Radiation effects of electron and photon radiation – biological materials

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  - Characteristics of electron and photon radiation effects
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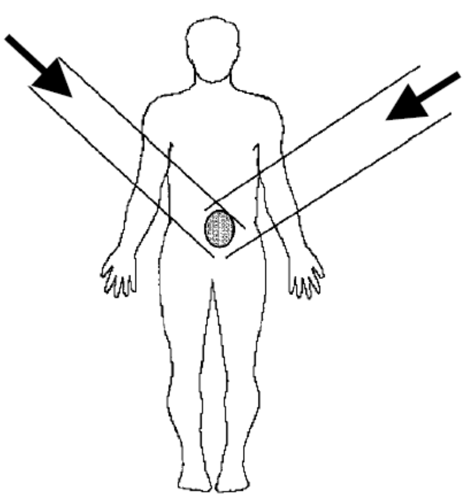
radiation = ionizing radiation
i.e. no cell phone radiation or
the like discussed

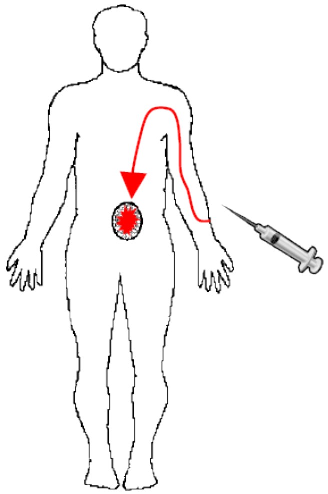
Introduction

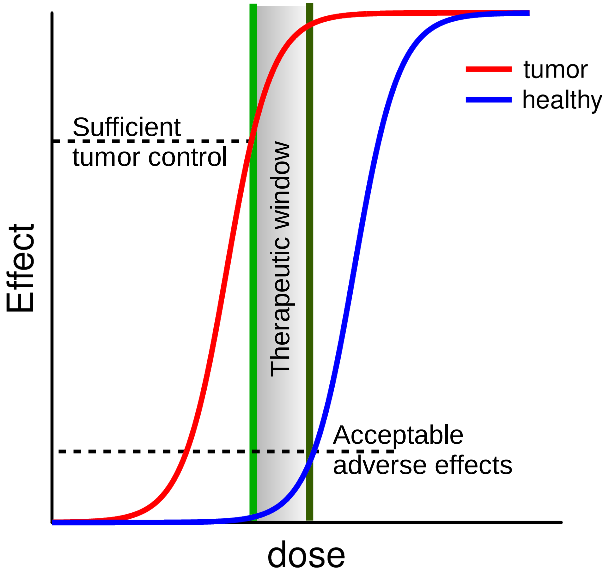
- Biological materials
  - Electronic effects: ionization, free radicals etc. → mutations, cell death, cancer
  - Cf. metals and semiconductors: atomic displacements
- Electron and photon radiation
  - Medical physics, electron spectroscopy methods in physics
  - Deeper penetration compared to ions
  - Cascades with secondary particles
  - Many interaction mechanisms
- Neutron irradiation
  - BNCT
- Ions (protons and heavier)
  - Hadron therapy

Introduction

- Radiation uses in medical physics
  - Imaging (low doses; hopefully)
  - Radiation therapy
    - External
      - Gammas from active sources or accelerators
      - Electrons from accelerators
    - Nuclear medicine
      - Active isotope attached to a biologically active molecule





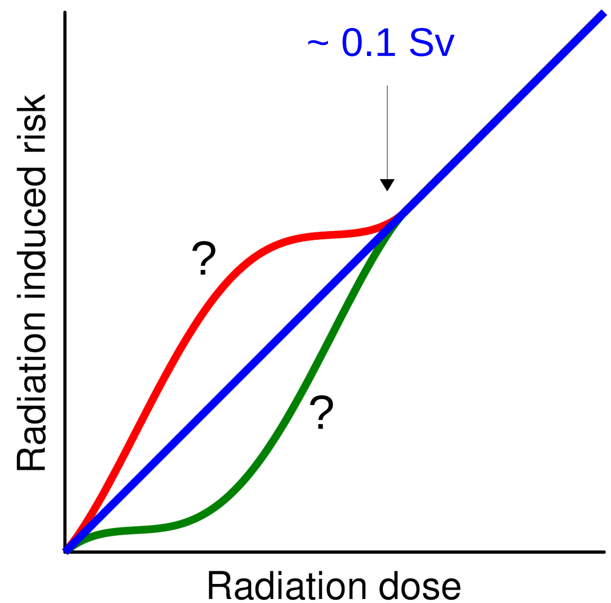


Radiation effects in biological materials

Radiation	W
Photons	1
Protons	2
Heavy ions	20

- Basic macroscopic quantity:
  absorbed dose (deposited energy) D (J/kg=gray=Gy)
  - Taking into account the biology:
    equivalent dose $H = WD$ (sievert=Sv)
    - Different weight factors for different radiation species
    - The higher the energy density the larger the factor
  - Damage–dose dependence
    - Damage ~ cell death, mutations, genetic instability, ...
    - LNT (linear, no threshold) model
      - Based on atom bomb survivors' doses
      - Questioned at low doses

Annual dose	A few mSv
Head CT scan	2 mSv
Lethal dose	A few Sv
Radiotherapy	*Many Gy's*



Macrodosimetry

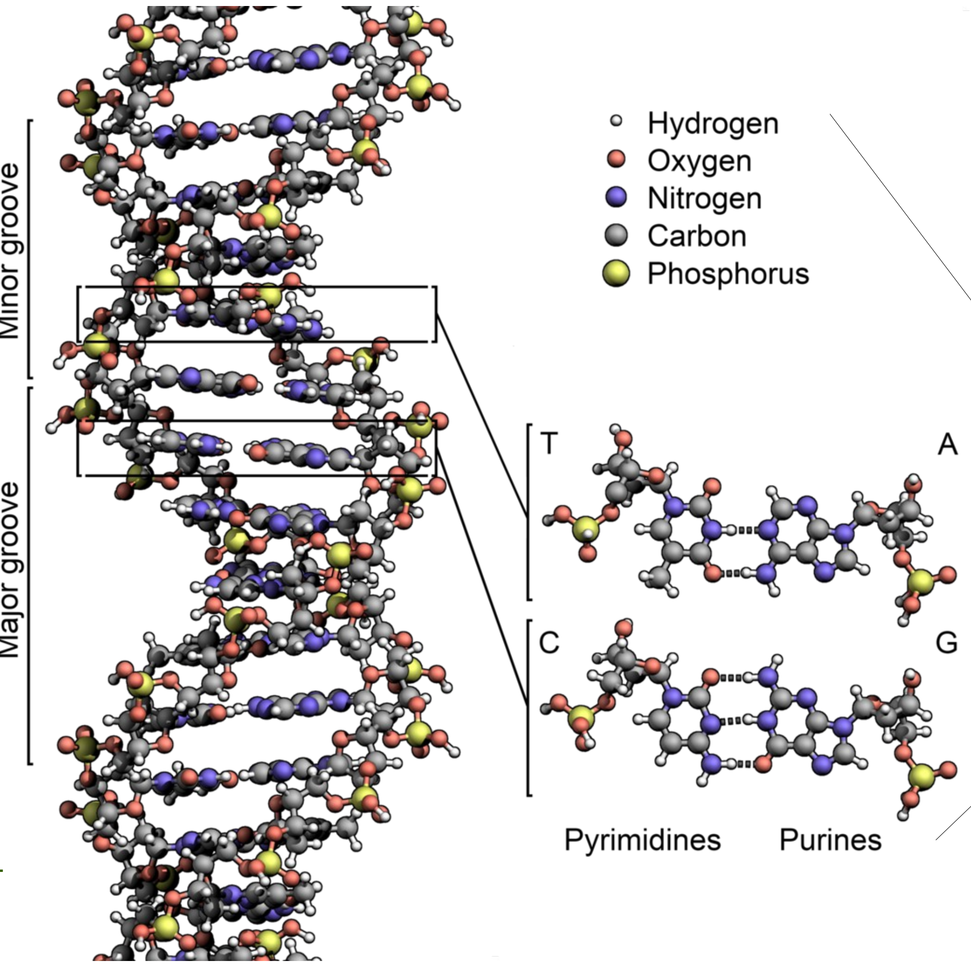
Radiation effects in biological materials

- Abrorbed dose: the most common quantity used in e.g. in radiotherapy
  - Only an average quantity
  - The weight factor reflects the energy deposition pattern of different radiation species
  - Does not take into account the stochastic nature of energy deposition
- Sufficient for external irradiation
  - Doses to organs
  - Length scales of the order of cm
- In nuclear medicine inhomogeneous activity distribution
  - Length scales may be in micrometers
  - Macrodosimetry in microscale

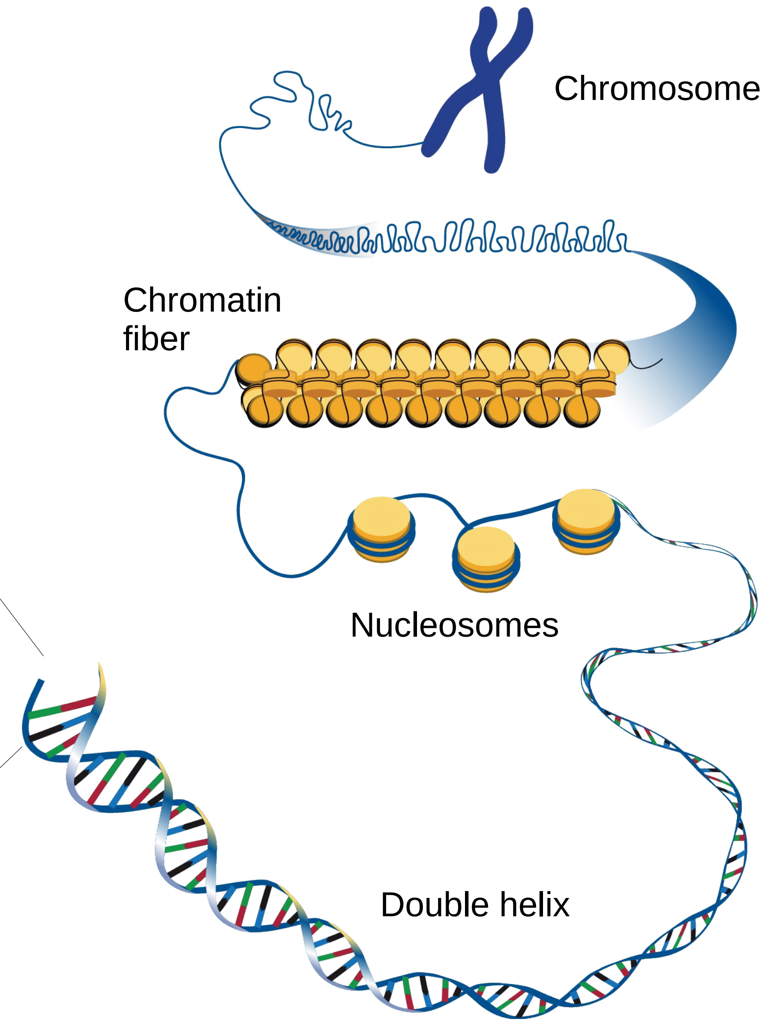
Macrodosimetry

Radiation effects in biological materials

- Microscopic picture: structure of the DNA



Wikipedia

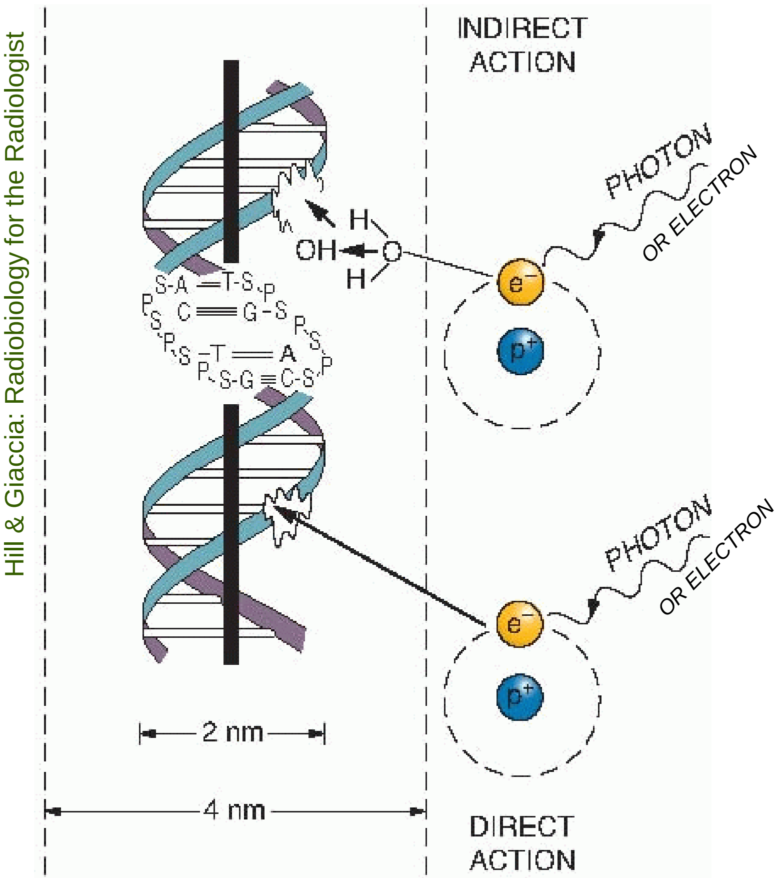


National Human Genome Research Institute

Radiation effects in biological materials

- Microscopic picture
  - Irradiation-caused ionization *events*
- Cell damage ⇔ damage to DNA
  - Direct damage
    - Direct hit to the double helix structure
  - Indirect damage
    - Reactive chemical species
  - Single or double strand breaks (SSB, DSB)
  - DNA crosslinking
- Cells have many DNA repair mechanisms

