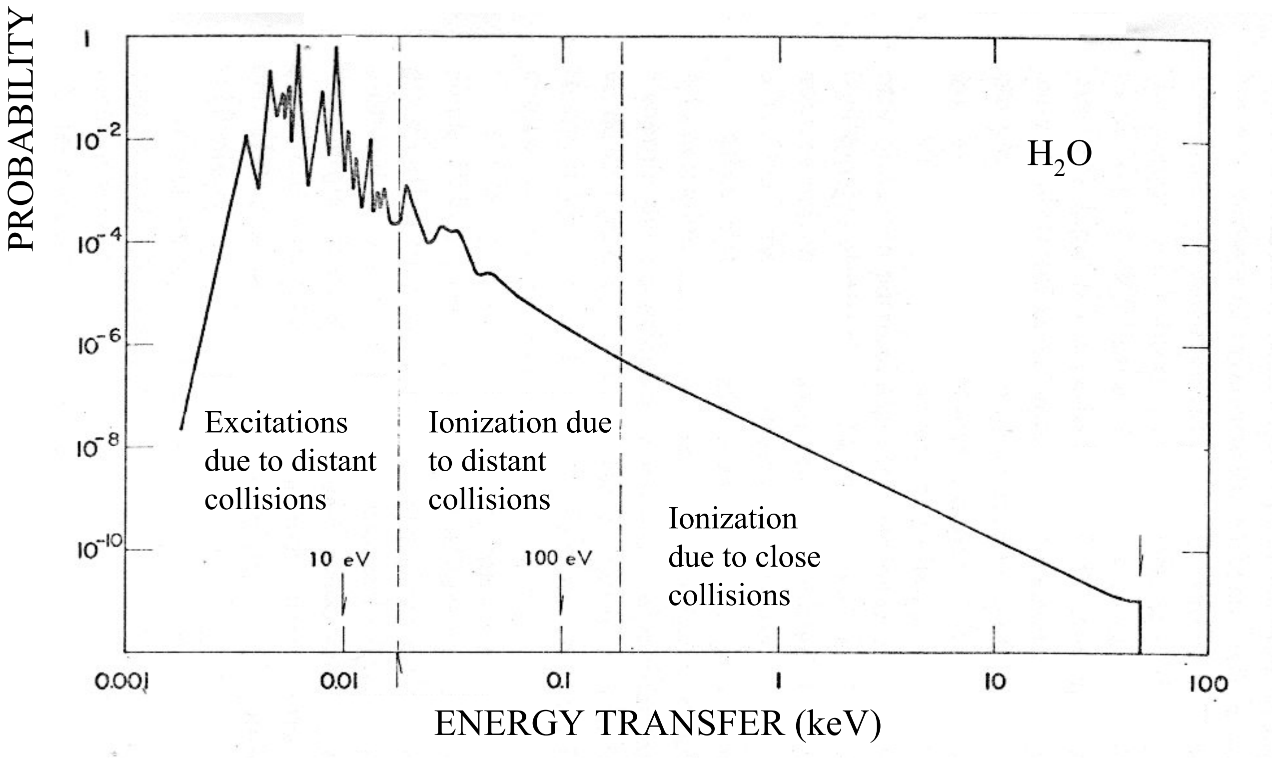
2

INTERACTIONS OF RADIATION WITH MATTER

PROBABILITY OF PRIMARY ELECTROMAGNETIC INTERACTION WITH MATTER

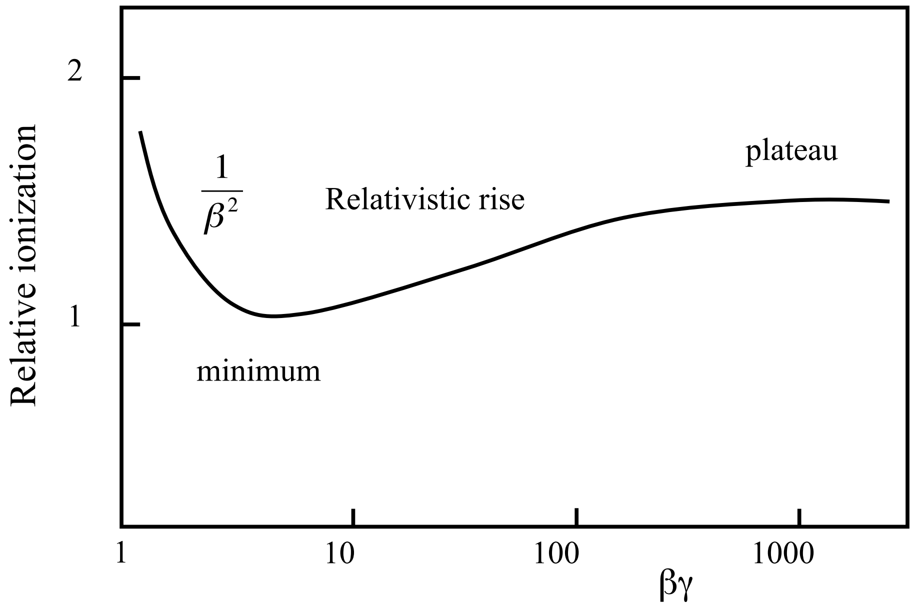


BETHE-BLOCH EXPRESSION

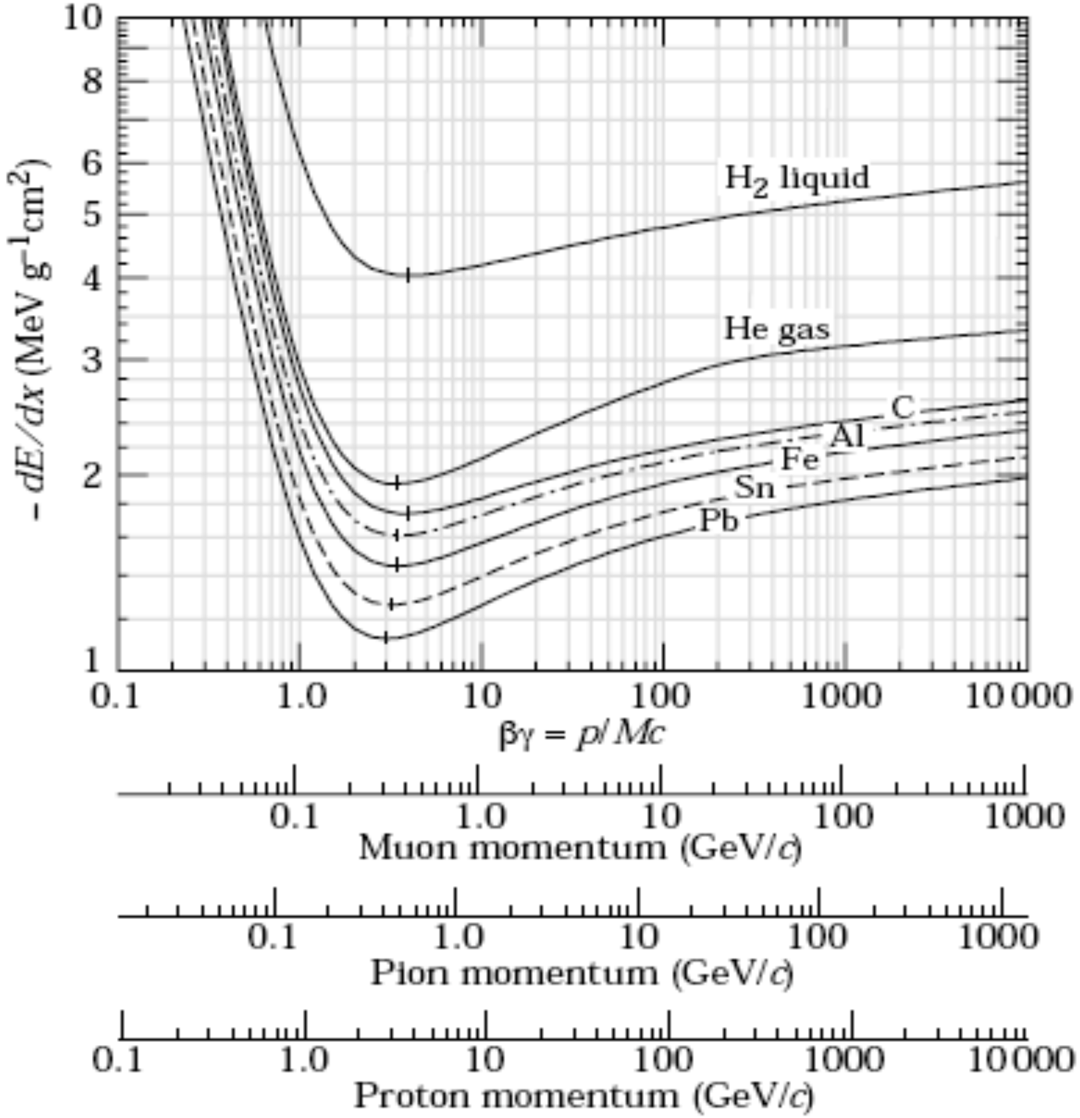
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e \gamma^2 v^2 W_{MAX}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

r_e : classic electron radius 2.817 10^{-13}cm
m_e: electron mass
N_a : Avogadro number 6.022 10^{23} mol^{-1}
I : average ionization potential
Z, A : atomic number and mass of target
ρ : target density

z: particle charge in units of e
β : v/c of particle
γ: $1/\sqrt{(1-\beta^2)}$
δ : density correction
C: shell correction
W_{MAX}: maximum energy transfer in a collision



z=1 particles



Reduced units:

$$\frac{dE}{d\chi} = \frac{1}{\rho}\frac{dE}{dx}$$ ρ: density

$$\chi(g\,cm^{-2}) = \rho(g\,cm^{-3})\,l(cm)$$

In composite materials:

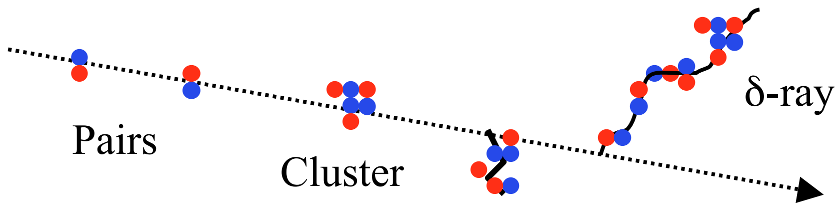
$$\frac{dE}{dx} = \sum p_i \left|\frac{dE}{dx}\right|_i$$

p_i: fraction of material i

Review of Particle Physics, Physics Letters B667 (2008) 1

http://pdg.lbl.gov/

CREATION OF ELECTRON-ION PAIRS



Primary ionization probability:

$$P_k^n = \frac{n^k}{k!} e^{-n}$$

k: actual number
n: average

Total ionization probability (Landau expression):

$$f(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\left(\lambda + e^{-\lambda}\right)}$$

