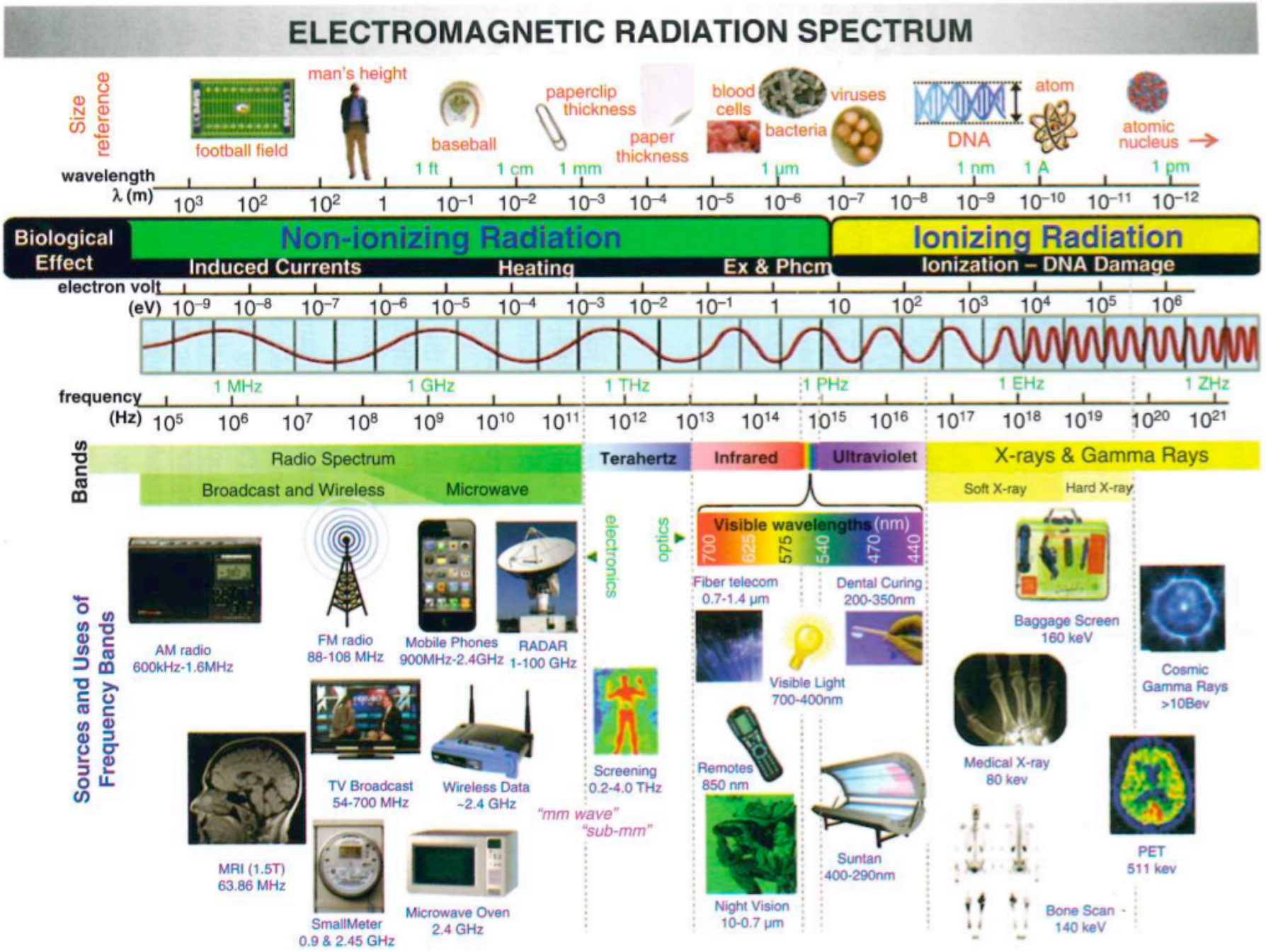
R*ichiami su radiazioni ionizzati*
e
interazione radiazione materia

ELECTROMAGNETIC RADIATION SPECTRUM



Photon energy

- The EM radiation also exhibits corpuscular characteristics.
- The concept of the photon is introduced.

c= 299792458 m/s ~ 3 x 10^8 m/s

Particle Characteristics

The discrete (particle-like) packets (or *quanta*) of EM energy are called *photons*. The energy of a photon is given by

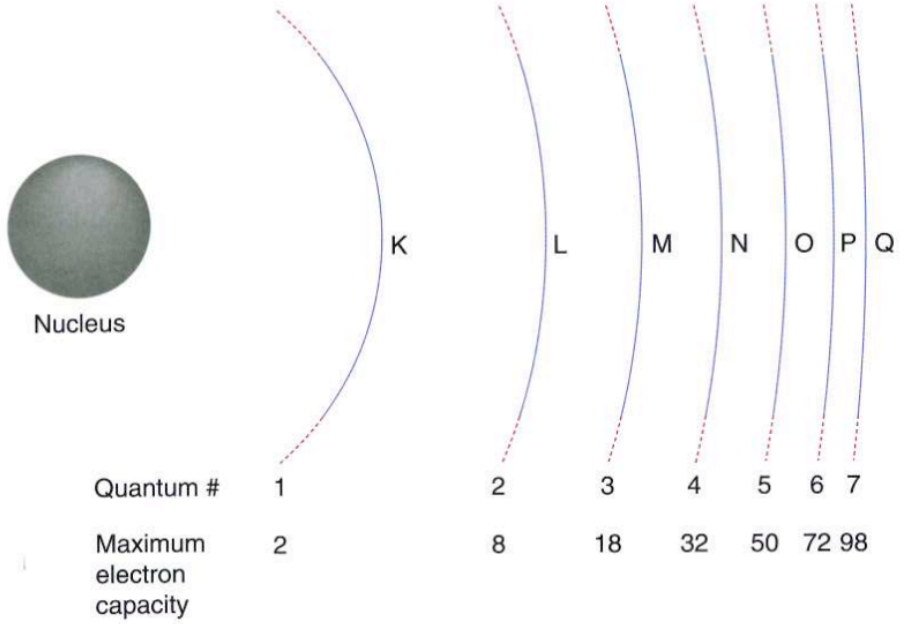
$$E = h\nu = \frac{hc}{\lambda}$$

where h (Planck's constant) $= 6.626 \times 10^{-34}$ J-s $= 4.136 \times 10^{-18}$ keV-s. When E is expressed in keV and λ in nanometers (nm),

$$E\ (\text{keV}) = \frac{1.24}{\lambda\ (\text{nm})}$$

Electron shell designations and orbital filling rules

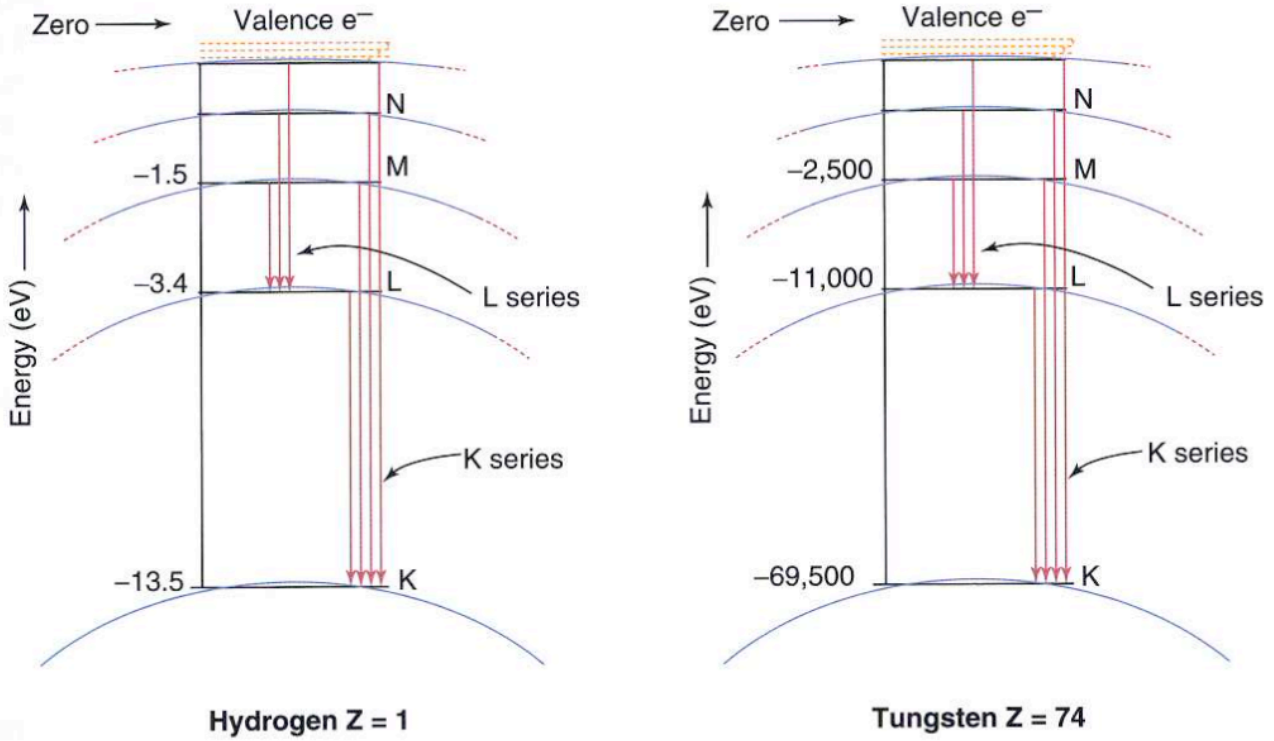
In the Bohr model of the atom (Niels Bohr 1913), electrons orbit around a dense, positively charged nucleus at fixed distances (Bohr radii). Bohr combined the classical Newtonian laws of motion and Coulomb's law of electrostatic attraction with quantum theory. In this model of the atom, each electron occupies a discrete energy state in a given electron shell. These electron shells are assigned the letters *K L, M, N,...*, with *K* denoting the innermost shell, in which the electrons have the lowest energies. The shells are also assigned the *quantum numbers* 1, 2, 3, 4,..., with the quantum number 1 designating the *K* shell. Each shell can contain a maximum number of electrons given by $(2n^2)$, where *n* is the quantum number of the shell. Thus, the *K* shell ($n = 1$) can only hold 2 electrons, the *L* shell ($n = 2$) can hold $2(2)^2$ or 8 electrons, and so on, as shown in Figure 2-5. The outer electron shell of an atom, the *valence shell*, determines the chemical properties of the element. Advances in atomic physics and quantum mechanics led to refinements of the Bohr model.



