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Introduction to Biophysics
Winter Semester 2025/26, Exercise Sheet 2

Problem P1.1 X-ray generation

a) How does an X-ray tube work? Draw the basic components, name and explain them.
Solution:

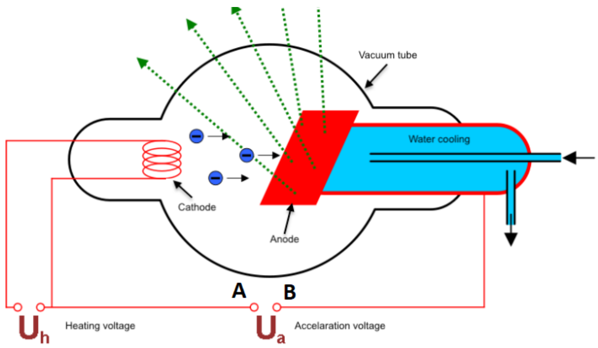

FIGURE 1

b) How does the source spectrum of a Molybdenum tube look like and how does it change? Draw a plot and indicate the major parts of the spectrum (hint: X-ray emission lines energies of Mo: $K\alpha_1 = 17.479$ keV; $K\alpha_2 = 17.374$ keV; $K\beta_1 = 19.608$ keV). What are the main physical effects in X-ray generation with a tube?
Solution: X-ray spectrum online calculator -
https://bps.healthcare.siemens-healthineers.com/booneweb/index.html
Plot relative intensity against energy (keV). Major parts result from the interaction of electrons with the target material - two main effects 1.) Bremsstrahlung - polychromatic, max. energy is equal to the accelaration voltage, and 2.) characteristic lines depending on the target material.

c) How do the spectra look like for peak tube voltage of 30 kV and 40 kV? What changes?
Solution: Main changes is the higher maximum energy, due to higher acceleration voltage, which is equal to the higher kinetic energy of the electrons, and the overall intensity of all energies is increased.

d) How does the spectrum change with different tube currents? Is there any limitation for the tube current?
Solution: Only the overall intensity changes - not the energy of the X-rays. The limitation is given by the acceleration voltage and the heat capacity/cooling/melting point of the target.

e) How does the spectrum change for Tungsten as target material? What is the minimum voltage for an X-ray tube with a tungsten target that the emitted spectrum contains characteristic K-lines? (Energy levels of Tungsten: K-shell -69.51 keV; L-shell -11.0 keV; M-Shell -2.8 keV)?
Solution: Tungsten has characteristic lines from the L-, and M-Shell in the low energy range, which is not relevant to the clinical imaging, as the energy is too low to penetrate patient's tissue. The chosen maximum voltage of 40 kVp is not sufficient for the emitted characteristic

lines Kα and Kβ. The minimum voltage required is -69.51 keV, corresponding to the K-shell energy level.

f) What is a rotating-anode X-ray tube and what are its advantages and limitations?
Solution: A rotating-anode, as the name indicates, has a rotating target to improve the cooling. The accelerated electrons hit the target in only one small region. The rest is dipped into oil for cooling. With this approach the heat load on the target can be strongly increased avoiding the melting of the material. Thus, rotating-anode sources provide a much higher X-ray flux than static anodes.

Problem P1.2 X-ray interaction with matter

a) What type of interaction exists/dominates in clinical X-ray imaging?
Solution: The main interaction effects in the clinical energy range are the Photo-electric effect, the Thomson (coherent) scattering and the Compton (incoherent) scattering.

b) What is the energy and material dependence of absorption?
Solution: Absorption is different from attenuation - it means the photo-effect, which is the only interaction, where a photon is fully absorbed and not just scattered to a different detector pixel. Latter would result in an attenuated beam, but is due to scattering not to absorption. The attenuation coefficient $\mu_{photo} \propto Z^4 E^-3$ for the photo-electric absorption.

c) How do the total attenuation cross sections compare for two different materials (e.g. Carbon and Lead; Hint: tabulated mass attenuation coefficients can be found here: https://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html)? Which interaction effect dominates the cross section at the clinical X-ray energy range?
Solution: At low Z materials (e.g. water) the Compton scattering is dominant in the relevant energy range (50-140 keV). For high Z material (e.g. lead) the photo-electric effect is dominating (see figure 2).

d) What are absorption edges and their nomenclature (e.g. for Iodine)?
Solution: See figure 3 for the nomenclature for absorption edges and figure 4 for the absorption edges of Iodine, which is a common contrast agent in clinical imaging.

e) What are the strategies to increase contrast in clinical X-ray imaging using contrast agents? How does the contrast agent influence the previously discussed interactions?
Solution: Looking at the high Z- and energy dependence of the photo-electric absorption, the strategy becomes obvious. There are two options: 1.) decrease the Energy - the contrast should increase with the third power of the energy, or 2.) increase Z of the material - give the patient a contrast agent with high Z. This increases the photo-effect contribution with the fourth power of Z.

