Dosimetry Principles

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Dosimetry Principles

AIM

Provide an overview of the underlying physical and chemical principles involved in radiation dosimetry.

Illustrate the relationships between these underlying principles and the particular issues and difficulties associated with industrial dosimetry.

Dosimetry Principles

Absorbed dose

- Definition
- Methods of measurement

Types of radiation used in radiation processing

- Photons (γ-rays & x-rays), Electrons
  - Energy absorption processes
  - Energy deposition profile

Examples of dosimeters

- Calorimeters
- Liquid – Ceric/Cerous
- Solid – Alanine

Dosimetry Principles

Absorbed dose is the mean energy imparted to a quantity of matter divided by the mass of that matter i.e. energy per unit mass

Unit: J kg^{-1}
Special name: gray (Gy) 1Gy = 1J kg^{-1}

Typical radiation processing dose of 25 kGy delivered to water results in a temperature rise of $\approx 6^{o}C$.

Dosimetry Principles

Absorbed dose has material dependence

The absorbed dose received by material in a radiation field depends on the composition of the material.

In radiation processing applications the quantity used is almost always **absorbed dose to water** i.e. the dose that would have been received by water at the position of interest in the radiation field.

Dosimetry Principles

Methods of dosimetry

Calorimetric: Most direct method. Use temperature rise to determine amount of energy deposited in material.

Chemical: Use measurements of radiation induced chemical change.

Physical: Use physical effects, such as induced ionisation or changes in semi-conductor properties.

Dosimetry Principles

Co-60 Production and Decay

Production

$$^{59}Co + n \rightarrow {}^{60}Co$$

Decay

$$^{60}Co \rightarrow {}^{60}Ni + \beta^{-} + 2\gamma$$

$$E_{\gamma} = 1.17 \text{ and } 1.33 \text{ MeV}$$

Dosimetry Principles

Source activity

Becquerel: 1Bq = 1 disintegration per second

Typical radiation processing sources are of the order of 10^{17} Bq (100 PBq)

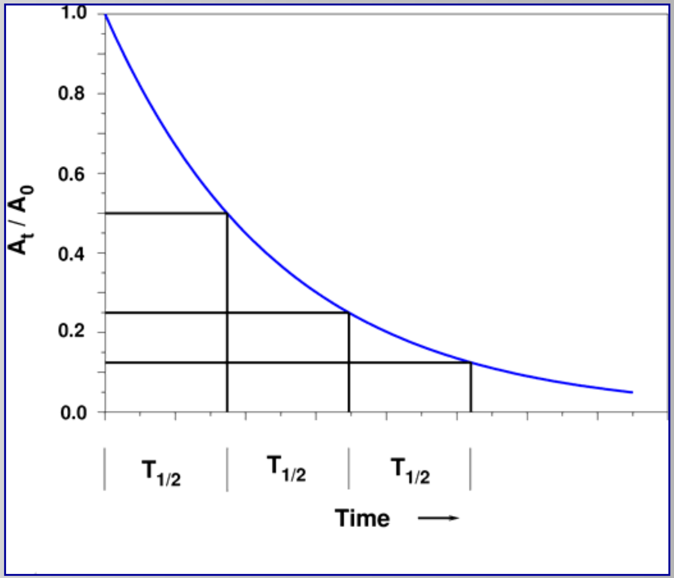
Curie: 1Ci = 3.7 x 10^{10} Bq

Dosimetry Principles – Source decay

Radioactive sources decay exponentially:

$$A_t = A_0\, e^{-\lambda t}$$

where A_0 initial activity,
A_t activity at time t.



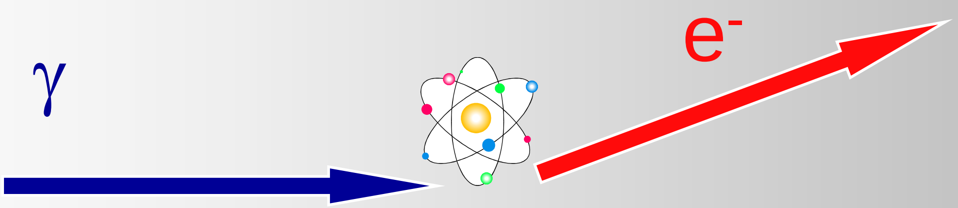
Half life ($T_{½}$) is time taken for activity to decrease by a factor of two:

$$T_{½} = \ln 2 / \lambda$$

For Co-60, $T_{½}$ = 5.271 years (~1% decrease per month)

Dosimetry Principles - γ-ray Interactions

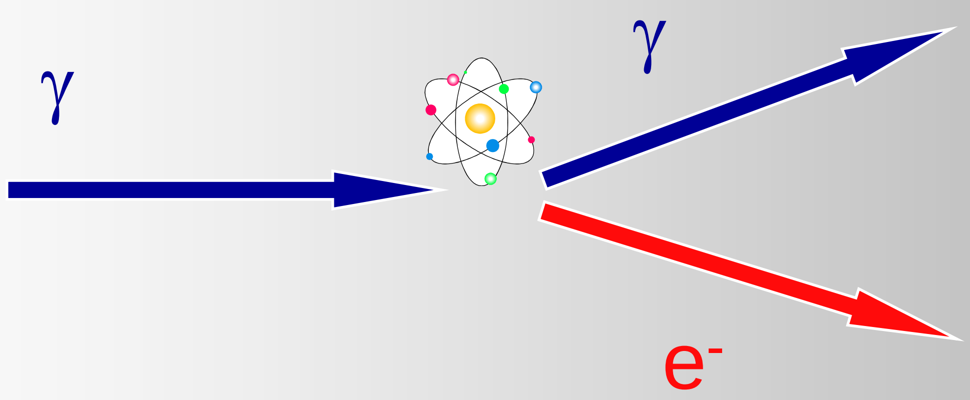
Photoelectric effect



Low energy photons
Ejection of a single atomic electron
$E_e = E_0$ – Binding energy

