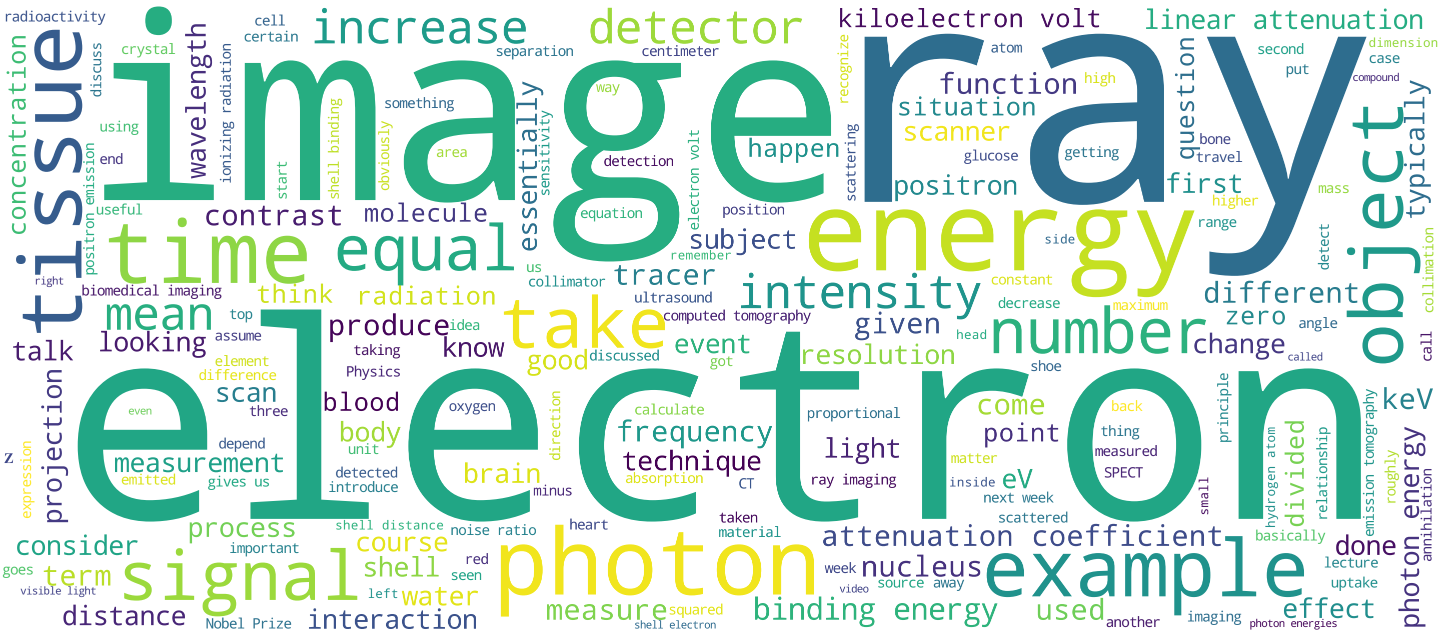
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

