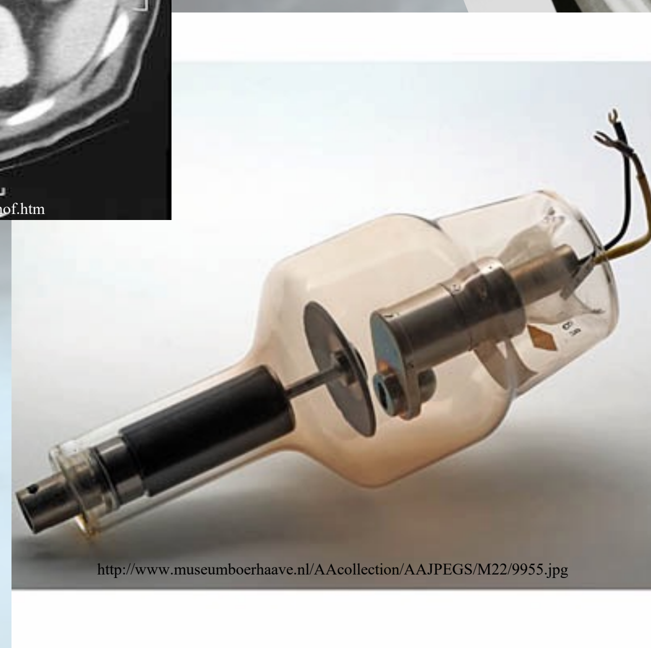
Diagnostic X-rays and CT Scans

- *X-ray vision*

http://www.uab.edu/surgonc/cases/GI/case2/ctscanof.htm



http://www.museumboerhaave.nl/AAcollection/AAJPEGS/M22/9955.jpg

http://www.bjwinslow.com/albums/medicalcharts/broken_arm_radius_and_ulna_x_ray_10.jpg

Diagnostic X-rays and CT Scans

- *motivation and outline*

- X-rays have been known for over 110 years.
- X-rays are the most utilized modern medical technique.
- "X-rays" in the colloquial sense are radiographs – or intensity mappings of the shadows created when an x-ray beam passes through materials.
- The x-rays are absorbed as they pass through tissue and bone and what emerges is displayed on a film or stored digitally (called a *CT* or *computed tomography* scan) and used to reconstruct an image of the object that absorbed the x-rays.
- One limitation of film x-rays is their lack of depth information.
- A *CT* or computed tomography scan can distinguish the different absorbing layers since the images are stored electronically and can be processed separately.
- Diagnostic x-rays are a type of ionizing radiation and there are inherent risks associated with an x-ray scan.

Diagnostic X-rays and CT Scans

- *motivation and outline*

- Even though x-rays are a form of ionizing radiation and produce ions in the body, the risks seem to be negligible, with small doses of radiation, compared to the medical benefits.
- We'll investigate x-ray production and then use it to produce a radiograph.
- In order to produce a radiograph, we need to determine how the x-rays interact with body tissues and bones.
- From here, we will see how organs, which normally cannot be imaged with x-rays, can be imaged by using a suitable contrast medium.
- Then we'll investigate computed tomography and see how to digitally reconstruct x-ray images.
- Some applications that will be considered, x-ray use in dentistry, breast cancer and lung cancer.

Diagnostic X-rays and CT Scans

- *Production of x-rays*

- Free electrons are produced at a (usually tungsten) filament and these free electrons are accelerated to the right by an electric field that is generated between the cathode (-) to the anode (+) by applying a potential difference across the cathode/anode.

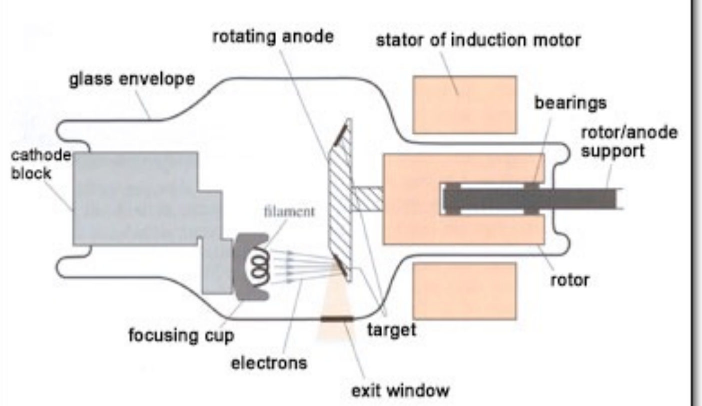
- To produce these electrons the filament is heated by passing an electric current through the (tungsten) wire and the electrons are thermally emitted.

- The anode geometry could be fixed or rotatable. Here we have a rotatable anode.

- The material that the anode is constructed from will determine the type of x-rays that are generated and their energies.

- The kinetic energy of the electron is given by $W = -q\Delta V$ and the energies are usually several keV's.

- Most of the electron's energy goes to heating the anode, but some will produce x-rays.



http://openlearn.open.ac.uk/file.php/3318/S809_1_004i.jpg

Diagnostic X-rays and CT Scans

- *Production of x-rays*

- The heat must be removed, or the x-ray tube will suffer damage. Usually, the anode gets so hot it well melt.

An Example: X-ray anode heating

Suppose that you have an x-ray tube with an anode made from tungsten and that there is a $100kV$ potential difference applied and a current of $100mA$ is flowing. 1% of the electric power is used to generate x-rays and the rest is lost as heat.

- How many electrons strike the anode per second.
- What is the power emitted as x-ray radiation? What is the power emitted as heat? This is called the thermal power.
- How long can the x-ray tube work without the anode fusing? Assume the tungsten anode has a mass $m = 74g$ and will melt when the temperature rises to $3000K$
- How can you lengthen this time?

Diagnostic X-rays and CT Scans

- *Production of x-rays*

- There are two mechanisms to produce x-rays from the anode.

Bremsstrahlung (or braking radiation) and *PIXE* (or Particle Induced X-ray Emission)

Bremsstrahlung

- The electrons are slowed down, or decelerated, and the accelerating charge produces a continuous emission of radiation (this is background).
- This is exactly how a light bulb works, except the electron energies are much less.
- Electrical interactions (forces) between the electrons and the atomic nucleus of the anode decelerate the electrons.

Diagnostic X-rays and CT Scans

- *Production of x-rays*

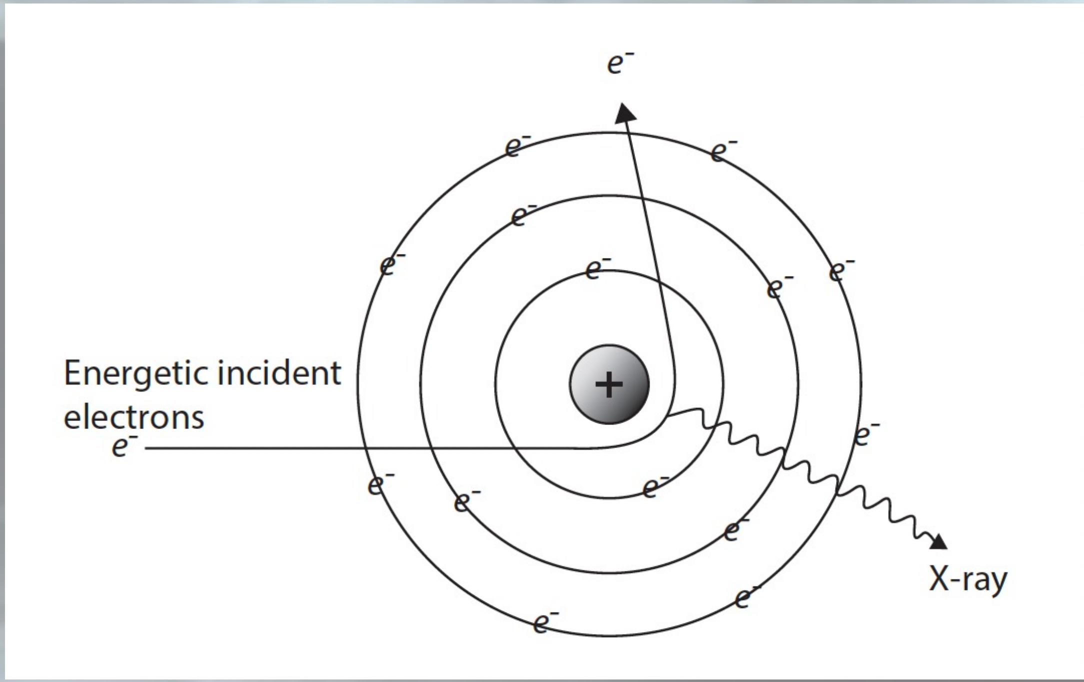
- Diagram of the Bremsstrahlung process.

- The electron's interaction is electromagnetic in nature.

- As the electron decelerates radiation is produced all along its path.

- Depending on how the electron interacts with the nucleus will determine its energy.

- This produces a continuum of energies and thus a background. Not wholly useful.



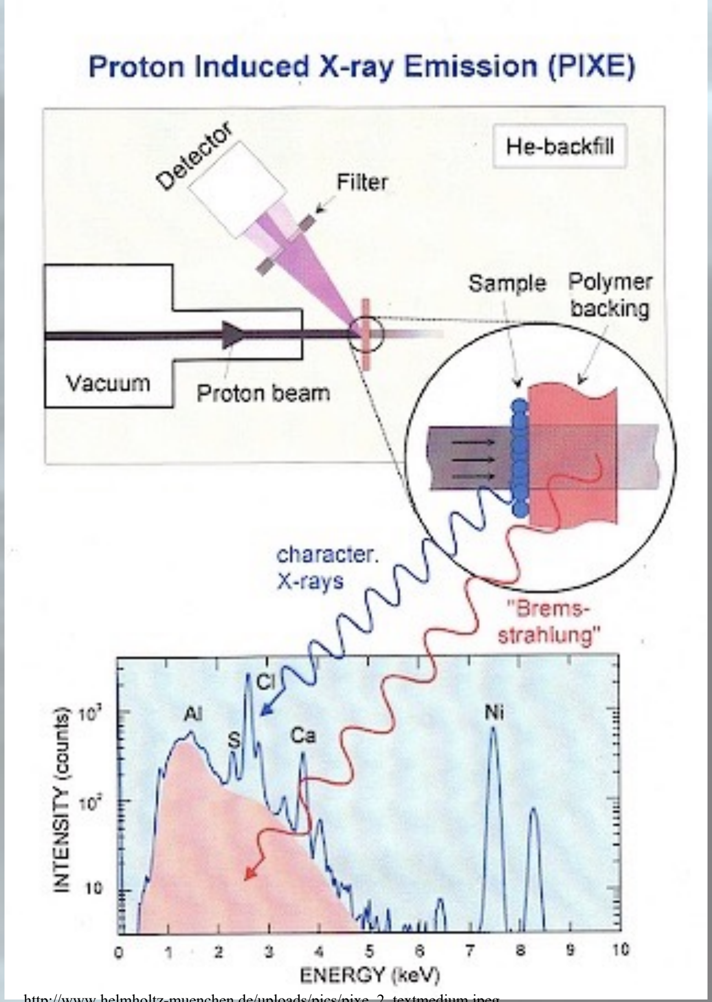
Problems and Solutions in Medical Physics, Diagnostic Imaging Physics, Ng, K., Wong, J, Clarke, G., CRC Press, 2018

- Glancing collisions produce low energy x-rays while "head-on" collisions convert almost all the energy of the electron into an x-ray.

