X-ray Imaging

BME/EECS 516

X-ray Lecture #1

Announcements

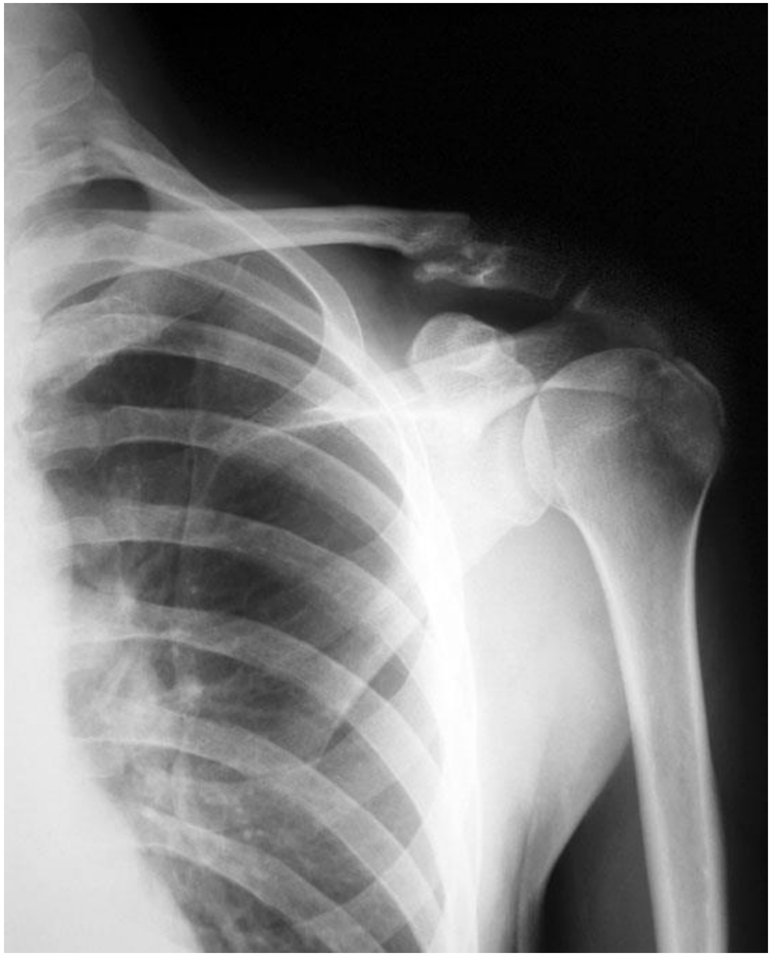
- HW #5 due Tuesday, 11/7
- MRI Project due Tuesday 11/21

- Tuesday, 11/14 – guest lectures from local medical imaging industry
  - David Sarment from Xoran Technologies
  - John Seamans (UM) formerly with Delphinus Medical and GE Healthcare

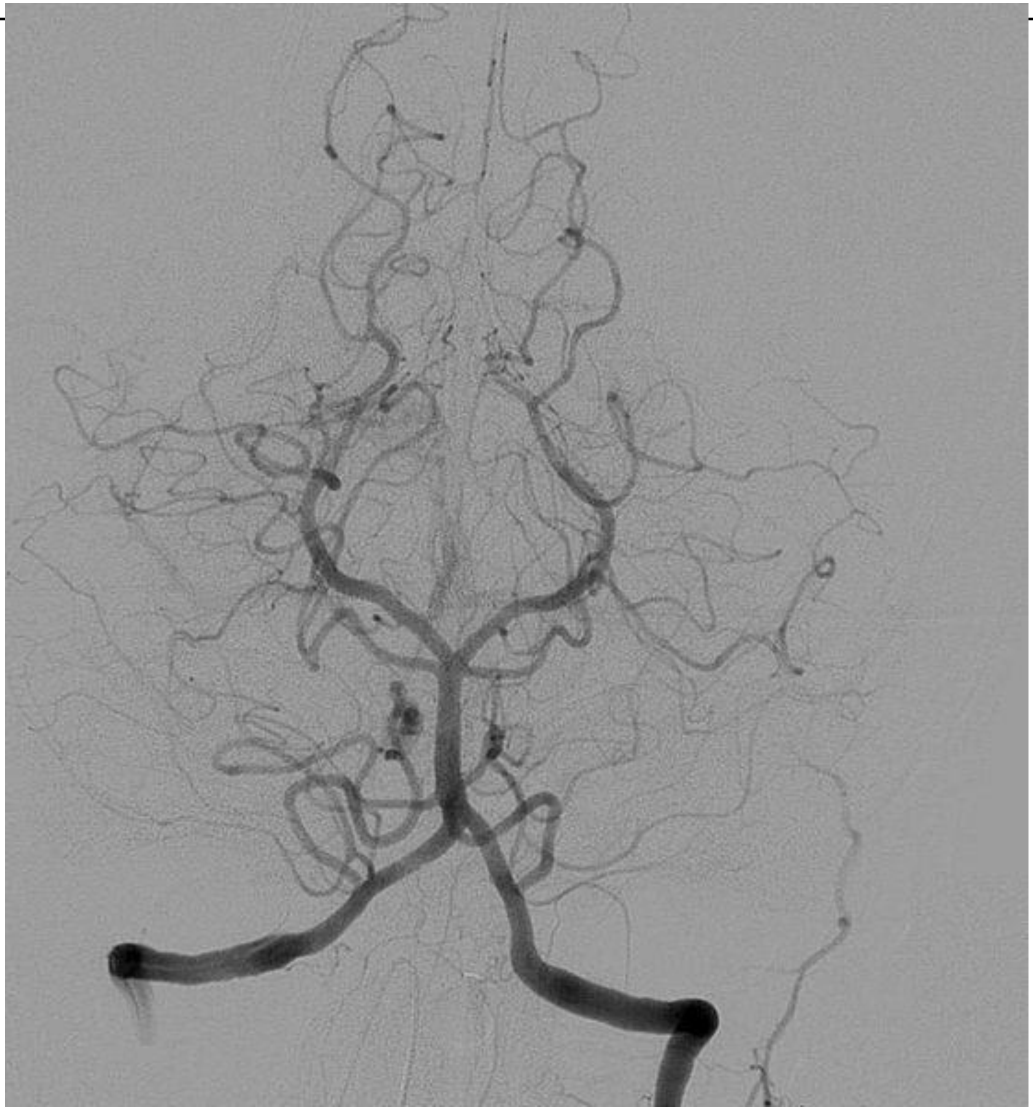
X-ray Imaging

- X-ray images are characterized by the interaction of x-ray photons and tissue.
- Applications for diagnostic imaging
  - Detection of pathology of the skeletal system (chest x-ray or dental x-ray)
  - Lung diseases (lung cancer, pulmonary edema)
  - Kidney stones,
  - Basis for CT, fluoroscopy (with contrast agent for vessel and brain imaging, e.g., angiography)

X-ray Images



Angiography



This Lecture

- Physics – Radiation
- Basic X-ray Imaging System
- Generation of x-rays
- Attenuation Coefficient
- Beam Hardening

