

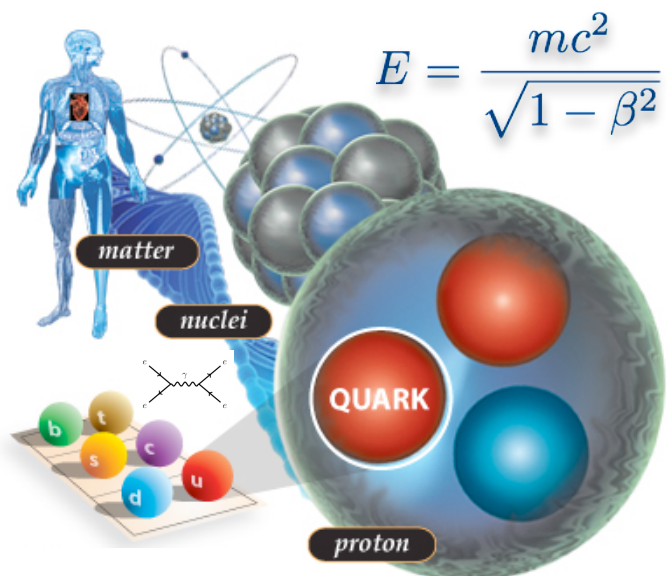
Nuclear and Particle Physics

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Topics covered in this course

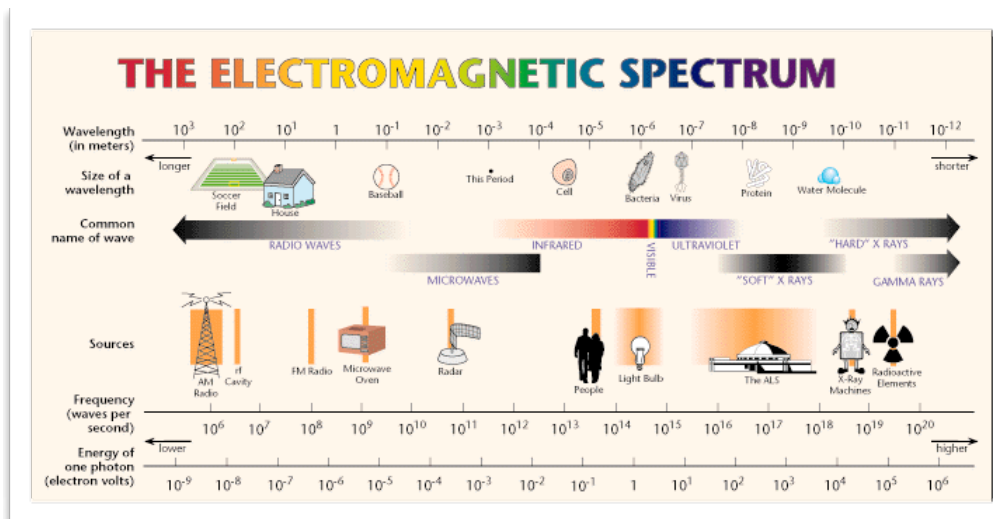
- I. Radiation
- II. Atomic nuclei
- III. Radioactivity and radioactive decay
- IV. Nuclear reactions
- V. Fundamental forces and particles
- VI. Quark model of hadrons
- VII. Special relativity theory



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



P2 Nuclear and Particle Physics - Dan Protopopescu

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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
 - $1\text{eV} = 1.602 \times 10^{-19} \text{ C} \times 1\text{V} = 1.602 \times 10^{-19} \text{ J}$
- 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*: $m_p = 1.672621637(83) \times 10^{-27} \text{ kg}$, but this is somewhat unwieldy
 - Instead convert to eV:

$$E = 1.673 \times 10^{-27} \text{ kg} \times (3 \times 10^8 \text{ ms}^{-1})^2 = 1.505 \times 10^{-10} \text{ J}$$