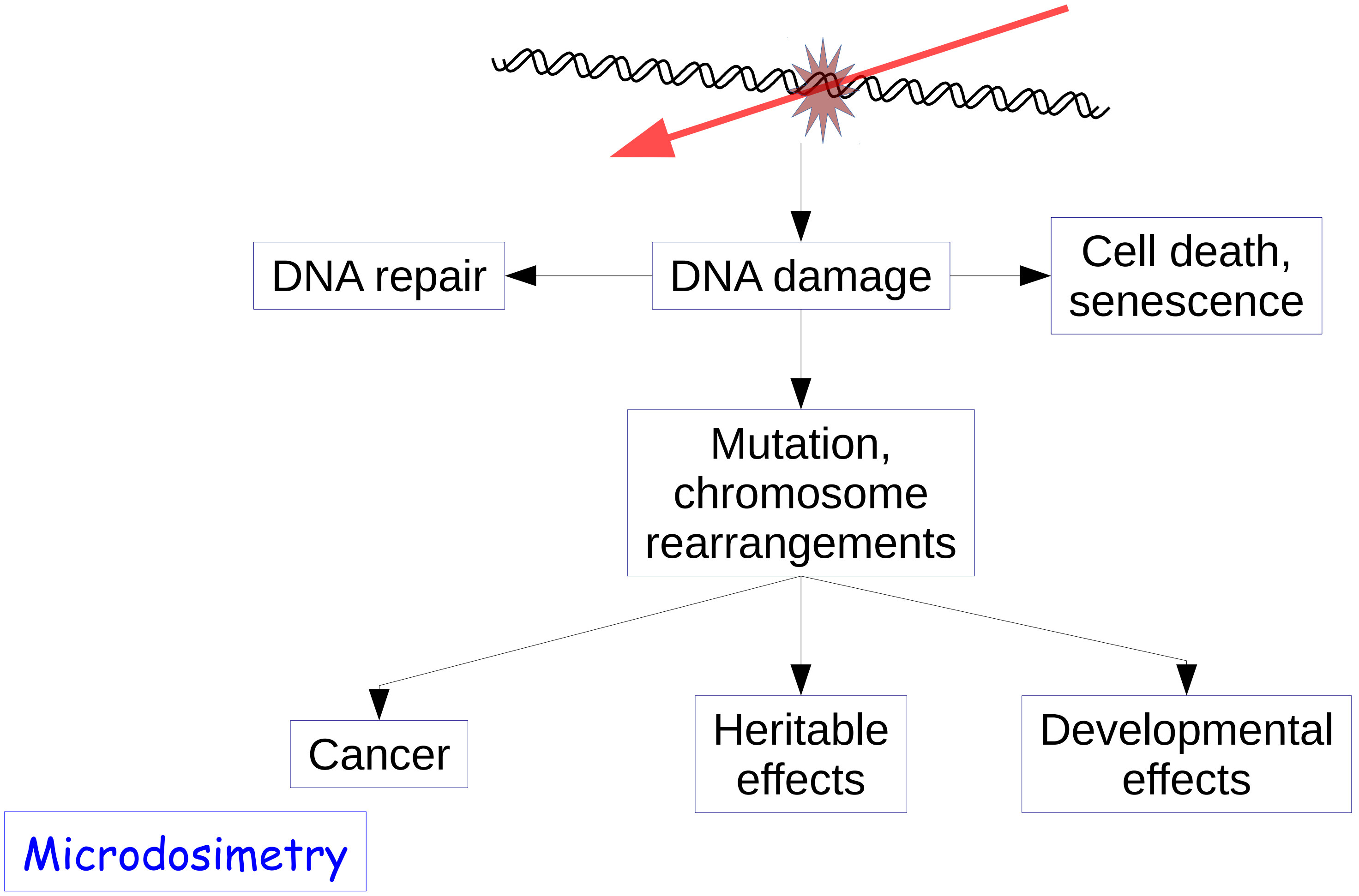
Hill & Giaccia: Radiobiology for the Radiologist



Microdosimetry

Radiation effects in biological materials

- Possible end points of the irradiation damage event



Radiation effects in biological materials

- Time scales of the irradiation events

	Time (s)	Event
Physical	10^{-18}	Ionising particle traverses a molecule
	10^{-15}	Ionization
	10^{-14}	Excitation
Chemical	10^{-12}	Diffusion of free radicals
	10^{-10}	Free radical reactions with the solute
	10^{-8}	Formation of molecule products
	10^{-5}	Completion of chemical reactions
Biological	1 – 1 h	Enzymatic reactions, repair process
	1 h – 100 y	Genomic instability, mutation, cell killing
	days – months	Stem cell killing, tissue damage, loss of cell proliferation
	days – years	Fibrosis, skin damage, spinal cord damage
	many years	Tumors

According to H. Nikjoo, *Iran. J. Radiat. Res.* **1** (2003) 3.

Radiation effects in biological materials

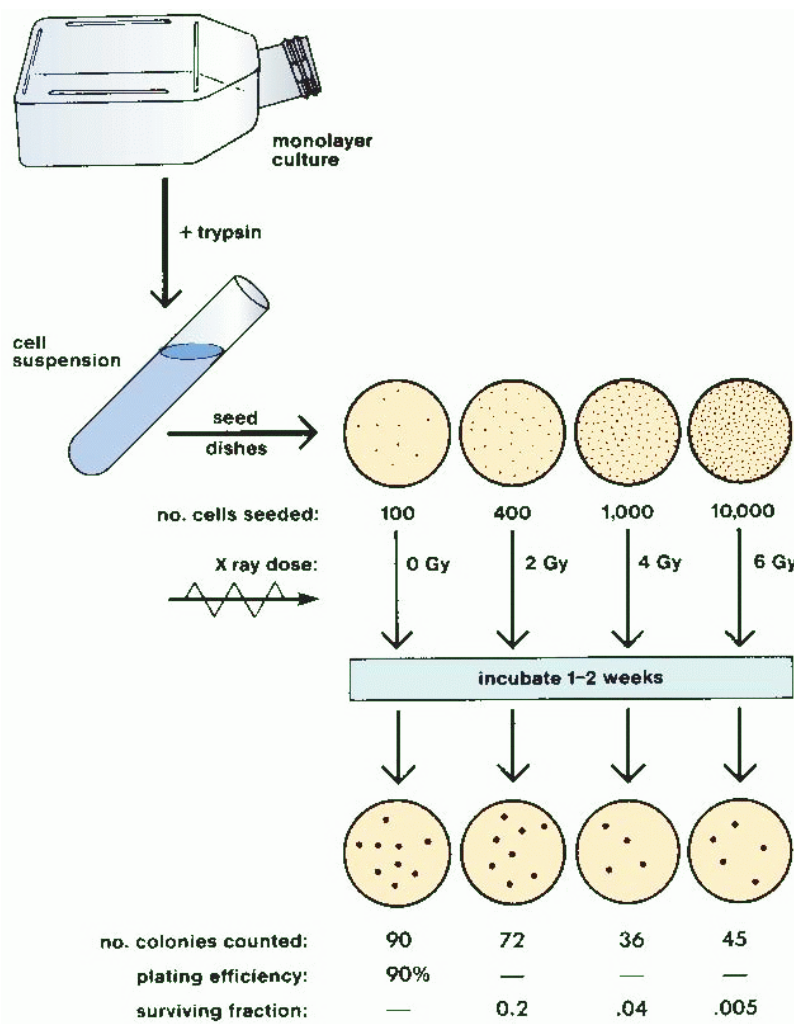
- Experimental methods: in vitro

Survival fraction $S(D)=e^{-\alpha D-\beta D^2}$

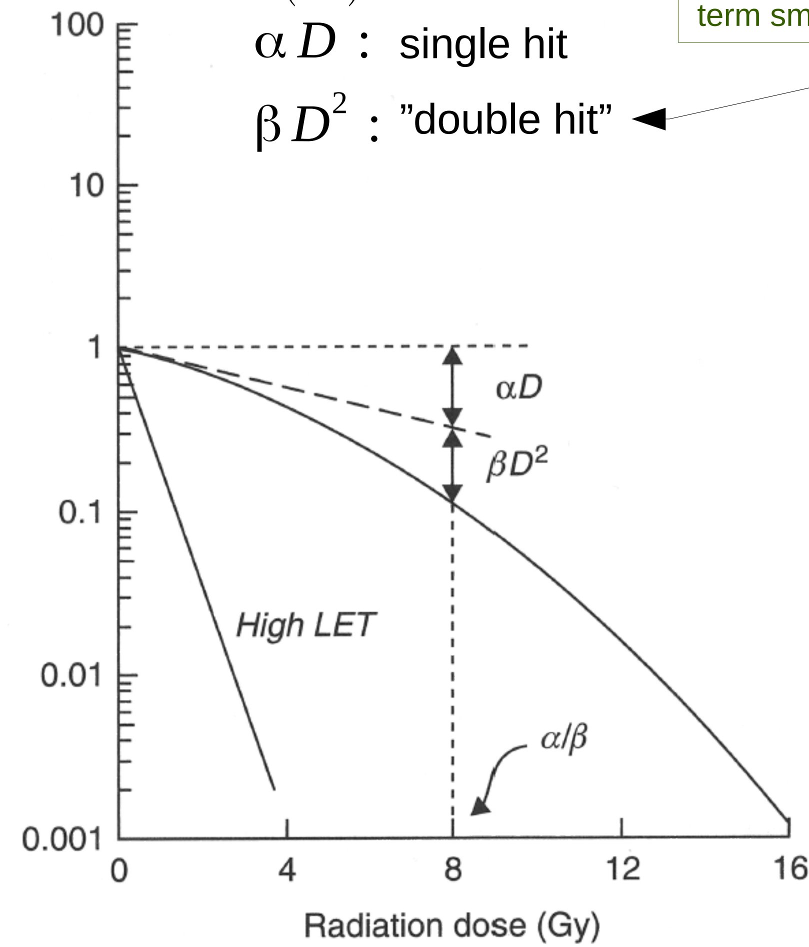
αD : single hit

βD^2 : ”double hit”

Justification: at low dose-rates quadratic term small



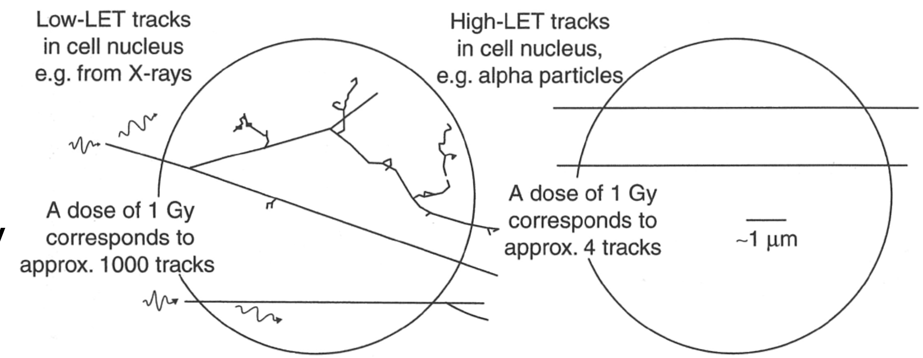
Hill & Giaccia: Radiobiology for the Radiologist



