Radiation and Interaction of Radiation with Matter

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Objectives

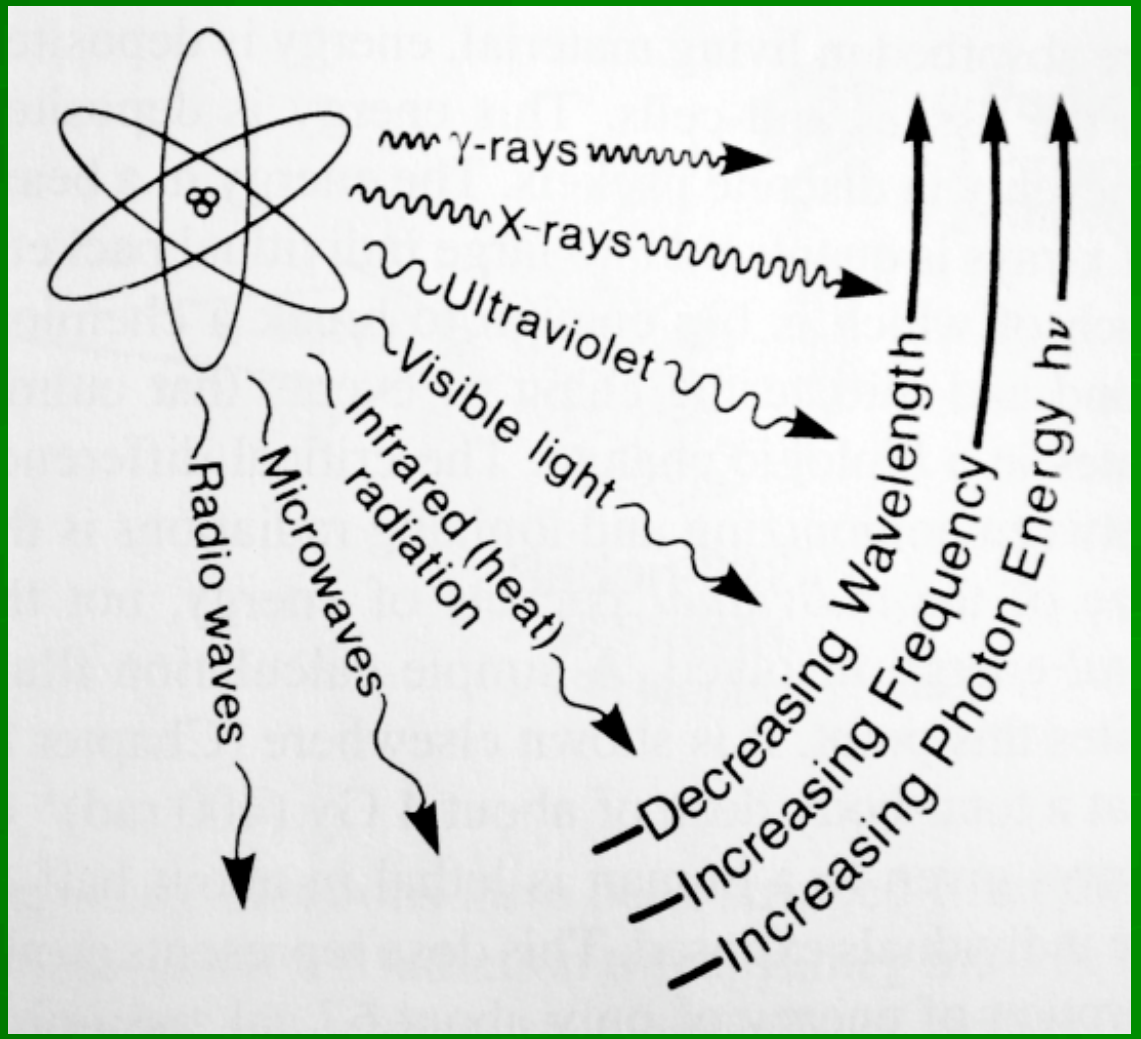
- Types of Radiation
- Ionizing vs Non-Ionizing Radiation
- Interactions of Ionizing Radiation
- Production of X-rays
- X-ray and Gamma-ray Interactions
- Attenuation

Types of Radiation

- Electromagnetic
  - X-rays (produced outside the nucleus)
  - γ-rays (emanate from within nuclei)
- Particulate
  - α particles
  - Protons
  - Neutrons
  - Electrons (β^-)
  - Positrons (β^+)

EM Radiation

- Characterized
  - Wavelength (λ)
  - Frequency (ν)
  - Energy (E)
- Behavior
  - Waves
  - Particles



EM Radiation

- Interaction with matter
  - Particle can exhibit particle-like behavior
- Photon energy
  - $E=h\nu$
  - h (Planck's constant)= 4.13x10-18 keV-sec
- E expressed in eV