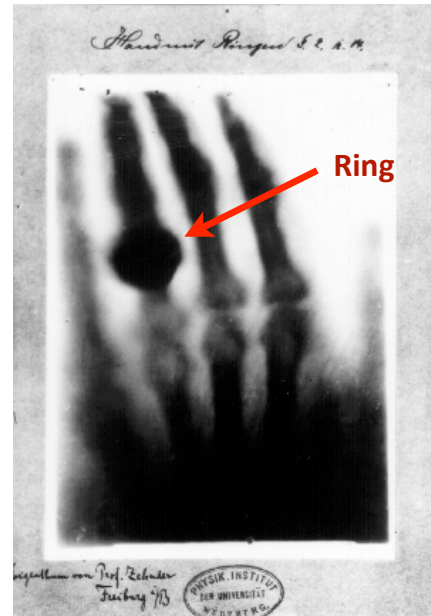
$$= 1.505 \times 10^{-10} \text{ J} / 1.602 \times 10^{-19} \text{ J/eV}$$

$$= 939.45 \text{ MeV}/c^2 (=1\text{GeV}/c^2)$$

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Discovery of X-rays

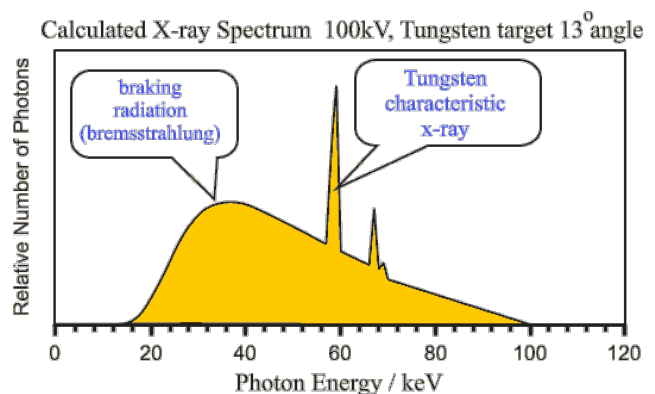
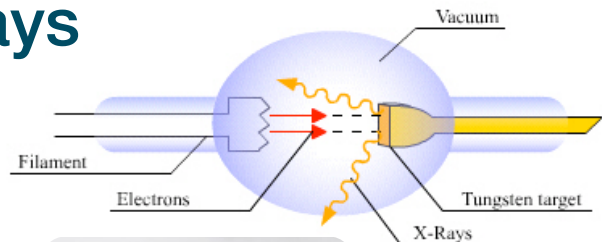
- X-rays were discovered by *Wilhelm C. Roentgen*. While he was studying cathode rays using a Hittorf-Crookes tube, he observed a glow from a fluorescent screen on a nearby table
- He determined that the fluorescence was due to penetrating rays that were being emitted from the tube
- Two weeks later, 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

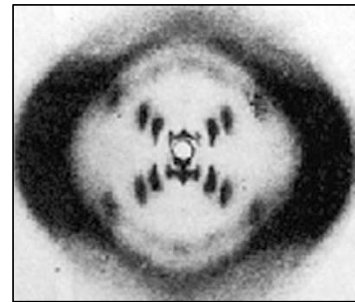
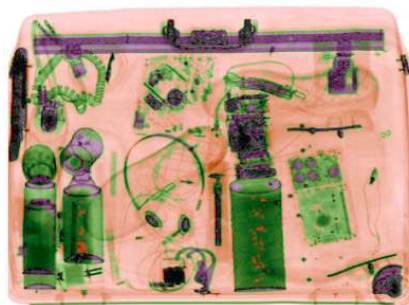
X-rays

- 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



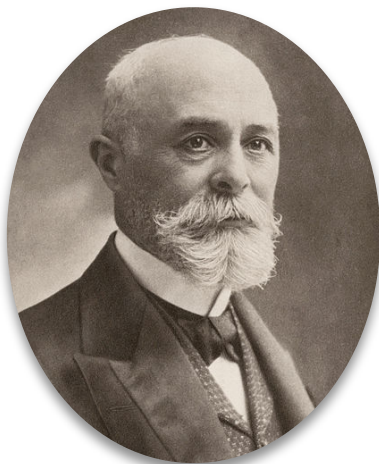
X-rays everywhere

- 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)