Diagnostic X-rays and CT Scans

- *Production of x-rays*

- The second mechanism for x-ray production is called *PIXE* or *particle induced x-ray emission*.
- The high energy electron can knock out an inner shell electron from the target atom and this creates a vacancy in the inner shell.
- In order to conserve energy an electron from a higher orbital will transition to the inner orbital, with an emission of a photon in the x-ray portion of the EM spectrum.
- Of course, you don't have to use electrons – you could use protons. This is what's done using the accelerator in the basement.
- The x-rays produced are characteristic of the anode material.



http://www.helmholtz-muenchen.de/uploads/pics/pixe_2_textmedium.jpeg

Diagnostic X-rays and CT Scans

- *Production of x-rays*

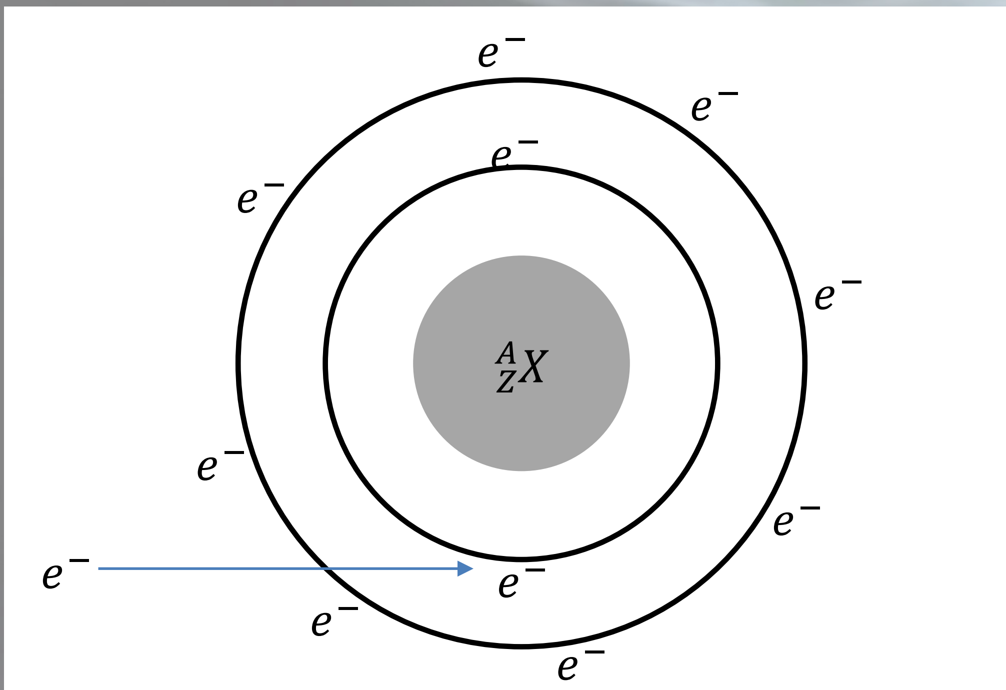


Figure made by S. LaBrake, 2023

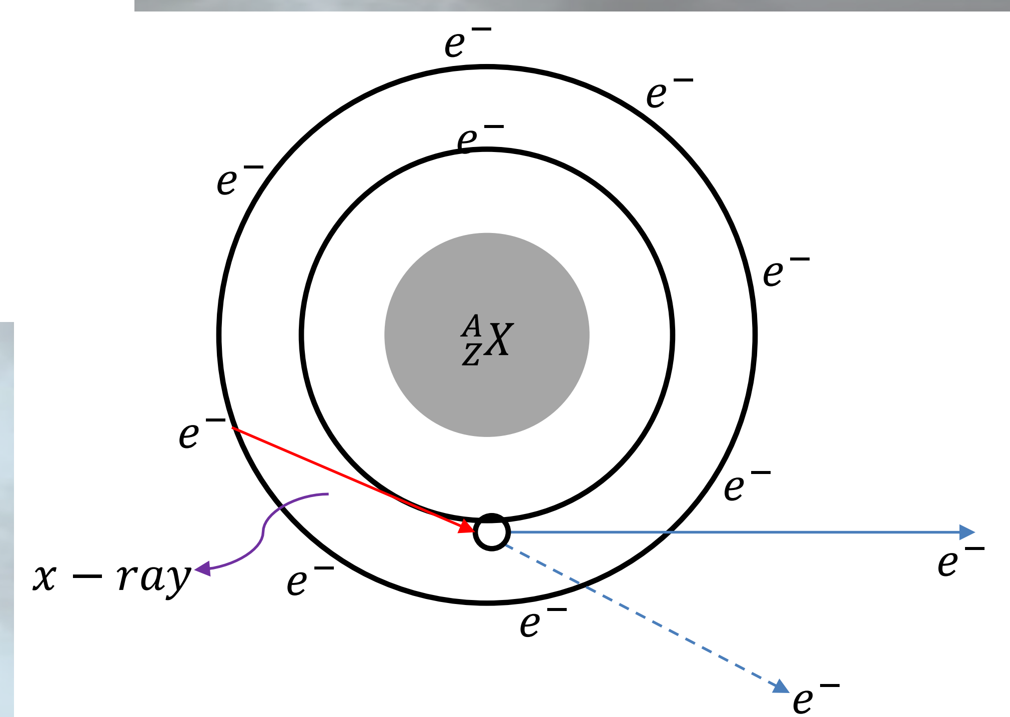


Figure made by S. LaBrake, 2023

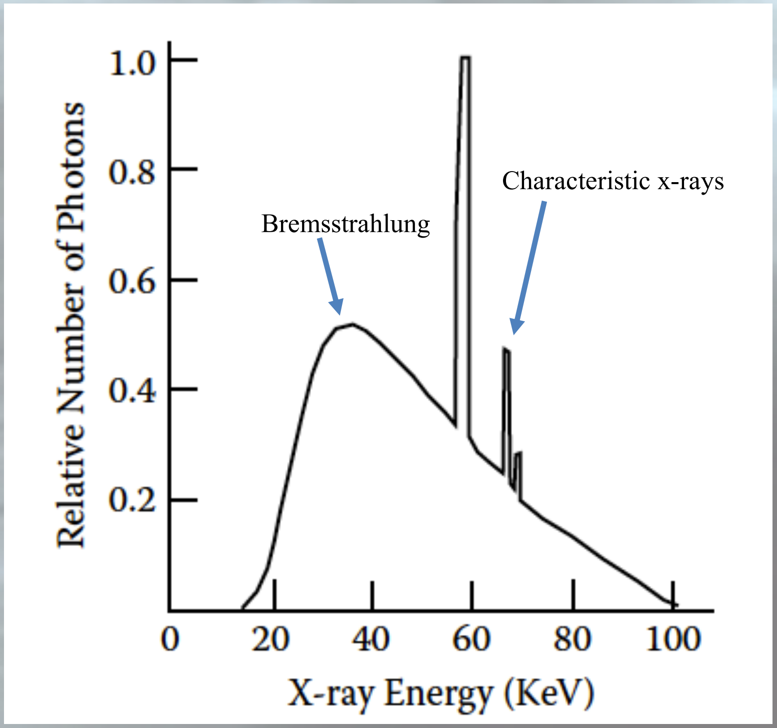
Diagnostic X-rays and CT Scans

- *The characteristic x-ray spectrum*

- The total spectrum is the sum of the contributions due to Bremsstrahlung and PIXE.

- The incident electrons eject inner shell electrons from the target material, and this produces characteristic x-rays with a given energy or wavelength.

- In addition, those incident electrons that don't eject inner shell electrons of the target material will however undergo glancing interactions and this produces the braking deceleration, and this produces the background



Introduction to Physics in Modern Medicine, Kane, S., & Gelman, B., 3rd Ed., CRC Press, 2020

$$\Delta E = E_{upper} - E_{lower} = -13.6eV \cdot (Z-1)^2 \left(\frac{1}{n_{upper}^2} - \frac{1}{n_{lower}^2}\right) = \frac{hc}{\lambda} = hf$$

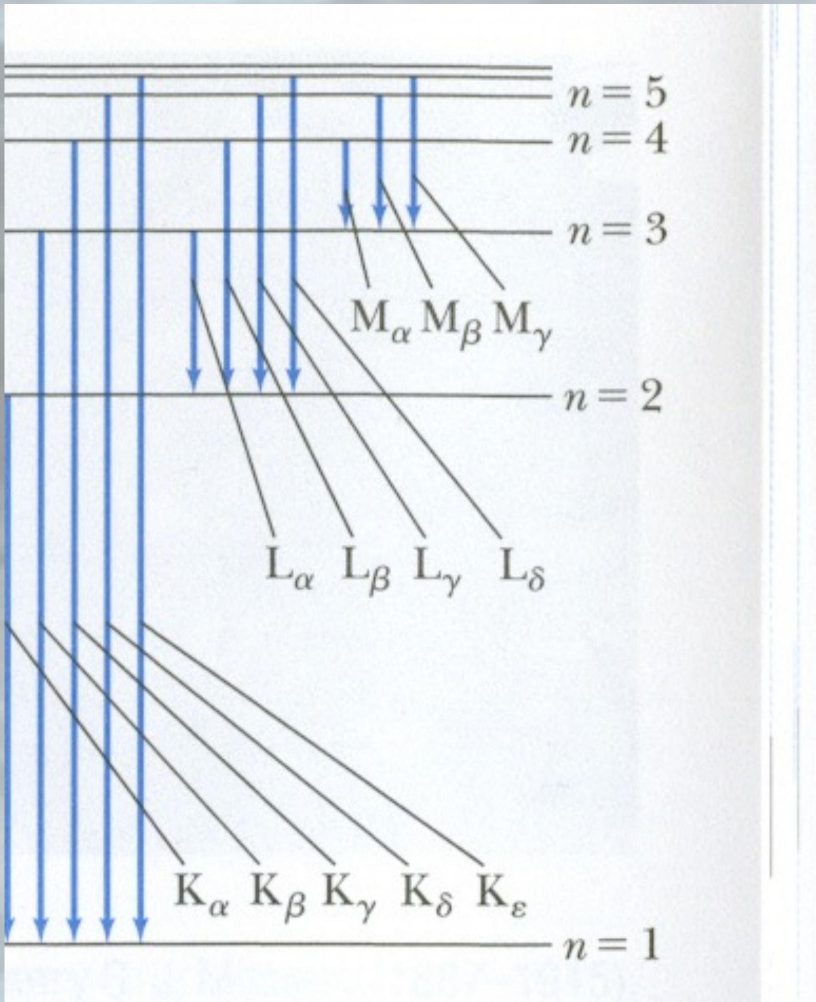
Diagnostic X-rays and CT Scans

- *The characteristic x-ray spectrum*

- The characteristic x-ray energies are due to the transitions that the electron makes from the higher orbital to the lower orbital.