- Electron charge: 1.602×10^{-19} C
- Masses
  - Mass of the proton m_p: 1.673×10^{-27} kg = 1.007 amu
    - 12 amu (atomic mass unit) is the weight of 1 mole of ^{12}C
    - one mole of a substance is the Avogadro number N_A of atoms
    - $N_A = 6.022 \times 10^{23}$ mol^{-1}
  - Mass of the neutron m_n: 1.675×10^{-27} kg = 1.009 amu
  - Mass of the electron m_{e^-}: 9.109×10^{-31} kg = 1/1836 m_p
- Dimension
  - Atomic radius ~ 10^{-10} m
  - Nucleus radius ~ 10^{-15} m
    - Note that the core is 5 orders of magnitude smaller than the atom

Orbital binding energy

The energy required to remove an orbital electron completely from the atom is its orbital binding energy. For ionization the energy transfer to the electron must be equal or exceed its binding energy. Binding energy increases with Z.



■ FIGURE 2-6 Energy-level diagrams for hydrogen and tungsten. The energy necessary to separate electrons in particular orbits from the atom (not drawn to scale) increases with Z and decreases with distance from the nucleus. Note that zero energy represents the point at which the electron is experiencing essentially no Coulomb attractive force from the protons in the nucleus (often referred to as a "free" electron). For a bound electron to reach that state, energy has to be absorbed. Thus, the energy states of the electrons within the atom must be below zero and are thus represented as negative numbers. The vertical lines represent various transitions (e.g., K and L series) of the electrons from one energy level to another.

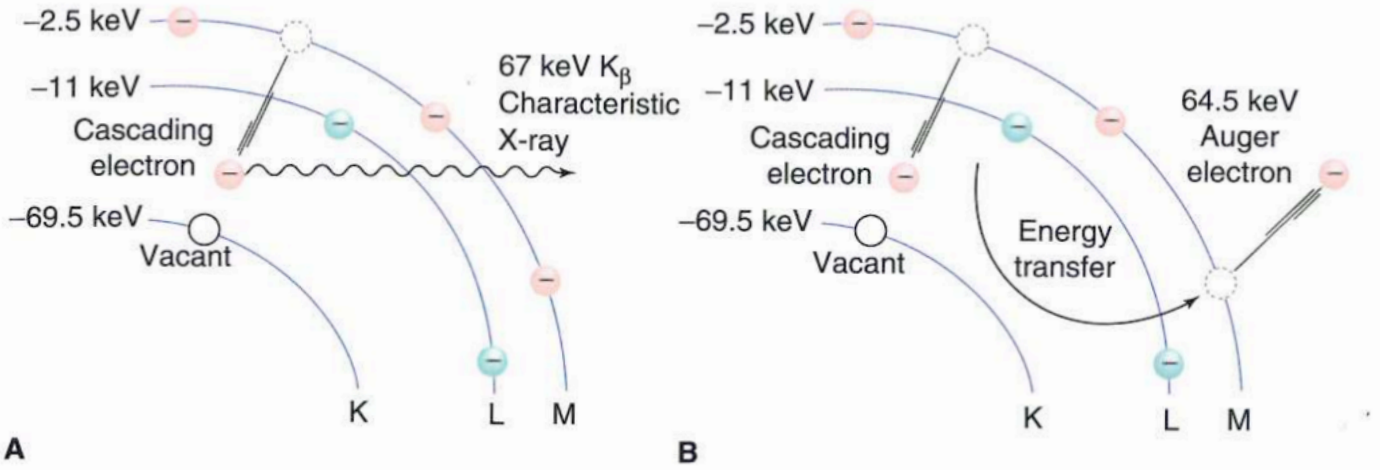
Energy required to remove 1 electron from K shell to Lshell is:

Hydrogen (Z=1): 13.5 eV – 3.4 eV = 10.1 eV

Tungsten (Z=74): 69500 eV – 11000 eV = 58500 eV (58.5 keV)

Radiation from electron transition

When an electron is removed from its shell by an x-ray or gamma ray photon or a charged particle interaction, a vacancy is created in that shell. This vacancy is usually filled by an electron from an outer shell, leaving a vacancy in the outer shell that in turn may be filled by an electron transition from a more distant shell. This series of transitions is called an *electron cascade*. The energy released by each transition is equal to the difference in binding energy between the original and final shells of the electron. This energy may be released by the atom as characteristic x-rays or Auger electrons.



■ FIGURE 2-7 De-excitation of a tungsten atom. An electron transition filling a vacancy in an orbit closer to the nucleus will be accompanied by either the emission of characteristic radiation (**A**) or the emission of an Auger electron (**B**).

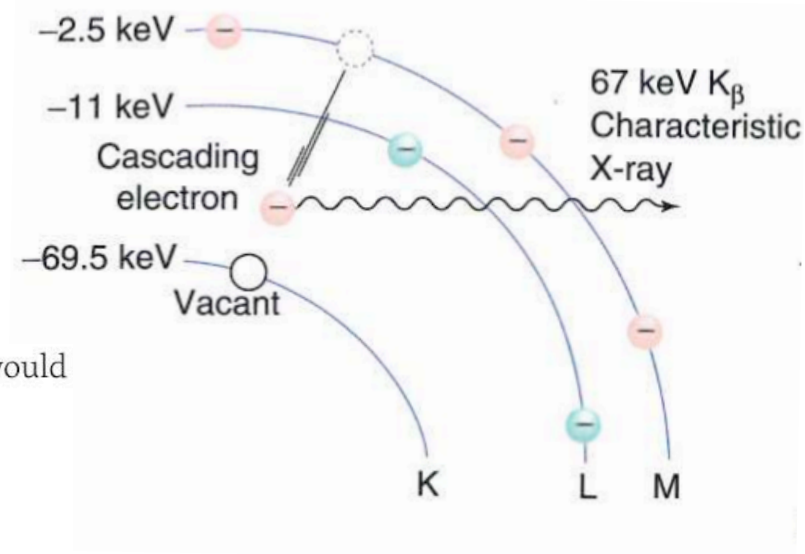
Ionizing radiation

Not all electromagnetic radiations can cause ionization.
In general, photons of higher frequency than far UV region of EM spectrum (i.e. wavelenght > 200 nm) have sufficient energy to remove bound electrons from atomic shell, producing ionized atoms and molecules.
Radiation in this range of the EM spectrum is called ionizing radiation (i.e. x-rays and gamma rays).
EM with photon energies in and below the UV region (i.e. visible, infrared, terahertz, microwave and radiowaves) is called non ionizing radiation.
The threshold energy for ionization depends on the type of matter.
The minimum energy necessary to remove an electron from calcium, glucose and liquid water are 6.1, 8.8, 11.2 eV, respectively.
Water is the most abundant molecular target in the body, so a practical radiobiological demarcation between ionizing and non ionizing EM radiation is about 11 eV. (lowest energy to produce ionization in water).