2.3 Basis of x-ray imaging

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



Search MOOC

Video

EPFL

X-rays

The beginnings of biomedical imaging

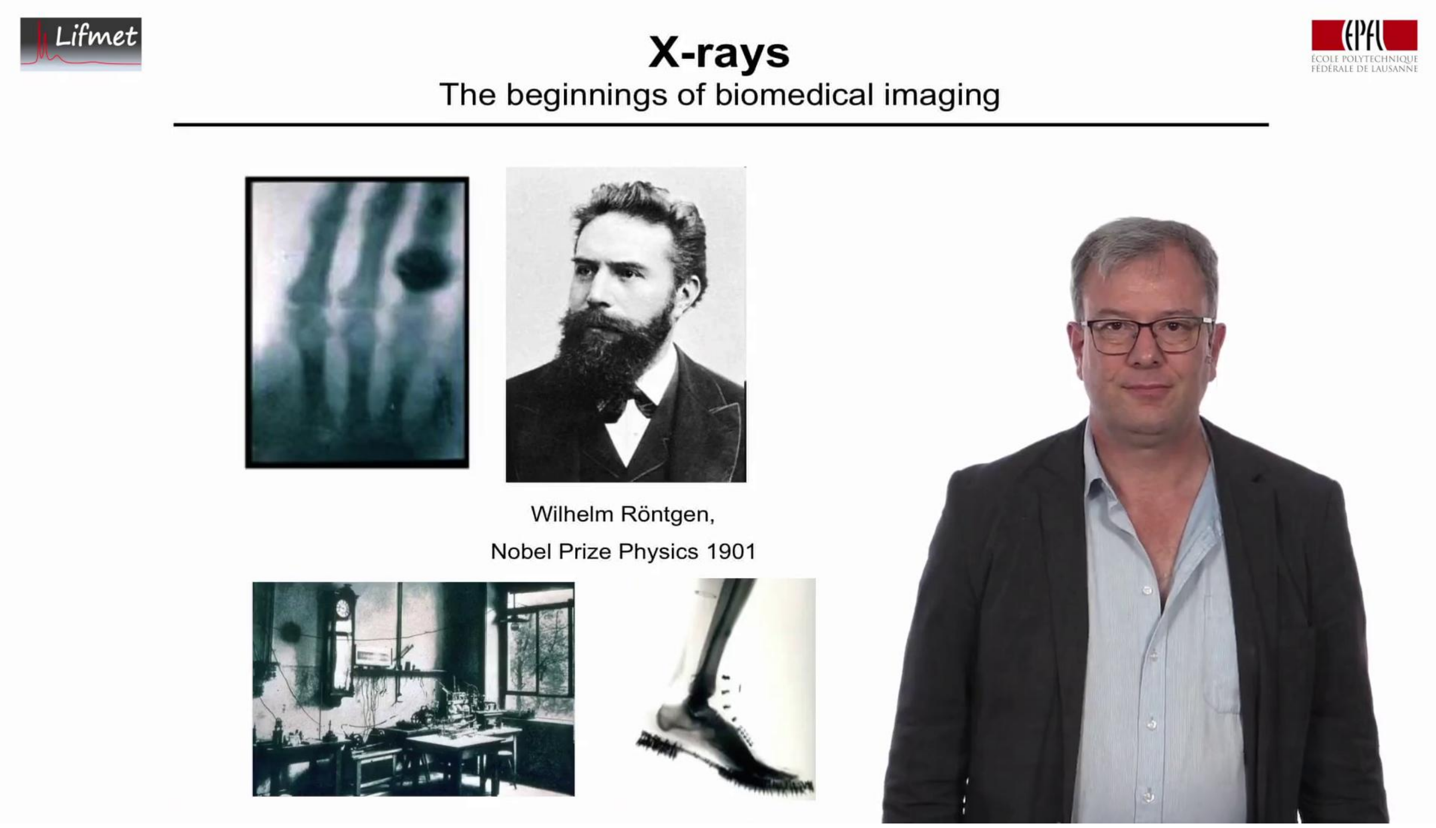
2-12

Now we'll switch gears. We'll go into the domain of X-rays, which will be with us for this second part of the week of this lecture. The next week's lecture will talk about X-rays interactions. Then we'll talk about computed tomography, and the following weeks are image and computed tomography. Now, X-rays are the beginnings of biomedical imaging. Do you recognize this image? This is actually taken in 1895 by Wilhelm Conrad Rontgen, and it is the hand of his wife. You can see here in the image, you can see the wedding band of his wife. So this is Wilhelm Conrad Rontgen, and it is actually quite befitting, he received the Nobel Prize in Physics, the first Nobel Prize in Physics, in 1901. Now, the first Nobel Prize in Physics, I find it remarkable, that this was given to the Father of Biomedical Imaging, Wilhelm Rontgen. The lab that he's taking these images in-- this image here on the top-- this is his lab where he did the development of the X-rays, the detection of the X-rays and the imaging. Now, if we look at this video here, this is taken from the Museum of Modern Art in San Francisco, It's actually more on the arts: I find it remarkable, the images that you see here.