Dosimetry Principles - γ-ray Interactions

Compton scattering



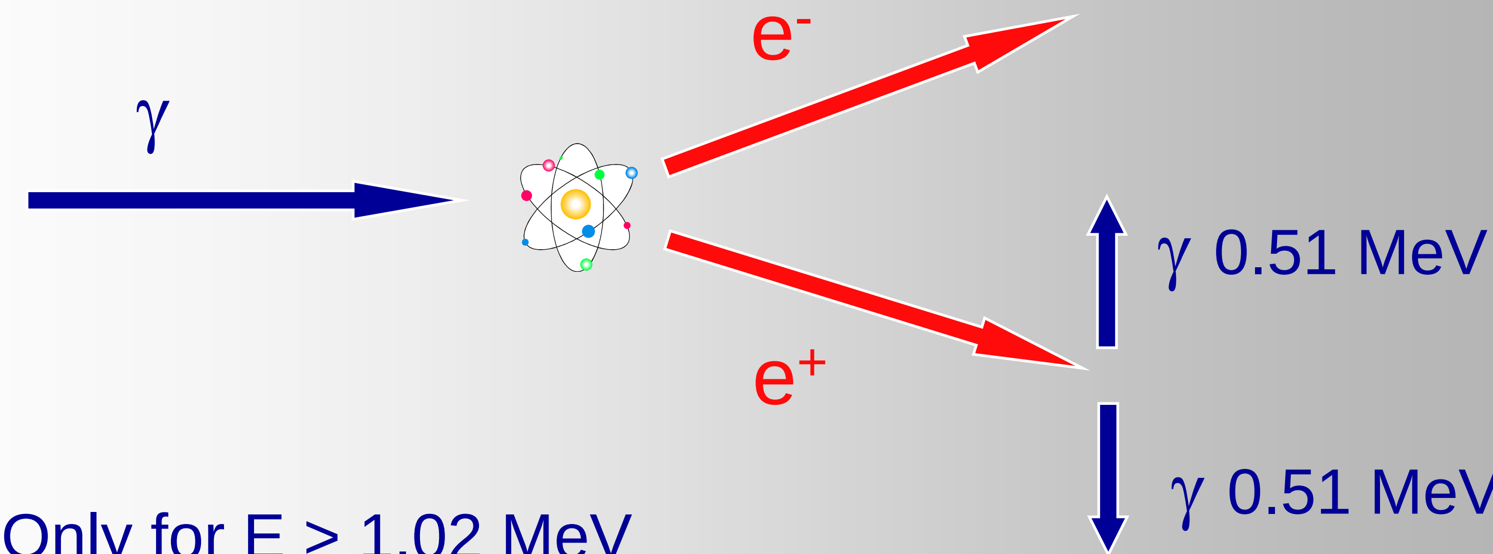
Medium energy photons

Interaction with atomic and free electrons

$E_e = E_0 - E_\gamma$ from 0 up to maximum when photon scattered through 180º

Dosimetry Principles - γ-ray Interactions

Pair production



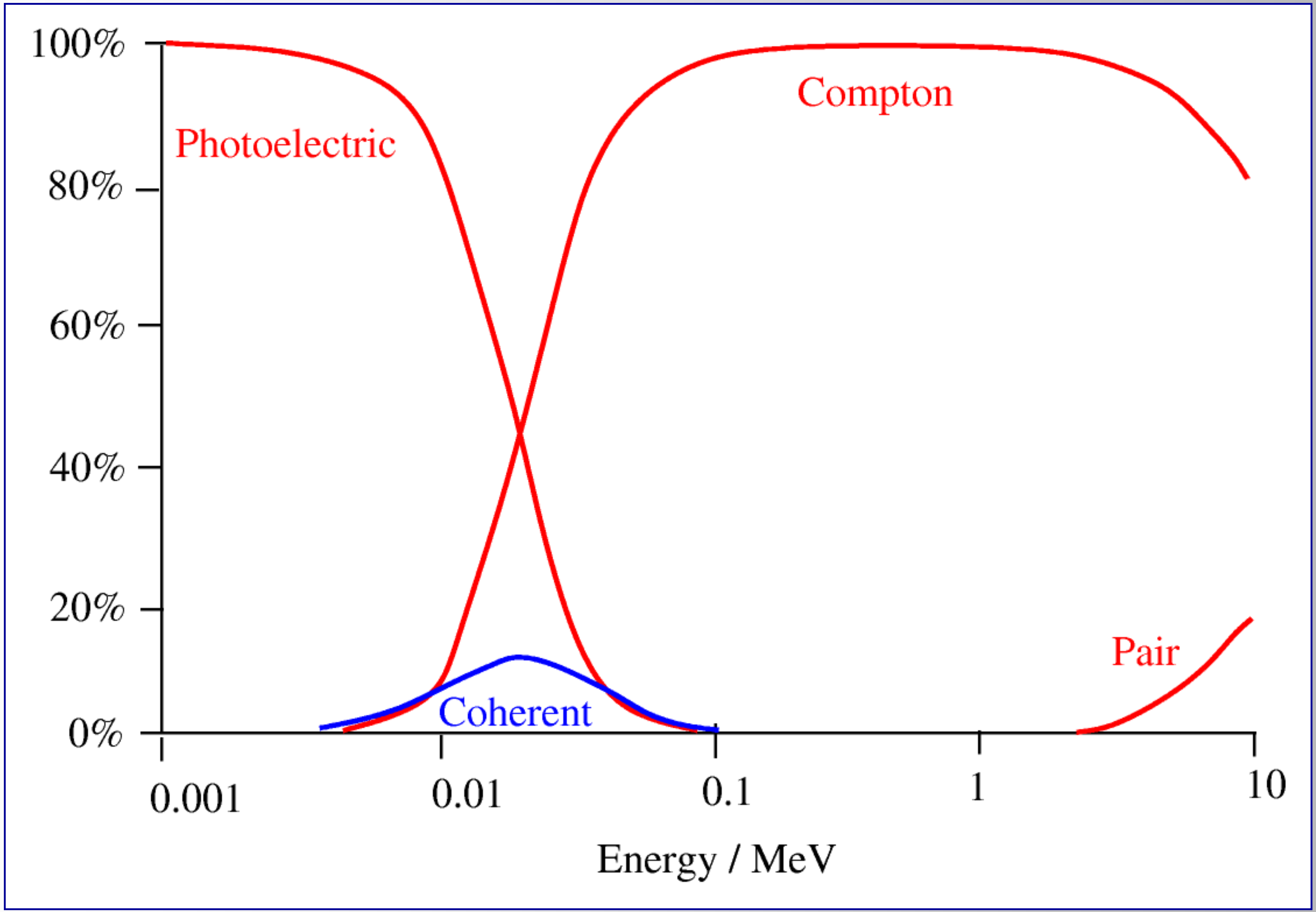
Only for E > 1.02 MeV

$E_0 = E_e + E_p + 1.02$ MeV

Positron slows down and annihilates with an electron

Dosimetry Principles - γ-ray Interactions

Relative interaction probabilities in polyethylene

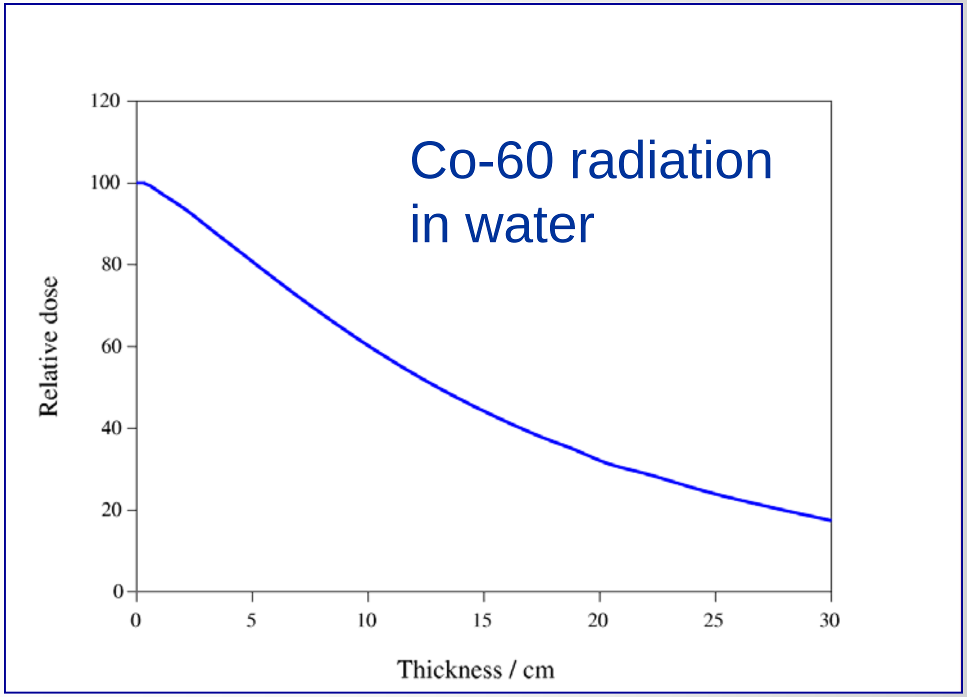


Dosimetry Principles - γ-ray Attenuation

Exponential attenuation: $I_x = I_0 e^{-\mu x}$

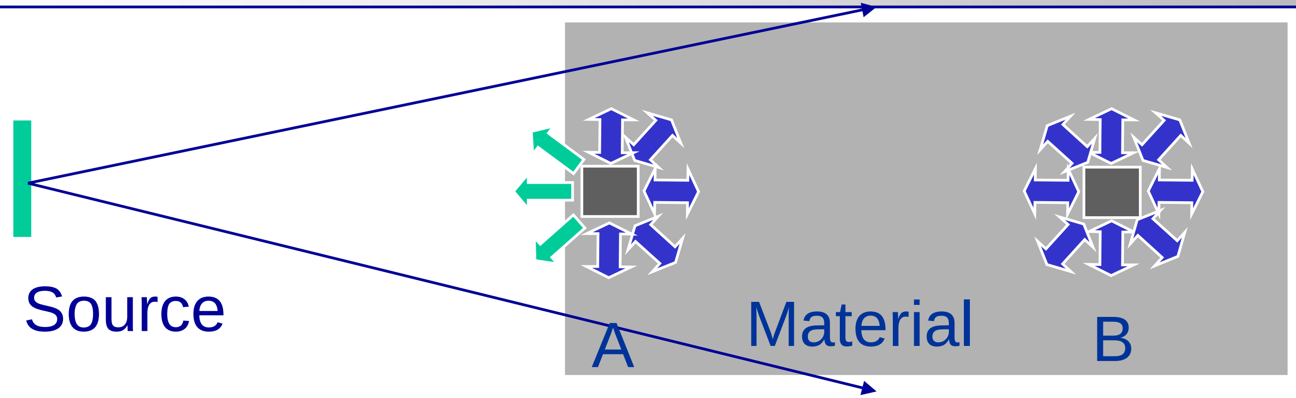
Where I_0 Initial intensity

I_x Intensity after travelling through thickness x

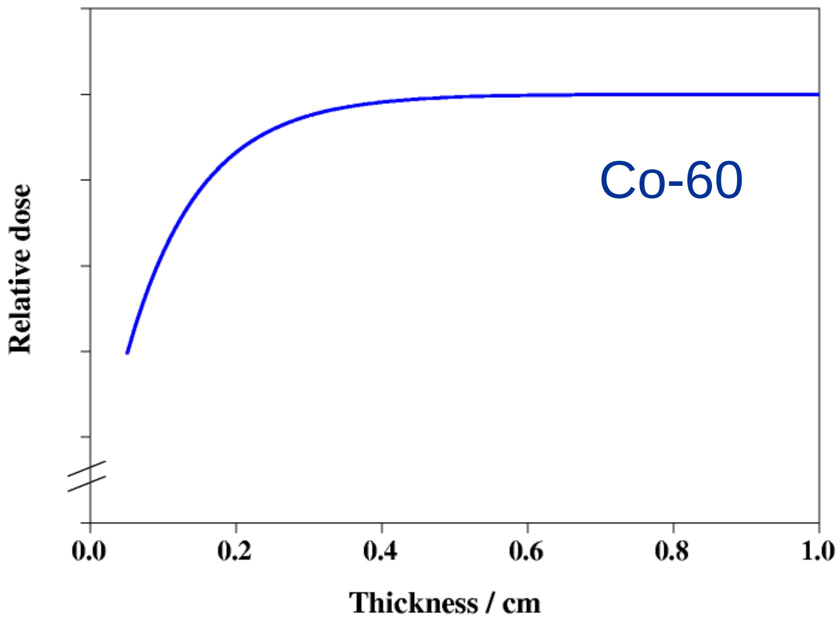


In practice, depth dose curves are close to exponential, but are influenced by source geometry and “build–up”.

