Medical Equipment II - 2010

Chapter 15: Interaction of Photons and Charged Particles with Matter(3)

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Web: http://ymk.k-space.org/courses.htm

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Pair Production

- High energy (γ,*e*$^+$ *e*$^-$) *interaction*

$$h\nu_0 = T_+ + m_e c^2 + T_- + m_e c^2 = T_+ + T_- + 2m_e c^2.$$

- One can show that momentum is not conserved by the positron and electron if the former equation is satisfied.
  - Interaction takes place in the Coulomb field of another particle (usually a nucleus) that recoils to conserve momentum.
  - Cross section for pair production involving nucleus is κ_n.

Pair Production

- Pair production with excitation or ionization of the recoil atom can take place at energies that are only slightly higher than the threshold
  - Cross section does not become appreciable until the incident photon energy exceeds *2.04 MeV*
  - A free electron (rather than a nucleus) recoils to conserve momentum.
  - $(\gamma, e^{+}\ e^{-}\ e^{-})$ process : Triplet production.
- Total cross section: $\kappa = \kappa_n + \kappa_e$

Linear Attenuation Coefficient

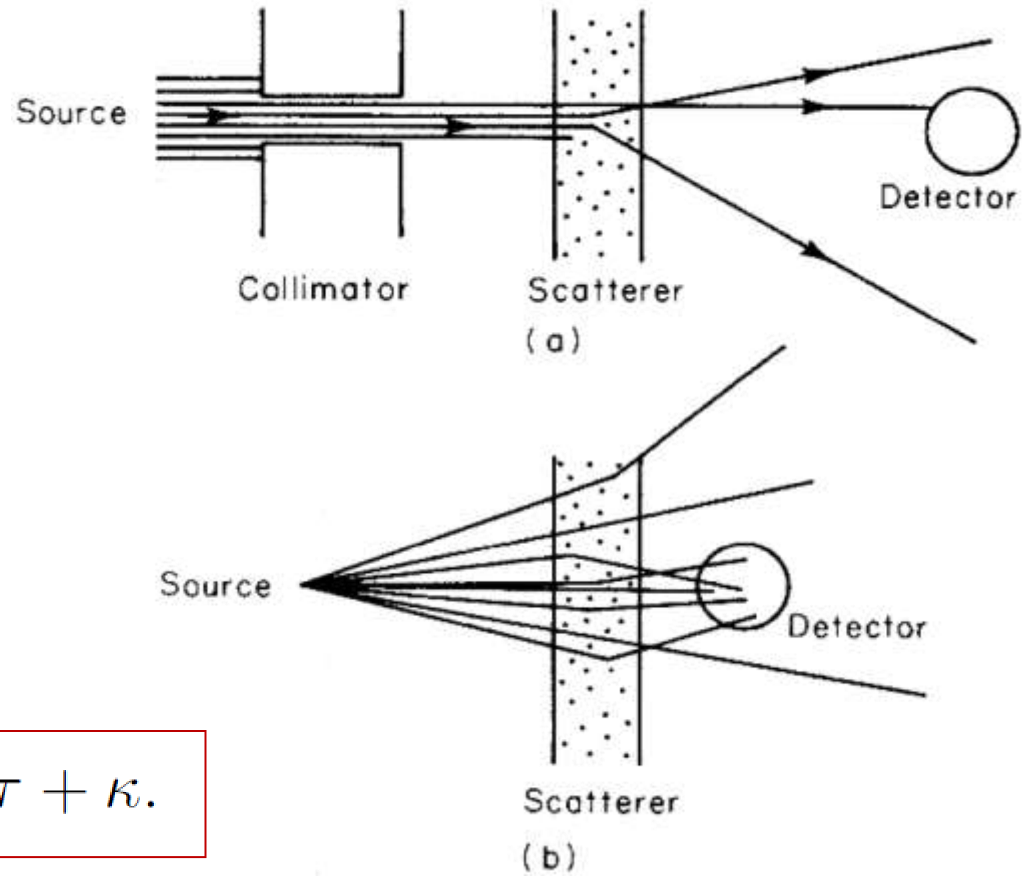
- Narrow- vs. Broad-beam geometries
  - Idealization ?

$$dN = -\frac{\sigma_{\text{tot}} N_A \rho}{A} N \, dz,$$

$$N(z) = N_0 e^{-\mu_{\text{atten}} z}.$$

$$\mu_{\text{atten}} = \frac{N_A \rho \sigma_{\text{tot}}}{A}.$$

$$\sigma_{\text{tot}} = \sigma_{\text{coh}} + \sigma_{\text{incoh}} + \tau + \kappa.$$