- The two highest energy transitions are called the K_α and K_β, for the electron being ejected from the innermost shell, termed the K-shell.

- The highest probability transition is the K_α and the lower probability transition is the K_β, and these are seen by intensity in the emission spectrum.

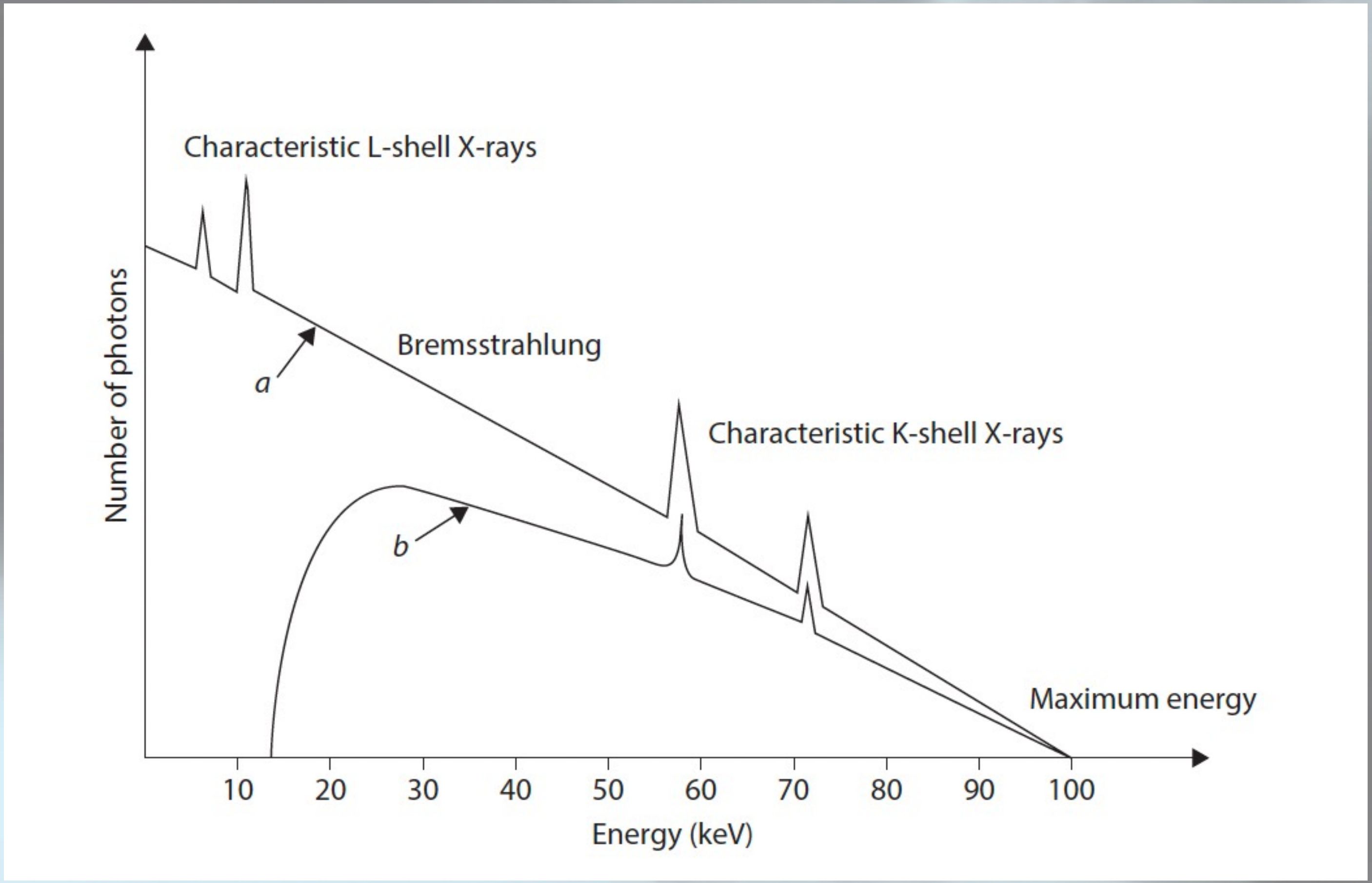


Modern Physics for Scientists and Engineers, Thornton, S., & Rex, A., 3rd Edition, Thomson Publishing, 2006

Diagnostic X-rays and CT Scans

- *The characteristic x-ray spectrum*

Putting the ideas together we get a picture like below.



Problems and Solutions in Medical Physics, Diagnostic Imaging Physics, Ng, K., Wong, J, Clarke, G., CRC Press, 2018

Diagnostic X-rays and CT Scans

- *Production of x-rays*

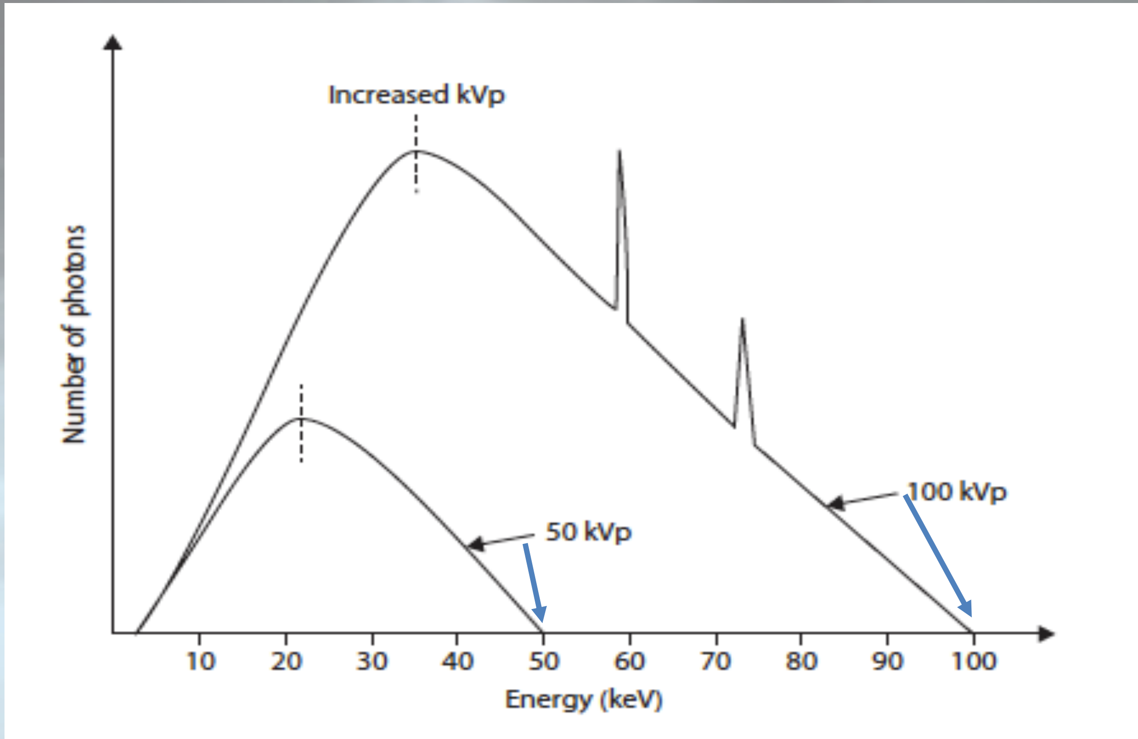
- Many factors affect the x-ray spectrum that is generated.
- If the overall shape remains unchanged, that is the number of photons at every photon energy changes by the same factor then we say that there has been a change in the radiation *quantity*.
- If the number of photons change as a result of a change in shape of the x-ray spectrum, we say there has been a change in the radiation *quality*.
- Some things that affect the x-ray spectrum generated by the tube are:
  - Tube voltage
  - Tube current
  - Time of exposure

Diagnostic X-rays and CT Scans

- *Production of x-rays*

- The tube voltage determines the maximum kinetic energy of the electrons.
- A higher energy leads to more energy that the electron can lose when it interacts with the atoms in the anode.
- In general, a small fraction of the incident electron's energy goes into x-ray production. Most of the energy is lost as heat in the anode.
- Changing the tube voltage changes the radiation *quality*. The shape of the curve changes.
- It's seen experimentally that the number of photons produced increases with the square of the tube voltage.

$$N \propto V^2$$

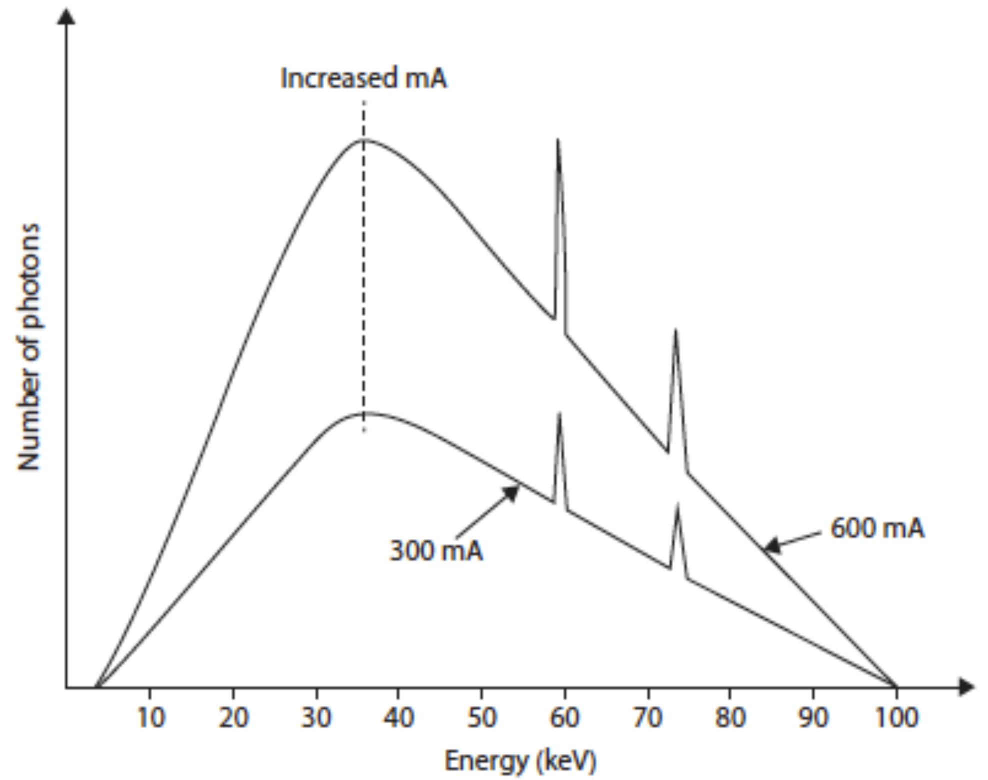


Problems and Solutions in Medical Physics, Diagnostic Imaging Physics, Ng, K., Wong, J, Clarke, G., CRC Press, 2018

Diagnostic X-rays and CT Scans

- *Production of x-rays*

- The tube current determines the number of electrons striking the anode.
- The more electrons striking the anode the greater the number of photons that can be produced.
- Changing the tube current changes, the radiation *quantity*. The shape of the curve does not change.