Discovery of radioactivity

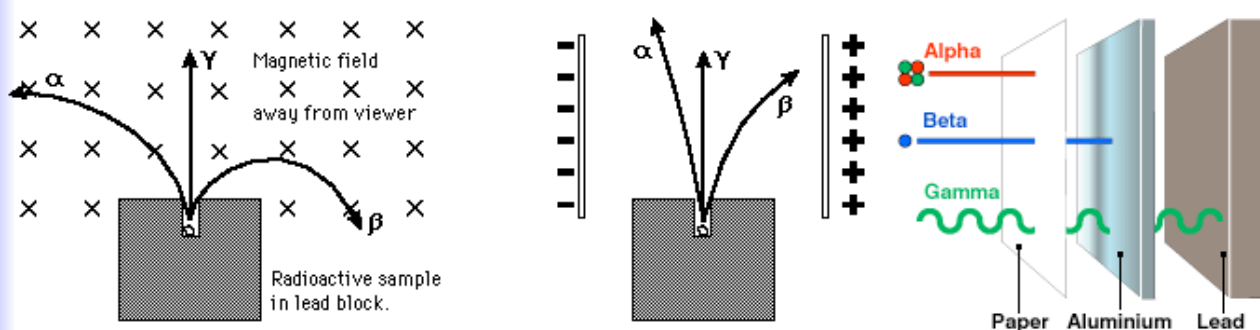
Feb 26, 1896



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

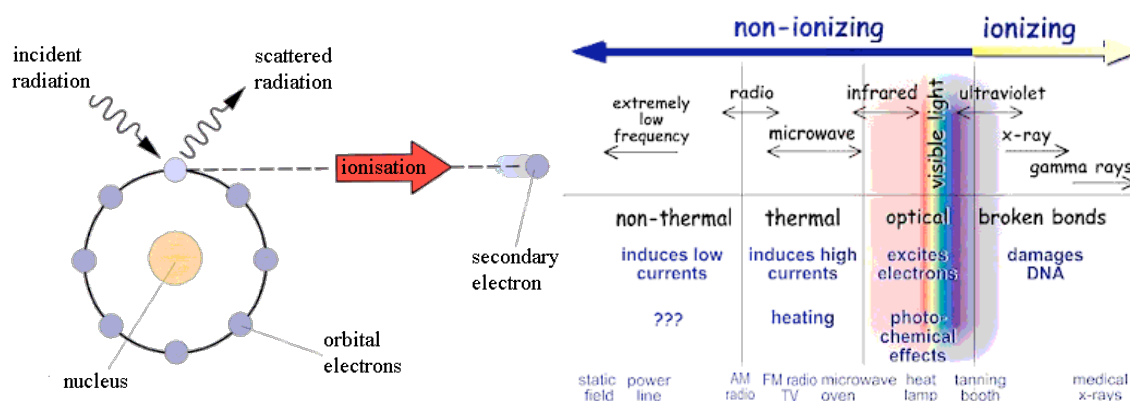


Different radiations were observed and characterised by their range and motion in electric and magnetic fields:

- ▶ 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 than 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.

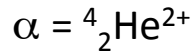
Ionising radiation

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

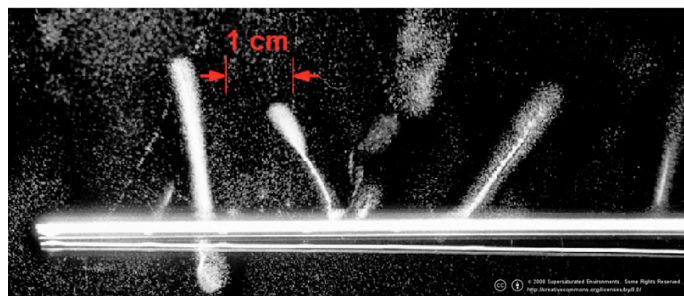
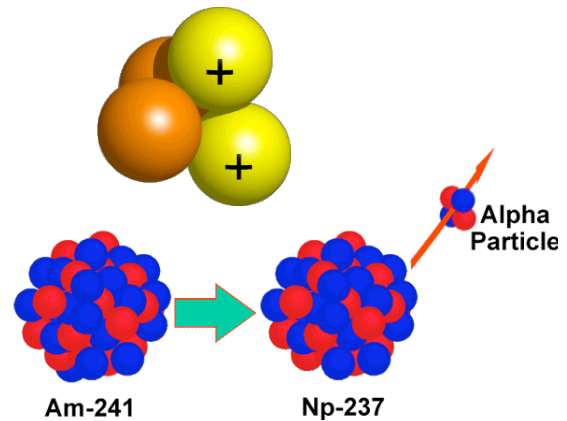


