Interaction of Electromagnetic Radiation with Matter

Quantification & Measurement of Dose

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- Radiation
  - Non-Ionizing
  - Ionizing
    - Directly ionizing (charged particles)
    - Indirectly ionizing (neutral particles)

Quantities for Describing the Interaction of Ionizing Radiation with Matter

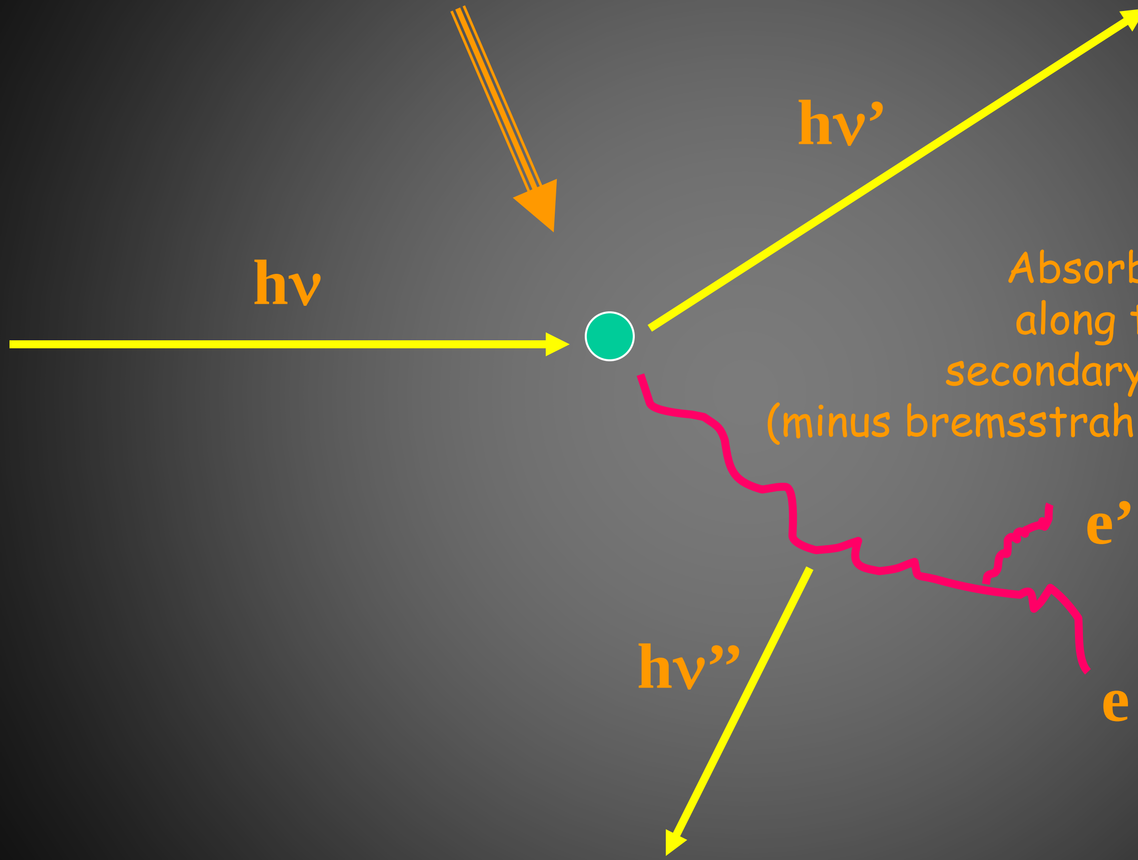
If we use an infinitesimal sphere at a point in free space as our reference location then....

- Kerma (K) - energy transferred to charged particles.

- Absorbed Dose (D) - energy imparted to matter by all kinds of ionizing radiations but delivered by the charged particles.

- Exposure (X) - described x- and γ-ray fields in terms of their ability to ionize air.

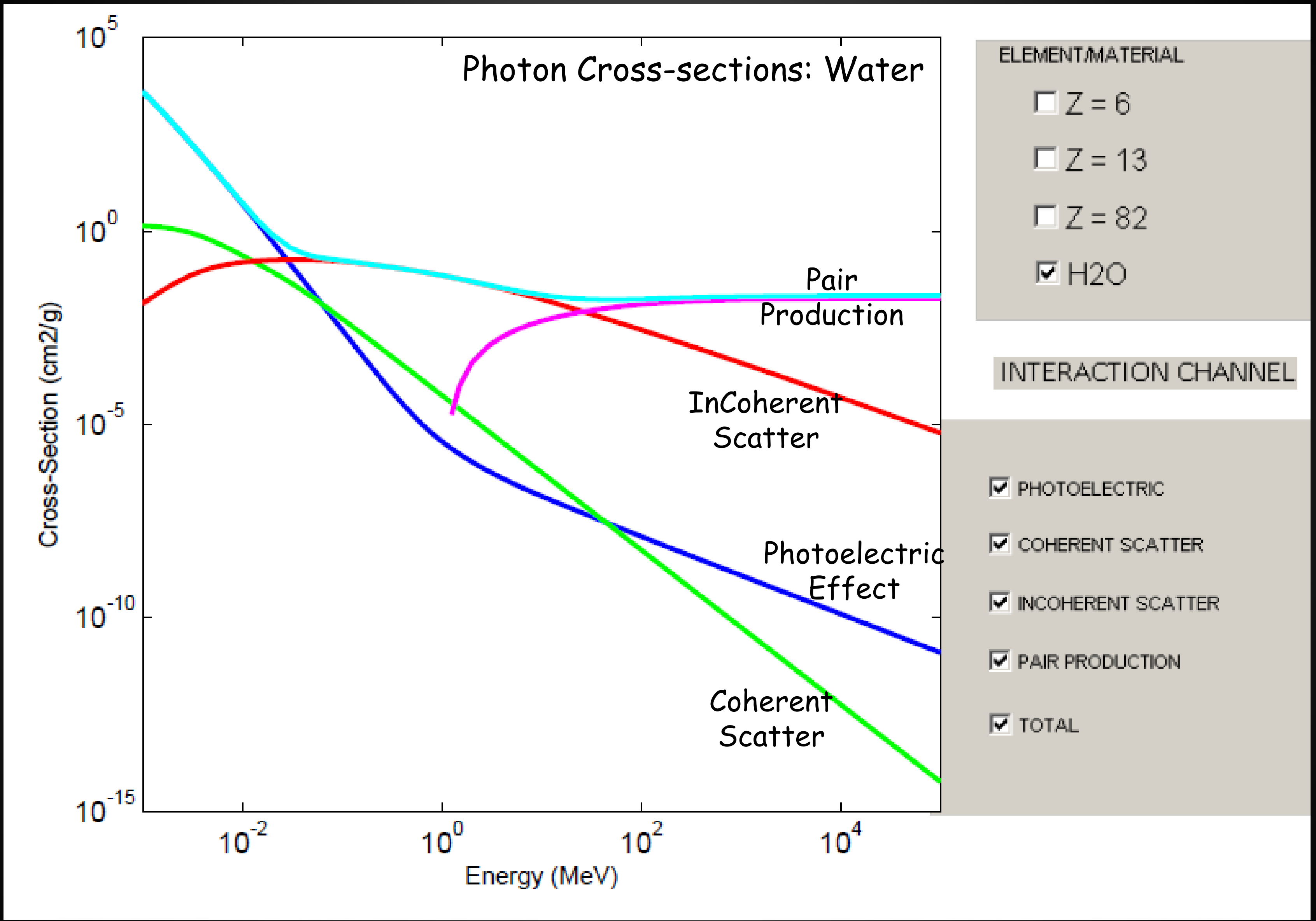
Kerma occurs at the Initial interaction point



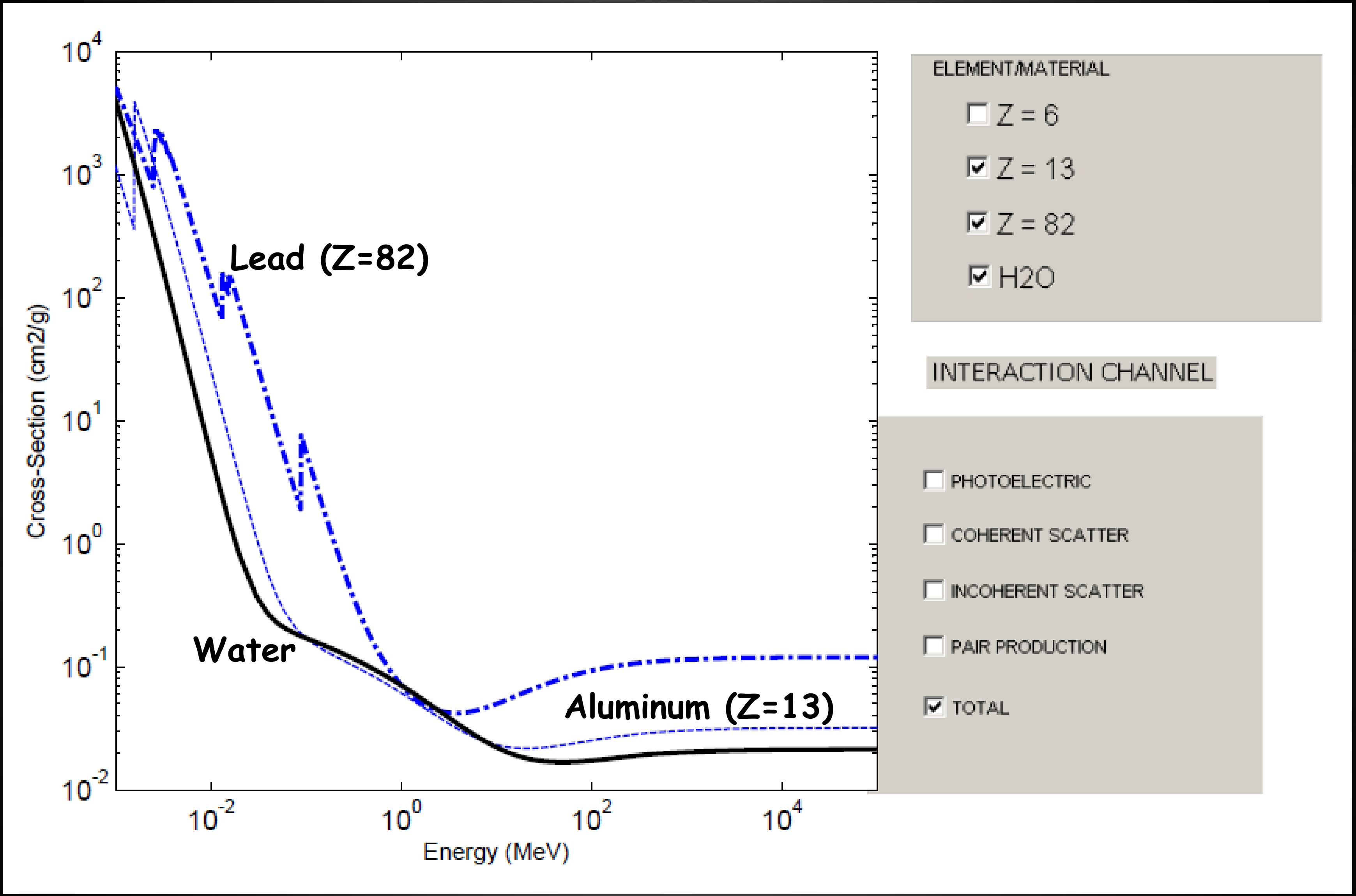
Absorbed dose occurs along the path of the secondary charged particles (minus bremsstrahlung & in-flight annihilation)

Photon Interactions

- Coherent Scattering
- Incoherent Scattering
- Photoelectric Absorption
- Pair Production in the nuclear field
- Pair Production in the electric field
- Photonuclear



Photon Cross-sections: Water
Cross-Section (cm2/g)
10^5
10^0
10^{-5}
10^{-10}
10^{-15}
10^{-2}
10^0
10^2
10^4
Energy (MeV)
Pair Production
InCoherent Scatter
Photoelectric Effect
Coherent Scatter
ELEMENT/MATERIAL
Z = 6
Z = 13
Z = 82
H2O
INTERACTION CHANNEL
PHOTOELECTRIC
COHERENT SCATTER
INCOHERENT SCATTER
PAIR PRODUCTION
TOTAL



Lead (Z=82)
Water
Aluminum (Z=13)
Cross-Section (cm2/g)
Energy (MeV)
ELEMENT/MATERIAL
Z = 6
Z = 13
Z = 82
H2O
INTERACTION CHANNEL
PHOTOELECTRIC
COHERENT SCATTER
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PAIR PRODUCTION
TOTAL

Total Mass Attenuation Coefficient

$$\frac{\mu}{\rho} = \frac{\sigma_{tot}}{uA}$$

$$\sigma_{tot} = \sigma_{pe} + \sigma_{coh} + \sigma_{incoh} + \sigma_{pair} + \sigma_{trip} + \sigma_{ph.n.}$$

