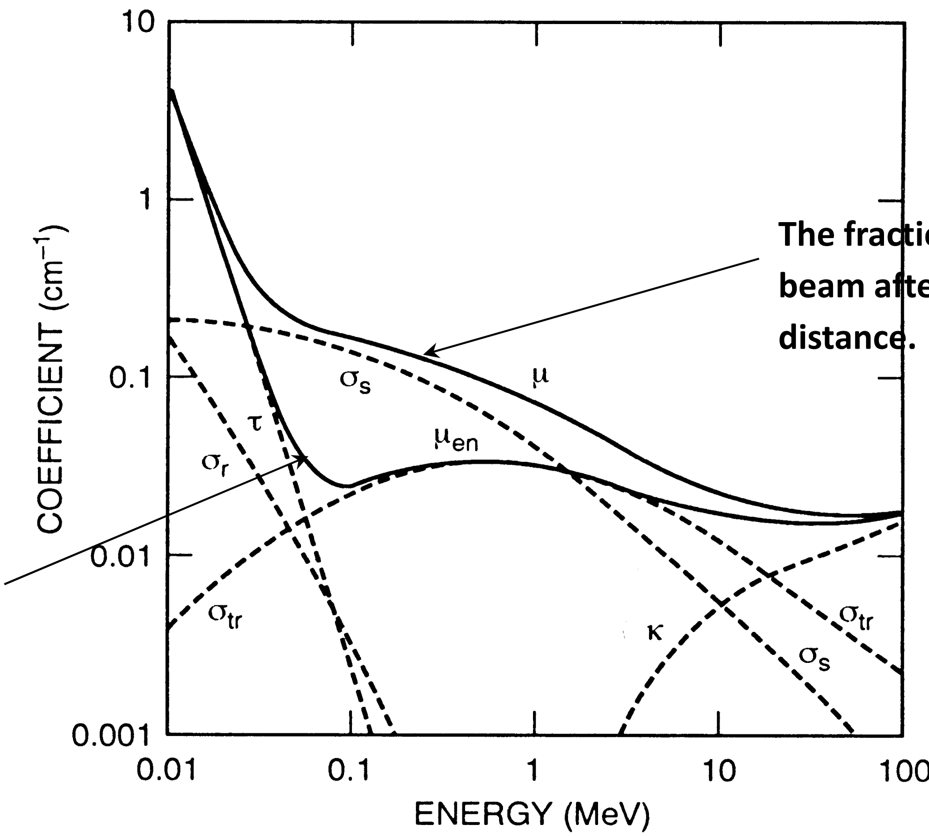
Energy transfer coefficient

&

Energy absorption coefficient

Comparison Between Linear Attenuation Coefficient and Energy Absorption Coefficient



The fraction of photons removed from the beam after traveling through a unit distance.

The fraction of energy carried by the photons being absorbed in material.

FIGURE 8.13. Linear attenuation and energy-absorption coefficients as functions of energy for photons in water.

Figure from Atoms, Radiation, and Radiation Protection, James E Turner, p195

Linear Attenuation Coefficients for Gamma-Rays

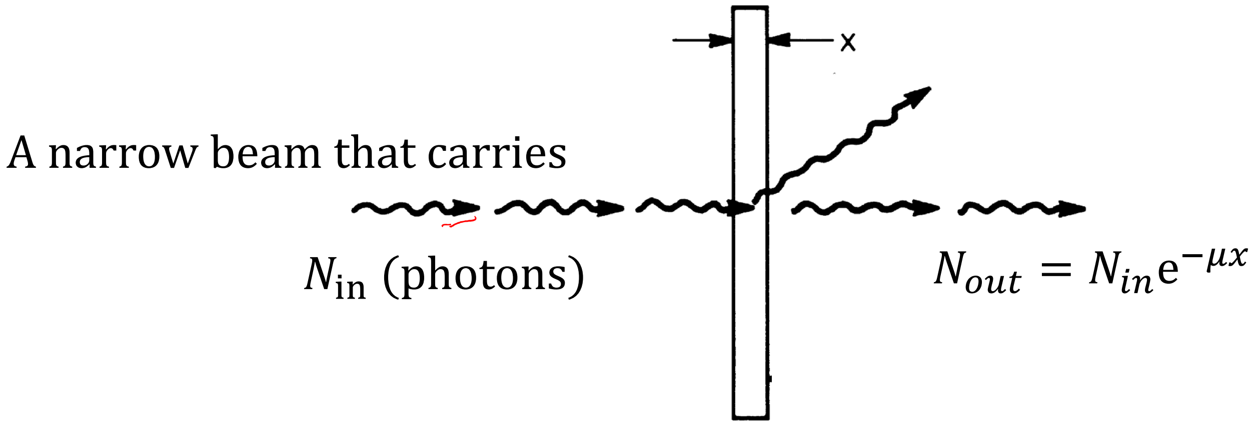


FIGURE 8.7. Illustration of "good" scattering geometry for measuring linear attenuatior coefficient μ. Photons from a *narrow* beam that are absorbed or scattered by the ab sorber do not reach a small detector placed in beam line some distance away.