Alpha particles

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

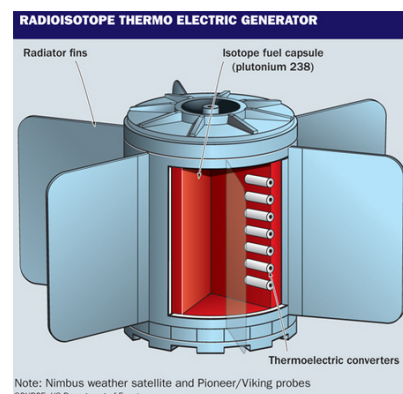
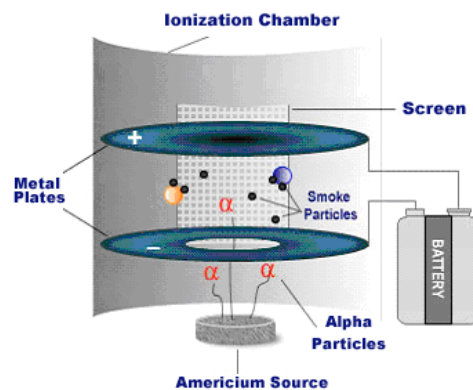


- Alpha particles are emitted from the nuclei
- Typical energies are 3-7 MeV
- They have a range of a few cm in air



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

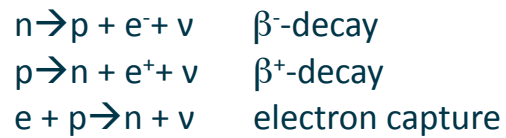
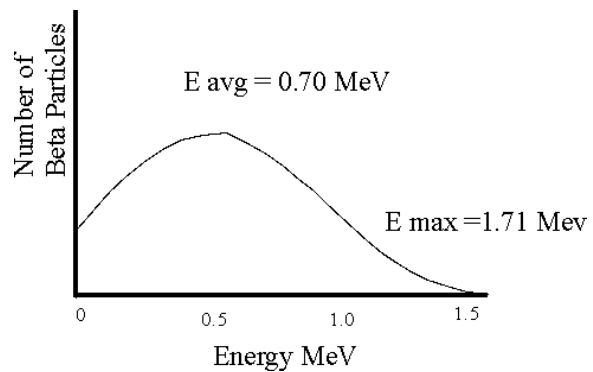


Note: Nimbus weather satellite and Pioneer/Viking probes
SOURCE: US Department of Energy

Beta radiation

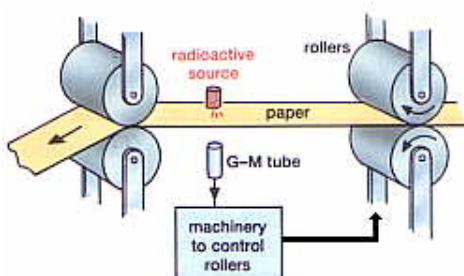
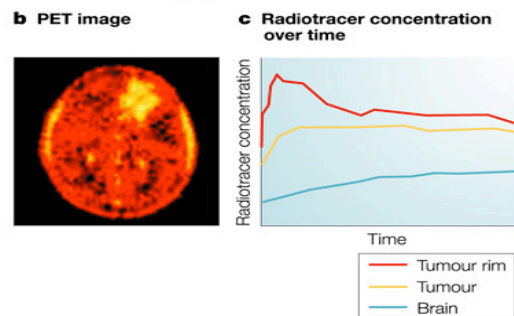
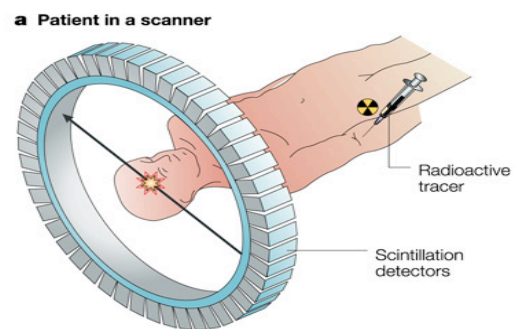
- Beta radiation consists of electrons e^- or positrons e^+
- Beta particles are emitted by nucleons undergoing beta decay (more later)
- Beta particles from a source have typical energies up to a few keV
- They are moderately penetrating, able to travel several metres in air but stopped by thin layers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