U = 1.660 540 2 × 10^{-24} g is the atomic mass unit

A = is the relative atomic mass of the target element

Total Linear Attenuation Coefficient

$\sigma \quad units\ of\ barns$

$1\,barn = 1x10^{-24}\,cm^2$

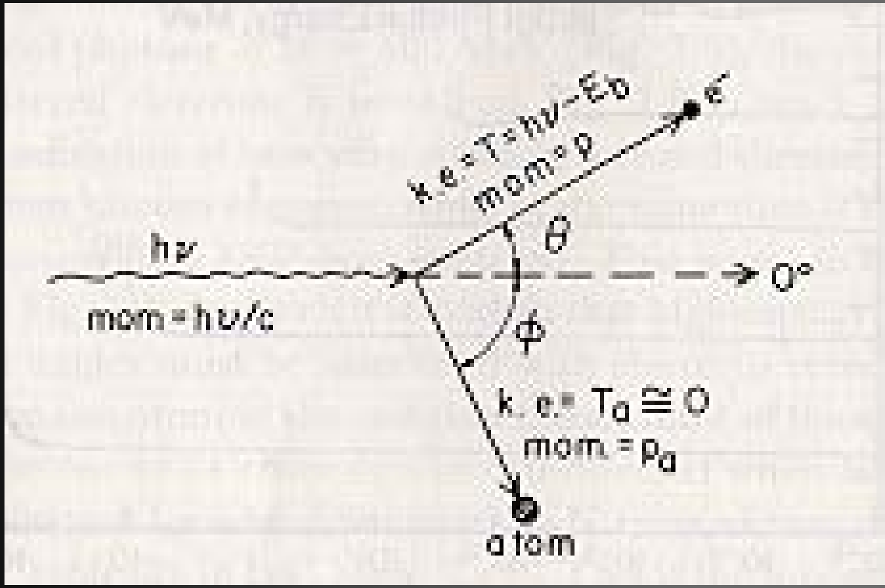
$$\frac{\mu}{\rho} = \frac{\sigma_{tot}}{uA}$$

$$\mu = \frac{\mu}{\rho} \cdot \rho$$

$units\ of\ cm^{-1}$

$$Mean\ Free\ Path = \frac{1}{\mu}$$

Kinematics of the Photoelectric Effect



From Attix

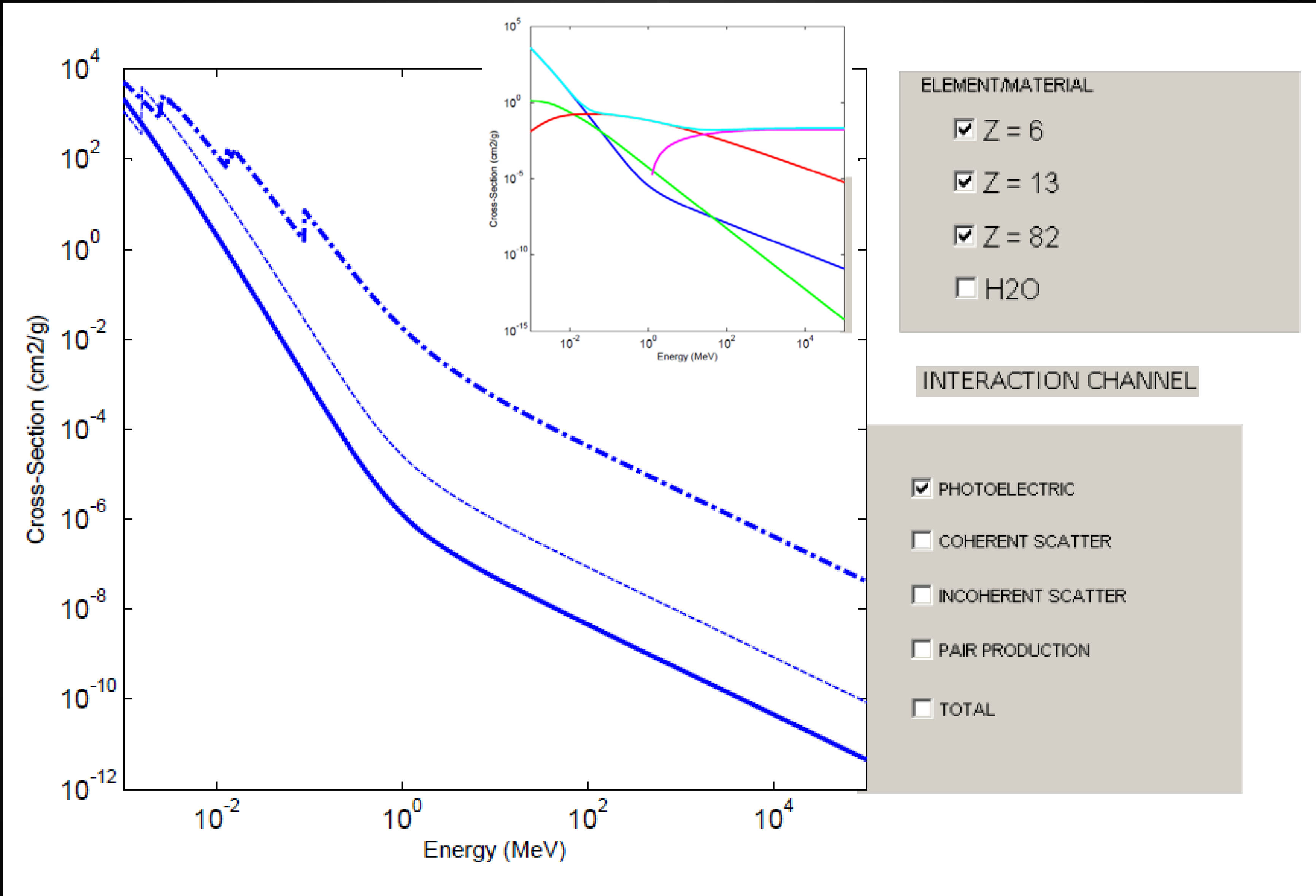
$$T = h\nu - E_b - T_a$$
$$= h\nu - E_b$$

Interaction Cross-Section for the Photoelectric Effect

$$\tau \propto \frac{Z^4}{(h\nu)^3} \qquad (cm^2/atom)$$

$$\frac{\tau}{\rho} \propto \left(\frac{Z}{h\nu}\right)^3 \qquad (cm^2/g)$$

- Calculated by Scofield (<1.5MeV)
- Solution of the Dirac equation for the orbital electrons moving in a static Hartree-Slater potential



Cross-Section (cm2/g)
Energy (MeV)
ELEMENT/MATERIAL
Z = 6
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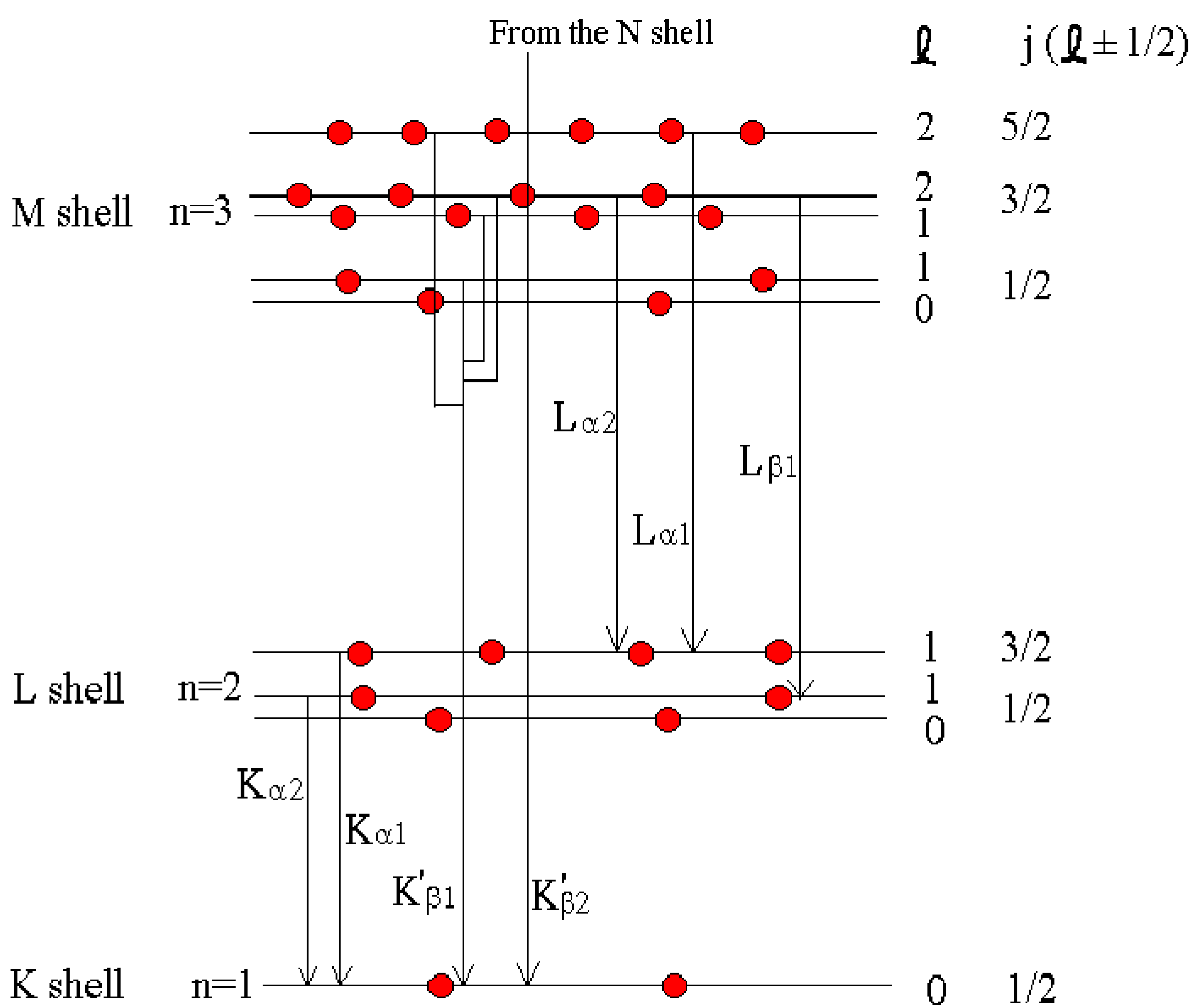
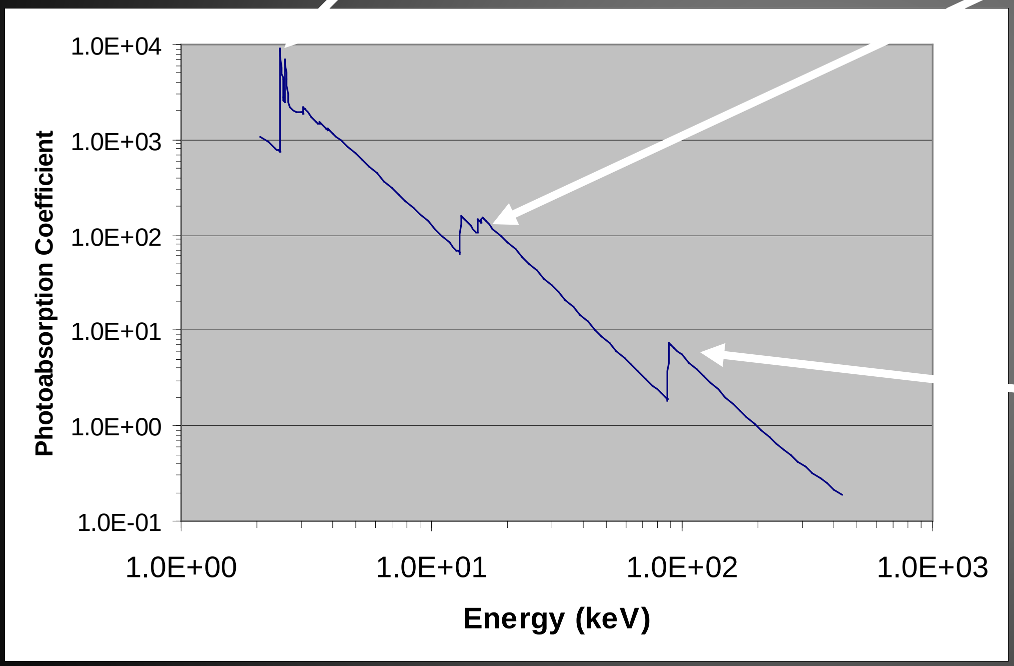
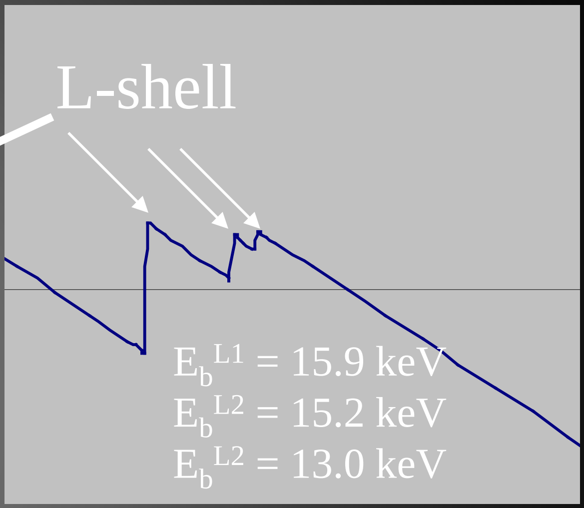
Generic Energy Level Diagram



Photoelectric cross-section for Pb

M-shell$_{1\text{-}5}$
3.85 keV> E_b > 2.48 keV





K-shell
E_b = 88.0 keV

Fluorescence & Auger Emission

• When a K-, L-, M- …shell vacancy occurs the resulting vacancy is filled by another electron falling from a less tightly bound shell.

