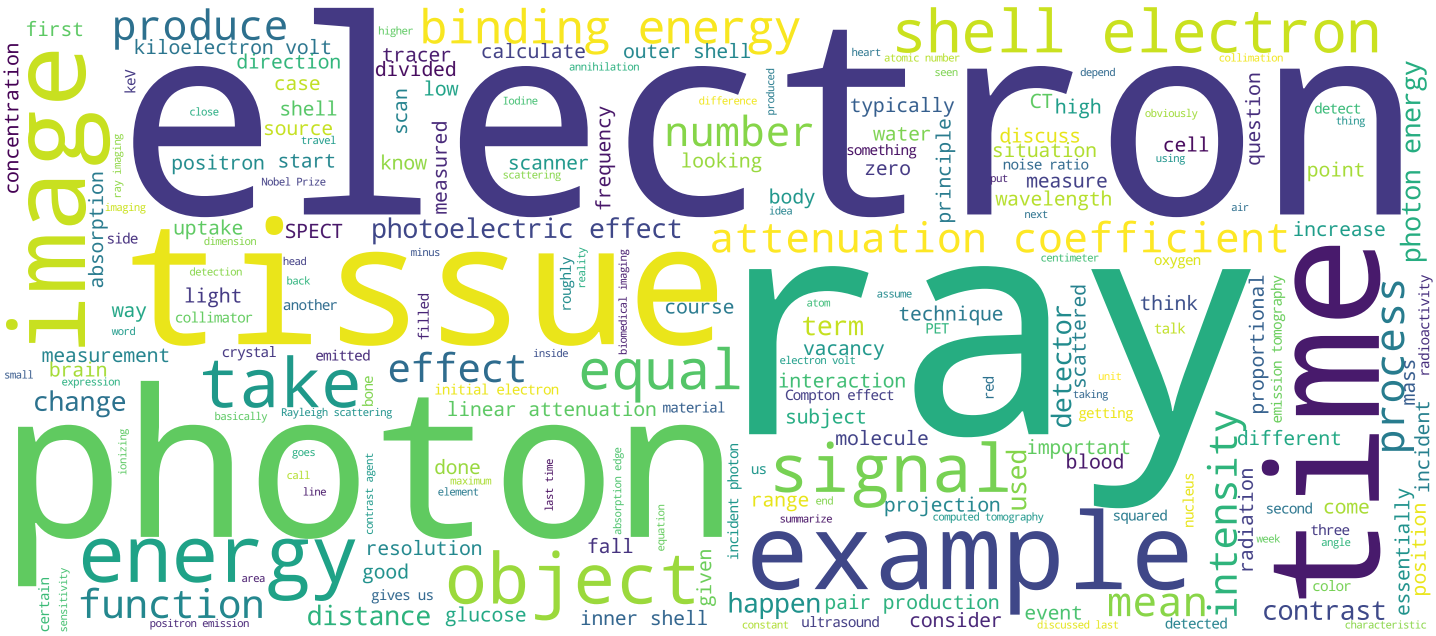
# 3.3 interactions of x-rays with tissue II
## (Photoelectric effect, Pair production)