EM Radiation

- eV defined
  - Energy acquired by an electron as it traverses an electrical potenti
    a
    l difference (voltage) of one volt in a vacuum
- KeV (1,000 eV)
- MeV (1,000,000 eV)

Ionizing versus non-ionizing Radiation

- Higher frequency than high UV region
  - Sufficient energy per photon to remove bound electrons from atomic shells
- Non-ionizing
  - Infrared, visible light, radio, TV
- Threshold depends on type of matter
  - H_2O: 12.6 eV
  - C_6H_6: 9.3 eV

Non-ionizing versus Ionizing Radiation

Non-Ionizing Radiation Symbol

Traditional International Symbol for Radiation

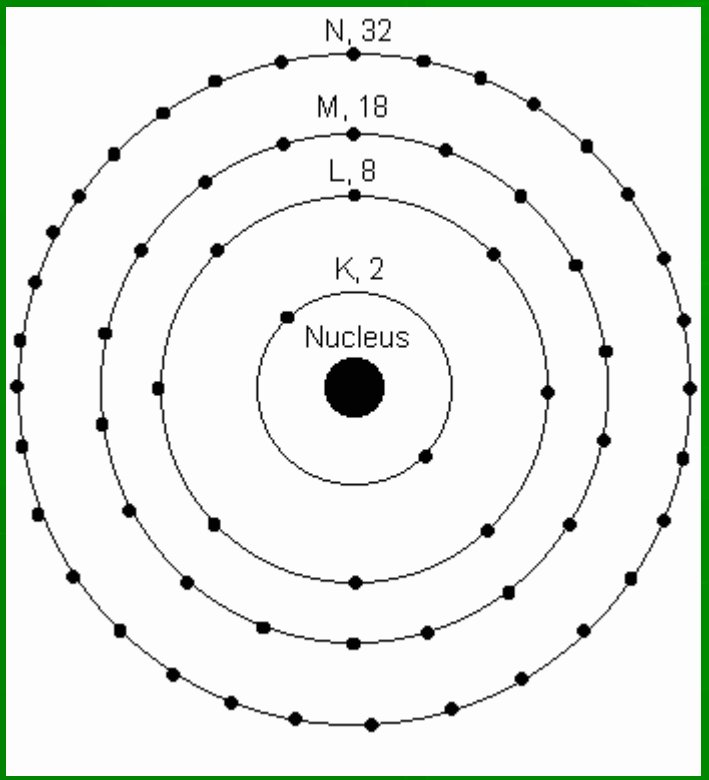
Non-ionizing versus Ionizing Radiation

Non-Ionizing Radiation Symbol

New Symbol for Ionizing Radiation (IAEA & ISO, 2007)