Mass Attenuation Coefficient

- Mass attenuation coefficient
  - Independent of density: very useful in gases

$$\frac{\mu_{\mathrm{atten}}}{\rho} = \frac{N_A \sigma_{\mathrm{tot}}}{A}.$$

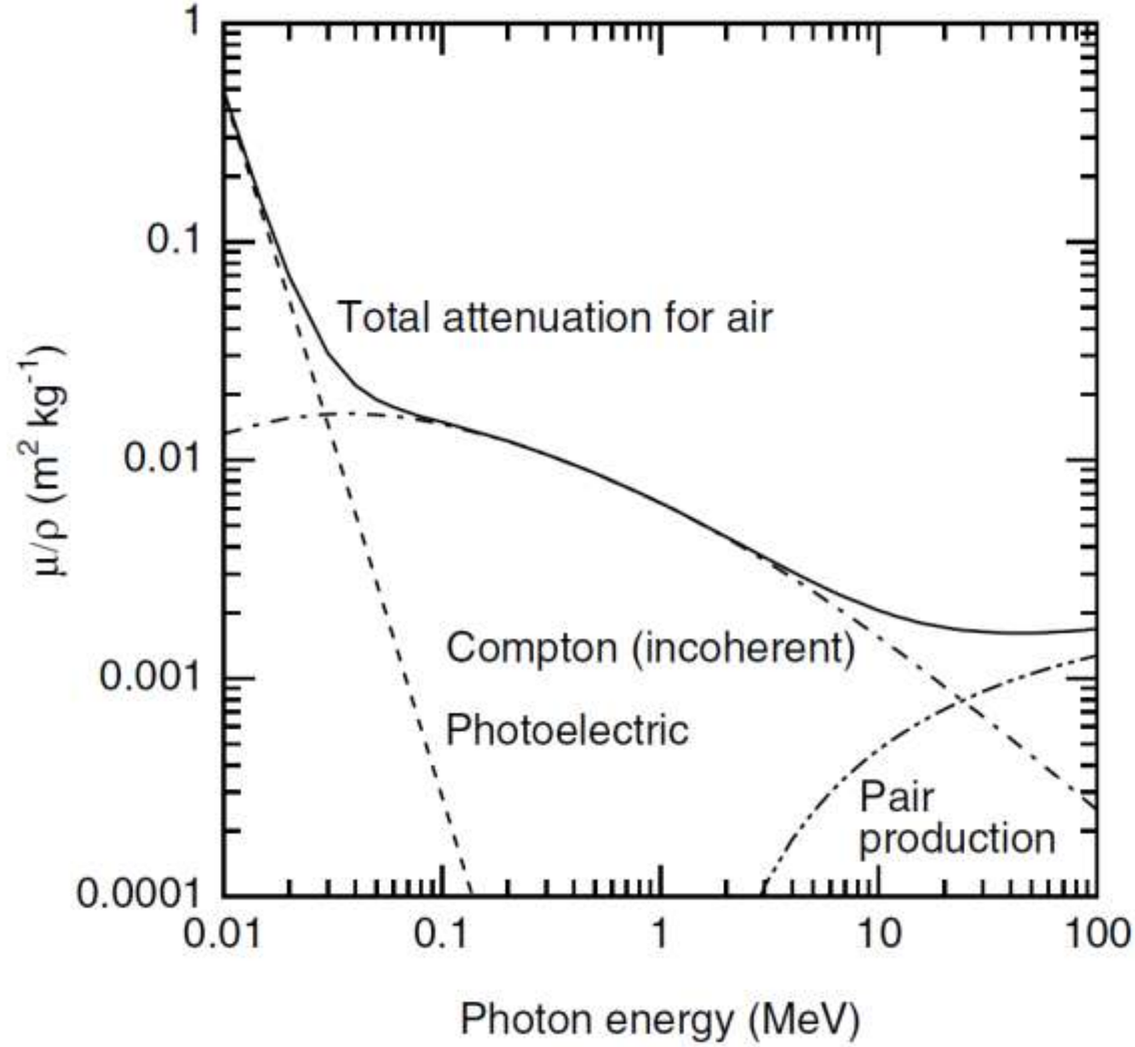
$$\Rightarrow$$

$$N(\rho z) = N_0 e^{-(\mu_{\mathrm{atten}}/\rho)(\rho z)}.$$

  - Additional advantage in incoherent scattering: Z/A is nearly ½ for all elements except H^1: minor variations over periodic table

$$\frac{\mu_{\mathrm{atten}}}{\rho} = \frac{Z \sigma_C N_A}{A}$$

Mass Attenuation Coefficient



Compounds and Mixtures

- Usual procedure for dealing with mixtures and compounds is to assume that each atom scatters independently.