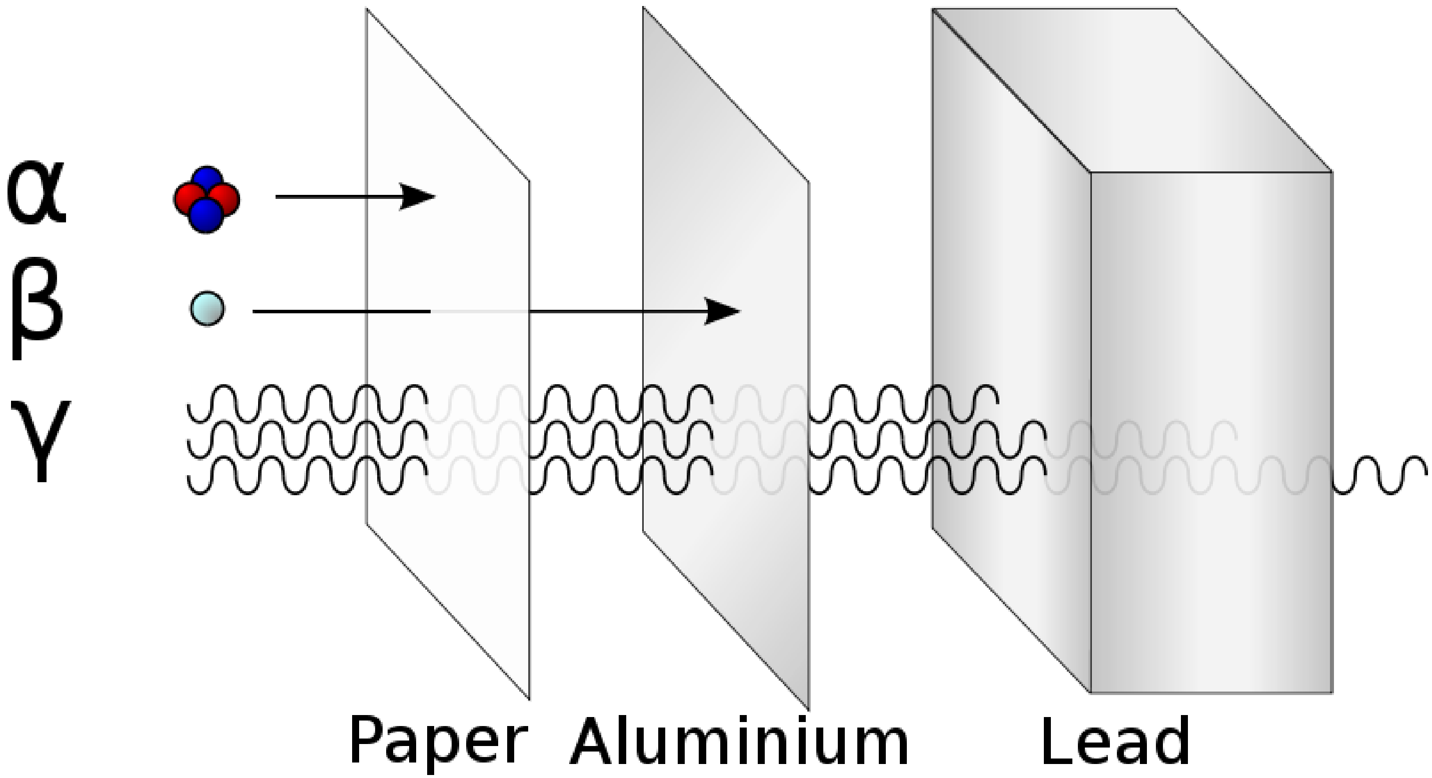
Physics

Radiation

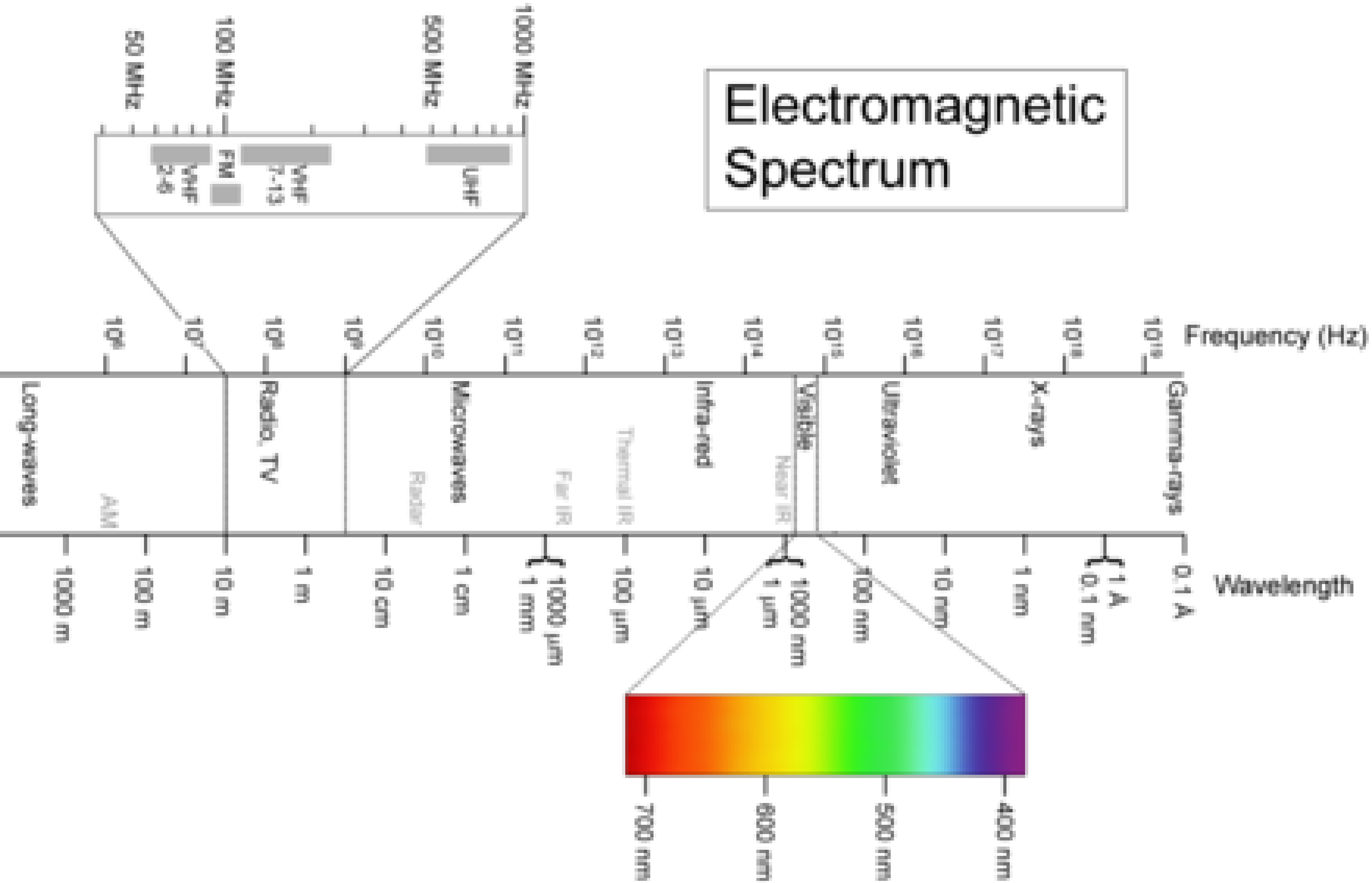
Radiation

- Definition: a process in which energetic streams of particles or photons travel through a medium or space.
- Particles: α (^{2+}He), e^- (electrons), β (electrons emitted from nuclei), β^+ (positrons), p^+ (proton), n^0 (neutrons)
- Photons: x-ray, γ-ray, annihilation photons, etc.

Particle and Photons



Electromagnetic Spectrum



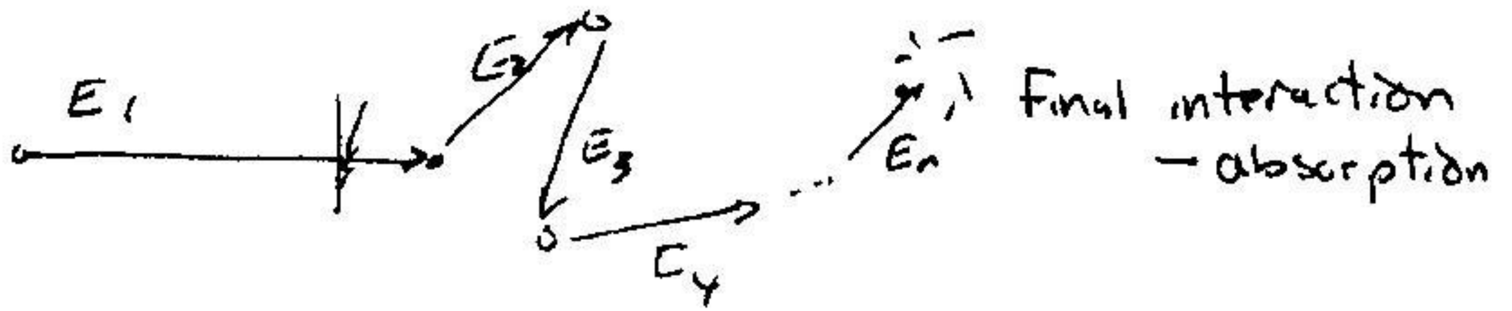
X-ray

- Wavelength: 0.01 - 10 nm
- Frequency: 3×10^{16} - 3×10^{19} Hz
- Energy: 120 eV - 120 keV (1eV = 1.602×10^{-19} J)
  - eV –the amount of kinetic energy gained by a single unbound electron when
    it accelerates through an electric potential difference of one volt.
- X-rays and γ-rays are distinguished by their origin
  - X-rays -emitted by electrons outside the nucleus
  - Gamma rays - emitted by the nucleus.

Models for interaction of radiation and matter

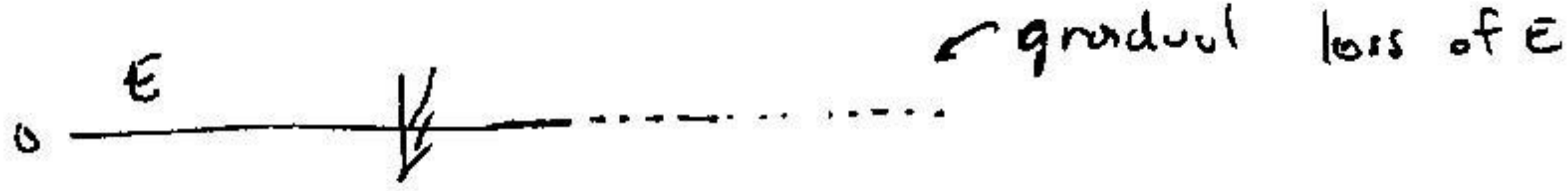
- Absorption (generally low kinetic energy (KE))

- Scattering



Models for interaction of radiation and matter

- Not a typical interaction – a gradual loss of energy



Models for interaction of radiation and matter

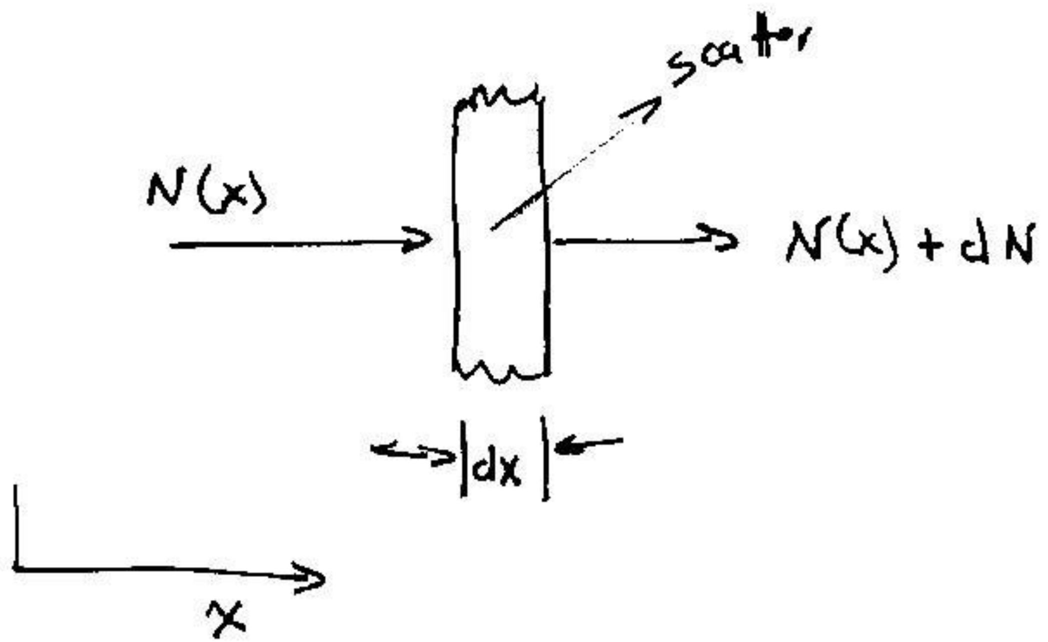
- The charged particles (α, e^-, β, β^+, p^+) interact very strongly with tissue and typically do not pass completely through the human body - cannot be used for imaging.
- Photons (including x-ray) and neutrons(n^0) pass through the body with an appropriate amount of interaction for imaging (too little interaction is also bad).

Behavior of Radiation Along a Line: Assumptions

- Matter in the pathway consists of discrete particles separated by distances that are large compared to the size of the particles.
- For a given path length along a line, an x-ray photon either interacts (with prob. p) or it doesn't.
- All interactions are independent.

Behavior of Radiation Along a Line: Assumptions

- Scattered photons scatter at a different angle and don’t contribute to the continuing flux of photons along the line.



Behavior of Radiation Along a Line: Assumptions

- The change in the number of photons is:

$$dN \propto -N(x)dx$$

$$dN = -\mu N(x)dx$$

$$\frac{dN}{dx} = -\mu N(x)$$

$$N(x) = N(0)\exp\left(-\int_0^x \mu(x')dx'\right)$$

- μ is the "linear attenuation coefficient" and has units (distance)$^{-1}$. For a constant μ :

$$N(x) = N(0)\exp(-\mu x)$$

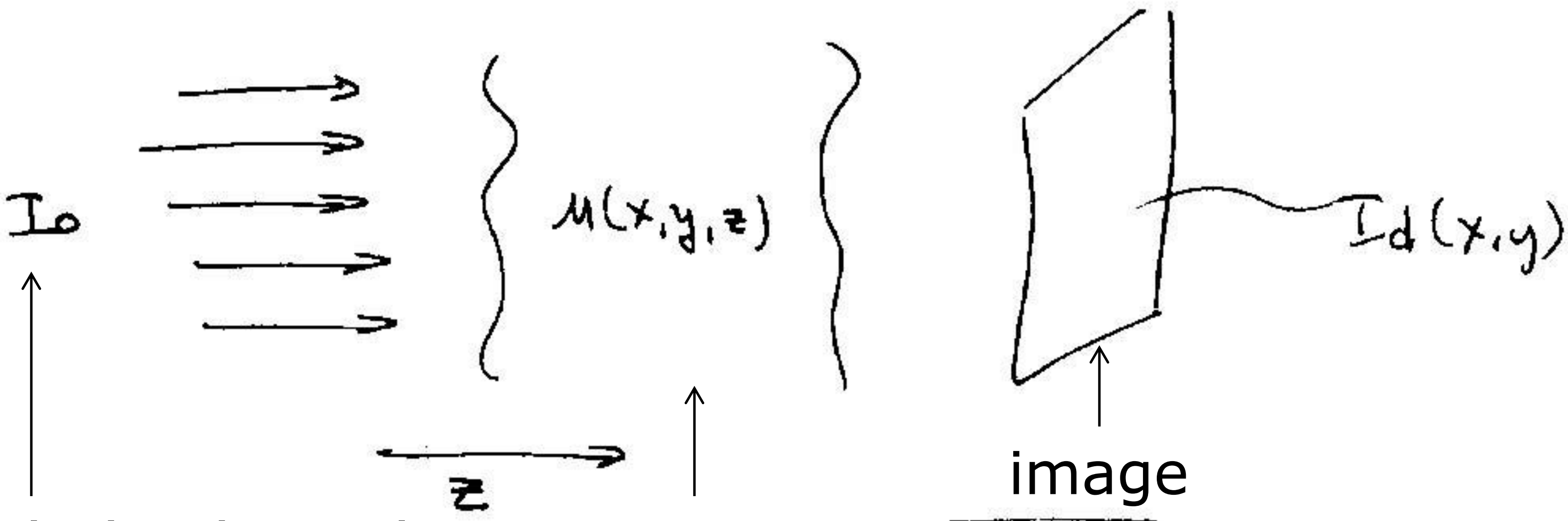
Questions?