Characteristic X-rays

Electron transitions between atomic shells can result in the emission of radiation in the visible, UV, and x-ray portions of the EM spectrum. The energy of this radiation is characteristic of each atom, since the electron binding energies depend on Z. Emissions from transitions exceeding 100 eV are called *characteristic* or *fluorescent* x-rays. Characteristic x-rays are named according to the orbital in which the vacancy occurred. For example, the radiation resulting from a vacancy in the *K* shell is called a *K*-characteristic x-ray, and the radiation resulting from a vacancy in the *L* shell is called an *L* characteristic x-ray. If the vacancy in one shell is filled by the adjacent shell, it is identified by a subscript alpha (e.g., $L \rightarrow K$ transition $= K_{\alpha}$, $M \rightarrow L$ transition $= L_{\alpha}$). If the electron vacancy is filled from a nonadjacent shell, the subscript beta is used (e.g., $M \rightarrow K$ transition $= K_{\beta}$). The energy of the characteristic x-ray ($E_{x\text{-ray}}$) is the difference between the electron binding energies (E_b) of the respective shells:

$$E_{x\text{-ray}} = E_{b\ \text{vacant shell}} - E_{b\ \text{transition shell}} \qquad [2\text{-}5]$$



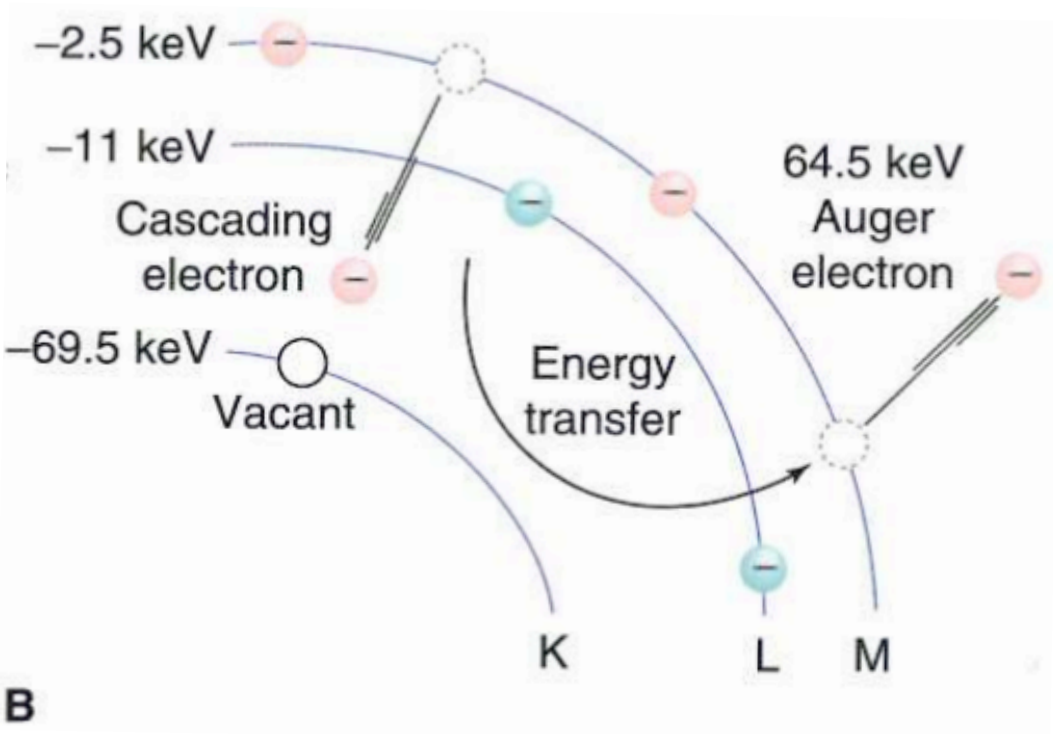
Thus, as illustrated in Figure 2-7A, an *M* to *K* shell transition in tungsten would produce a K_{β} characteristic x-ray of

$$E\ (K_{\beta}) = E_{bK} - E_{bM}$$

$$E\ (K_{\beta}) = 69.5\ \text{keV} - 2.5\ \text{keV} = 67\ \text{keV}$$

Auger electrons

An electron cascade does not always result in the production of a characteristic x–ray or x-rays. A competing process that predominates in low Z elements is *Auger electron emission*. In this case, the energy released is transferred to an orbital electron, typically in the same shell as the cascading electron (Fig. 2-7B). The ejected Auger electron possesses kinetic energy equal to the difference between the transition energy and the binding energy of the ejected electron.



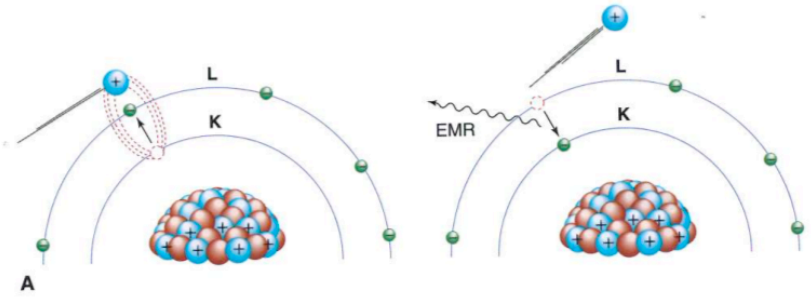
De-excitation of a tungsten atom. Electron transition filling a vacancy in an orbit closer to the nucleus accompanied by emission of an Auger electron (kinetic energy 67 keV-2.5 keV)

Fluorescent Yield

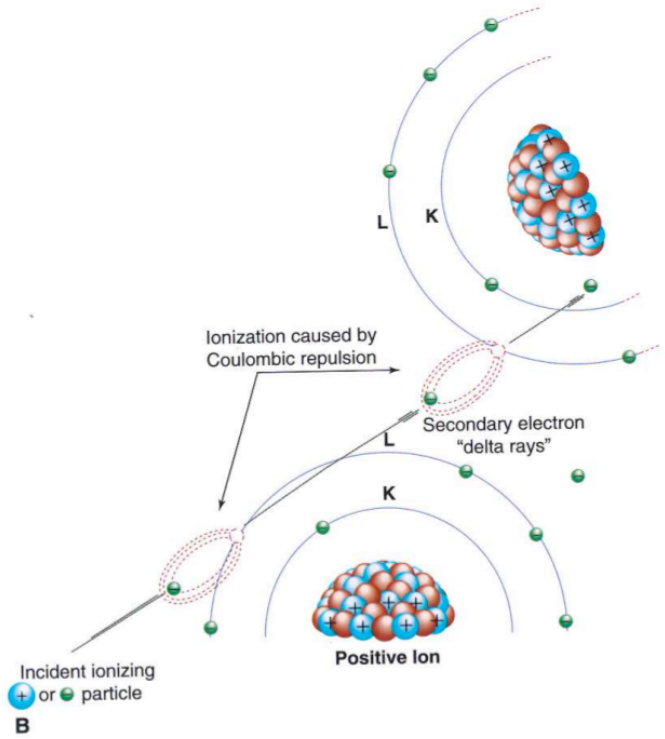
The probability that the electron transition will result in the emission of a characteristic x-ray is called the *fluorescent yield* (ω). Thus, $1-\omega$ is the probability that the transition will result in the ejection of an Auger electron. Auger emission predominates in low Z elements and in electron transitions of the outer shells of heavy elements. The *K*-shell fluorescent yield is essentially zero ($\leq 1\%$) for elements $Z < 10$ (i.e., the elements comprising the majority of soft tissue), about 15% for calcium ($Z = 20$), about 65% for iodine ($Z = 53$), and approaches 80% for $Z > 60$.

Charged particle interaction with matter

Energetic charged particles interact with matter by electrical (i.e., coulombic) forces and lose kinetic energy via *excitation*, *ionization*, and *radiative losses*. Excitation and ionization occur when charged particles lose energy by interacting with orbital electrons



Excitation and de-excitation with subsequent release of EM radiation



Ionization and production of delta rays

Specific ionization and charge particle tracks

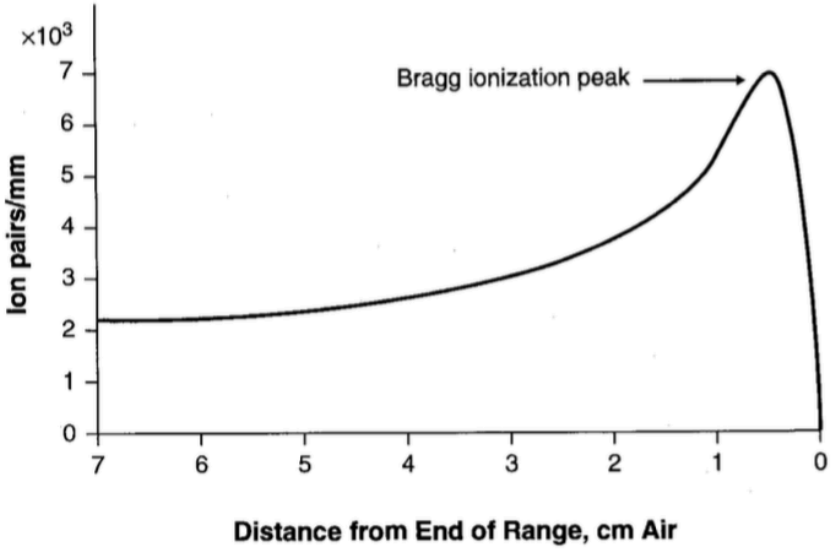


FIGURE 3-2. Specific ionization (ion pairs/mm) as a function of distance from the end of range in air for a 7.69-MeV alpha particle from polonium 214 (Po 214). Rapid increase in specific ionization reaches a maximum (Bragg peak) and then drops off sharply as the particle kinetic energy is exhausted and the charged particle is neutralized.