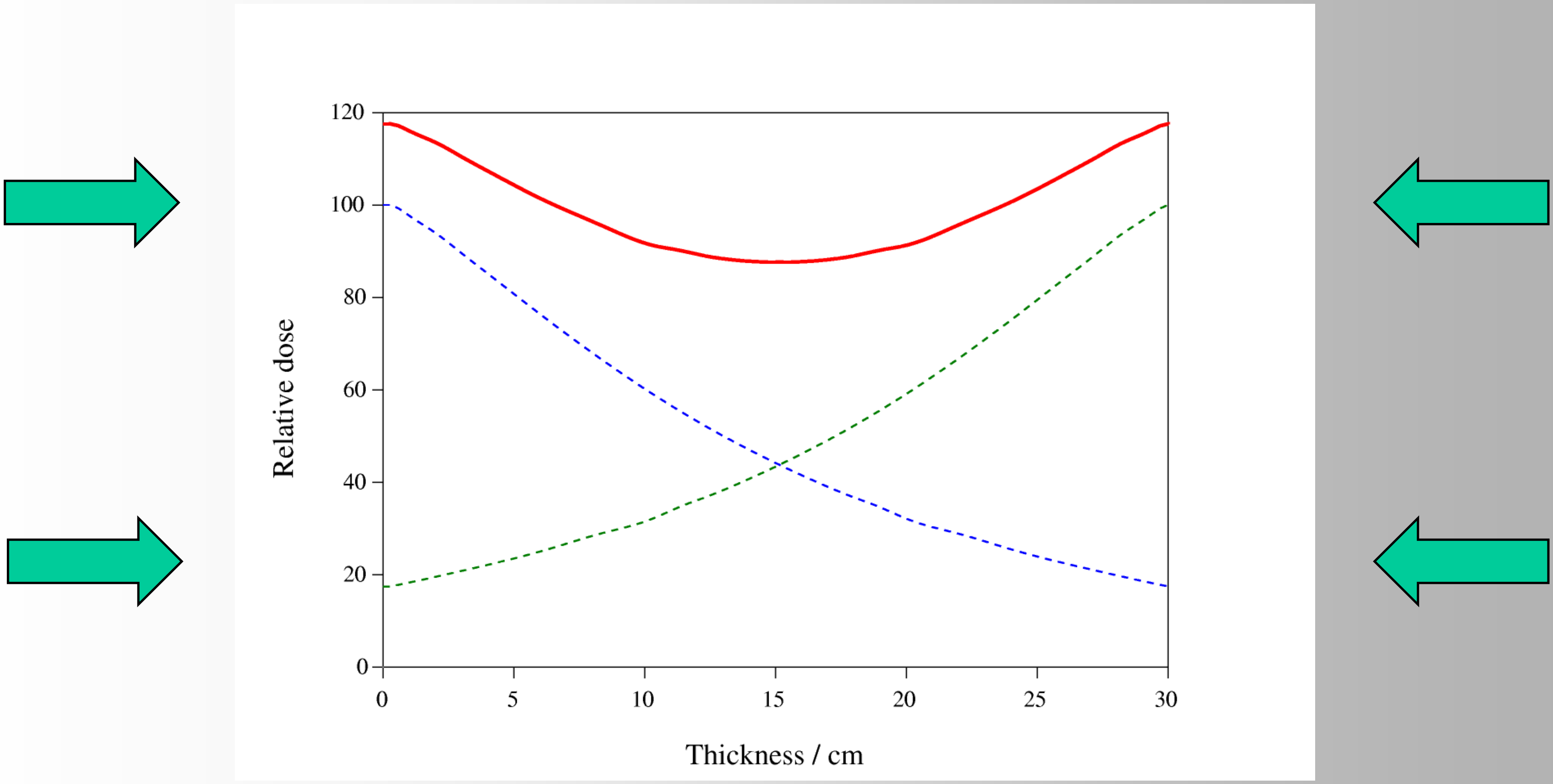
Dosimetry Principles – Electronic equilibrium



"Build-up" of dose occurs close to surface as electronic equilibrium is established.

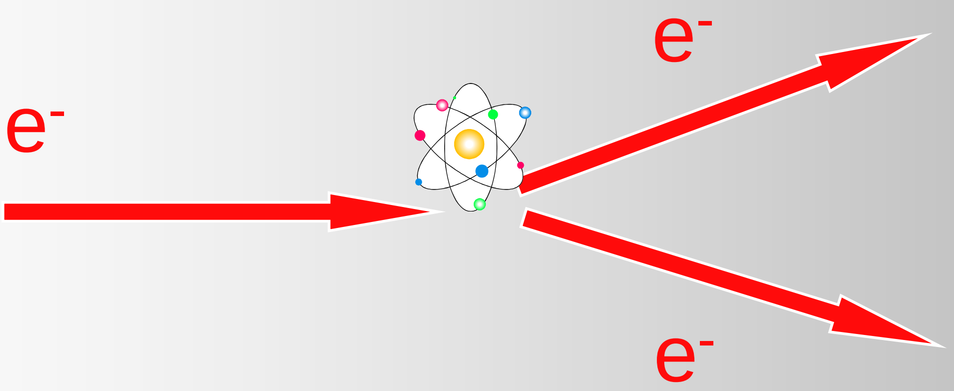


Dosimetry Principles – Two sided Co-60 irradiation



Dosimetry Principles – Electron Interactions

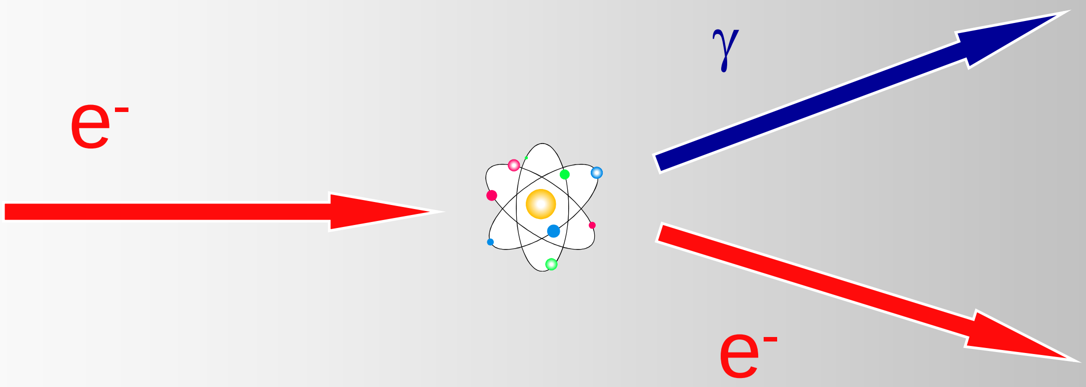
Collision energy loss



Scattering, mainly by electrons
Energy loss by excitation or ionization
Dominates for low electron energies and low atomic number