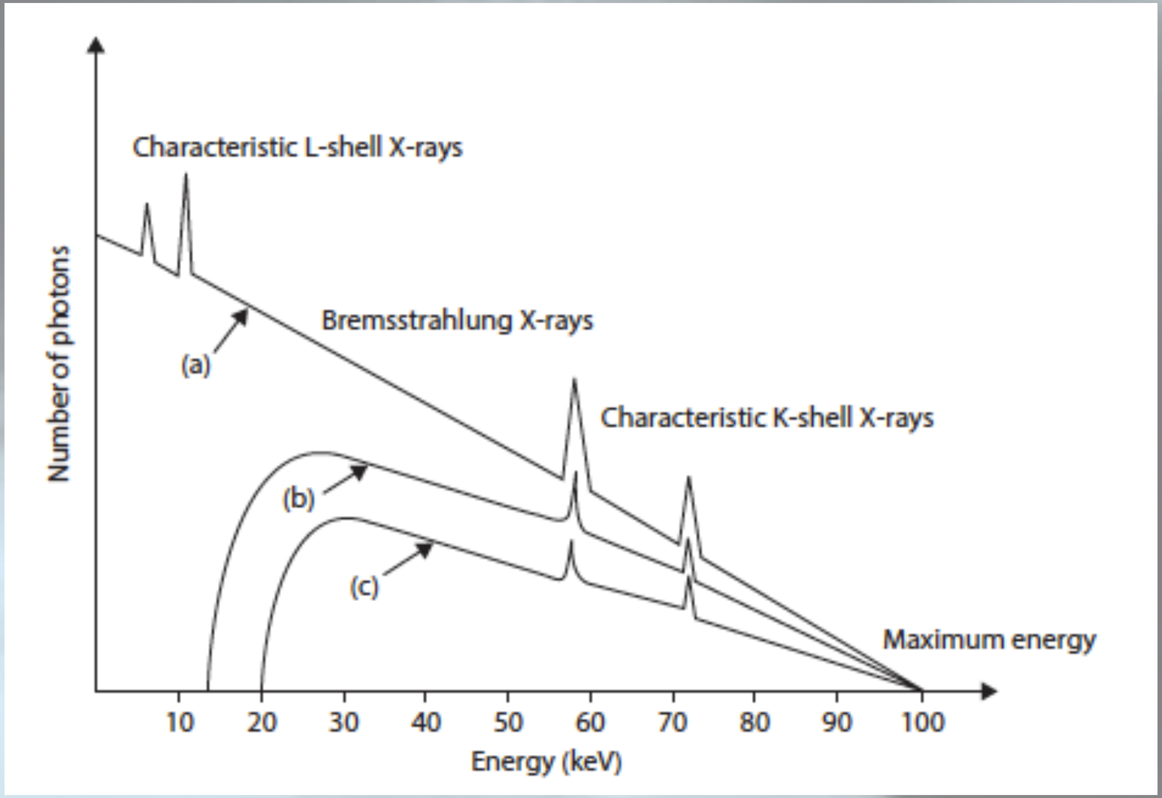


Problems and Solutions in Medical Physics, Diagnostic Imaging Physics, Ng, K., Wong, J, Clarke, G., CRC Press, 2018

Diagnostic X-rays and CT Scans

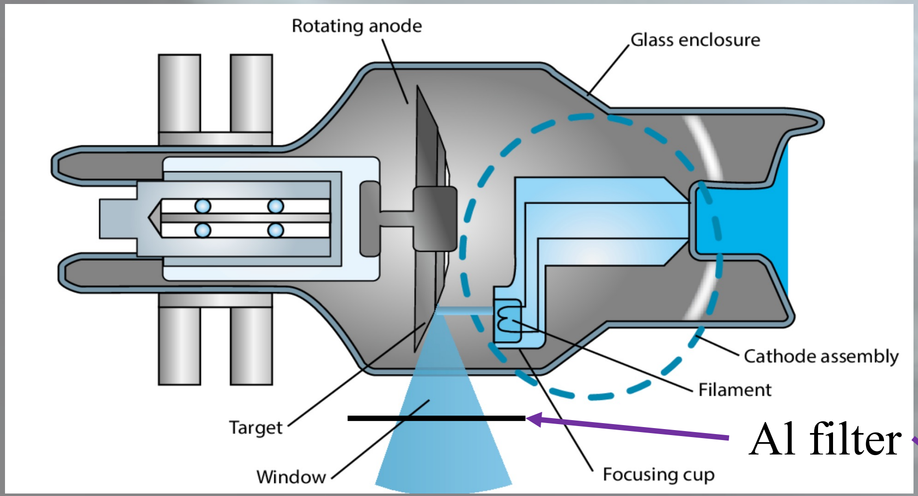
- *Production of x-rays*

- Filters can be placed in front of the emerging x-ray beam.
- The filter has the effect of removing low energy x-ray photons from the beam.
- The thickness of the filter has an increased ability to remove photons from the beam.
- Filters affect the radiation quantity. The overall shape doesn't change, just the number of photons produced.
- What do the three curves represent?
- How do x-rays interact with materials?



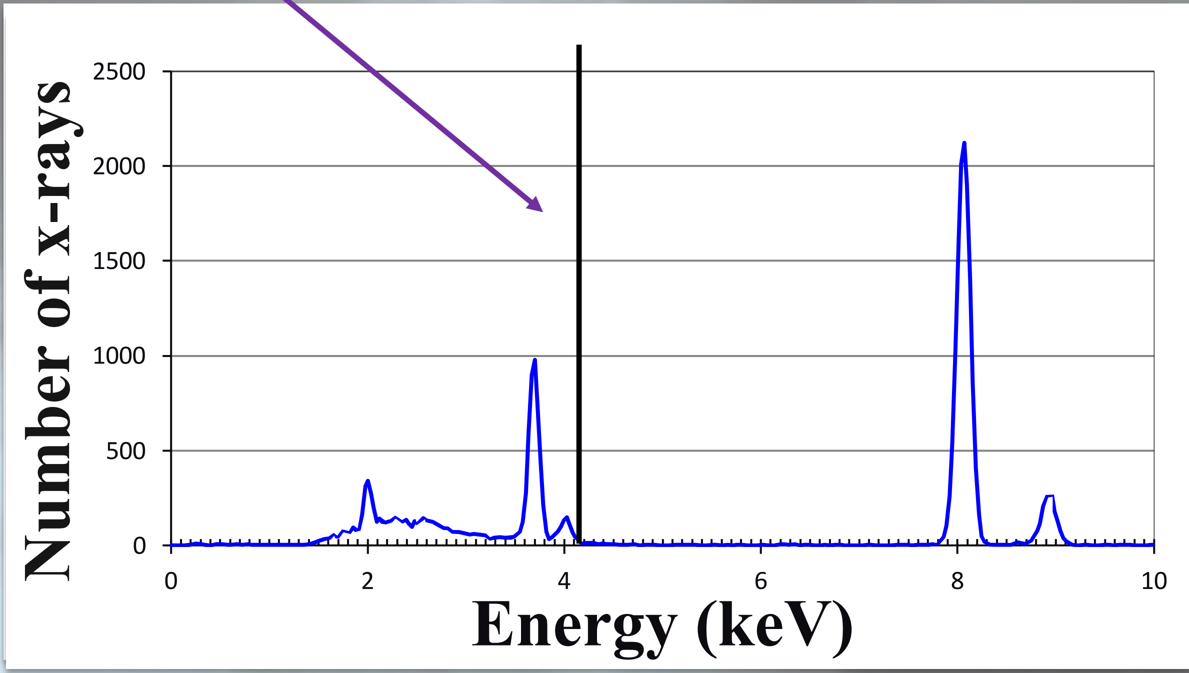
Problems and Solutions in Medical Physics, Diagnostic Imaging Physics, Ng, K., Wong, J, Clarke, G., CRC Press, 2018

A PIXE Spectrum for Cu on Mylar



https://www.semanticscholar.org/paper/Radiation-Physics%2C-Biology%2C-and-Protection.-Matthews/9e8162eb35c4d52ad8f6bce589e5bdc8146ce232/figure/4

- A “fictitious” x-ray tube anode made from copper with some impurities present.



This spectrum was generated using a 2.2MeV proton beam but the ideas are the same.