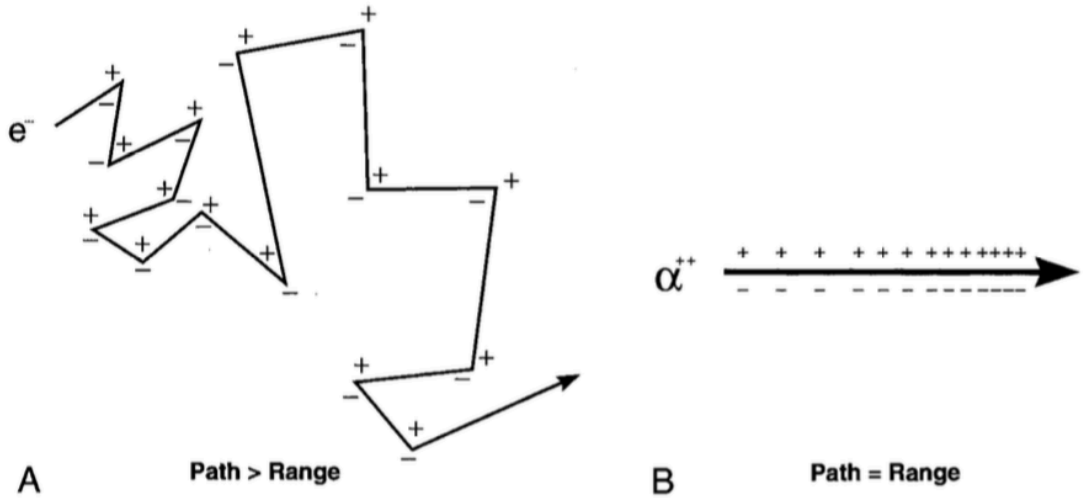


FIGURE 3-3. A: Electron scattering results in the path length of the electron being greater than its range. **B:** Heavily charged particles, like alpha particles, produce a dense nearly linear ionization track, resulting in the path and range being essentially equal.

Bremsstrahlung spectrum

According to classical theory, if a charged particle is accelerated it will radiate electromagnetic energy. When energetic electrons are incident upon a metal target (as in an x-ray tube), the electrons interact with the coulomb field of the nucleus of the target atoms and experience a change in their velocity, and hence undergo deceleration. *Bremsstrahlung radiation* ("braking radiation") is produced by this process. The total intensity of bremsstrahlung radiation (integrated over all angles and all energies) resulting from a charged particle of mass m and charge ze incident onto target nuclei with charge Ze is proportional to:

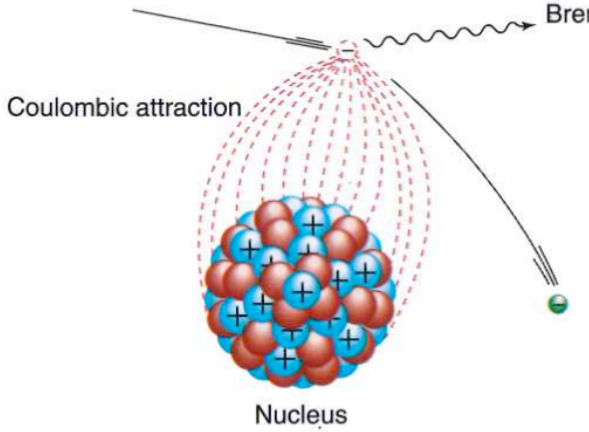
$$I_{\text{bremsstrahlung}} \propto \frac{Z^2 z^4 e^6}{m^2}. \tag{1.3}$$

The bremsstrahlung efficiency is markedly reduced if a massive particle such as a proton or alpha particle is the charged particle. Relative to an electron, protons and α particles are over 3 million times less efficient (1836^{-2}) than electrons at producing bremsstrahlung x rays. Electrons therefore become the practical choice for producing bremsstrahlung. The Z^2 term in Eq. (1.3) also indicates that bremsstrahlung production increases rapidly as the atomic number of the target increases, suggesting that high-Z targets are preferred.

Bremsstrahlung

While most electron interactions with the atomic nuclei are elastic, electrons can undergo inelastic interactions in which the path of the electron is deflected by the positively charged nucleus, with a loss of kinetic energy. This energy is instantaneously emitted as electromagnetic radiation (i.e., x-rays). Energy is conserved, as the energy of the radiation is equal to the kinetic energy lost by the electron.

The radiation emission accompanying electron deceleration is called *bremsstrahlung*, a German word meaning "braking radiation" (Fig. 3-4). The deceleration of the high-speed electrons in an x-ray tube produces the bremsstrahlung x-rays used in diagnostic imaging.



■ FIGURE 3-4 Radiative energy loss via bremsstrahlung (braking radiation).

Bremsstrahlung emission per atom is proportional to Z^2 and inversely proportional to the square mass of the incident particle ~ Z^2/m^2

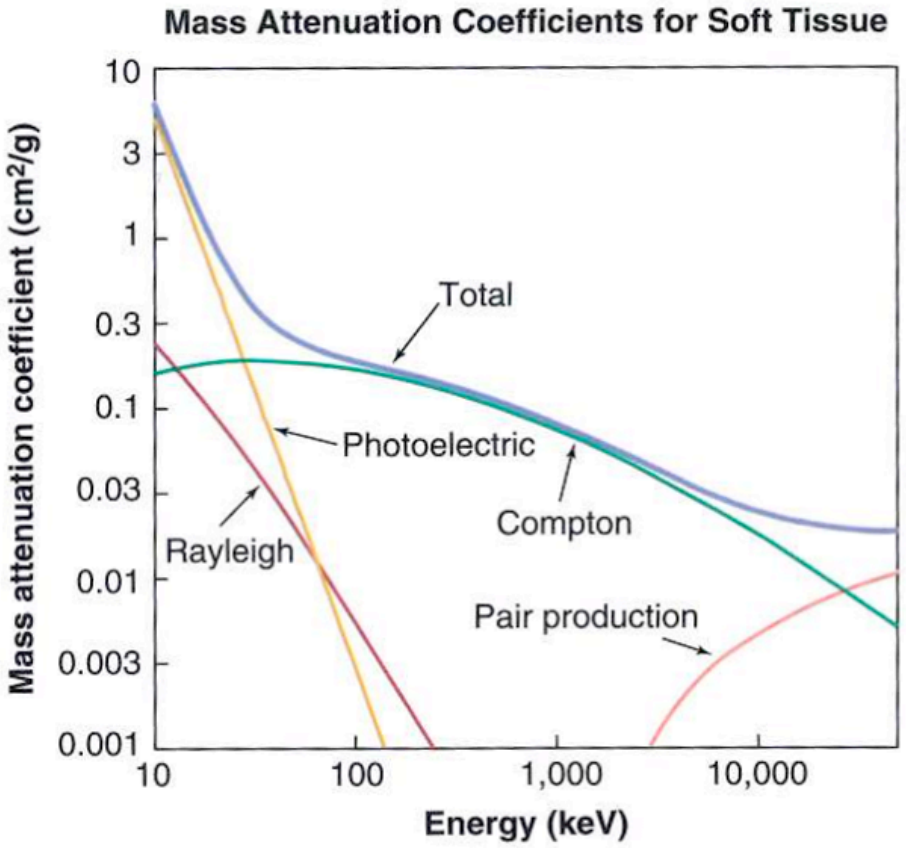
The energy of the Bremsstrahlung x-ray photons can have any value up to the entire kinetic energy of the deflected electron.

X-ray interaction with matter

The 4 major interactions of x-ray and gamma-ray photons with matter are:

- Photoelectric effect
- Rayleigh scattering
- Compton scattering
- Pair production (above 1.022 MeV)

■ FIGURE 3-13 Graph of the Rayleigh, photoelectric, Compton, pair production, and total mass attenuation coefficients for soft tissue ($Z \approx 7$) as a function of photon energy.