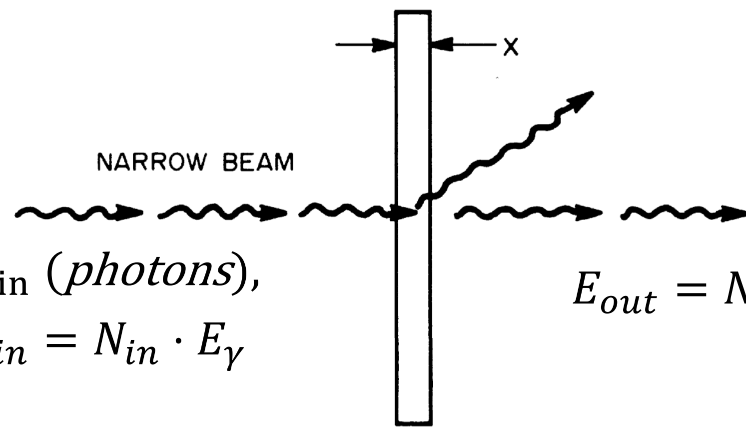
☞ Considering a thin slab of absorbing media, the number of photons being removed/attenuated from the beam through the distance x is given by

$$dN = N_{in} - N_{out} = N_{in}(1 - e^{-\mu x}) = \mu N_{in} dx$$

where $\boldsymbol{\mu}$ is the linear attenuation coefficient (the probability that a photon is removed from the beam by the absorbing media per unit distance it travels)

$$\mu = \tau_{photoelectric} + \sigma_{Compton} + \kappa_{pair}$$

Linear Attenuation Coefficients for Gamma-Rays



N_{in} (*photons*),
$E_{in} = N_{in} \cdot E_{\gamma}$

$E_{out} = N_{out} \cdot E_{\gamma} = N_{in} \cdot \mathrm{e}^{-\mu x} \cdot E_{\gamma}$

Instead, if we consider the gamma-ray beam as a flow of energy, where $E_{in} = N_{in} \cdot E_{\gamma}$, for each unit distance that the beam transmitted through, what is the fraction of the incident energy that is transferred to the secondary electrons within the absorbing media?

Linear Attenuation Coefficients

Linear attenuation coefficient μ is the probability that a photon is removed/attenuated in the absorber per unit distance it travels,

$$\mu = \tau_{photoelectric} + \sigma_{Compton} + \kappa_{pair}$$

Can we define a **linear energy transfer coefficient**, μ_{tr}, which is the fraction of the energy carried by the incident beam that is subsequently transferred to the absorber per unit distance the beam is transmitted through?

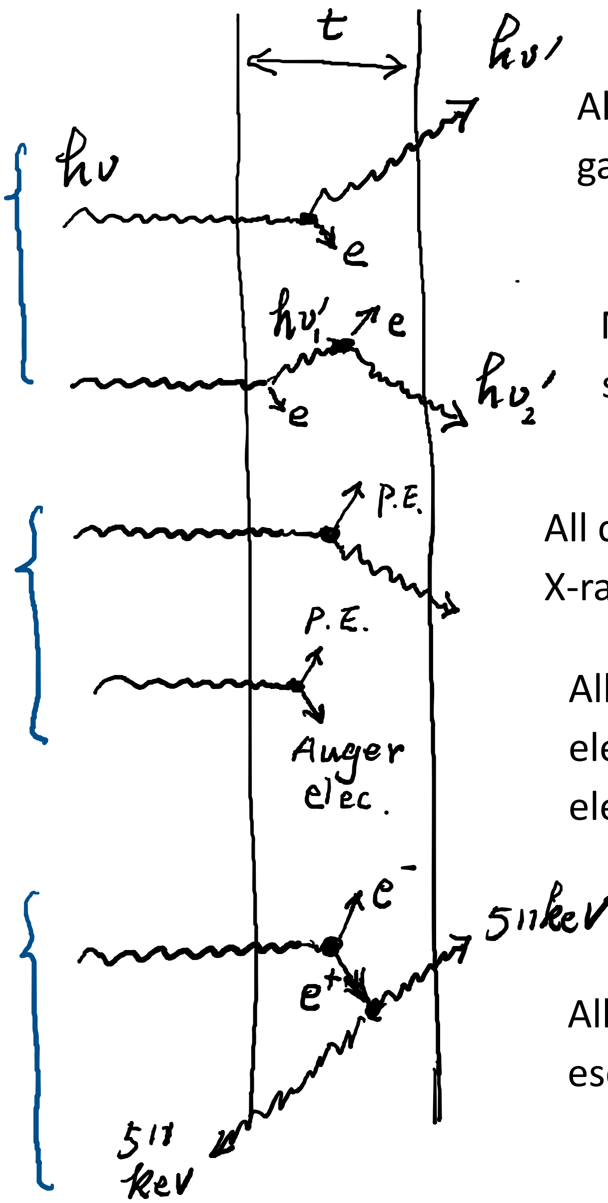
$$\mu_{tr} = \tau_{photoelectric} \times ? + \sigma_{Compton} \times ?? + \kappa_{pair} \times ???$$

Energy Transfer by a Gamma-Ray Beam

Compton scattering

Photoelectric effect

Pair production



All Compton scattered gamma rays escaped

Multiple Compton scattering ignored

All characteristic X-rays escaped

All photoelectrons, auger electrons and Compton recoil electrons are absorbed

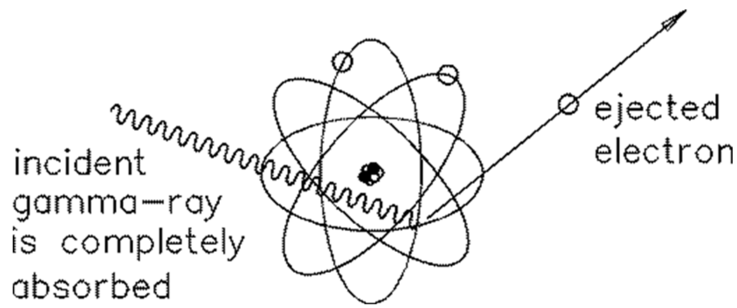
All annihilation gamma rays escaped

What is Energy Transfer Coefficients?