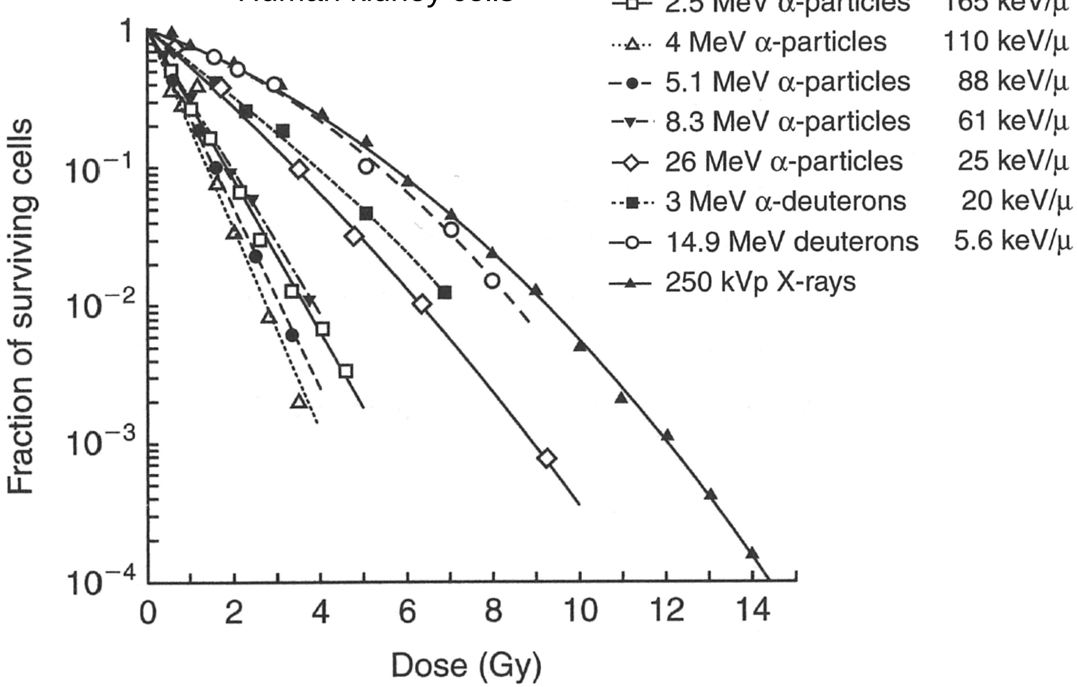
Joiner, van der Kogel: Basic Clinical radiobiology

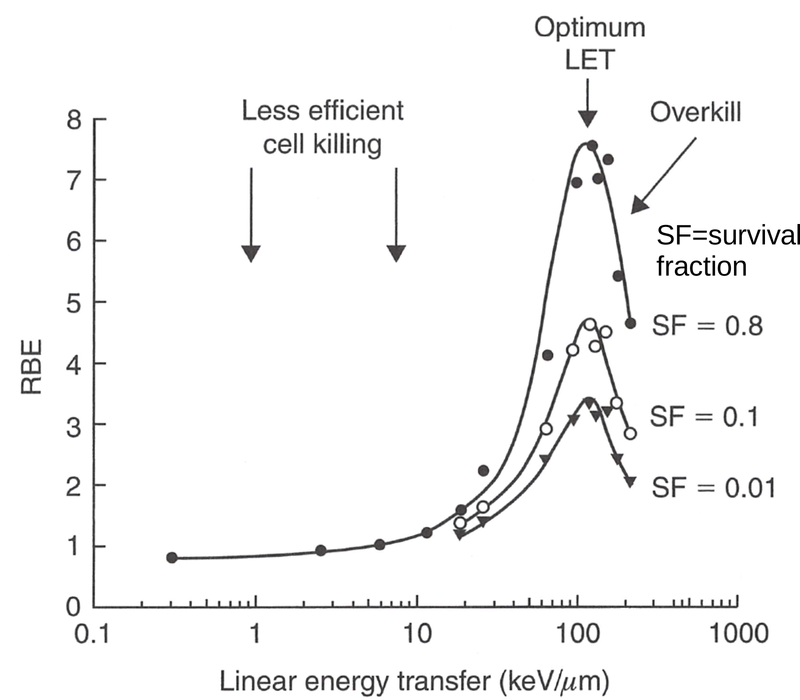
Radiation effects in biological materials

- An example of survival curves
  - Demonstrates the dependence of the relative biological effectiviness (RBE) on the radiation linear energy transfer (LTE)



Human kidney cells



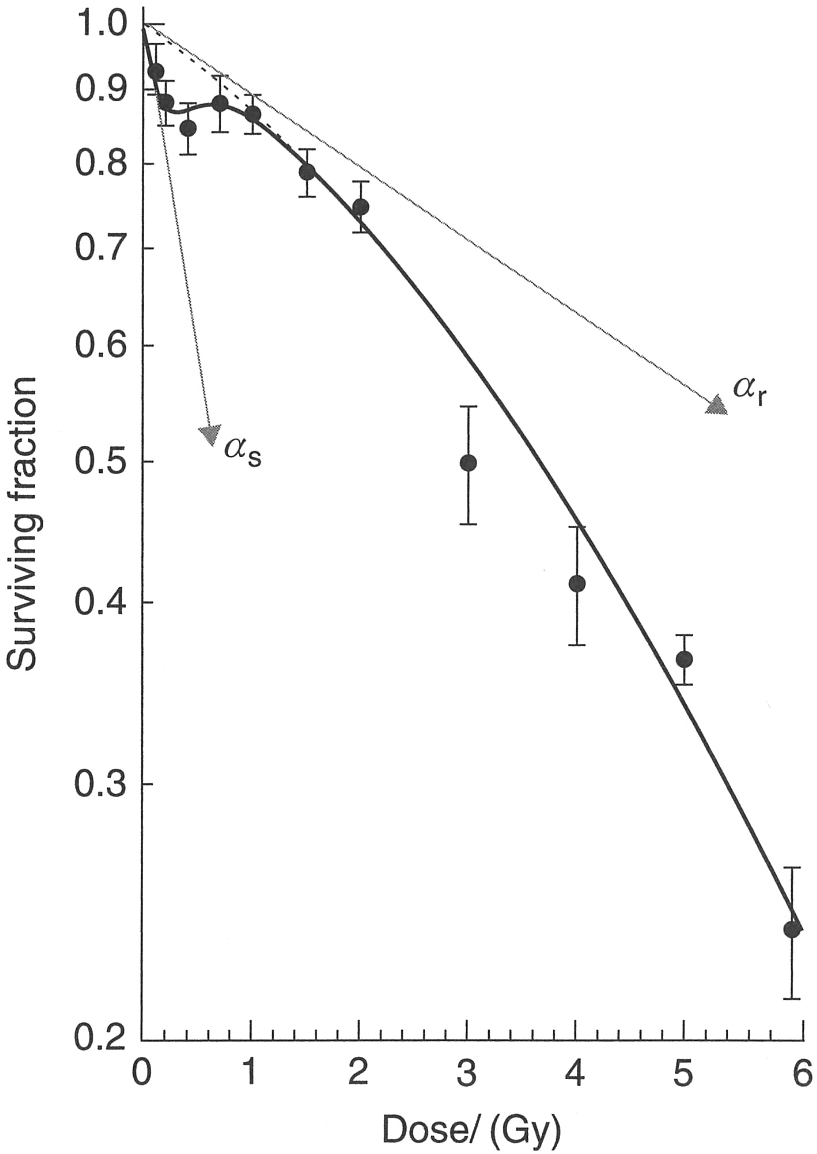


Joiner, van der Kogel: Basic Clinical radiobiology

Radiation effects in biological materials

- Survival curves are not always this simple
  - E.g. the DNA repair mechanisms and damage point interactions may change the behavior

Survival of human glioma cells irradiated with 240 kVp X-rays.



Joiner, van der Kogel: Basic Clinical radiobiology

Radiation effects in biological materials

- Experimental methods: macroscopic scale (clinical)
  - Embedded detectors
    - Ionization chambers, semiconductor and thermoluminescent detectors

Radiation effects in biological materials

- Modeling of the radiation transport in biological materials
  - Typical calculations: energy deposition by
    1) external photon or electron beam
    2) radioactive substance in material
  - Methods
    - Lookup tables (MIRD pamphlets): only standard geometries
    - Analytical methods (pencil beam convolution): heterogeneity only approximately
    - **Monte Carlo!** : the most accurate; may be slow

Monte Carlo simulation of radiation transport

- Assume we have target material with the atomic density n
- A monoenergetic particle beam with current density $\mathbf{J}_{\text{inc}}$ scatters from target T
  - Direction and energy change: $(\mathrm{d}, E) \rightarrow (\mathrm{d}', E-W)$
  - The double *differential cross section* (DCS) is defined as

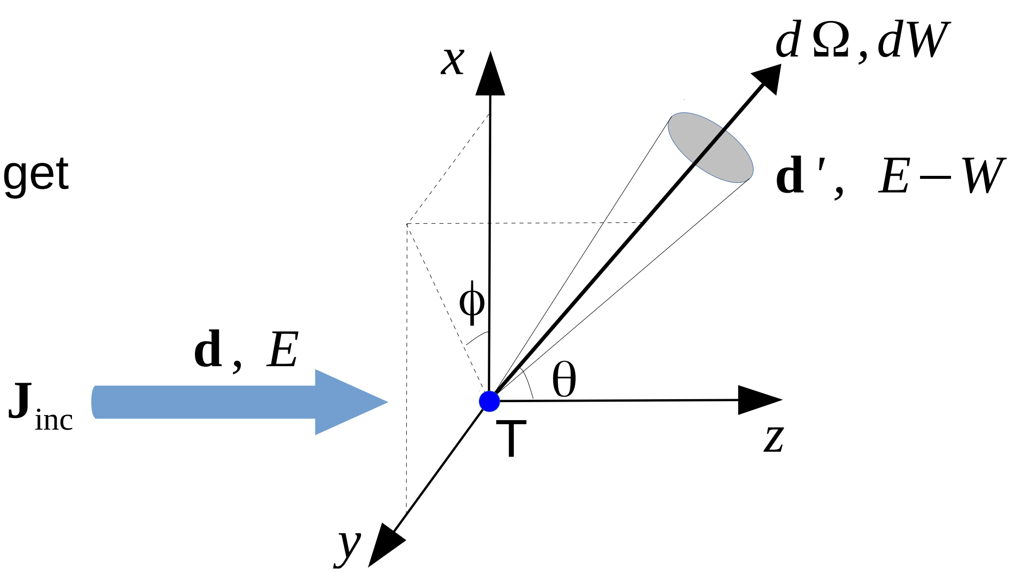
$$\frac{d^2\sigma}{d\Omega\, dW} = \frac{\dot{N}_{\text{count}}}{|\mathbf{J}_{\text{inc}}|\, d\Omega\, dW}$$

  - Integrating out the solid angle we get the energy-loss DCS

$$\frac{d\sigma}{dW} = \int_{4\pi} \frac{d^2\sigma}{d\Omega\, dW} d\Omega$$

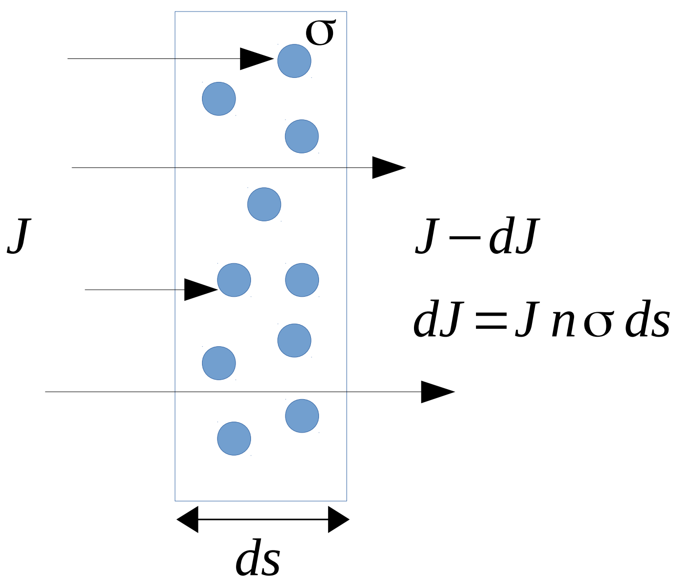
  - The total cross section is

$$\sigma = \int_0^E \frac{d\sigma}{dW} dW$$



Monte Carlo simulation of radiation transport

- In the MC algorithm we need the distribution of the distance s from the current position to the next interaction $p(s)$
  - Each scatterer has a cross section $\pi r_s^2 = \sigma$
  - Particle sees $n\,ds$ spheres per unit surface
  - Number of particles undergoing interaction is
    $$dJ = J\, n\sigma\, ds$$
  - Interaction probability per unit path length
    $$\frac{dJ}{J\,ds} = n\sigma$$
  - The probability that a particle travels a path s without interacting is
    $$F(s) = \int_s^{\infty} p(s')\,ds'$$



Monte Carlo simulation of radiation transport

- The probability $p(s)ds$ of having the next interaction in $[s, s+ds]$ is

$$p(s) = n\sigma \int_s^{\infty} p(s')ds'$$

- This is actually an integral equation with solution (bc: $p(\infty)=0$)

$$p(s) = n\sigma e^{-sn\sigma}$$

- Mean free path is

$$\lambda = \int_0^{\infty} s\, p(s)ds = \frac{1}{n\sigma} \qquad \frac{1}{\lambda} = \text{prob. of interaction per unit path} = n\sigma$$

- Assume that we have two interaction mechanism A and B:

$$\frac{d^2\sigma_{\mathrm{A}}(E;\theta,W)}{d\Omega\, dW} \qquad \frac{d^2\sigma_{\mathrm{B}}(E;\theta,W)}{d\Omega\, dW}$$

- Without azimuthal dependence we can write

$$\sigma_{\mathrm{A,B}}(E) = \int_0^{E} dW \int_0^{\pi} 2\pi \sin\theta\, d\theta \frac{d^2\sigma_{\mathrm{A,B}}(E;\theta,W)}{d\Omega\, dW}$$