**Fundamentals of Biomedical Imaging**


Prof. Rolf Gruetter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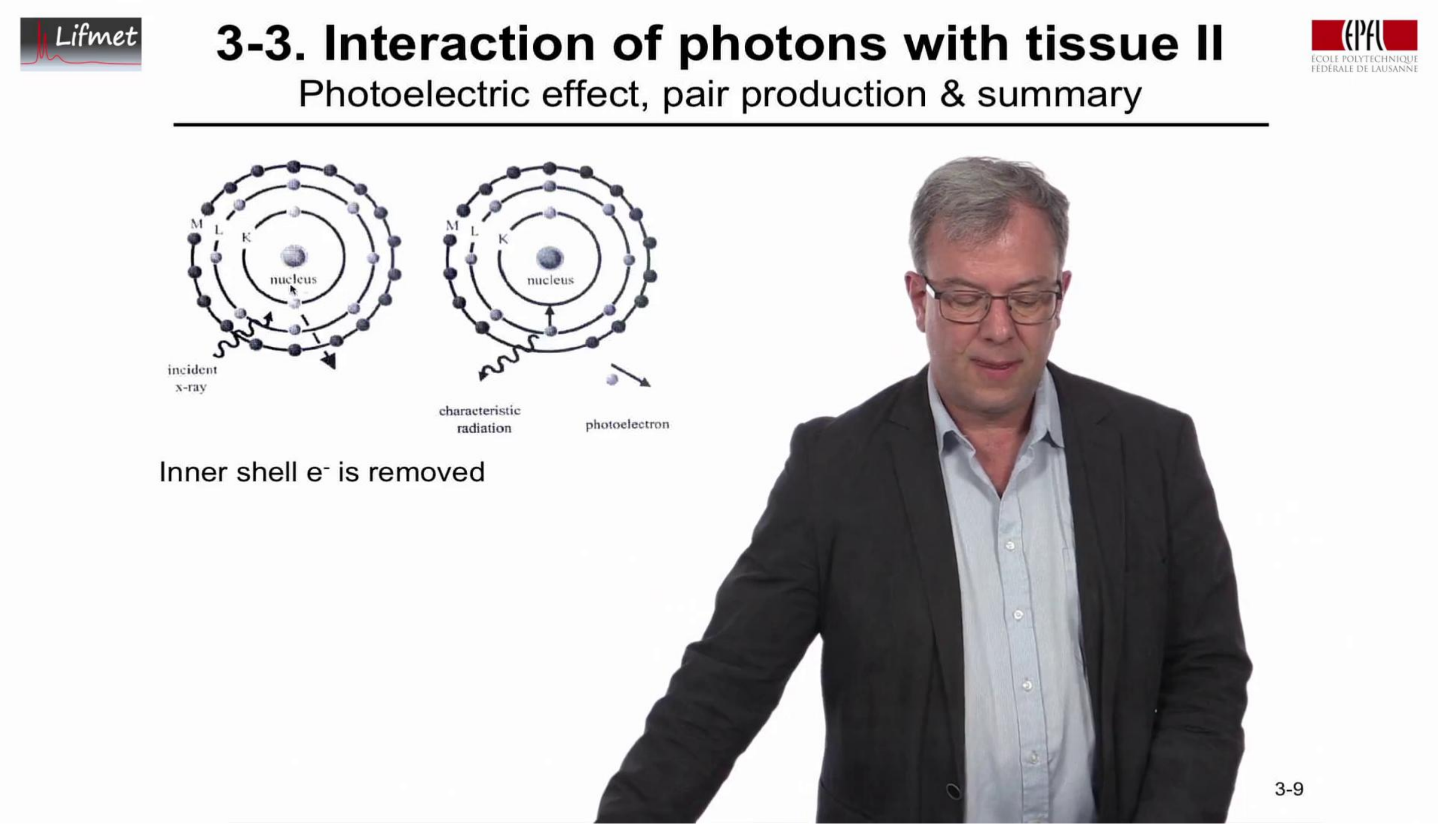
Video

