1 Photons

1. Directly ionizing radiation: Fast particles having a charge that transfers energy through a series of small Coulomb interactions.

2. Indirectly ionizing radiation: Photons or neutrons which transfer energy to charged particles in the matter.

The "cross section" is proportinonal with the interaction strenght. A simple visulisation could be imagining two disks of radiis r, the total area is then

$$s = \pi(r_1^2 + r_2^2) \tag{1}$$

Consider now N particles coming towards an area S with n atoms. The probability for interaction then becomes

$$p = \frac{n * \sigma}{S} \tag{2}$$

and the with the number of *interacting* particles

$$Np = N\frac{n * \sigma}{S} \tag{3}$$

We separate between electronic and atomic cross sections. The cross sections depends on the type of target, and the type of the incoming particle.

The differential cross section is the number of particles scattered into the angle $\mathrm{d}\Omega$ per units area. For photons we can have (in principle) two different kinds of processes:

1. Absorbtion

2. Scattering

1.1 Scattering, Thompsom and Comton

The scattering can be coherent, or incoherent.

The coherent scattering is called Rayleigh scattering. Here the photon is scattered without loss of energy

The atomic cross section for Rayleigh-scattering is

$$\sigma_r \propto \left(\frac{Z}{h\upsilon}\right)^2 \tag{4}$$

Dependence mainly on atomic structire and photon energy. Larger Z and smaller $h\upsilon$ will increase the chance for Rayleigh scattering

The incoherent scattering is called Comtpon-scattering. Here, the photon will hit an electron (which can be considered almost free) and loose some energy.

We can simply consider the kinematics of what is happening and get the result:

$$h\upsilon = \frac{h\upsilon}{1 + \frac{h\upsilon}{m_e c^2}(1 - \cos\theta)} \tag{5}$$

The forward-scattered photons will have the same energy as the incoming photons, whereas the scattered photons of other angles will have lower and lower energy. The cross section of Compton-scattering was derived by Klein and Nishina, with a free electron assumed

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\theta}\right) = \pi r_0^2 \left(\frac{\upsilon'}{\upsilon}\right)^2 \left(\frac{\upsilon'}{\upsilon} + \frac{\upsilon}{\upsilon'} - \sin^2\theta\right) \sin\theta \tag{6}$$

We can perform some substitution to get the cross section for a certain scatter-energy

$$\frac{\mathrm{d}\sigma}{\mathrm{d}(h\upsilon')} = \frac{\pi r_0^2 m_e c^2}{(h\upsilon)^2} \left(\frac{h\upsilon'}{h\upsilon} + \frac{h\upsilon}{h\upsilon'} - 1 + \left(1 - \left(\frac{h\upsilon}{h\upsilon'} - 1\right)\frac{m_e c^2}{h\upsilon}\right)^2\right) \tag{7}$$

The fractional cross section with respect to the scattered energy has a sharp rise at the lower limit, this is because the back-scattered photons can only have a certain energy. At the upper max we could have a compton-edge, a rise of the cross section before an abrupt stop while we approach the incoming energy.

The Klein-Nishina cross section assumes a "free" electron, and for atomic electrons and for lower photon energies, this do not hold. The cross section then becomes smaller for high Z-materials for lower energies.

In the compton process, some energy gets transfered to the electron:

$$T = h\upsilon - h\upsilon' \tag{8}$$

This energy transfer can be expressed as a fractional cross section, and gives a nice expression for the mean transfered energy

$$\bar{T} = \frac{\sigma_{tr}}{\sigma} h\upsilon \tag{9}$$

1.2 Photo-electric effect

A photon is absorbed by an atom or molecule, it can result in an excitation or an ionization. An electron is ejected from the atom. When the atom de-excites, it can give off characteristic radiation.