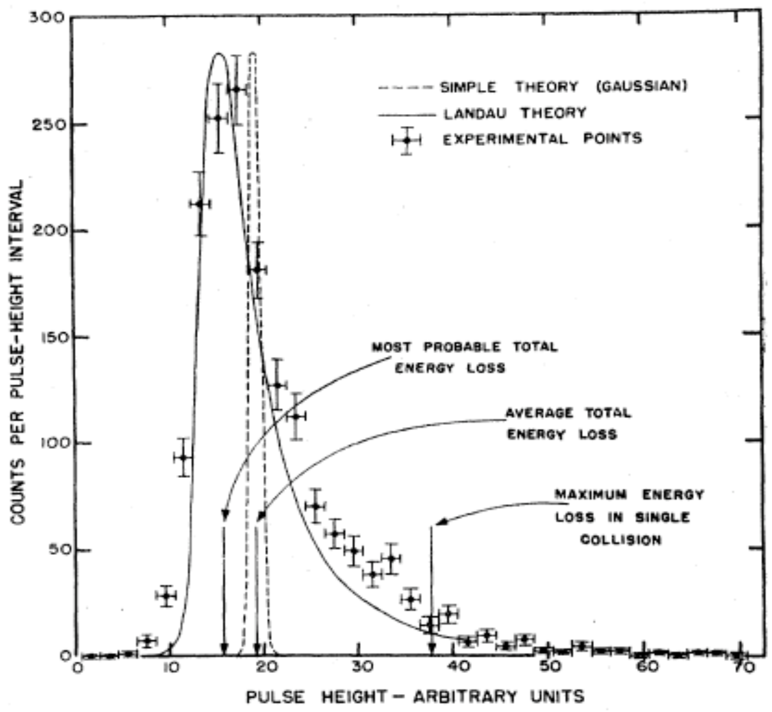
$$\lambda = \frac{\Delta E - \Delta E_{MP}}{\xi} \qquad \xi = K \frac{Z}{A} \frac{\rho}{\beta^2} x$$

Average total ionization:

$$N = \frac{\Delta E}{W_i}$$

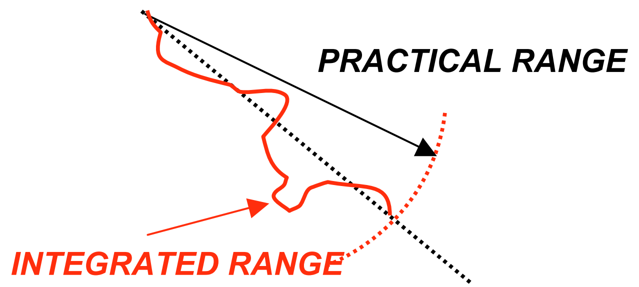
ΔE: energy loss
W_i: average energy per ion pair

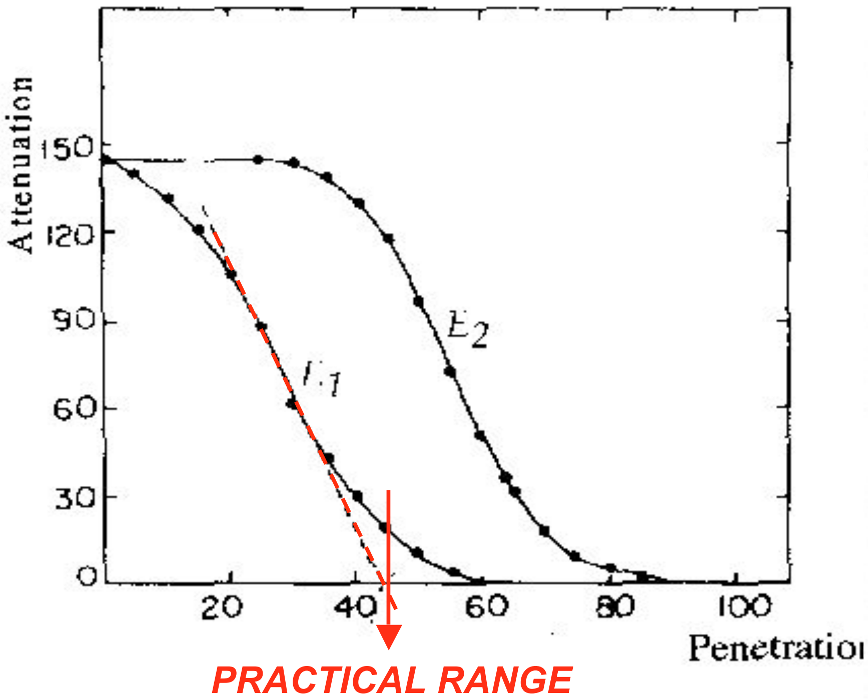
TOTAL IONIZATION ENERGY LOSS

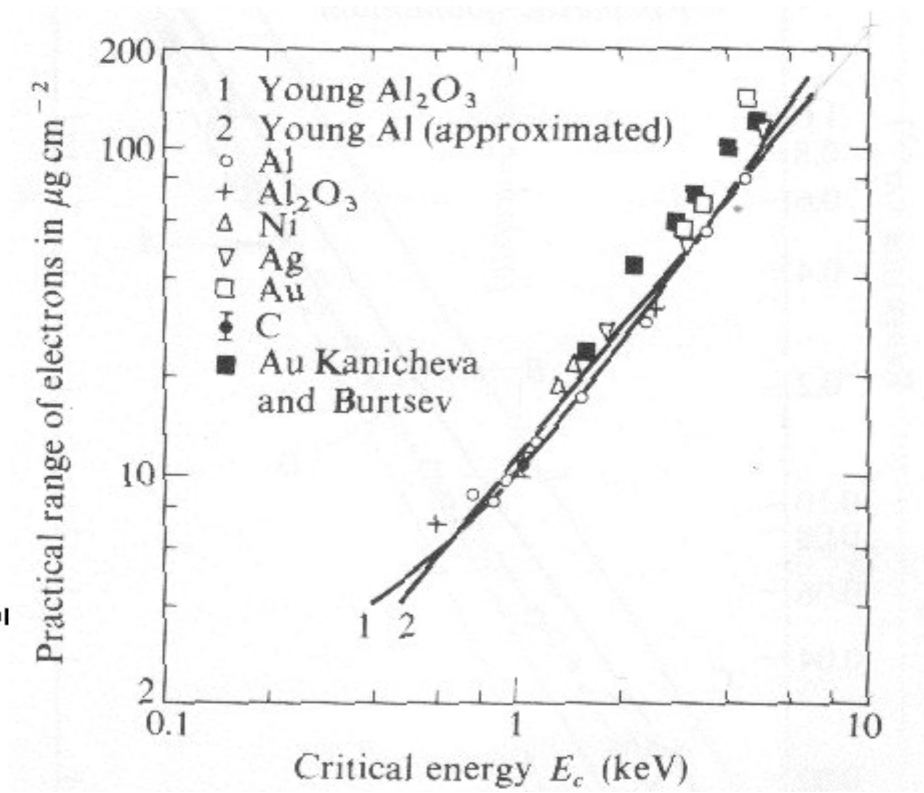


G. Igo et al, Phys. Rev. 89(1953)879

PATH IN MATERIALS OF DELTA ELECTRONS
Dispersed by multiple scattering







H. Kanter, Phys. Rev. 121(1961)461

ENERGY LOSS IN SEMICONDUCTORS (MINIMUM IONIZING PARTCLES)

MATERIAL	Z	ρ (g cm^{-3})	W_i (eV)	dE/dx (MeV g^{-1} cm^2)	dE/dx (MeV cm^{-1})
Silicon	14	2.34	3.6	1.6	3.7
Germanium	32	5,32	2.96	1.4	7.5

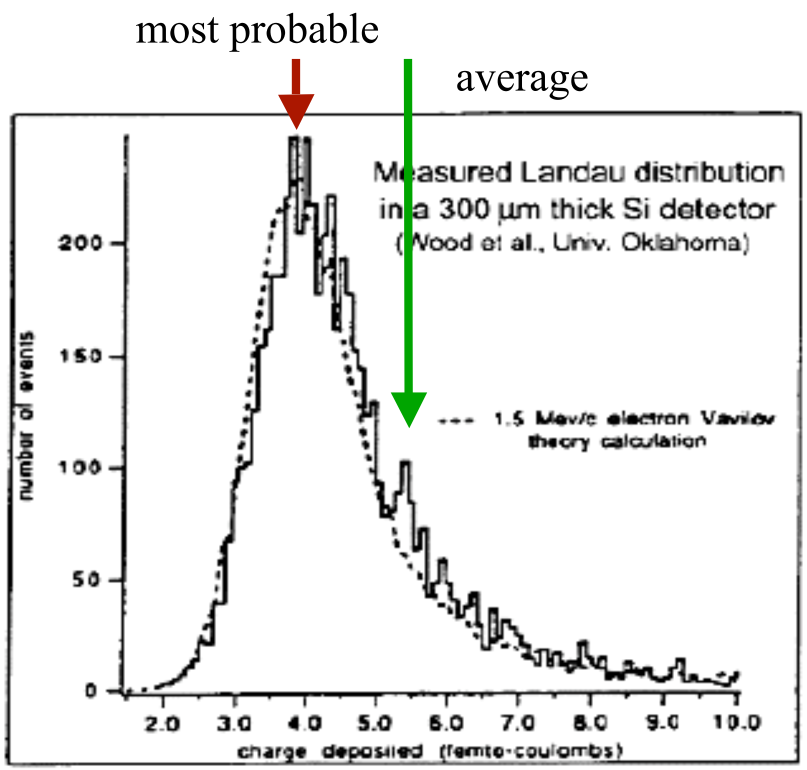
Z : charge ρ : density W_i average ionization energy

Average number of ion pairs:

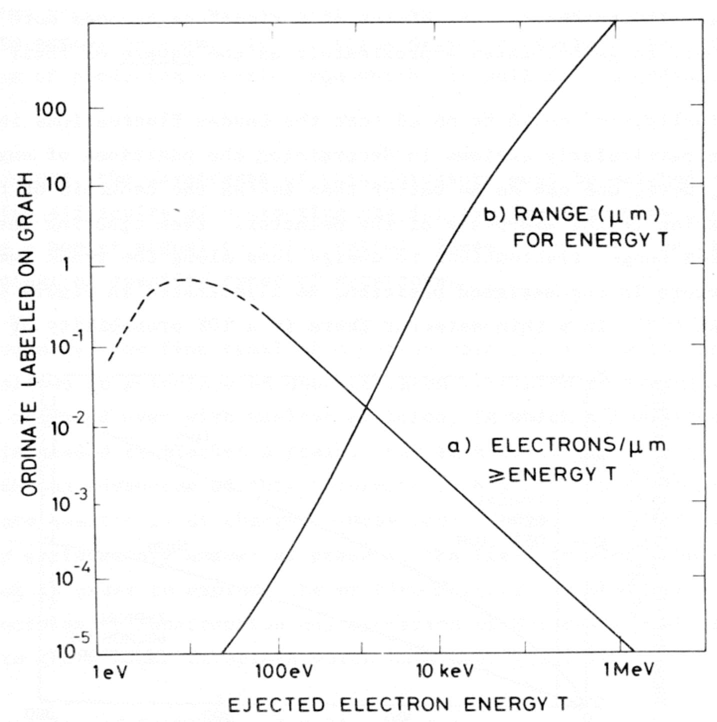
$$n = \frac{\Delta E}{W_i} = \frac{dE/dx}{W_i} s$$

For silicon, 300 μm thick:

n ~ 30,000 electron-hole pairs
or
$$\Delta q = n \times 1.6 \times 10^{-19} C = 4.8 \; fC$$