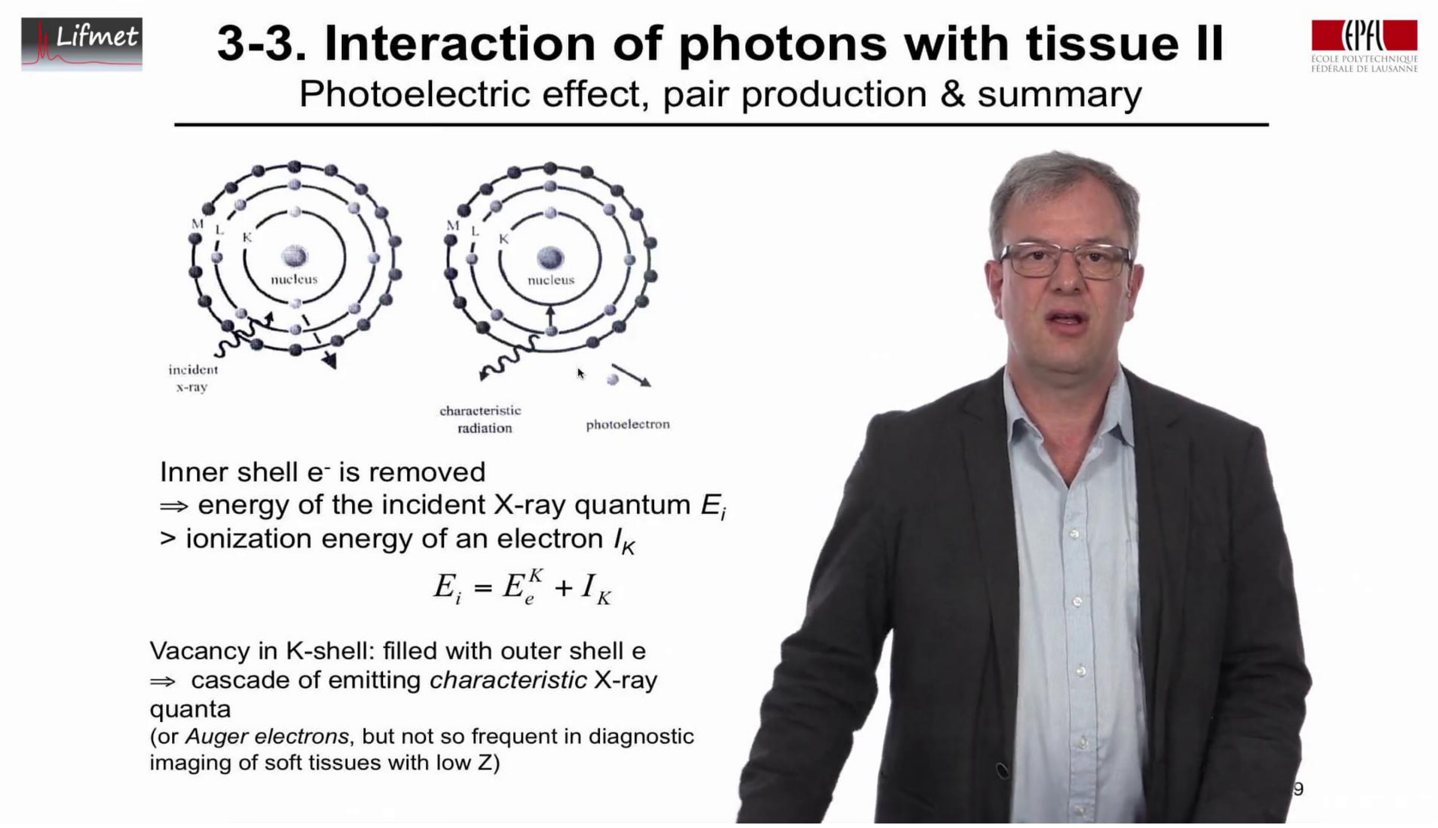



Now I'll come to the second part of the interaction with photons, and here we have two more effects to discuss, that is the photoelectric effect, pair production, and we'll make a short summary of the effects. Now if we look at photoelectric effect, which I want to talk about first, then we have the incident x-ray. Now we're looking at the interaction with an inner shell electron, K shell or L shell electron, and this point the incident x-ray is assumed to have sufficient energy that it can overcome the binding energy of the initial electron. This will eject it and therefore create a vacancy. So the inner shell electron in this process is being removed. What now happens is, as we've discussed last time, we have now an excited atom; we have a vacancy here at the K shell. This way you can see now the atom is excited, it's in a higher energy state, this vacancy is filled by an outer shell electron, which falls from the shell to the inner shell. Here in this graphic we have an L shell electron that falls into K shell, and as it falls down it liberates energy, it's binding energy, and therefore it releases a characteristic radiation. We have from the initial electron, we also have a photoelectron that's being produced, that's the...