Diagnostic X-rays and CT Scans

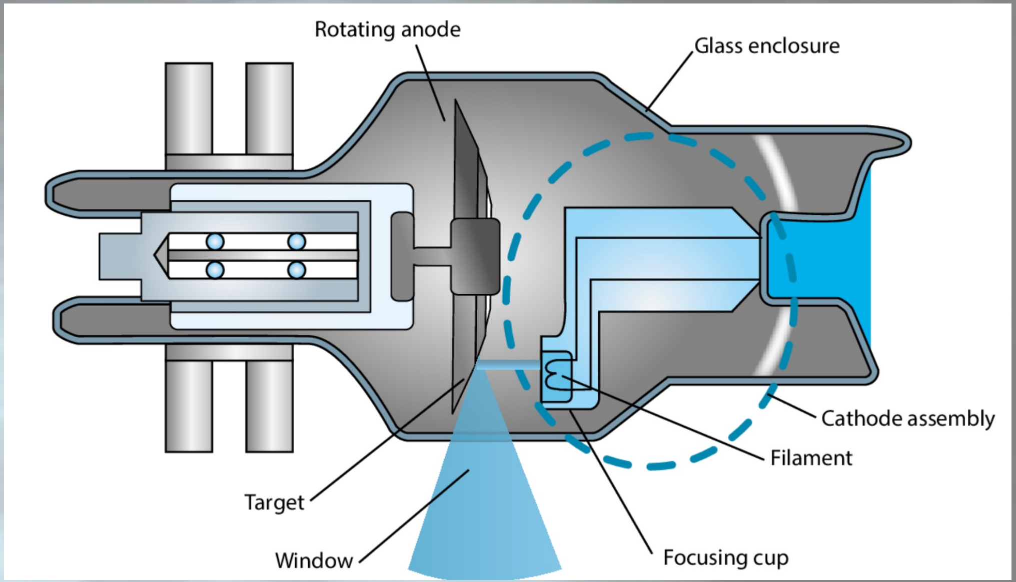
- *The Interactions of X-rays and Matter*

- In addition, it is seen that experimentally at lower x-ray tube voltage, most x-rays are emitted at angles of 90^0 about to the incident beam direction.

- This is why are anodes are usually angled toward the patient.

- The x-ray production efficiency is small for diagnostic x-rays at these smaller x-ray tube voltages. This is good because after filtering we will have a small dose to the body.

- At higher voltages we have more of the electrons forward scattered and this produces in general a higher efficiency along with higher x-ray energies. These higher energy beams we use for therapeutic treatments.



https://www.semanticscholar.org/paper/Radiation-Physics%2C-Biology%2C-and-Protection.-Matthews/9e8162eb35c4d52ad8f6bce589e5bdc8146ce232/figure/4

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- For diagnostic x-rays about 99% of the energy lost by the electrons with the medium (through collisions) result in heating of the anode. Only about 1% (or less) produce usable x-rays for diagnosis.

- Of the x-rays produced, we try to generally filter the beam to remove unwanted x-rays.

- Filtering is the removal of these low energy x-rays from the beam spectrum which would otherwise not contribute to image quality but would add to patient dose and scattering.

- Filtering decreases the total number of x-rays but since we are removing the lower energy x-rays, we tend to increase the average x-ray energy, and thus increase the intensity of the beam.

- The efficiency of x-ray production is defined as the ratio of the energy of the x-rays to the total energy deposited in the target from the electron from the filament.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- The efficiency of x-ray production:

$$\epsilon = \frac{E_r}{E_d} = \frac{x - ray\ energy}{energy\ deposited\ in\ the\ target}$$

- The rate at which energy is deposited in target is determined from the power.

$$P_d = \frac{E_d}{t} = IV$$

where I is the x-ray tube current and V is the x-ray tube voltage.

- The rate at which energy is released as x-rays in target is determined experimentally. We call this the emitted power, where Z is the atomic number of the anode material.

$$P_r = \frac{E_r}{t} = 0.9\times10^{-9}\frac{C}{J}\times ZIV^2$$

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- Taking the ratio of these two powers, we get the efficiency:

$$\epsilon = \frac{P_r}{P_d} = \left(0.9\times10^{-9}\frac{C}{J}\right) ZV$$

- Notice that
  1. The efficiency increases with Z and V. Thus, in higher Z materials there is more energy per x-ray and
  2. a greater number of x-rays are produced in general

- This is why our anode material is usually high Z, something like W (Z= 74).

Example: Suppose that an x-ray tube is operated at a voltage of $V = 100kV$ and that the tube draws a current of $I = 400mA$. What are P_d, P_r, and the efficiency of the x-ray production?

- Note that the x-ray tube potential is related to the maximum energy of x-ray production. If the x-ray tube potential is large enough, we will produce x-rays characteristic of the anode material.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- X-rays can interact with matter in many ways.
- The "ways" depend on the energy of the beam and whether we're trying to image (diagnostic) or treat (therapeutic). The diagnostic ways the beam interacts with matter are:

Photoelectric Effect *Compton Effect* *Coherent Scattering*

- These three effects are primarily responsible for the absorption and scattering of x-rays and thus the ultimate quality of the radiograph.
- The incoming *x-ray photon* interacts with inner shell electrons of usually light elements, say C, H, O or N that makes up soft tissues.
- The inner shell electron can absorb *some or all* of the incident photon's energy (leading to attenuation of the primary beam) and the ejection of an electron. Implications?
- Any excess energy (outside what it takes to unbind the electron) shows up as KE in the electron.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- The photoelectron is free to travel throughout the body, but in general it only travels a small distance before its energy is reabsorbed.
- The vacancy that was created by the production of a photoelectron is quickly filled by a higher orbital electron with an emission of an x-ray characteristic of the element that produced the photoelectron (along with a cascading set of photons of lower energy).
- This x-ray photon (and the rest of the photons) can be produced in any random direction and are responsible for scattering in the x-ray beam and are another source of ionizing radiation in the body.
- The probability that an x-ray photon will be absorbed or transmitted depends on the elements in the absorbing material.

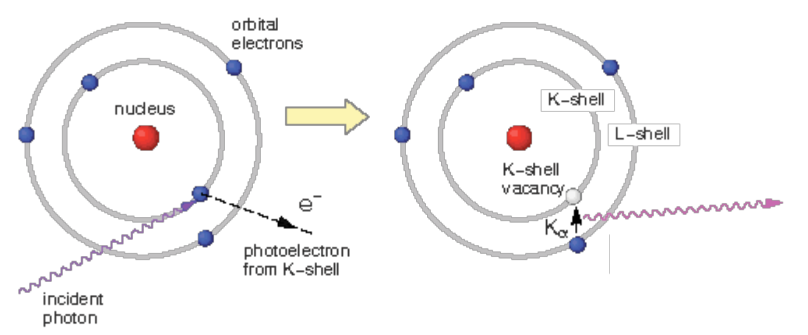
Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- Through the photoelectric effect transfers energy to an inner shell (usually) electron.
- This electron gets ejected through the interaction and the excess energy of the electron shows up as kinetic energy.

$$K_e = E_{photon} - \phi$$

- The vacancies created are filled through a cascading process and we get characteristic photon emission with can be absorbed by tissues near the ejection site.
- Experimentally low-energy x-rays are scattered near 90^0 to the incident beam.
- As the energy of the x-rays increases the photons produced (and electrons ejected) are more likely in the forward direction.



http://www.thermo.com/eThermo/CMA/Images/Various/151Image_15772.gif

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- The photoelectric effect also increases with decreasing photon energy, a consequence of the uncertainty principle.
- This interaction produces, again, a photon with most likely lower energy and this is in a random direction.
- This lowers the intensity of, or attenuates the incident beam, and produces ions in the body.
- Most interactions of photons and bones and the ultimately the image receptor (say film) are photoelectric in nature (because they are dense and higher Z materials).
- Photoelectric events are usually viewed as an elastic collision.
- These produce the shadows in the x-ray film due to photons created as scattered events in the film or detector.
- High Z materials make for good shielding devices as the transmission of the primary photon beam is decreased.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- The probability of photoelectric interactions depends on of the absorbing material.
- Low-energy photons have absorption probabilities that are proportional to Z^3.
- This of course means that the higher the Z of the material the more likely the photons are photoelectrically absorbed.
  - Bone (high Z) absorbs many of these photons while soft tissue (low Z) does not.
  - High Z materials like lead ($Z = 82$) make for good shielding materials
  - High materials like iodine ($Z = 53$) and barium ($Z = 56$) make for good contrast media in things like vascular structures.
- Photoelectric interactions rarely occur at high photon energies (a consequence of the uncertainty principle).
- The photoelectric interactions by different material produces contrast in the x-ray images and is responsible for the images in diagnostic radiology.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- The other photon-electron interaction is the due to the Compton effect.

- In the Compton effect, which can be viewed as an inelastic collision, the incident photon (usually with an energy between $30kV$ and $30MV$) gives some of its energy to the electron in the atom with which it collides, but the photon is scattered.

- The photon interacts with "loosely" bound electrons in the materials and the excess energy (minus the binding energy) shows up a kinetic energy in the recoiling electron.

- The scattered photon has less energy (it transferred momentum to the electron) and this produces longer wavelength radiation in a perhaps different direction than the incident beam.

- Here the interaction time is very short (due to the uncertainty principle) and Compton scattering also attenuates the x-ray beam.

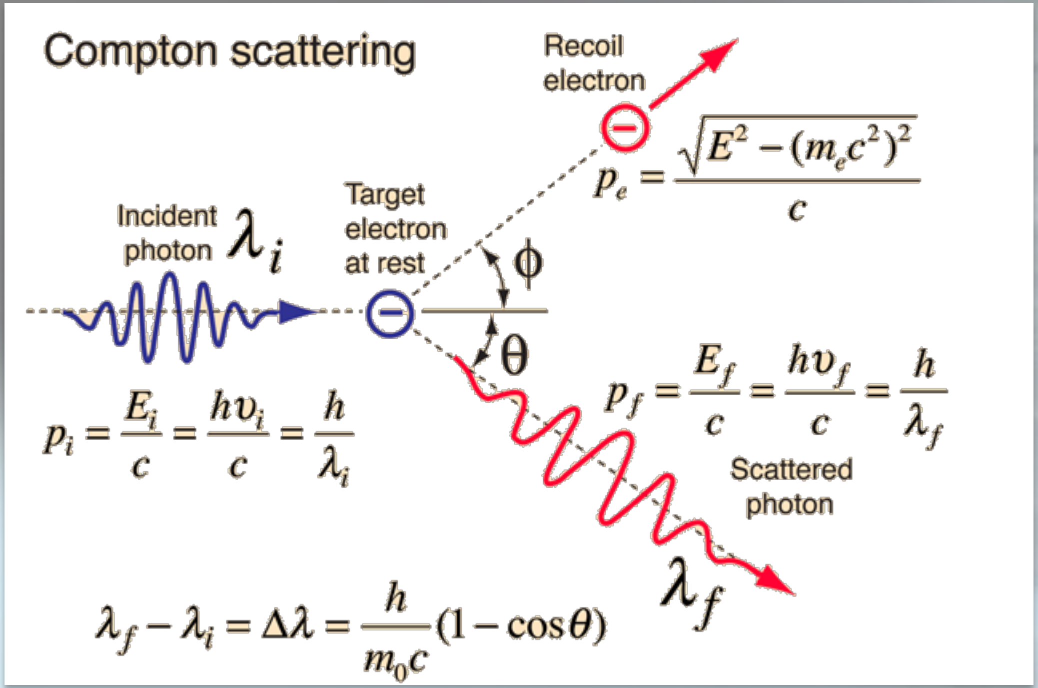
- Most interactions between x-rays and soft tissues are Compton scattering events.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- As the photon energy increases the post-collision photon and recoiling electron are more likely to forward scatter. This produces shadows and “fog” in the detector from the scattered photon.