• This transition is sometimes accompanied by the emission of a fluorescence x-ray of energy equal to the energy difference of the two electron shells.

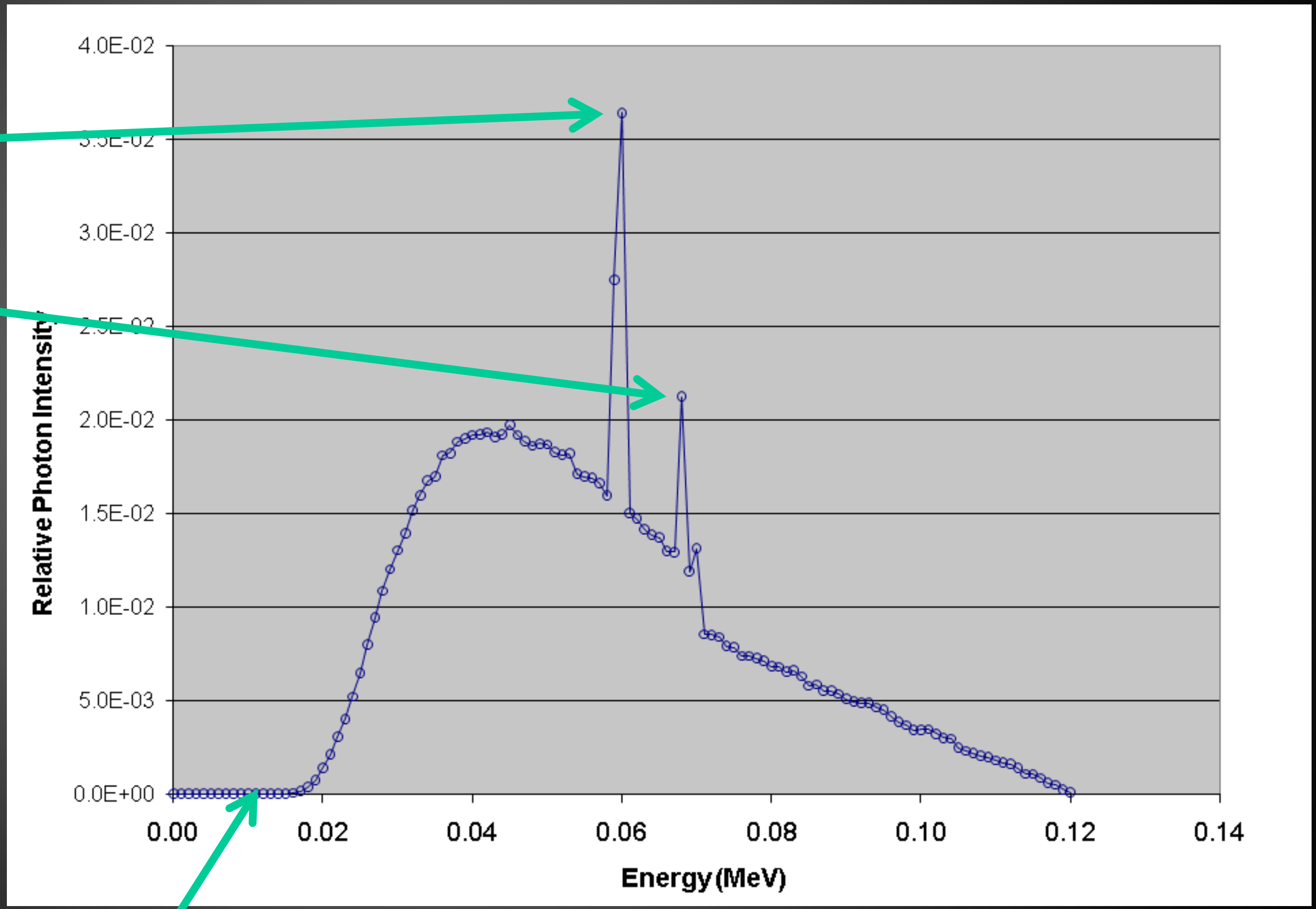
• The probability for emission of a fluorescence x-ray is called the fluorescence yield (Y_K , Y_L , Y_M). The fluorescence yield « 0 for vacancies in the M (or higher) shell.

• The competing interaction is the Auger effect. The atom ejects one or more of its electrons to account for the excess energy.

120 kVp bremsstrahlung spectra
120 keV electrons incident on a tungsten target

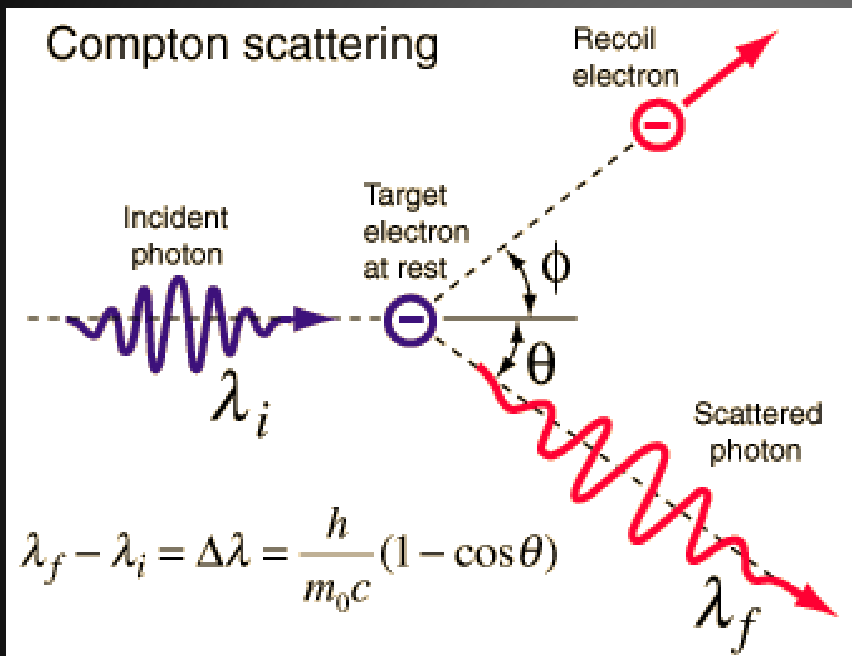
K alpha1	59.32	*
K alpha2	57.98	*
K alpha3	57.43	
K beta 1	67.24	*
K beta 2	69.07	*
K beta 3	66.950	*
K beta 4	69.27	
K beta 5	67.69	
K O23	69.48	
L alpha1	8.398	*
L alpha2	8.335	*
L beta1	9.672	*
L beta2	9.955	*
L beta3	9.819	
L beta4	9.525	
L beta5	10.2	
L beta6	9.612	
L gamma 1	11.29	*
L gamma 2	11.61	
L gamma 3	11.68	
L gamma 4	11.54	

* greater than 1% intensity



Low-energy photons attenuated due to inherent filtration

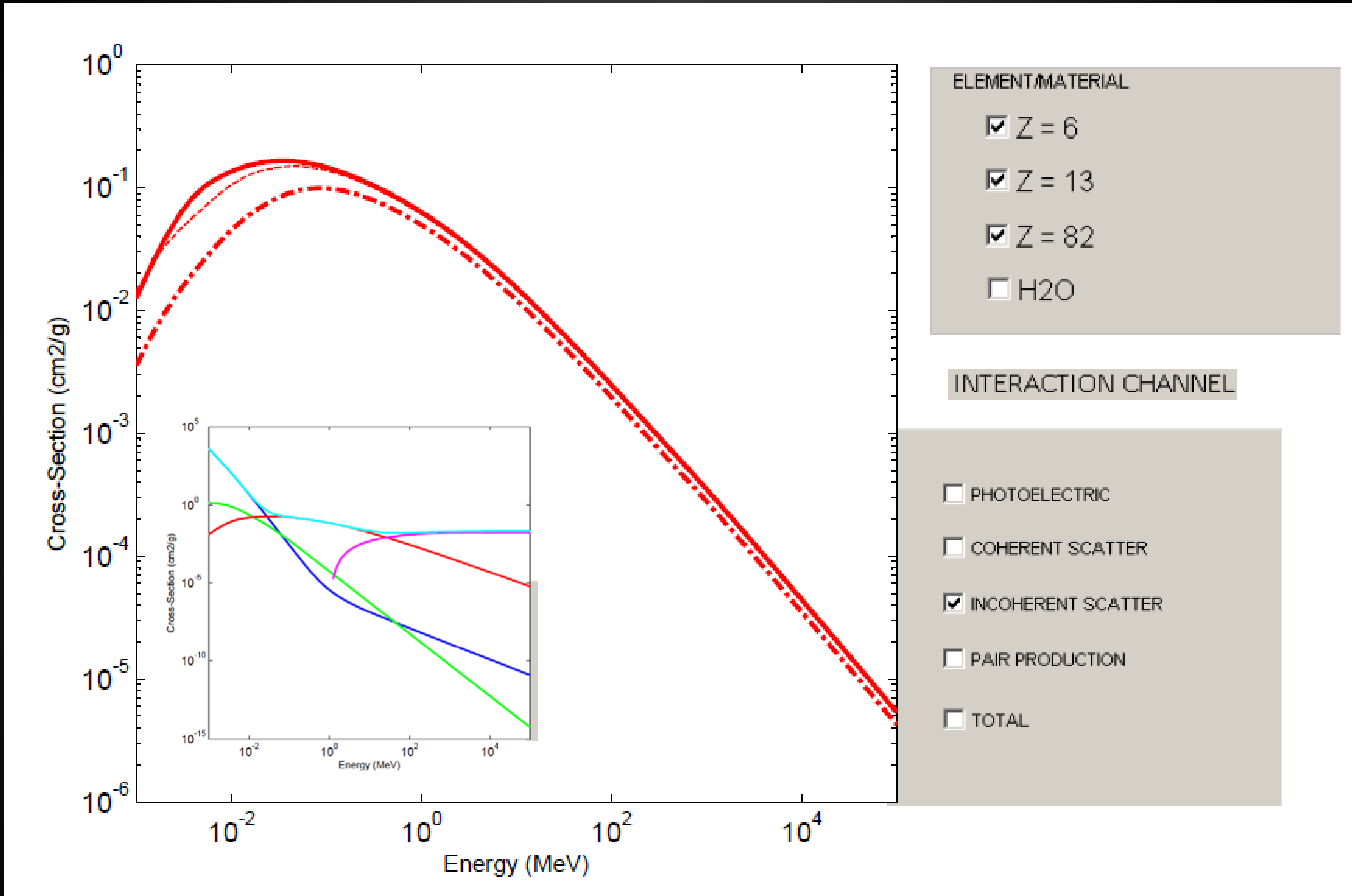
Kinematics of the Compton Effect (incoherent scatter)



$$h\nu' = \frac{h\nu}{1+\frac{h\nu}{m_o c^2}(1-\cos\varphi)}$$

$$T = h\nu - h\nu'$$

$$\cot\theta = \left(1+\frac{h\nu}{m_o c^2}\right)\tan\frac{\varphi}{2}$$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Compton mass attenuation coefficient

$${}_{e}\sigma \propto Z^{0} \qquad Total\ K-N\ cross\ section\ per\ electron$$

$${}_{a}\sigma = Z \cdot {}_{e}\sigma \qquad Total\ K-N\ cross\ section\ per\ atom$$