Notes

Summary

0m 04s




ejected electron. So what we need is for this to happen obviously if the incident photon that comes in here does not have enough energy to overcome the binding energy of the K shell electron, K shell electron will just say, "So what? I don't care. I am not moving anywhere." And nothing happens. This process will only happen if the energy of the incident x-ray *Ei* is bigger than the ionizing energy of the electron here for the K shell, the *IK*, that's the binding energy of the K shell electron. So the incident energy should be equal to the energy of the electron afterwards, the photoelectron plus the binding energy of the electron that it has displaced. So that means in other words the binding energy of the electron-- this guy here-- is equal to the incident photon energy minus the binding energy. So to summarize, we have a vacancy in the K shell, this vacancy is filled with an electron from the outer shell. It could be the L shell like it is shown here in the graphic here. It could me the M shell. If it is in the L shell then this will create a vacancy and the L shell will be filled by an electron, for example, from the M shell, etc. etc.

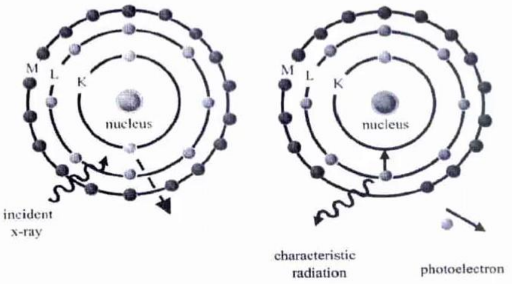
Notes

Summary

1m 31s

# 3-3. Interaction of photons with tissue II

## Photoelectric effect, pair production & summary




Inner shell e⁻ is removed
⇒ energy of the incident X-ray quantum $E_i$
> ionization energy of an electron $I_K$

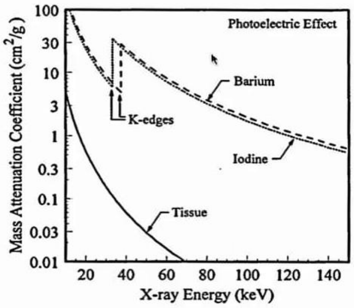
$$E_i = E_e^K + I_K$$

Vacancy in K-shell: filled with outer shell e
⇒ cascade of emitting *characteristic* X-ray quanta
(or *Auger electrons*, but not so frequent in diagnostic imaging of soft tissues with low Z)

Photoelectric absorption effect:

Abruptly increases when $E$ is slightly above $I_K$ – **absorption edges**

Absorption edge energy increases with $Z$ (very low for H, C, N, O)




3-9

So you could have a cascade of characteristic x-ray quanta that are being emitted in this process. We have also another process that we've discussed last time is the process of producing OJ electrons. This is in principle possible, but this is not so frequent in biological tissues, where we have soft tissues with a low *zed*. So the photoelectric effect is abruptly increased when the energy is just above the binding energy of the electron, and this gives rise to so called absorption edges. The absorption edge increases with **Z**, it is actually very low for Hydrogen, Carbon, Nitrogen, and Oxygen, which are primary compounds of tissue. The absorption edge energy is a reflection of the binding energy of the initial electrons, and therefore as we've discussed last time it makes perfect sense for Coulomb's law, that this is proportion to the number of protons, which is therefore proportional to the atomic number **Z**. So here's a display of the mass continuation coefficient as a function of x-ray energy. We have two examples here: Barium and Iodine with high **Z** and we can see here the mass continuation coefficient decreases rapidly and then suddenly increases.

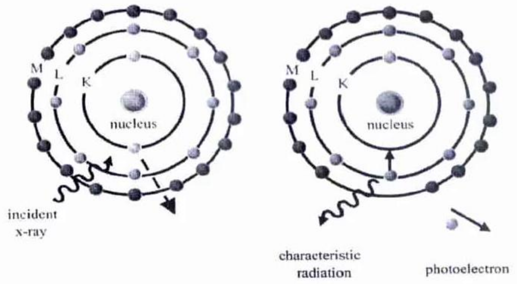
Notes

Summary

2m 58s

# 3-3. Interaction of photons with tissue II

## Photoelectric effect, pair production & summary

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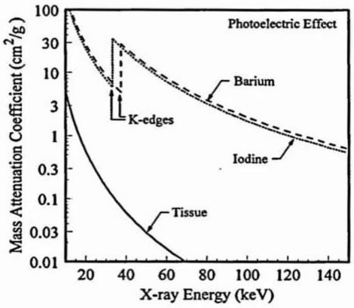
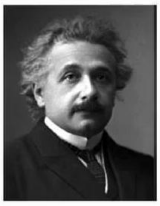


