Interactions of Photons with Matter

- Photons are electromagnetic radiation with zero mass, **zero charge**, and a velocity that is always c, the speed of light.

- Because they are electrically neutral, they **do not steadily lose energy** via coulombic interactions with atomic electrons, as do charged particles.

- Photons travel some considerable distance before undergoing a more **"catastrophic" interaction** leading to **partial or total transfer** of the photon energy to **electron energy**.

- These electrons will ultimately deposit their energy in the medium.

- Photons are far **more penetrating** than charged particles of similar energy.

Energy Loss Mechanisms
- photoelectric effect
- Compton scattering
- pair production

Interaction probability

- **linear attenuation coefficient**, μ,
  The probability of an interaction per unit distance traveled
  Dimensions of inverse length (eg. cm^{-1}).

$$N = N_0 \, e^{-\mu x}$$

- The coefficient μ depends on **photon energy** and on the **material being traversed**.

- **mass attenuation coefficient**, $\dfrac{\mu}{\rho}$

  The probability of an interaction per $g\ cm^{-2}$ of material traversed.
  Units of $cm^2\ g^{-1}$

$$N = N_0 \, e^{-\left(\frac{\mu}{\rho}\right)(\rho x)}$$

Mechanisms of Energy Loss: Photoelectric Effect

- In the photoelectric absorption process, a photon undergoes an interaction with an absorber atom in which the **photon completely disappears**.

- In its place, an energetic **photoelectron** is ejected from one of the bound shells of the atom.

- For gamma rays of sufficient energy, the most probable origin of the photoelectron is the most tightly bound or *K* shell of the atom.

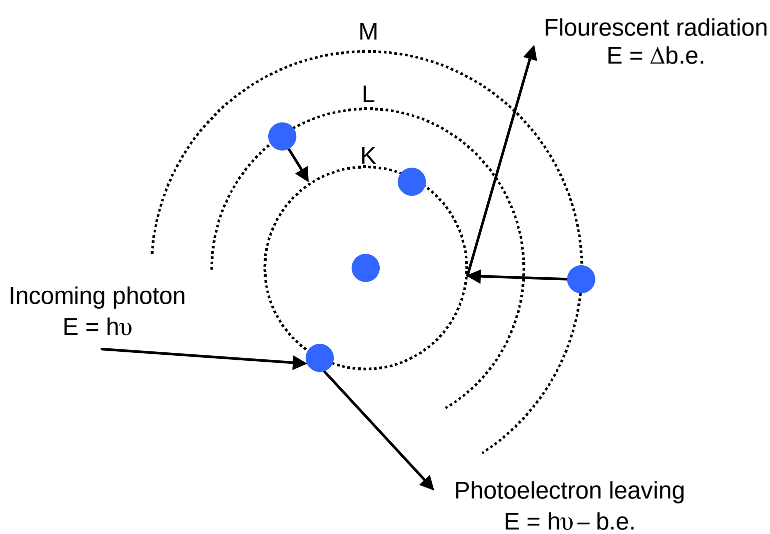
- The photoelectron appears with an energy given by

$$E_{e-} = h\nu - E_b$$

(E_b represents the binding energy of the photoelectron in its original shell)

Thus for gamma-ray energies of more than a few hundred keV, the photoelectron carries off the majority of the original photon energy.

Filling of the inner shell vacancy can produce **fluorescence radiation**, or x ray photon(s).



Events in the photoelectric scattering process
(after Alpen, E. L. *Radiation Biophysics*, 2nd ed. San Diego, CA: Academic Press, 1990. Fig. 4.3)

The photoelectric process is the ***predominant mode of photon interaction*** at

- **relatively low photon energies**
- **high atomic number Z**

The probability of photoelectric absorption, symbolized τ (tau), is roughly proportional to

$$\tau \propto \frac{Z^n}{(h\nu)^3}$$

where the exponent n varies between 3 and 4 over the gamma-ray energy region of interest.

This severe dependence of the photoelectric absorption probability on the atomic number of the absorber is a primary reason for the preponderance of **high-Z materials (such as lead) in gamma-ray shields**.

The photoelectric interaction is most likely to occur if the energy of the incident photon is **just greater than the binding energy** of the electron with which it interacts.