Physics - Radiation

The Basic X-ray Imaging System

Basic X-ray Imaging System

- Consider a parallel x-ray flux



Emission intensity (photons/unit area/unit time)

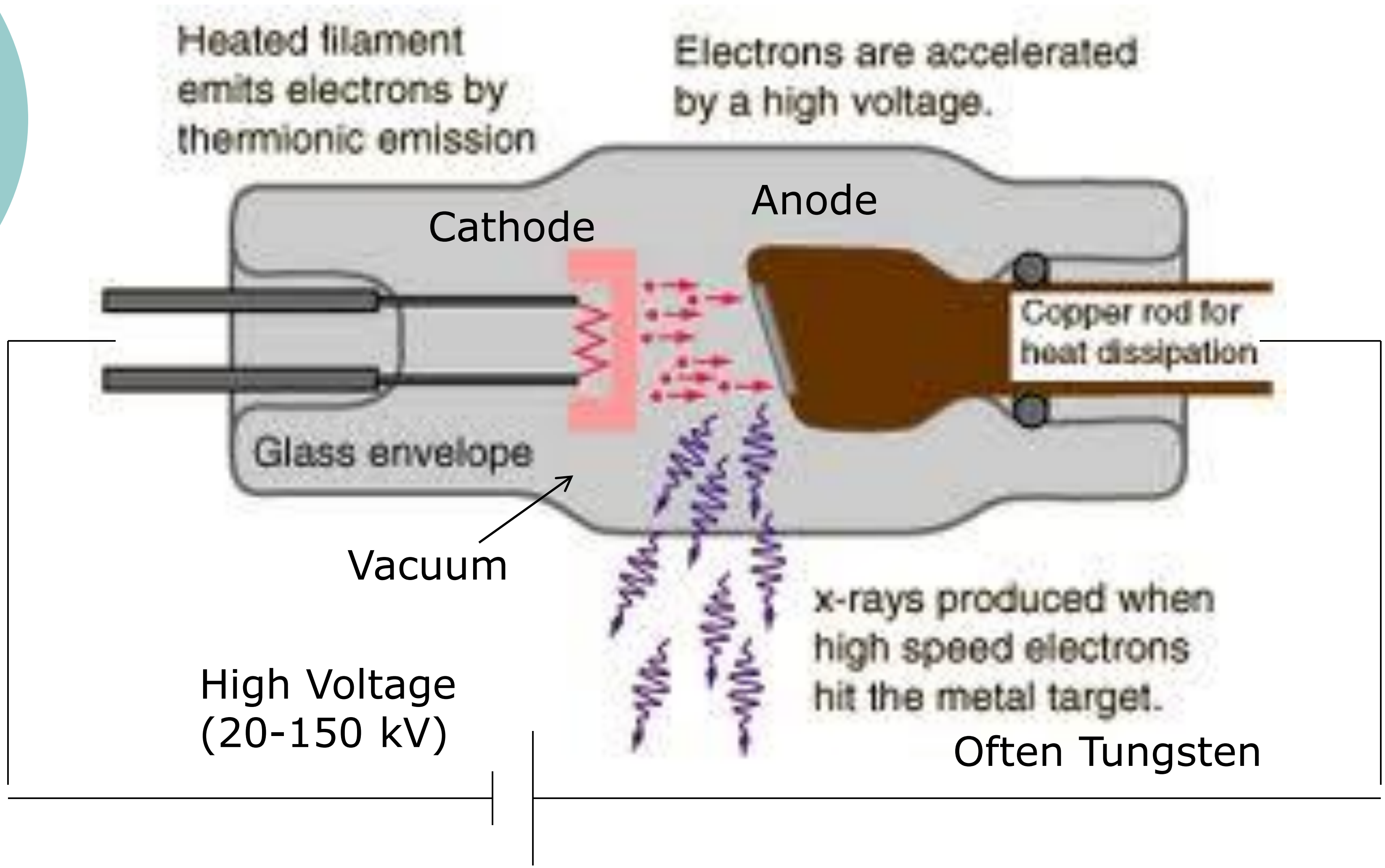
3D object

$$I_d(x, y) = I_0 \exp\left(-\int \mu(x, y, z)dz\right)$$

Basic X-ray Imaging System

- Source - Generation of x-ray
- Detector

X-ray Tube



http://hyperphysics.phy-

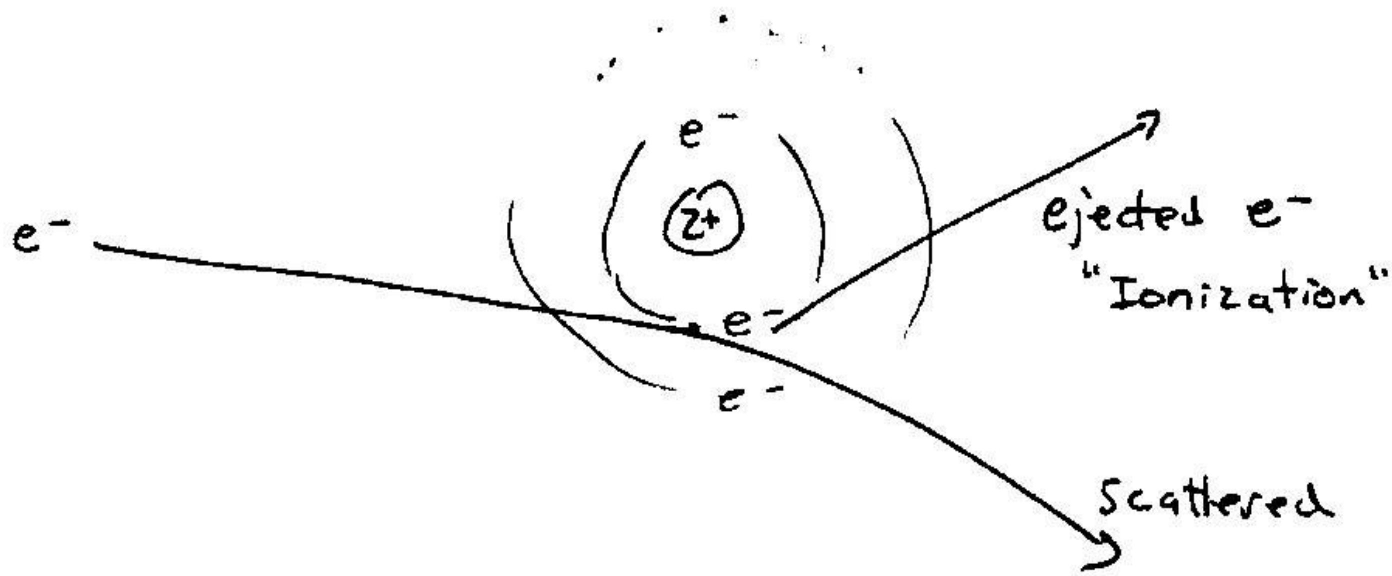
X-ray Tube

http://newsroom.varian.com

Generation of x-rays: electron interactions

1. Inelastic (energy absorbing) scattering with atomic electrons
    - An electron with enough energy can eject an orbital electron out of the inner shell of a metal atom.
    - Electrons from higher energy level fill up the vacancy
    - X-ray photon are emitted from **spontaneous energy state transitions**.

Generation of x-rays: electron interactions

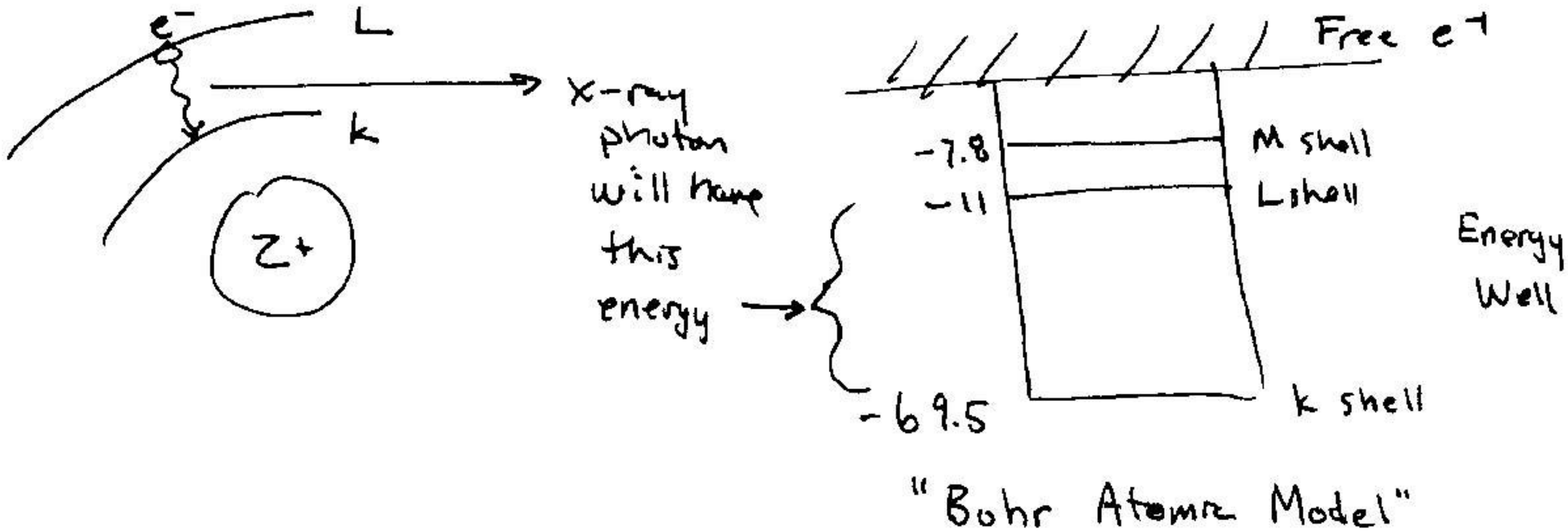


Generation of x-rays: electron interactions

- The process produce discrete emission spectrum –spectral lines. "Characteristic" x-ray energies for W
  - 58.5 keV
  - Any combination of shell transition energies (e.g. 3.2 and 61.7 keV).

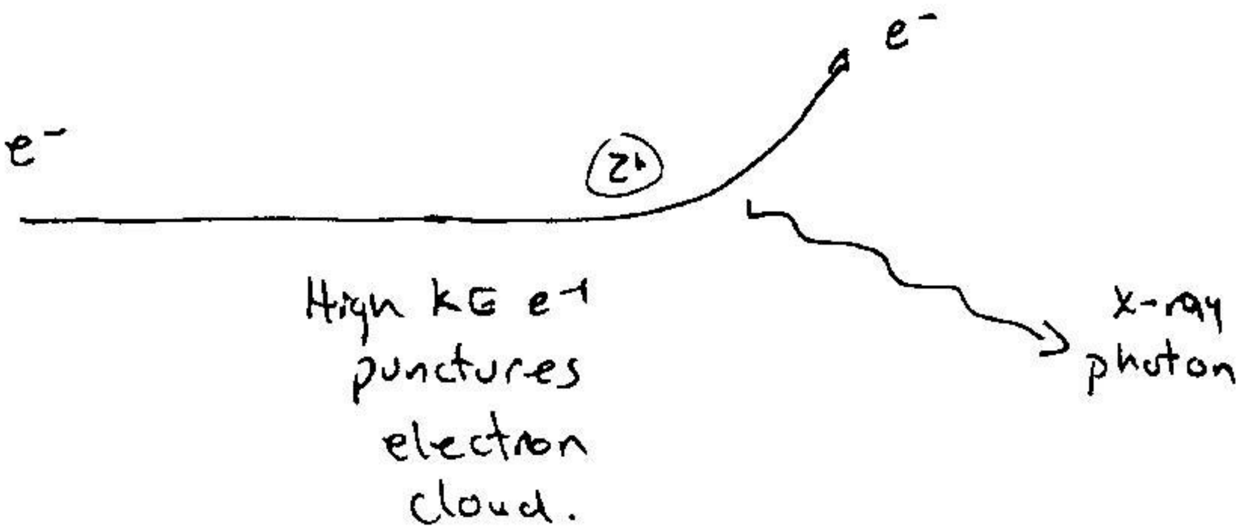
- Bohr model accounts for absorption/generation of discrete valued energies.