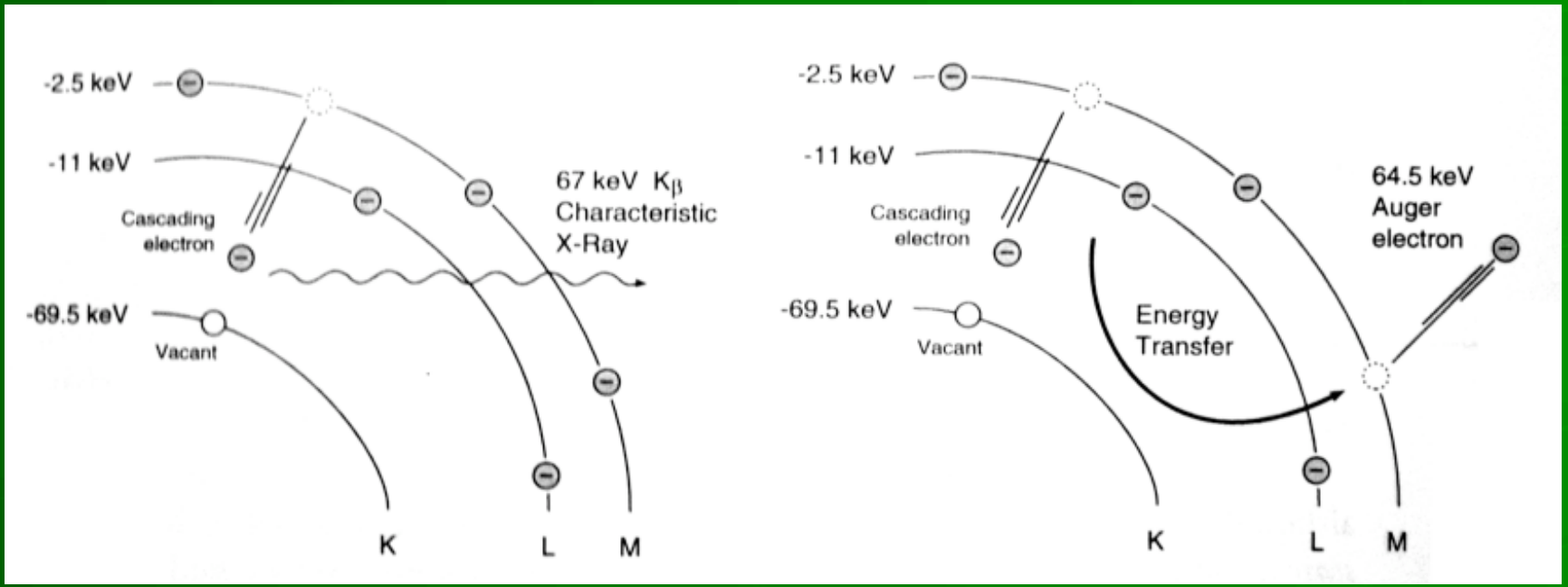
Radiation from Electron Transitions

- Electron cascade
  - Vacancy filled by Electron from an outer shell
- Electron transitions emit
  - Visible, UV and x-rays
- Characteristic x-rays
  - > 100 eV
  - K-characteristic x-ray
  - K_α (L → K transition)
  - K_β (M → K transition)



Radiation from Electron Transitions

- Energy released by each transition
  - $E_{Characteristic} = E_{b\ vacant\ shell} - E_{b\ transition\ shell}$



  - $E(K_\beta)$ = 69.5 keV – 2.5 keV = 67 keV

Atomic Nucleus

- Nuclear Stability
  - Only certain combinations of neutrons and protons in the nucleus are stable
- Radioactivity
  - Unstable nuclei achieve stability by the conversion of a neutron to a proton, or vice versa, and these events are accompanied by the emission of energy
- Energy emissions
  - Particulate and EM radiations.