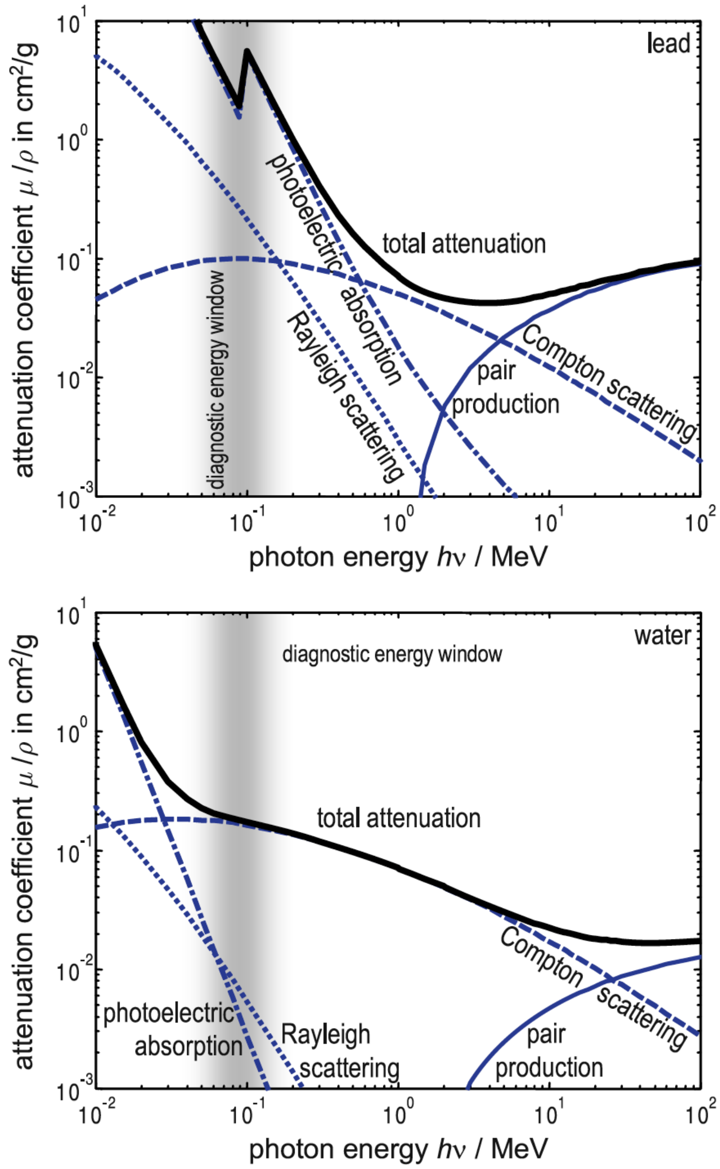

Fig. 2.17. Mass attenuation coefficient, μ/ρ, versus incident photon energy for lead (*top*) and water (*bottom*). For the diagnostic energy window of CT, $E = [50\,\text{keV}–140\,\text{keV}]$, photoelectric absorption is dominant for lead and Compton scattering is dominant for water. Pair production is possible for quantum energies of $E > 1\,\text{MeV}$ (compiled with data from the web database XCOM [Berger et al. 2004])

FIGURE 2: copied from the book T. Buzug, "Computed Tomography"

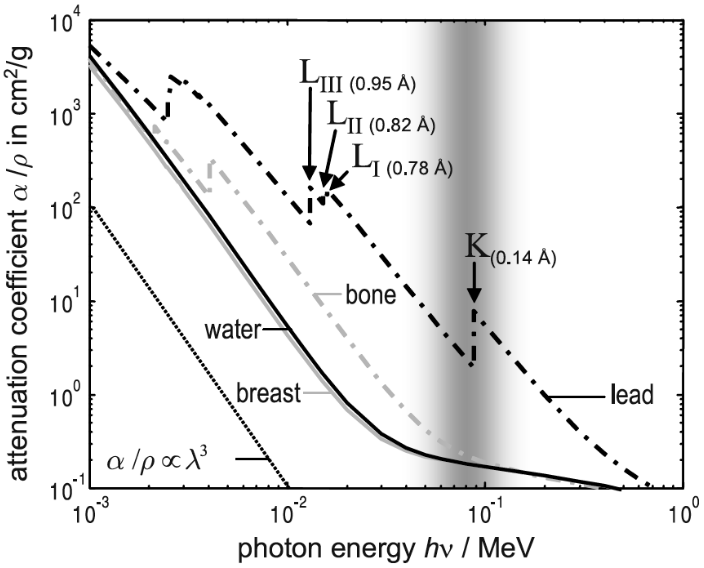

Fig. 2.16. Mass attenuation coefficient (α/ρ measured in units of cm^2/g) for lead and water as well as for the bio-tissues bone and soft tissue given versus the incident radiation energy. For absorption processes above the K-shell the curve shows a fine structure (compiled with data from the web database XCOM [Berger et al. 2004])

FIGURE 3: copied from the book T. Buzug, "Computed Tomography"