Generation of x-rays: electron interactions



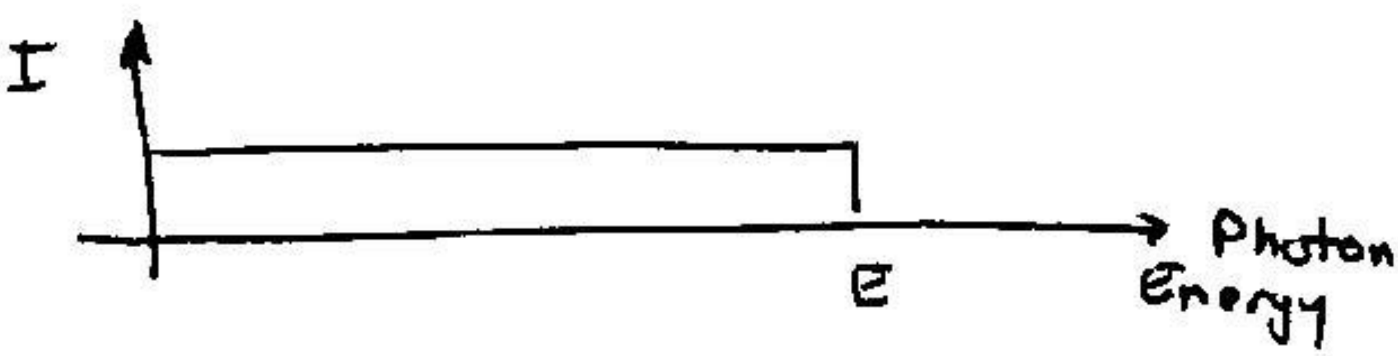
Generation of x-rays: electron interactions

2. Bremsstrahlung “Braking” Radiation – accelerated electrons scattered by a strong electric field near the high-Z nuclei. X-rays have continuous spectrum



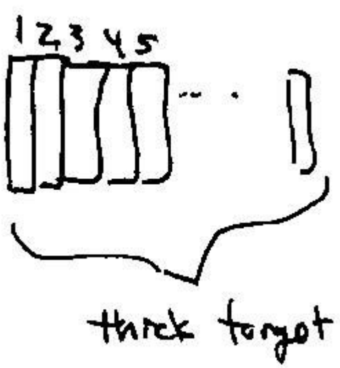
Generation of x-rays: electron interactions

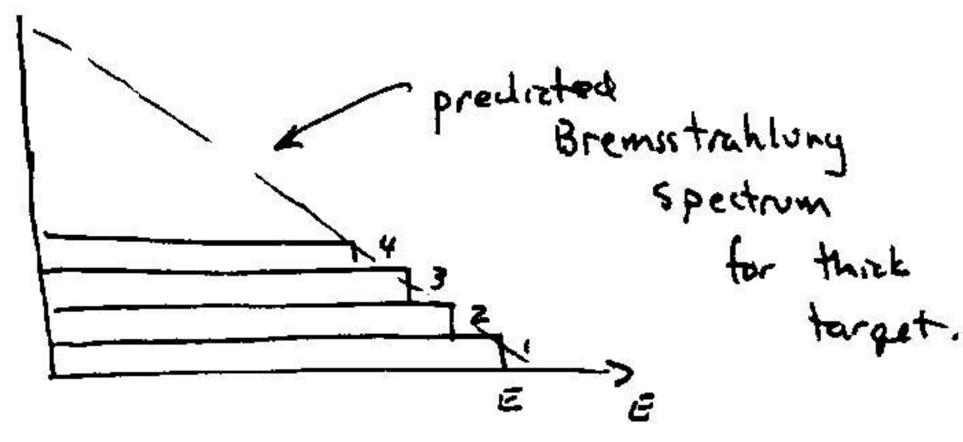
- Thin target (anode) - for electrons of a particular energy, E, striking an infinitely thin target, Bremsstrahlung radiation will have a uniform distribution of energy



Generation of x-rays: electron interactions

- Thick target (anode)
  - Modeled as a series of thin targets.
  - Each thin target produces a new uniform spectrum, but with a lower peak energy.
  - Resultant spectrum is approximately linear from a peak at 0 keV to 0 at E.



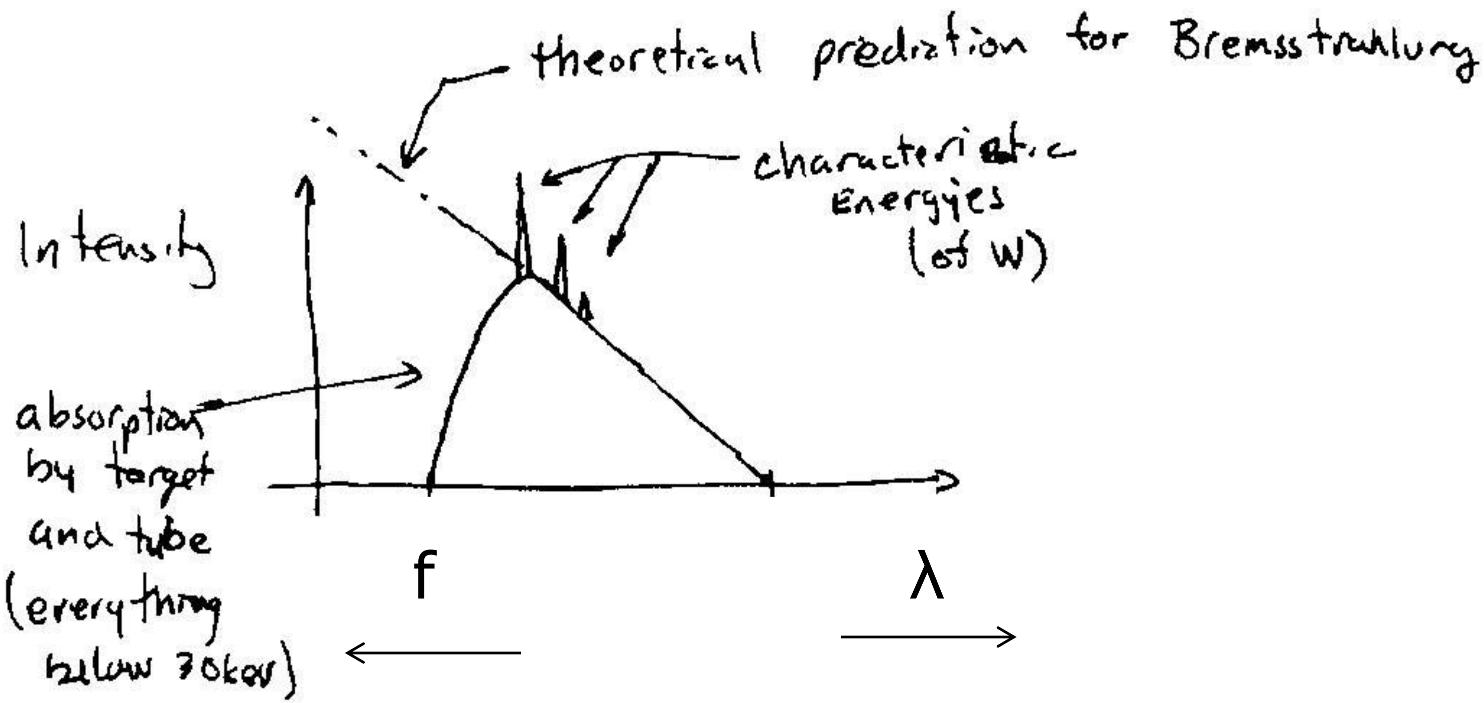


The x-ray Spectrum

- For electrons with energy E, the maximum x-ray photon energy is E.
  - 80kV x-ray tube cannot generate proton with energy (electron charge x voltage field) higher than 80keV
- Very low energy photons are absorbed by the target and by the glass in the x-ray tube.

The x-ray Spectrum

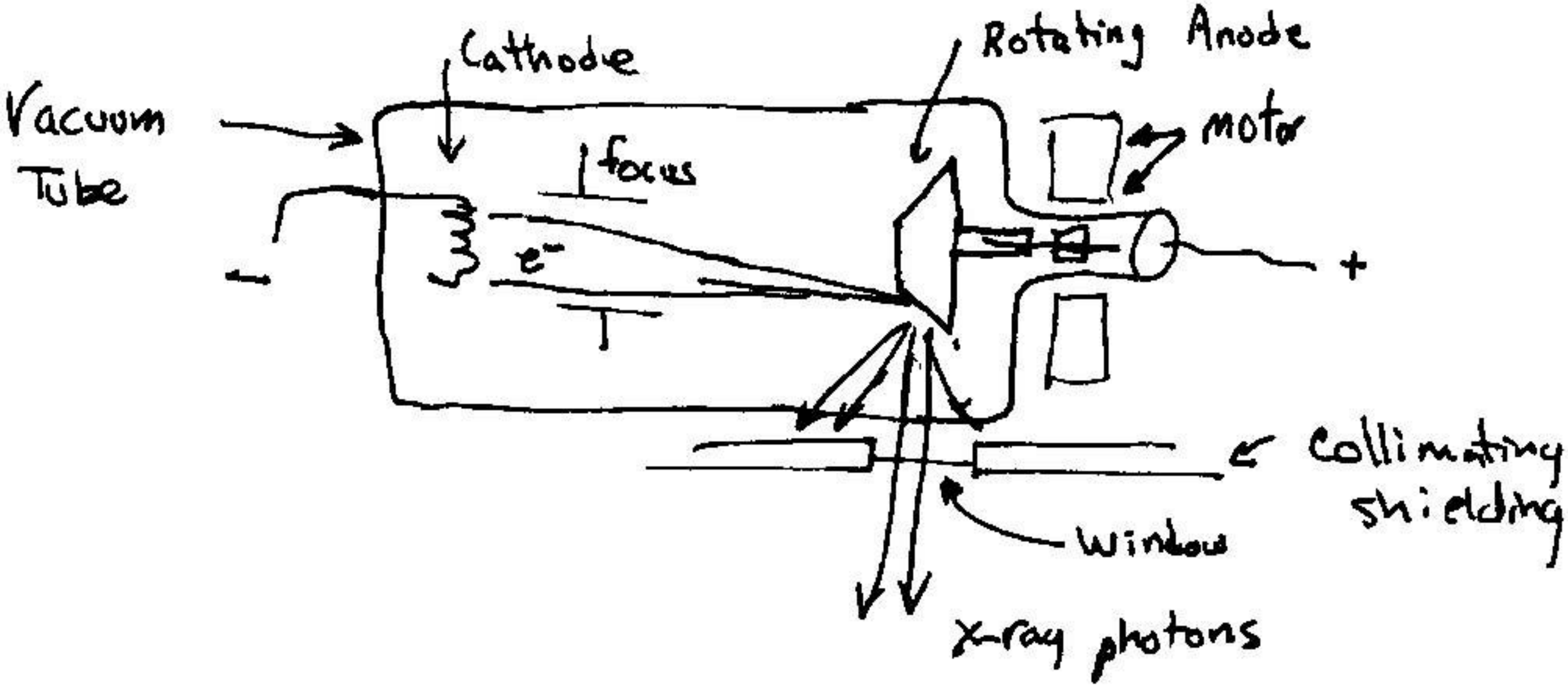
- Spectrum will have a combination of Bohr (discrete) energies and Bremsstrahlung