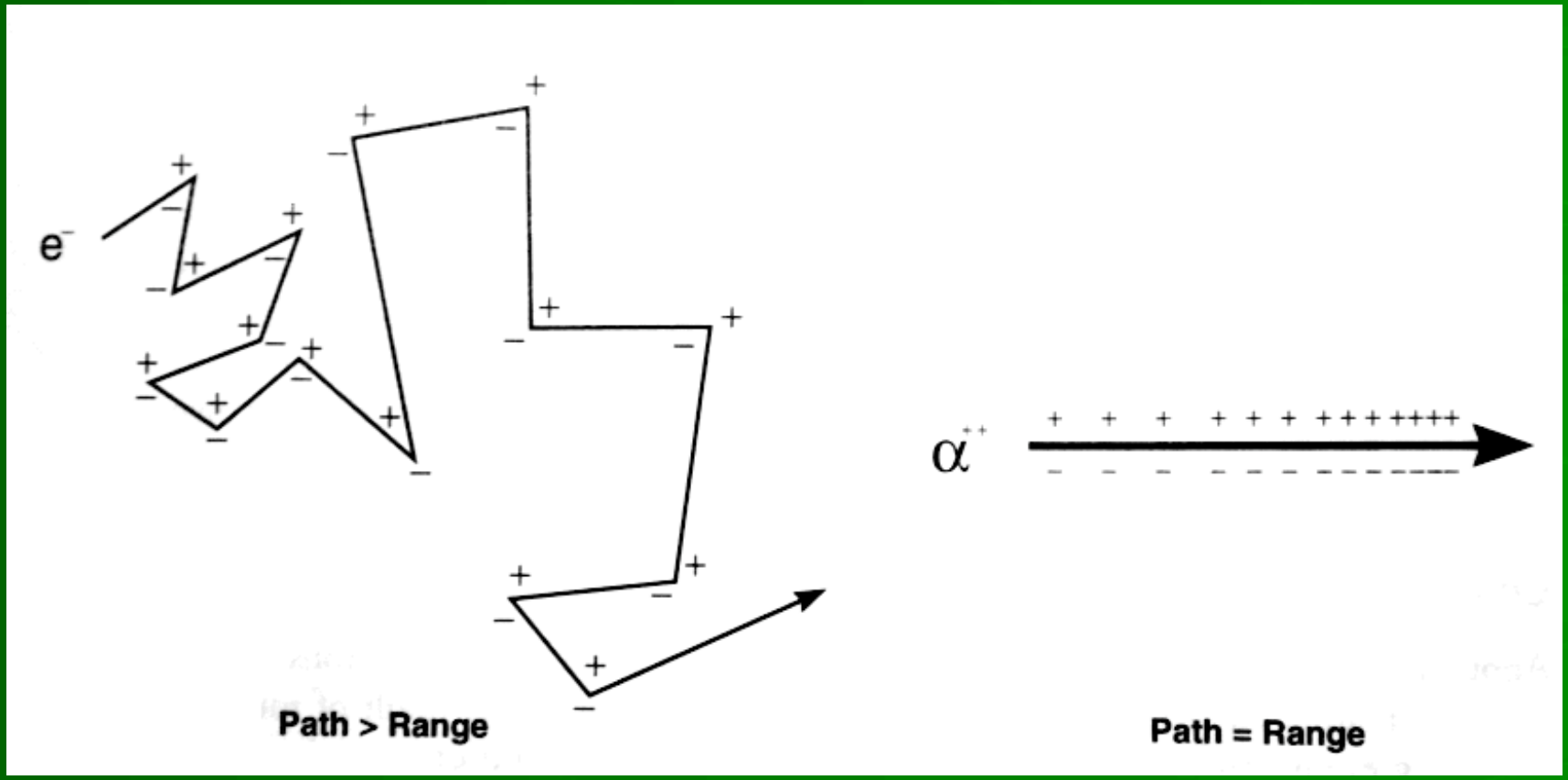
Interactions of Ionizing Radiation

- Ionizing radiation
  - α particles, protons, electrons, β^-, β^+
  - Neutrons
- Charged particles kinetic energy lost by
  - Excitation
    - Energy transferred to electrons (< binding energy)
    - De-excitation (return to lower level)
  - Ionization
    - Energy transferred to electrons (> binding energy)
  - Radiative losses

Specific Ionization

- Number of ion pairs (IP) produced per unit length of the particles path
  - Primary & secondary ion pairs
  - IP/mm
- Higher: Heavy charged particles
- Lower: Electrons

Charged Particle Tracks



Linear Energy Transfer (LET)

- The amount of energy deposited per unit path length is called LET
  - Expressed in eV/cm
- "High LET"
  - α particles, protons, etc.
- "Low LET"
  - e^-, β^-, β^+, gamma and x-rays
- In general:
  - "High LET" radiations are more damaging to tissue than "Low LET" radiations.

Scattering & Bremsstrahlung

- Deflection of a particle or photon
  - Elastic (kinetic energy unchanged)
  - Inelastic (loss of kinetic energy)
- Path of electron is deflected
  - Lost kinetic energy released as EM radiation
  - X-rays
- Bremsstrahlung
  - “braking radiation”
  - X-ray tubes, linear accelerators

X- and Gamma-ray Interactions

- 4 major types of interactions
  - Rayleigh scattering
  - Compton scattering
  - Photoelectric absorption
  - Pair production