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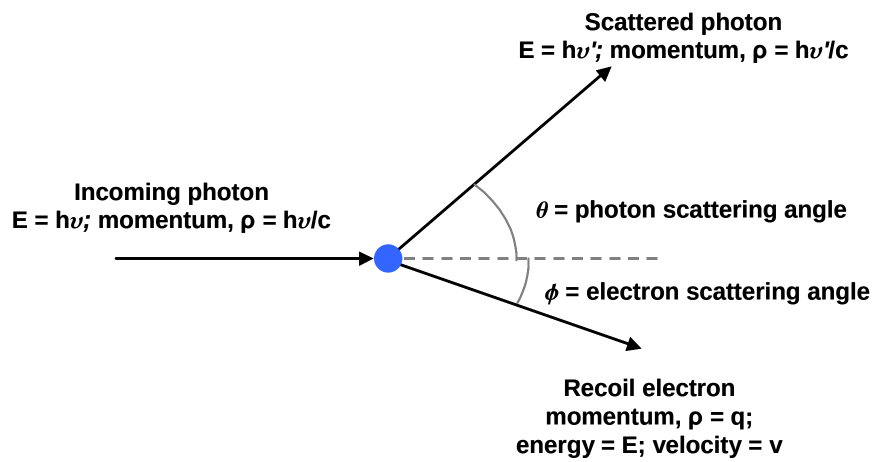
Fig 4.4 in Alpen, E. L. *Radiation Biophysics*, 2nd ed. San Diego, CA: Academic Press, 1990.

Compton Scattering

- Compton scattering takes place between the incident gamma-ray photon and an electron in the absorbing material.

- It is most often the predominant interaction mechanism for gamma-ray energies typical of radioisotope sources.

- It is the **most dominant interaction mechanism in tissue**.



Events in the Compton (incoherent scattering process)
(after Alpen, E. L. Radiation Biophysics, 2nded. San Diego, CA: Academic Press, 1990. Fig. 4.5)

In Compton scattering, the incoming gamma-ray photon is **deflected** through an angle θ with respect to its original direction.

The photon transfers a portion of its energy to the electron (assumed to be initially at rest), which is then known as a *recoil electron*, or a ***Compton electron***.

- All angles of scattering are possible.

- The energy transferred to the electron can vary from zero to a large fraction of the gamma-ray energy.

- The Compton process is **most important** for energy absorption for **soft tissues** in the range from 100 keV to 10MeV.

- The Compton scattering probability is is symbolized σ (sigma):
    - almost ***independent of atomic number Z***;
    - decreases as the photon energy increases;
    - directly proportional to the number of electrons per gram, which only varies by 20% from the lightest to the heaviest elements (except for hydrogen).

Compton Scattering Energetics

The energies of the scattered photon $h\nu'$ and the Compton electron E_e, are given by

$$h\nu' = h\nu \frac{1}{1+\alpha(1-\cos\theta)}$$

$$E_e = h\nu \frac{\alpha(1-\cos\theta)}{1+\alpha(1-\cos\theta)}$$

where $$\alpha = \frac{h\nu}{m_0 c^2}$$

[$m_0 c^2$ is the electron rest energy, 0.511 MeV, $h\nu$ is the incoming photon energy]

Limits of Energy Loss

Maximum energy transfer to recoil electron:

- angle of electron recoil is forward at 0°, ϕ = 0°,
- the scattered photon will be scattered straight back, θ = 180°
- With θ = 180°, cos θ = -1 the expressions above simplify to:

$$E_{e(max)} = h\nu \frac{2\alpha}{1+2\alpha}$$

and

$$h\nu'_{min} = h\nu \frac{1}{1+2\alpha}$$

The Table below illustrates how the amount of energy transferred to the electron varies with photon energy. Energy transfer is not large until the incident photon is in excess of approximately 100 keV.

Photon Energy, 5.11 keV	Photon Energy, 5.11 MeV
$\alpha = \frac{5.11 \text{ keV}}{0.511 \text{ MeV}} = 0.010$	$\alpha = \frac{5.11 \text{ MeV}}{0.511 \text{ MeV}} = 10$
$E_{e(max)} = 5.11 \text{ keV} * \left(2 * \frac{0.01}{1.02}\right) = 0.10 \text{ keV}$	$E_{e(max)} = 5.11 \text{ MeV} * \left(2 * \frac{10}{21}\right) = 4.87 \text{ MeV}$
$h\nu' \text{ (min)} = 5.11 \text{ keV} * \frac{1}{1.02} = 5.01 \text{ keV}$	$h\nu' \text{ (min)} = 5.11 \text{ MeV} * \frac{1}{21} = 0.24 \text{ MeV}$
Energy transferred: 2%	Energy transferred: 95%

Figure by MIT OCW.