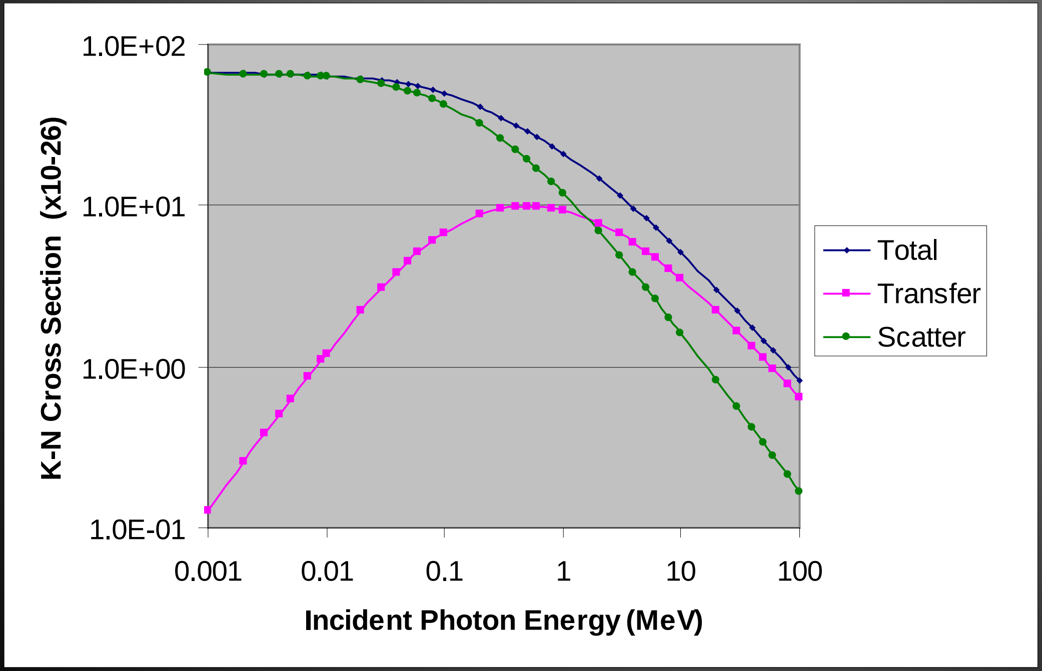
$$\frac{\sigma}{\rho} = \frac{N_{A}Z}{A}\,{}_{e}\sigma \qquad Compton\ mass\ attenuation\ coefficient$$

$$\frac{N_{A}Z}{A} \qquad electron\ density \quad \#\,of\ e^{-}\ per\ gram$$

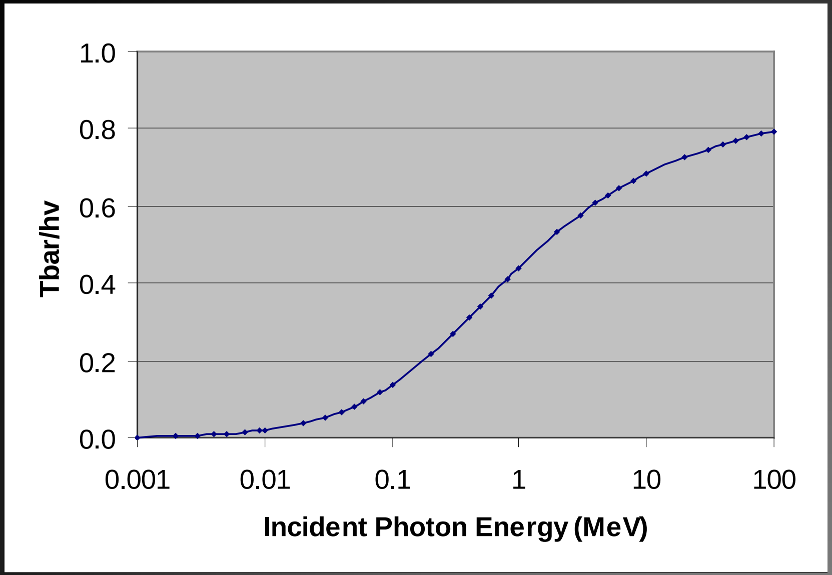
The average fraction of the incident photon energy given to the scattered electron is:

$$\boxed{\frac{\overline{T}}{h\nu} = \frac{{}_e\sigma_{tr}}{{}_e\sigma}}$$

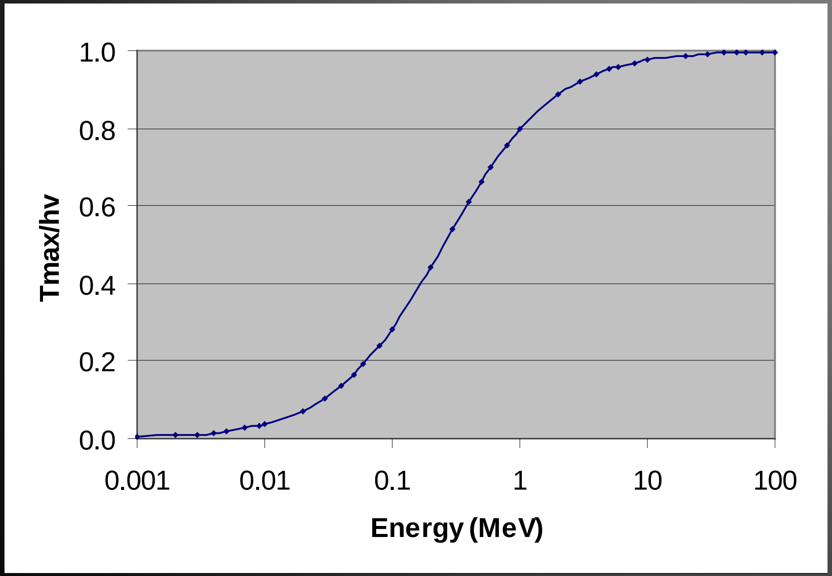
Where T is the average energy of the compton recoil electrons.



$$\boxed{{}_e\sigma = \underbrace{{}_e\sigma_{tr}}_{\text{electron}} + \underbrace{{}_e\sigma_s}_{\text{photon}}}$$



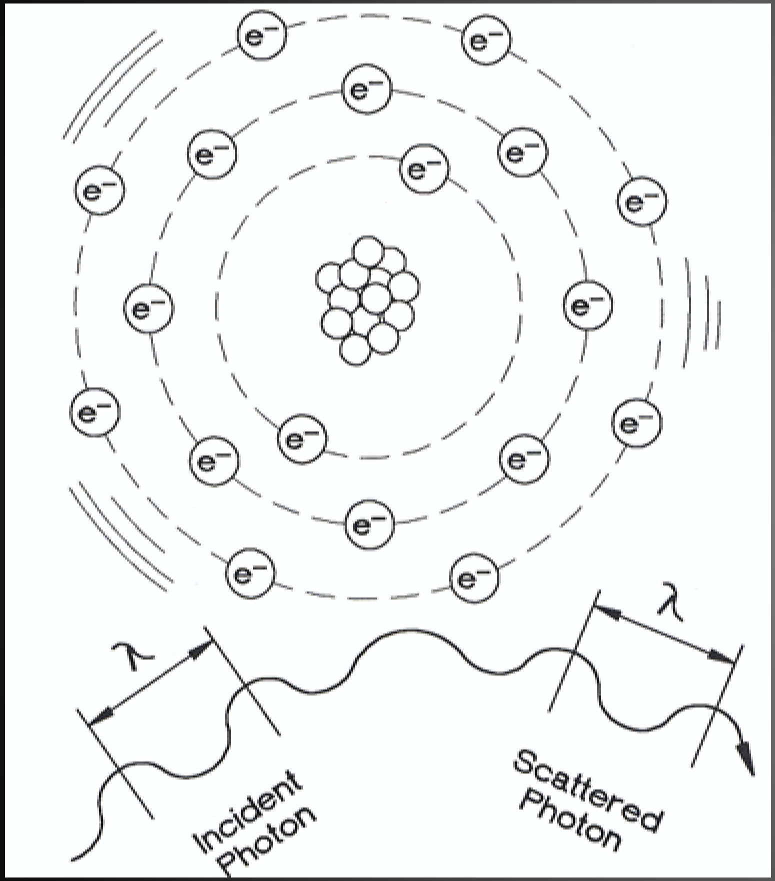
$$\frac{\overline{T}}{h\nu} = \frac{{}_e\sigma_{tr}}{{}_e\sigma}$$



$$\frac{T_{max}}{h\nu} = \frac{2h\nu}{2h\nu + m_o c^2}$$

The maximum electron energy (T_{max}) resulting from a head-on Compton collision (θ=0°) by a photon of energy $h\nu$ approaches $h\nu$ - 0.2555 MeV for large $h\nu$.

Rayleigh (Coherent) Scattering



- Photon energy loss is zero
- Photon scatter angle is small
- Photon scatter angle increases
As Z increases and hν decreases
- Contributes ≈5% or less to the total μ

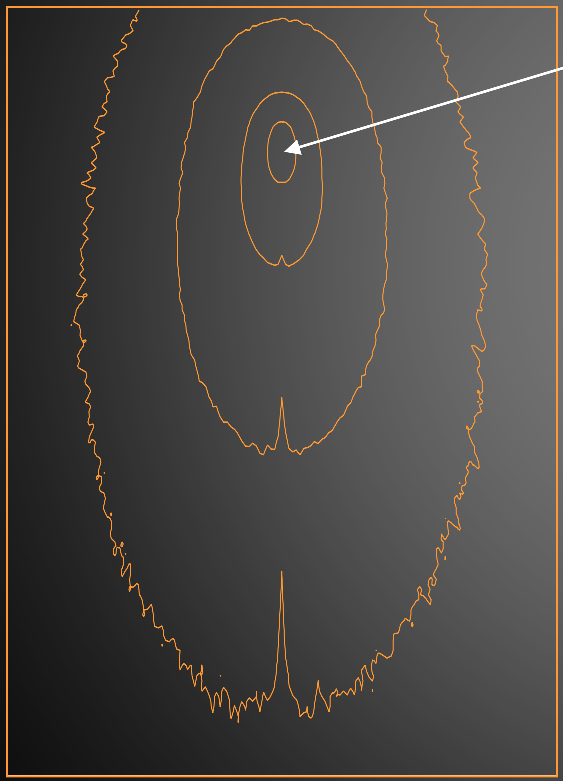
$$_a\sigma_R \propto \frac{Z^2}{(h\nu)^2} \qquad (\text{cm}^2/\text{atom})$$

$$\frac{\sigma_R}{\rho} \propto \frac{Z}{(h\nu)^2} \qquad (\text{cm}^2/\text{g})$$

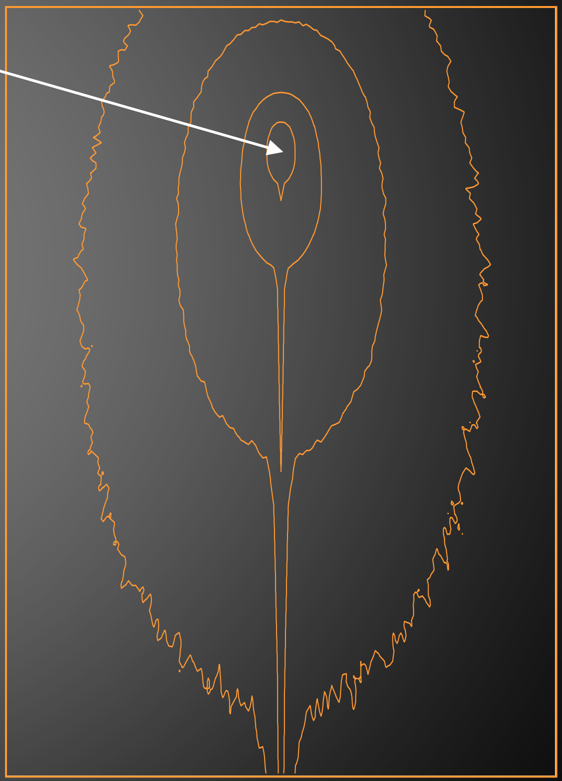
Incoherent Form Factor
S(v, Z)

Atomic Form Factor
F(v, Z)