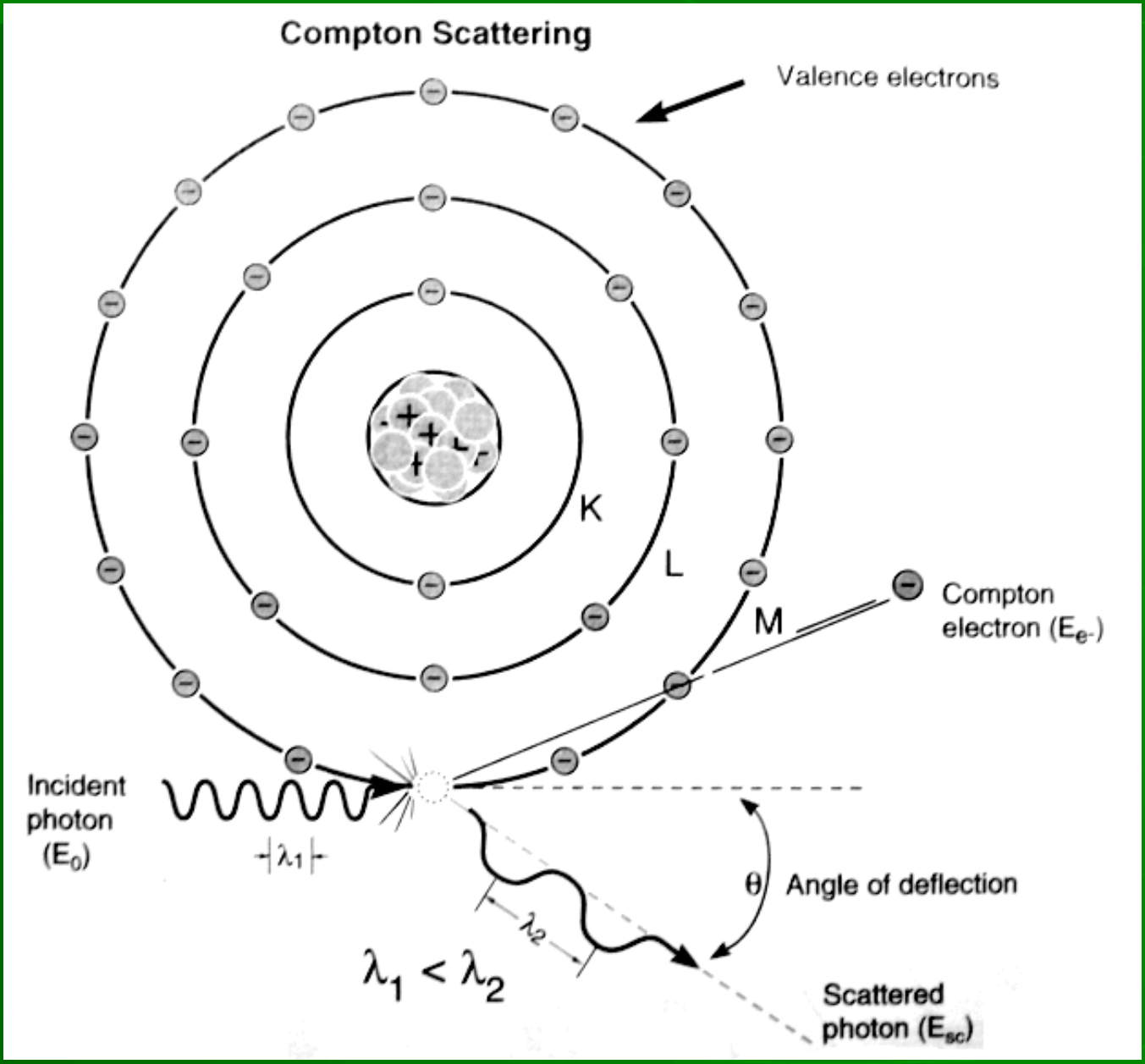
Rayleigh Scattering

- Very low energy diagnostic x-rays
  - Mammography
- Atom is excited (not individual electrons)
  - Elect
    r
    o
    n cloud immediately radiates absorbed energy
- At *most* accounts for
  1
  2
  % of interactions at approximately 30 keV

Compton Scattering

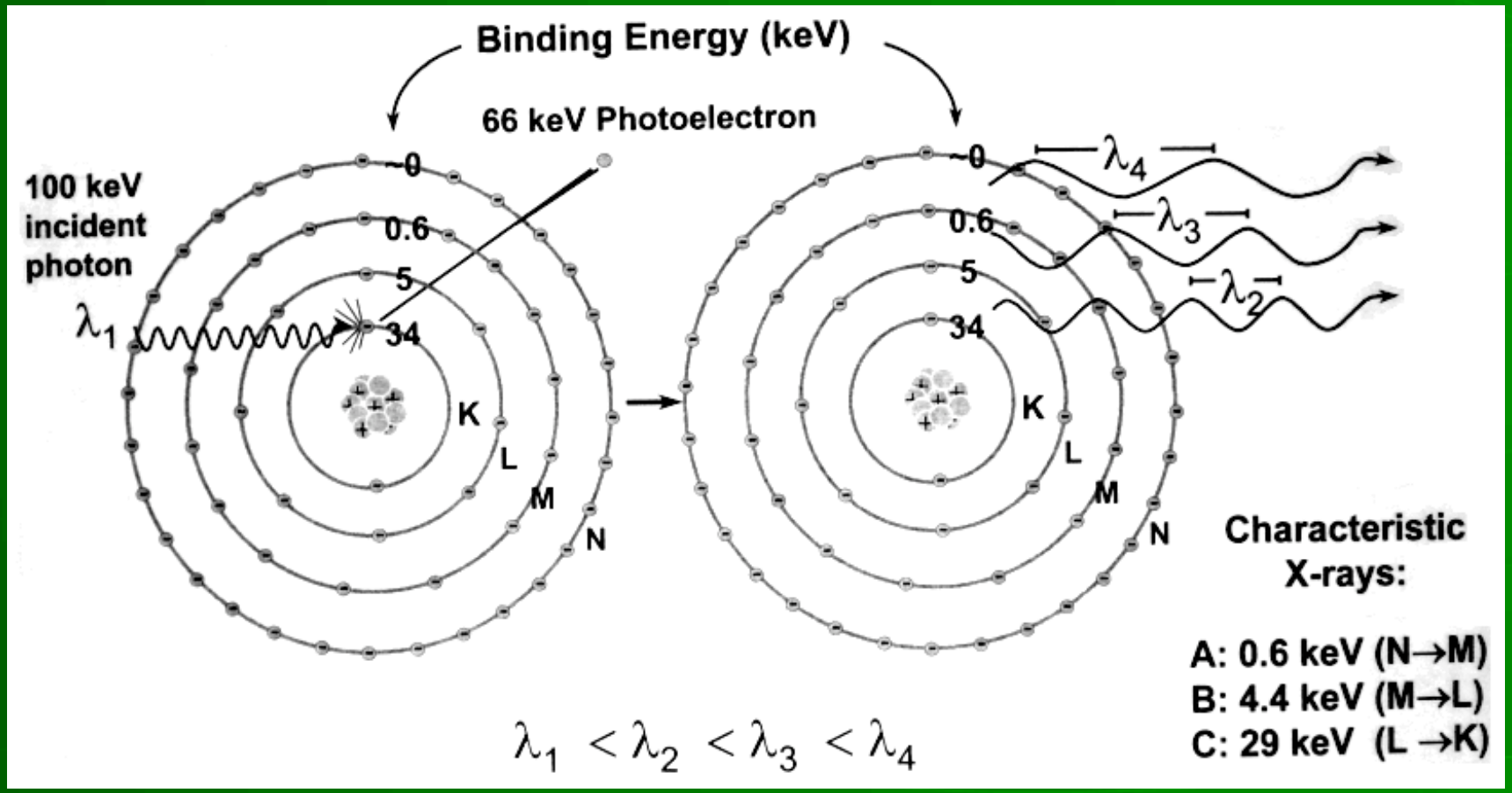
- Predominant interaction
  - 26 keV to 30 MeV
  - Most likely occurs in outer shell electrons
- Ejected e^- will lose it's kinetic energy via excitation and ionization of atoms
- Scattered photon may undergo subsequent interactions