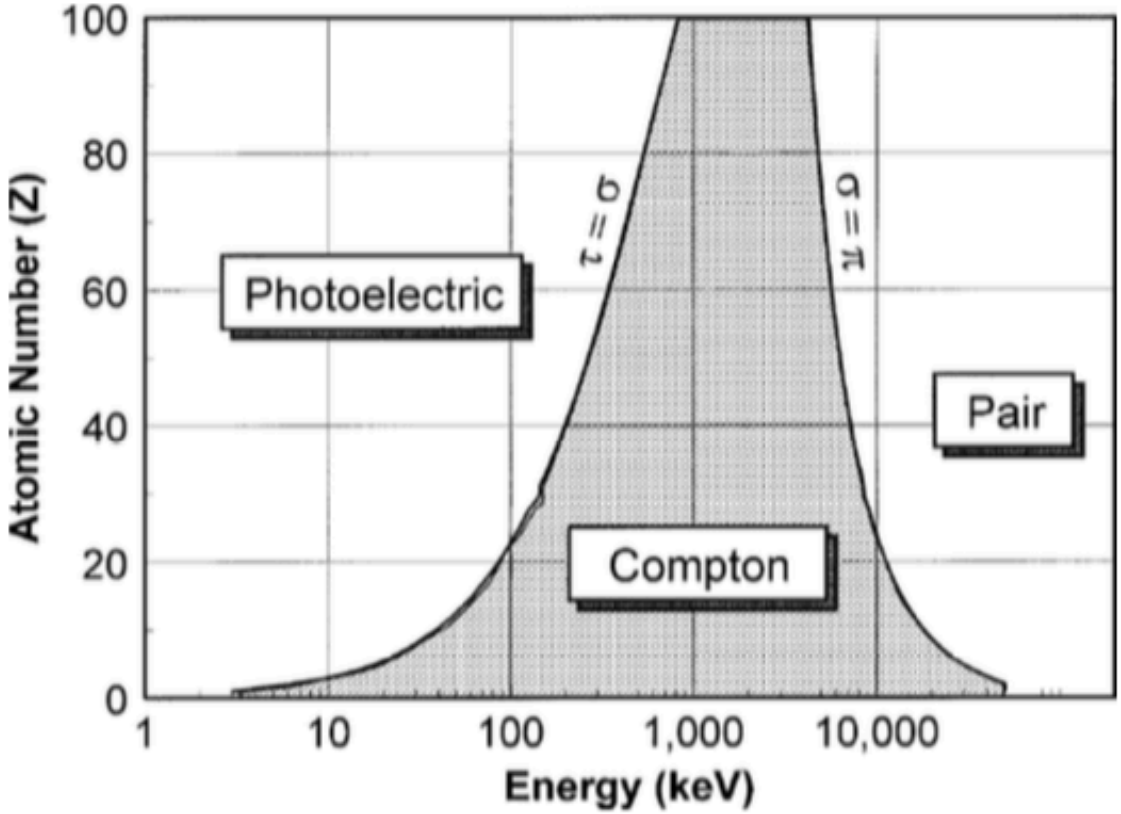


Figure 1.27: The region where each x-ray interaction process is most likely is shown as a function of atomic number and x-ray energy. The transition zones between regions correspond to the two cross sections being equal ($\tau = \sigma$ and $\sigma = \pi$).

Rayleigh scattering

In Rayleigh scattering no ionization occurs: the energy of the scattered photon is equal to the incident photon

In Rayleigh scattering the incident photon interacts with the total atom and excites. It occurs mainly with very low energy x-rays (such as those used in mammography). The electric field of the incident electromagnetic wave expends energy, causing all of the electrons in the atom to oscillate in phase. The atom's electron cloud radiates this energy, emitting a photon of the same energy but with a slightly different direction.

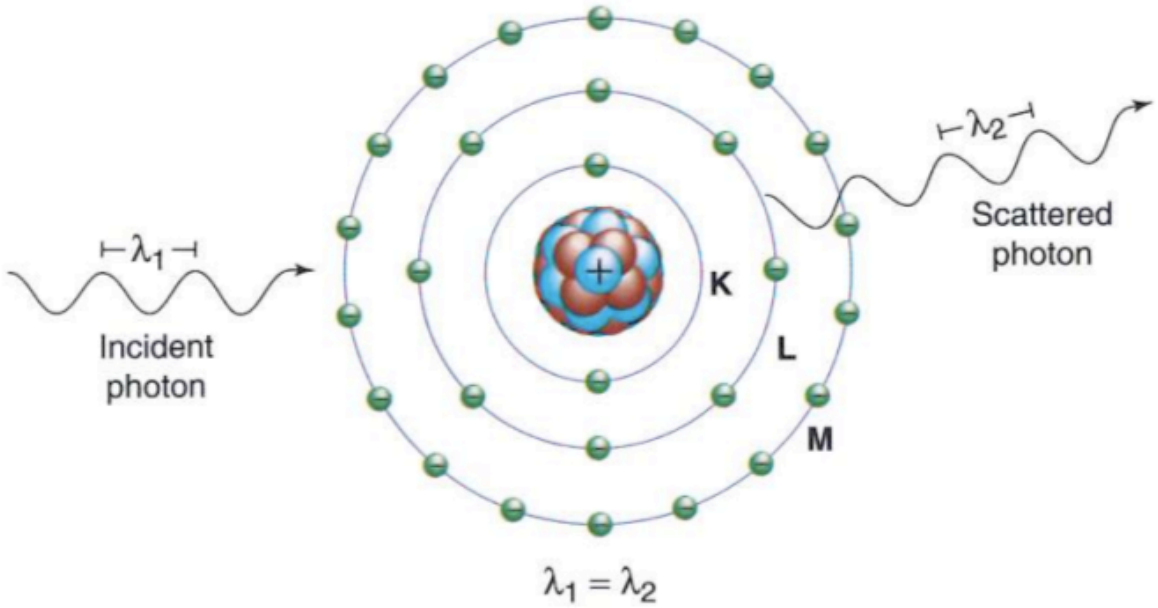


FIGURE 3-6 Rayleigh scattering. The diagram shows that the incident photon λ_1 interacts with an atom and the scattered photon λ_2 is being emitted with the same wavelength and energy. Rayleigh scattered photons are typically emitted in the forward direction fairly close to the trajectory of the incident photon. *K*, *L*, and *M* are electron shells.

Rayleigh scattering

In this interaction, electrons are not ejected, and thus, ionization does not occur. In general, the average scattering angle decreases as the x-ray energy increases. In medical imaging, detection of the scattered x-ray will have a deleterious effect on image quality. However, this type of interaction has a low probability of occurrence in the diagnostic energy range. In soft tissue, Rayleigh scattering accounts for less than 5% of x-ray interactions above 70 keV and at most only accounts for about 10% of interactions at 30 keV. Rayleigh interactions are also referred to as "coherent" or "classical" scattering.

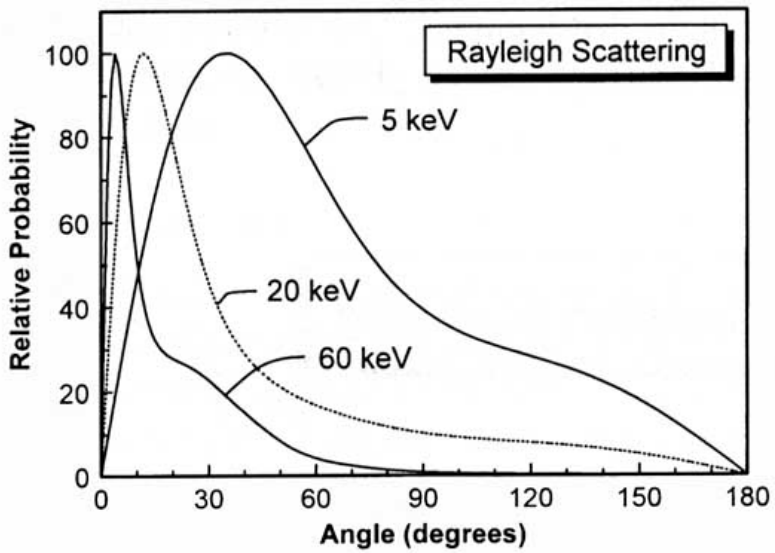


Figure 1.16: The probability density functions for Rayleigh scattering angles are illustrated for three x-ray energies in water. As the x-ray energy increases, forward scattering (small angle scattering) becomes increasingly likely. The PDF at each x-ray energy is normalized to 100%.

Photoelectric effect

In the photoelectric effect, all of the incident photon energy is transferred to an electron, which is ejected from the atom. The kinetic energy of the ejected *photoelectron* (E_{pe}) is equal to the incident photon energy (E_o) minus the binding energy of the orbital electron (E_b) (Fig. 3-9 left).

$$E_{pe} = E_o - E_b$$

In order for photoelectric absorption to occur, the incident photon energy must be greater than or equal to the binding energy of the electron that is ejected. The ejected electron is most likely one whose binding energy is closest to, but less than, the incident photon energy.