2 Charged Particles

2.1 Kinematics

An incoming electron (or another charged particle) interacts with an atom (or another charged particle). The collision (or interaction) can either result in an excitation or an ionization. In the excitation, the atom is elevated to a higher energy state, where as in the ionization case, a fast electron is ejected. A cross section can be derived using elastic collision formulae, dependent on energy of the incoming particle. The cross section rises quickly to some energy E_{peak} and decreases gradually to some E_{max} The "stopping power" S is the most crucial parameter. It describes how the particle looses energy over some distance x. If kinetic energy is T, distance traveled is x and the stopping power is S, we can simply write

$$S = \frac{\mathrm{d}T}{\rho \mathrm{d}x} \tag{10}$$

where ρ is the density of the material.

2.2 Hard and soft collisions

We separate between soft and hard collisions. The soft collisions are collision where the impact parameter is much longer than the atomic radius. There are only weak Coulomb-interaction and low amounts of energy are transferred. Predominantly excitation, but there could be some ionization. The energy transfer range on the spectrum from $E_{\min}$ to some H.

For hard collisions, the particle travels through the atom. The transfers of energy are large (but few) and the spectral energies are from H and up to $E_{\max}$. If the binding energy is negligible, it can be considered as an elastic collision between free particles. If we add them up, we get a "final" stopping power. The stopping power increases with the charge of the incoming particle and decreases with the square of the velocity. There exist some cross-sections that describe hard electron-electron interaction, but they are complicated. Shell corrections are the corrections when one excludes the simplification that the velocity of the incoming particles are much higher than the atomic electrons. The K-shell electrons are most energetic, they are the first that has to be corrected for, then the L-shell and so on. When this is corrected for, a slightly lower stopping power can be found. A second correction are done for so called "density effects" in which the particle polarizes the surrounding medium, resulting in weaker interactions.

Linear energy transfer denotes the part of the energy transferred in the surroundings of the particle. The energy spectrum is integrated up to a certain cut-off δ

2.3 Radiation loss

Bremsestrahlung is emitted from a charged particle that traverses the field from the electrons and nuclei. The effect from the radiation is given by Larmors formula (from classical electromagnetism) for an accelerated charged particle. As it depends on the mass ratio squared, it is not important for any other particles than the electron. Losses from the bremsstrahlung are called radioactive losses. The maximal energy lost is up to the total kinetic energy of the particle. One can define a radiation stopping power, dependent of the square of the Z-number (higher Z-material leads to higher amount of bremsstrahlung) The yield from bremsstrahlung is called radiation yield. Some energy can also be lost from Cerenkov radiation, if the speed of the electrons are higher than the phase speed of light in that medium. One can also have nuclear interactions where a charged particle is scattered. An annihilation of positrons (or electron encountered by a positron) can also happen.

2.4 Range

The range $\mathcal{R}$ of a charged particle is the expected path-lenght travelled by that particle. The projected range is then the largest depth a particle can travel *into* a medium. For electrons the projected range are smaller than the range, and for heavy particles they are roughly equal. The range can be approximated by using the stopping power and the "continious slowing down approximation"

$$\mathcal{R}_{\mathrm{CSDA}} = \int_0^{T_0} \left(\frac{\mathrm{d}T}{\mathrm{d}x} \right)^{-1} \mathrm{d}T \tag{11}$$

The range depends on

1. The charge and the kinetic energy
2. The density, mean electron density and excitation potential of the absorbing media.

For low Z-media, the range and the projected depth will be approximately equal, but at higher and higher Z-media, the range will be much longer than the depth.

2.5 Scattering

In a beam of charged particles, one can have variations in energy depositions from straggling, and some variations in angular scattering. This leads to the beam being "smeared out" when traversing a medium. The energy will shift downwards and the energy width will be substantially broader.