For a parallel beam of monochromatic gamma rays transmitting through a unit distance in an absorbing material, **the energy-transfer coefficient is the fraction of energy that was originally carried by the incident gamma-ray beam and transferred into the kinetic energy of secondary electrons per unit distance of travel**.

Photoelectric Effect

In **photoelectric** process, an incident photon transfer its energy to an orbital electron, causing it to be ejected from the atom.



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

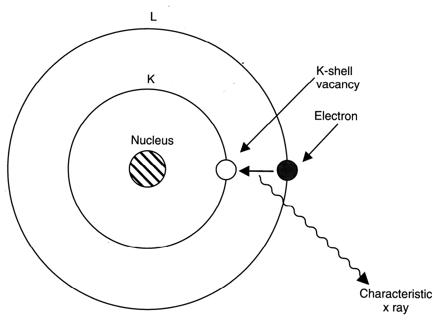
h is the Planck's constant

ν is the frenquency of the photon

- Photoelectric interaction is **with the atom in a whole** and can not take place with free electrons.
- Photoelectric effect **creates a vacancy in one of the electron shells**, which leaves the atom at an excited state.

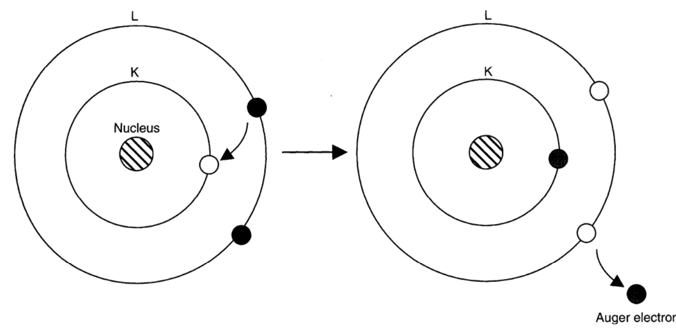
Relaxation Process after Photoelectric Effect

☞ The excited atoms will **de-excite** through one of the following processes:



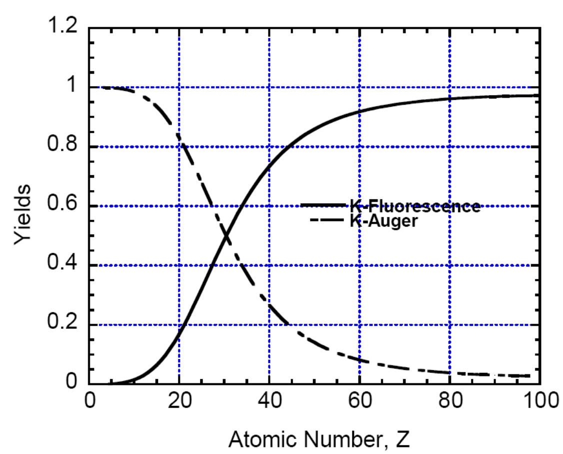
Generation of characteristic X-rays

Competing Processes



Generation of Auger electrons

☞ **Auger electron** emission dominates in **low-Z** elements. **Characteristic X-ray** emission dominates in **higher-Z** elements.



Energy-Transfer Coefficients through Photoelectric Effect

Based on these considerations, we can define the **mass energy transfer coefficient**, which is the fraction of photons that interact by photoelectric absorption per g·cm^{-2},

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

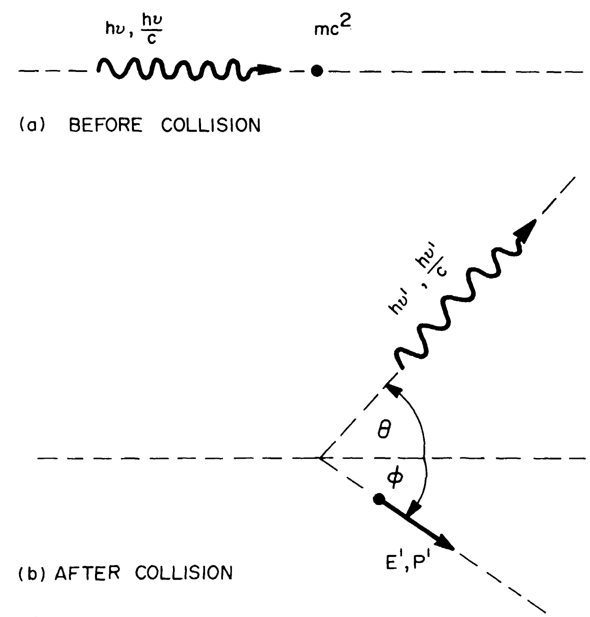
δ is the fraction of the gamma ray energy got converted into characteristic x-rays following the photoelectric interaction.