$$w_i = \frac{a_i A_i}{A_{\text{mol}}}$$

$$\frac{\overline{n}}{N} = \sum_i \sigma_i (N_T)_i = \left(\sum_i \sigma_i (N_{TV})_i \right) dz,$$

$$(N_{TV})_i = \frac{M_i N_A}{A_i V} = \frac{w_i}{A_i} \rho N_A.$$

$$\begin{aligned} \sum_i \sigma_i (N_{TV})_i &= \left(\sum_i \frac{a_i \sigma_i}{A_{\text{mol}}} \right) \rho N_A \\ &= \left(\sum_i a_i \sigma_i \right) \frac{\rho N_A}{A_{\text{mol}}} = \sigma_{\text{mol}} (N_{TV})_{\text{mol}}. \end{aligned}$$

Compounds and Mixtures

- When a target entity (molecule) consists of a collection of subentities (atoms), we can say that in this approximation (all subentities interacting independently), the cross section per entity is the sum of the cross sections for each subentity.
  - For example, for CH4, total molecular cross section is $\sigma_{carbon} + 4\sigma_{hydrogen}$ *and the molecular weight is* $[(4 \times 1) + 12 = 16]\times 10^{-3}$ *kg* mol^{-1}

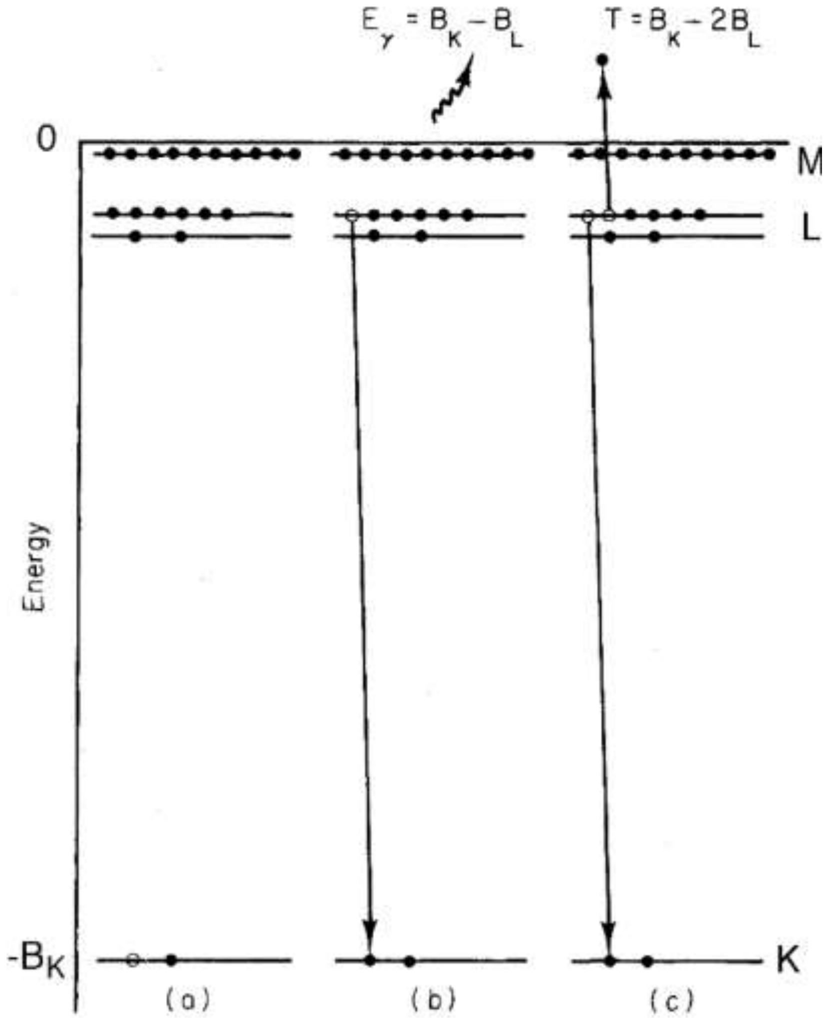
Deexcitation of Atoms

- Excited atom is left with a hole in some electron shell.
  - Similar state when an electron is knocked out by a passing charged particle or by certain transformations in the atomic nucleus
- Two competing processes:
  - Radiative transition: photon is emitted as an electron falls into the hole from a higher level,
  - Nonradiative or radiationless transition: emission of an Auger electron