Albert Einstein
Physics, 1921

3-9

That is where suddenly the photon energy surpasses the K shell binding energy of either Barium or Iodine, Iodine here and Barium here. For tissue we do not see those K shell edges because the binding energies-- the K shell binding energies are well below 10 kiloelectron volts. So why do we have these edges increase, and then we have the effect increase? Well basically the way to look at it is if the energy is only sufficient to ionize initial electrons that are more electrons than the photon can interact with in the material and so if there are more electrons that are now potential candidates for interaction, then the attenuation coefficient discreetly increases. Interestingly, the photoelectric effect is what Albert Einstein received his Nobel Prize for. It was not the Einstein-Stokes relationship for diffusion, and it wasn't special relativity, it was the photoelectric effect that he was awarded the Nobel Prize for in 1921.

Notes

Summary

4m 31s

## What is the relative contribution of x-ray scattering mechanisms ?

in soft tissue

### IV. Pair production

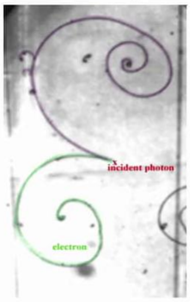
When the photon energy > $2m_ec^2$ = 1.02MeV

It interacts with the electric field of the nucleus of an atom

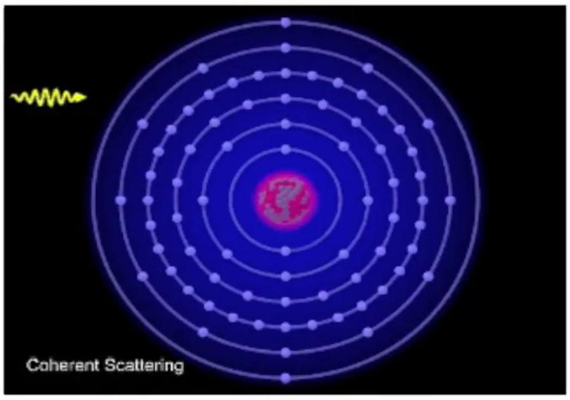
$\nu \rightarrow e^- + e^+$

The kinetic energy of the produced particles is

$$E = E_\nu - 2m_ec^2$$




Not important in Bio-imaging




3-10

So now the fourth effect that I want to discuss, for completeness sake, is pair production. Pair production happens when the photon energy is bigger than twice the rest energy of the electron. In case that photon interacts with the electric field of the nucleus then it can disintegrate and produce an electron positron pair. So It produces an electron and it's at the matter equivalent of a positron. The kinetic energy of the produced particles, $E$ is equal to the photon energy minus the rest energy of the two-- of the electron and positron combined. They have the same mass so it's two times the mass of the electron. Here's an illustration in a Wilson cloud chamber. So we have an incident photon, it's in a magnetic field that produces a positron here and an electron on this side. Now this effect is not important in bio-imaging. Why is this so? Well, we have to look at the photon energies that are being used in bio-imaging, and as you will see the energies that are being used in x-ray imaging are well below the 1 mega-electron volt required for pair production. Pair production effect is not important in tissue.

Notes

Summary

5m 44s

## What is the relative contribution of x-ray scattering mechanisms ?

in soft tissue

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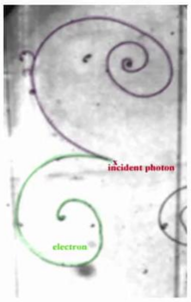
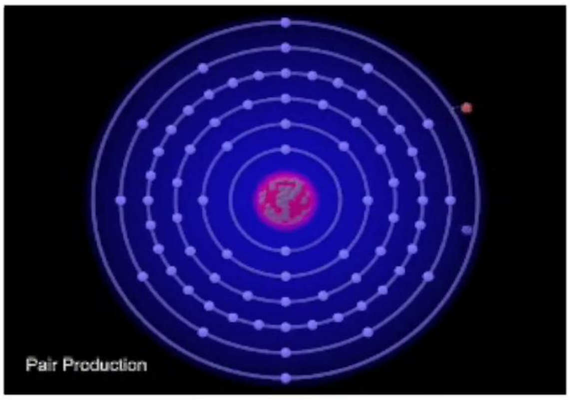