Note that the photoelectrons and Auger electrons may also lead to secondary photon emission through Bremsstrahlung. So the energy transfer coefficient defined above does not fully describe **energy absorption** in the slab. We will return to this point later.

Energy-Transfer Coefficients Through Compton Scattering

For Compton scattering of monoenergetic photons, the mass energy transfer coefficient

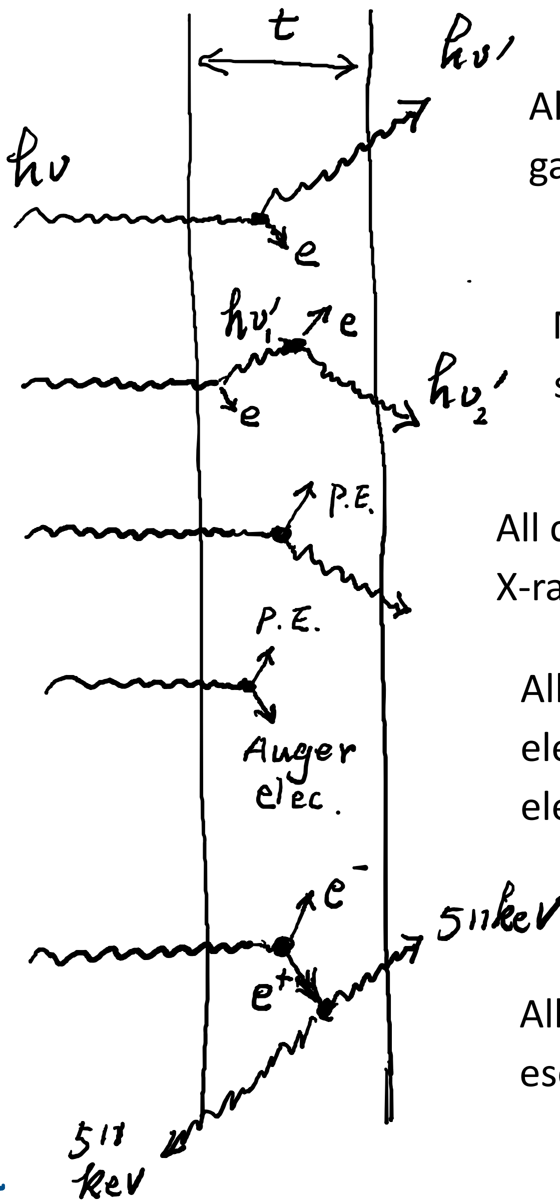
$$\sigma_{tr} = \sigma \left(\frac{E_{avg}}{h\upsilon} \right)$$



The factor $E_{avg}/h\nu$ is the fraction of the incident photon energy that is converted into the initial kinetic energy of Compton electrons.

As with the photoelectric effect, the above mass energy transfer coefficient does not take into account the subsequent photon emission due to bremsstrahlung.

Energy Transfer by a Gamma Ray Beam



Compton scattering

All Compton scattered gamma rays escaped

Multiple Compton scattering ignored

Photoelectric effect

All characteristic X-rays escaped

All photoelectrons, auger electrons and Compton recoil electrons are absorbed

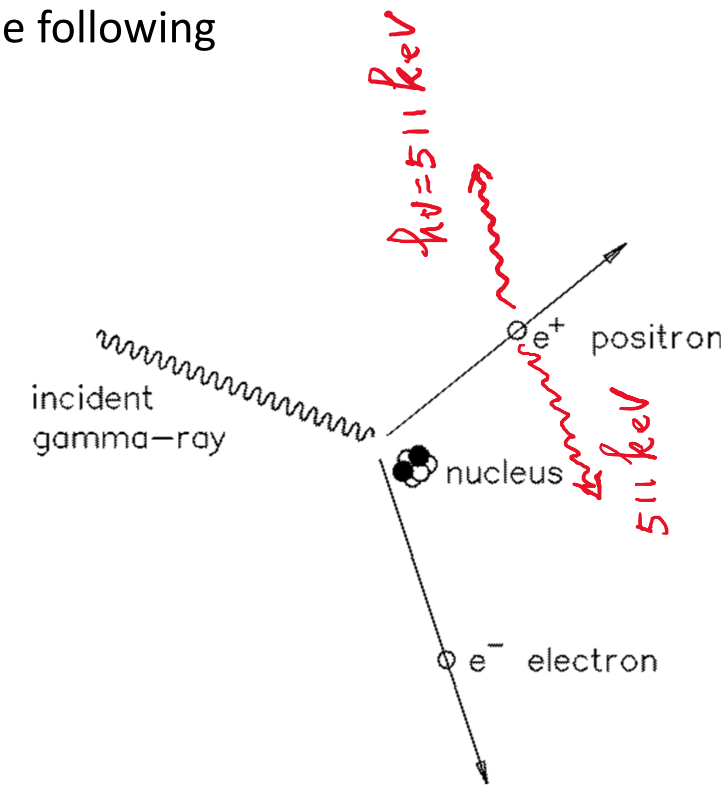
Pair production

All annihilation gamma rays escaped

Energy-Transfer Coefficient through Pair Production

For **pair production process**, the initial energy carried by the electron-positron pair is $h\nu - 2mc^2$. Therefore the mass energy transfer coefficient for pair production is related to the mass attenuation coefficient as the following

$$\kappa_{tr} = \kappa\left(1 - \frac{2m_e c^2}{h\upsilon}\right)$$



Energy-Transfer Coefficient

The **total energy transfer coefficient** is given by

The fraction of energy that is carried away by characteristic x-rays following the photoelectric effect.