Monte Carlo simulation of radiation transport

- The total cross section is

$$\sigma_{\mathrm{T}}(E)=\sigma_{\mathrm{A}}(E)+\sigma_{\mathrm{B}}(E)$$

- The total mean free path and the PDF of the path length are

$$\lambda_{\mathrm{T}}=(\lambda_{\mathrm{A}}^{-1}+\lambda_{\mathrm{B}}^{-1})^{-1}=\frac{1}{n\sigma_{\mathrm{T}}} \qquad p(s)=\lambda_{\mathrm{T}}^{-1}\exp(-s/\lambda_{\mathrm{T}})$$

- The kind of interaction taking place is a discrete random variable with values A and B and probabilities

$$p_{\mathrm{A}}=\frac{\sigma_{\mathrm{A}}}{\sigma_{\mathrm{T}}} \qquad p_{\mathrm{B}}=\frac{\sigma_{\mathrm{B}}}{\sigma_{\mathrm{T}}}$$

- The PDF of the polar scattering angle and the energy loss in a single scattering event is

$$p_{\mathrm{A,B}}(E;\theta,W)=\frac{2\pi\sin\theta}{\sigma_{\mathrm{A,B}}(E)}\frac{d^2\sigma_{\mathrm{A,B}}(E;\theta,W)}{d\Omega\, dW} \qquad \text{Note: } p(\phi)=\frac{1}{2\pi}$$

Monte Carlo simulation of radiation transport

- The quantities defined above allow us to generate random tracks of particles advancing from interaction to interaction
  - Each particle has a state (after leaving the source or after interaction)
    - Position $\mathbf{r}=(x\,y\,z)$
    - Direction of flight $\mathbf{d}=(u\,v\,w)$
    - Energy E
  - Each track consists of series of states $(\mathbf{r}_n, \mathbf{d}_n, E_n)$
  - To generate the next interaction we need to

$\xi=$ uniform RN in $[0,1[$

    - generate the free path length

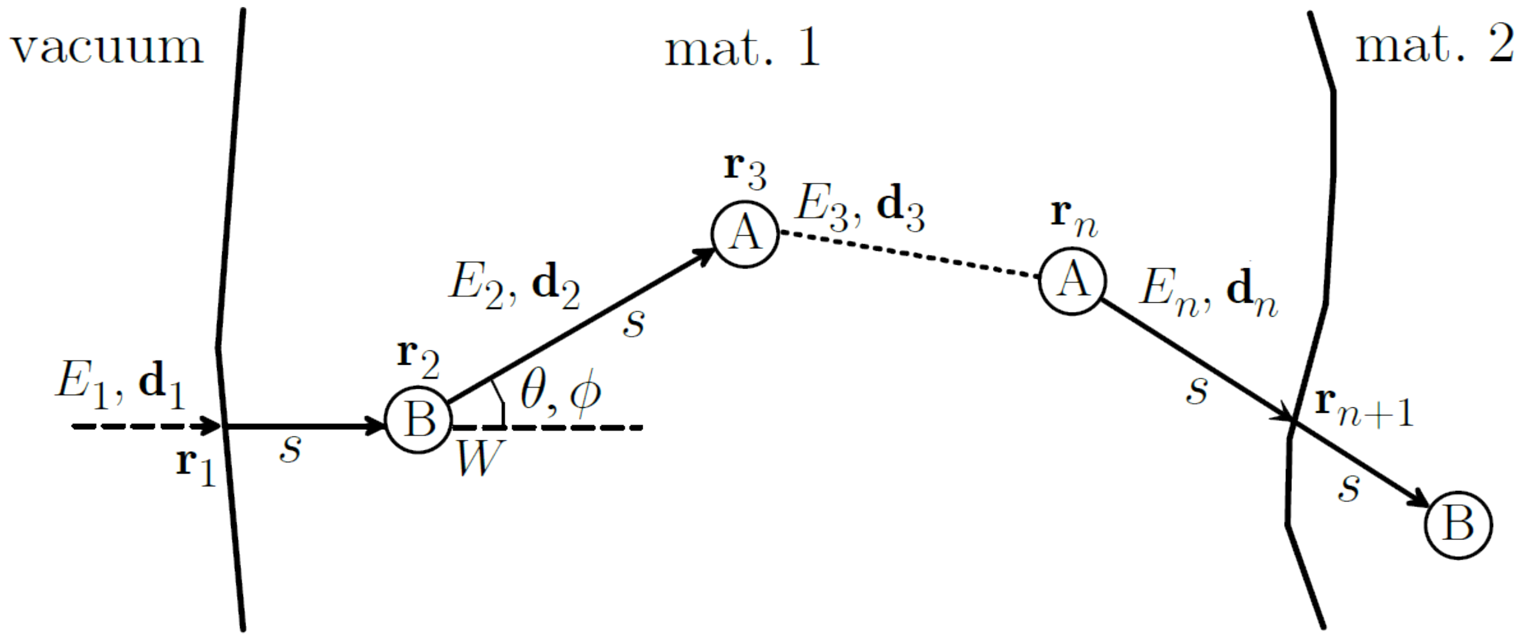
$$s=-\lambda_\mathrm{T}\ln\xi \qquad \mathbf{r}_{n+1}=\mathbf{r}_n+s\,\mathbf{d}_n$$

    - generate the next interaction
      interaction type $\{p_\mathrm{A}, p_\mathrm{B}\}$
      scattering angle and energy loss $p_\mathrm{A,B}(E;\theta,W) \quad \phi=2\pi\xi$

Monte Carlo simulation of radiation transport

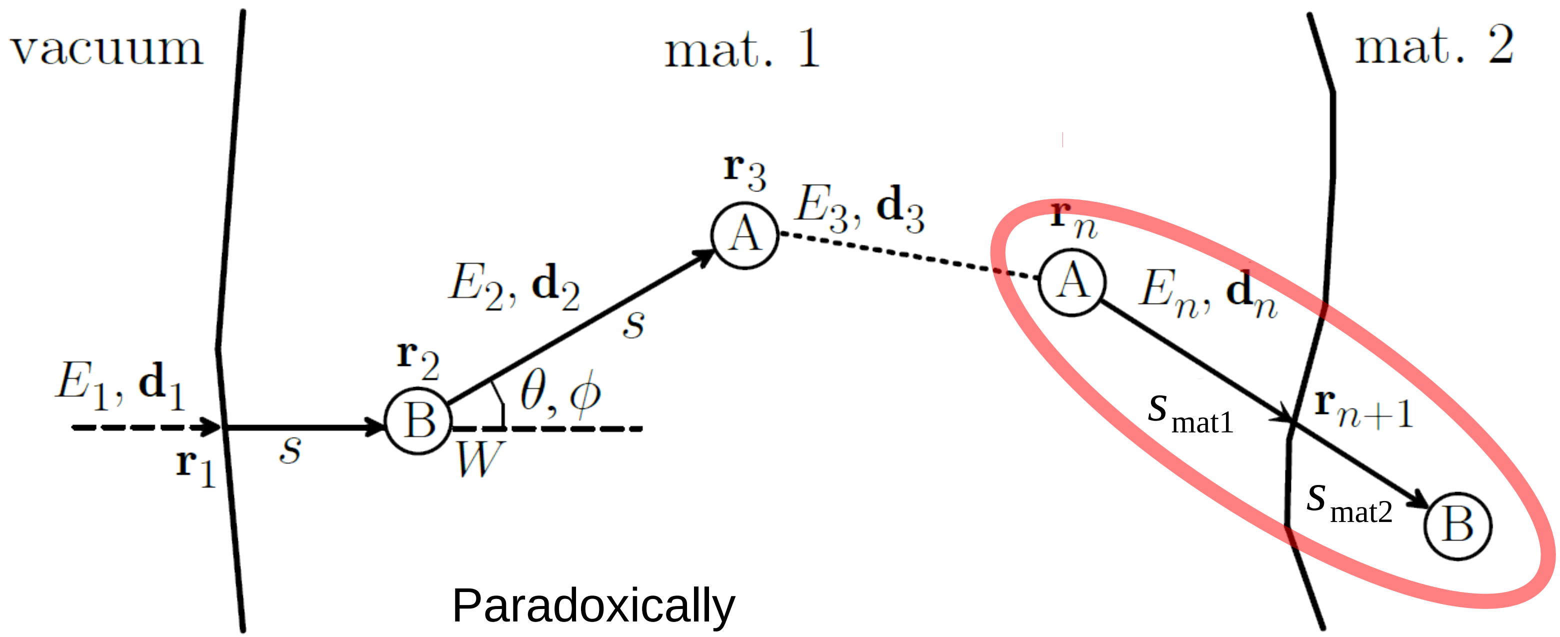
- In each scattering event the particle state is updated

$$\mathbf{d}_{n+1} = R(\theta, \varphi)\, \mathbf{d}_n$$
$$E_{n+1} = E_n - W$$



Monte Carlo simulation of radiation transport

– Crossing the material boundary is simple: Stop there and resume simulation with new material parameters



Paradoxically

$$\langle s_{\mathrm{mat1}} \rangle = \lambda_{\mathrm{mat1}}$$

$$\langle s_{\mathrm{mat2}} \rangle = \lambda_{\mathrm{mat2}}$$

Particle transport is a Markov chain.

Try it with a simple 1D simulation and with mat1 = mat2 !

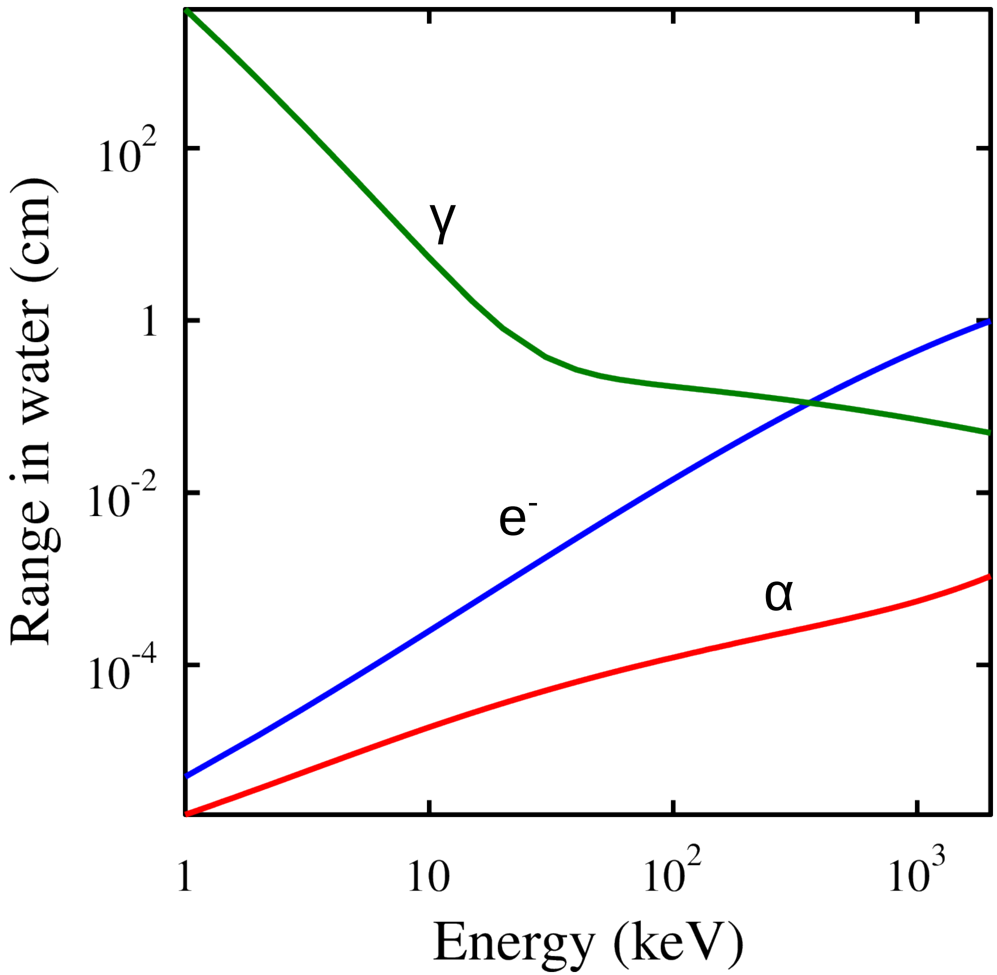
Monte Carlo simulation of radiation transport

- In electron and positron transport the step length it is sometimes necessary to limit the step length to $s_{\max}$
  - Sample s normally
  - If $s > s_{\max}$ advance only a distance s and do nothing in the end of the path
  - Otherwise do the normal scattering
  - Due to the Markovian character the addition of these *delta interactions* does not bias the results
- When the particle energy has dropped below some predefined threshold the simulation is stopped

- During the simulation of one history secondary particles may be created
  - They are pushed into a stack
  - When the energy of the current particle has dropped below the threshold a new particle is popped from the stack and its history is simulated
  - When the stack is empty a new primary particle is started