Incoherent Scatter

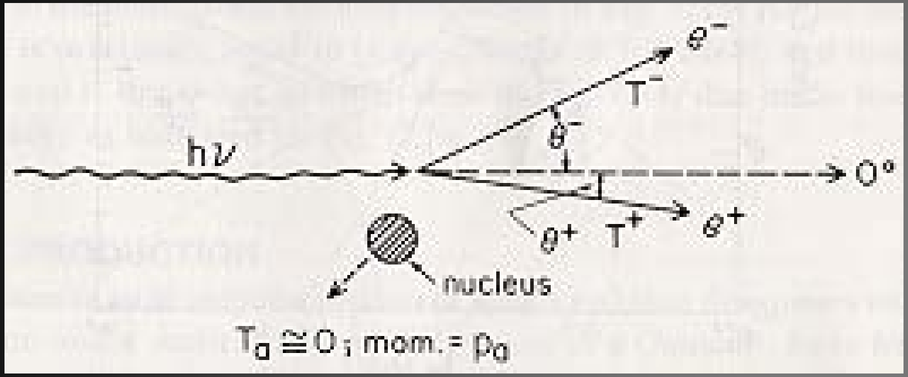


Coherent Scatter



Primary interaction site

Kinematics of Pair Production in the Nuclear Coulomb Force Field



Threshold energy of 1.022 MeV

$$h\nu = 2m_o c^2 + T^+ + T^-$$

$$\overline{T} = \frac{h\nu - 2m_o c^2}{2}$$

$$\overline{\Theta} \cong \frac{m_o c^2}{T}$$

Interaction Cross-Section for Pair Production

$$d({}_a\kappa) = \frac{\sigma_o Z^2 P}{h\nu - 2m_o c^2} dT^+$$

The atomic differential cross-section for the creation of a e^+ of energy T^+ and an e^- of energy $h\nu - 1.022 - T^+$

$$\sigma_o = \frac{r_o^2}{137}$$

P is a function of $h\nu$ and Z

$${}_a\kappa = \sigma_o Z^2 \int_0^{h\nu - 2m_o c^2} \frac{P dT^+}{h\nu - 2m_o c^2} = \sigma_o Z^2 \int_0^1 P d\left(\frac{T^+}{h\nu - 2m_o c^2}\right) = \sigma_o Z^2 \overline{P}$$

$$\frac{\kappa}{\rho} = {}_a\kappa \frac{N_A}{A}$$

Kinematics of Pair Production in the Electron Field

$$h\nu = 2m_oc^2 + T^+ + T_1^- + T_2^-$$

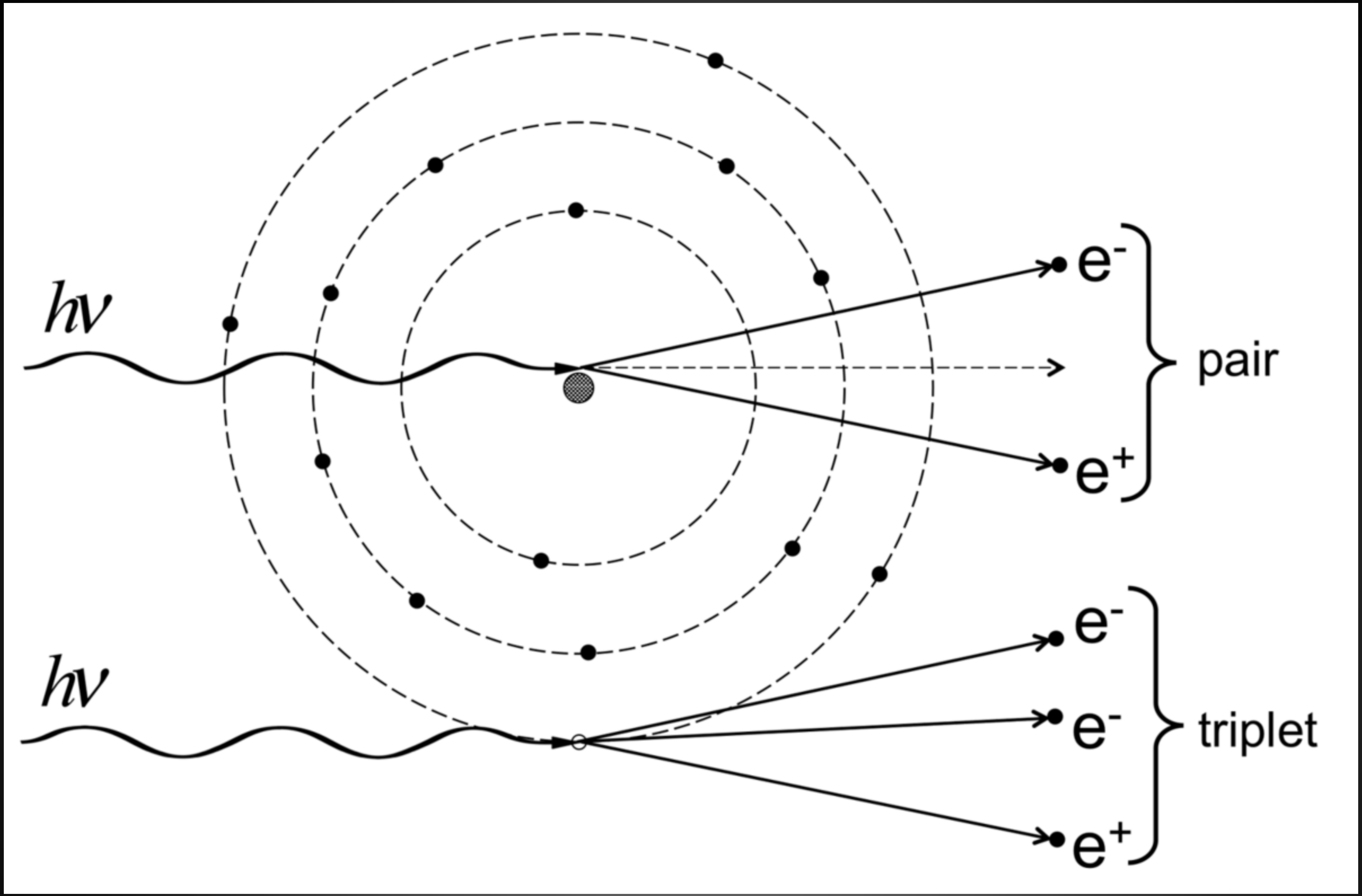
$$\overline{T} = \frac{h\nu - 2m_oc^2}{3}$$

Threshold energy of 2.044 MeV

$$\frac{{}_a k(electron)}{{}_a k(nucleus)} \cong \frac{1}{CZ}$$

Ratio of triplet to pair production

$$\left(\frac{k}{\rho}\right)_{\text{pair}} = \left(\frac{k}{\rho}\right)_{\text{nuclear}} + \left(\frac{k}{\rho}\right)_{\text{electron}}$$



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D.W. O. Rogers and Joanna E. Cygler, Editors
Chap. 2 , Basic Radiation Interactions, Definition of Dosimetric Quantities, and Data Sources, J. V. Siebers and G. D. Hugo

Photonuclear Interactions

• Photonuclear absorption of the photon by the atomic nucleus results most usually in the ejection of one or more neutrons and/or protons.

• At low energies (<30MeV) the Giant Dipole Resonance (GDR) is the dominant excitation mechanism, where the collective bulk oscillation of the neutrons against the protons occurs.

• At higher energies (up to 150MeV), where the wavelength of the photon decreases, the phenomenological model of photoabsorption on a neutron-proton (quasi-deuteron, QD), which has a large dipole moment, becomes important.

$$\sigma_{\mathrm{abs}}\left(\mathrm{E}_{\gamma}\right)=\sigma_{\mathrm{GDR}}\left(\mathrm{E}_{\gamma}\right)+\sigma_{\mathrm{QD}}\left(\mathrm{E}_{\gamma}\right)$$

$$h\nu_{min} = -BE\left(1 - \frac{BE}{2Mc^2}\right)$$

Nucleus	Photonuclear Threshold (MeV)
^{12}C	18.7
^{14}N	10.5
^{16}O	15.7
^{27}Al	13.1
^{40}Ca	15.6
^{65}Cu	9.9
^{182}W	8.0
^{208}Pb	7.4

Data source: http://www.nndc.bnl.gov/qcalc/

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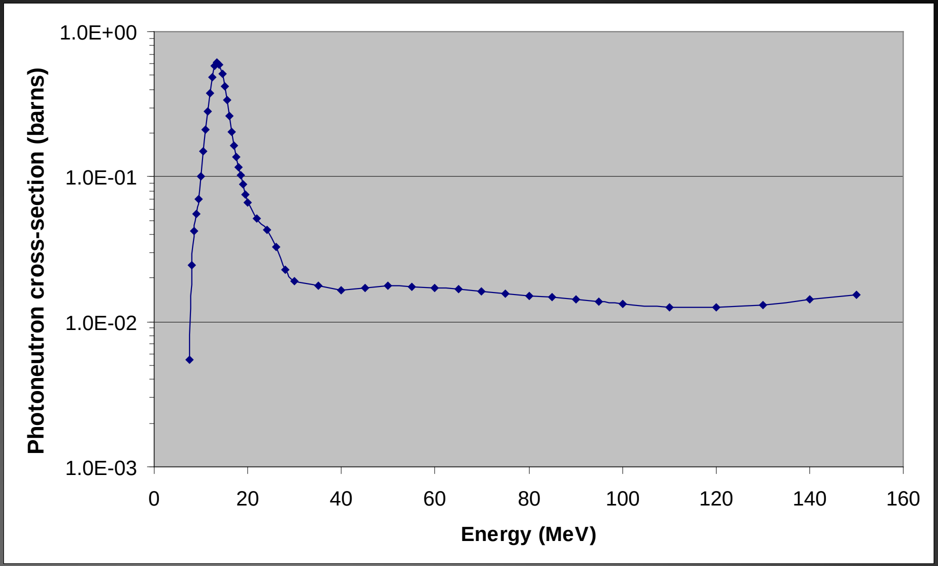
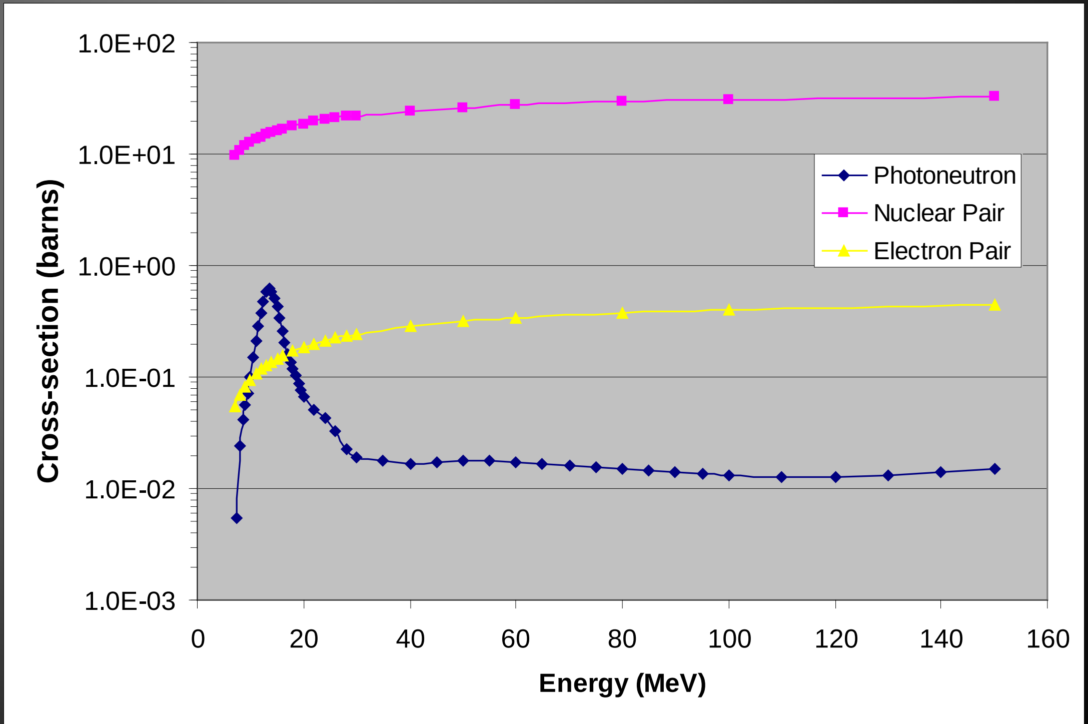
Photoneutron cross-section for Pb-208





Total Mass Attenuation Coefficient

Present tabulations of μ/ρ rely heavily on theoretical values for the total cross section per atom, σ_{tot}

$$\frac{\mu}{\rho} = \frac{\sigma_{tot}}{uA}$$

$$\sigma_{tot} = \sigma_{pe} + \sigma_{coh} + \sigma_{incoh} + \sigma_{pair} + \sigma_{trip} + \sigma_{ph.n.}$$

U = 1.660 540 2 × 10^{-24} g is the atomic mass unit
A = is the relative atomic mass of the target element

Mass energy-transfer coefficient

- f_{pe} is the fraction of energy given to electrons after photoelectric effect

- f_{incoh} is the fraction given to electrons after a compton scatter

- f_{pair} is the fraction of energy given to the electron and positron after pair production minus the annhilation energy

$$\boxed{\left(\frac{\mu_{tr}}{\rho}\right) = \frac{f_{pe}\sigma_{pe} + f_{incoh}\sigma_{incoh} + f_{pair}\sigma_{pair}}{uA}}$$

Mass energy-absorption coefficient

- g represents the average fraction of secondary-electron energy that is lost in radiative interactions (bremsstrahlung production or in-flight annihilation)

$$\boxed{\left(\frac{\mu_{en}}{\rho}\right) = \left(\frac{\mu_{tr}}{\rho}\right)(1-g)}$$