Compton Scattering



Photoelectric Effect

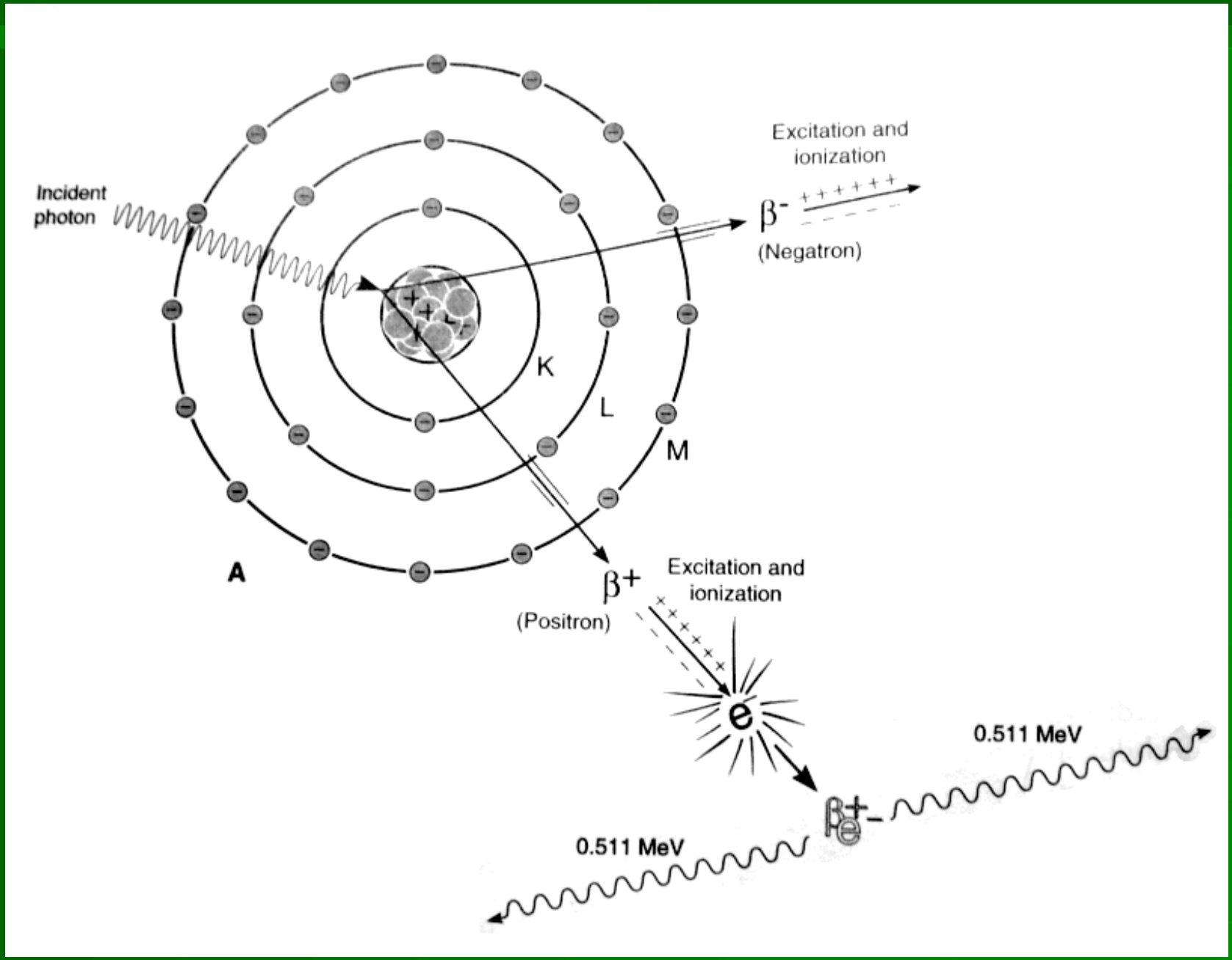
- Photon energy completely absorbed by e^-
  - e^- ejected; closest, but < photon energy