Deexcitation of Atoms

Process	Total photon energy	Total electron energy	Atom excitation energy	Sum
Before photon strikes atom	$h\nu$	0	0	$h\nu$
After photoelectron is ejected [Fig. 15.12(a)]	0	$h\nu - B_K$	B_K	$h\nu$
Case 1: Deexcitation by the emission of a K and an L photon				
Emission of K fluorescence photon [Fig. 15.12(b)]	$B_K - B_L$	$h\nu - B_K$	B_L	$h\nu$
Emission of L fluorescence photon	$B_K - B_L$, B_L	$h\nu - B_K$	0	$h\nu$
Case 2: Deexcitation by emission of an Auger electron from the L shell				
Emission of Auger electron [Fig. 15.12(c)]	0	$h\nu - B_K$, $B_K - 2B_L$	$2B_L$	$h\nu$
First L-shell hole filled by fluorescence	B_L	$h\nu - B_K$, $B_K - 2B_L$	B_L	$h\nu$
Second L-shell hole filled by fluorescence	B_L, B_L	$h\nu - B_K$, $B_K - 2B_L$	0	$h\nu$

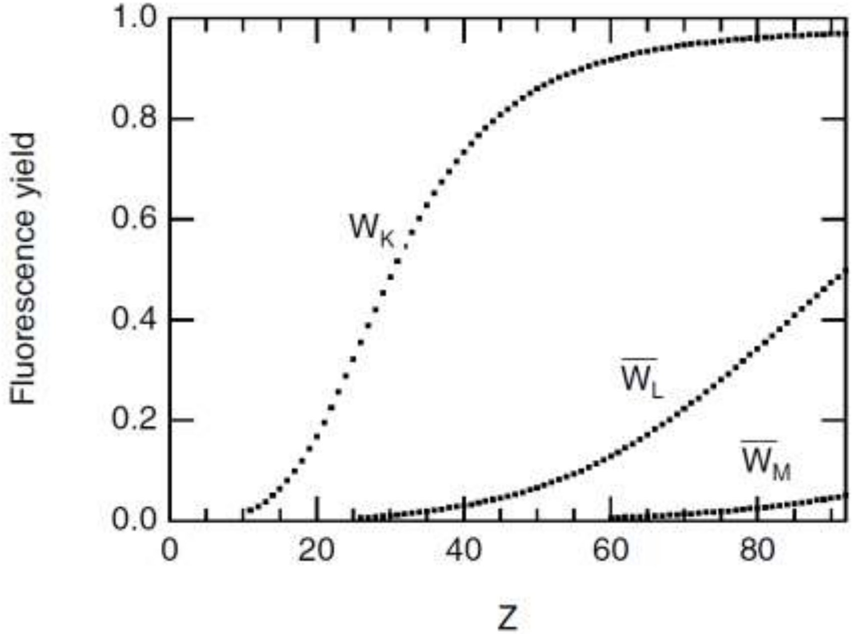
Deexcitation of Atoms



$$\Delta l = \pm 1, \qquad \Delta j = 0, \pm 1.$$

Deexcitation of Atoms

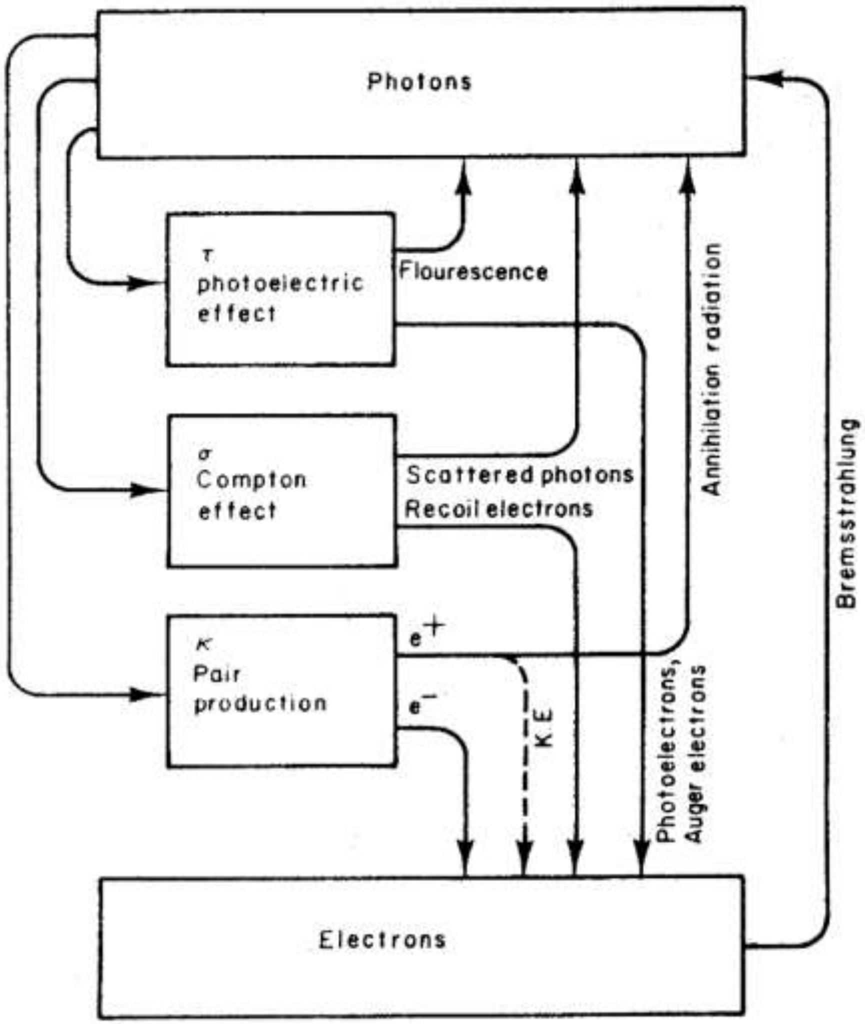
- Probability of photon emission is called the fluorescence yield, W_K.
  - *Auger yield is $A_K = 1 - W_K$.*
  - *L* or higher shells: consider yield for each subshell



Deexcitation of Atoms

- Coster–Kronig transitions
  - Radiationless transitions within the subshell