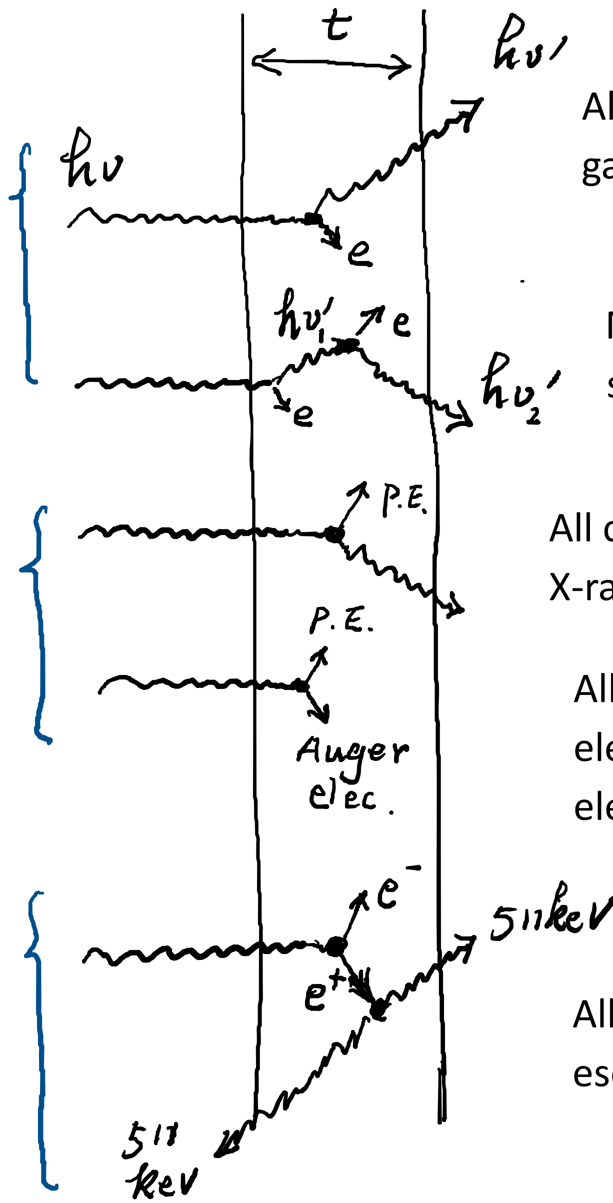
The fraction of energy that is carried away by the two 511keV gamma-rays generated during the annihilation of the positron.

$$\mu_{tr} = \tau\left(1 - \frac{\delta}{h\upsilon}\right) + \sigma\left(\frac{E_{avg}}{h\upsilon}\right) + \kappa\left(1 - \frac{2mc^2}{h\upsilon}\right)$$

The average fraction of energy that is transferred to recoil electron through Compton scattering.

For a parallel beam of monochromatic gamma rays transmitting through a unit distance in an absorbing material, **the energy-transfer coefficient is the fraction of energy that was originally carried by the incident gamma ray beam and subsequently transferred into the kinetic energy of secondary electron** inside the absorber.

Energy Transfer by a Gamma Ray Beam



Compton scattering
- All Compton scattered gamma rays escaped
- Multiple Compton scattering ignored

Photoelectric effect
- All characteristic X-rays escaped
- All photoelectrons, auger electrons and Compton recoil electrons are absorbed

Pair production
- All annihilation gamma rays escaped

What is Energy Absorption Coefficients?

The **total mass energy transfer coefficient** is given by

$$\mu_{tr} = \tau\left(1 - \frac{\delta}{h\upsilon}\right) + \sigma\left(\frac{E_{avg}}{h\upsilon}\right) + \kappa\left(1 - \frac{2mc^2}{h\upsilon}\right)$$

Consider the fraction of energy that may be carried away by the subsequent bremsstrahlung photons, one can define the **mass energy-absorption coefficient** as

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

where g is the average fraction of energy of the initial kinetic energy transferred to electrons that is subsequently emitted as bremsstrahlung photons.

For a parallel beam of monochromatic gamma rays transmitting through a unit distance in an absorbing material, **the energy-absorption coefficient is the fraction of energy that was originally carried by the incident gamma ray beam and eventually absorbed** inside the absorber.

Energy Loss by Bremsstrahlung

- For beta particles to stop in a given medium, the **fraction of energy loss** by **Bremsstrahlung** process is approximately given by

$$f_\beta = 3.5 \times 10^{-4} Z E_m,$$

where f_β = the fraction of the incident beta energy converted into photons,
Z = atomic number of the absorber,
E_m = maximum energy of the beta particle, MeV.