β -spectrum of ^{32}P



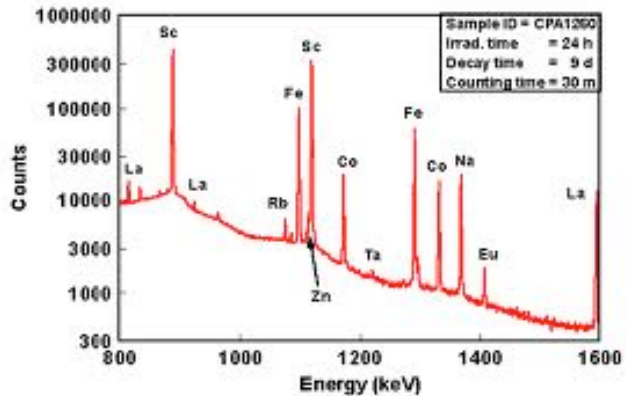
Beta radiation all around

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



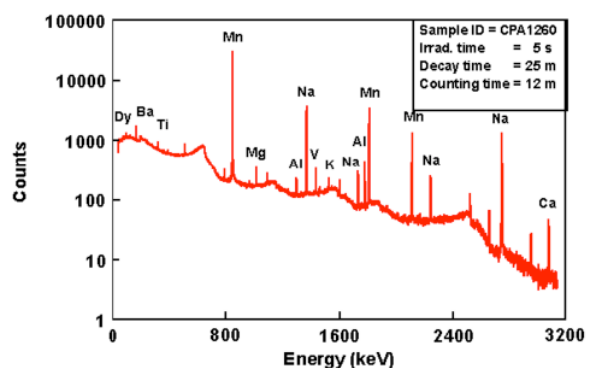
Gamma radiation

- 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

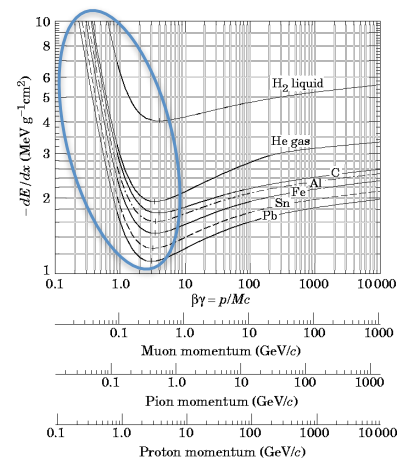
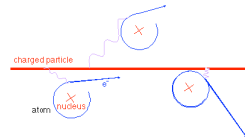
- Radiotherapy
 - Cancer treatment
- Neutron activation analysis
 - Excite nuclei by firing neutrons at them and look at resulting γ -ray spectrum, similar to atomic spectra
 - Sensitive from micro- to picograms of elements
- Gamma ray bursts
 - are flashes of γ -rays associated with extremely energetic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



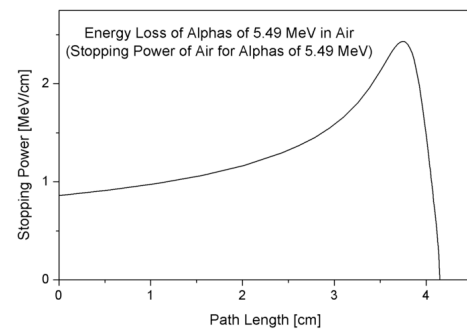
Interaction of radiation with matter

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

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



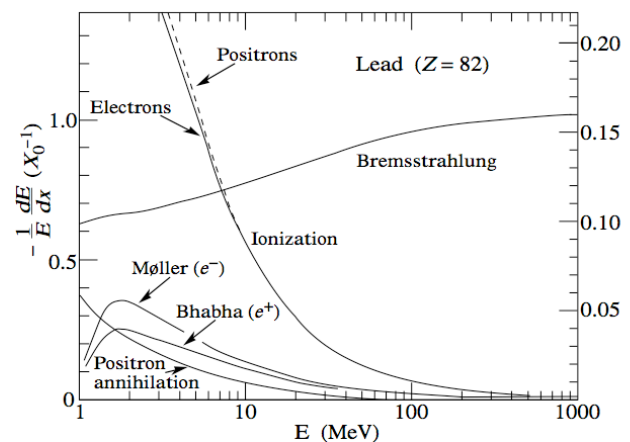
- Slow moving heavy charged particles ionise more
- Alpha particle exhibit a Bragg peak and a well defined range