  - Hole in L_I-shell can be filled by an electron from the L_{III}-shell with the ejection of an M-shell electron
- Super-Coster–Kronig transitions
  - Involves electrons all within same shell (e.g., all M)
- Auger cascade
  - Bond breaking – important for radioactive isotopes

Energy Transfer from Photons to Electrons

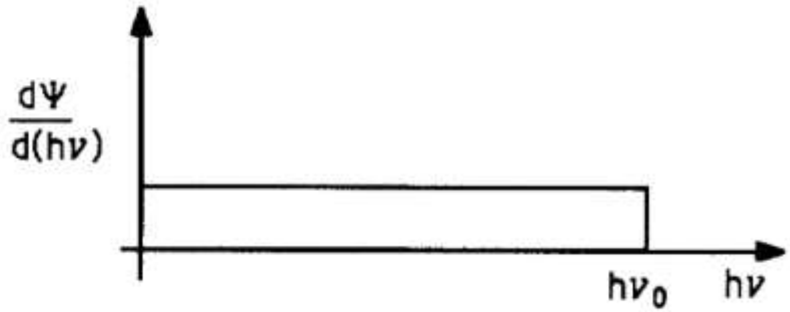


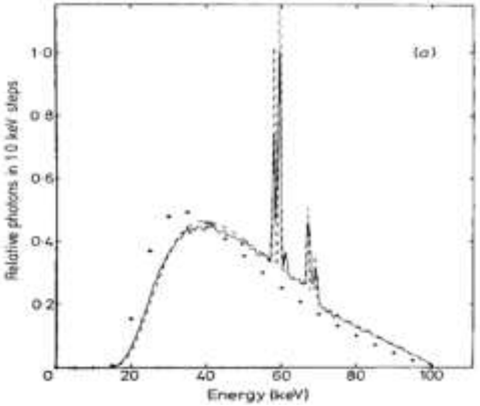
Bremsstrahlung

- Classically, a charged particle at rest creates an electric field which is inversely proportional to squared distance from charge.
- When in motion with a constant velocity it creates both electric and magnetic fields.
- When accelerated, additional electric and magnetic fields appear
  - fall off less rapidly—inversely with the first power of distance from charge with continuous distribution.

Bremsstrahlung

- Quantum-mechanically, when a charged particle undergoes acceleration or deceleration, it emits photons.
- Radiation is called deceleration radiation, braking radiation, or *bremsstrahlung*.
  - It has a continuous distribution of frequencies up to some maximum value.





Problem Assignments

- Information posted on web site
- Chapter 15 problems: 17, 18, 19, 21, 23, 24, 25, 27