Mass Energy Absorption Coefficient

Mass attenuation coefficient

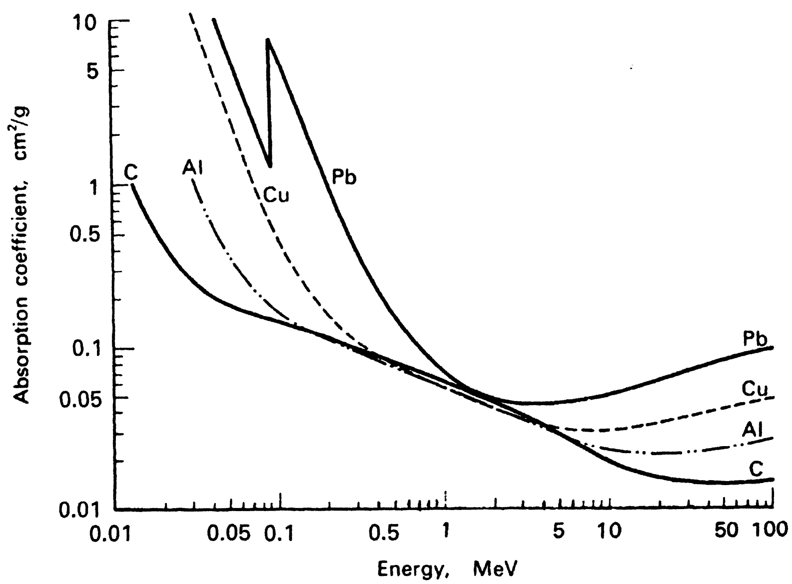


FIGURE 5.12. Curves illustrating the systematic variation of attenuation coefficient with atomic number of absorber and with quantum energy.

Mass energy absorption coefficient

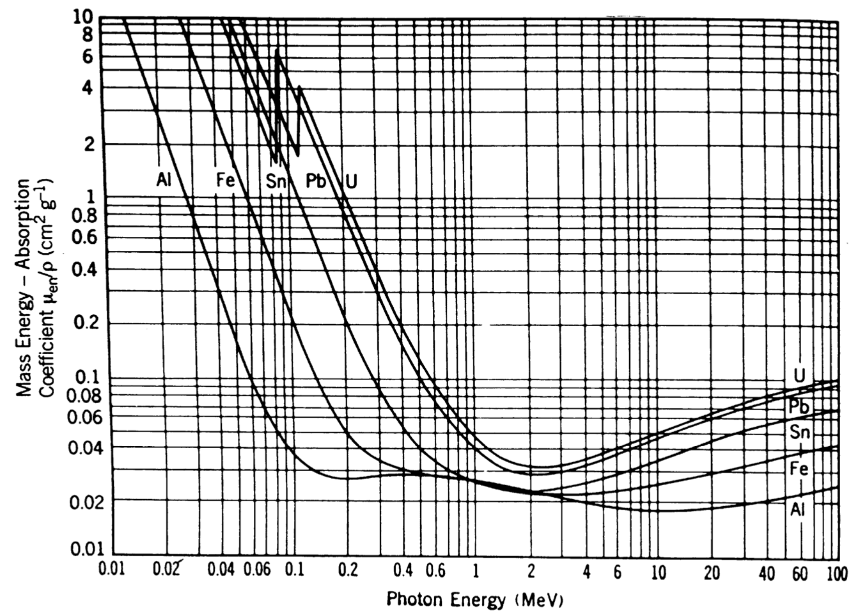


FIGURE 8.11. Mass energy-absorption coefficients for various elements. [Reprinted with permission from K. Z. Morgan and J. E. Turner, eds., *Principles of Radiation Protection*, Wiley, New York (1967). Copyright 1967 by John Wiley & Sons.]

Figure from Atoms, Radiation, and Radiation Protection, James E Turner, p195

Mass Energy Absorption Coefficient

Mass attenuation coefficient

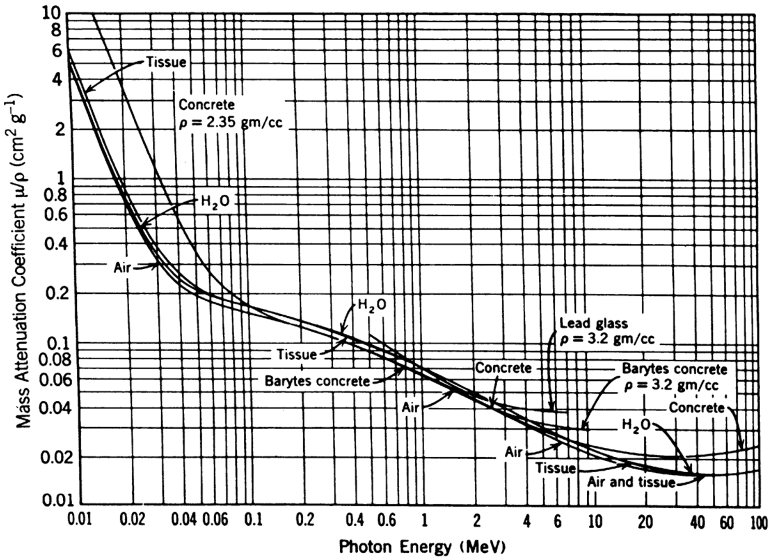


FIGURE 8.9. Mass attenuation coefficients for various materials. [Reprinted with permission from K. Z. Morgan and J. E. Turner, eds., *Principles of Radiation Protection*, Wiley, New York (1967). Copyright 1967 by John Wiley & Sons.]