For **low-energy photons**, when the scattering interaction takes place, **little energy is transferred**, regardless of the probability of such an interaction.

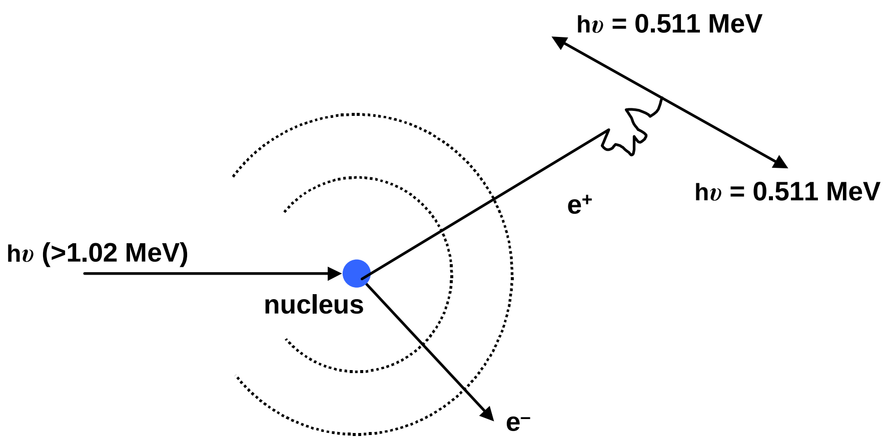
As the energy increases, the fractional transfer increases, approaching 1.0 for photons at energies above 10 to 20 MeV.

Pair Production

If a photon enters matter with an energy **in excess of 1.022 MeV**, it may interact by a process called ***pair production***.

The photon, passing near the nucleus of an atom, is subjected to strong field effects from the nucleus and may **disappear as a photon** and **reappear as a positive and negative electron pair**.

The two electrons produced, e- and e+, are **not scattered orbital electrons**, but are created, *de novo*, in the energy/mass conversion of the disappearing photon.



(after Alpen, E. L. *Radiation Biophysics*, 2nd ed. San Diego, CA: Academic Press, 1990. Fig. 4.7)

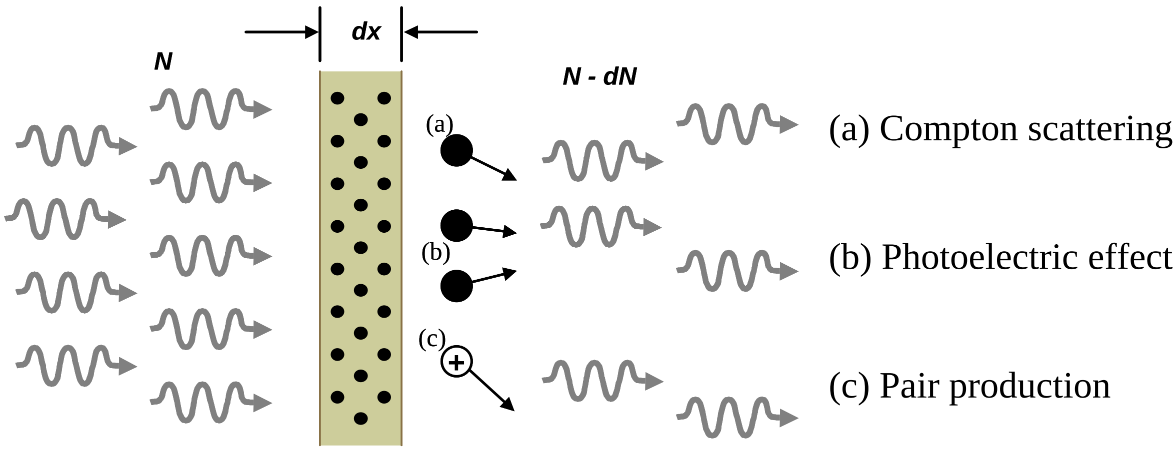
Pair Production Energetics

The kinetic energy of the electrons produced will be the difference between the energy of the incoming photon and the energy equivalent of two electron masses (2 x 0.511, or 1.022 MeV).