Notes

Summary

0m 04s

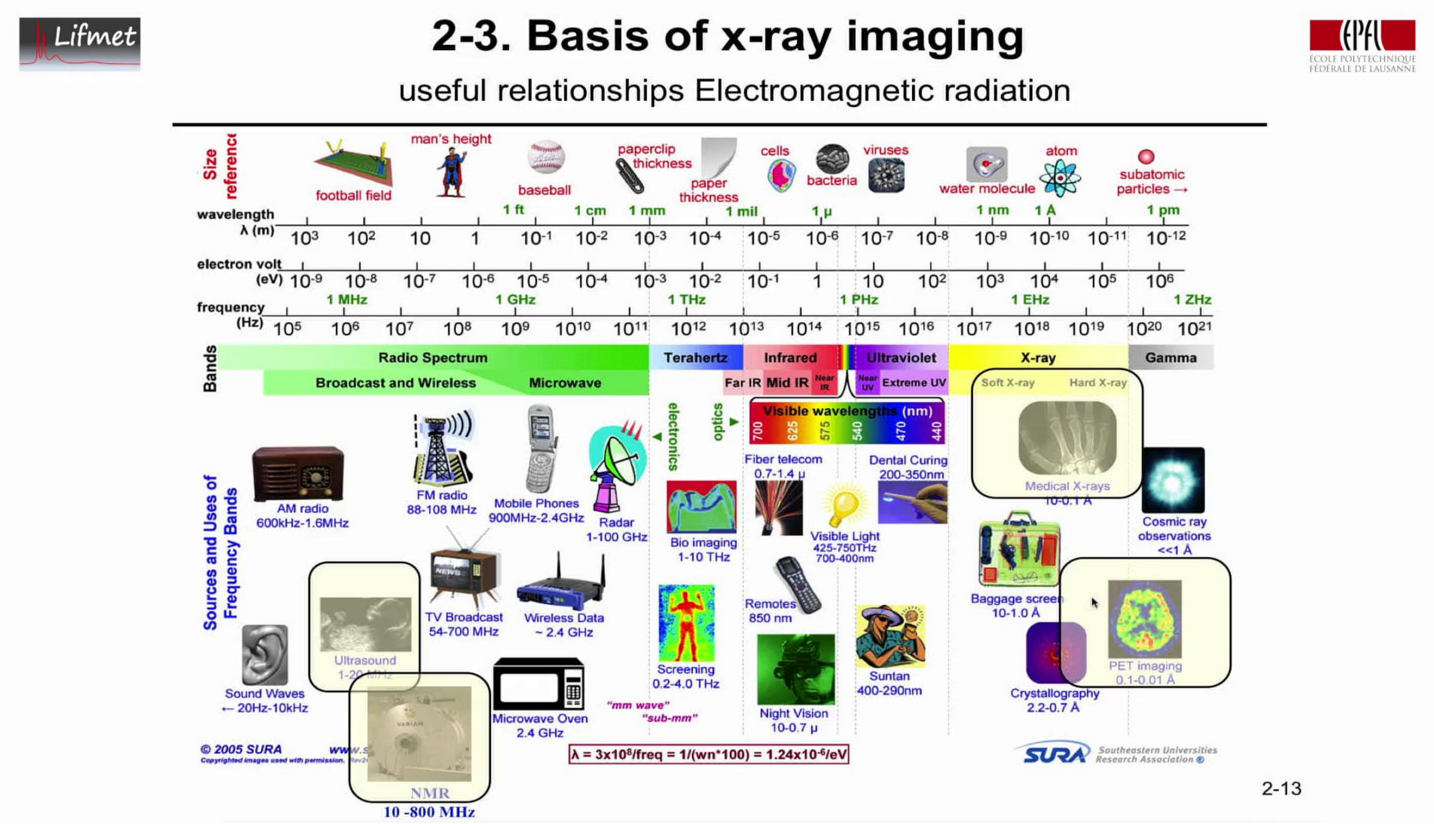


We'll start out with the image from Rontgen's wife. Then we'll see a more modern X-ray image at higher resolution. We can see the image of animals, of a fish, and of an embryo. I think this is an embryo of a chicken. And finally, do you recognize the last image? Look at this image as we zoom through it, and as we go through it, you can also see here at the top you see the safety pin. At the bottom you can see the foot inside a shoe. You see the nails of the shoe, the places for the laces-- the laces you don't see, but the metal there, that depicts very nicely. So X-rays were actually used very artistically to depict objects, and in the 50s, the shoemakers, they were actually so excited about X-ray imaging that in most shoe stores, you could actually put your foot in the shoe that you were about to buy into an X-ray machine, and see whether your foot fits into the shoe. You could actually see your toes, etc. This was very exciting. People were very excited. Of course, over the years, they started to become concerned about the use of X-rays and the health issues, as we will discuss next week the health considerations. So this was not the ideal use of X-rays but nonetheless very popular at the time.