- Experimentally the electron gets a larger share of the photon energy if the energy of the photon is large and and a smaller share if the photon energy is small.



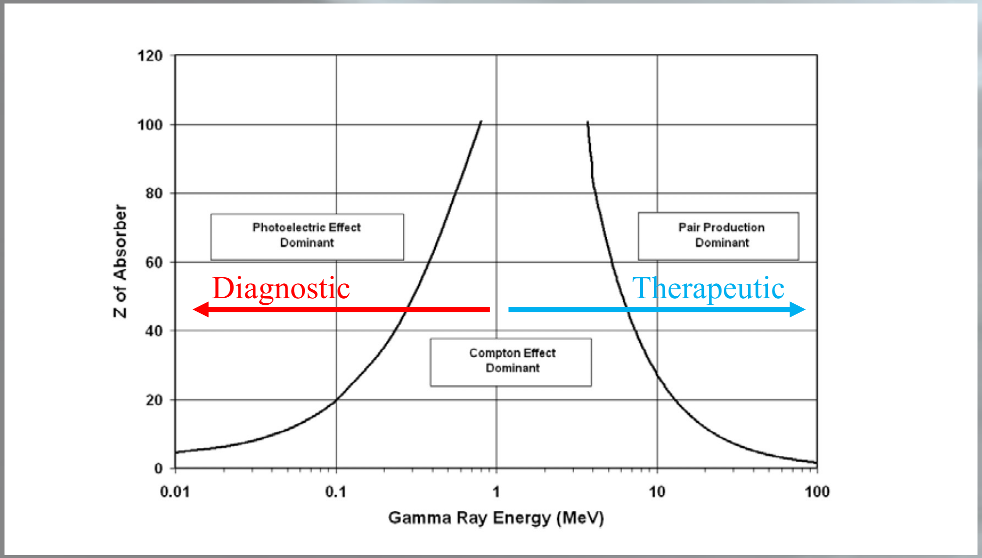
http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compeq.html

- Compton scattering events are generally independent of Z.

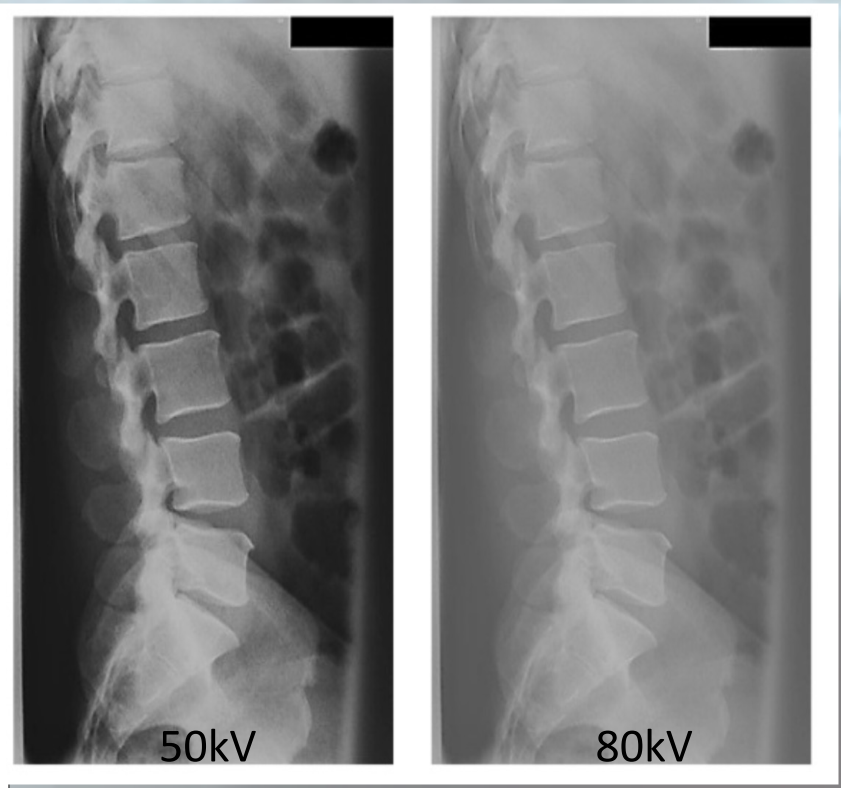
- But since the photon interacts with “loosely” bound electrons the occurrence probability decreases experimentally with increasing photon energy.

Diagnostic X-rays and CT Scans

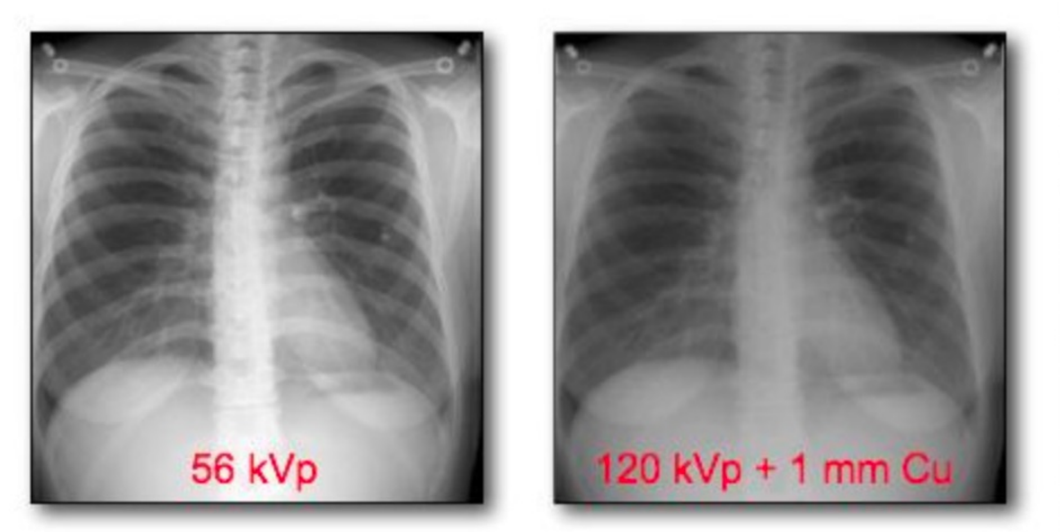
- *The Interactions of X-rays and Matter*



https://www.google.com/url?sa=i&url=http%3A%2F%2Fwww.phys.utk.edu%2Flabs%2Fmodphys%2FCompton%2520Scattering%2520Experiment.pdf&psig=AOvVaw2YdpdoKiGQgBWz8y8Aq0My&ust=1619642821261000&source=images&cd=vfe&ved=0CA0QjhxqFwoTCPib5feln_ACFQAAAAAdAAAAABAx



https://www.slideshare.net/sehlawi/rad-206-p11-fundamentals-of-imaging-control-of-scatter-radiation



http://199.116.233.101/index.php/Dual_Energy_X-Ray

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

The central theme of radiology

X ray photons are removed from a beam and the energy is given to a medium by a two-stage process:

1. The photon first ionizes the medium's atoms or molecules by either the Compton or photoelectric effects by a collision with an orbital electron and therefore the photon is removed from the beam. This produces anatomic shadow patterns in the beam and is related to what will be what is imaged.

2. The result produces a high velocity photoelectron or Compton scattered electron which ionizes hundreds or thousands of other atoms or molecules and this produces a medium response, which is usually tissue damage. This is the origin of radiation dose in the body.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- There are functionally three categories of materials with which the x-rays interact.

  1. The soft tissues and bones in the body.
  2. The materials involved in detecting the radiation that passes through the body.
  3. The shielding.

- These arise out of the interactions of the x-rays with the material in which they are propagating.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- *Photon Removal from the Beam*

- Photon-electron interactions (photoelectric or Compton effects) remove photons from the incident beam.
- The number of photons removed depends on the material in which the photon is incident.
- Removing photons from the beam produces the radiographic shadows in the detector material.
- Compton scattered photons are usually useless for imaging since they won't necessarily strike your detector.
- The Compton scattered photons will either get absorbed and deposit energy in the body (which can produce chemical or cellular changes) or simply become background fog on your detector.
- The absorption of photons by the photoelectric effect help to provide effective shielding for sources such as by using lead. (In high Z materials the photoelectric effect dominates.)

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- Energy deposition in the material

- Energy deposition in the body does not help the image formation process.

- Could be bad for the body leading to cellular or chemical changes.
  - How much is too much? → Dose

- For the detector material, it is the subsequent ionization in the material that is used to form the image.

- The x-rays that make it to the detecting material interact with the detecting material and these interactions are what's used to make an image.

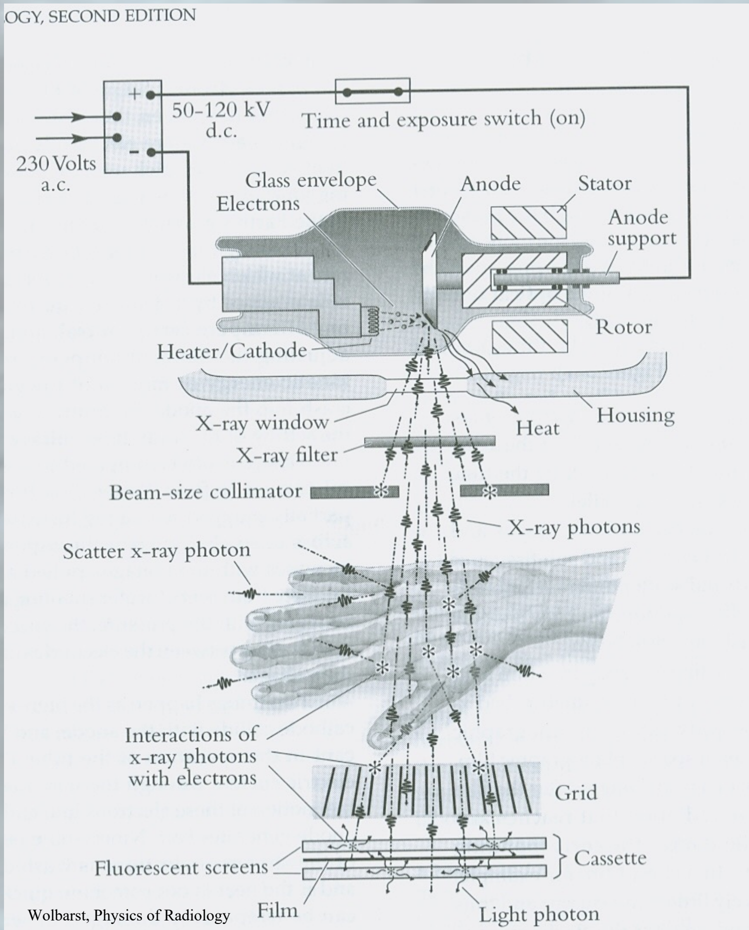
- For example, in a film the x-rays stimulate and excite a chemical emulsion to expose the film. In a silicon crystal detector, the x-ray creates electron-hole pairs and placing an electric field across the silicon crystal causes the electron-hole pairs to drift and this current is recorded as a measure of the x-ray energy.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

The production of a radiograph

- The x-ray tube generates the x-rays, and the x-rays are produced and spread out through space.
- A collimator is placed in the beam's path and most x-rays get absorbed in the collimator.
- A fraction get through, and a narrow beam strikes the patient.
- These x-rays are mostly absorbed by the body but about 1% make it out and are used to expose a film or to create electrical signals in a detector for image formation.