$$E_{e+} + E_{e-} = h\nu - 1.022 \text{ (MeV)}$$

Pair production probability, symbolized κ (kappa),

- Increases with **increasing photon energy**
- Increases with atomic number approximately as $\mathbf{Z^2}$



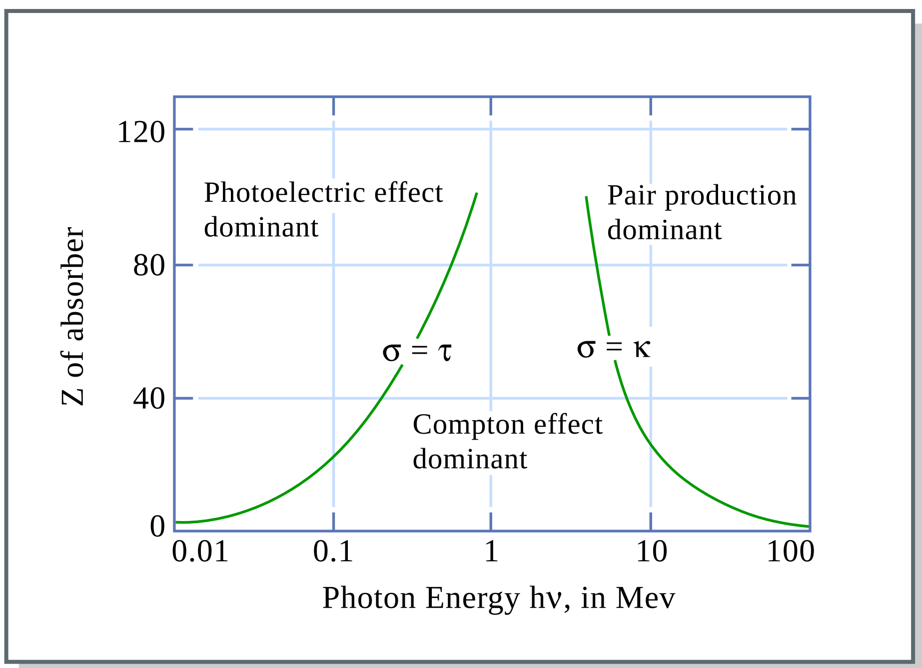


Figure by MIT OCW.

- Photoelectric effect: produces a scattered photon and an electron, varies as ~ Z^4/E^3
- Compton effect: produces an electron, varies as ~ Z
- Pair production: produces an electron and a positron, varies as $\sim Z^2$

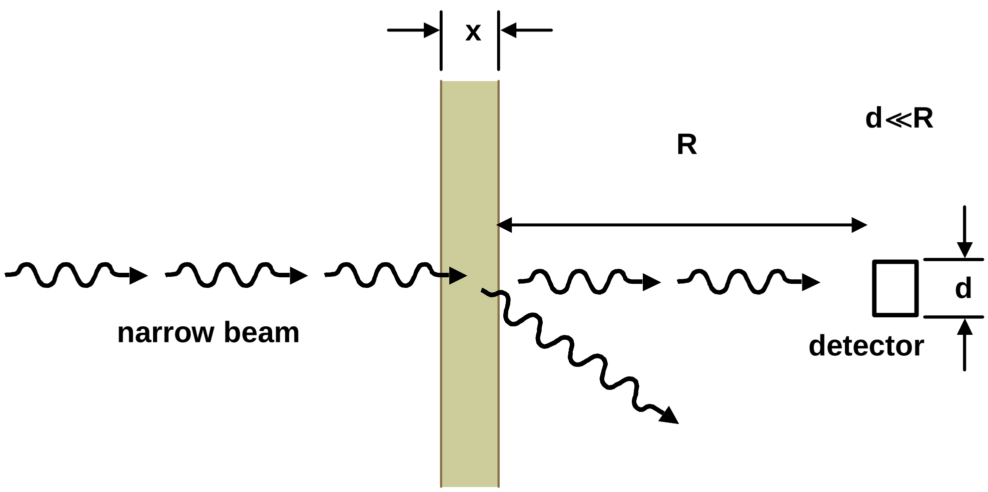
Bulk Behavior of Photons in an Absorber

Attenuation Coefficients

Linear attenuation coefficient μ:
The probability of an interaction per unit distance traveled. μ has the dimensions of inverse length (eg. cm^{-1}).

$$N = N_0 \, e^{-\mu x}$$

The coefficient μ depends on **photon energy** and on the **material being traversed**.