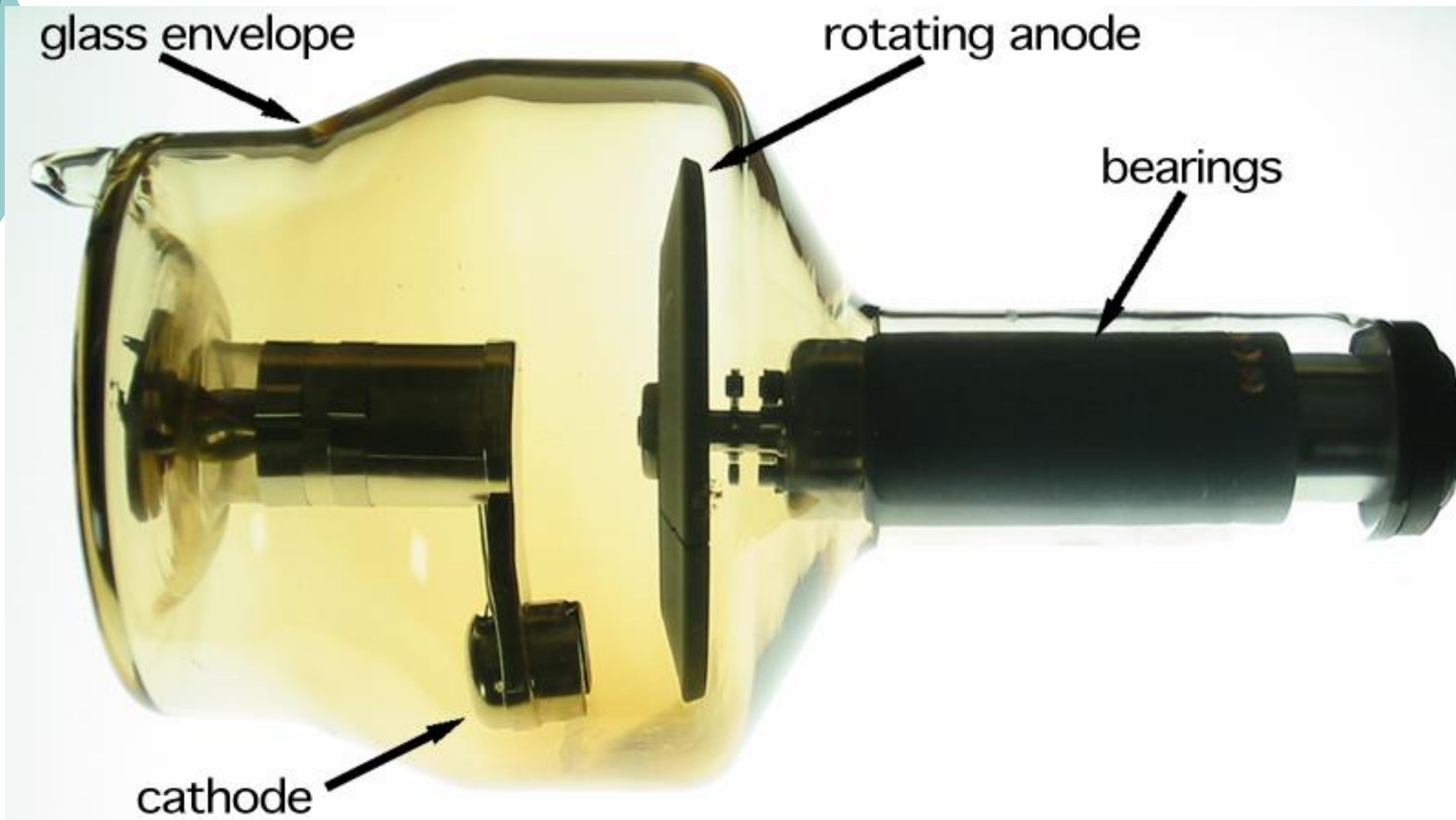
The x-ray Spectrum

- The x-ray spectrum is function of photon energy: $I_0 = I_0(\mathrm{E})$
- I represents energy/unit time/unit area or power/unit area.

Practical x-ray tube



Practical X-ray Tube



http://upload.wikimedia.org/

Practical x-ray tube

- Metal target, anode, is usually made of Tungsten. Why Tungsten?
  - x-ray spectrum in desired range
  - High Z (high efficiency in stopping electrons)
  - High melting point (3300 deg. C)

Question

- For a x-ray tube connected to 100kV power supply, what is the highest cutoff energy of the x-ray photons emitted?

Question

- To increase the energy level of the x-ray photons, you can
- A) Increase the temperature to the cathode
- B) increase the voltage between the cathode and anode.

Question

- To increase the energy level of the x-ray photons, you can
- A) Increase the temperature to the cathode
- **B)** increase the voltage between the cathode and anode – $E = mv$

- Heat up the cathode can increase the amount of x-ray photons emitted.

Questions?

Generation of x-ray

The Attenuation Coefficient

Attenuation Coefficient

- The x-ray spectrum is a function of photon energy E: $I_0 = I_0(\mathrm{E})$
- The attenuation function is also a function of E: $\mu = \mu(x,y,z,\mathrm{E})$.
- The intensity at the output to form image:

$$I_d(x,y) = \int_E I_0(E)\exp\left(-\int \mu(x,y,z,E)dz\right)dE$$

I_d tells us nothing about z or E – it only gives us x,y information.

Attenuation Coefficient

- Two important material properties affecting *μ*: tissue density ρ and the atomic number Z
  - Because most x-ray photon/tissue interactions are photon/electron interactions.

- Attenuation is caused by x-ray photon interaction with the matter

X-ray Photon Interactions

- **Rayleigh-Thompson Scattering** – spontaneous, very low energy phenomenon
- **Photoelectric Absorption** – low energy phenomenon
- **Compton Scattering** – mid energy phenomenon
- **Pair Production** – high energy phenomenon

- In general, attenuation coefficient constituents:

$$\mu(E) = \mu_{rt}(E) + \mu_{pe}(E) + \mu_{cs}(E) + \mu_{pp}(E)$$

Rayleigh-Thompson Scattering

- Atomic absorption with spontaneous emission at the same energy *E*.
- Very low energy – a few keV
- Rarely important in the diagnostic energy range (50-200 keV)

Photoelectric Absorption

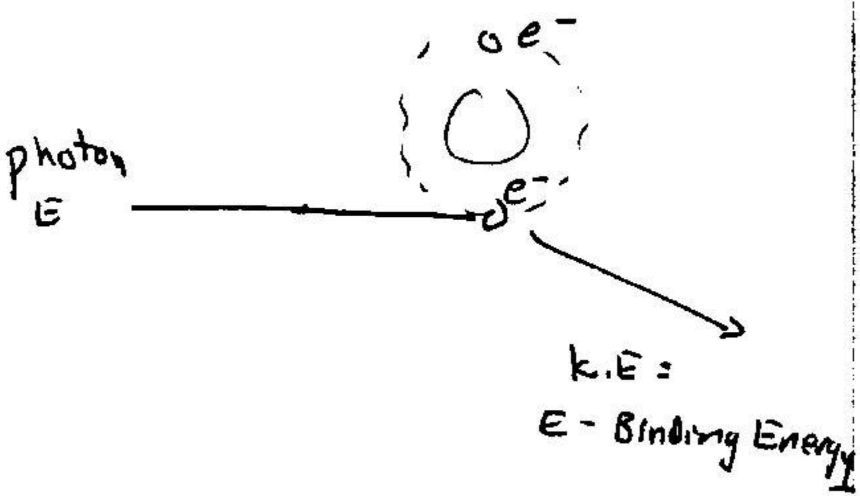
- Absorption of photon by interacting with a tightly bound electron

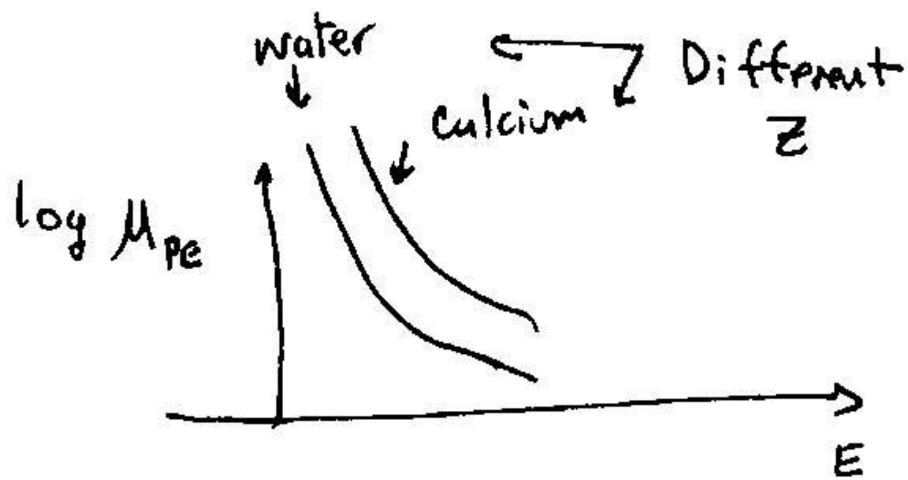
- Leads to ejection of an electron – vacancy filled by an electron falling into it from the next shell

- If the ejected electron kinetic energy (= Absorbed photon energy) is less than binding energy of the electron, the electron is unable to escape the material.

Photoelectric Absorption

- photoelectric effect increases rapidly with atomic number, Z and with decreasing photon energy .

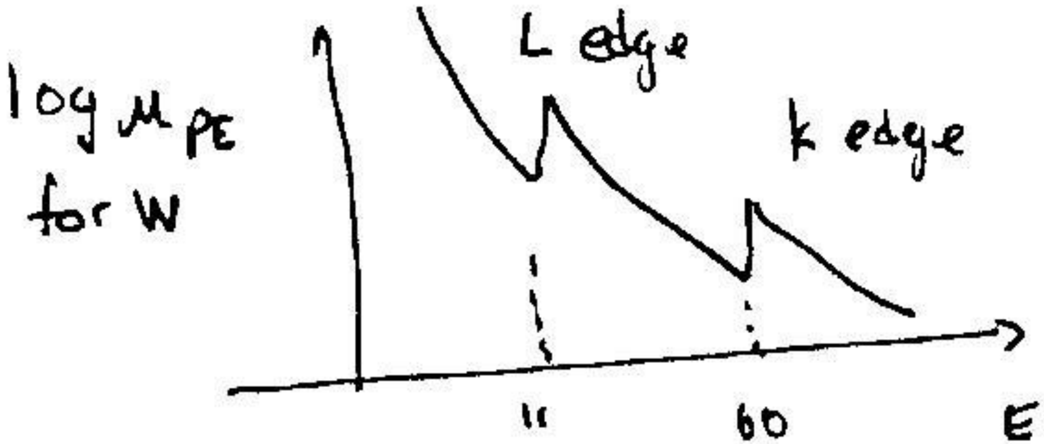




- Dominates μ in the lower energy part of the diagnostic spectrum (<50 keV)

Photoelectric Absorption

- For high Z materials (e.g. Lead, Iodine, Tungsten), shell energy boundaries are evident in *μ* vs. *E* plots.