Wolbarst, Physics of Radiology

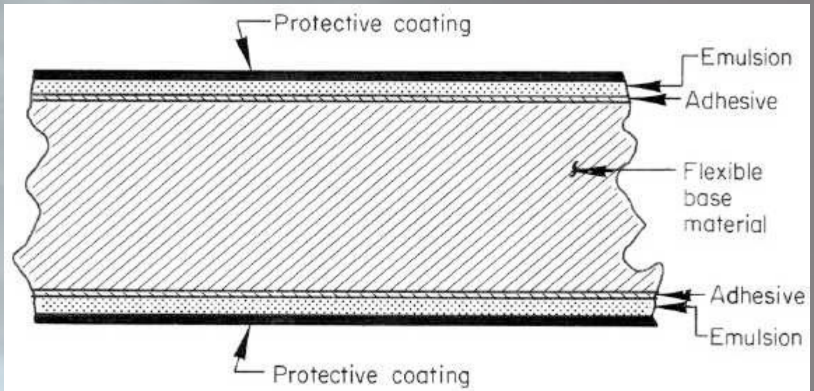
Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- *X-ray Detectors*

Radiological film:

- The emulsion consists of a gelatin material containing an even distribution of the radiation-sensitive silver bromide crystals or grains.
- The double emulsions essentially reduce exposure requirements to one-half that required for a single emulsion, but most radiography films have emulsion only on one side.
- The interaction of the x-rays with the emulsion material (a cubic lattice of Ag^+ and Br^- ions) sensitizes (excites) the grains and during the development process this turns the grains black.
- The grains not sensitized are removed during the development process.



http://www.tpub.com/content/chemical-biological/TM-1-1500-335-23/css/TM-1-1500-335-23_528.htm

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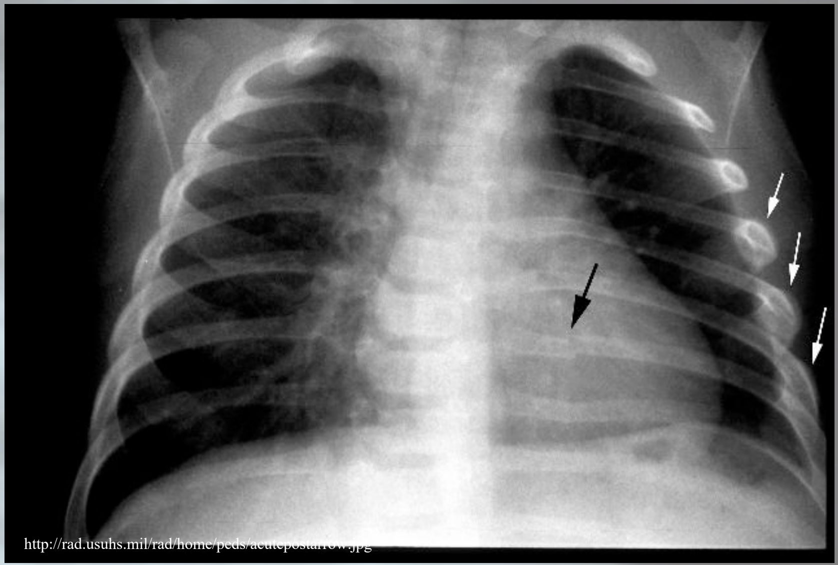
- The net result for film are regions of black (complete sensitization) and regions of various shades of grey.
- The degree of sensitization depends on the energy of the incident x-ray.
- To determine the energy of the ray on the film or detector we need to look at how materials absorb the x-rays.
- Posterior rib fracture of the left 7th rib as well as lateral fractures of the 4th – 6th ribs



Typically, this is part of violent shaking. The infant or young child is held very tightly around the chest and squeezed while being shaken. This compresses the ribs front to back and tends to break them next to their attachment to vertebrae and laterally where they are being literally almost folded in half. Therefore, lateral & posterior rib fractures are highly specific for abuse.

The Child Abuse Referral and Education (CARE) Network of the Uniformed Services University of the Health Sciences

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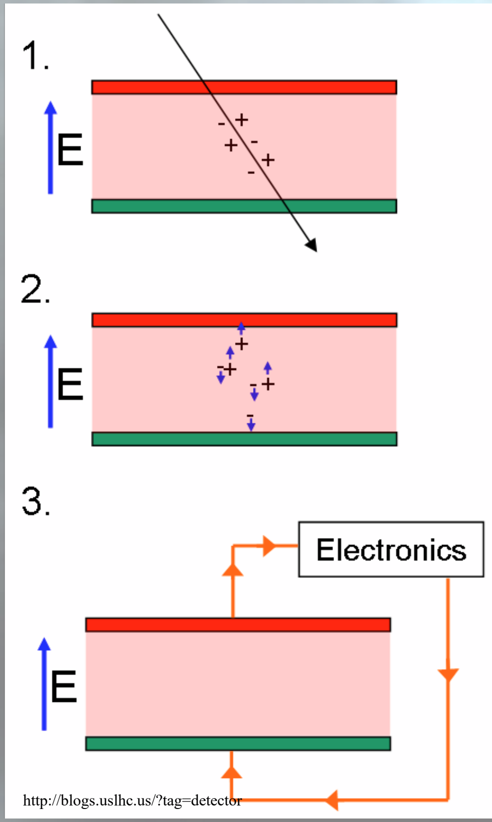
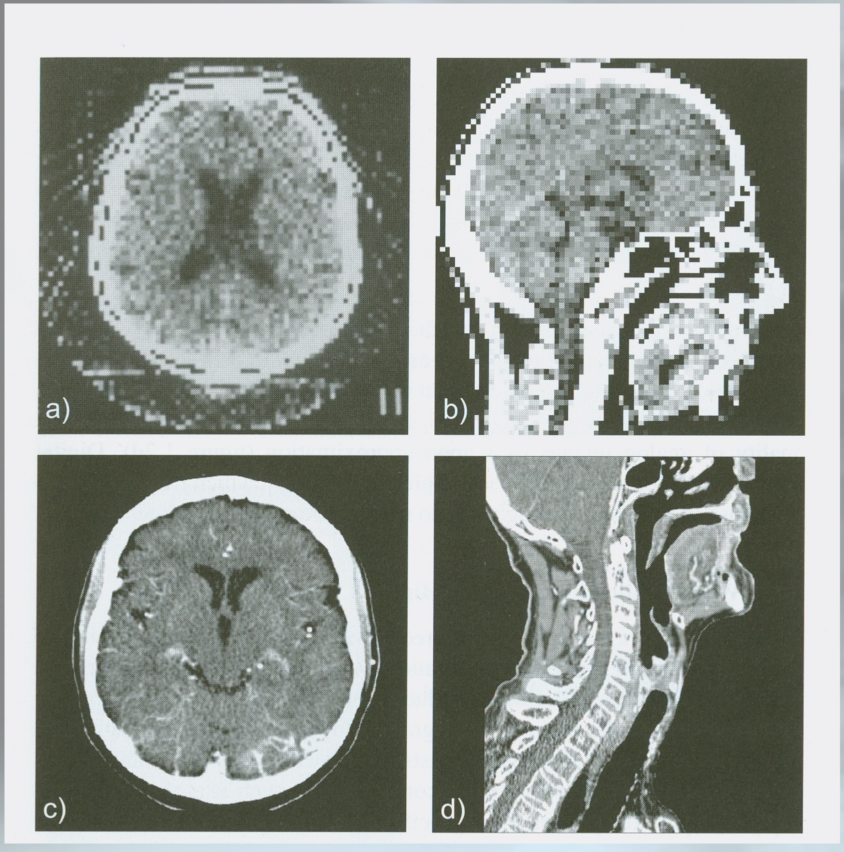
- *X-ray Detectors*

- A typical Si(Li) X-ray detector
- An array of these form the basis for a CT scan.
- These are lithium drifted silicon detectors – semiconductor devices.
- The incident x-ray produces equal and opposite charge carriers that are separated by the application of an electric field.
- The subsequent current pulses measured (from each and almost every incident photon (dead time)) are produced on a screen as a function of the intensity at a spot on the detector.
- The more time the detector is busy the lower the image quality.
- The lower the resolution of your detector the lower the image quality – the detector can't tell two x-rays apart in energy.



Diagnostic X-rays and CT Scans

- *Number of Detectors*



- Images *a* and *b* show a small number of x-ray detectors. The image quality is rather poor due to the small number of detectors.

- Images *c* and *d* show a larger number of x-ray detectors. The image quality is much better due to increase in number of detectors.

Number of Pixels

- In images *a* and *b* we have an 80 x 80 images matrix, and you can easily see the discrete pixels.

- In images *c* and *d* we have a 1024 x 1024 image matrix. Here the individual pixels are not seen, and the image quality increases.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- *X-ray attenuation*

- X-ray attenuation in matter depends on the thickness of the material, the density of the material, the effective atomic number and the beam energy.

- Experimentally these effects are tested by placing different attenuating material in front of an x-ray beam and seeing how much of the incident intensity passes through the material.

- It is found that the intensity of the transmitted x-ray beam decreases with increasing thickness as a decaying exponential function.

$$I = I_o e^{-\mu x}$$

- μ is defined as the linear attenuation coefficient.

- μ is a function of density, effective atomic number and the beam energy and x is the distance traversed by the photons.