Dosimetry Principles – Electron Interactions

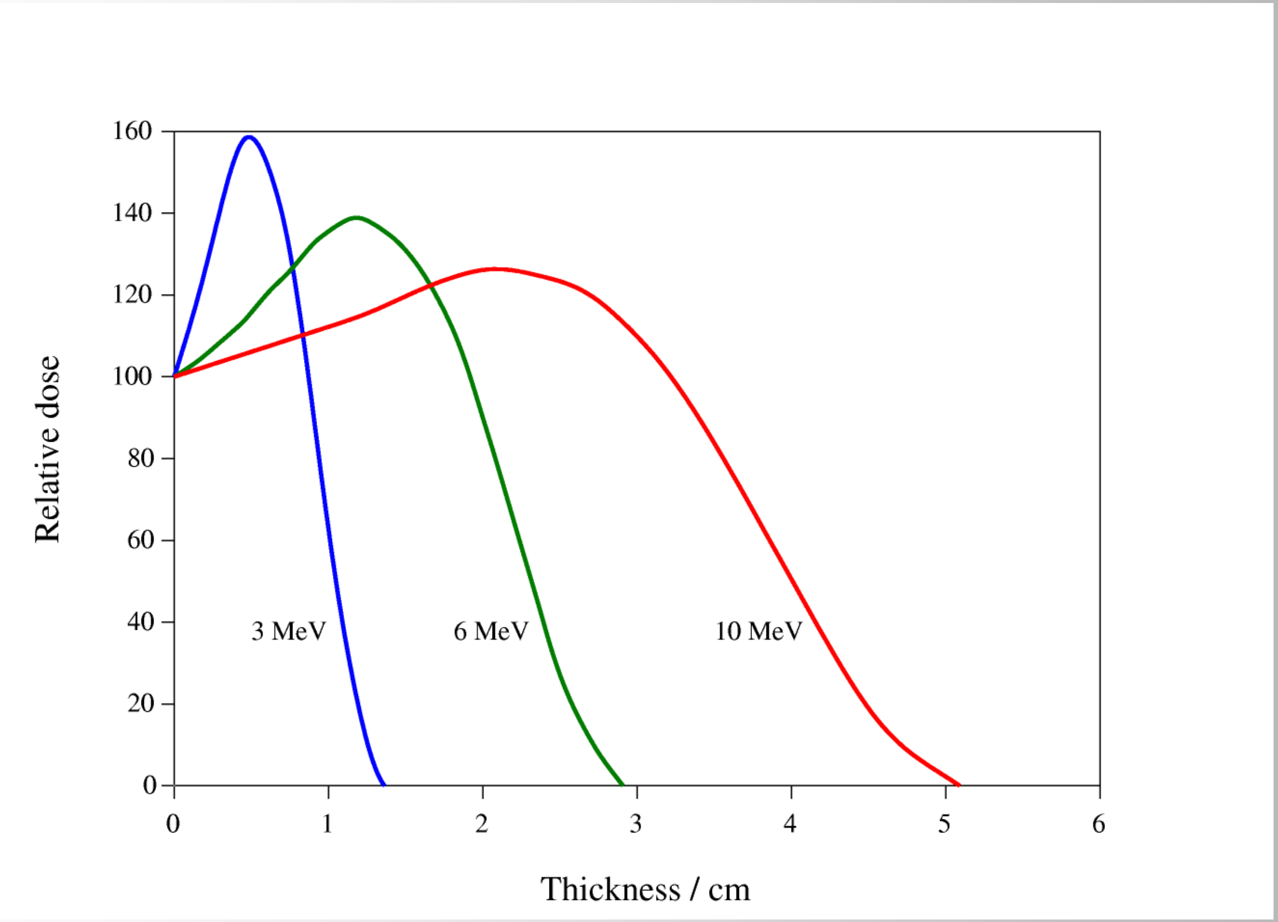
Bremsstrahlung



Scattering, primarily by nuclei
Energy loss by emission of γ-ray
Dominates for high electron energies and high atomic number.

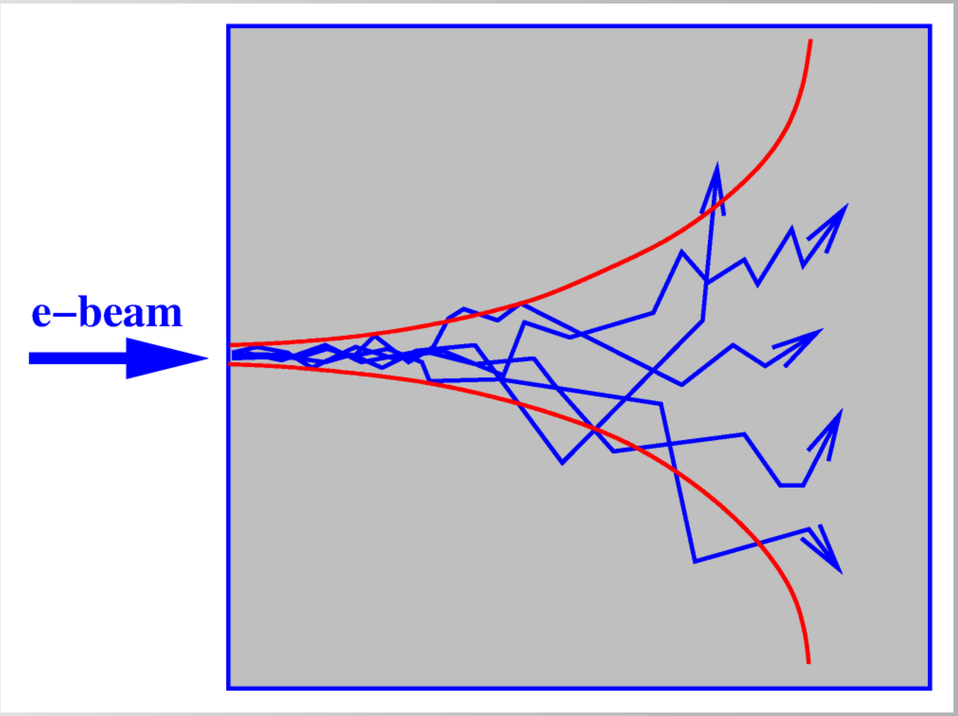
Dosimetry Principles – Electron Interactions

Electron depth dose distribution



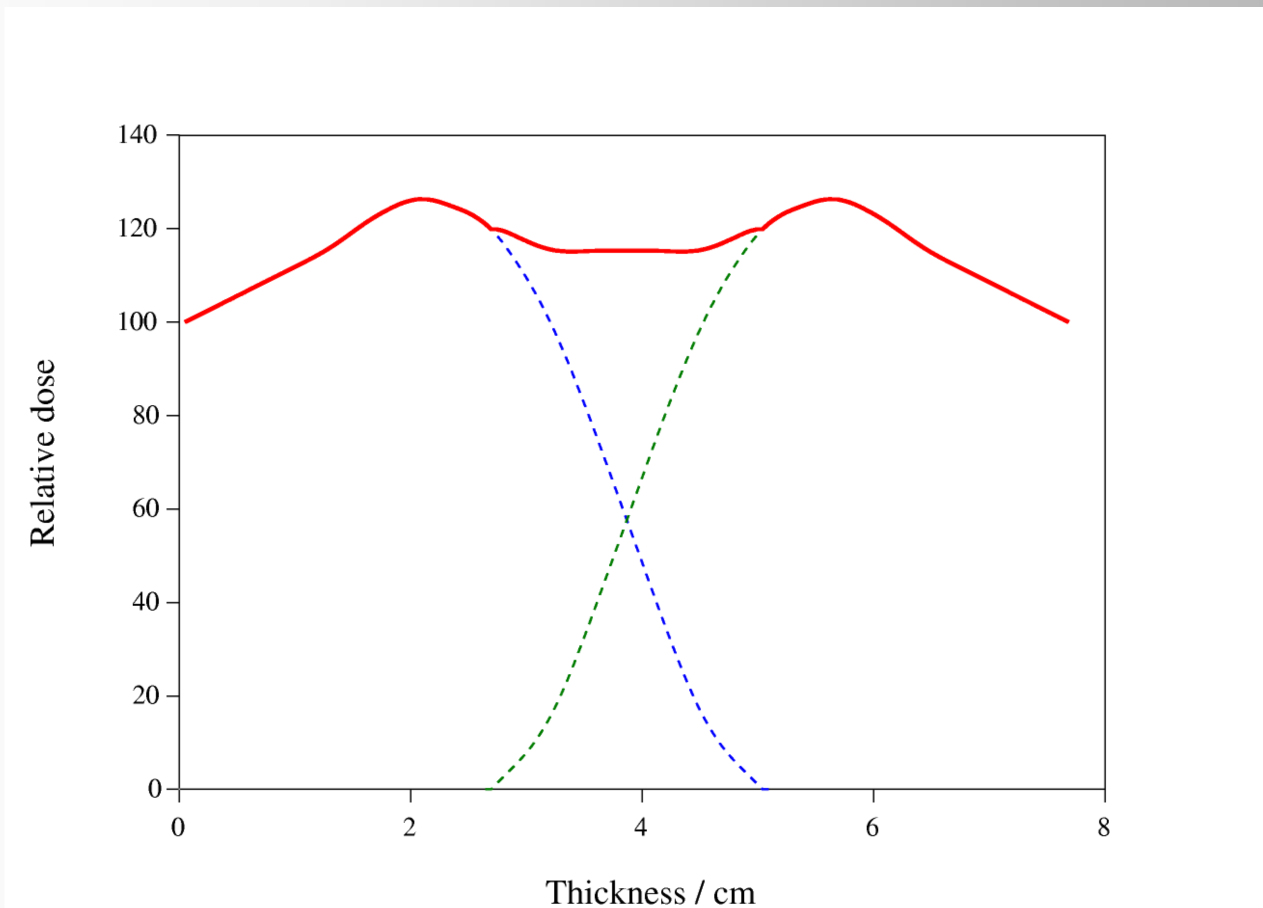
Dosimetry Principles – Electron Scattering

As electrons penetrate into a material they become increasingly scattered and the distance travelled by an electron to achieve a given amount of motion in the direction of the beam increases.



As energy deposited is roughly proportional to distance travelled, the absorbed dose also increases with depth into the material.