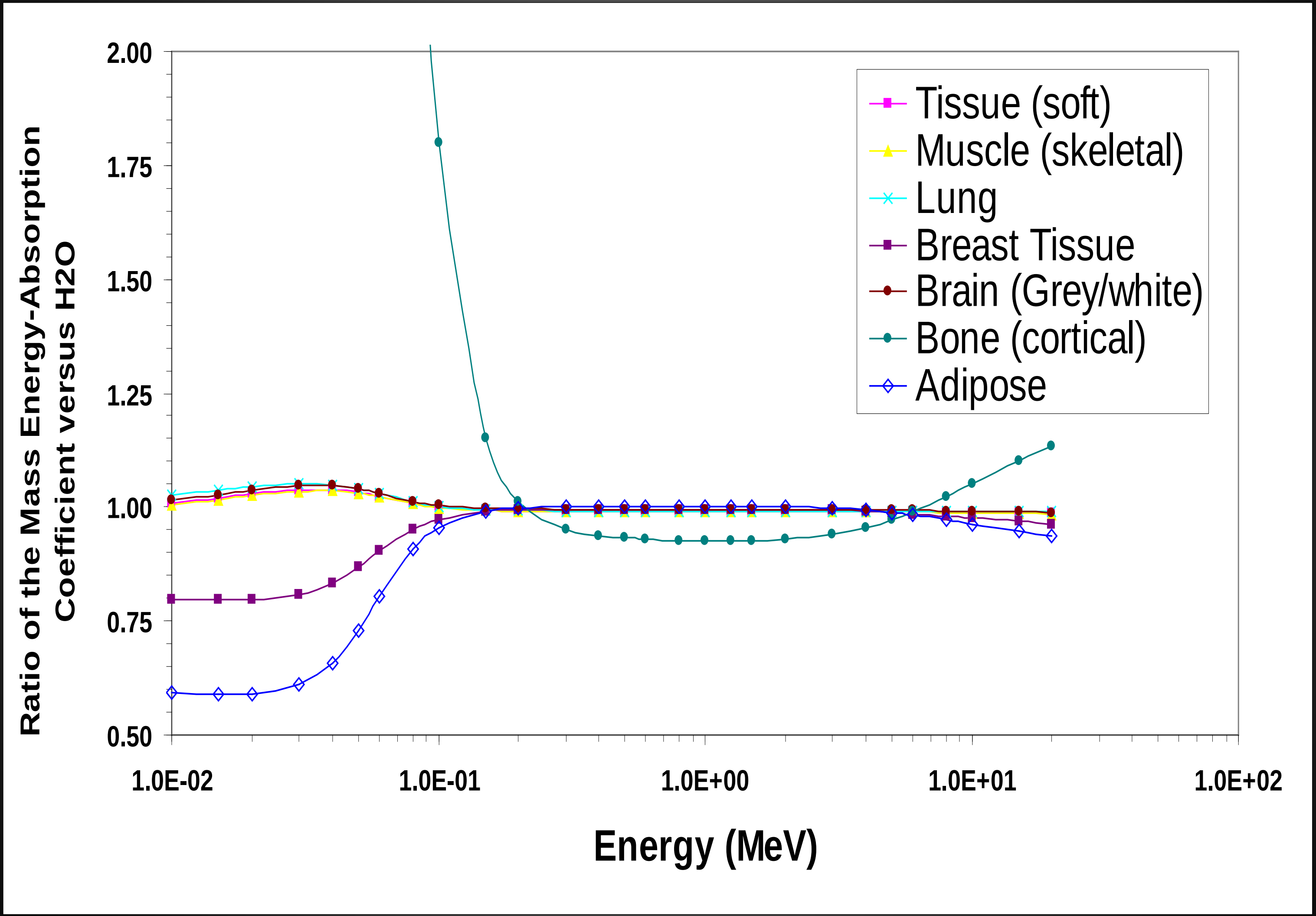
Compounds and Mixtures

$$\left(\frac{\mu}{\rho}\right)_{mix} = \left(\frac{\mu}{\rho}\right)_A f_A + \left(\frac{\mu}{\rho}\right)_B f_B + \ldots$$

$$\left(\frac{\mu_{en}}{\rho}\right)_{mix} \cong \left(\frac{\mu_{enr}}{\rho}\right)_A f_A + \left(\frac{\mu_{enr}}{\rho}\right)_B f_B + \ldots$$

(Assuming radiative losses are small)

Comparison of mass energy-absorption coefficients



Quantities for Describing the Interaction of Ionizing Radiation with Matter

If we use an infinitesimal sphere at a point in free space as our reference location then…

- Kerma (K) - energy transferred to charged particles.

- Absorbed Dose (D) - energy imparted to matter by all kinds of ionizing radiations but delivered by the charged particles.

- Exposure (X) - described x- and γ-ray fields in terms of their ability to ionize air.

Kerma (Kinetic Energy Released in the Medium)

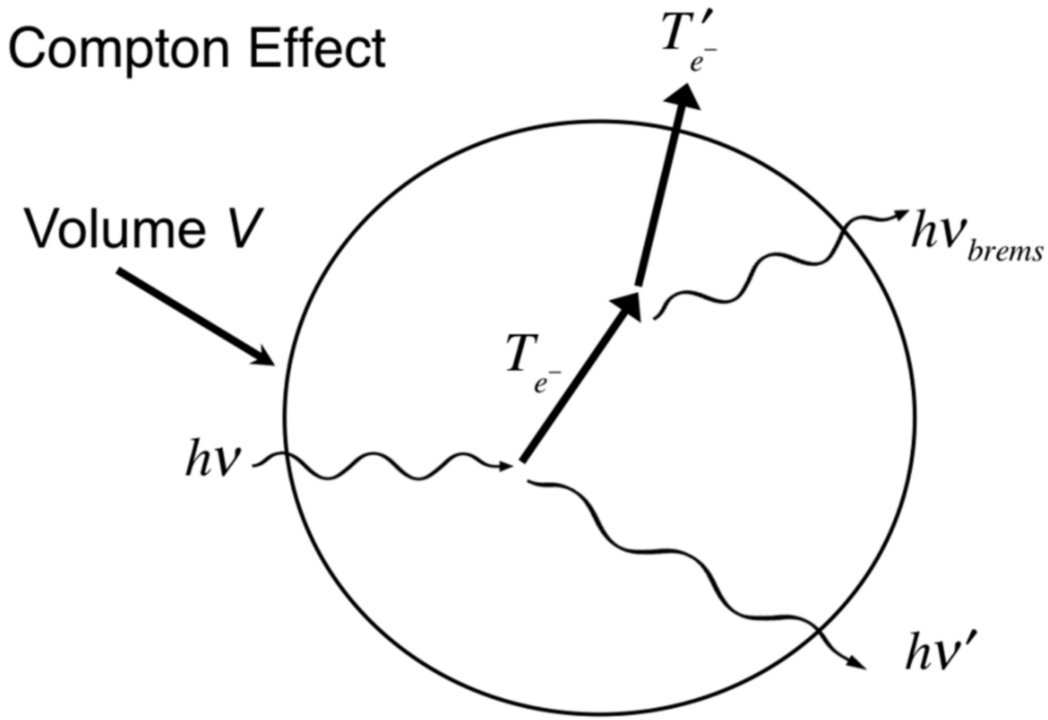
- The expectation value of the energy transferred to charged particles per unit mass at a point of interest, including radiative-loss energy but excluding energy passed from one charged particle to another.

- Relevant only for fields of indirectly ionizing radiations.

$$K = \frac{d\varepsilon_{tr}}{dm}$$

$$1Gy = 1\ J/kg = 100\ rad = 10^4\ erg/g$$

Energy transferred is just the kinetic energy received by charged particles in the specified finite volume V, regardless of where or how they in turn spend that energy.



$$\varepsilon_{tr} = T_{e^-}$$

$$\varepsilon_{tr}^{net} = T_{e^-} - h\nu_{brems}$$

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Kerma for photons

$$K = \psi \left(\frac{\mu_{tr}}{\rho} \right)_{E,Z}$$

$$K = \int_{E=0}^{E_{\max}} \psi'(E) \bullet \left(\frac{\mu_{tr}}{\rho} \right)_{E,Z} dE$$

- K is the photon kerma at point P typically expressed in Gy
- $(\mu_{tr}/\rho)_{E,Z}$ = mass energy-transfer coefficient (cm^2/g)
- Ψ = photon energy fluence (MeV/cm^2 or J/m^2)
- $\Psi'(E)$ = differential distribution of photon energy fluence ($J\ m^2\ keV^{-1}$)

Components of Kerma for Photons

• kerma for photons is basically the energy transferred to electrons or positrons per unit mass of medium.

• The kinetic energy of these electrons may be spent as:

- electrons interact via coulomb force interactions. Local energy dissipation via ionization and excitation of the atoms surrounding the electron track.

- radiative interactions via the coulomb force field of the surrounding atoms. X-ray photons are emitted via bremsstrahlung. Also in-flight annihilation of positrons to produce photons.

$$\boxed{K = K_C + K_R}$$

Collision Kerma

- The expectation value of the net energy transferred to charged particles per unit mass at a point of interest, excluding both the radiative-loss energy and the energy passed from one charged particle to another.

- R_U^R = the radiant energy emitted as radiative losses by the charged particles originating in volume V.

- $(\mu_{en}/\rho)_{E,Z}$ = mass energy-absorption coefficient (cm^2/g)

$$\boxed{K_C = \frac{d\varepsilon_{tr}^{net}}{dm} = \Psi\left(\frac{\mu_{en}}{\rho}\right)_{E,Z}}$$

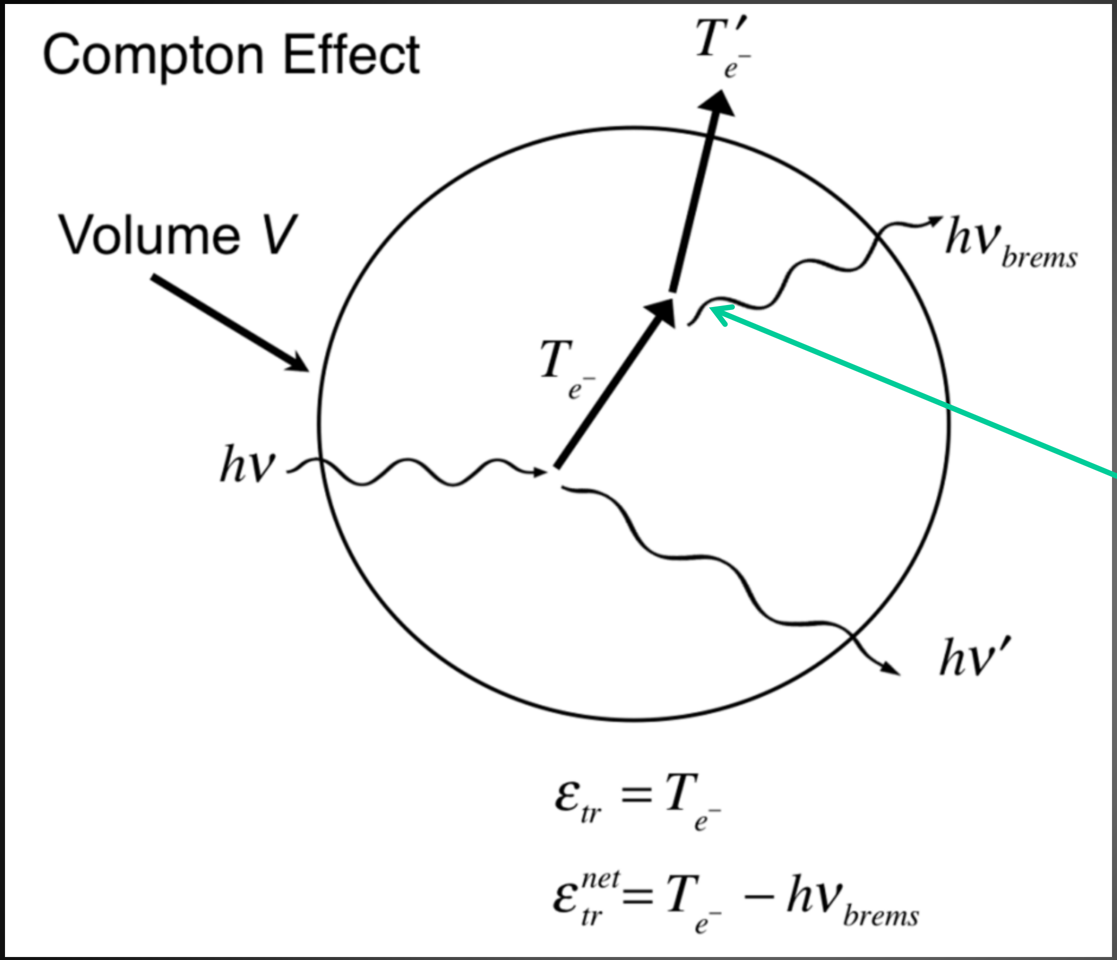
$$\boxed{\varepsilon_{tr}^{net} = (R_{in})_U - (R_{out})_U^{nonR} - R_U^R + \sum Q = \varepsilon_{tr} - R_U^R}$$

bremsstrahlung (German word for "braking radiation")

An electron passing near a nucleus will undergo an inelastic radiative interaction. The electron is deflected and will give up a significant fraction of its kinetic energy (up to 100%) to produce an x-ray photon.