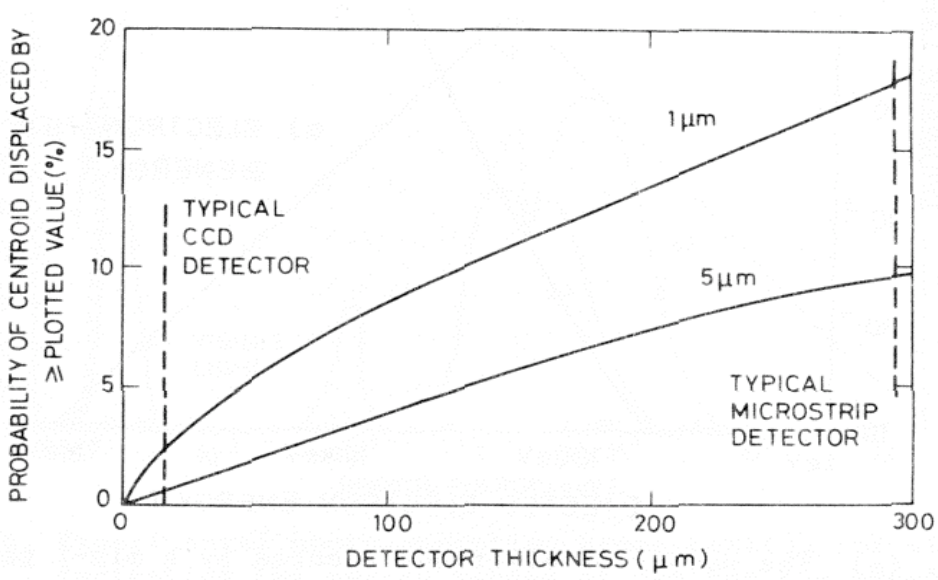


DELTA ELECTRON PRODUCTION PROBABILITY AND RANGE IN SILICON



C. Damerell, RAL 86-77(1986)

POSITION ERROR AS A FUNCTION OF THICKNESS IN SILICON DETECTORS (PERPENDICULAR MIPS)



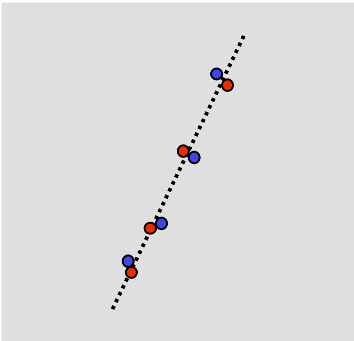
C. Damerell, Nucl. Instr. and Meth. 226(1984)26

MAIN PARAMETERS:

C. Amsler et al,
Review of Particle Physics
Physics Letters B667 (2008) 1

Gas	Density, $mg\,cm^{-3}$	E_x eV	E_I eV	W_I eV	$dE/dx\|_{min}$ $keV\,cm^{-1}$	N_P cm^{-1}	N_T cm^{-1}
Ne	0.839	16.7	21.6	30	1.45	13	50
Ar	1.66	11.6	15.7	25	2.53	25	106
Xe	5.495	8.4	12.1	22	6.87	41	312
CH_4	0.667	8.8	12.6	30	1.61	37	54
C_2H_6	1.26	8.2	11.5	26	2.91	48	112
iC_4H_{10}	2.49	6.5	10.6	26	5.67	90	220
CO_2	1.84	7.0	13.8	34	3.35	35	100
CF_4	3.78	10.0	16.0	54	6.38	63	120

PRIMARY IONIZATION:



Minimum ionizing particles in Argon NTP:

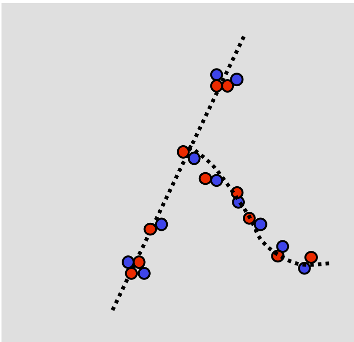
dE/dx: 2.4 keV/cm n_P: 25 ion pairs/cm

Detection efficiency: $\varepsilon = 1 - P_0^n = 1 - e^{-n}$

Thickness:

s (mm)	ε (%)
1	91.8
2	99.3

TOTAL IONIZATION:

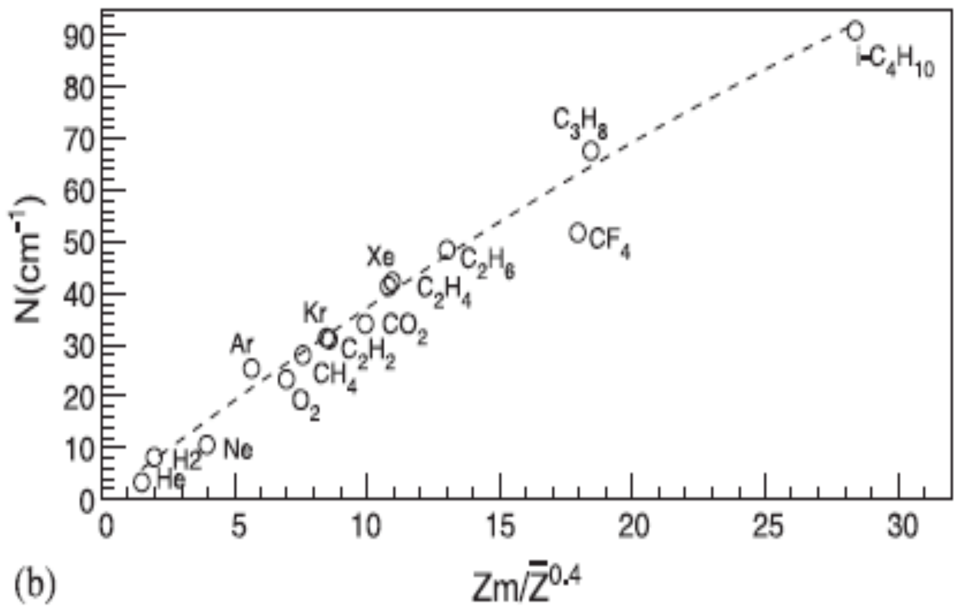


Total number of ion pairs: $n_T = \frac{\Delta E}{W_i}$

ΔE = 2.4 keV/cm w_i = 26 eV $n_T \approx 90$ ip/cm

$$\frac{n_T}{n_P} \approx 3$$

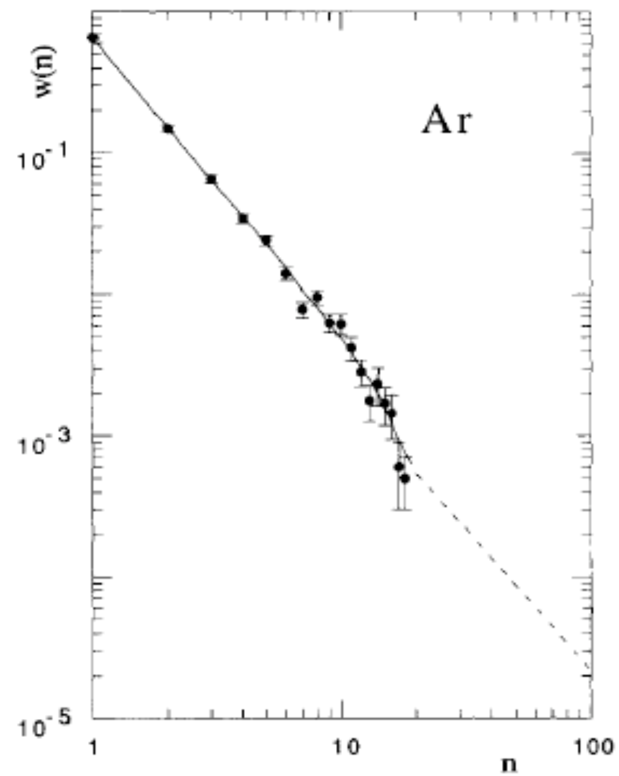
PROGRAM HEED:
NUMBER OF PRIMARY INTERACTIONS (CLUSTERS) IN GASES AT STP



I. B. Smirnov, Nucl. Instr. and Meth. A554(2005)474

http://consult.cern.ch/writeup/heed/

EXPERIMENTAL CLUSTER SIZE PROBABILITY:



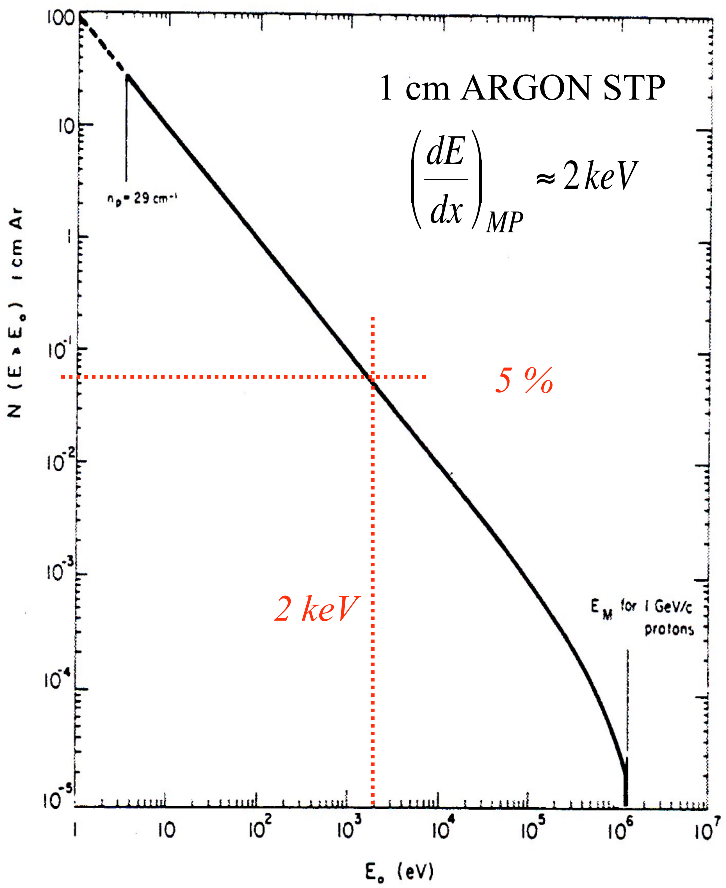
H. Fischle et al, Nucl. Instr. and Meth. A301 (1991) 202

APPROXIMATE EXPRESSIONS

Number of electrons with energy larger than E_0:
(first term of Bethe-Block)

$$N(E \geq E_0) \cong \frac{W}{E_0} \qquad W = K\frac{Z}{A}\rho x$$

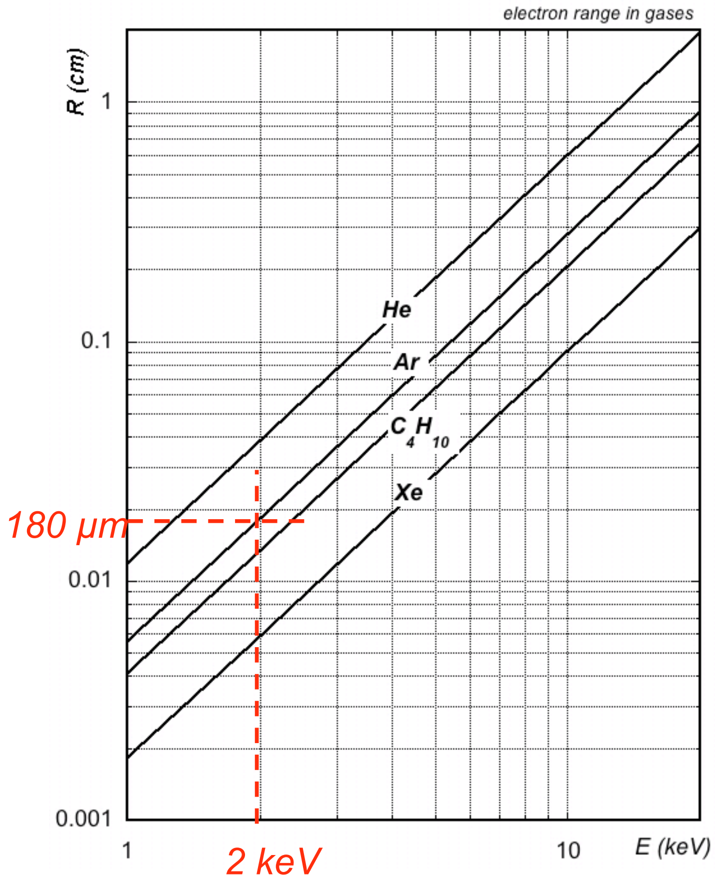
K= 0.154 MeV cm^2/g
ρ: density (g/cm^3)
x: material thickness (cm)