Dosimetry Principles - Two sided electron irradiation (10 MeV)



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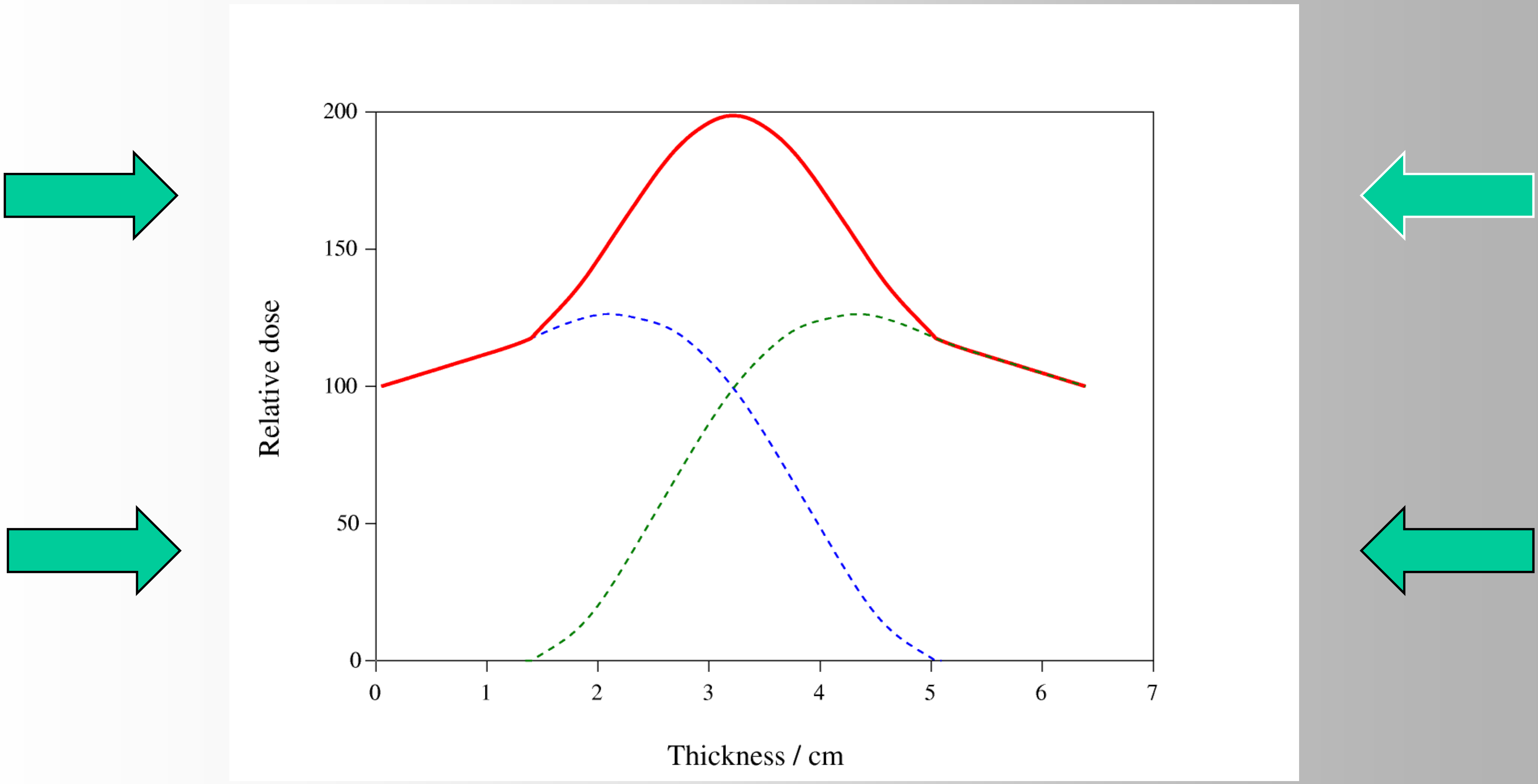
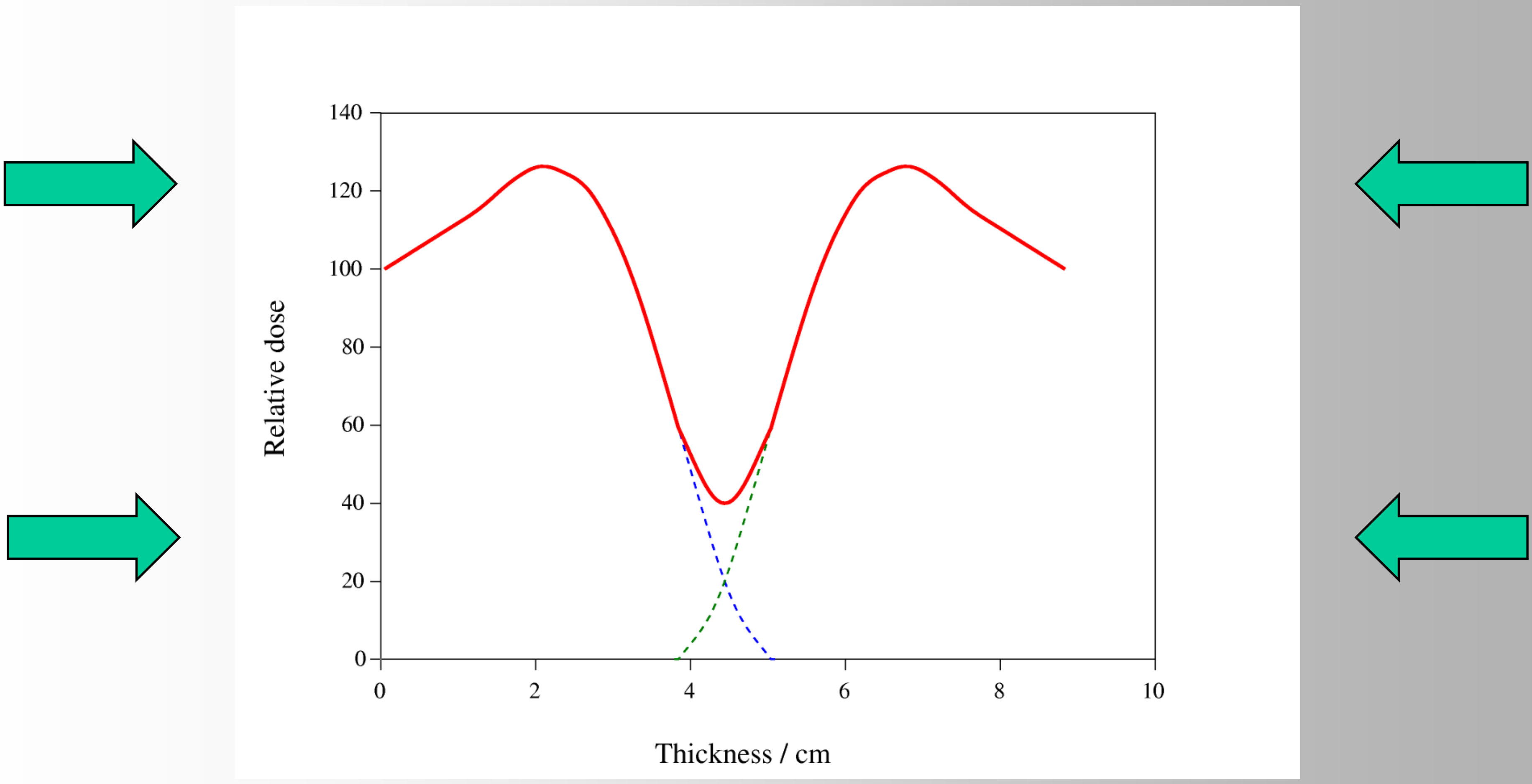


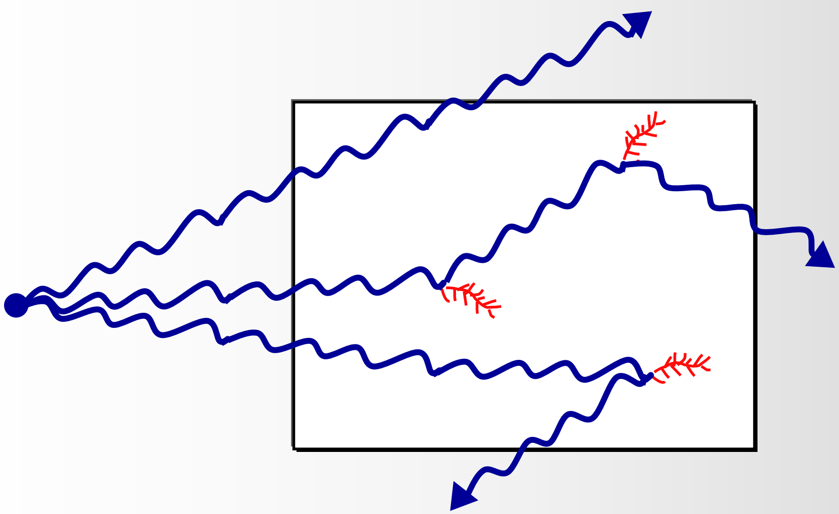
Dosimetry Principles - Two sided electron irradiation (10 MeV)



Dosimetry Principles - γ/electron comparison

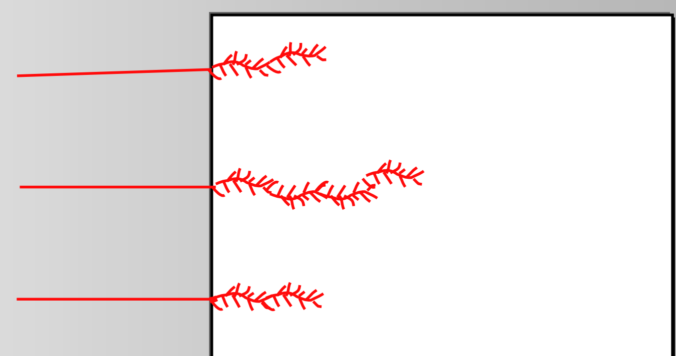
γ – irradiation

- Source emits in all directions
- Large inventory of material irradiated at any one time
- Moderate dose rate: ~10Gy s^{-1}



EB -irradiation

- Beam highly concentrated
- Small volume of material irradiated at any one time
- High dose rate: ~10 kGy s^{-1} (mean)
  ~10 MGy s^{-1} (peak)



Dose actually delivered in both cases by secondary electrons.