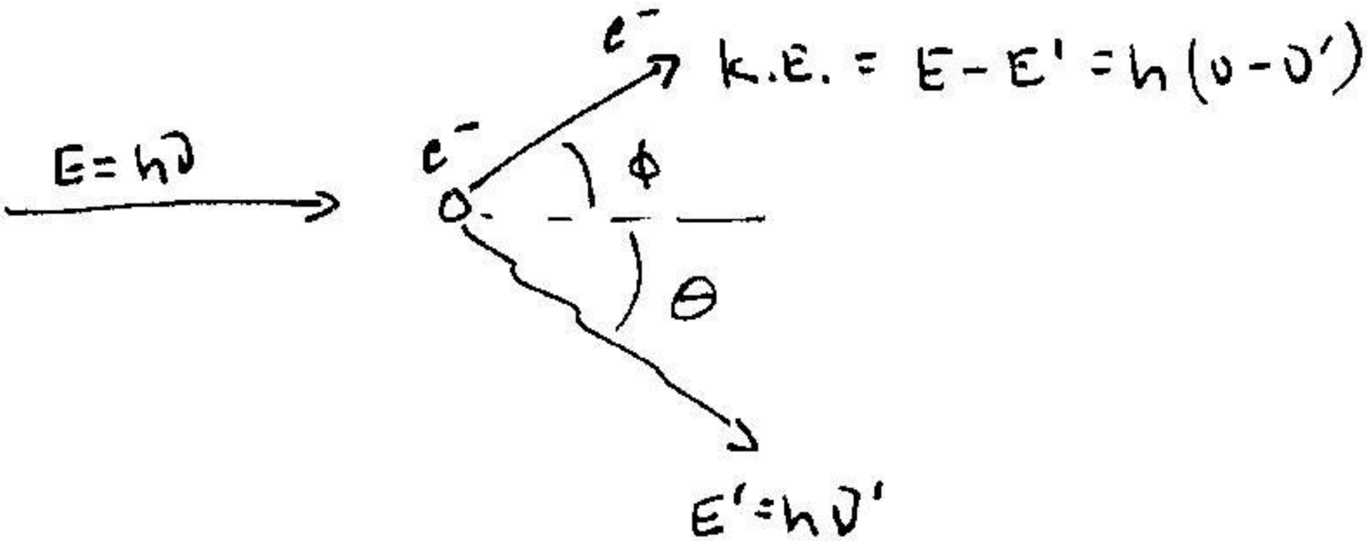
- When the energy gets high enough to make that shell's electrons available to the PE effect (when *E* exceeds the binding energy), then the probability of a PE interaction increases.

Compton Scattering

- Scatting of photons by an elastic collision with a free electron in the outer shell.
- Part of the x-ray energy is transferred to the electron; the rest taken by the scattered “degraded” photon.
- Elastic collisions preserve *E* and momentum (*p*).

Compton Scattering

- For loosely bound electrons or very high energy photons, the equations for free electrons hold reasonably



Compton Scattering

- Conservation of energy:

  K.E. = $E - E' = (m - m_0)c^2$

  m_0 – mass of the rest electron

  c – speed of light

  $m = \dfrac{m_0}{\sqrt{1 - v^2/c^2}}$ - mass of the moving electron

  E – photon energy before collision

  E′ – photon energy after collision

Compton Scattering

- Conservation of momentum in x and y directions:

$$\frac{E}{c} = \frac{E'}{c}\cos\theta + mv\cos\phi$$

$$\frac{E'}{c}\sin\theta = mv\sin\phi$$

Compton Scattering

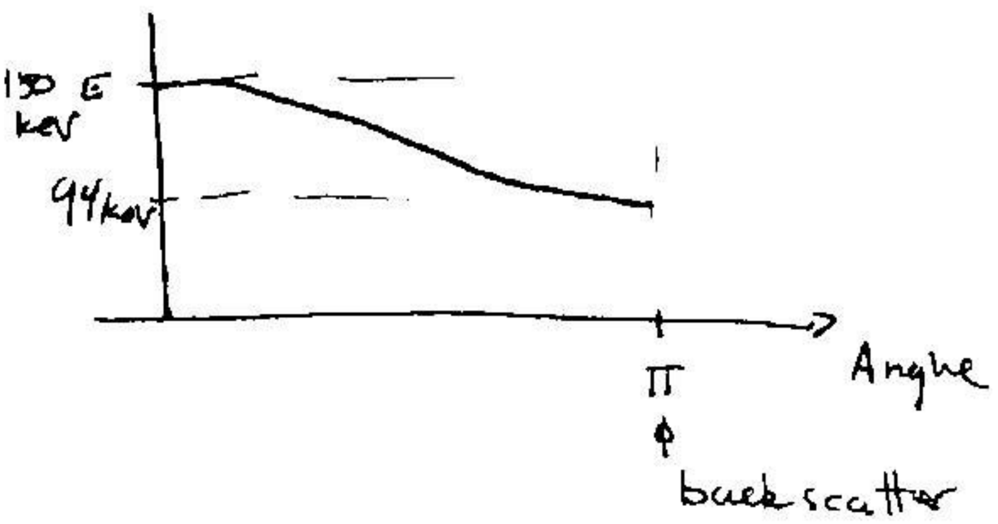
- solving these equations → energy of the scattered photon:

$$E' = \frac{E}{1 + \frac{E}{E_e}(1 - \cos\theta)}$$

where $E_e = m_0c^2$ = 511 keV, the rest energy of an electron.

Compton Scattering

- For $E << E_e$, there is very little change in energy with angle.
- For higher E:



Compton Scattering

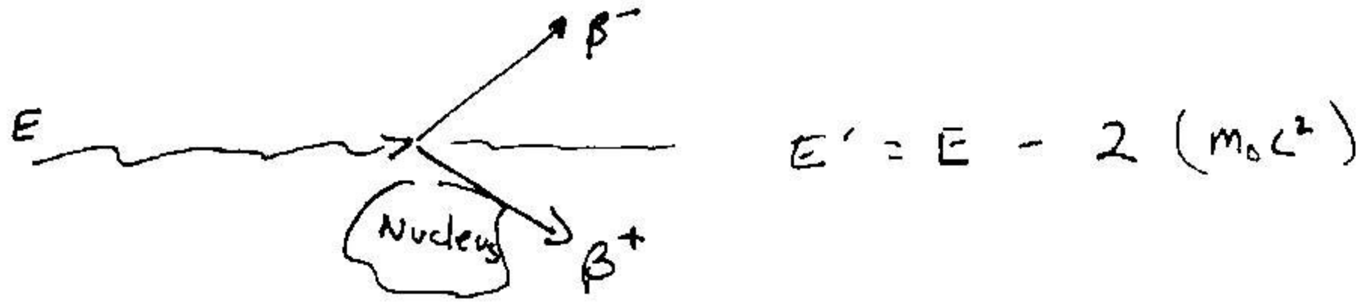
- For low *E*, scatter is essentially isotropic in angle
- For higher *E*, scatter is preferentially forward scattered (little change in photon *E*).
- Very hard to discriminate between forward scattered photons and unimpeded photons based on energy.

Compton Scattering

- μ_{cs} is nearly constant across diagnostic spectrum
- Compton scatter comes mostly from atomic electrons (μ_{cs} is proportional to ρ)
- At higher *E*, Compton scatter dominates over the PE effect.

Pair Production

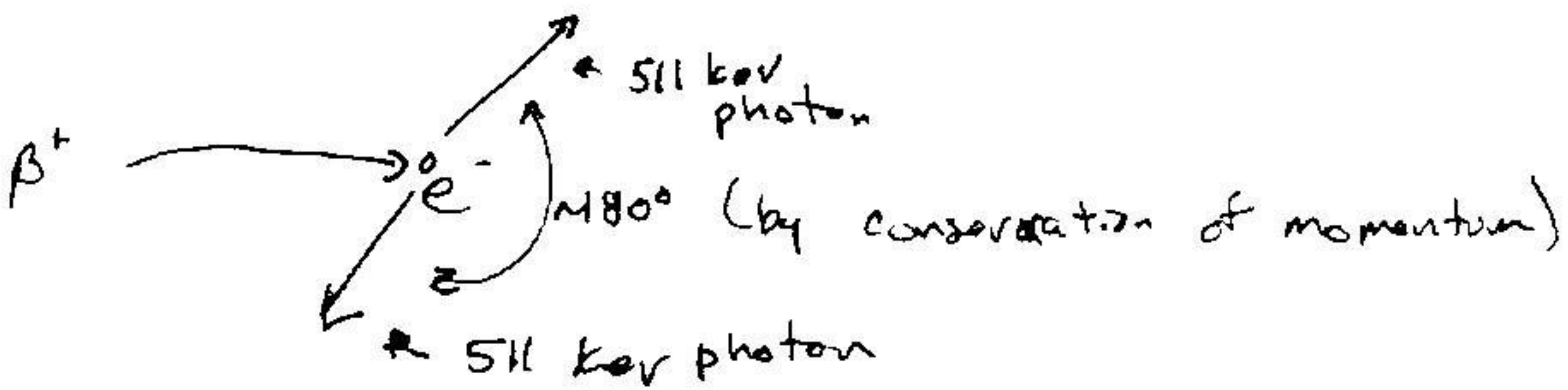
- Spontaneous creation of an electron/positron pair



- Photon energy in transferred to mass energy in the electron and positron.

Pair Production

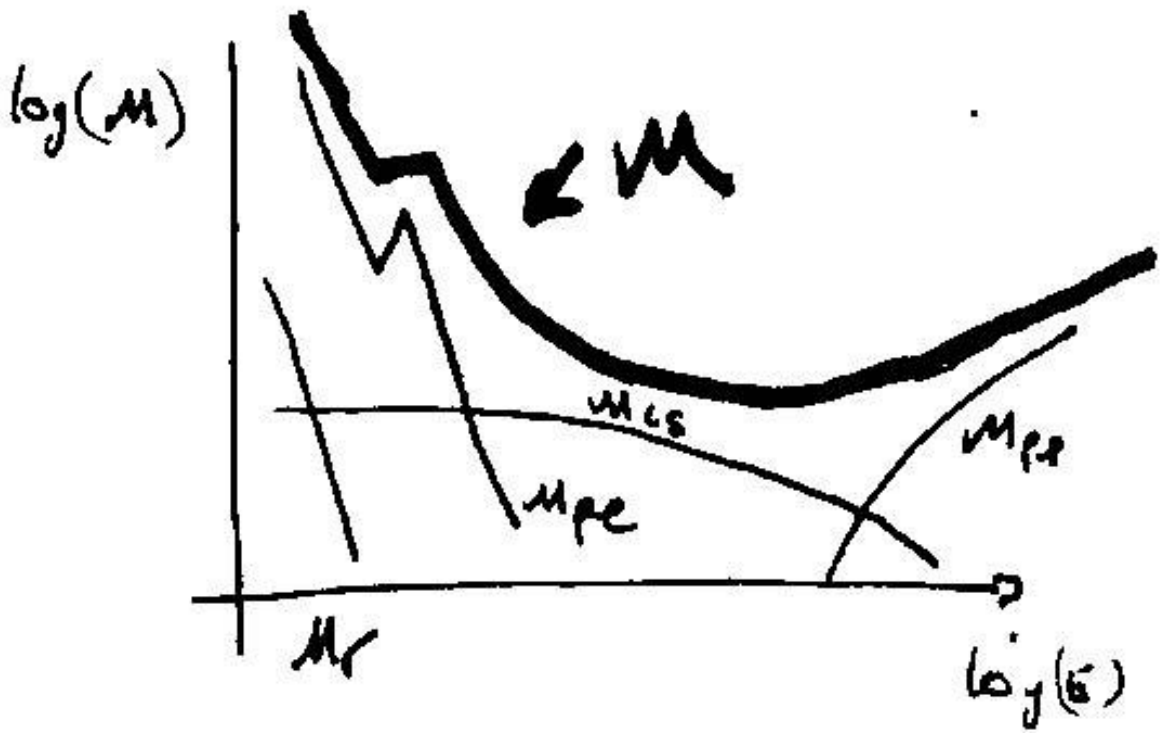
- Only occur for x-ray photons > 1022 keV (not in the diagnostic spectrum)
  - Since the rest energy of electron and poistron is 511 keV



Total Linear Attenuation Coefficient for Photons

- The combined coefficient

$$\mu(E) = \mu_{rt}(E) + \mu_{pe}(E) + \mu_{cs}(E) + \mu_{pp}(E)$$



Total Linear Attenuation Coefficient for Photons

- An alternate to linear attenuation coefficient is the “mass attenuation coefficient” $\tau = \mu / \rho$

  (units: cm^2/gm)

- convenient when describing the behavior of composite materials with *N* constituent components:

$$\tau = \frac{1}{M}\sum_{i=1}^{N} m_i \tau_i$$

m_i are the masses of the components and *M* is the total mass.

