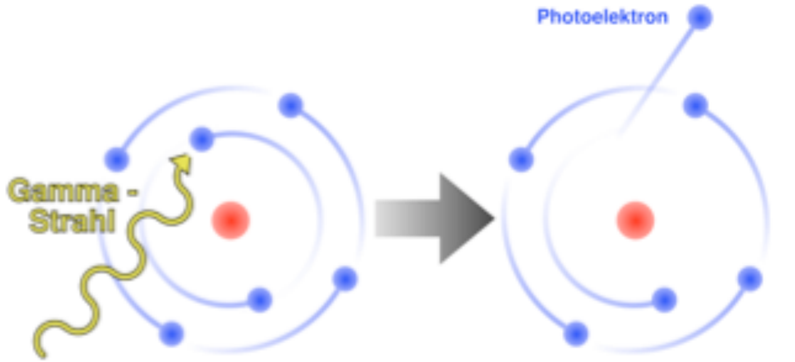
Interaction of β-particles with matter

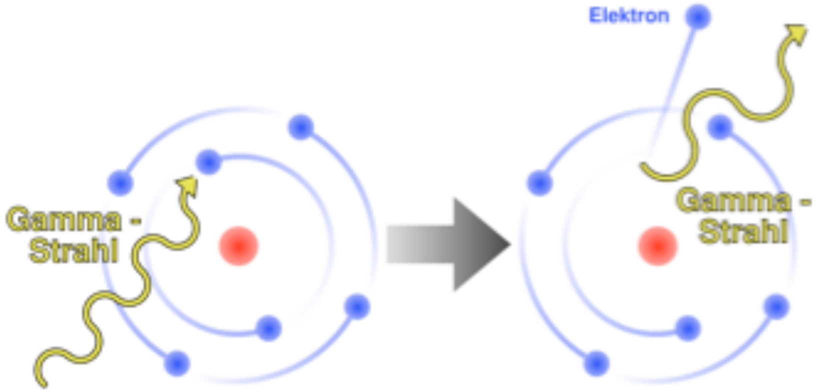
- Beta particles interact mostly via:
  - Ionisation
    Extraction of an electron from an atom or molecule
  - Bremmstrahlung
    (as for X-rays)
    High energy β-particles lose energy via emission of electromagnetic radiation in the field of a nucleus

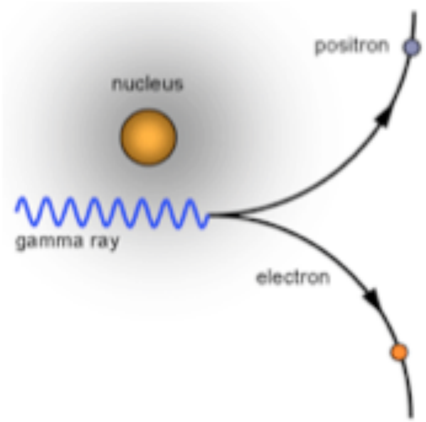


Energy loss by γ-rays

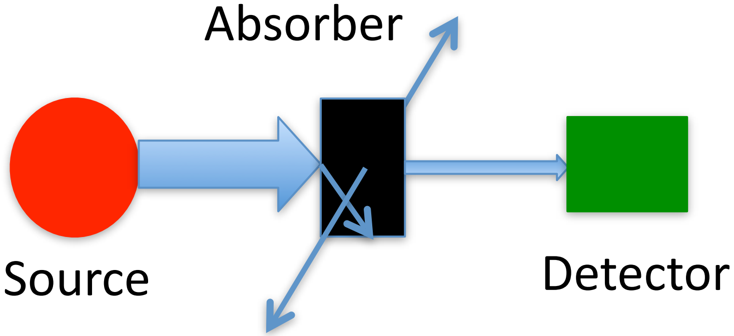
- Gamma rays lose energy through three distinct processes.
- The energy loss depends on
  - Z of absorber
  - Energy of gamma ray
- Photoelectric effect
  - An incoming photon of sufficient energy is absorbed by an atomic electron, which then has sufficient energy to escape from the atom
- Compton scattering
  - An incoming photon scatters off an atomic electron. The resulting photon has less energy and the electron is ejected from the atom
- Pair production
  - An electron-positron pair is formed in the electric field of a nucleus