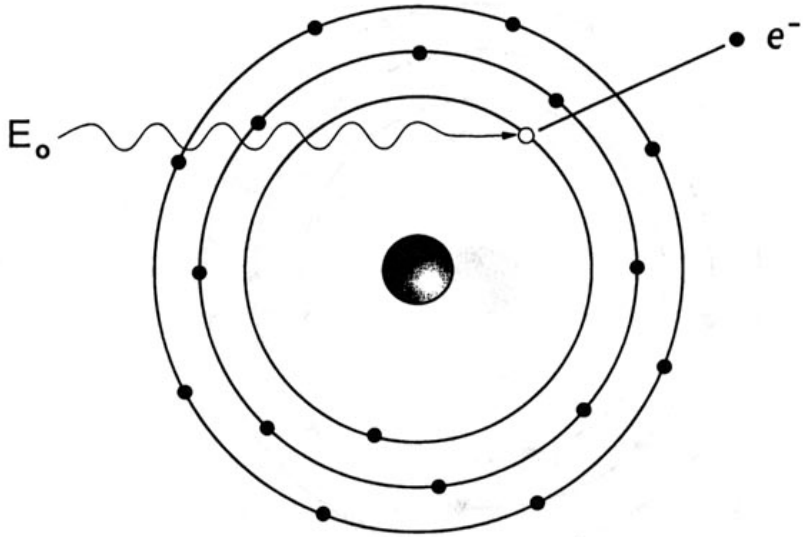
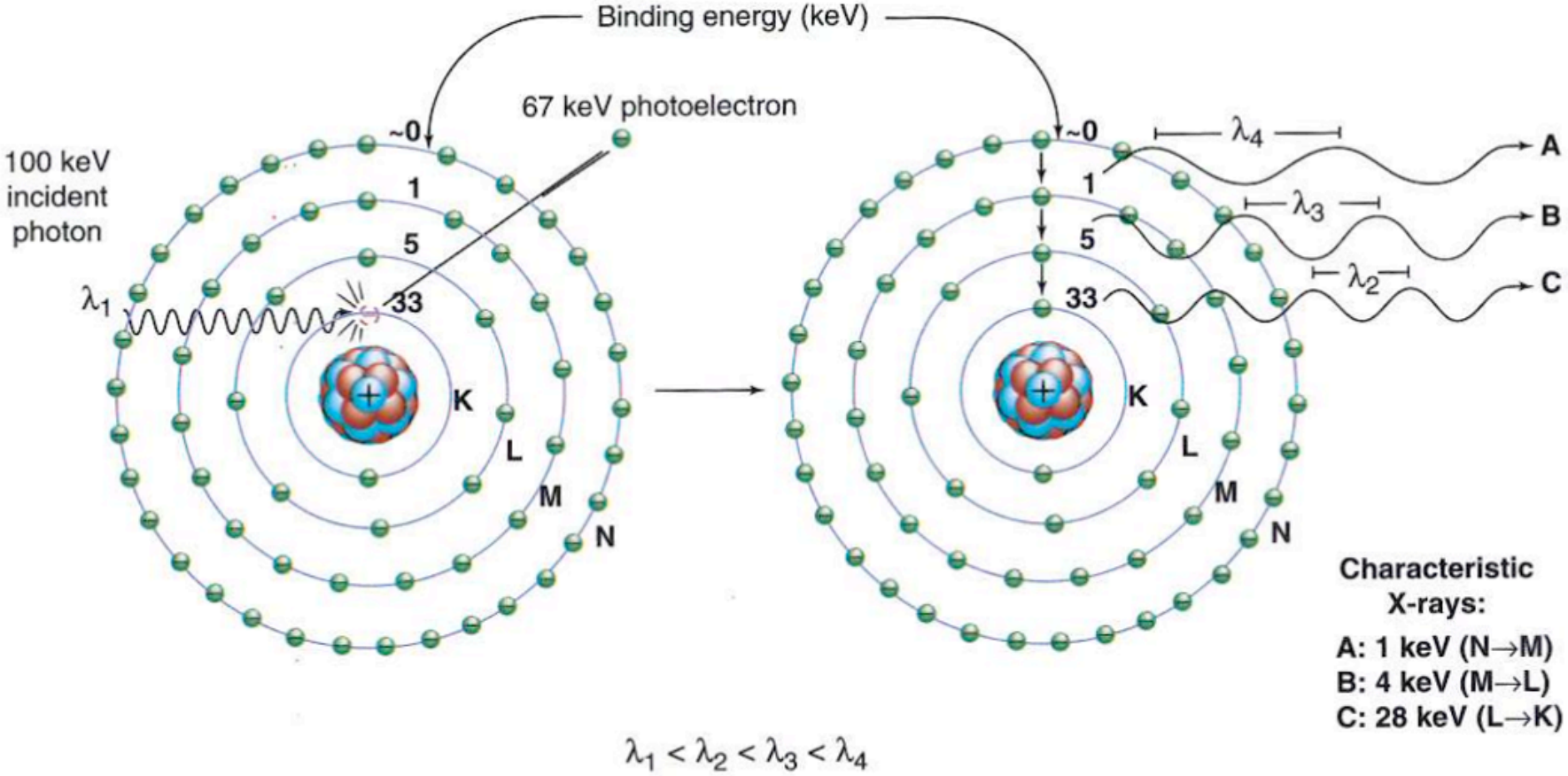


Figure 1.13: In the photoelectric effect, an x ray with energy E_0 is absorbed by an atomic electron, which is ejected from the atom causing ionization. The photoelectron will have kinetic energy equal to $E_0 - E_{BE}$, where E_{BE} is the binding energy of the electron to the nucleus.

Photoelectric effect



■ FIGURE 3-9 Photoelectric absorption. **Left**. The diagram shows that a 100-keV photon is undergoing photoelectric absorption with an iodine atom. In this case, the *K*-shell electron is ejected with a kinetic energy equal to the difference (67 keV) between the incident photon energy (100 keV) and the *K*-shell binding energy (33 keV). **Right**. The vacancy created in the *K* shell results in the transition of an electron from the *L* shell to the *K* shell. The difference in their binding energies (i.e., 33 and 5 keV) results in a 28-keV K_α characteristic x-ray. This electron cascade will continue, resulting in the production of other characteristic x-rays of lower energies. Note that the sum of the characteristic x-ray energies equals the binding energy of the ejected photoelectron (33 keV). Although not shown on this diagram, Auger electrons of various energies could be emitted in lieu of the characteristic x-ray emissions.

Photoelectric effect

The probability of photoelectric absorption per unit mass is approximately proportional to Z^3/E^3, where Z is the atomic number and E the energy of the incident photon.

In photoelectric absorption there are no scattered photons to degrade the image.

Since the probability of photoelectric interaction in proportional to $1/E^3$, image contrast decreases when higher energies are used for imaging.

For example, the probability for iodine (Z=53) is $(53/20)^3$ or 18.6 times greater than in calcium (Z=20) for a fixed x-ray energy

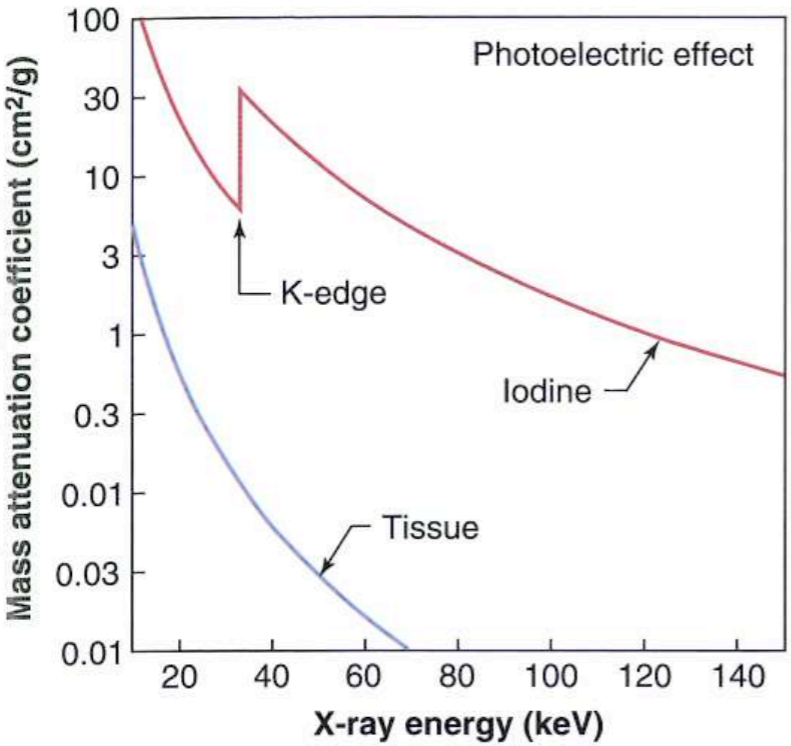
EXAMPLE: The *K*- and *L*-shell electron binding energies of iodine are 33 and 5 keV, respectively. If a 100-keV photon is absorbed by a *K*-shell electron in a photoelectric interaction, the photoelectron is ejected with a kinetic energy equal to $E_o - E_b = 100 - 33 = 67$ keV. A characteristic x-ray or Auger electron is emitted as an outer-shell electron fills the *K*-shell vacancy (e.g., *L* to *K* transition is $33 - 5 = 28$ keV). The remaining energy is released by subsequent cascading events in the outer shells of the atom (i.e., *M* to *L* and *N* to *M* transitions). Note that the total of all the characteristic x-ray emissions in this example equals the binding energy of the *K*-shell photoelectron (Fig. 3-9, right).

Thus, photoelectric absorption results in the production of

1. A photoelectron
2. A positive ion (ionized atom)
3. Characteristic x-rays or Auger electrons

Photoelectric effect

Although the probability of the photoelectric effect decreases, in general, with increasing photon energy, there is an exception. For every element, the probability of the photoelectric effect, as a function of photon energy, exhibits sharp discontinuities called *absorption edges* (see Fig. 3-10). The probability of interaction for photons of energy just above an absorption edge is much greater than that of photons of energy slightly below the edge. For example, a 33.2-keV x-ray photon is about six times as likely to have a photoelectric interaction with an iodine atom as a 33.1-keV photon.



■ **FIGURE 3-10** Photoelectric mass attenuation coefficients for tissue ($Z_{effective}$ = 7), and iodine (Z = 53) as a function of energy. Abrupt increase in the attenuation coefficients called "absorption edges" occur due to increased probability of photoelectric absorption when the photon energy just exceeds the binding energy of inner-shell electrons (e.g., *K, L, M,*...), thus increasing the number of electrons available for interaction. This process is very significant in high-Z elements, such as iodine and barium, for x-rays in the diagnostic energy range.