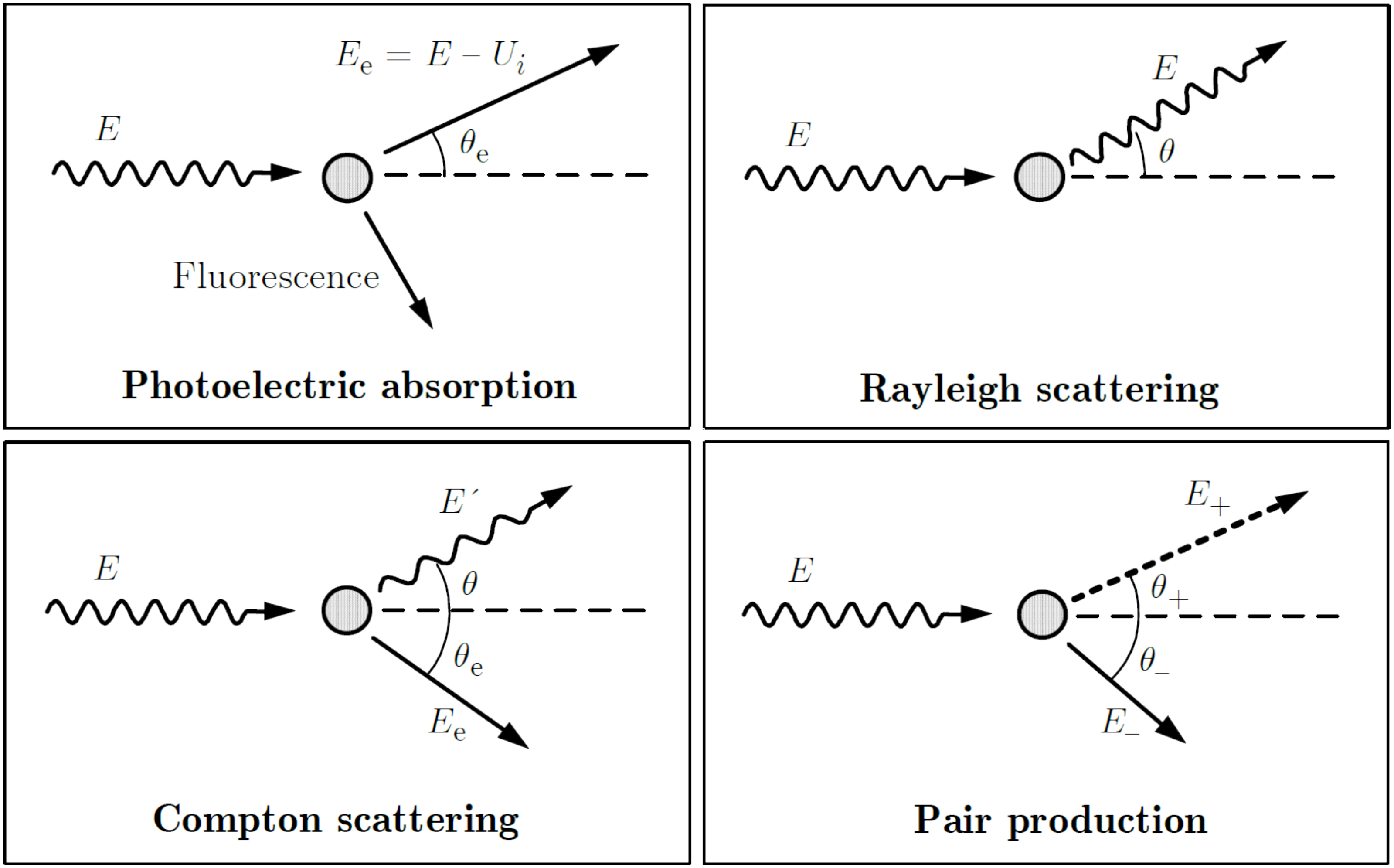
Characteristics of electron and photon irradiation

- Penetration depths larger compared with ion irradiation
  - Electron CSDA range
  - Photon mass attenuation constant
  - Ion mean range
- Many interaction mechanisms
- Generation of secondary particles → electron – γ-cascade



Interaction mechanisms of photons

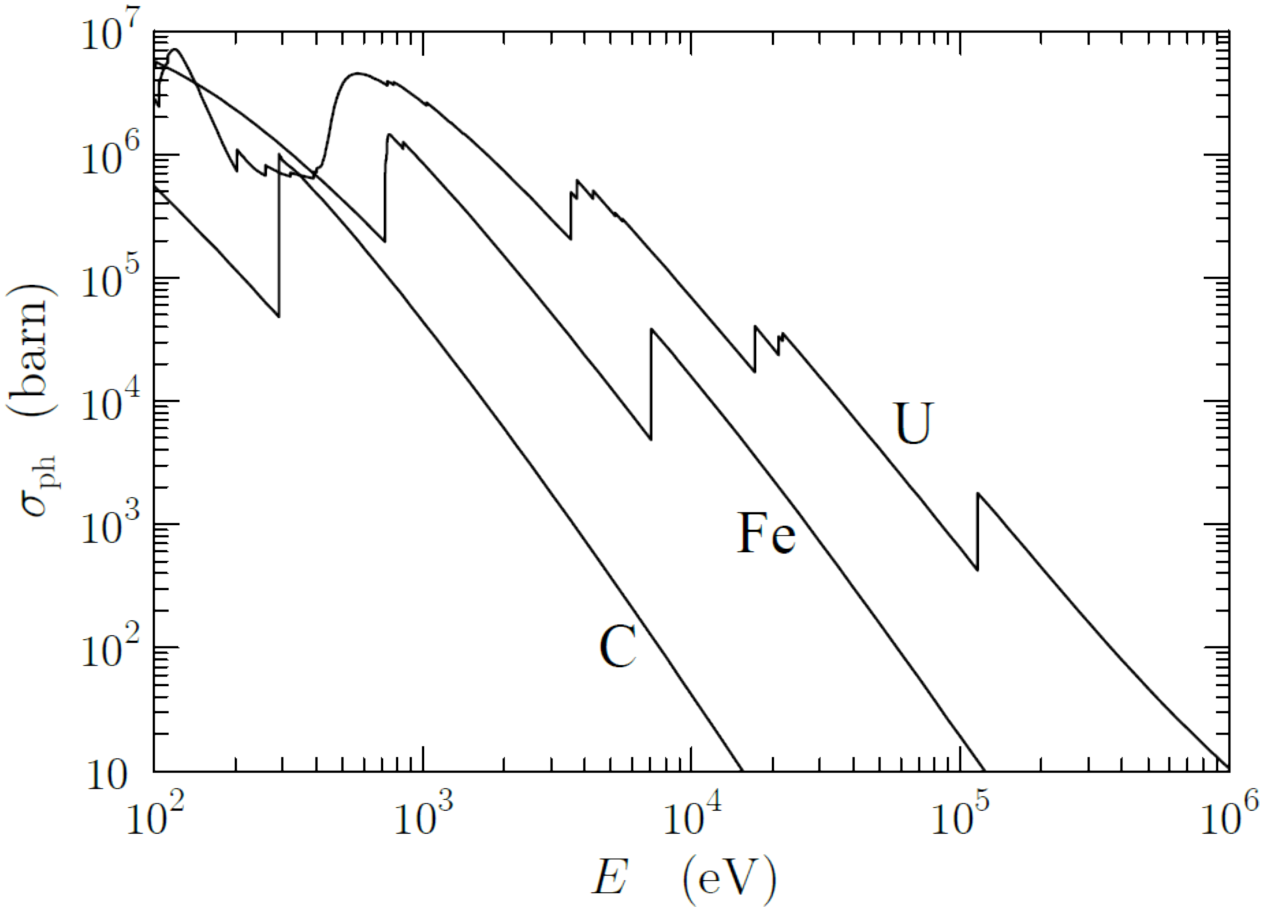
- Photons interact with matter with the following mechanisms (photonuclear reactions neglected)



Interaction mechanisms of photons

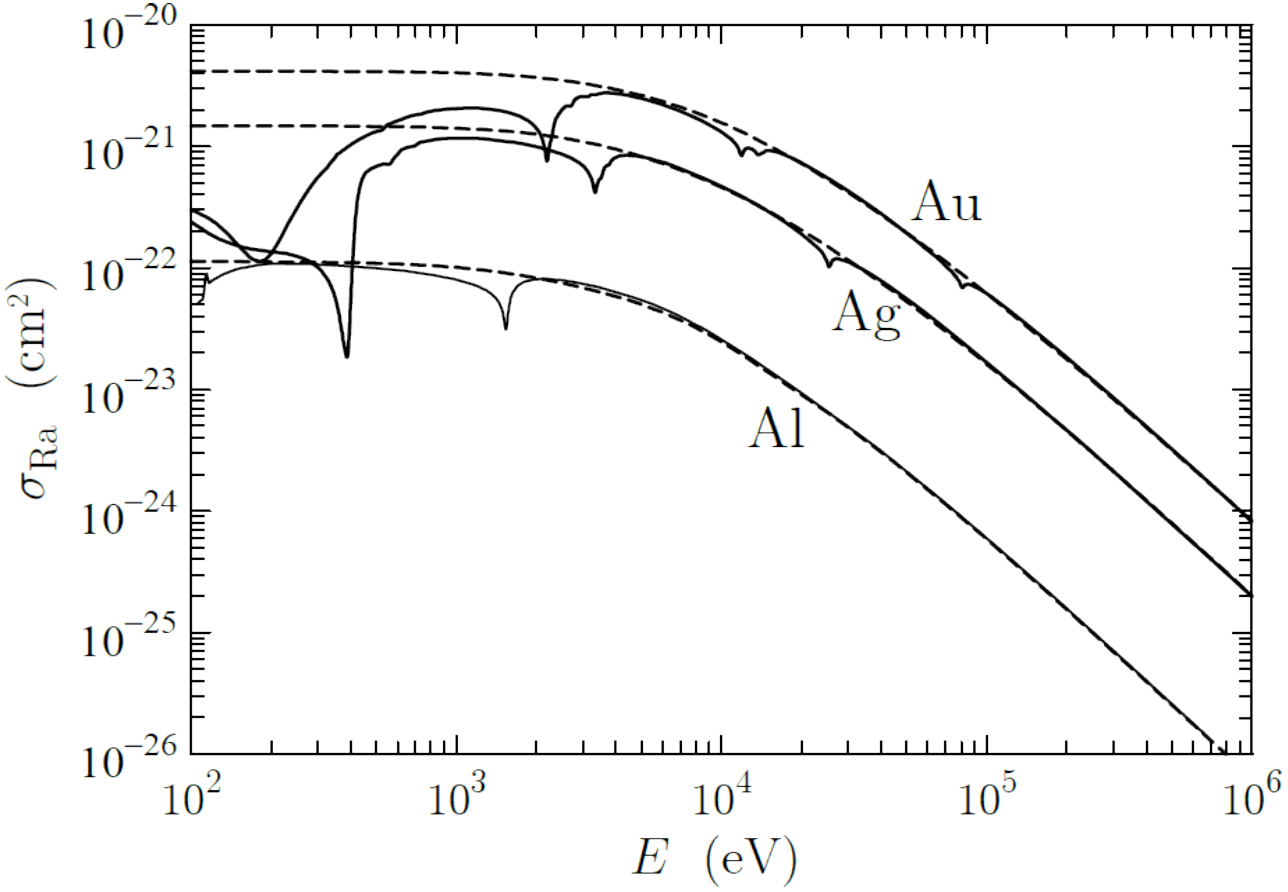
- In photoelectric effect photon kicks out an electron from the atom
  - If the atom originates from the inner shells → atom relaxation via X-ray and Auger emission

$1\,\text{barn} = 10^{-24}\,\text{cm}^2$



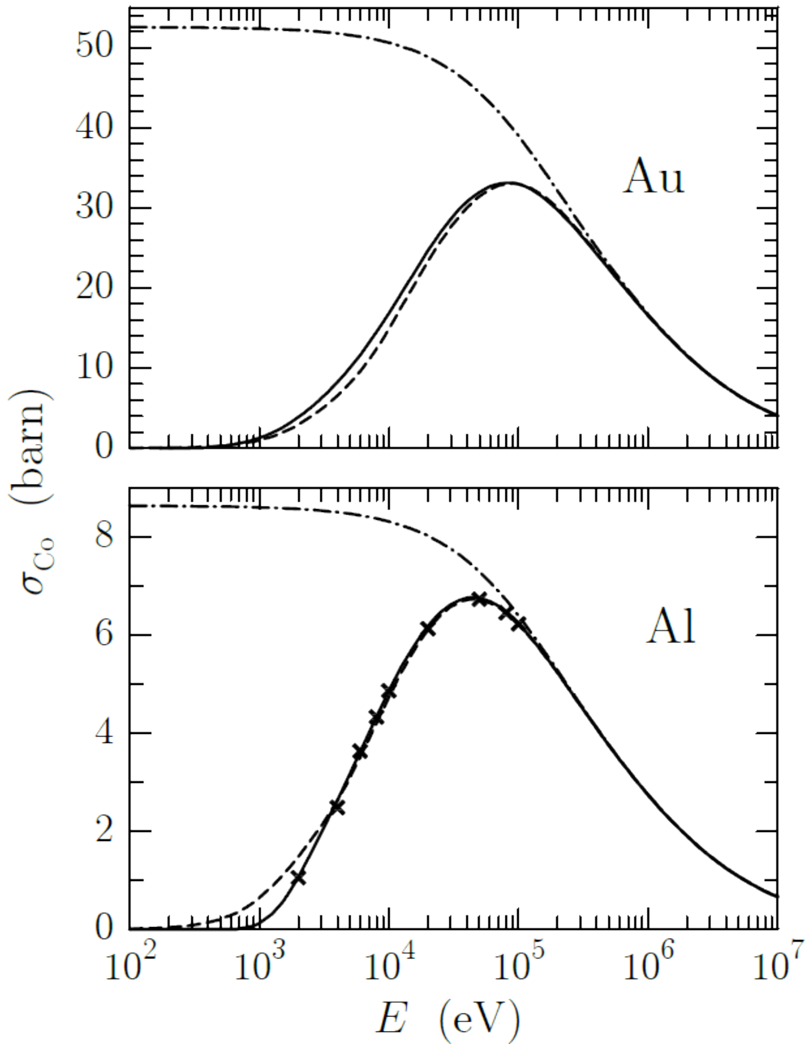
Interaction mechanisms of photons

- In Rayleigh (coherent) scattering the photon scatters elastically from an atom
  - Below are shown the cross sections for a couple of materials