Mass energy absorption coefficient

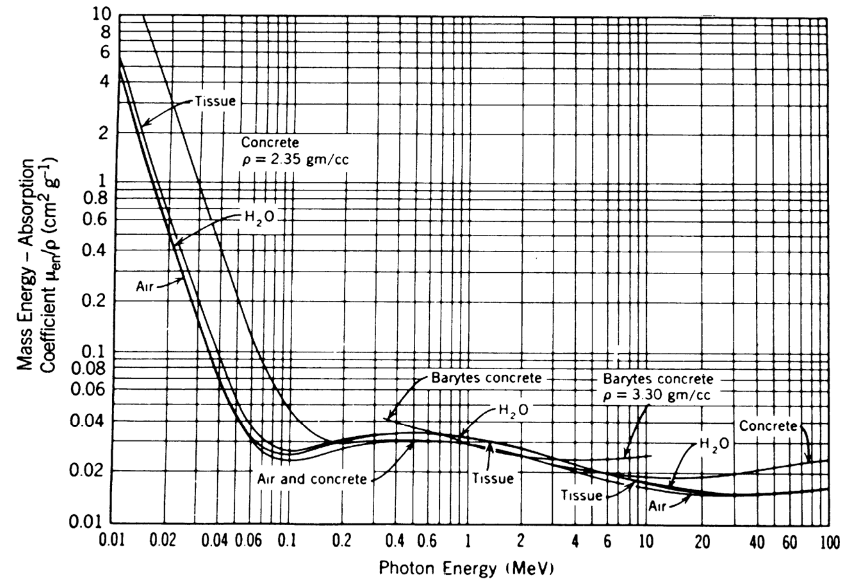


FIGURE 8.12. Mass energy-absorption coefficients for various materials. [Reprinted with permission from K. Z. Morgan and J. E. Turner, eds., *Principles of Radiation Protection*, Wiley, New York (1967). Copyright 1967 by John Wiley & Sons.]

Figure from Atoms, Radiation, and Radiation Protection, James E Turner, p195

Energy-Transfer and Energy Absorption Coefficients

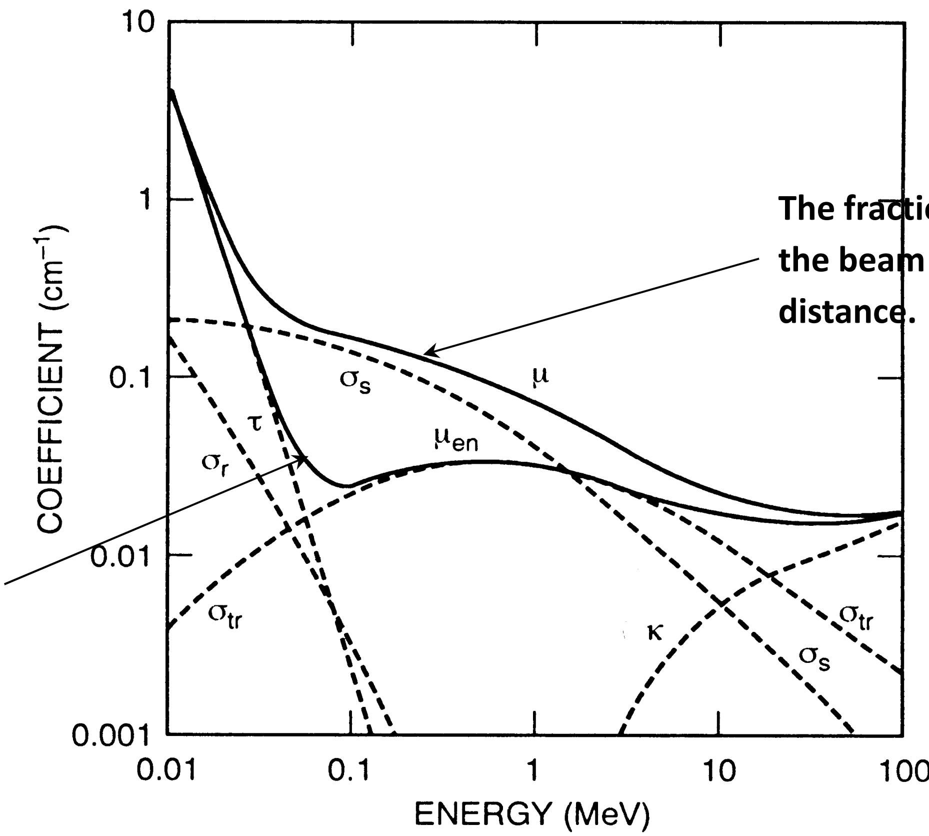
TABLE 8.3. Mass Attenuation, Mass Energy-Transfer, and Mass Energy-Absorption Coefficients ($cm^2\ g^{-1}$) for Photons in Water and Lead

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).

- As expected, bremsstrahlung is relatively unimportant for photon energy of less that ~10MeV, whilst it accounts for a significant difference between the mass energy-transfer coefficient and the mass energy absorption coefficient.

Comparison Between Linear Attenuation Coefficient and Energy Absorption Coefficient



The fraction of photons removed from the beam after traveling through a unit distance.

The fraction of energy carried by the photons being absorbed in material.