Interaction of β -particles with matter

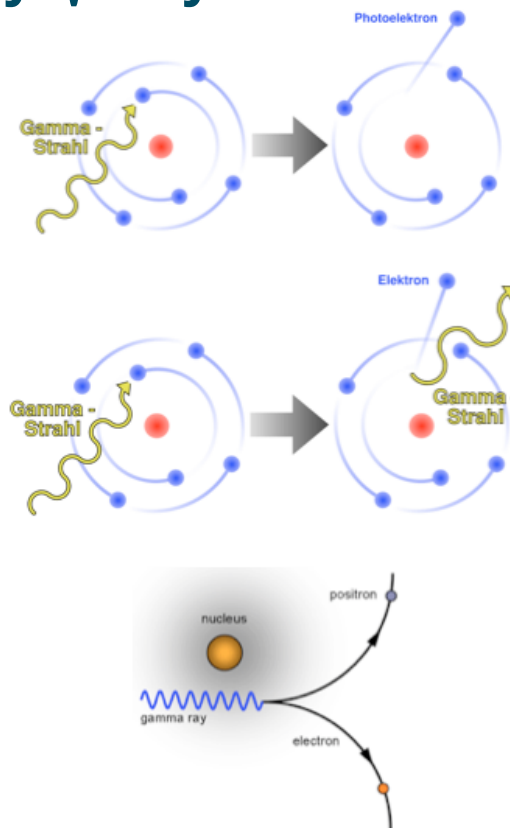
- Beta particles interact mostly via:

- Ionisation
Extraction of an electron from an atom or molecule
- Bremsstrahlung (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

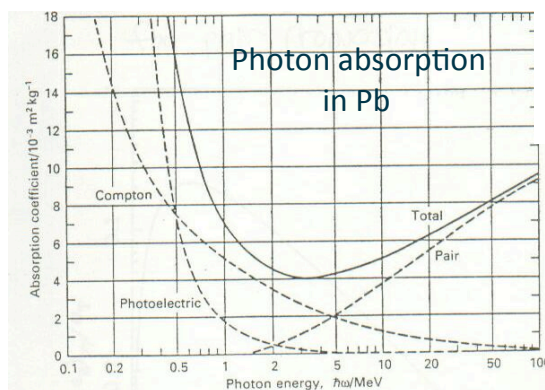
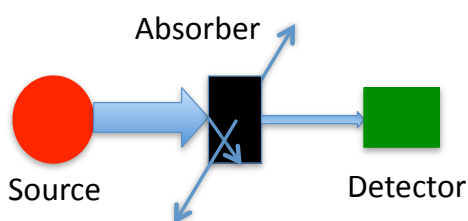


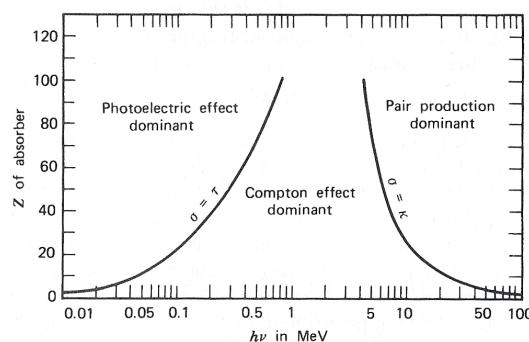
Figure 4.16. The total mass absorption coefficient for high energy photons in lead, indicating the contributions associated with the photoelectric absorption, Compton scattering and electron-positron pair production. (From H. A. Enge (1966). *Introduction to nuclear physics*, page 193, London: Addison-Wesley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

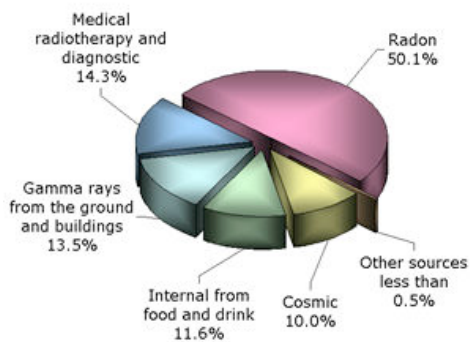
- **Equivalent dose:** $H = Q \times D$, where D is the absorbed dose and Q is the RBE. The equivalent dose can not be measured directly.
- The RBE factors for each type radiation are:

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