Interaction mechanisms of photons

- In Compton (incoherent) scattering the photon scatters inelastically from an atom
  - Examples of cross sections

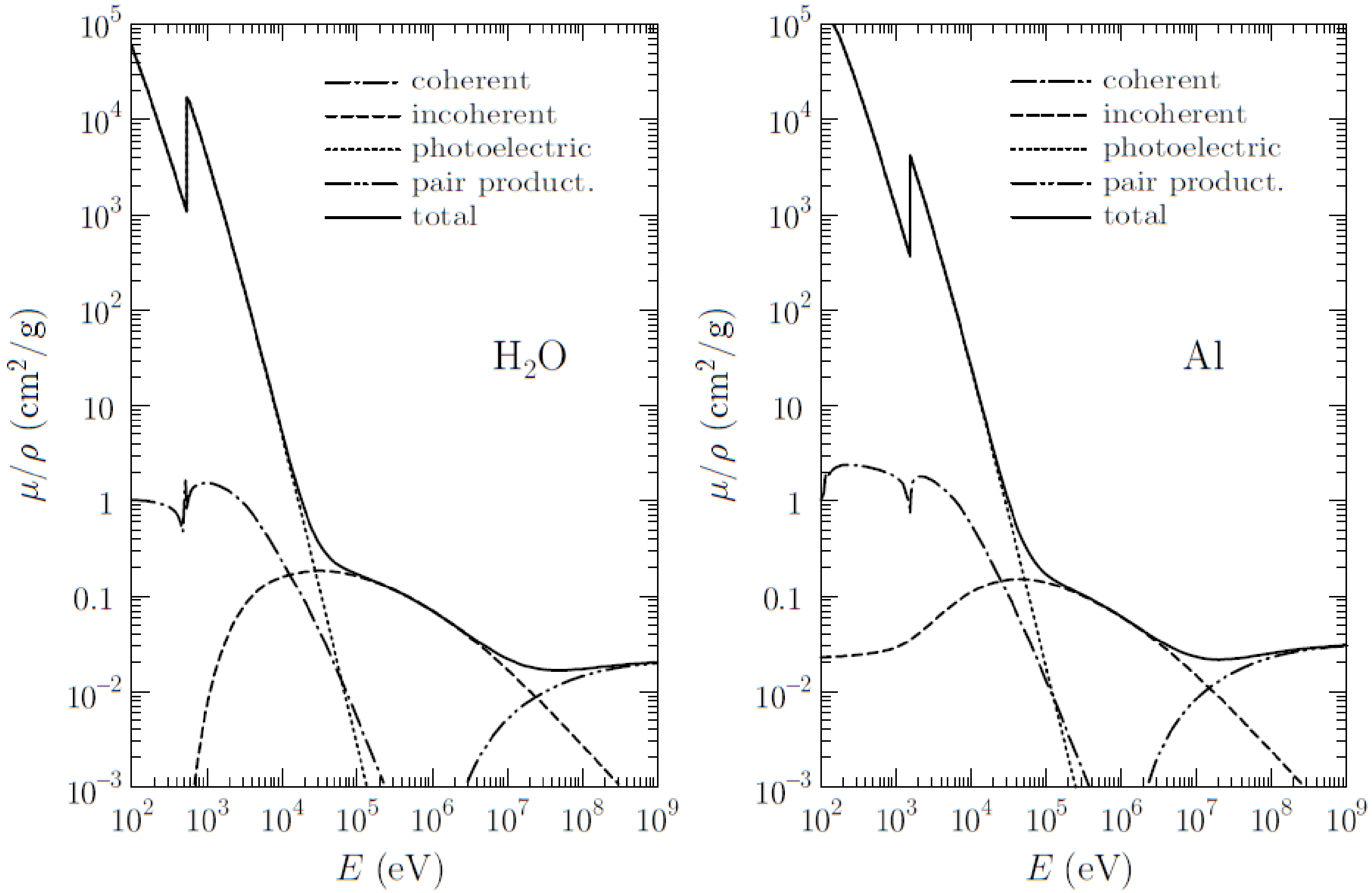


- In pair production a photon near an atom or an electron is absorbed and an electron and positron pair is produced

Interaction mechanisms of photons

- The photon inverse mean free path is called the attenuation coefficient

  $\mu_{ph} = n\sigma_{ph}$



Interaction mechanisms of photons

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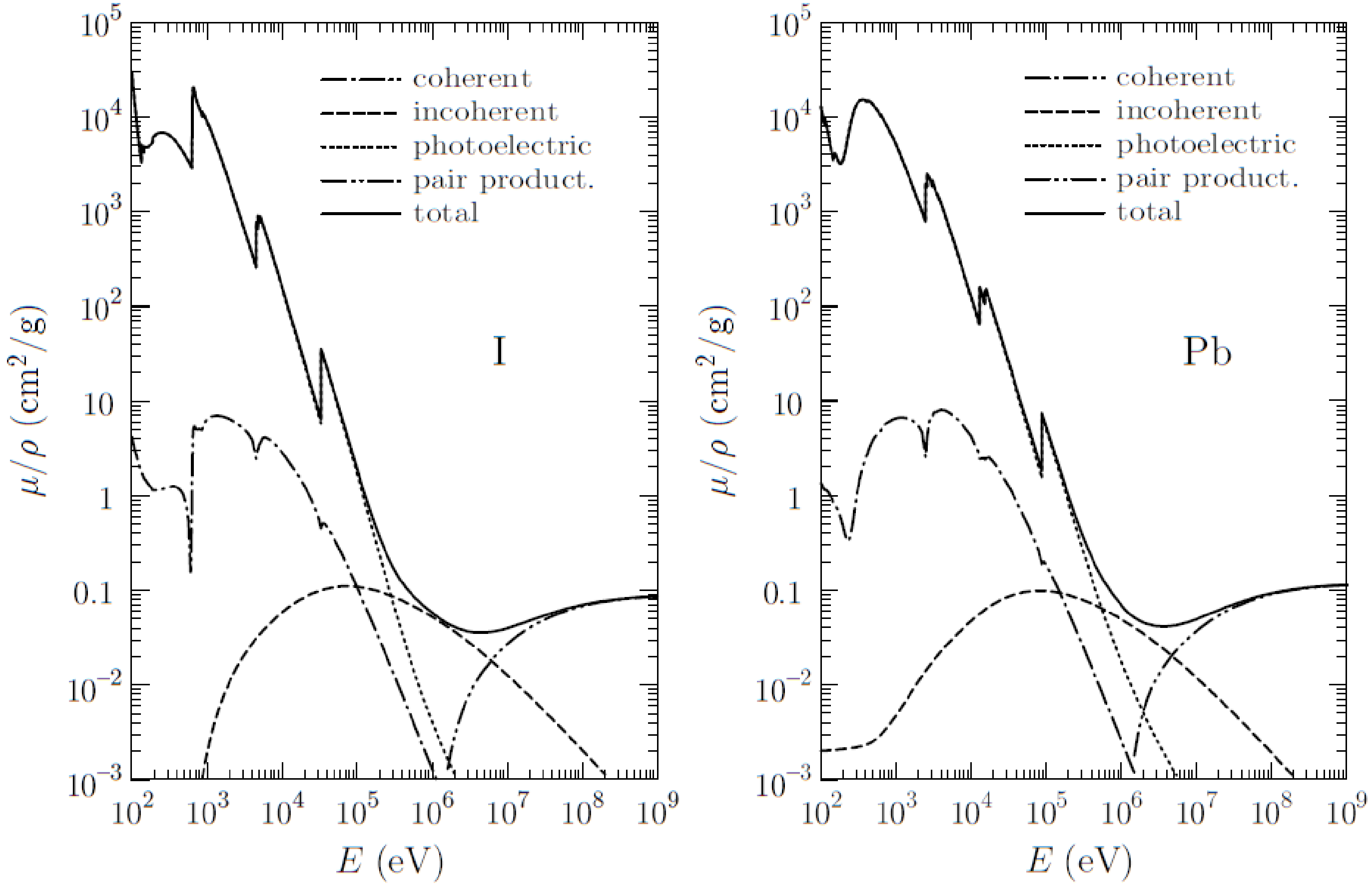
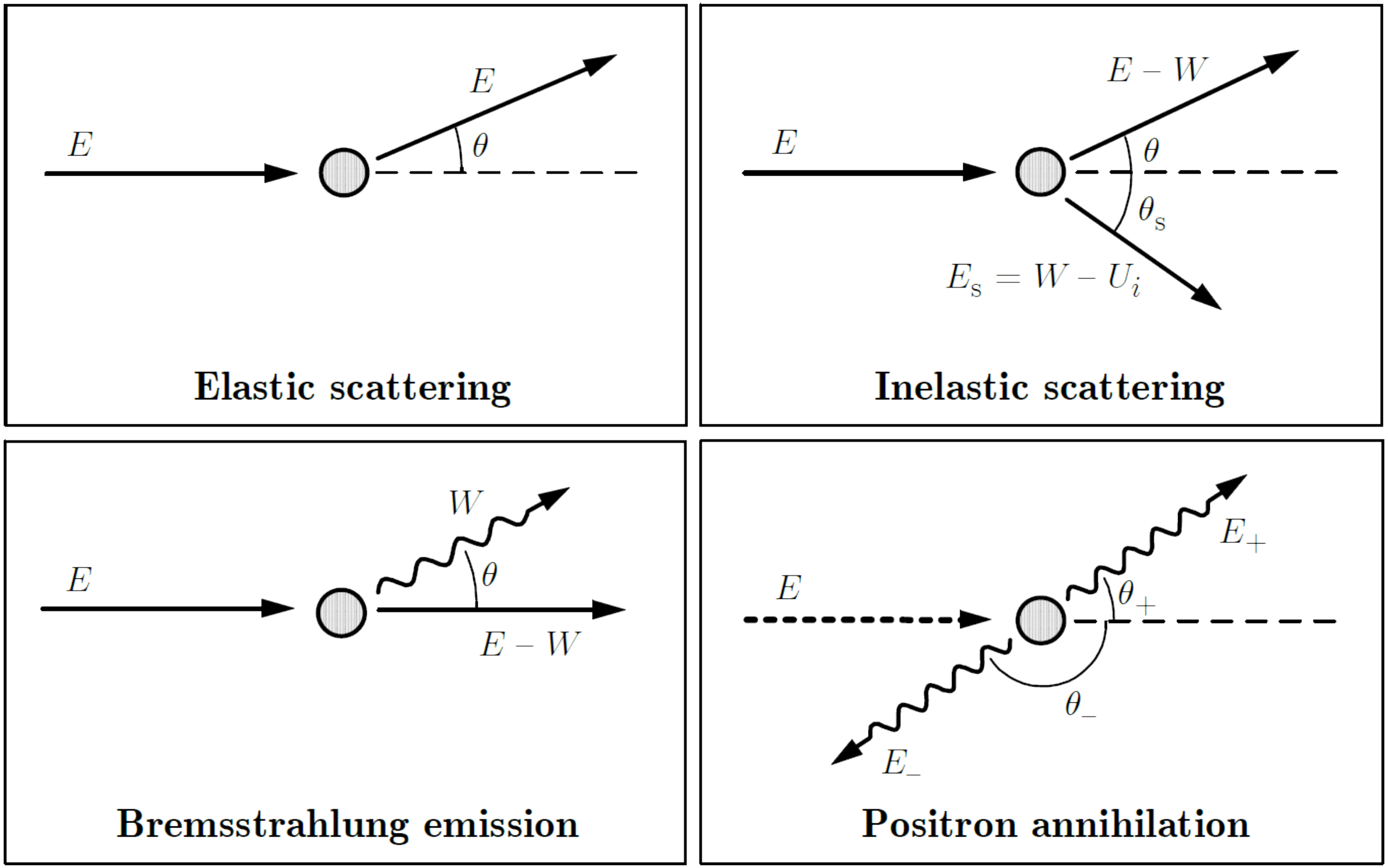