ELECTRON RANGE IN GASES AT STP:

$$R \approx \frac{1}{\rho} 10\, E^{1.7}$$

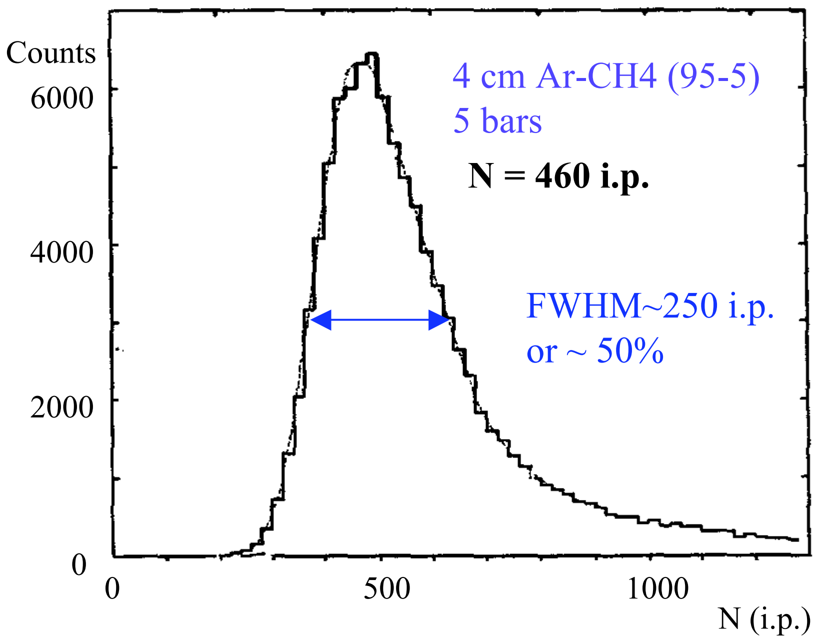
R : range in cm
E : electron energy in keV
ρ : density in μg cm^{-3}



F. Sauli, Nucl. Instr. and Meth. 156 (1978) 147

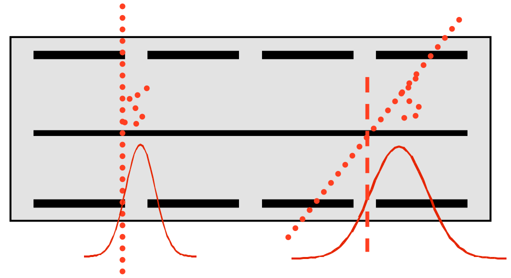
CONSEQUENCES OF DELTA ELECTRON STATISTICS

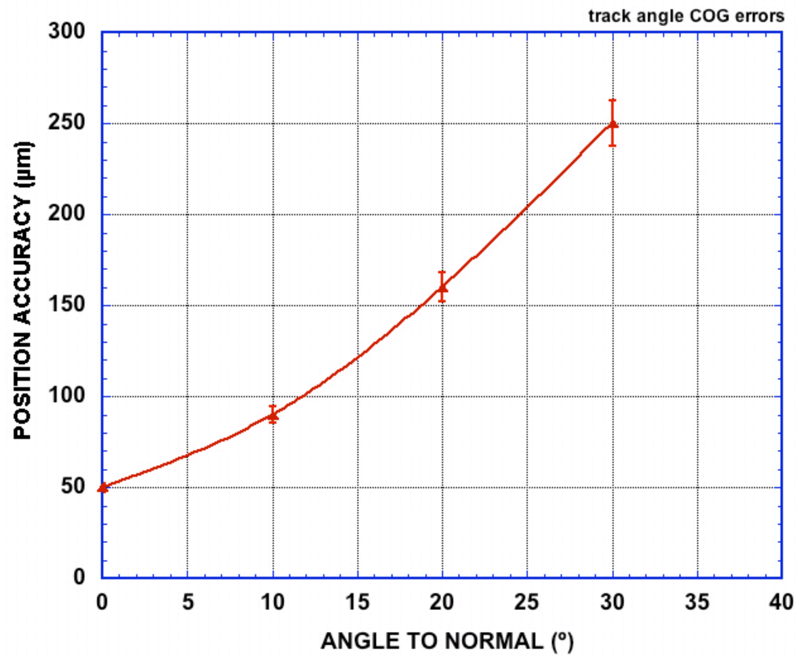
DIFFERENTIAL ENERGY LOSS RESOLUTION:



I. Lehraus et al, Phys. Scripta 23(1981)727

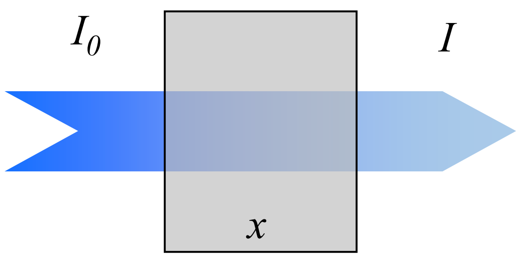
POSITION ACCURACY (CENTER OF GRAVITY) :





G. Charpak et al, Nucl. Instr. and Meth. 167 (1979) 455

PHOTON ABSORPTION



$$I = I_0 e^{-\frac{x}{l}} = I_0 e^{-\mu \chi}$$

$$l = \frac{1}{N\sigma}$$

$$N = N_0 \frac{\rho}{A}$$

x : material thickness (cm)

l : linear absorption length (cm)

$\chi = x\rho$: reduced thickness (g cm^{-2})

$\mu = 1/(l\rho)$: mass absorption coefficient (cm^2 g^{-1})

σ : cross section (cm^2)

N : molecules cm^{-3}

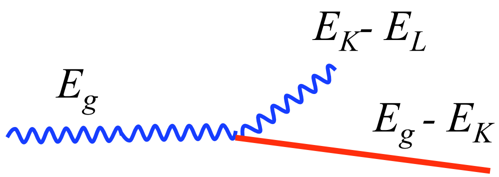
N_0= 6.0247 10^{23} molecules/gmole

A : atomic or molecular mass

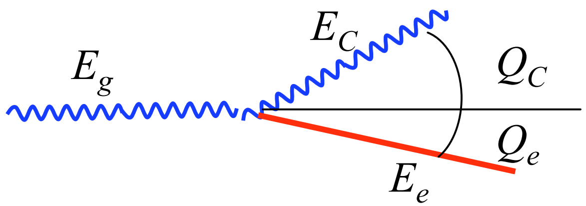
ρ : density (g cm^{-3})

INTERACTION PROCESSES

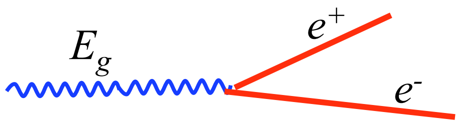
PHOTOELECTRIC: Interaction with an electronic shell with emission of a photoelectron. The excited atom/molecule returns to ground state through fluorescence or radiation-less (Auger) process.



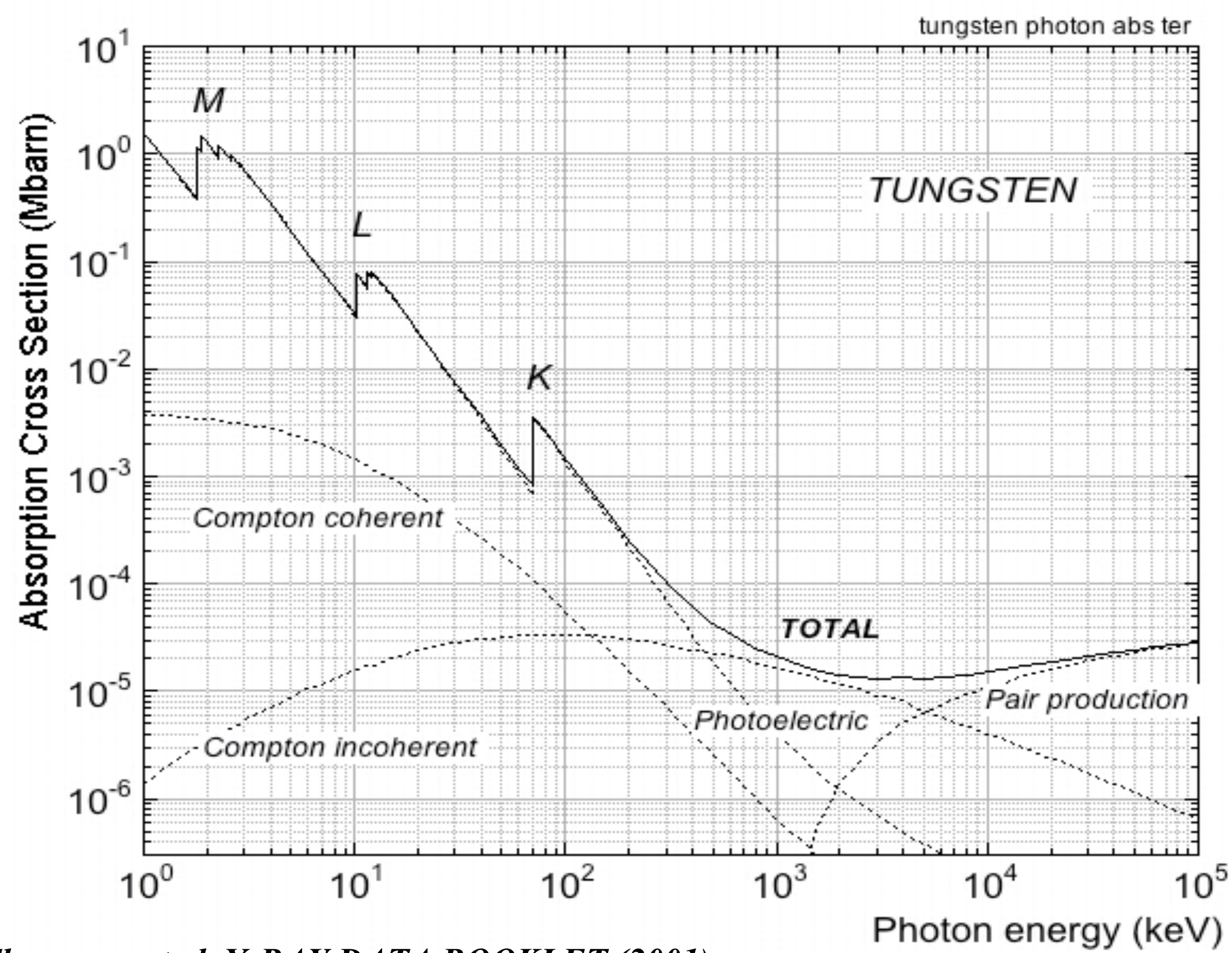
COMPTON: Scattering of the photon by quasi-free electrons; can be coherent or incoherent



PAIR PRODUCTION: Conversion in a e^+e^- pair in the field of the atom/molecule. Possible for $E_g > 2\ m_e = 1.022$ MeV



PHOTON ABSORPTION CROSS SECTION FOR TUNGSTEN



A. Thompson et al, X-RAY DATA BOOKLET (2001)

http://xdb.lbl.gov/

Absorption tables for atoms and molecules: ***http://henke.lbl.gov/optical_constants/***

http://physics.nist.gov/PhysRefData/FFast/html/form.html

PHOTOELECTRIC EFFECT

WORK FUNCTION:
Minimum photon energy required to remove an electron from a solid (lower than the first ionization potential)