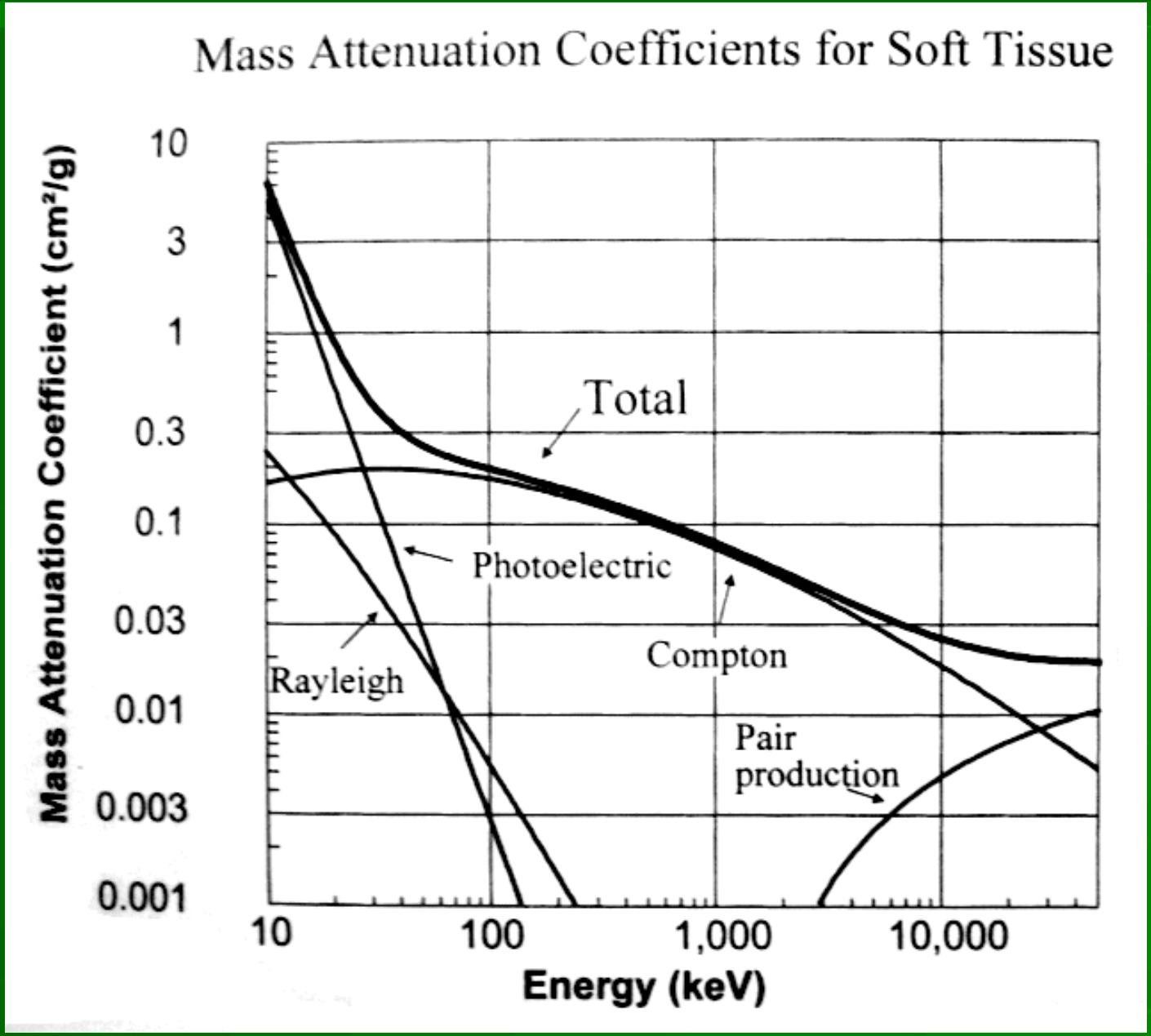
Pair Production

- Energies must exceed 1.02 MeV
- Photon interacts w/electric field of nucleus
  - Converted into an electron-positron pair
  - Rest mass equivalent of each e^- is 0.511 MeV