Dosimetry Principles – Calorimetry

- **Almost all of the energy deposited by electrons or γ-rays finally ends up as heat.**
- **The fraction which does not (Thermal Defect) is negligible for some materials in dose range of interest.**
- **Hence it is possible to measure dose directly by calorimetry.**

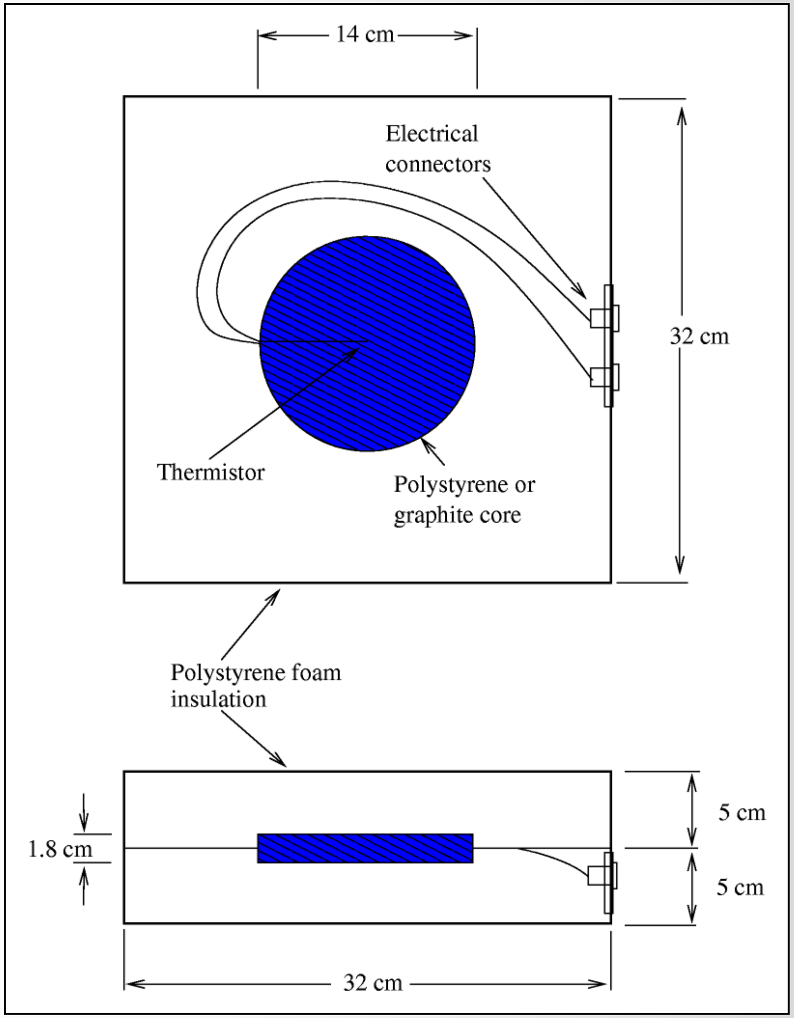
Water: 0.24°C/kGy
Graphite: 1.33°C/kGy
Polystyrene: 0.71°C/kGy

Change in temperature: $$\Delta T = \frac{D}{C}$$

D - dose **C** - specific heat of calorimeter material

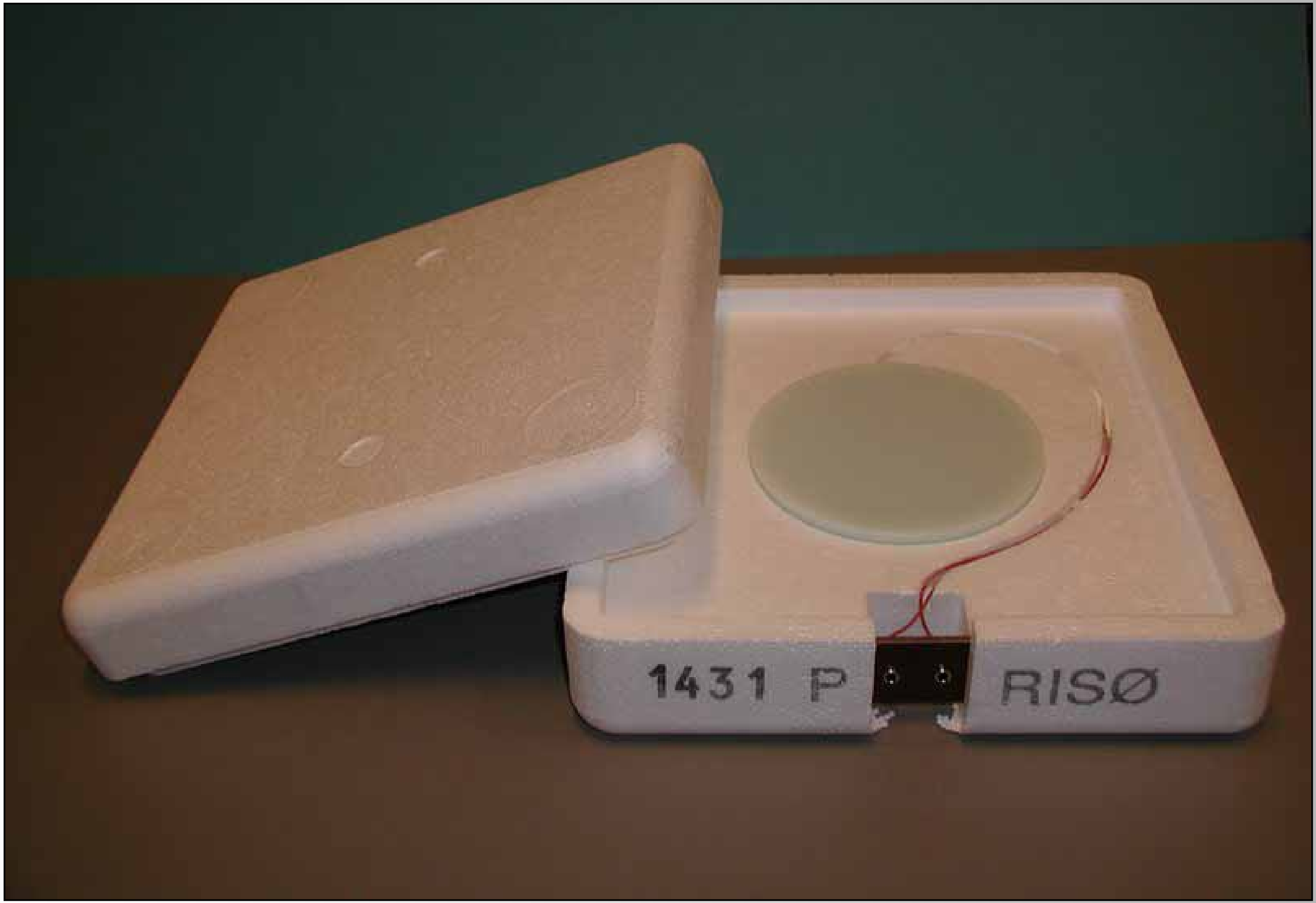
- **Only practical for electron irradiations.**
- **Low dose rate in γ-irradiation make thermal isolation of calorimeter virtually impossible.**

High Dose Calorimetry



Calorimeter based on polystyrene or graphite absorber enclosed in expanded polystyrene insulation.

High Dose Calorimetry



Dosimetry Principles - Chemical effects

The absorption of ionising radiation in a material results in a cascade of secondary electrons. These, in turn, transfer energy to molecules, resulting in ionisation, excitation and the breaking of chemical bonds.

Many radiation induced chemical species are extremely reactive, but often lead to **relatively stable products**. The detection of these stable products is the basis of chemical methods of dosimetry.

Dosimetry Principles

Ceric / Cerous Dosimeter

Description: Solution of ceric (Ce^{4+}) and cerous (Ce^{3+}) ions in 0.4M sulphuric acid.

Mechanism: Reduction of ceric ion to cerous

Dose range: 1 to 50 kGy

Readout: Spectrophotometry at 320 nm (Ce^{4+}) or potentiometric readout.

Dosimetry Principles

Ceric / Cerous Dosimeter

$$H_2O \xrightarrow[\text{radiation } (H^+)]{\text{ionising}} H^\bullet,\ OH^\bullet,\ H_2O_2$$

$$Ce^{4+} + H^\bullet \Rightarrow Ce^{3+} + H^+$$

$$Ce^{4+} + H_2O_2 \Rightarrow Ce^{3+} + {}^\bullet HO_2 + H^+$$

$$Ce^{4+} + {}^\bullet HO_2 \Rightarrow Ce^{3+} + H^+ + O_2$$

$$Ce^{3+} + OH^\bullet \Rightarrow Ce^{4+} + OH^-$$

Dosimetry Principles

Radiation Chemical Yield, G(x) of an entity is the mean amount of that entity produced, destroyed, or changed in a system by radiation, divided by the amount of radiation energy imparted to the matter in that system.