"good" scattering geometry for measuring linear attenuation coefficient μ
(after Turner, J.E. *Atoms, Radiation, and Radiation Protection*, 2nd ed. New York, NY: Wiley-Interscience, 1995. Fig. 8.7)

The interaction probability μ is actually the sum of the three possible photon interaction mechanisms:

$$\mu = \tau + \sigma + \kappa$$

τ is the photoelectric effect interaction probability
σ is the Compton scattering interaction probability
κ is the pair production interaction probability

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Flux = photons/cm^2 sec

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Intensity = energy x flux

$$Intensity\,(I) = \left(\frac{h\nu}{photon}\right)\left(\frac{\#\,photons}{Area \bullet time}\right)$$

$$Intensity = \frac{MeV}{cm^2\,\sec}$$

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The **mass attenuation coefficient,** μ/ρ, is obtained by dividing μ by the density ρ of the material, usually expressed in cm^2g^{-1}.

Each of the components, τ, σ, and κ can be expressed as mass attenuation coefficients. $\frac{\mu}{\rho}=\frac{\tau}{\rho}+\frac{\sigma}{\rho}+\frac{\kappa}{\rho}$

3 energy transfer processes…
each depends differently
on Z and E.

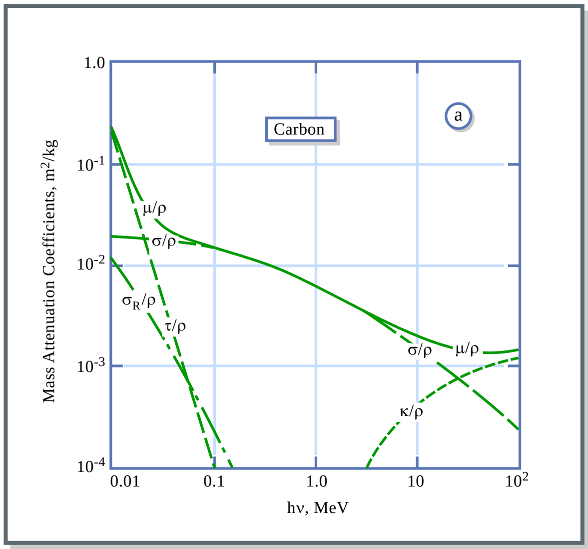
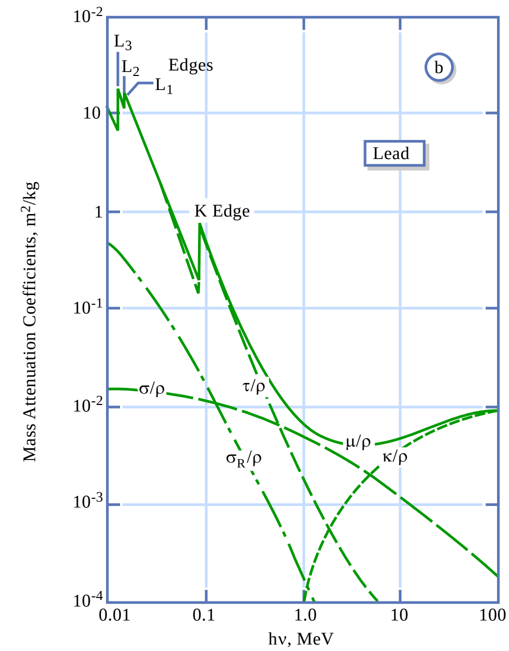


Figure by MIT OCW.



Mass attenuation coefficients for carbon (a) and lead (b). τ/ρ indicates the contribution of the photoelectric effect, σ/ρ is that of the Compton effect, κ/ρ that of pair production, and σ_R/ρ that of Rayleigh (coherent) scattering. μ/ρ is their sum, which is closely approximated in Pb by the τ/ρ curve below $h\nu$ = 0.1 MeV.

Figure by MIT OCW.

Linear Attenuation, Energy Transfer and Energy Absorption

Not all of the energy of the incoming photons that interact in the material is necessarily absorbed there.

Energy absorbed = Energy transferred – Energy “lost”

Some energy may be lost from the absorber region due to fluorescence or bremsstrahlung.