X-ray Attenuation Coefficients from Muscle, Fat and bone

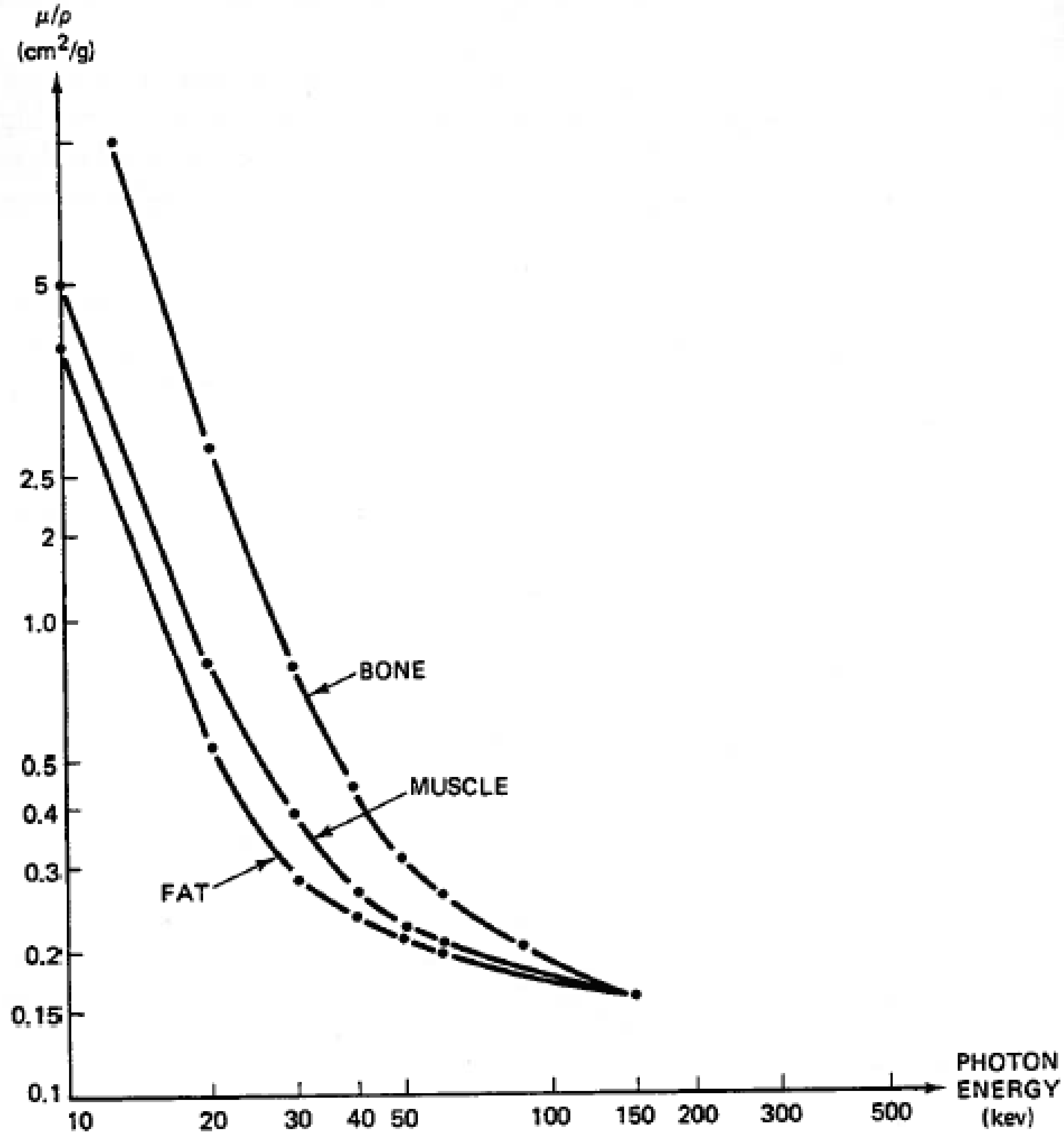


FIG. 3.7 X-ray attenuation coefficients for muscle, fat, and bone, as a function of photon energy.

Macovski – Fig. 3.7

True or False

- Attenuation of clinical x-ray imaging primary come from Compton scattering and photoelectric absorption.

Compton Scattering

- Which of the following X-ray photon property decreases as it goes through through Compton Scattering.
  - A) Energy
  - B) Speed
  - C) Frequency
  - D) Wavelength

Compton Scattering

- Which of the following X-ray photon property decreases as it goes through through Compton Scattering.
  - **A)** Energy
  - B) Speed
  - **C)** Frequency
  - D) Wavelength

Questions?

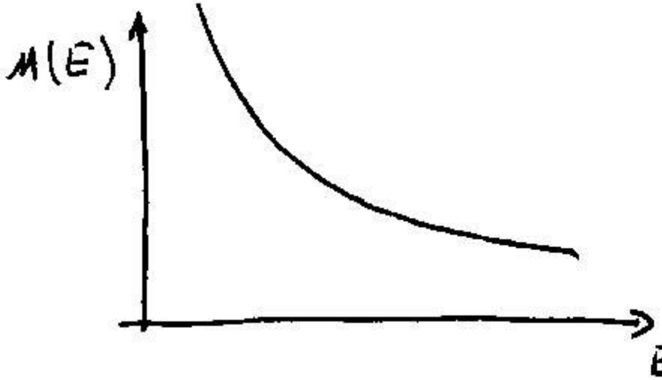
Attenuation Coefficient

X-ray Photon interaction

Total Linear Attenuation Coefficient for Photons

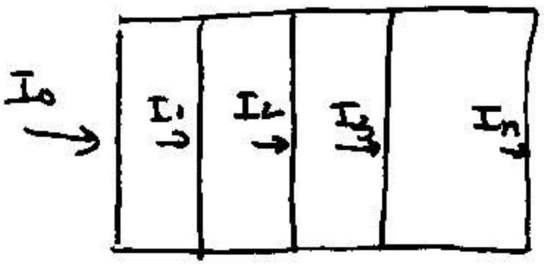
Beam Hardening

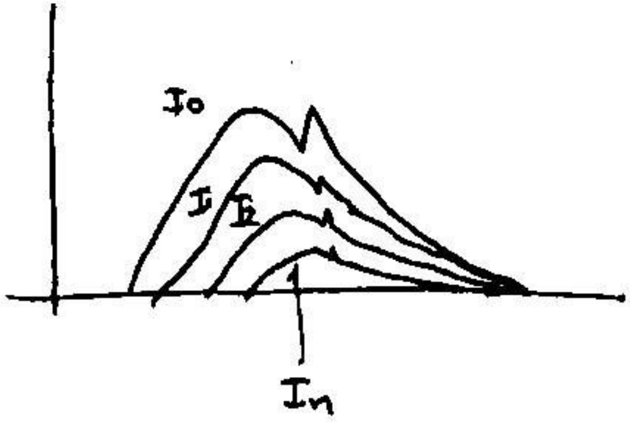
- Because the attenuation spectrum is not uniform across the diagnostic energy spectrum, the output spectrum will have a different intensity distribution than the input spectrum, $I_0(E)$.



Beam Hardening

- If we split an object into several smaller parts, and look at then energy spectrum at for each part:





Beam Hardening

- The mean energy:

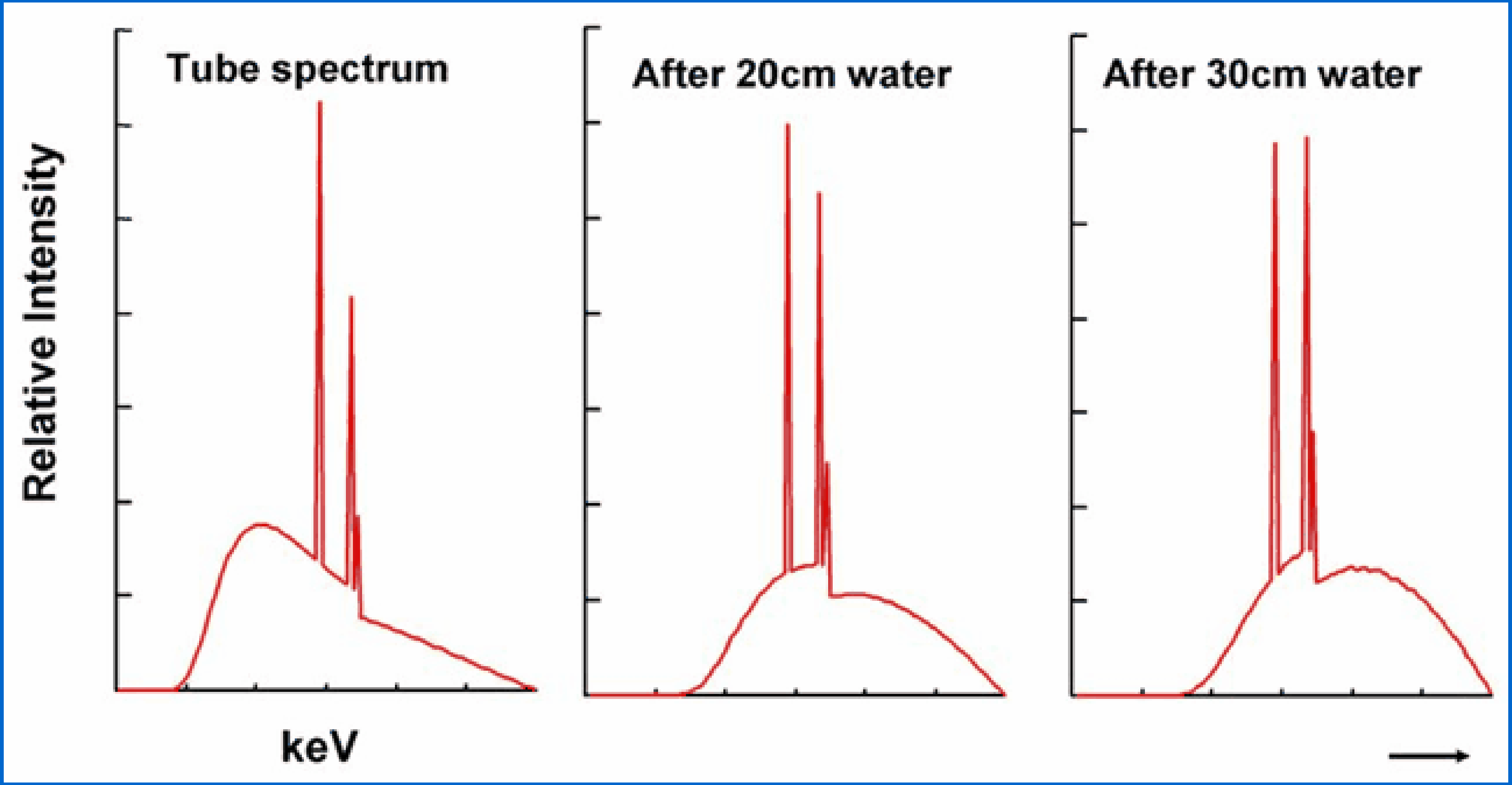
$$\overline{E} = \frac{\int EI(E)dE}{\int I(E)dE}$$