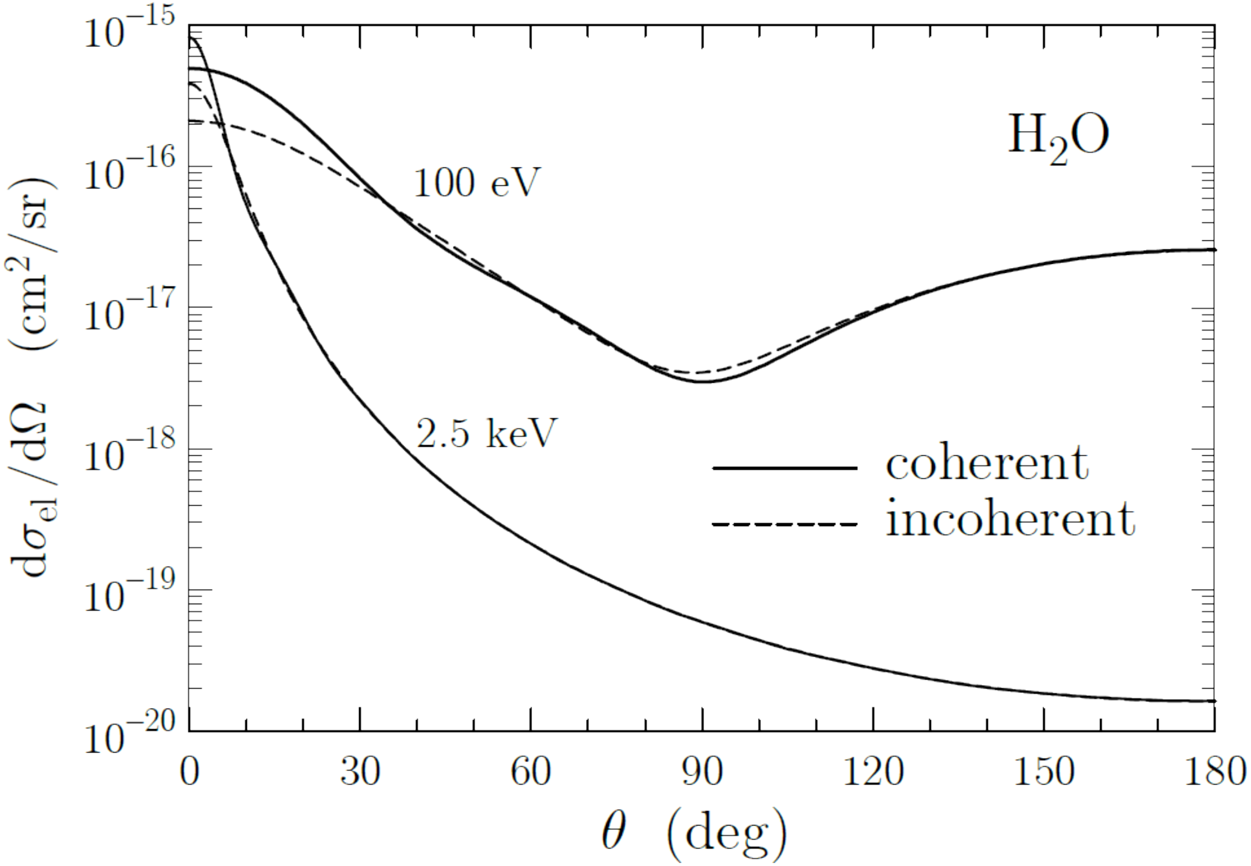
Interaction mechanisms of electrons

- Electrons and positrons interact with the following mechanisms



Interaction mechanisms of electrons

- Elastic scattering is elastic from the point of view of the atom
  - Scattering from the screened Coulomb potential
  - Below an example of differential cross section in water



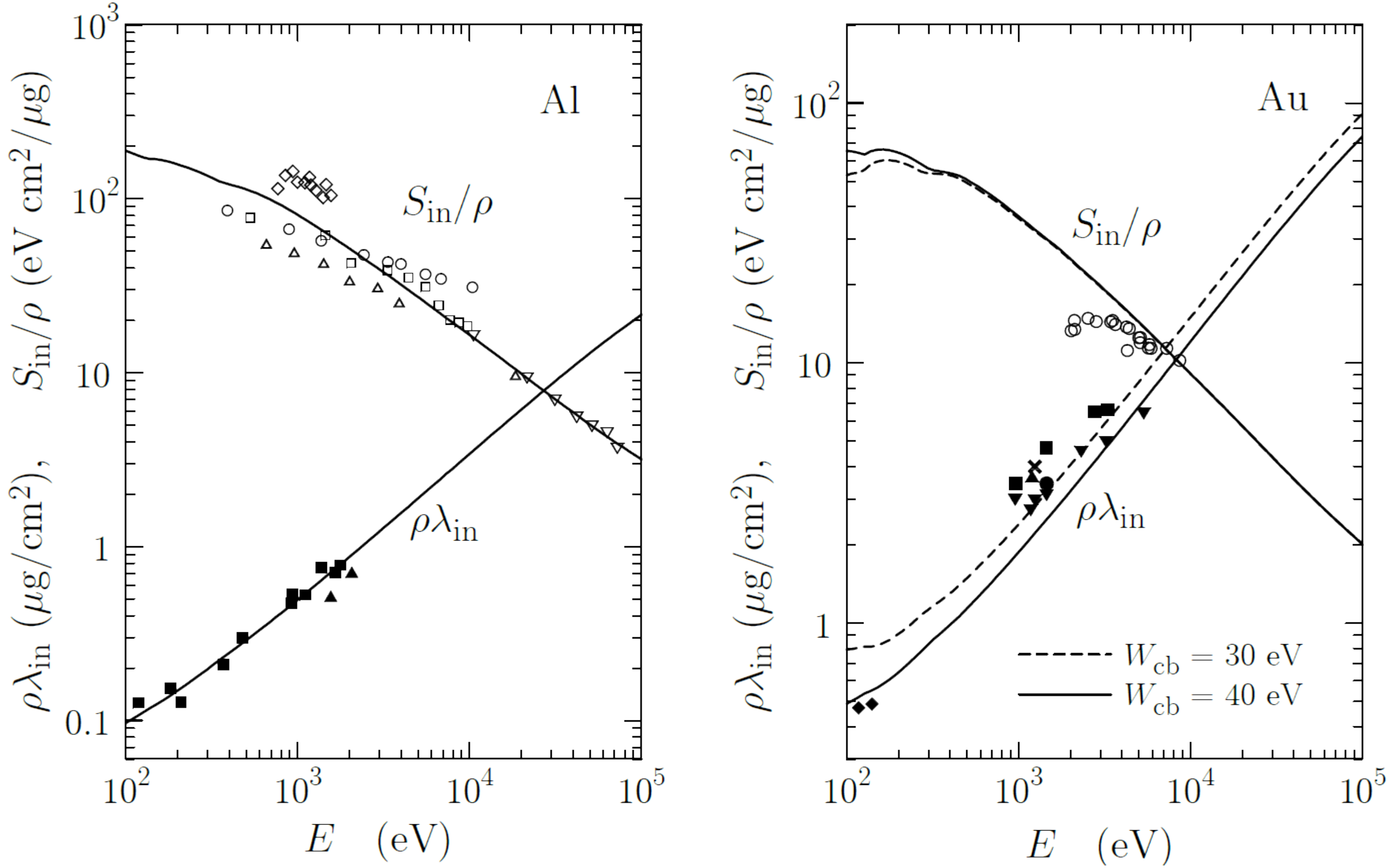
Coherent: Include molecular effects
Incoherent: Sum atomic contributions

Interaction mechanisms of electrons

- Inelastic scattering is is the dominant energy loss mechanism of electrons and positrons at low and intermediate energies
  - Collisional excitations and ionizations of the electrons in the medium
  - Cross section experssions complicated; MC needs fast sampling
  - May be split into contributions from each electron shell
  - In close collisions corrections from the indistinguishability of electrons
  - Positrons: annihilation–re-creations instead of direct scattering

Interaction mechanisms of electrons

- Below a few examples of MFP's and stopping powers for electrons

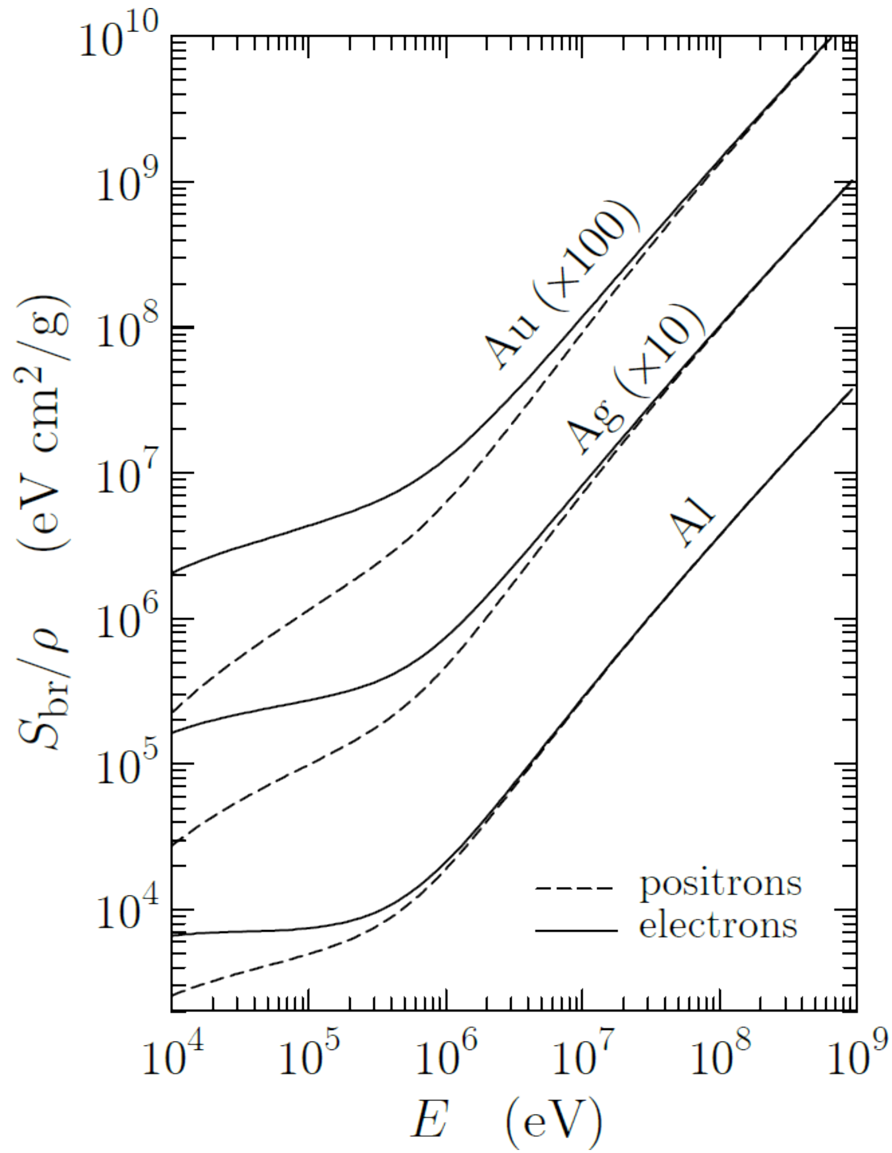


Interaction mechanisms of electrons

- Electrons (or positrons) accelerating in the electrostatic field of atoms emit photons (Bremsstrahlung)
  - Electron with kinetic energy E may emit a photon with energy $W \in [0, E]$