Notes

Summary

1m 36s

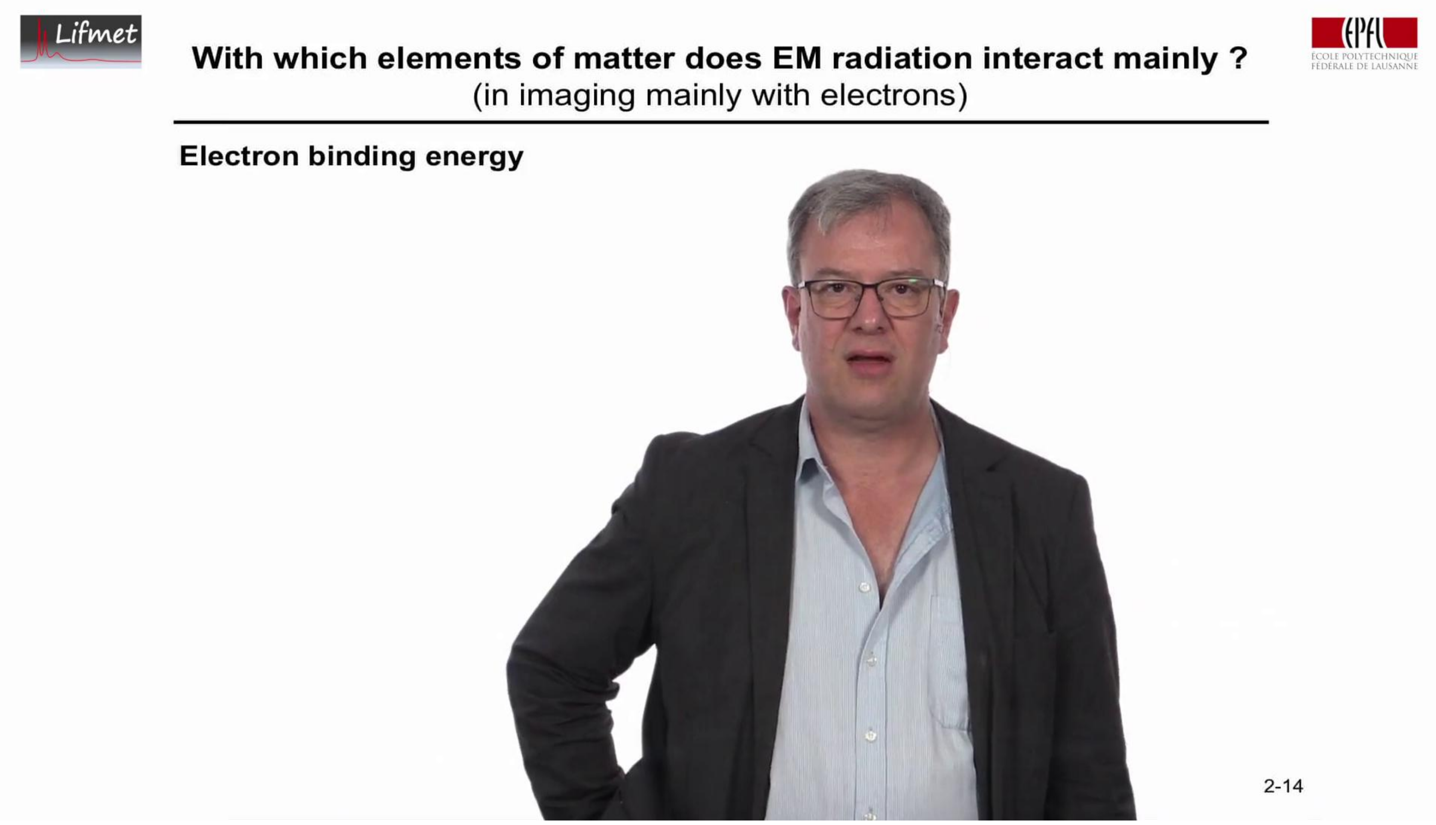


Now we'll talk about the basis of X-ray imaging, and actually, X-ray imaging is nothing but a part of the electromagnetic spectrum. And here is a display of the magnetic spectrum. We have wave length, electron volts-- that is a unit that is frequently used we will be using here for the first part of the lecture-- and the frequency of the different objects we have, the wavelength, the representation of objects with the wavelength, and the frequency here, and the energy of the photons that are involved. We have on the lower range, we have ultrasound imaging. We have discussed that already today. We have magnetic resonance imaging also working in the low frequency, low wavelength, long wavelength regime. We have medical X-rays. They are in this area here, and we have positron emission tomography at the high end of the photon energy studies short wavelengths that are over here. So you can see the techniques that we're discussing here in this course range from relatively long wavelengths, ultrasound to very short wavelengths and high photon energies for positron emission tomography. Now, I want to introduce here some very important relationships that are useful.