Photoelectric effect

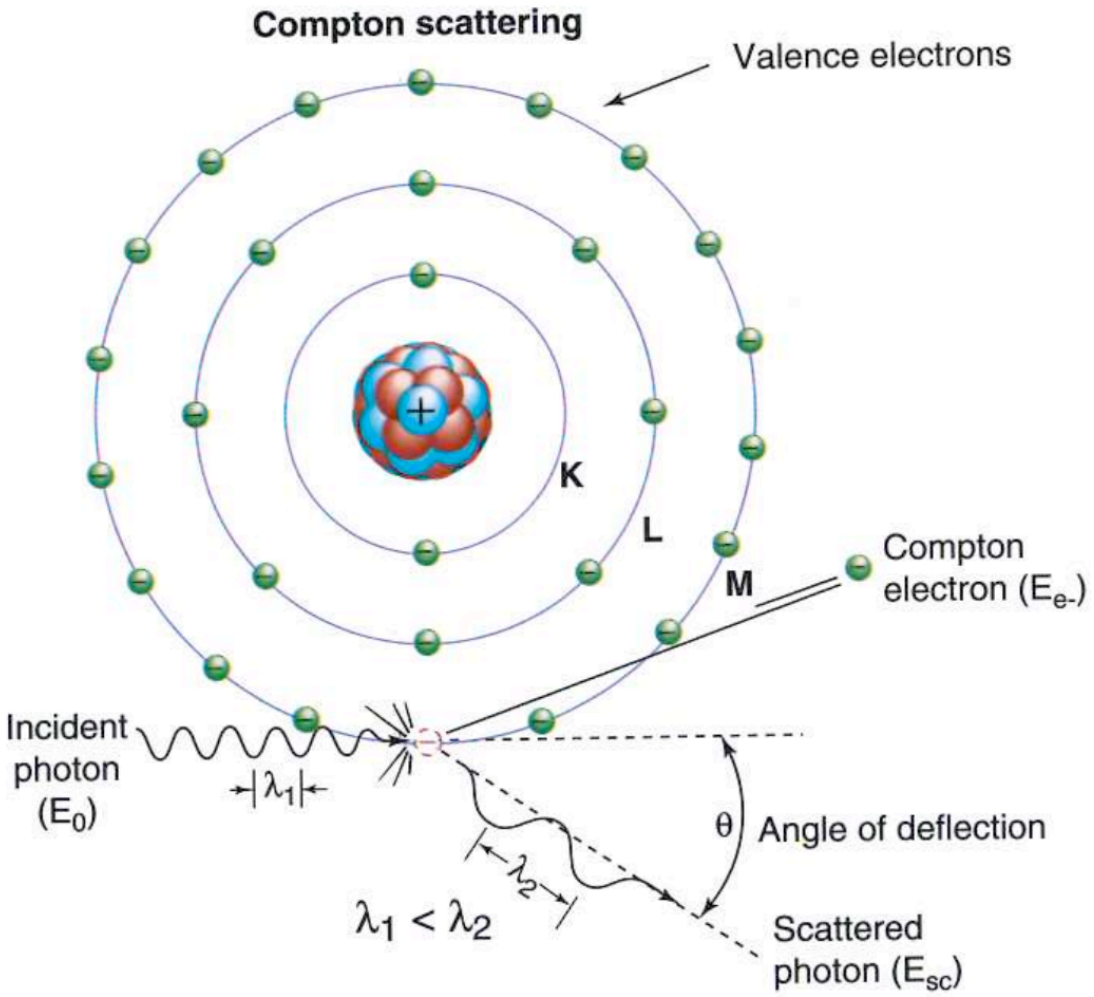
As mentioned above, a photon cannot undergo a photoelectric interaction with an electron in a particular atomic shell or subshell if the photon's energy is less than the binding energy of that shell or subshell. This causes the dramatic decrease in the probability of photoelectric absorption for photons whose energies are just below the binding energy of a shell. Thus, the photon energy corresponding to an absorption edge is the binding energy of the electrons in that particular shell or subshell. An absorption edge is designated by a letter, representing the atomic shell of the electrons, followed by a number denoting the subshell (e.g., *K*, *L*1, *L*2, *L*3, etc.). The photon energy corresponding to a particular absorption edge increases with the atomic number (Z) of the element. For example, the primary elements comprising soft tissue (H, C, N, and O) have absorption edges below 1 keV. The elements iodine (Z = 53) and barium (Z = 56), commonly used in radiographic contrast agents to provide enhanced x-ray attenuation, have *K*-absorption edges of 33.2 and 37.4 keV, respectively (Fig. 3-10). The *K*-edge energy of lead (Z = 82) is 88 keV.

At photon energies below 50 keV, the photoelectric effect plays an important role in imaging soft tissue. The photoelectric absorption process can be used to amplify differences in attenuation between tissues with slightly different atomic numbers, thereby improving image contrast. This differential absorption is exploited to improve image contrast in the selection of x-ray tube target material and filters in mammography

Compton scattering

Compton scattering (inelastic scattering) is predominant interaction in diagnostic energy range of soft tissue above 26 kev and also up to approximately 30 MeV. An incident x-ray with energy E_0 interacts with an outer- (valence) shell electron which is ejected. For conservation of energy and momentum:

$$E_0 = E_{sc} + E_{electron}$$



■ FIGURE 3-7 Compton scattering. The diagram shows the incident photon with energy E_0, interacting with a valence-shell electron that results in the ejection of the Compton electron (E_{e-}) and the simultaneous emission of a Compton scattered photon E_{sc} emerging at an angle θ relative to the trajectory of the incident photon. *K*, *L*, and *M* are electron shells.

Compton scattering

Compton scattering results in the ionization of the atom and a division of the incident photon's energy between the scattered photon and the ejected electron. The ejected electron will lose its kinetic energy via excitation and ionization of atoms in the surrounding material. The Compton scattered photon may traverse the medium without interaction or may undergo subsequent interactions

The energy of the scattered photon can be calculated from the energy of the incident photon and the angle of the scattered photon with respect to the incident trajectory

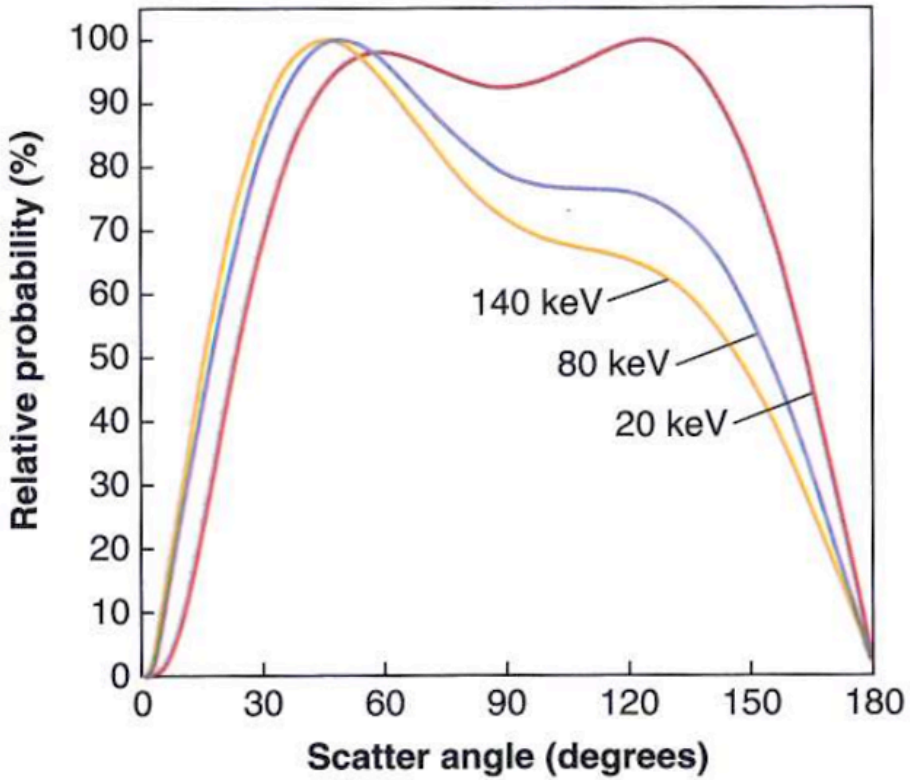
$$E_{sc} = \frac{E_o}{1 + \frac{E_o}{511\ \text{keV}}(1 - \cos\theta)}$$

where E_{sc} = the energy of the scattered photon, E_o = the incident photon energy, and θ = the angle of the scattered photon.

Compton scattering: angular distribution

As the incident photon energy increases, both scattered photons and electrons are scattered more toward the forward direction (Fig. 3-8). In x-ray transmission imaging, these photons are much more likely to be detected by the image receptor. In addition, for a given scattering angle, the fraction of energy transferred to the scattered photon decreases with increasing incident photon energy. Thus, for higher energy incident photons, the majority of the energy is transferred to the scattered electron. For example, for a 60-degree scattering angle, the scattered photon energy (E_{sc}) is 90% of the incident photon energy (E_o) at 100 keV but only 17% at 5 MeV.