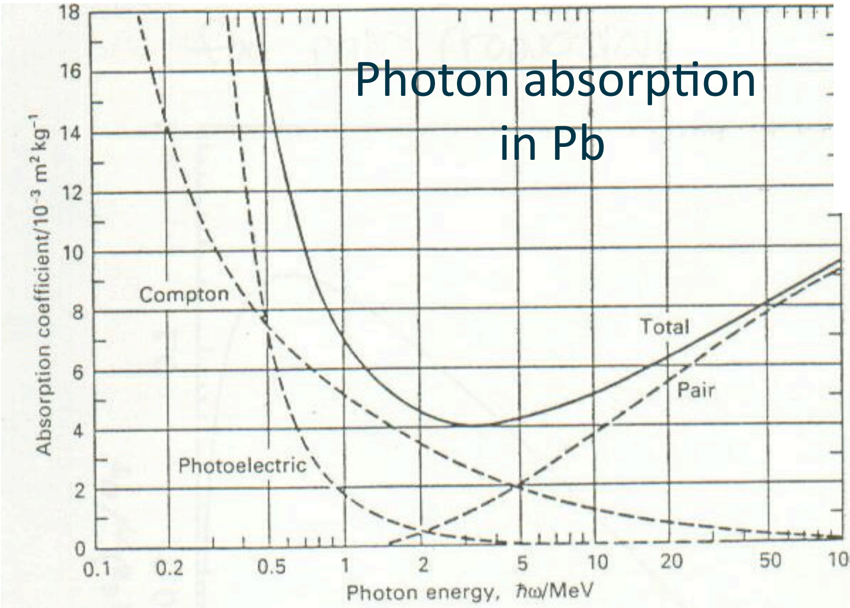
Absorption of γ-rays



Absorber

Source

Detector



Photon absorption in Pb

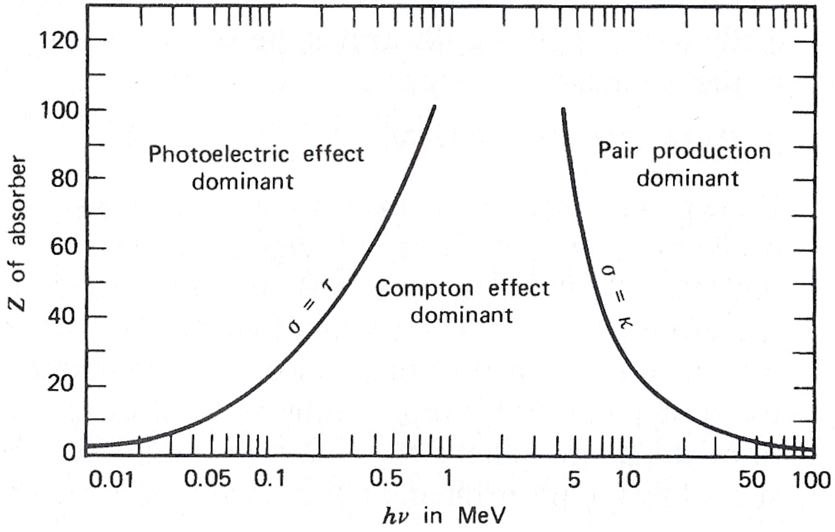
Figure 4.16. The total mass absorption coefficient for high energy photons in lead, indicating the contributions associated with the photoelectric absorption, Compton scattering and electron–positron pair production. (From H. A. Enge (1966). *Introduction to nuclear physics*, page 193. London: Addison-Wesley Publishing Co.)

Absorption coefficient μ

$$\frac{dI}{I} = -\mu dx$$

$$I = I_0 e^{-\mu t}$$

$$\mu = \sum \mu_{\text{photoelectric}} + \mu_{\text{Compton}} + \mu_{\text{pair}}$$