Notes

Summary

3m 26s



So we have the wave equation, that is the wave speed of light, *3 x 10^8 m/s* is equal to the wavelength times the frequency. We have the energy of the photon, which is equal to $h\nu$, h being Planck's constant, ν the frequency. h is even in Joule seconds, that's the value of h. We can express this in kiloelectron volts is *4 x 10^-18 keVs*. An electron volt is essentially the electron that the energy of an electron acquired in an electric field of 1 volt. We can re-express the energy of the photon as the Planck's constant times the speed of light divided by the wavelength, and if we express the wavelength in nanometers and the energy in kiloelectron volts, then this is easy to remember. This is 1.2 keV per nanometer. So if we have a wavelength of 1 nanometer, then we have 1.2 keV of energy. So now, we're looking at the interaction of electromagnetic radiation with tissue. So matter here, but we'll basically talk about the interaction with matter. What are the elements that we have in matter that electromagnetic radiation can interact? And this is basically, we've got the nucleus, and we've got the electrons. Now, in imaging, we are mainly concerned with interaction between X-rays and electrons. And here it's very useful to look at the structure of the atom.

Notes

Summary

4m 49s

With which elements of matter does EM radiation interact mainly ?

(in imaging mainly with electrons)

Electron binding energy

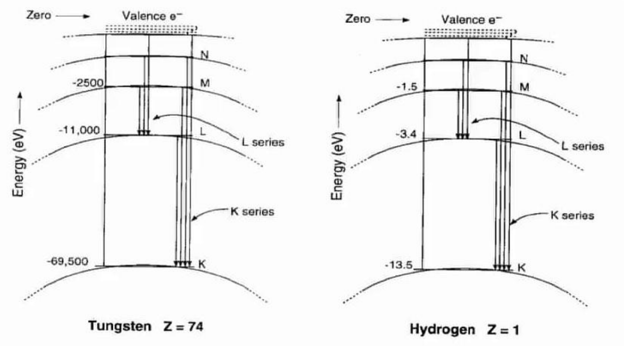


FIGURE 2-5. Energy-level diagrams for hydrogen and tungsten. Energies associated with various electron orbits (not drawn to scale) increase with Z and decrease with distance from the nucleus.

Binding energy

1. decreases with shell distance
2. increases with Z

(Why?)

2-14

We know very well that the electrons have a binding energy that is associated to where they are in the molecule. So we have the *K* shell, which is here at the bottom, binding energy for tungsten, here is about -70 keV. So this is the strongest binding energy here, and then we have different levels at which the electrons can be bound. They are discreet levels that come from quantum mechanics. This makes sense because the binding energy decreases with shell distance. This makes sense so we have the M-shell here which is -2.5 keV. It decreases with shell distance so we can make relationship to the Coulomb interaction. The nucleus is positive. The electron is negative, so it's attracted to the nucleus, the further away it is, it decreases *1 / Ar^2* so we have a decrease with the shell distance relative to the nucleus. If we take hydrogen here, the K-shell binding energy is now only 13 eV. So it's much lower. This is the closest an electron can be to the nucleus. It's in the K-shell. So the binding energy increases with ***Z***, that is the number of protons in the atom. So why does this increase with ***Z***?

Notes

Summary

6m 35s

With which elements of matter does EM radiation interact mainly ?
(in imaging mainly with electrons)

Electron binding energy

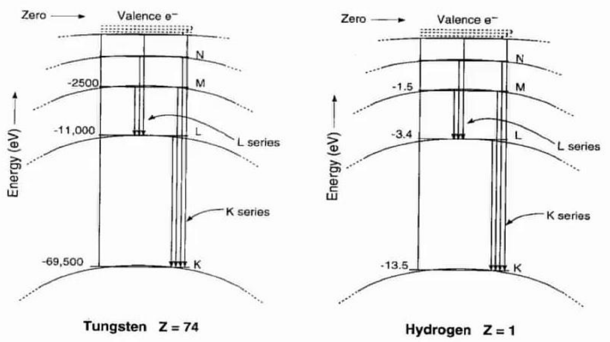


FIGURE 2-5. Energy-level diagrams for hydrogen and tungsten. Energies associated with various electron orbits (not drawn to scale) increase with Z and decrease with distance from the nucleus.

Binding energy
1. decreases with shell distance
2. increases with Z

(Why?)