- will increase (get harder) as we move through the object:

$$\overline{E}_0 < \overline{E}_1 < \overline{E}_2 < \ldots < \overline{E}_n$$

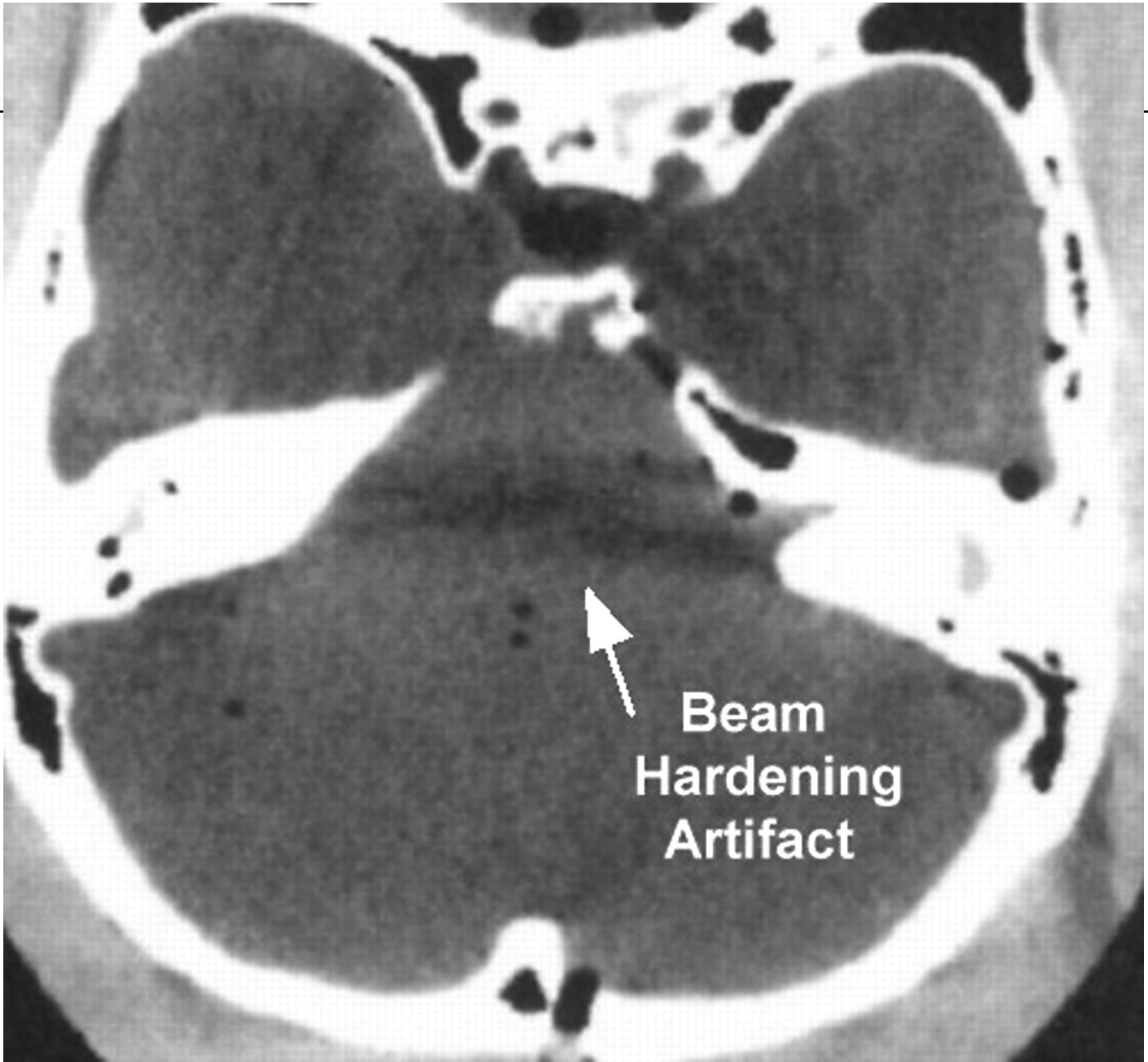
Beam hardening

As an x-ray beam passes through an object, its mean energy increases

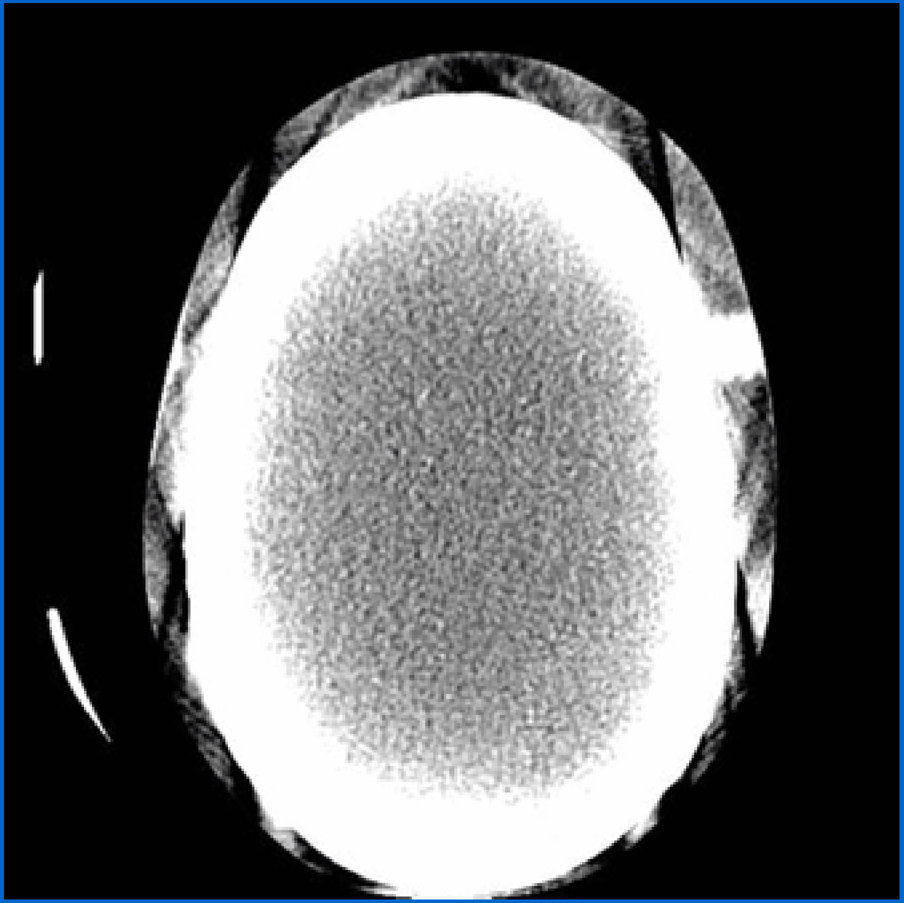


http://www.impactscan.org/slides/impactcourse/artefacts/img10.gif

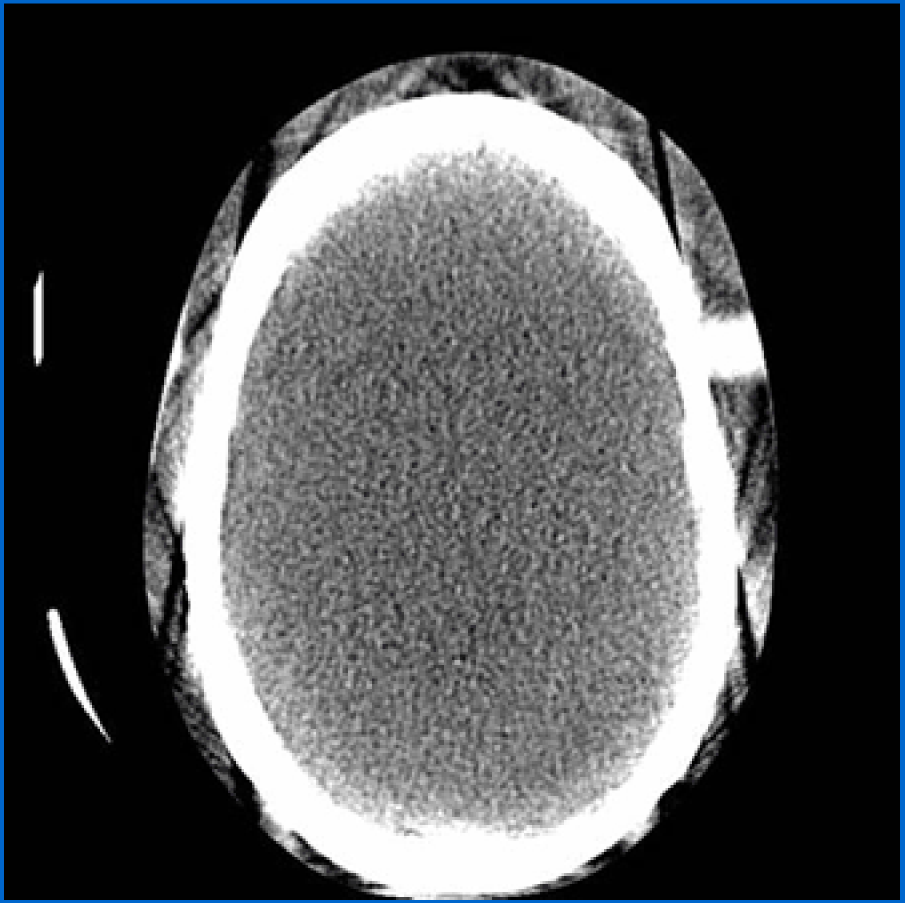
Beam Hardening Artifact



Beam hardening correction software



Raw image



After beam hardening correction

True or False

- As the X-ray photons move deeper into the object, the apparent attenuation coefficient will increase.

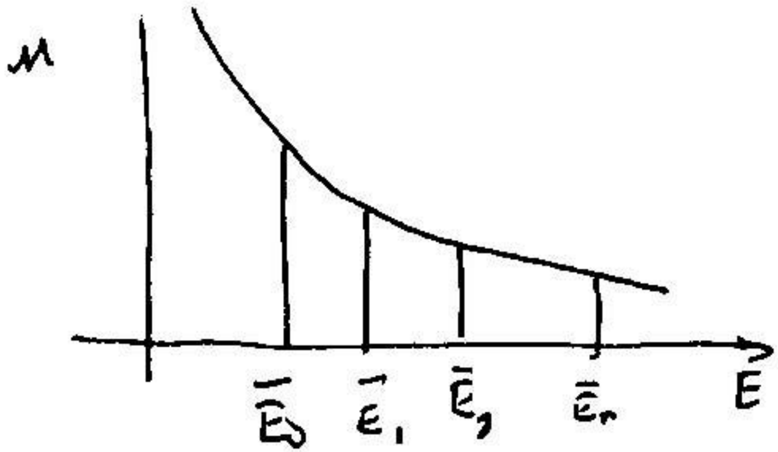
True or False

- As the X-ray photons move deeper into the object, the apparent attenuation coefficient will increase.

- False – As the X-ray photons move deeper, less lower energy photons (with higher attenuation coefficient).

Beam Hardening

- A particular tissue type will have a μ that changes as a function of position along the path.



- As we move deeper into the object, there is less attenuation than expected, given the initial spectrum, $I_0(E)$.

Beam Hardening

- One solution is to make the beam "hard" to begin with - often accomplished by filtering out the low *E* photons with a thin metal plate (often use aluminum).

Questions?

Beam Hardening?