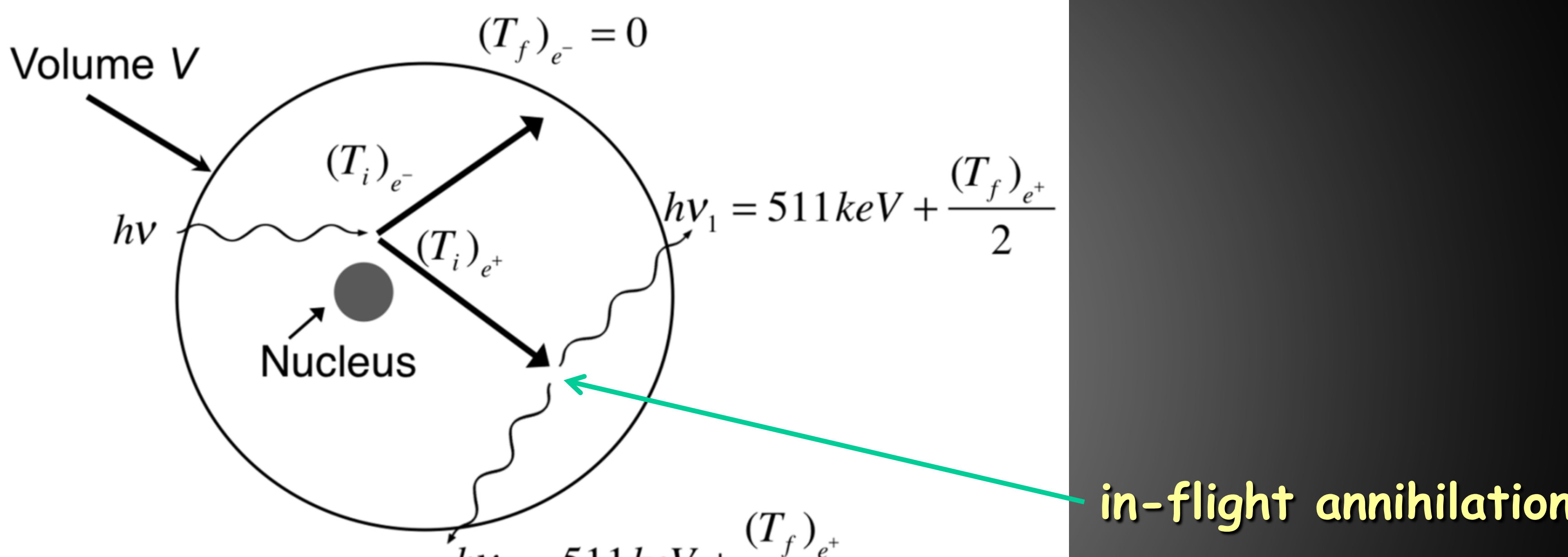
in-flight annihilation

An antimatter interaction whereby a positron is annihilated in encountering an electron before stopping. The remaining kinetic energy of the positron is given to one or both of the annihilation photons.



Bremsstrahlung

Pair production with annihilation in flight



$$\varepsilon_{tr} = (T_i)_{e^-} + (T_i)_{e^+}$$

$$\varepsilon_{tr}^{net} = (T_i)_{e^-} + (T_i)_{e^+} - \left[(T_f)_{e^-} + (T_f)_{e^+} \right]$$

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Energy Imparted (ε)

• The energy imparted by ionizing radiation to the matter in a volume is regarded as the fundamental quantity of radiation dosimetry (stochastic quantity).

• Imparted Energy (δ_ε)

$$\delta_\varepsilon = T_b - \sum_i T_{a,i} + Q$$

• T_b is the kinetic energy of the interacting ionizing particle immediately before the interaction.

• $\Sigma T_{a,i}$ is the sum of the kinetic energies of all ionizing particles created in the process, including the residual kinetic energy of the primary particle if this is still an ionizing particle after interaction.

• Q is the release of rest-mass energy of nuclei and elementary particles.

Absorbed dose (D)

dε is the mean energy imparted by ionizing radiation to the matter in this volume element (1 J/kg = 1 Gy)

The energy imparted by ionizing radiation to the matter in a volume is regarded as the fundamental quantity of radiation dosimetry (stochastic quantity).

$$D = \frac{d\bar{\varepsilon}}{dm}$$

$$\varepsilon = (R_{in})_U - (R_{out})_U + (R_{in})_C - (R_{out})_C + \sum Q$$

Dose Equivalent

units of rem or sievert

D represents the dose in rads or cGy, Q is the quality factor relating the biological effectiveness of the radiation relative to a reference radiation (e.g. 250 kVp x-rays, Co-60,…) and N represents other factors such as time, oxygen tension, etc.

Necessary when evaluating the cumulative effect of different types of radiation to the whole body.

$D_{T,R}$ is the average dose from radiation R in the tissue or organ T and w_R is the radiation weighting factor (1 J/kg = 1 Sv)

$$H_{T,R} = w_R D_{T,R}$$

Exposure

• The absolute value of the total charge of the ions of one sign produced in air when all the e-'s (+&-) liberated by photons in air of mass dm are completely stopped in air.

• The ionization arising from the absorption of bremsstrahlung emitted by the e-'s is not to be included in dQ.

• The exposure is the ionizational equivalent of the collision kerma (K_c) in air for x- and gamma rays.

$$X = \frac{dQ}{dm}$$

Relation of exposure to collision kerma

- W/e = the mean energy expended in a gas per ion pair formed
- W/e for air = 33.97 ev/i.p.

$$\frac{\overline{W}_{air}}{e} = \left(\frac{33.97 ev/i.p.}{1.602x10^{-9} c/e}\right)\left(1.692x10^{-19} J/ev\right)_{air} = 33.97 J/c$$

$$X = \psi\left(\frac{\mu_{en}}{\rho}\right)_{E,air}\left(\frac{e}{\overline{W}}\right)_{air} = \frac{K_C^{air}}{33.97}$$

$$1R = \left(\frac{1esu}{0.001293g}\right)\left(\frac{1c}{2.998x109esu}\right)\left(\frac{1000g}{1kg}\right) = 2.580x10^{-4}\,c/kg$$

$$K_C^{air} = \underline{0.876 \cdot X} = D_{air} \quad \textit{assumes CPE}$$

charged-particle equilibrium

This relationship is significant because it allows one to calculate the absorbed dose based upon the exposure reading from a calibrated ion chamber

Cavity Theory *Redux*

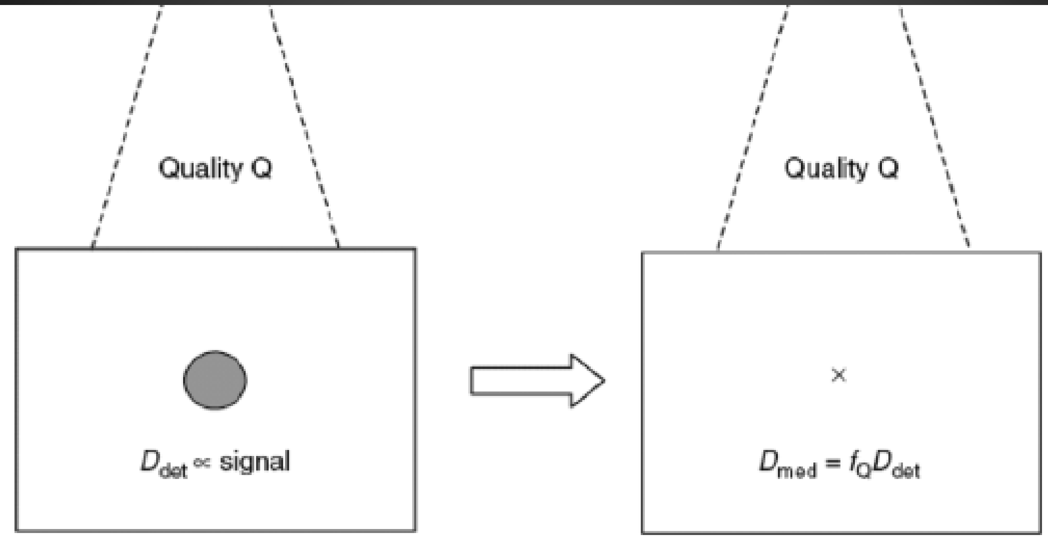
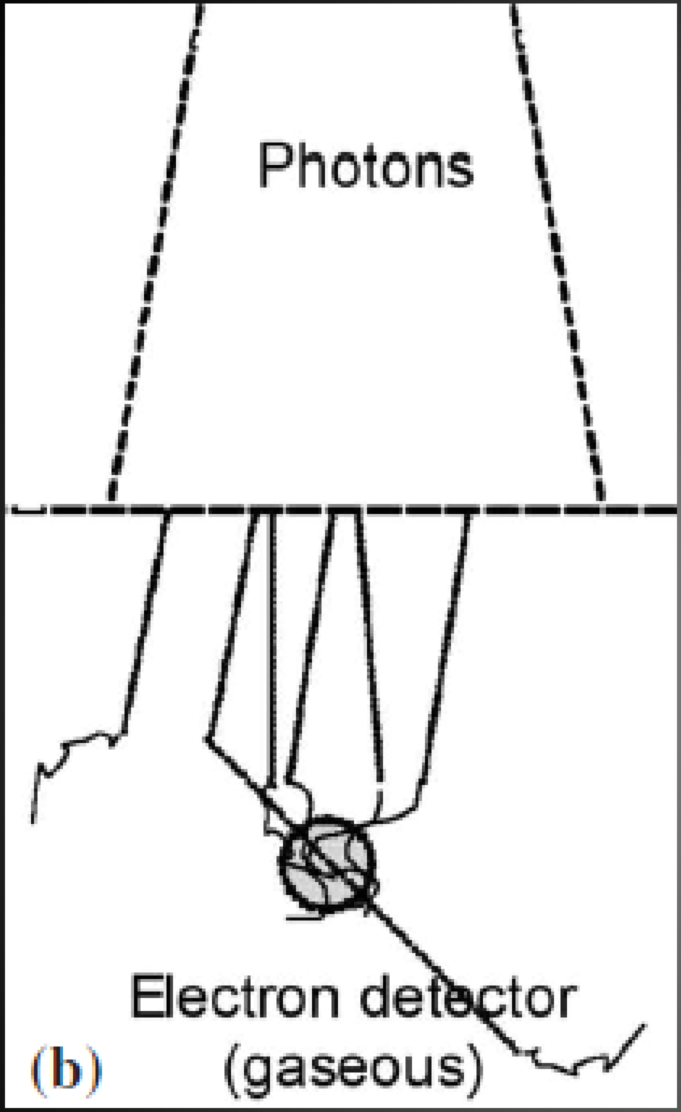


Figure 3-1. The general situation of a detector introduced into a medium (left), yielding D_{det} for a given "exposure" to radiation of Quality Q and then being converted into the dose D_{med} at position x in the absence of the detector by multiplying by the cavity-theory factor $f(Q)$ (Reproduced from *Handbook of Radiotherapy Physics Theory and Practice*. P. Mayles, A. Nahum, J.-C. Rosenwald (eds.), © 2007 Taylor & Francis with permission.)

The aim of cavity theory is to determine f_Q

$$f_Q = \left(\frac{D_{med}}{\overline{D}_{\text{det}}} \right)_Q$$



Bragg-Gray

$$\frac{D_w}{D_g} = \frac{(dT/\rho dx)_{c,w}}{(dT/\rho dx)_{c,g}} = {}_c S_g^w$$

Ratio of stopping powers

Spencer-Attix

$$\frac{D_w}{D_g} = \frac{(dT/\rho dx)^{\Delta}{}_{c,w}}{(dT/\rho dx)^{\Delta}{}_{c,g}} = {}_c L_g^w$$

Ratio of "restricted" stopping powers

Reproduced from A. Nahum (Cavity Theory, Stopping-Power Ratios, Correction Factors)

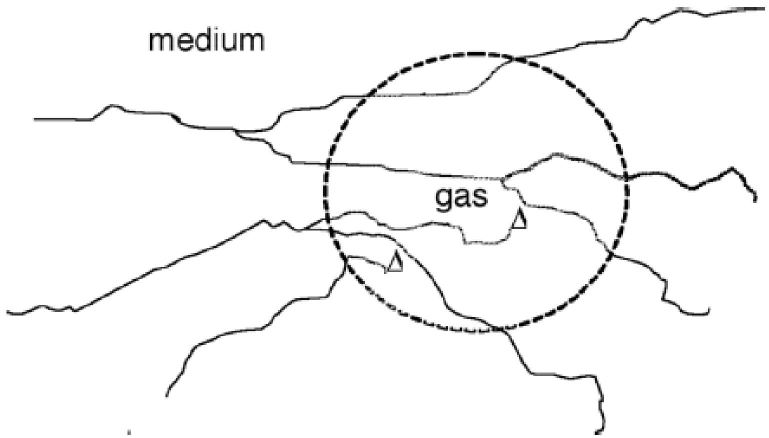


Figure 3-6. Schematic illustration of energy deposition in a cavity according to the Spencer-Attix local energy-deposition model. All generations of incoming electrons are included in the incoming fluence Φ^{tot}. These electrons deposit energy in the cavity "locally" through "continuous" transfers up to Δ in energy—the first term in equation (3.14). The track-ends, indicated by their residual energy Δ, are accounted for explicitly by the second term in the cavity integral. A long-range δ-ray is shown leaving the cavity—this is implicitly assumed to be part of the fluence existing in the undisturbed medium.

$$D_{gas} = \int_{\Delta}^{E_{max}} \left(\Phi_E^{tot}(E)\right)_{med} \left[L_\Delta(E)/\rho\right]_{gas} \mathrm{d}E + \left\{\Phi_E^{tot}(\Delta)\left[S_{col}(\Delta)/\rho\right]_{gas} \Delta\right\}$$

$$\left(\frac{\overline{L_\Delta}}{\rho}\right)_{gas}^{med} = \frac{\int_{\Delta}^{E_{max}} \left(\Phi_E^{tot}(E)\right)_{med} \left[L_\Delta(E)/\rho\right]_{med} \mathrm{d}E + \left\{\Phi_E^{tot}(\Delta)\left[S_{col}(\Delta)/\rho\right]_{med} \Delta\right\}}{\int_{\Delta}^{E_{max}} \left(\Phi_E^{tot}(E)\right)_{med} \left[L_\Delta(E)/\rho\right]_{gas} \mathrm{d}E + \left\{\Phi_E^{tot}(\Delta)\left[S_{col}(\Delta)/\rho\right]_{gas} \Delta\right\}}$$

Reproduced from A. Nahum (Cavity Theory, Stopping-Power Ratios, Correction Factors)

Spencer-Attix theory forms the basis behind high-energy photon calibration protocols

When can a radiation detector be treated as a Bragg-Gray cavity?