Unit: mol J^{-1}

For ceric / cerous dosimeter:

$$G(-Ce^{4+}) = G(H^{\bullet}) + 2G(H_2O_2) - G(OH^{\bullet})$$

$$\approx 2.4 \times 10^{-7} \text{ mol J}^{-1}$$

Dosimetry Principles

Alanine Dosimeter

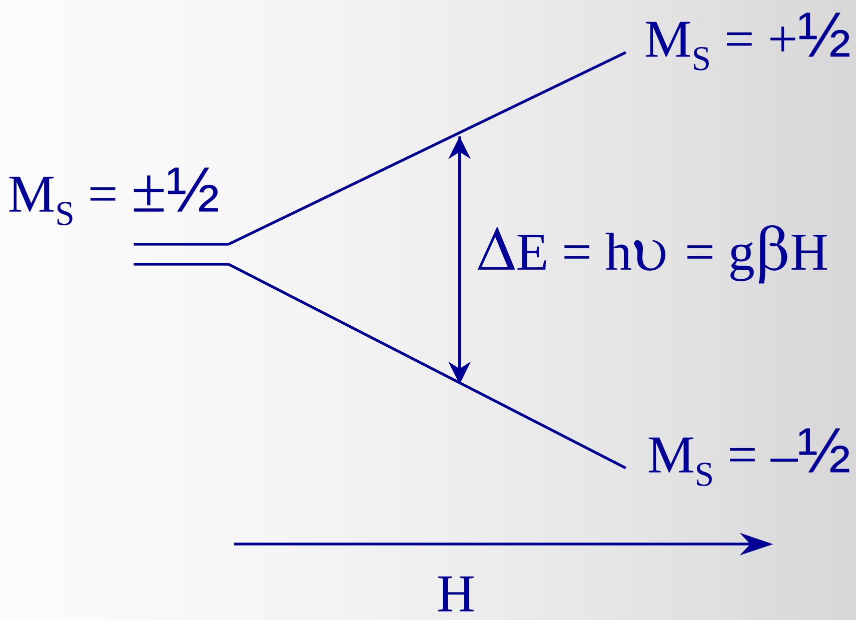
Irradiation of the amino acid alanine produces stable free radicals:

$$
\begin{array}{c}
\text{H} \\
| \\
H_3C\text{-}C\text{-}COOH \\
| \\
NH_2
\end{array}
\quad
\xrightarrow[\text{Radiation}]{\text{Ionising}}
\quad
\begin{array}{c}
\text{H} \\
| \\
H_3C\text{-}\dot{C}\text{-}COOH
\end{array}
$$

The concentration of the radicals is proportional to the absorbed dose and can be measured by Electron Paramagnetic Resonance (EPR) spectroscopy.

Principles of Electron Paramagnetic Resonance

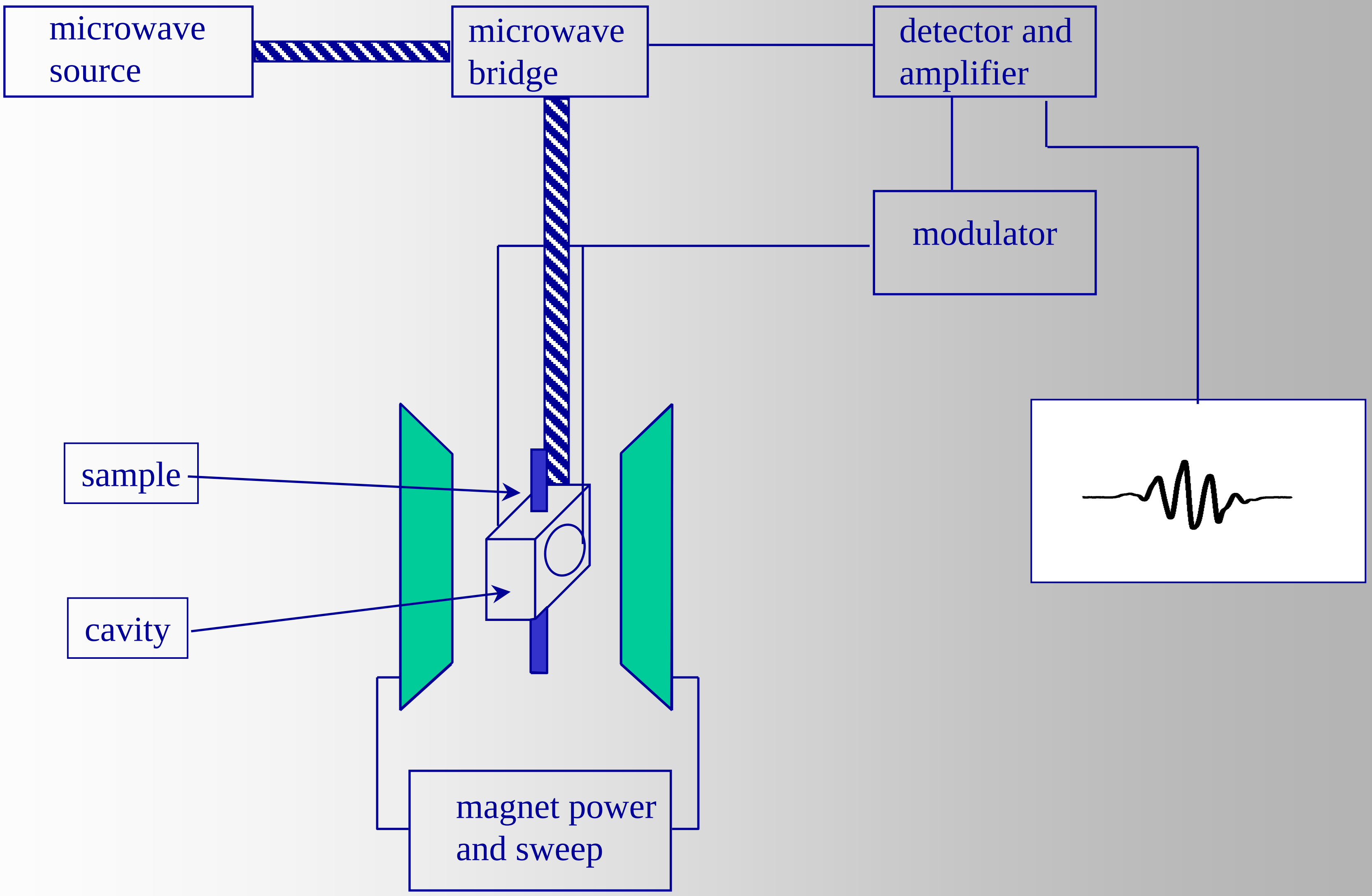
In magnetic fields unpaired electrons exist in one of two discrete energy levels. The separation between the levels is proportional to the magnetic field.



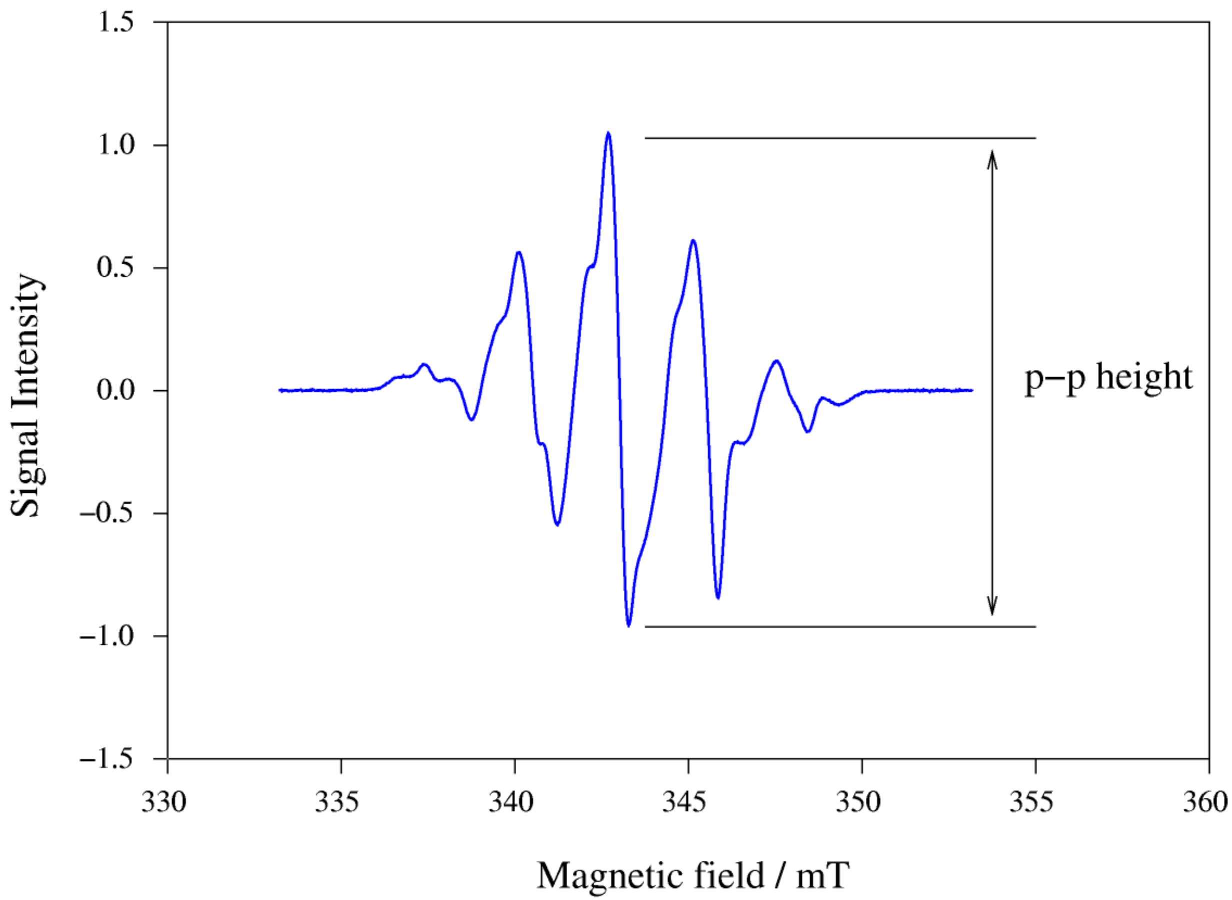
Transitions between the energy levels can be induced by photons of the correct energy.