Lowest K-shell binding e⁻ energy:

E_K^{min} = 13.6eV (^{1}H)

$h\nu > E_K^{min}$: ionizing

$h\nu < E_K^{min}$: non-ionizing

Ionizing radiation is above 13.6 eV

2-14

This is again with Coulomb, the interaction that is the force increases with the electrical charge, it's multiplication of the two electrical charges. The electron is alway one electron charge and the positive charge is the number protons that is proportionate to Z. So it increases with Z. That also makes. just from a classical consideration, makes perfect sense. So if you now look at the lowest K-shell binding energy that we have out there from the periodic table of elements, the lowest binding K-shell energy that we have is for the hydrogen atom. It is 13.6 eV. And here we make an important classification. If the photon energy, $h \times \nu$ is bigger than this-- than the K-shell binding energy for the hydrogen, than we consider the radiation as ionizing, and if it's below that, the radiation is non-ionizing. Ionizing means that the photon has sufficient energy that is able to bump the electron out of the K-shell, and therefore, produce a charged atom and therefore, arises the term ionizing. So the take home message here is that the ionizing radiation is for photons whose energy is above 13.6 eV. Here are some additional useful constants.

Notes

Summary

8m 07s

With which elements of matter does EM radiation interact mainly ?
(in imaging mainly with electrons)

Electron binding energy

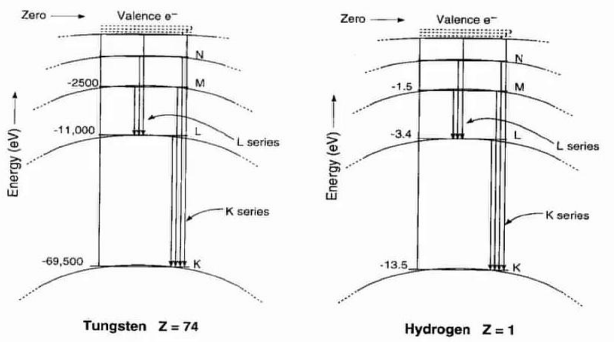


FIGURE 2-5. Energy-level diagrams for hydrogen and tungsten. Energies associated with various electron orbits (not drawn to scale) increase with Z and decrease with distance from the nucleus.

Binding energy
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(Why?)

Lowest K-shell binding e^- energy:

E_K^{min} = 13.6eV (^{1}H)

$h\nu > E_K^{min}$: ionizing

$h\nu < E_K^{min}$: non-ionizing

Electron (some useful constants)

m_e = mass = $9 \cdot 10^{-31}$kg

q_e = charge = $1.6 \cdot 10^{-19}$ C (As)