1st B-G Condition (and the most important)

The thickness of the gas volume is assumed to be so small in comparison with the range of the charged particles striking it that its presence does not perturb the charged-particle field.

- Cavity must be "small" compared to the electron ranges.
- For photon beams you can only use gas-filled detectors (ionization chambers)

2nd B-G Condition

The absorbed dose in the cavity is assumed to be deposited entirely by the charged particles crossing it.

- only applies to photon beams

$$K_{air} = X\frac{W}{e}\frac{1}{1-g} = \frac{Q_{air}}{m_{air}}\frac{W}{e}\frac{1}{1-g}$$

Photon energies < 400 kVp

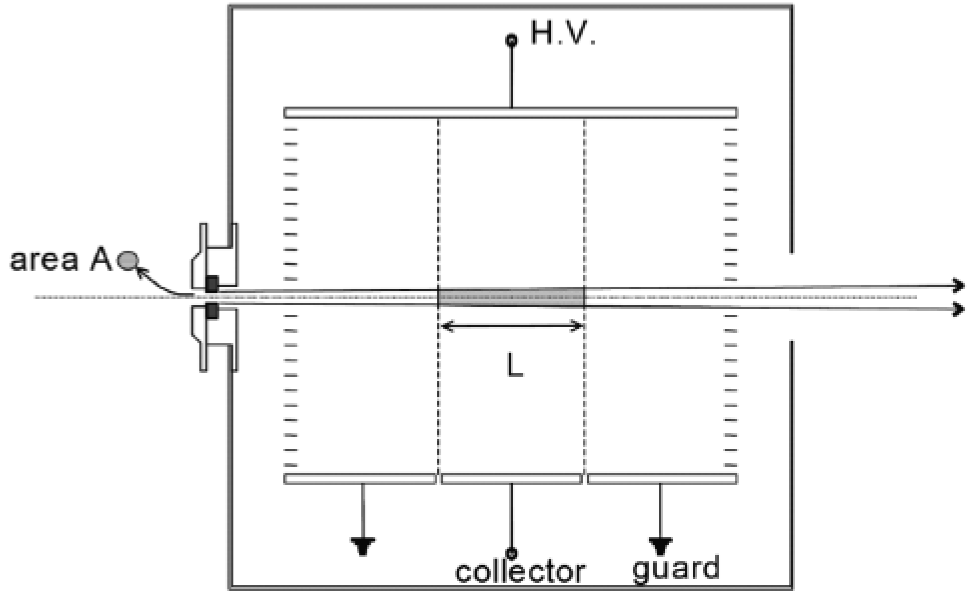


Figure 15-1. Diagram of a free-air chamber. The collecting volume is defined by *A*, the area of the aperture and *L*, the length of the collecting electrode. The series of short lines at each end of the electrodes signify the guard wires or bars (see text). (Courtesy of National Physical Laboratory.)

$$K_{air} = \frac{Q_{air}}{\rho_{air}V}\left(\frac{W}{e}\right)_{air}\frac{1}{1-g}K_{att}K_{sc}K_{e}K_{hum}P_{pol}P_{ion}$$

Photon energies > 400 kVp, *Cs*-137 (667 keV), *Co*-60 (1250 keV)

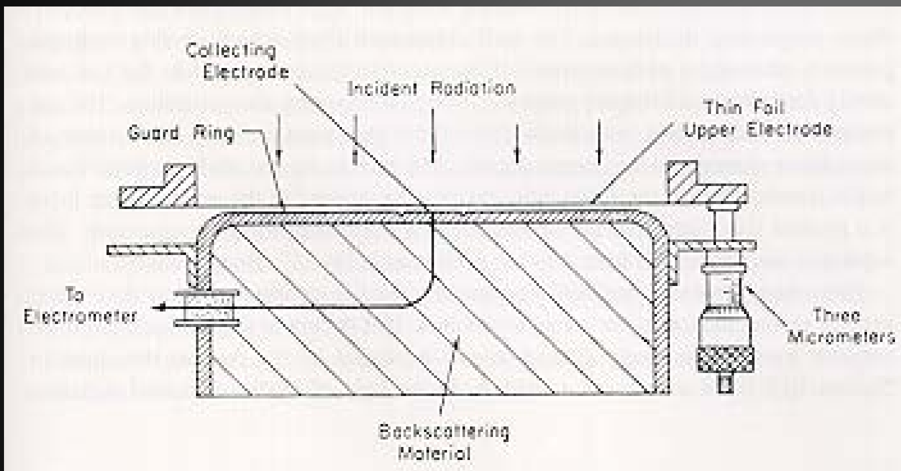
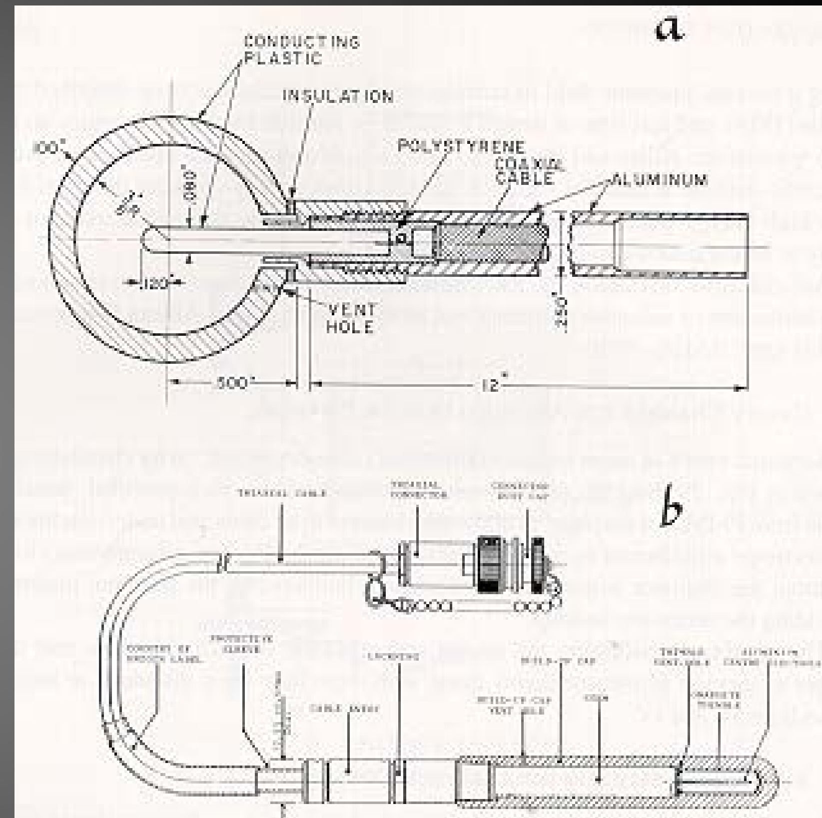


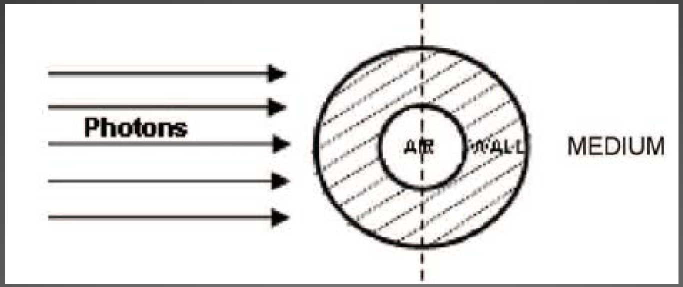
Fig. 31. Extrapolation chamber (Failla, 1937).

Reproduced from Attix



$$K_{air} = \frac{Q_{air}}{\rho_{air} V}\left(\frac{W}{e}\right)_{air} \frac{1}{1-g}\left(\frac{\bar{L}_{\Delta}}{\rho}\right)_{air}^{wall}\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{wall}^{air} K'$$

Photon energies ≥ Co-60 (TG-21)
Based upon in-air chamber calibration



$$K_{air} = \frac{Q_{air}}{\rho_{air} V}\left(\frac{W}{e}\right)_{air} \frac{1}{1-g}\left(\frac{\bar{L}_{\Delta}}{\rho}\right)_{air}^{wall}\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{wall}^{air} K'$$

$$D_{air} = K_{air}\left(\frac{\bar{L}_{\Delta}}{\rho}\right)_{wall}^{air}\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{air}^{wall} K'_{calibration}$$

$$N_{air} = \frac{D_{air} A_{ion}}{M_{calibration}}$$

$$D_{med} = M_{user} N_{air}\left(\frac{\bar{L}_{\Delta}}{\rho}\right)_{air}^{med} K'_{user}$$

Report No. ION13241

University of Wisconsin - Madison
Department of Medical Physics
Accredited Dosimetry Calibration Laboratory

Cobalt-60 Measurement Data

Calibration Completed: 13/APR/2011

Report Date: 13/APR/2011

Ionization Chamber

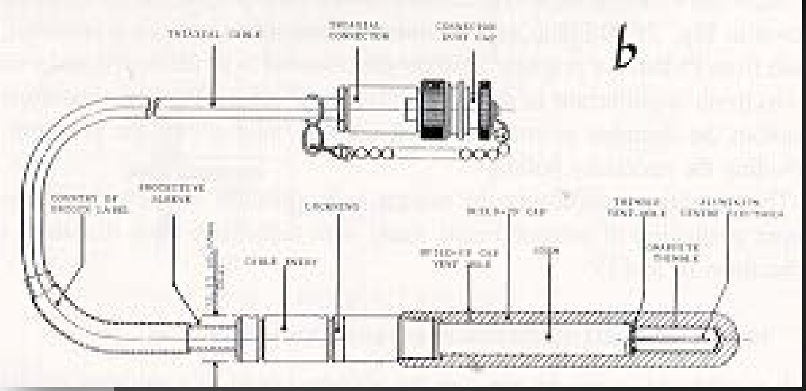
PTW
Model: N30006
S/N: 0245

Electrometer used in Calibration

Standard Imaging, Inc.
Model: MAX-4000
S/N: E992941

Type	:	Waterproof Farmer
Atmospheric Communication	:	Open
Field Size	:	10 cm x 10 cm at 100 cm Source-Chamber Distance
Chamber Orientation	:	Black stripe toward beam
Chamber Reference Point	:	Center of chamber volume
Collecting Electrode Bias	:	+300 V
Charge Collected	:	Negative
Pre-Irradiation Leakage	:	-8.0×10^{-15} A
Calibration Uncertainty	:	1.5 %
Ion Collection Efficiency (Aion)	:	1.000

Beam Quality	Air Kerma Rate (mGy/s)	Air Kerma Calibration Coeff. (Gy/C)	Exposure Calibration Coeff. (R/C)	Buildup Material
Co-60	16.45	**4.906×10^{7}**	**5.581×10^{9}**	Acrylic



Comments: *The reported calibration coefficient has been corrected to 22 °C and 101.325 kPa. Please refer to the appendix for a complete description of reported calibration coefficients.*

Photon energies ≥ Co-60 (TG-51)
Based upon in-water chamber calibration

$$N_D^{Co60} = \frac{D_w^{Co60}}{M}$$

$$D_w^Q = M k_Q N_w^{Co60}$$

K_Q corrects for the difference in beam quality between the Co-60 calibration and the clinical beam

TG-51 eliminates the in-air calibration concept, exposure (X), and K_{air}

A calibration lab (NIST) positions your ion chamber in a known x-ray field/phantom setup. Chamber is irradiated to produce a given reading (M) for a known exposure (X).

$$M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw}$$

recombination

Temperature & Pressure

Electrometer

polarity