Pair Production



Attenuation – Removal of photons



Positron Annihilation

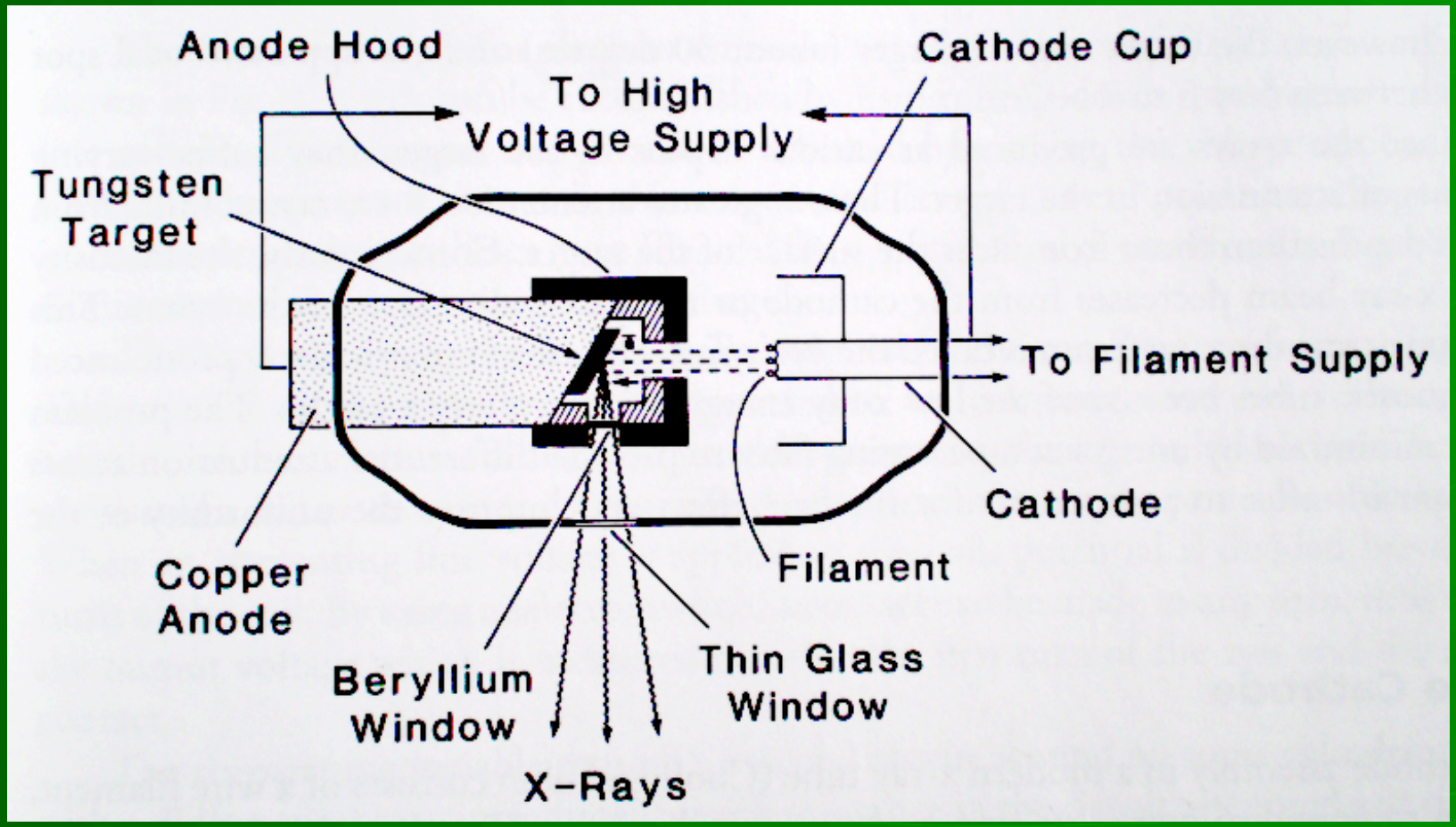
- Positrons at rest interact with electrons
- Electron-positron pairs annihilate
- Complete conversion of their rest mass to energy in the form of two oppositely directed 0.511 MeV annihilation photons.
- PET scanners

Neutron Interactions

- Uncharged Particles
  - Do not directly cause excitation and ionization
  - Interact with atomic nuclei
- Captured by atomic nuclei;
  - Converting atom to a different nuclide when retained
  - Produced nuclide may be stable or radioactive

Production of X-rays (keV)

- 1% of energy loss due to Bremsstrahlung
  - Photons are emitted 60-90° to incident e^-



Production of X-rays (MeV)

- Brem photons emitted in the forward direction