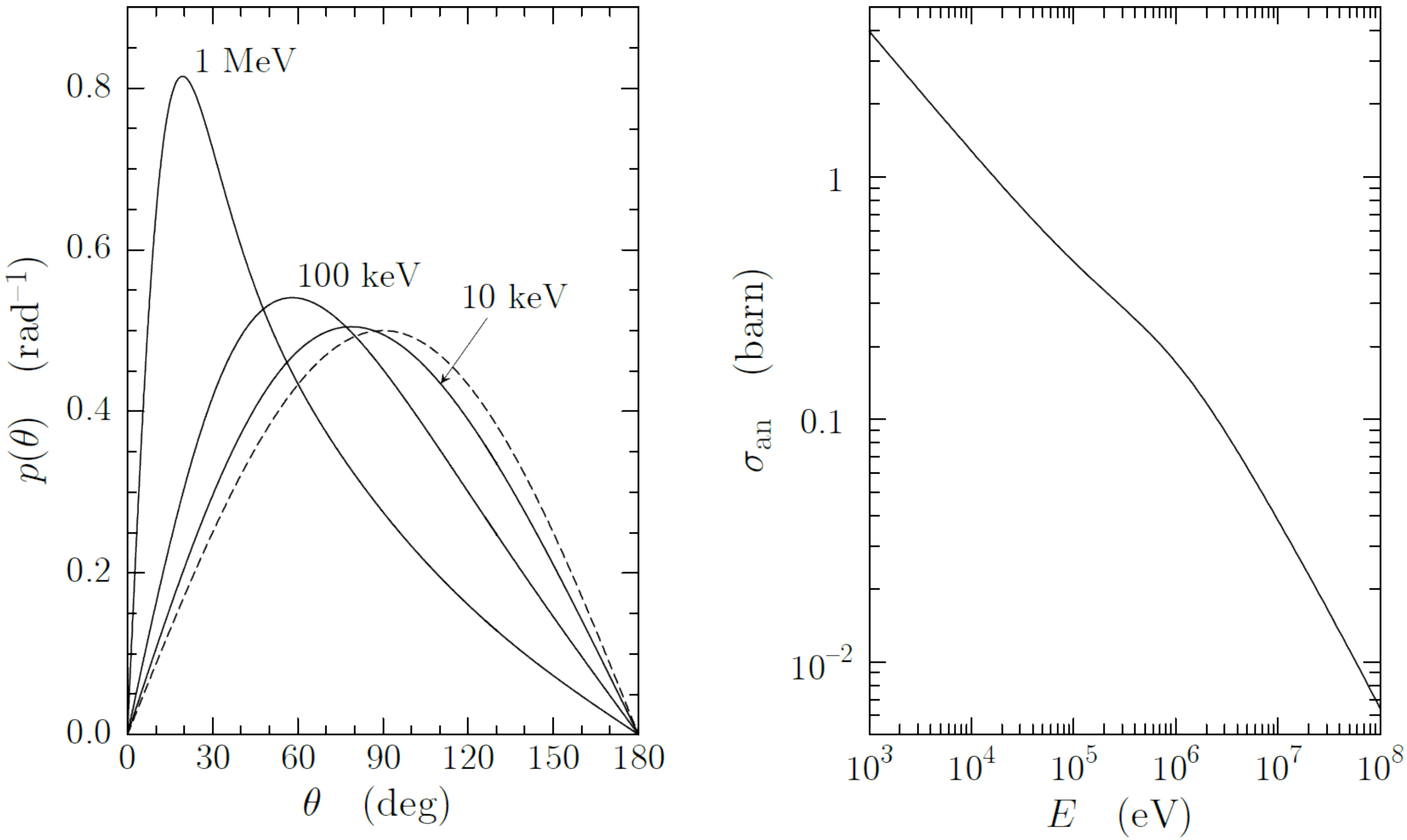
Stopping power

$$S(E) = n \int_0^{W_{max}} W \frac{d\sigma}{dW} dW$$



Interaction mechanisms of electrons

- In positron annihilation two photons are created
  - The angular distribution of the photons depends on the positron energy



Interaction mechanisms of electrons

- In principle the MC simulation can be done in a *detailed* fashion:
  all interaction events are simulated in detail
- However, this is in most cases too time consuming → *mixed simulation scheme*
  - Define threshold values for angular defelection θ of energy W loss

    $$W \geq W_c \text{ or } \theta \geq \theta_c \Rightarrow \text{hard event, simulate in detail}$$

    $$W < W_c \text{ or } \theta < \theta_c \Rightarrow \text{soft event, condensed simulation}$$

  - For example in the case of electron elastic scattering the effect of many soft events is calculated by so called multiple elastic scattering theory

    $$\langle \theta^s \rangle \quad \langle z^2 \rangle \quad \langle x^2 + y^2 \rangle$$

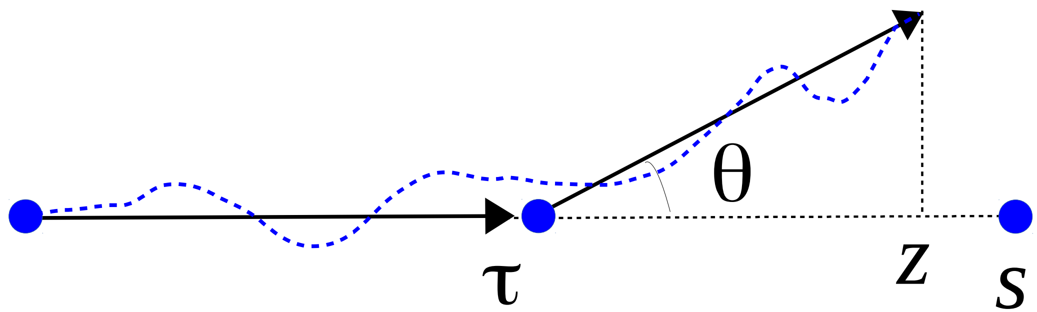
  - The mean free path between hard collisions ($\theta \geq \theta_c$), its PDF and the scattering angle PDF can be calculated as

$$\frac{1}{\lambda_{el}^{h}} = n 2\pi \int_{\theta_c}^{\pi} \frac{d\sigma_{el}(\theta)}{d\Omega} \sin\theta \, d\theta \qquad p(s) = \frac{\exp(-s/\lambda_{el}^{h})}{\lambda_{el}^{h}} \qquad p^{h}(\theta) = \frac{d\sigma_{el}(\theta)}{d\Omega} \sin\theta \, \Theta(\theta - \theta_c)$$

$$\Theta(x) = \text{step function}$$

Interaction mechanisms of electrons

- The angular deflection and the lateral deflection in a multiple scattering event can be calculated by e.g. using the so called *random hinge method*
  - First, the electron moves a random distance $\tau \in [0, s]$
  - A ”multiple scattering event” takes place
  - The electron moves a distance $s-\tau$ in the new direction



- In the case of inelastic collisions the soft events are often modeled using the continuous slowing down approximation (CSDA), possible with straggling

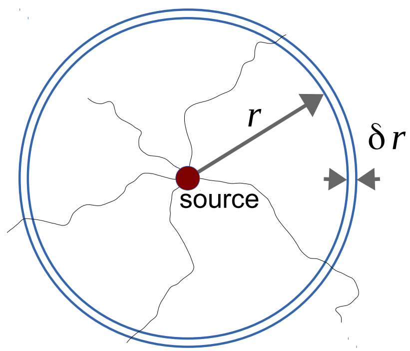
MC simulation codes

- EGS4, EGSnrc, EGS5
  - **E**lectron-**G**amma **S**hower
  - From a few keV up to several TeV
  - Mortran (Modular/Morbid Fortran)
  - Downloadable from http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/egsnrc_index.html
- GEANT
  - Electrons, positrons, gammas, and hadrons
  - Downloadable from http://geant4.cern.ch/support/index.shtml
- PENELOPE
  - **P**enetration and **ENE**rgy **LO**ss of **P**ositrons and **E**lectrons
  - Electrons, positrons, gammas
  - From 50 eV to 1 GeV
  - Geometry described by homogeneous bodies limited by quadric surfaces
  - Fortran77
- MCNP
  - Neutrons, electrons, photons
- And many more...

Can be obtained from OECD/NEA via the liaison officer.

Examples

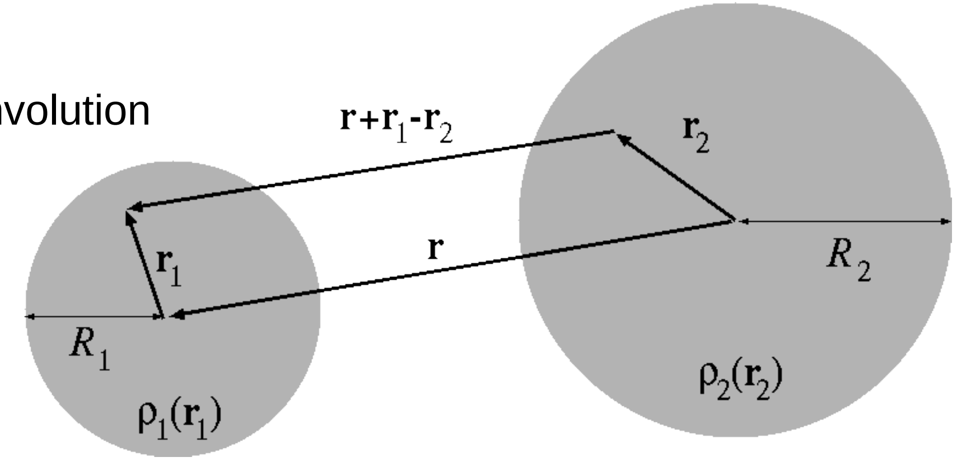
- Probably the most common quantity is the energy deposition (or absorbed dose; in grays)
  - Example: dose point kernel (DPK)
    - Gives the energy deposition of a pointlike source



$$K'(r)\,\delta r = \text{energy left to a spherical shell } (r, \delta r) \text{ by one particle}$$

$$K(r) = \frac{K'(r)}{4\pi r^2 \delta r}$$

    - Dose sphere 1 → sphere 2 by DPK convolution



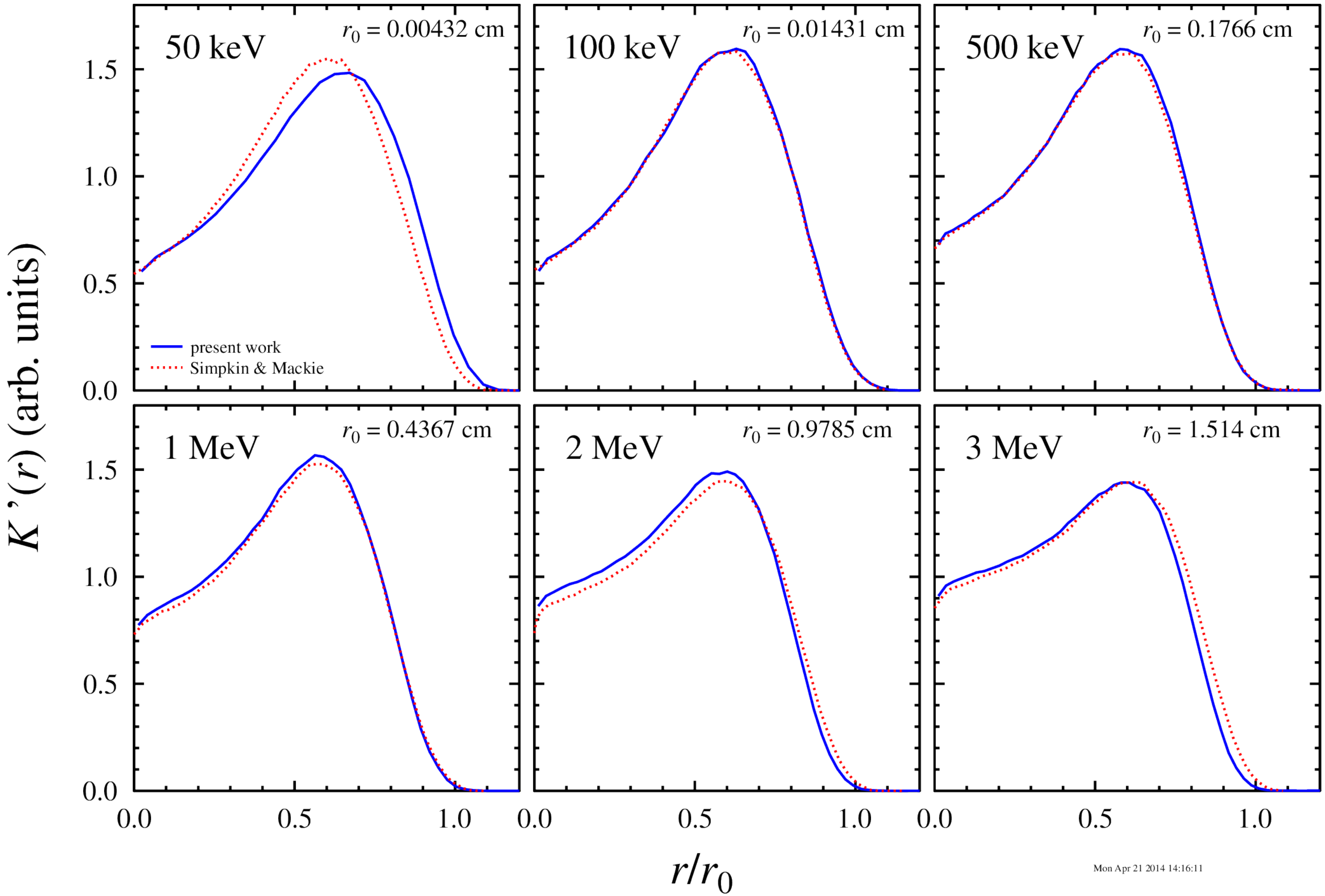
$$F(R_1, R_2; r) = E_{\text{el}} \int_{\Omega_1} d\Omega_1 \int_{\Omega_2} d\Omega_2 K(r')$$

$$= E_{\text{el}} \int \int \rho_1(r_1)\rho_2(r_2) K(|\mathbf{r} + \mathbf{r}_1 - \mathbf{r}_2|)\, d\mathbf{r}_1\, d\mathbf{r}_2$$

Examples

Electron DPK's in water. Calculated using EGS4.

r_0 = CSDA range



Examples

- Demo of PENELOPE/Shower code (Windows only, hope it works...)

Conclusions

- Irradiation on biological materials
  - Beneficial (imaging, therapy)
  - Damage (radiation protection)
  - On cellular level many open questions (low doses, bystander effect,...)
- MC simulations
  - The most accurate method
  - Uncertainties at low energies (cross sections)
  - Used heavily in medical physics
  - Even in clinical use (some treatment plannig systems use MC)