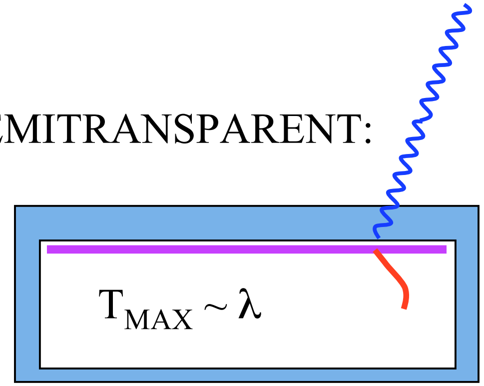
Element	W (eV)	I (eV)
Ag	4.52-4.74	7.57
Au	5.1-5.47	9.22
Al	4.06-4.26	5.99
Fe	4.67-4.81	7.87
Na	2.36	5.14
Li	2.93	5.39
Cs	2.14	3.89

PHOTOIONIZATION THRESHOLD AND QUANTUM EFFICIENCY OF MULTIALKALI

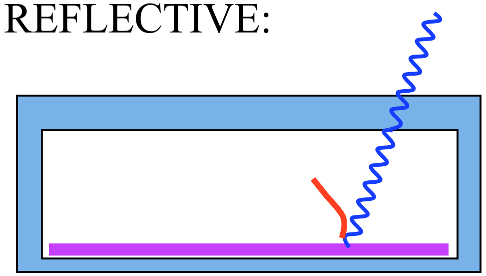
Compound	W (eV)	Max QE (%)
SbCs	1.8	16
SbNaKCs	1.45	20
SbKCs	1.98	26

ELECTRON EMISSION FROM PHOTOCATHODES (IN VACUUM)

SEMITRANSPARENT:

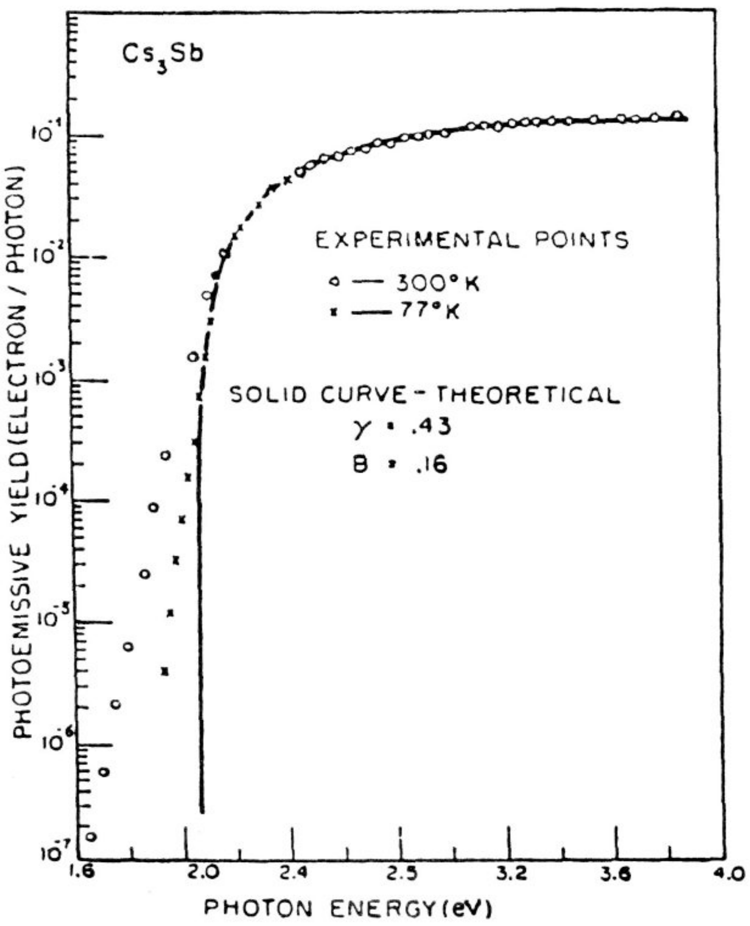


REFLECTIVE:



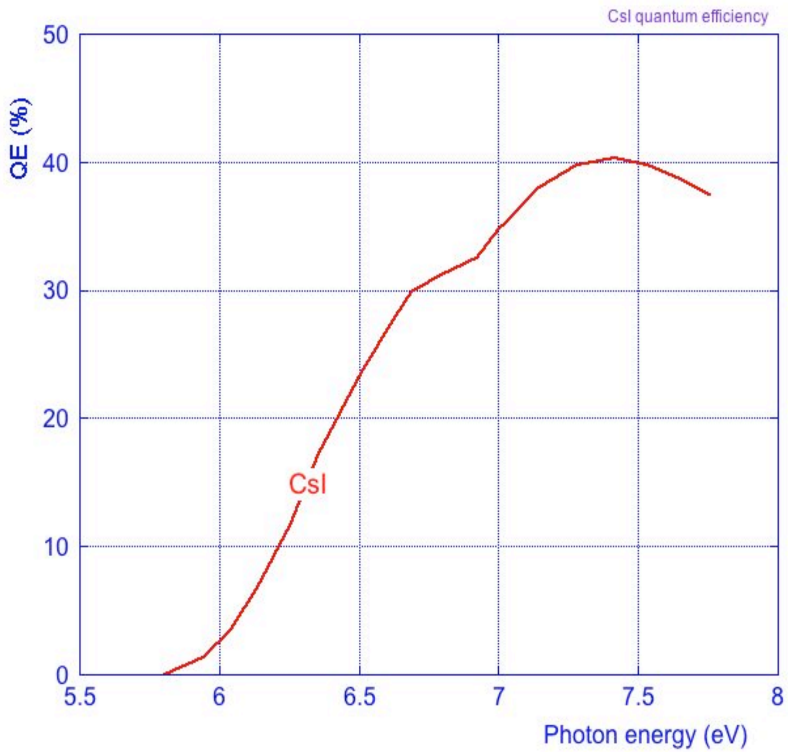
BIALKALI PHOTOCATHODES (VISIBLE LIGHT)

QUANTUM EFFICIENCY OF Cs_3Sb



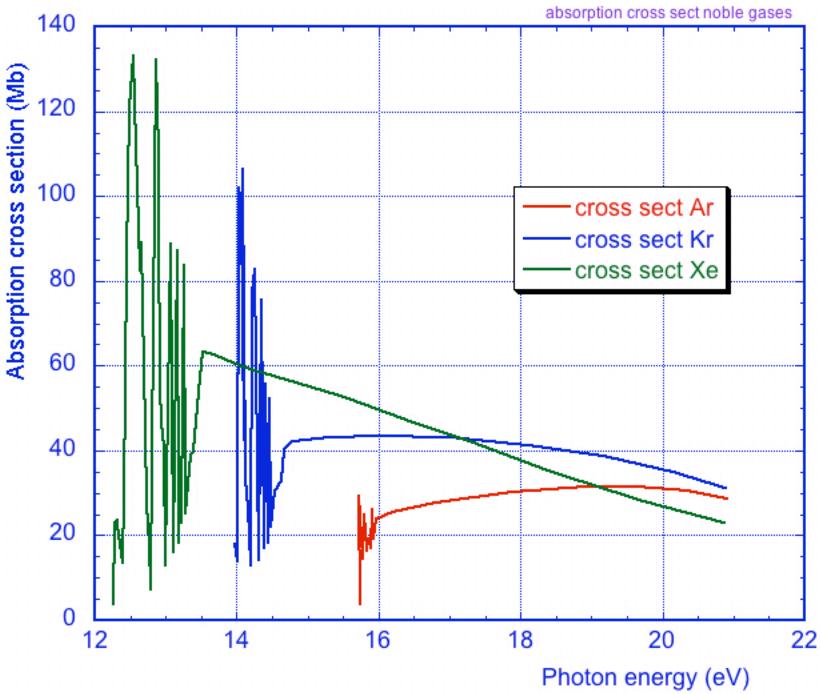
W. E. Spicer, Phys. Rev. 112(1958)114

UV PHOTONS
CAESIUM IODIDE QUANTUM EFFICIENCY



→ *CHERENKOV RING IMAGING*

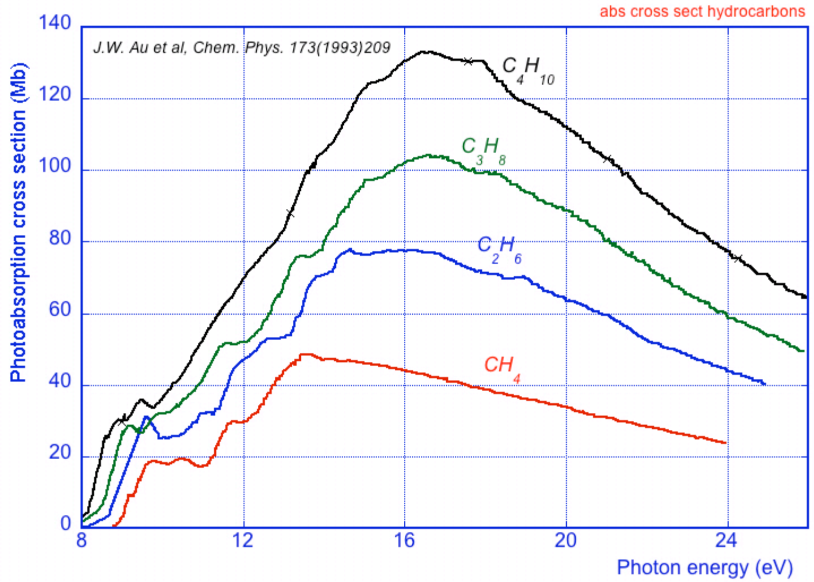
ATOMIC GASES:

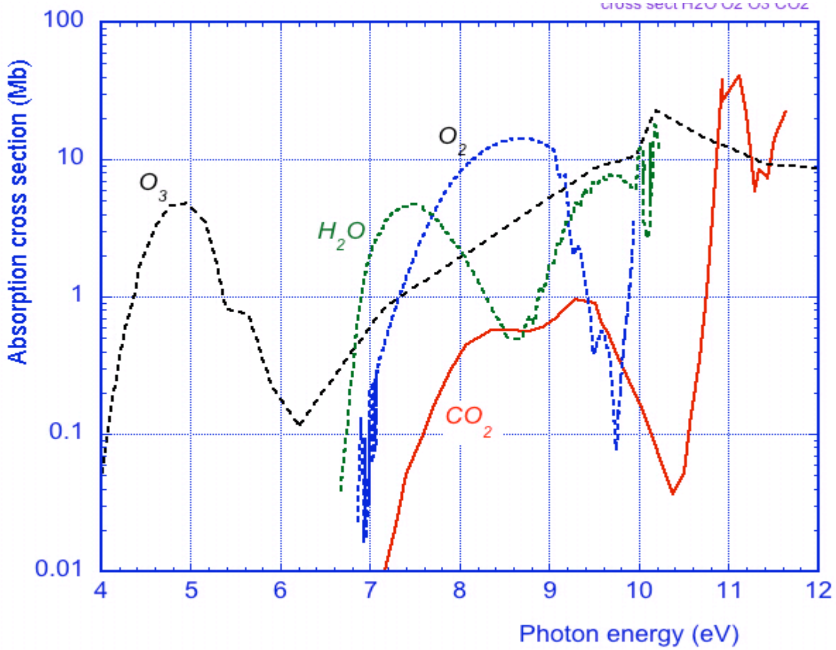


H. S. W. Massey, Electronic and Ionic impact Phenomena (Oxford Press 1969)

G. Marr, Photoionization Processes in Gases (Academic Press NY 1967)

MOLECULAR GASES:





PHOTOIONIZATION IN GASES

For a photon energy E_γ above the photoionization threshold E_I the absorption can result in the emission of a photoelectron with energy equal to the difference:

$$E_e = E_\gamma - E_I$$

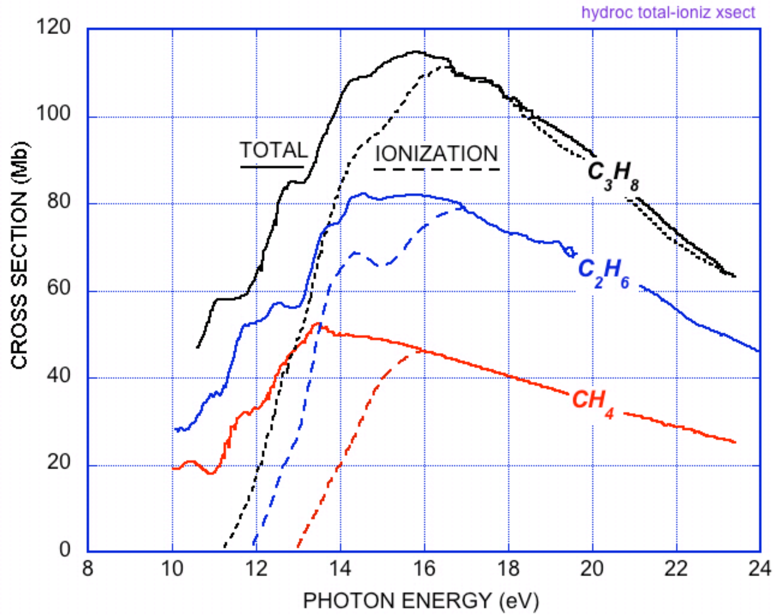
The quantum efficiency (QE) is the ratio between the probability of photoelectron emission and total absorption.

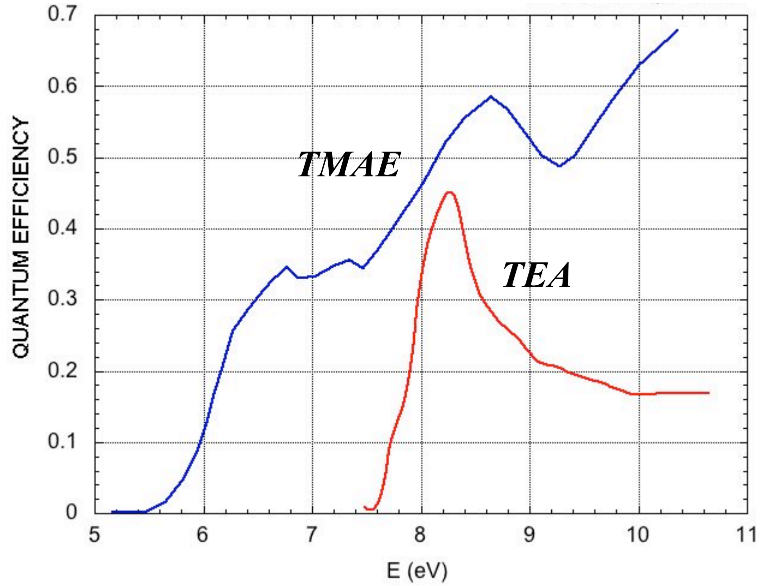
	E_I (eV)
C_6H_6	9.3
TEA	7.45
TMAE	5.6

TEA: Triethylamine $(C_2H_5)_3N$
TMAE: Tetrakis-dimethylamino ethylene $[(CH_3)_2N]_2C$

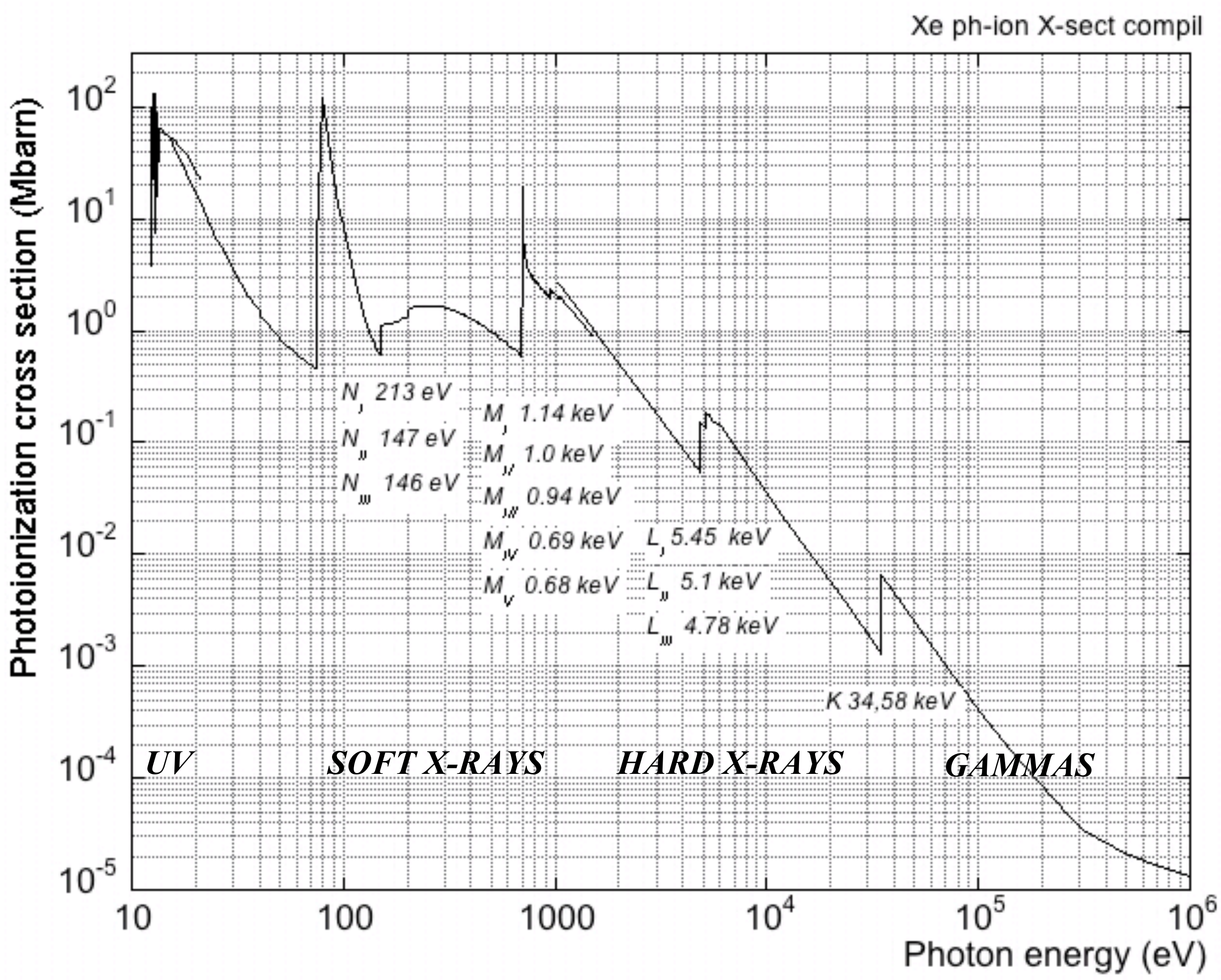
⇒ CHERENKOV RING IMAGING

TOTAL AND PHOTOIONIZATION CROSS SECTIONS:





PHOTOIONIZATION CROSS SECTION IN XENON



ABSORPTION LENGTH FOR GASES AT NTP

For gases at STP (0°C, 1 Atm):
N=2.687 10^{19} cm^{-3}

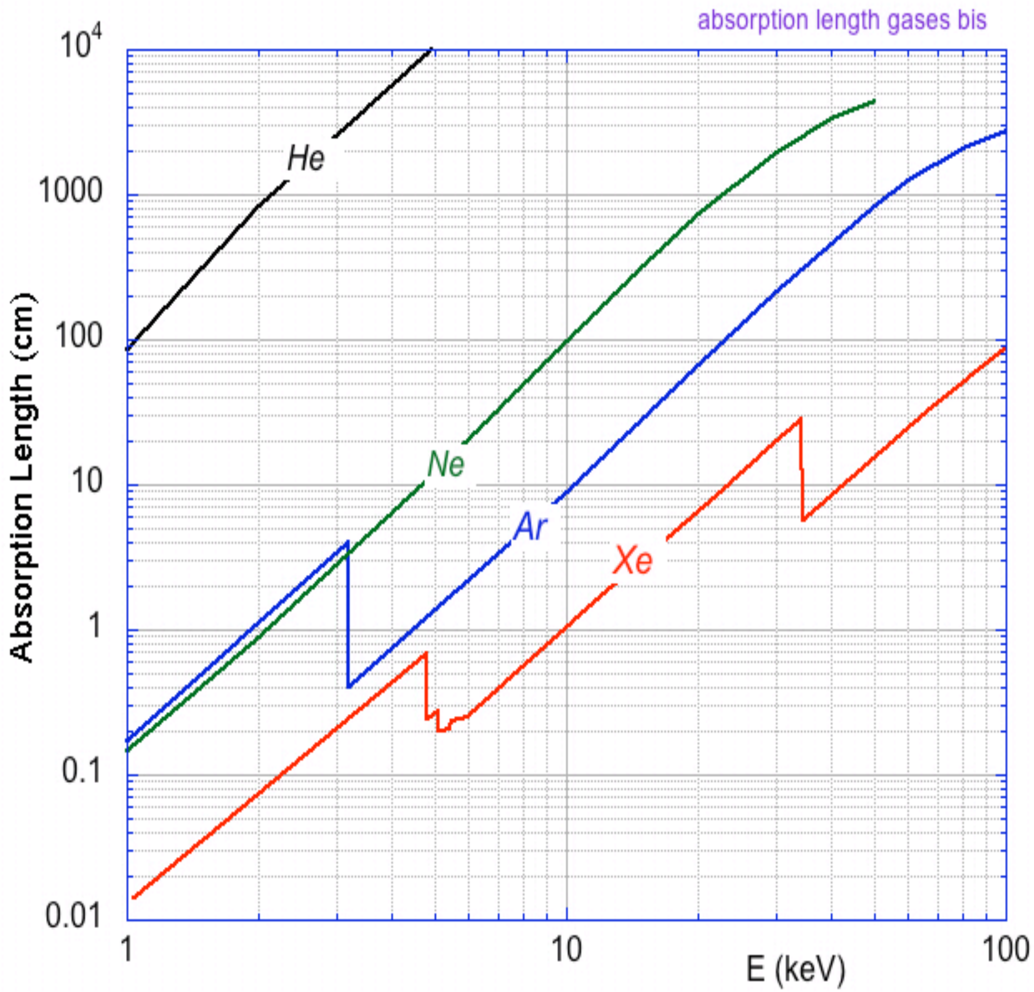
Absorption length:

$$\lambda(cm) = \frac{1}{26.87\,\sigma(MBarns)}$$

The mass absorption coefficient for molecules:

$$\mu_M = \frac{N_0}{M}\sum_i n_i\sigma_i$$

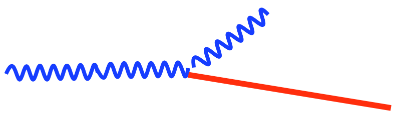
M: molecular weight
n_i, σ_i : atoms, cross section type *i*



PHOTOELECTRIC FLUORESCENCE YIELD

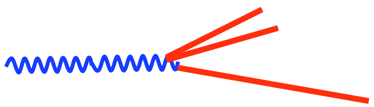
An excited atom returns to the ground state with a cascade of internal transitions that can be radiative (with the emission of photons) or non-radiative:

RADIATIVE:



N_{FL}

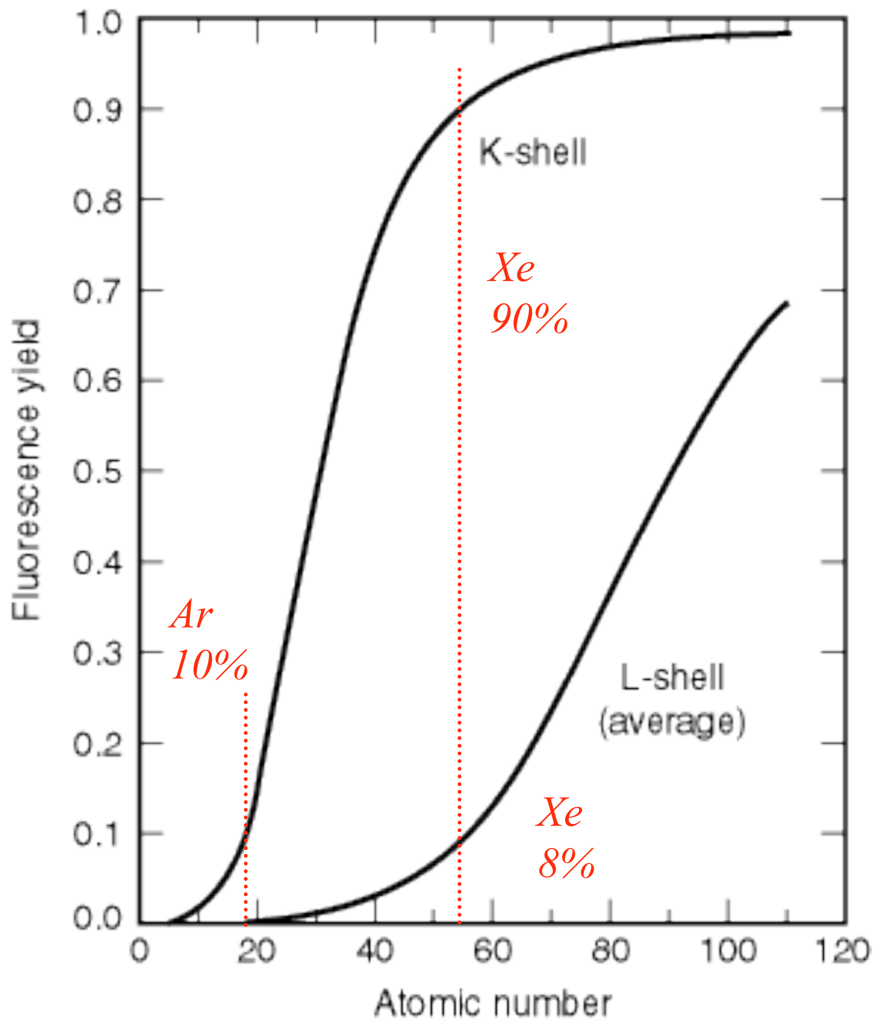
NON-RADIATIVE (AUGER):



N_{NR}

The fluorescence yield is the ratio of radiative to total transitions, and increases with the atomic number:

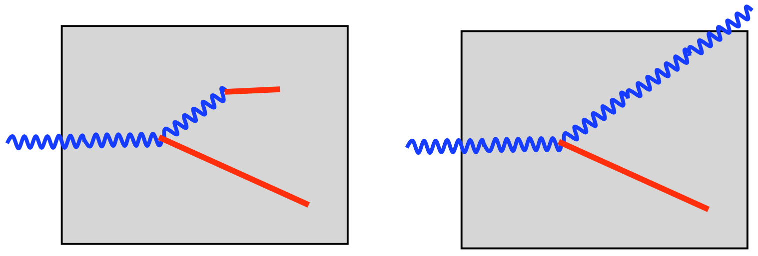
$$\text{FLUORESCENCE YIELD} = \frac{N_{FL}}{N_{FL} + N_{NR}}$$

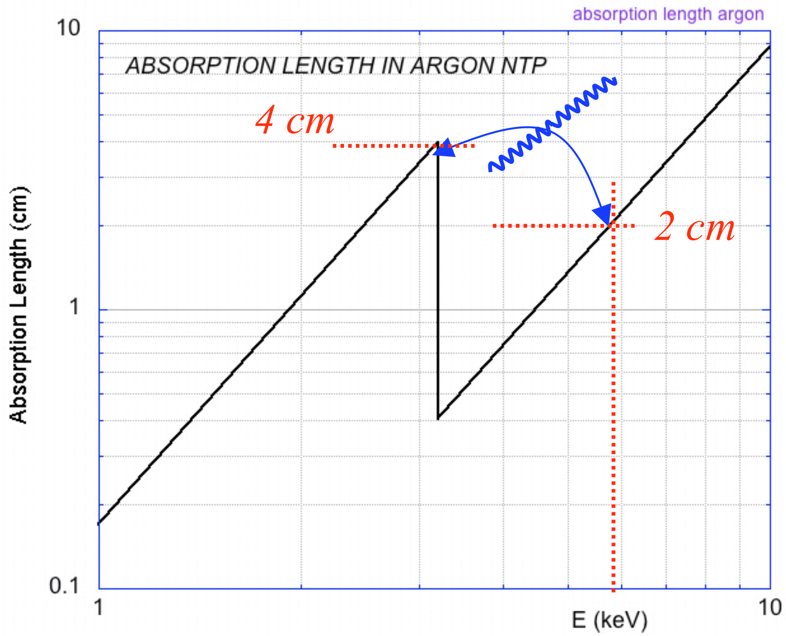


M. O. Krause, J. Phys. Chem. Ref. Data 8 (1979) 307

FLUORESCENCE PHOTONS FATE

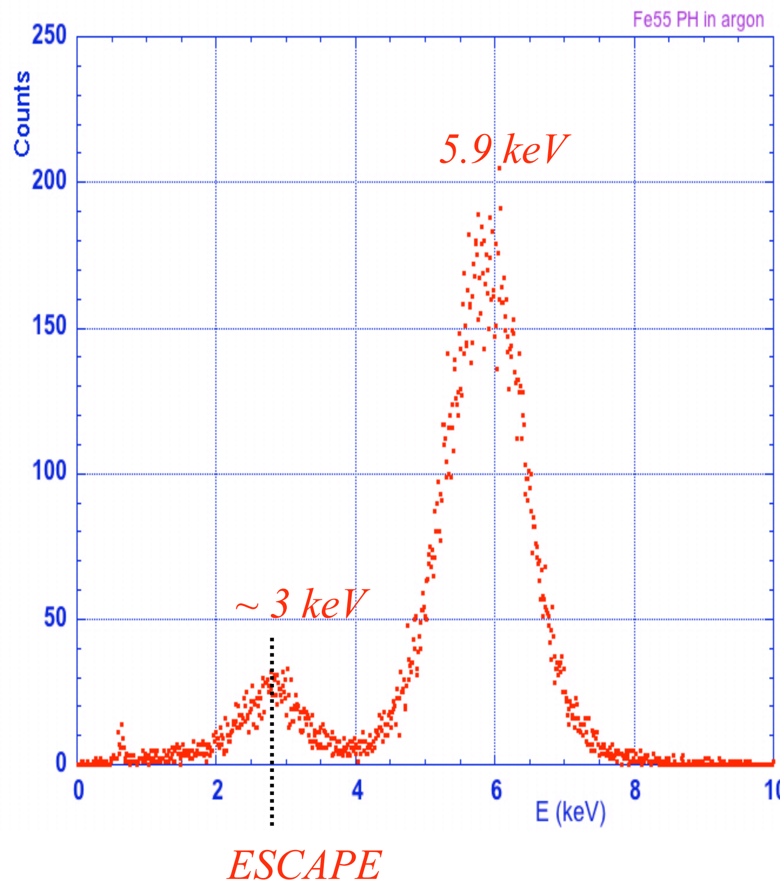
Fluorescence photons can convert far from the primary interaction, or escape from the sensitive volume (escape peak):





X-RAY ABSORPTION SPECTRUM

^{55}Fe X-Rays (5.9 keV) in Argon:



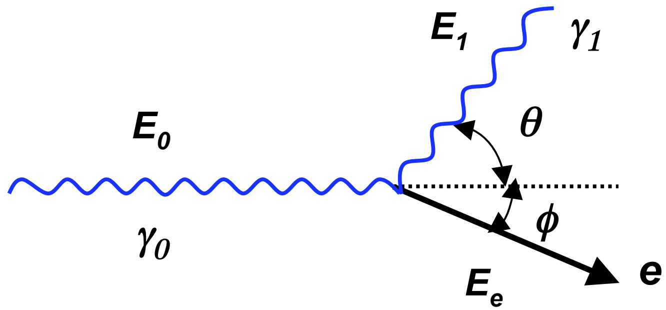
COMPTON EFFECT

Scattering of the photon on a quasi-free electron of electronic shells

$E_e = E_0 - E_1$

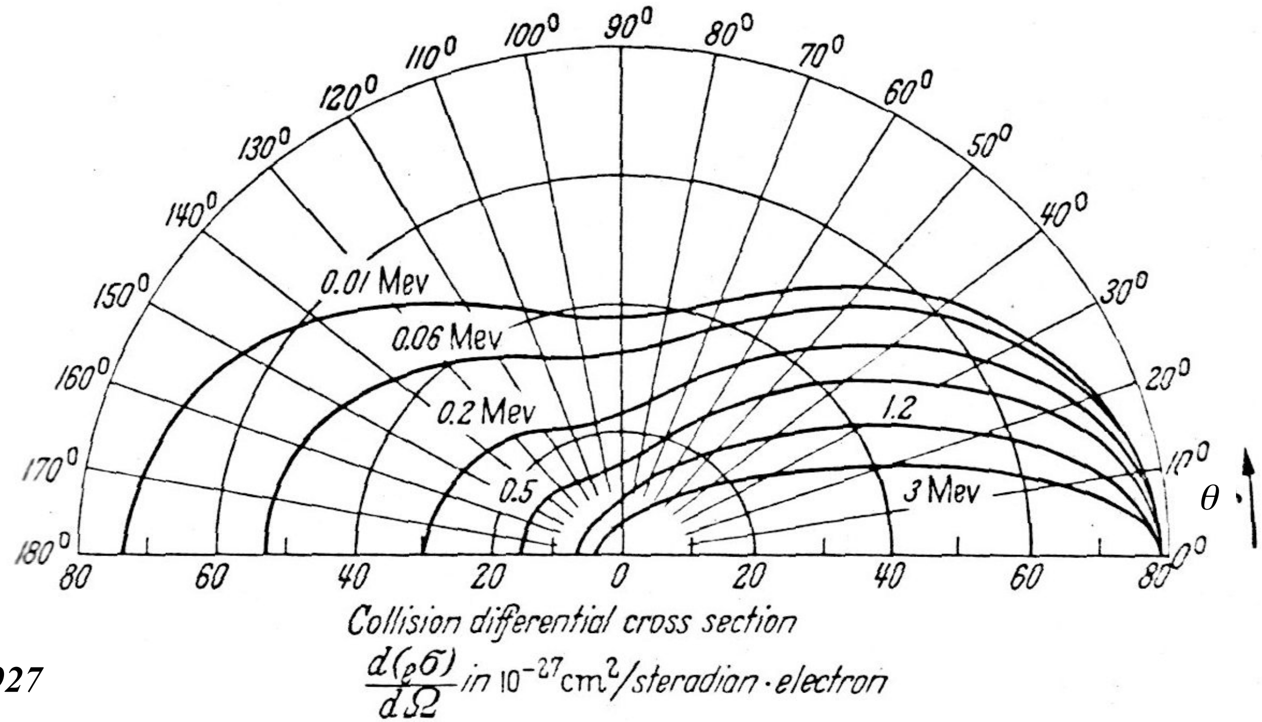
$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_1} - \frac{1}{E_0} \right)$$