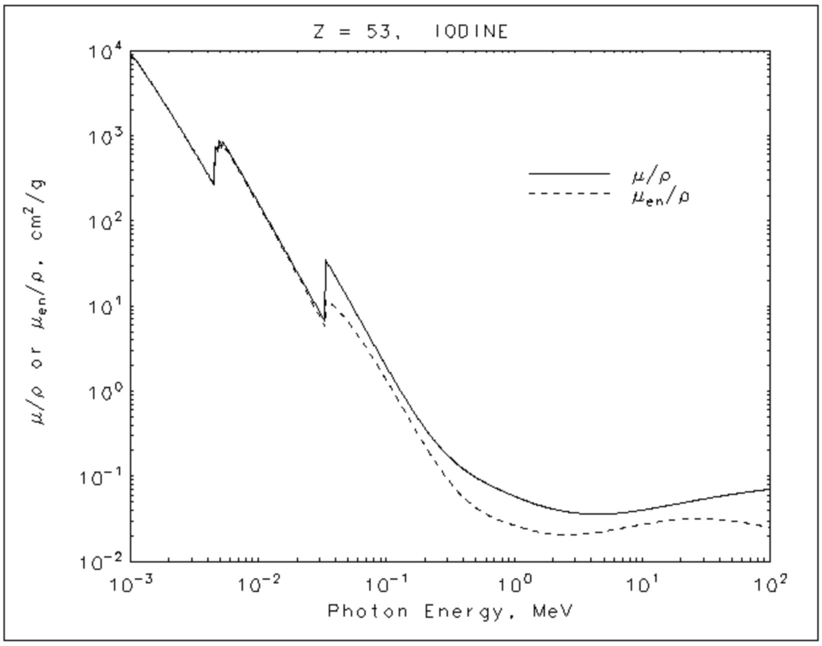

FIGURE 4: plot generated from the NIST data base (https://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html)

Problem P1.3 Dual-Energy Imaging

a) What is dual-energy imaging?

Solution: Dual-energy imaging is analysing the energy-dependent attenuation of different materials by taking images at two different X-ray energies (monochromatic applications) or energy windows (polychromatic applications). This information can be used to clearly distinguish these two materials and even to quantify their concentrations. The two quantities measured can be used to determine the Compton and the Photo-effect contribution to the measured contrast of the corresponding materials and with that to create images showing only one of the materials (e.g. soft tissue and iodine contrast agent), the image contrast of the object at any monochromatic energy, or the effective-atomic number Z_{eff} distribution (e.g. for treatment planning in radiation therapy).

b) Which technical realizations exist? What are the advantages/limitations of these realizations?
Solution:

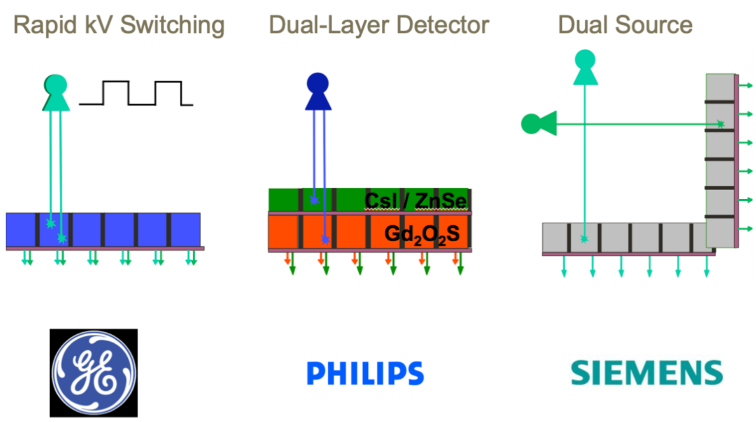

FIGURE 5: Different realizations of dual-energy imaging from corresponding manufacturers.

The main task of all the existing realizations is to take two images of the same object at two different effective energies. The rapid kV switching is the simplest method, but is time-limited (e.g. beating heart will not be imaged in the same state with two energies).
Philips decided to modify the detector to include two detection layers - upper layer for lower energies and lower layer for higher energies. This is the more complicated method (i.e. the detector calibration becomes more challenging), but it is the most elegant way. The major advantage is the simultaneous measurement of the object at two energy levels. The challenge is a sufficient separation of the two spectra and that one cannot change the two energy levels built into the detector side.
The 'two CTs in one' solution by Siemens is more complicated and expensive, but gives the fastest system (e.g. CT of a beating heart can be easily done). The challenge with this system is the scattering-correction from the high-energy tube in the low-energy detector and the matching the images taken 90 degrees apart from each other.
All these realizations do not allow to detect the energy of the X-ray photons. This is, why all the manufacturers are switching to photon-counting detectors with spectral resolution. These detectors are very complex (i.e. more electronics in it, the calibration needs to be adjusted, etc.), but this is the only way to combine the advantages of a simultaneous measurement of the object at two different and adjustable energy levels.