FIGURE 8.13. Linear attenuation and energy-absorption coefficients as functions of energy for photons in water.

Figure from Atoms, Radiation, and Radiation Protection, James E Turner, p195

Calculation of Energy Transfer and Energy Absorption

For simplicity, we consider an idealized case, in which

- Photons are assumed to be monoenergetic and in broad parallel beam.
- Multiple Compton scattering of photons is negligible.
- Virtually all fluorescence and bremsstrahlung photons escape from the absorber.
- All secondary electrons (Auger electrons, photoelectrons and Compton electrons) generated are stopped in the slab.

Calculation of Energy Transfer and Energy Absorption

Assuming $\mu_{en}x<<1$, which is consistent with the thin slab approximation and the energy fluence rate carried by the incident gamma ray beam is $\dot{\Psi}_0(J \cdot cm^{-2} \cdot s^{-1})$. Then the energy absorbed in the thin slab per second over a unit cross section area is given by

$$\Delta\Psi = \dot{\Psi}_0 - \Psi = \dot{\Psi} = \dot{\Psi}_0(1 - e^{-\mu_{en}x}) \approx \dot{\Psi}_0 \cdot \mu_{en} \cdot x \ \ (J \cdot cm^{-2} \cdot s^{-1})$$

The rate of energy absorbed in the slab of area A (cm^2) and thickness *x* is

$$A\dot{\Psi}_0\mu_{en}x \ (J \cdot s^{-1})$$

Given the density of the material is ρ, the rate of energy absorption per unit mass (**Dose Rate**) in the slab is

$$\dot{D} = \frac{A(cm^2)\cdot\dot{\Psi}_0(J\cdot cm^{-2}\cdot s^{-1})\cdot\mu_{en}(cm^{-1})\cdot x\,(cm)}{\rho(g\cdot cm^{-3})\cdot A(cm^2)\cdot x(cm)},$$

$$Dose\ rate\ in\ the\ absorber:\ \ \dot{D} = \dot{\Psi}_0\frac{\mu_{en}}{\rho}\,(J \cdot g^{-1} \cdot s^{-1})$$

Calculation of Energy Transfer and Energy Absorption

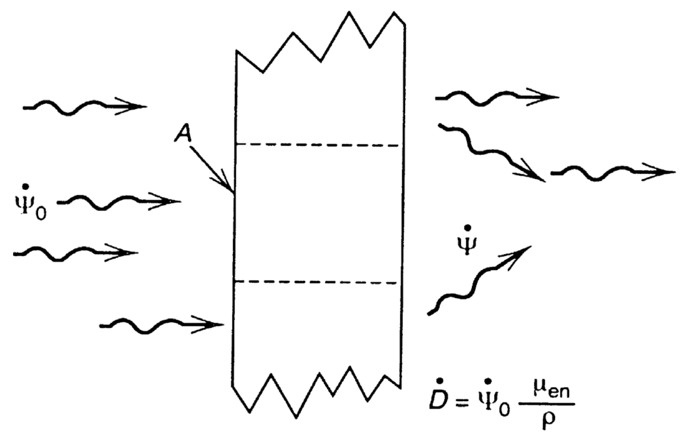


FIGURE 8.14. Rate of energy absorption per unit mass in thin slab (dose rate, $\dot{D}$) i equal to the product of the incident intensity and mass energy-absorption coefficient.

- The thin slab geometry discussed is approached in practice only by various degrees of approximation.
- Non-uniformity and finite width of real beams are two examples that deviate from the ideal.

Calculation of Energy Transfer and Energy Absorption

Example

A ^{137}Cs source is stored in a laboratory. The photon fluence rate in air at a point in the neighborhood of the source is $5.14 \times 10^7\ m^{-2}\,s^{-1}$. Calculate the rate of energy absorption per unit mass (dose rate) in the air at that point.

Solution

The desired quantity is given by Eq. (8.61). The mass energy-absorption coefficient of air for the photons emitted by ^{137}Cs ($h\nu = 0.662$ MeV, Appendix D) is, from Fig. 8.12, $\mu_{en}/\rho = 0.030\ cm^2\,g^{-1}$. The incident fluence rate is $\dot{\Phi} = 5.14 \times 10^7\ m^{-2}\,s^{-1}$, and so the energy fluence rate is

$$\dot{\Psi} = \dot{\Phi} h\nu = 3.40 \times 10^7\ \text{MeV}\,\text{m}^{-2}\,\text{s}^{-1} = 3.40 \times 10^3\ \text{MeV}\,\text{cm}^{-2}\,\text{s}^{-1}. \tag{8.66}$$

Thus, Eq. (8.61) gives

$$\dot{D} = \dot{\Psi}\frac{\mu_{en}}{\rho} = 102\ \text{MeV}\,\text{g}^{-1}\,\text{s}^{-1}. \tag{8.67}$$

Expressed in SI units,

$$\dot{D} = \frac{102\ \text{MeV}}{\text{g}\,\text{s}} \times 1.60 \times 10^{-13}\,\frac{J}{\text{MeV}} \times 10^3\,\frac{\text{g}}{\text{kg}} \tag{8.68}$$

$$= 1.63 \times 10^{-8}\ \text{J}\,\text{kg}^{-1}\,\text{s}^{-1} = 0.0587\ \text{mGy}\,\text{h}^{-1}. \tag{8.69}$$