Rest energy $m_e c^2$ = 511 keV

Ionizing radiation is above 13.6 eV

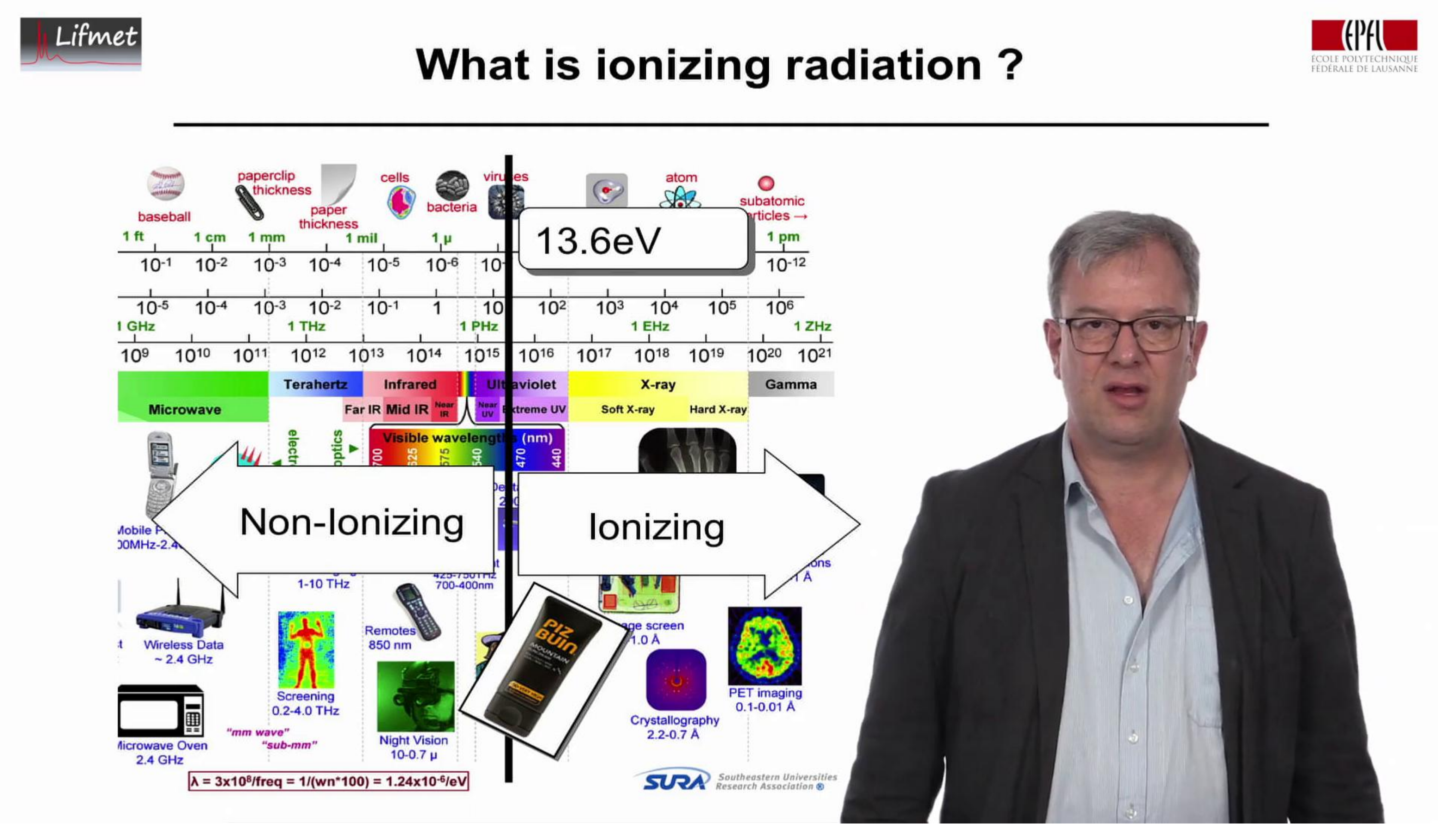
2-14

We have the mass of the electron, the charge of the electron and the rest energy of the electron, that is from Einstein's famous equation *MC^2* The energy of an electron is equal to 511 keV. These are some constants that are useful for the problem sets of this course and for addressing some quantitative questions, we'll reuse some of those values later on in weeks to come.