- μ is independent of the distance traveled by the x-rays.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- *X-ray attenuation*

- A perhaps more meaningful quantity is the *half-value layer* or *HVL*.
- The *HVL* is the thickness over which the x-rays travel to lose ½ of the incident beam intensity.

$$\mu x_{1/2} = 0.693$$

- These arguments assume a monochromatic x-ray beam passing through a homogenous medium.
- The body is neither a homogenous medium nor is the diagnostic x-ray beam exactly monochromatic (we'll filter it), but we'll make it work.
- An example: The *HVL* for a monochromatic x-ray beam in a material is 3cm. What fraction of the beam's original intensity remains after passage through 9cm of material?

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

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- For many different layers of materials, we can generalize the intensity function to include these layers.

- For layers of thickness, x_1, x_2, ... and attenuation coefficients μ_1, μ_2, ... in each of these layers, we have for the intensity transmitted through all the layers

$$I = I_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \cdots)}$$

- This of course means that the attenuated intensity is the beam intensity minus the intensity transmitted.

- The intensity absorbed by the body will eventually need to be worried about.

- These absorbed intensities are related to the dose your body gets.

Diagnostic X-rays and CT Scans

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- Another example: Suppose that $60keV$ x-rays are needed to pass through two layers of material, one of which is $3cm$ of soft tissue ($\mu_{m,ST} = 0.2045\frac{cm^2}{g}$ with density $\rho_{ST} = 1\frac{g}{cm^3}$) and the second is $1cm$ of bone ($\mu_{m,B} = 0.2824\frac{cm^2}{g}$ and density $\rho_B = 1.65\frac{g}{cm^3}$). What is the transmitted intensity if the incident intensity as a fraction of the incident intensity of the beam?

- μ_m is called the mass absorption coefficient.

- This considers the density of the material and the atomic number dependence of the linear absorption coefficient.

Diagnostic X-rays and CT Scans

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- *X-ray attenuation*

- The linear absorption coefficients can be though of as being composed of several mechanisms that attenuate the x-ray beam.

- These are the ways in which the x-rays interact with matter. They are:

  - *Diagnostic:* $\mu = \tau + \sigma + \omega + \kappa \sim \tau + \sigma + \omega$

    Photoelectric Effect (τ)
    Compton Effect (σ)
    Coherent Scattering (ω) – can produce photons in random directions
    Pair Production (κ) - energy of the beams below the rest energy of e^- and e^+

  - *Therapeutic:* $\mu = \tau + \sigma + \omega + \kappa \sim \tau + \sigma + \kappa$

    Photoelectric Effect (τ)
    Compton Effect (σ)
    Coherent Scattering (ω). – most are forward scattered (CS) so no random directions.
    Pair Production (κ) – energy of therapeutic beams higher than the rest energy of e^- and e^+.

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- *X-ray attenuation*

Implications:

- I know all the absorption coefficients and the sizes of the structures the x-ray beam passed through. (I don't)
- What intensity comes out corresponds to a shade of grey.
- The "shade" of grey is all the 3D information displayed as a single value on the film.
- I've lost the 3D nature of you and the image is 2D with no depth.

$$I = I_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \cdots)}$$

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

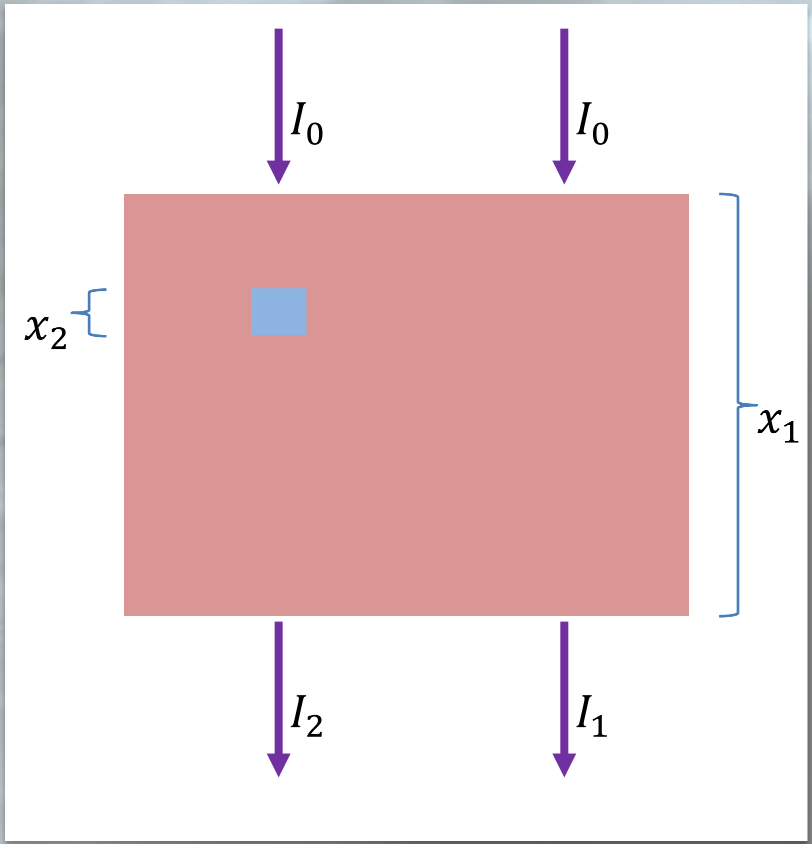
- *Contrast*

- Contrast agents are used to enhance structures and to make them distinct from their surroundings.

- One contrast agent is Iodine used in vascular structures. Iodine is a heavy Z material and will photoelectrically absorb the incident x-rays.

- We define the contrast as the percent difference in intensity between two paths in the body.

$$C = \frac{I_1 - I_2}{I_1} = 1 - e^{-(\mu_2 - \mu_1)x_2}$$



Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- *Contrast*

- What is the contrast between normal fatty tissue ($\mu_{fat} = 0.5cm^{-1}$) and say a $1mm$ micro-calcification imbedded in the tissue for x-rays with an energy of $20keV$. We can model the calcification as bone with $\mu_{bone} = 4.8cm^{-1}$.

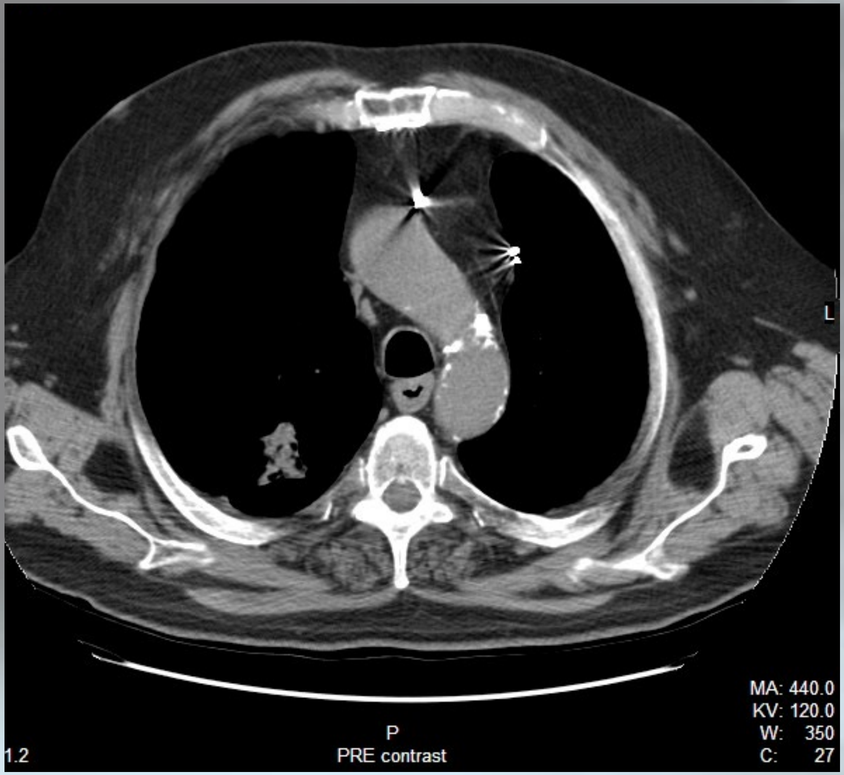
- Compare this with the contrast of a lump or a cyst imbedded in the fatty tissue of the same size. Take the lump or cyst to be modeled as water with $\mu_{water} = 0.76cm^{-1}$.

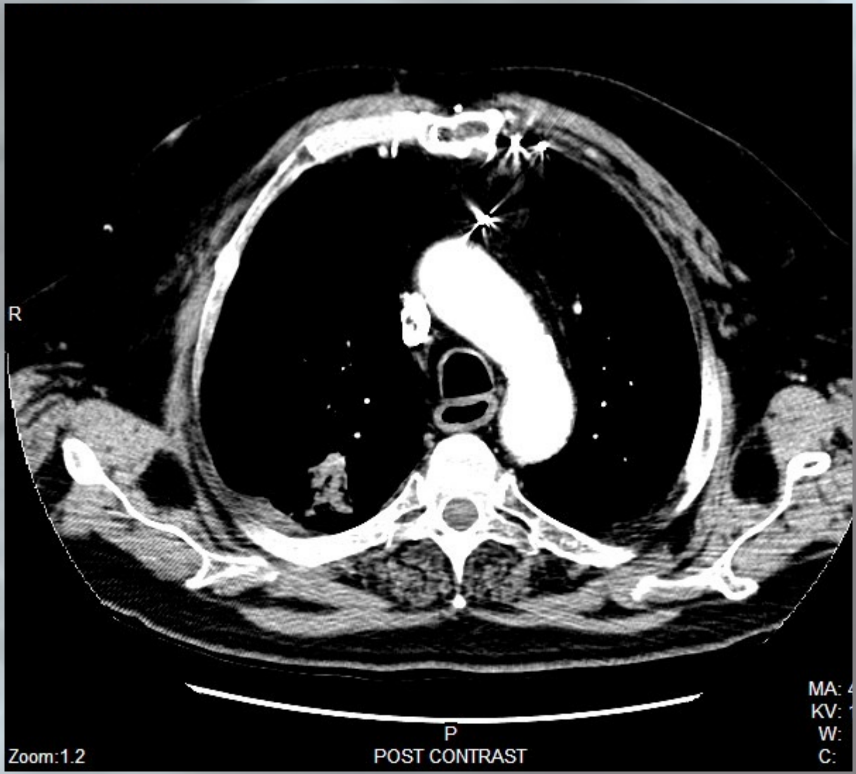
- Imagine injecting the lump or cyst with iodine $\mu_I = 125.5cm^{-1}$. What is the contrast now?

Diagnostic X-rays and CT Scans

- *The Interactions of X-rays and Matter*

- *Contrast*





The above two images are courtesy of Dr. William Moore, MD