Linear Attenuation: probability of an interaction

Energy Transfer: energy transferred to short-range electrons

Energy absorbed: energy transferred to short-range electrons ***minus*** the bremsstrahlung photons

- A photon interaction will, in general, result in ***transfer*** of energy to a **short range particle** (mostly electrons).

- The energy transferred to the electron may be ***absorbed*** within the material, dx, or it may leave the region of interest.

- Each of the energy transfer mechanisms has an **energy transfer attenuation coefficient** and an **energy absorption attenuation coefficient**.

- These coefficients each depend differently on the incoming photon energy and the Z of the absorber.

Energy transferred "locally" i.e., to electrons.

$$\tau_{tr} = \tau\left(1 + \frac{\delta}{h\nu}\right)$$

photoelectric effect:

δ is the average energy emitted as fluorescence

$$\sigma_{tr} = \sigma \frac{E_{avg}}{h\nu}$$

Compton scattering: $E_{avg}/h\nu$ is the average photon energy converted into electron energy

$$\kappa_{tr} = \kappa\left(\frac{h\nu - m_0 c^2}{h\nu}\right)$$

pair production: $(h\nu - mc^2)/h\nu$ is the fraction of energy converted to photons by β^+ β^- annihilation.

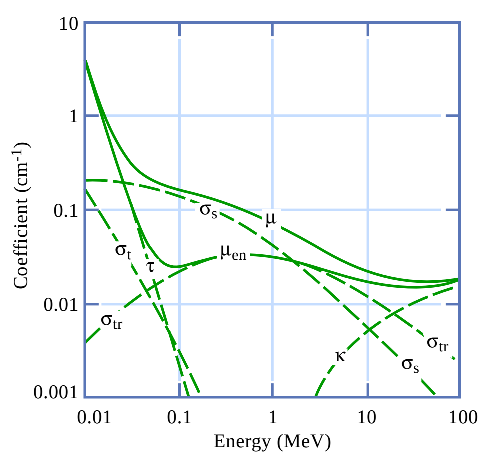
$$\mu_{tr} = \tau_{tr} + \sigma_{tr} + \kappa_{tr}$$

- μ_{tr} is the total kinetic energy of all electrons produced by photons
- ***μ_{tr} takes no account of subsequent bremsstrahlung***

$$\mu_{en} = \mu_{tr}(1 - g)$$

g is the average fraction of initial photon energy, hν, transferred to electrons and subsequently emitted as bremsstrahlung.

g is largest for high-Z absorbers



Linear attenuation and energy-absorption coefficients as functions of energy for photons in water.

Figure by MIT OCW.

***** μ_{en} is the most important parameter for calculation of dose*****

$$I = I_0 \, e^{-\mu x}$$

$$E_{ab} = E_{tr}(1-g)$$

Energy Transferred and Energy Absorbed for Incident Photons of Various Energy (for Carbon)

Photon energy, E_{tot} (MeV)	Average energy transferred, E_{tr} (MeV)	Average energy absorbed, E_{ab} (MeV)
0.01	0.00865	0.00865
0.10	0.0141	0.0141
1.0	0.440	0.440
10.0	7.30	7.04
100.0	95.63	71.90

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$$\mu_{en} = \mu_{tr}(1-g)$$

Mass Attenuation, Mass Energy-Transfer, Mass Energy-Absorption Coefficients ($cm^2 \, g^{-1}$) for photons in Water and Lead

Photon Energy (MeV)	Water			Lead		
	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ
0.01	5.33	4.95	4.95	131.	126.	126.
0.10	0.171	0.0255	0.0255	5.55	2.16	2.16
1.0	0.0708	0.0311	0.0310	0.0710	0.0389	0.0379
10.0	0.0222	0.0163	0.0157	0.0497	0.0418	0.0325
100.0	0.0173	0.0167	0.0122	0.0931	0.0918	0.0323

Source: Based on P. D. Higgins, F. H. Attix, J. H. Hubbell, S. M. Seltzer, M. J. Berger, and C. H. Sibata, *Mass Energy-Transfer and Mass Energy-Absorption Coefficients, Including In-Flight Positron Annihilation for Photon Energies 1 keV to 100 MeV,* NISTIR 4680, National Institute of Standards and Technology, Gaithersburg, MD (1991).

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Figs. 8.12, 8.13 in [Turner].