Notes

Summary

9m 35s

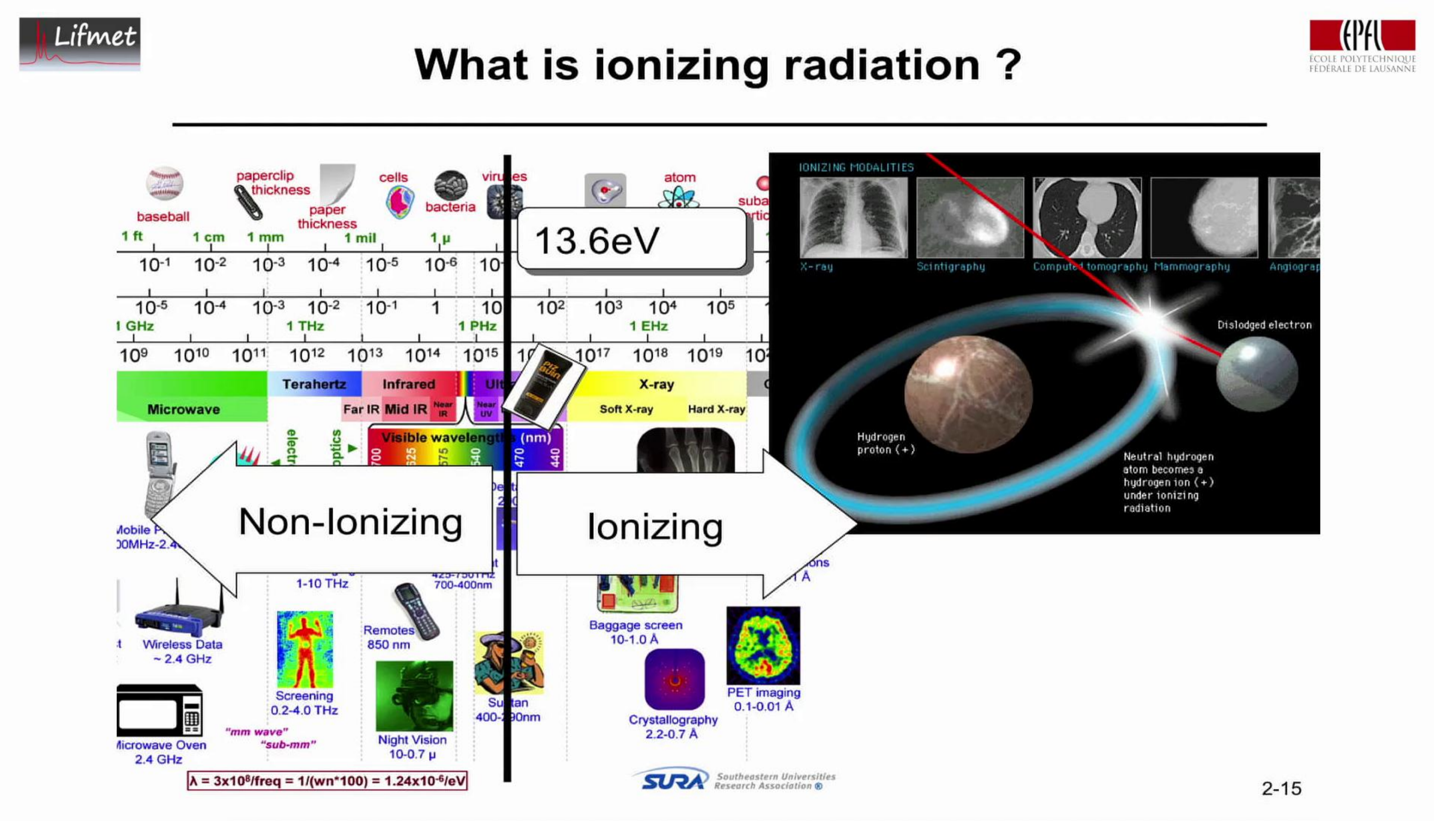


So where does ionizing radiation occur? What is typically considered ionizing radiation? Here we retake the electromagnetic spectrum, the whole range here, from microwave to gamma rays, PET imaging is here. And this is the 13.6 eV. Here we have the energy. This is 10 eV, this is 100 eV, it's a logarithmic scale. This is where 13.6 eV is. The separation, that's the distinction, everything to the right is considered ionizing, and everything to the left is considered non-ionizing. Now if we look at where the separation is, we see it is in the ultraviolet range. The visible light, what we see here is here. This is the light where we see the rainbows. So it's actually quite close to visible light, slightly above. This is why we use products like this one-- this is typical for Switzerland-- sunscreen. We use sunscreen to lock out the harmful ultraviolet rays which have sufficient energy so that they can start to be ionizing in our skin. And when they are ionizing, as we will see next week, they can produce harmful effects in the body and ultimately, cancer, so this is important why we carry sunscreen when we go outside to protect ourselves from these effects.

Notes

Summary

10m 05s



It's not just in sunburn, but also from a standpoint of health. So this is the use of sunscreen locking out the bad ultraviolet. So in summary, we are going to talk about ionizing modalities for the next few weeks. We have X-rays, scintigraphy-- we're not going to talk about this too much-- computer tomography in two weeks, mammography, and geography, PET SPECT, and the separation that is done between when we consider it's ionizing is that we are using photon energies that are sufficient that they can dislodge an electron in the hydrogen atom. Here's the nucleus, the proton. Here's the electron in the K-shell, and the neutral hydrogen atom becomes positively charged upon interaction with an X-ray.

Notes

Summary

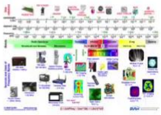
11m 38s

Credits

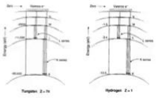


Wilhelm Conrad Röntgen (Creative Commons)
https://commons.wikimedia.org/wiki/File:Roentgen2.jpg
https://www.nobelprize.org/nobel_prizes/physics/laureates/1901/rontgen-photo.html

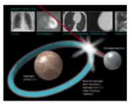
Early Science Photography: X-Rays
https://youtu.be/SZROh4j5Dec *(video extract)*



SURA (Southeastern Universities Research Association)
http://www6.sura.org



“The Essential Physics of Medical Imaging”
Fig. 2-5, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone



Ionizing radiation
http://healthwise-everythinghealth.blogspot.ch/2009_11_01_archive.html

Piz Buin suncream
https://www.pizbuin.com/

Notes

Summary

12m 30s