3 Neutrons

The neutron, having no charge will behave somewhat like photons. Neutrons will collide with nuclear targets until they reach thermal equilibrium. They are unstable and will disintegrate into a proton, anti neutrino and electron after 12 min. The two main interactions are

1. Scattering. The incoming neutron collides with a nucleus, they both change direction and speed
2. Absorption - the nucleus absorbs the neutron and later deexcitates. This can yield fission products, protons, α-particles...

The cross sections of these interactions will depend on the energy of the neutron and the atomic structure. For low energy neutrons, capturing is most probable. Then as the energy of the neutrons increases, elastic scattering becomes more and more probable. When the neutron energy is high, inelastic scattering occurs, and for even higher energy, more than two particles are ejected. At the highest energies, fission becomes possible. It can be shown that hydrogen-rich absorbers are the best moderators. For low energies ($T_n < 500$ keV), "Potential" and "Resonance"-scattering is possible

1. Scattering on the surface of the nucleus.
2. The neutron is absorbed, but reemitted

U^{235} has a high cross-section for thermal neutrons. Thermal neutrons is in thermal equlibrium with the surroundings (around 0.025 keV at room temperature).

For high energy neutrons one has inelastic collisions. They appear at given energies, giving rise to "resonance" phenomena. This can lead to the emission of more than one particle, the cross-sections are complicated. The neutron beam is attenuated exponentially like the photon.

In the light of dosimetry, one can estimate a KERMA-factor and use that to calculate the absorbed dose for neutrons. Mixed field dosimetry - for later

4 Dosimetry concepts and ionometry

4.1 Dosimetry methods

One large group of dosimeters is calorimetry. The measurement of an increase of temperature. This increase is minuscule, as 1 Gy will make a temperature increase in Al of 1 mK. A circuit is connected to a thermistor, a semiconductor that changes resistance with temperature. The accuracy has to be high, about 10 μK A general formula for temperature increase could for example be

$$\delta T = \frac{E(1 - \delta}{h} \tag{12}$$

Here, h is thermal capacity.

Pros:

1. Absolute, the measurement is direct
2. The sensitive volume can be in a wide range of materials
3. It is independent of dose-rate

Cons:

1. The temperature increase is minute
2. The apparatus tends to be bulky

Another class, closely connected class of dosimeters are ones with thermally activated luminescence. These operates by containing crystals that gives off visible light when heated. One need a way to detect them, possibly a photo-multiplicator tube or similar contraptions. The crystals glow with a given wavelength, and the intensity is proportional to the temperature increase.

They consist of "traps" and "holes" that can hold the electrons for a certain amount of time. The traps holds the electrons away from the "hole" When the electrons are allowed to recombine in so-called "luminescence-centers", light is emitted.

Pros:

1. They are very sensitive
2. Small, reusable

3. Provides rapid readout
4. Avaliable in different materials

Cons:

1. Uniformity is an issue
2. The response is supralinear
3. Fading, light sensitivity
4. Sensitivity changes with exposure

5 Cavity theory

Problem when measuring the dose to a media with a probe. If the probe and the media have different compositions, the dose will *not* be equal. Now, start with a γ-beam. We have N photons hitting a thin foil, and we have CPE-conditions. Further more, the attenuation of the photon-beam is close zero. We have some photons entering, with some electrons, but we assume that for each electron entering, we have another electron exiting. The transferred energy to the foil is then

$$\epsilon_{tr} = R_{in,\gamma} + R_{in,e} - R_{out,\gamma} - R_{out,e} \tag{13}$$

and under CPE:

$$\epsilon_{tr} = R_{in,\gamma} - R_{out,\gamma} = N(hv)\mu_{tr}\Delta x \tag{14}$$

The absorbed dose is simply the Kerma,

$$D = K = \frac{\epsilon_{tr}}{m} = \frac{N(hv)\mu_{tr}\Delta x}{m} = \Upsilon\frac{\mu_{tr}}{\rho} \tag{15}$$

And if we allow bremsstrahlung

$$D = \Upsilon\frac{\mu_{en}}{\rho} \tag{16}$$