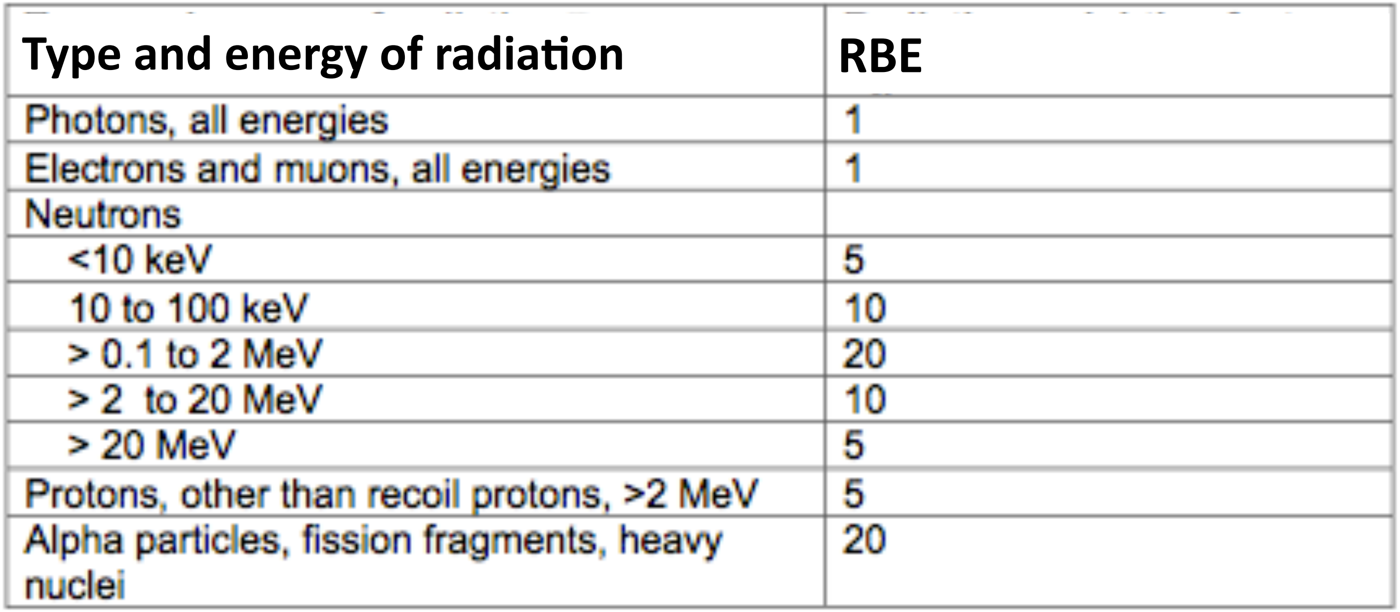


Biological effects of radiation

- Radiation damages cells by ionising the atoms
- The unit of activity i.e. number of disintegrations per second is the becquerel (Bq).
  This unit is independent of the type of radiation and its energy.
- *Absorbed dose* is defined as the energy absorbed in the medium from the radiation and is measured in gray (Gy).
- 1Gy = 1J of energy absorbed in 1kg
- As we have seen, different radiations ionise media via different processes and this results in different biological effects for each radiation.
  A relative biological effectiveness (RBE) can be determined for each type of radiation.

Relative biological effectiveness

- **Equivalent dose**: $H = Q \times D$, where D is the absorbed dose and Q is the RBE. The equivalent dose can not be measured directly.
- The RBE factors for each type radiation are:

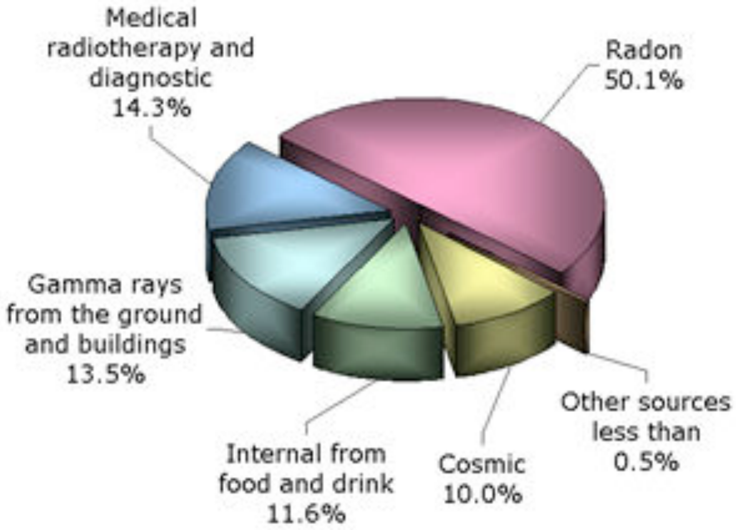


Type and energy of radiation	RBE
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons	
<10 keV	5
10 to 100 keV	10
> 0.1 to 2 MeV	20
> 2 to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

- The unit for equivalent dose is the sievert (Sv)
- Equivalent dose should not be confused with *effective dose*, which takes into account the sensitivity to radiation of various body tissues

Examples of doses

	Equivalent Dose (Sv)
Dose required to sterilise medical products	25000
Typical total radiotherapy dose to cancer tumour	60
50% survival probability, whole body dose	4
Legal worker dose limit (whole body)	0.02
Average annual dose from all sources in Cornwall	0.008
Average annual dose from natural radiation	0.002
Typical chest X-ray dose	0.00002
Average dose from a flight from UK to Spain	0.00001



Sources of radiation dose to the UK population. Source: NPL website

The total annual equivalent dose is 0.0026 Sv, but individual doses vary enormously, depending on location and job