Not important in Bio-imaging




3-10

So here I want to summarize the interactions. We'll start with coherent scattering, that is Rayleigh scattering. We have the photon, the way the light is being deflected, but it retains the same wavelength, therefore in this animation the color does not change. Then we have the Compton effect which happens on the outer shell. An electron is being liberated, and it's ionizing and the photon changes it's wavelength as you can see with the change in color. Then we have the effect of the photoelectric effect, in this case the photon is being absorbed by the inner shell, electron inner shell, it is completely absorbed. There is an inner shell electron is being liberated and then we have the cascading event from an outer shell electron filling the vacancy in the inner shell and thereby releasing the characteristic x-ray for this particular atom. And finally, pair production, the photon interacts with the electric field in the nucleus, and it produces a positron electron pair as a result. So to summarize, if we look now here and the tissue we have the linear attenuation coefficient *mu* as a function of the photon energy here on the X axis.

Notes

Summary

7m 14s

## IV. Pair production

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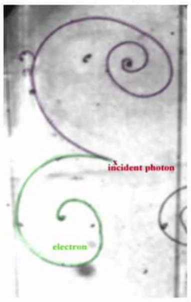
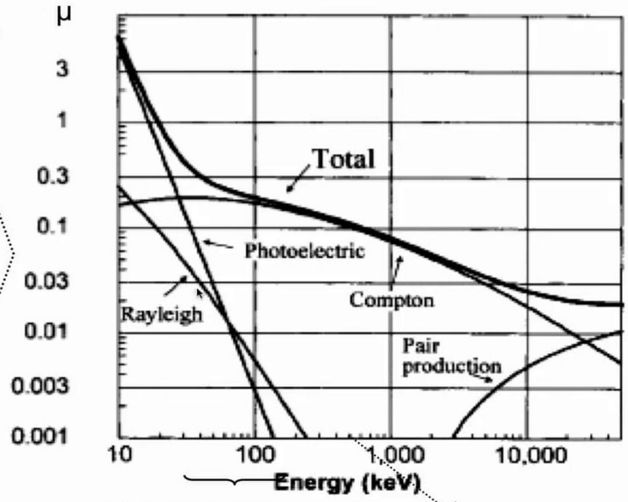



Not important in Bio-imaging




x-ray (CT, SPECT)

PET

3-10

Notice that both scales are logarithmic, and if you look at these two, at this graph here, this is a total absorption and then these here are the different contributions. Rayleigh falls are fast. We have the photoelectric effect, which falls off also very fast. Compton effect has a relatively smooth dependence and here pair production only starts to happen here at above 8 mega-electron volt. Now what are typical energies that we are dealing with for CT and SPECT, which we will discuss in the next two weeks. We are in the range of 30 kiloelectron volts to around 150 kiloelectron volts. So this is roughly the range for CT and SPECT and for positron emission tomography, which happens at 511 kiloelectron volts. We are here at this range. We're far from pair production and we are at a point where Rayleigh scattering is really not much of a contributor.

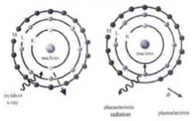
Notes

Summary

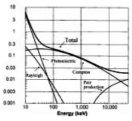
8m 43s

# Credits

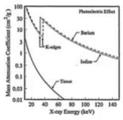
**Albert Einstein**, The Nobel Foundation
http://www.nobelprize.org/nobel_prizes/physics/laureates/1921/einstein-facts.html



**"Introduction to biomedical imaging"**
Fig. 1-8, from Andrew Webb

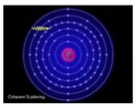


**"The Essential Physics of Medical Imaging"**
Fig. 3-13, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone



**"The Essential Physics of Medical Imaging"**
Fig. 3-10, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone

**Electron-positron pair production**
http://teachers.web.cern.ch/teachers/archiv/hst2002/bubblech/mbitu/electromag-events1.htm



**X-ray interactions** *(video extract)*
https://youtu.be/4p47RBPiOCo

So in reality, to understand the absorption in tissue we really need to just concentrate on photoelectric effect and on the Compton effect.

Notes

Summary

9m 38s