For practical magnetic fields (300 mT) the transitions are caused by microwave radiation (9 GHz)

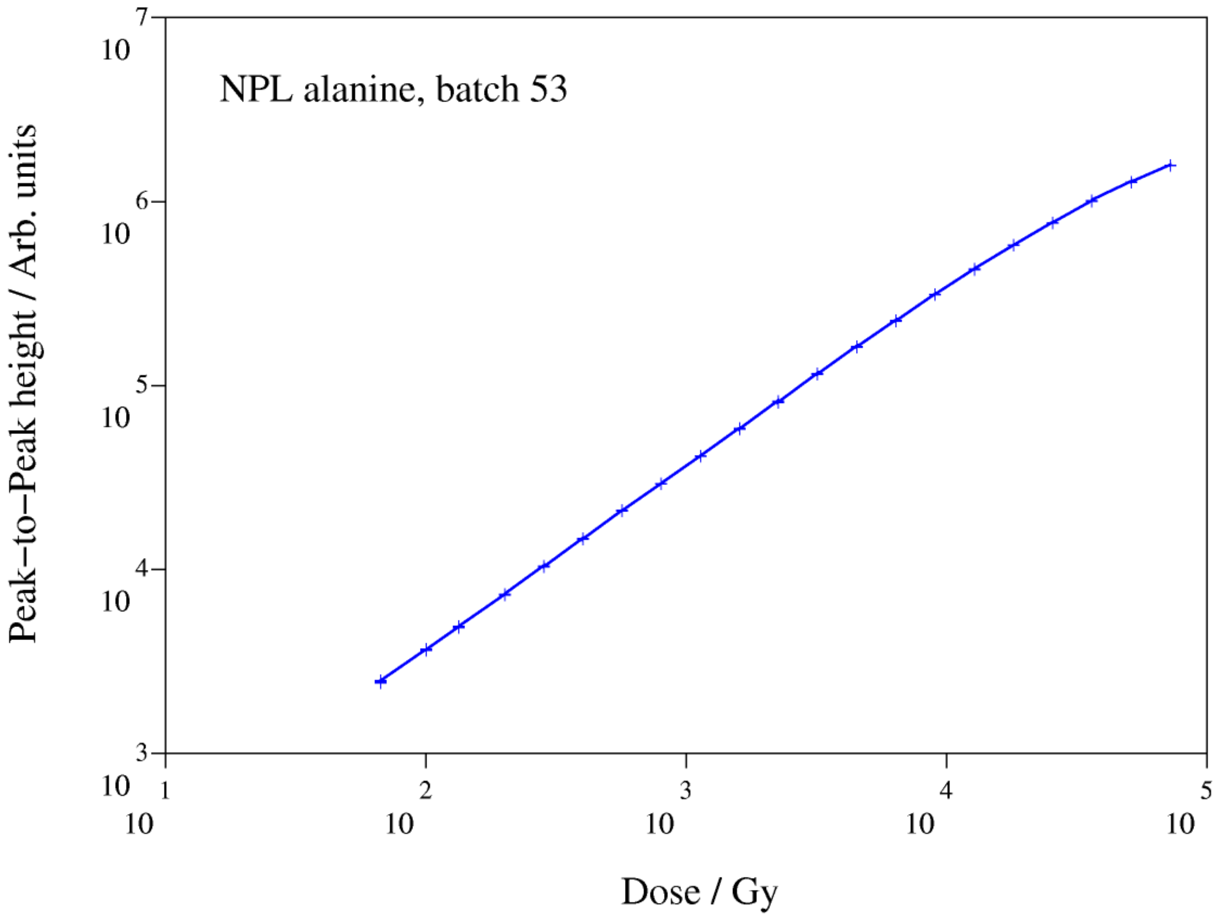
Block Diagram of EPR Spectrometer



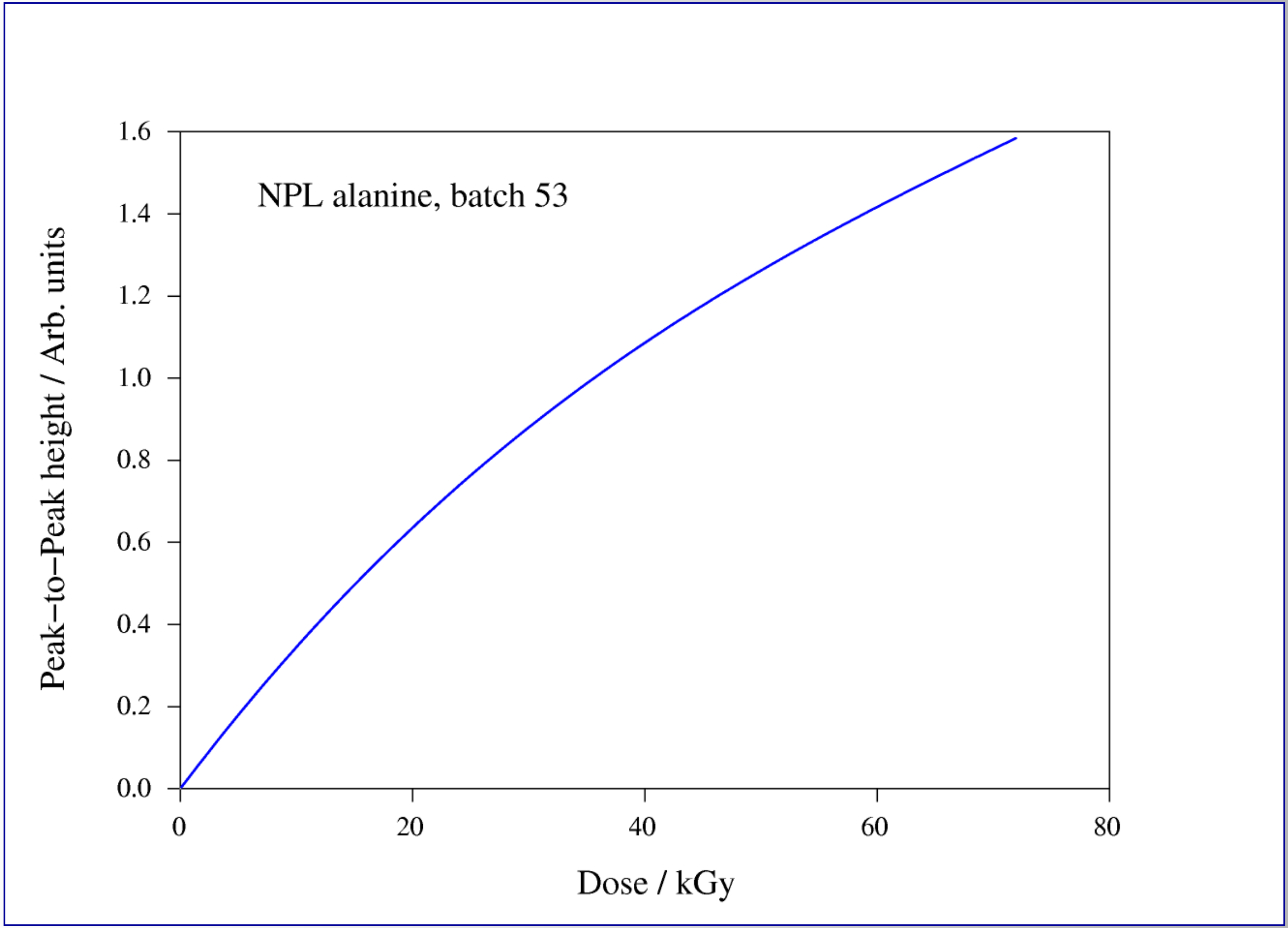
EPR Spectrum of Irradiated Alanine



Alanine Dose Response Curve



Alanine Dose Response Curve



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Dosimetry Principles

Summary

Many of the issues and difficulties associated with industrial dosimetry have their roots in the underlying physical and chemical processes involved.

An understanding of these processes is essential in both the design and routine operation of industrial dosimetry systems.