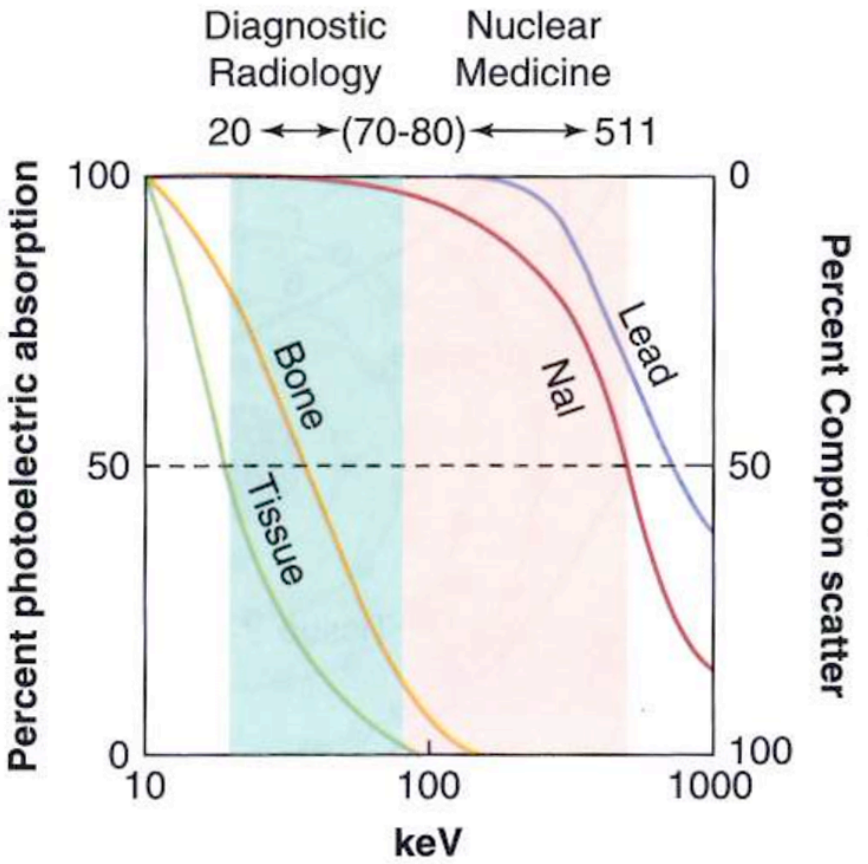
■ **FIGURE 3-8** Graph illustrates relative Compton scatter probability as a function of scattering angle for 20-, 80-, and 140-keV photons in tissue. Each curve is normalized to 100%. (From Bushberg JT. The AAPM/RSNA physics tutorial for residents. X-ray interactions. *RadioGraphics* 1998;18:457–468, with permission.)



Compton vs. Photoelectric

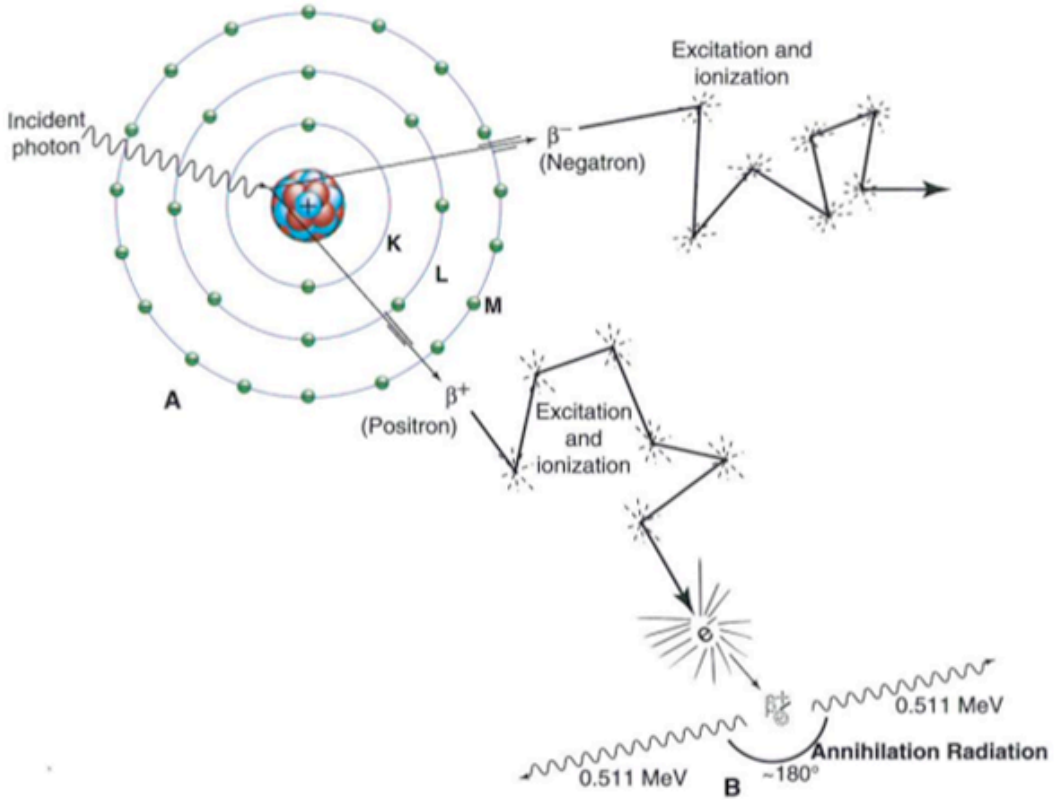
The photoelectric process predominates when lower energy photons interact with high Z materials (Fig. 3-11). In fact, photoelectric absorption is the primary mode of interaction of diagnostic x-rays with screen phosphors, radiographic contrast materials, and bone. Conversely, Compton scattering will predominate at most diagnostic photon energies in materials of lower atomic number such as tissue and air.

■ FIGURE 3-11 Graph of the percentage of contribution of photoelectric (**left scale**) and Compton (**right scale**) attenuation processes for various materials as a function of energy. When diagnostic energy photons (i.e., diagnostic x-ray effective energy of 20 to 80 keV; nuclear medicine imaging photons of 70 to 511 keV) interact with materials of low atomic number (e.g., soft tissue), the Compton process dominates.



Pair production

Pair production can only occur when the energies of x-rays and gamma rays exceed 1.02 MeV. In pair production, an x-ray or gamma ray interacts with the electric field of the nucleus of an atom. The photon's energy is transformed into an electron-positron pair (Fig. 3-12A). The rest mass energy equivalent of each electron is 0.511 MeV, and this is why the energy threshold for this reaction is 1.02 MeV. Photon energy in excess of this threshold is imparted to the electron (also referred to as a negatron or beta minus particle) and positron as kinetic energy. The electron and positron lose their kinetic energy via excitation and ionization. As discussed previously, when the positron comes to rest, it interacts with a negatively charged electron, resulting in the formation of two oppositely directed 0.511-MeV annihilation photons (Fig. 3-12B).



Pair production

Pair production does not occur at diagnostic x-ray energies

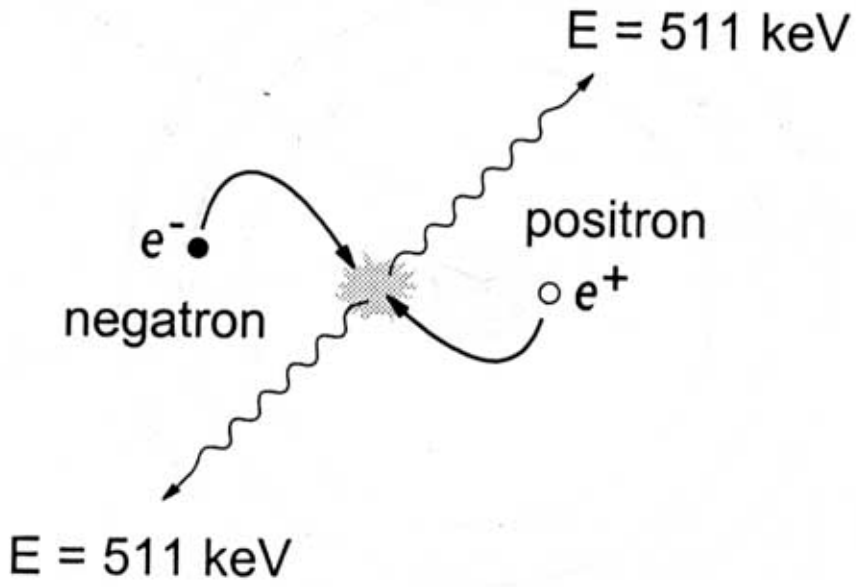


Figure 1.21: The positrons produced in pair and triplet production will lose their kinetic energy by interaction with the medium, and then rapidly interact with any available negative electron (negatron) and *annihilate*, producing two 511-keV photons being emitted in opposite directions. The photons produced are called *annihilation radiation*.