$$\cot\phi = \left(1 + \frac{E_0}{m_e c^2} \right) \tan\frac{\theta}{2}$$

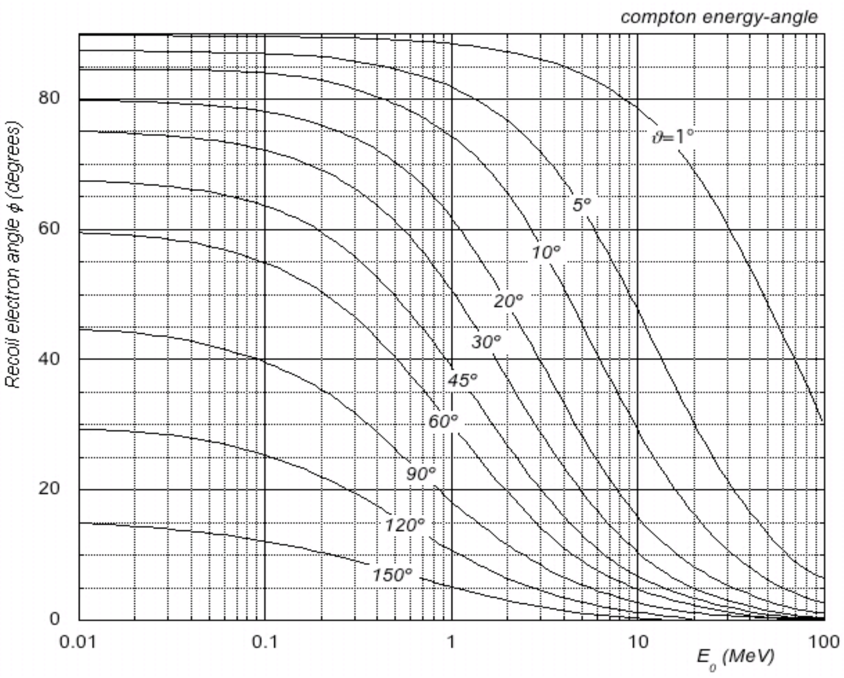


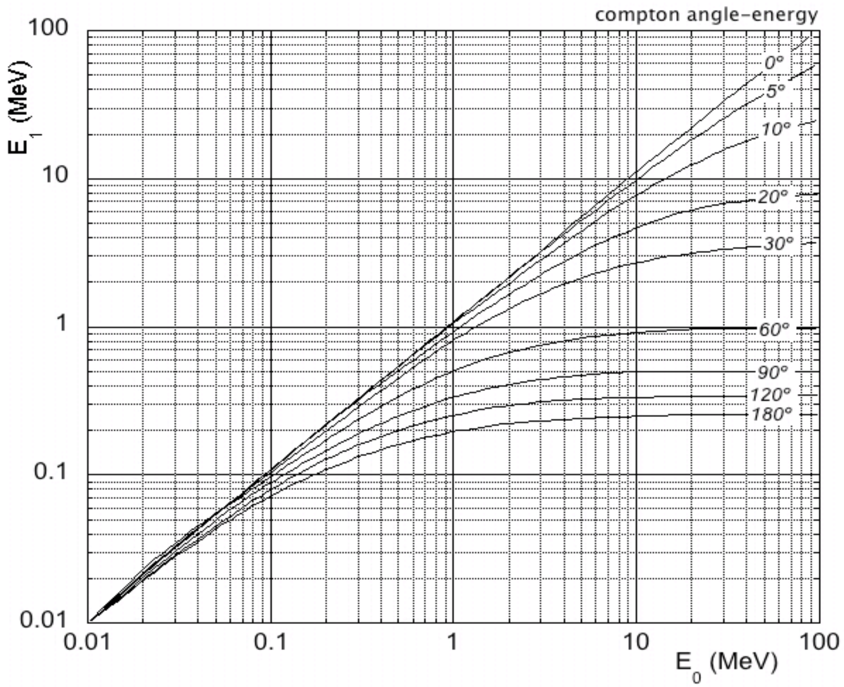
Arthur Holly Compton
Nobel Laureate in Physics 1927

DIFFERENTIAL CROSS SECTION FOR SCATTERING AT AN ANGLE θ FOR SEVERAL PHOTON ENERGIES:



COMPTON SCATTERING: ANGLE-ENERGY CORRELATIONS



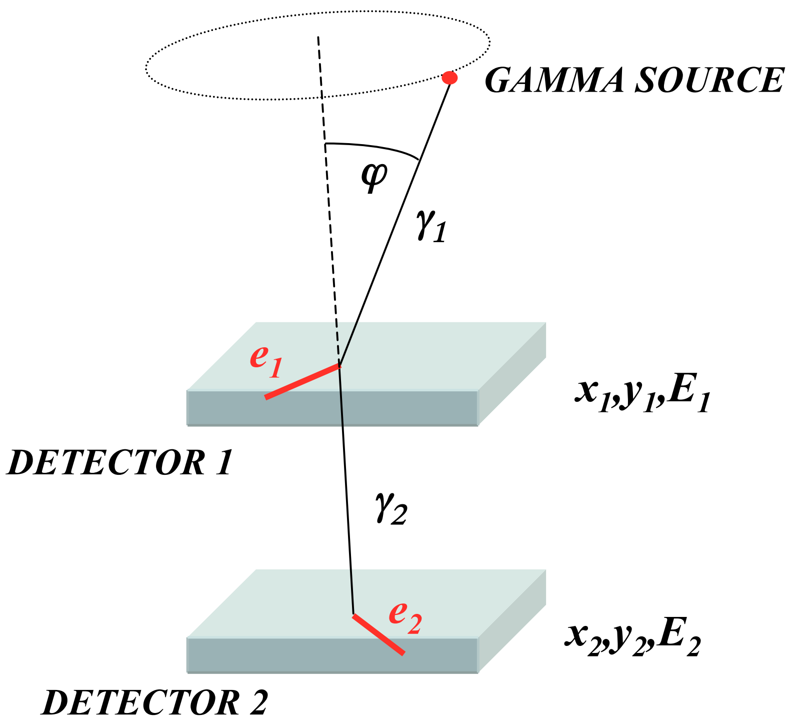


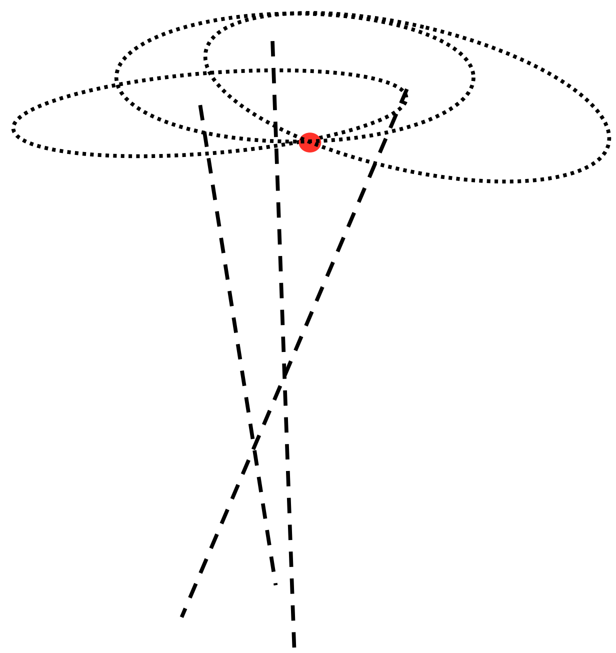
R. D. Evans, Compton Effect
Handbuch der Physik 34 p. 218 (Springer Verlag 1958)

DOUBLE COMPTON SCATTERING

Measurement of recoil electrons energy and position in two cascades detectors allows to define a circle of origin for the source; intersection of many events provides the source position:

$$\varphi = \arcsin\left(1 - \frac{m_0c^2}{E_2} + \frac{m_0c^2}{E_1 + E_2}\right)$$

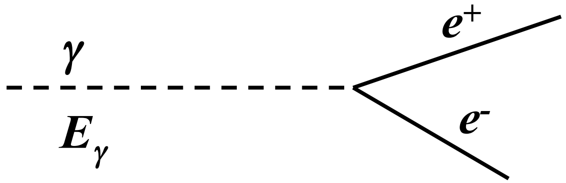




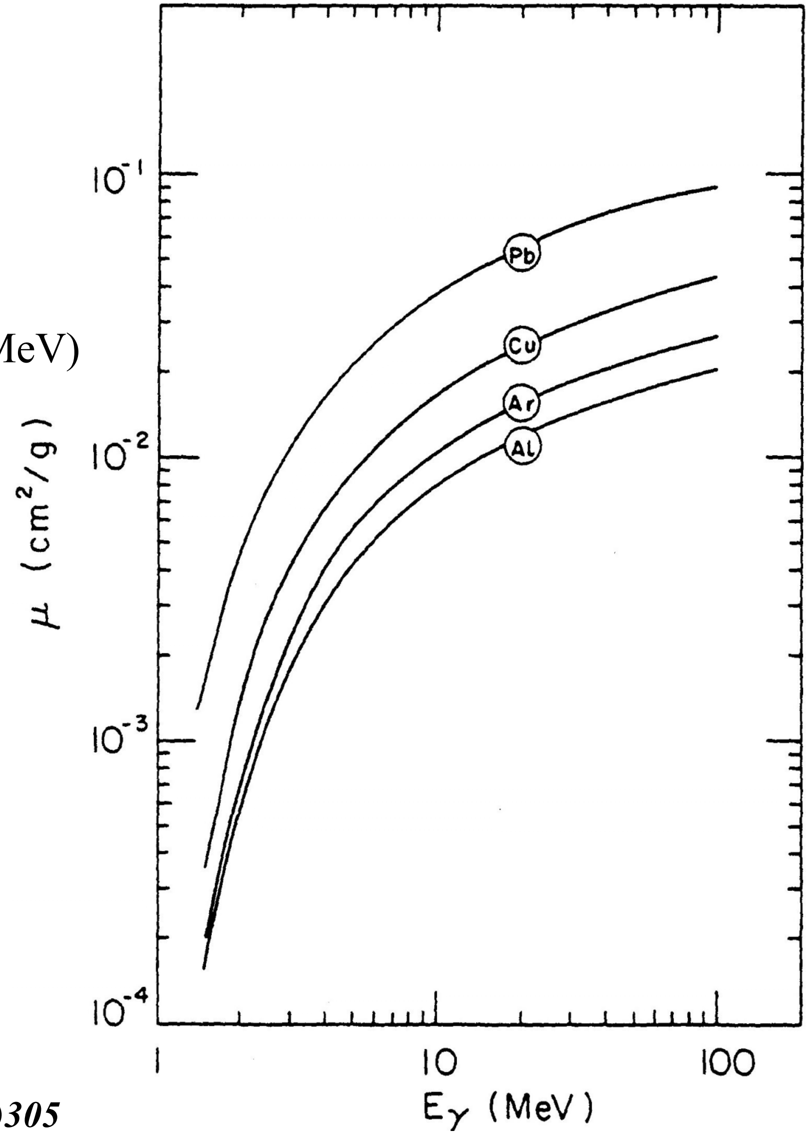
→ ASTROPHYSICS
MEDICAL IMAGING

HIGH ENERGY: PAIR PRODUCTION

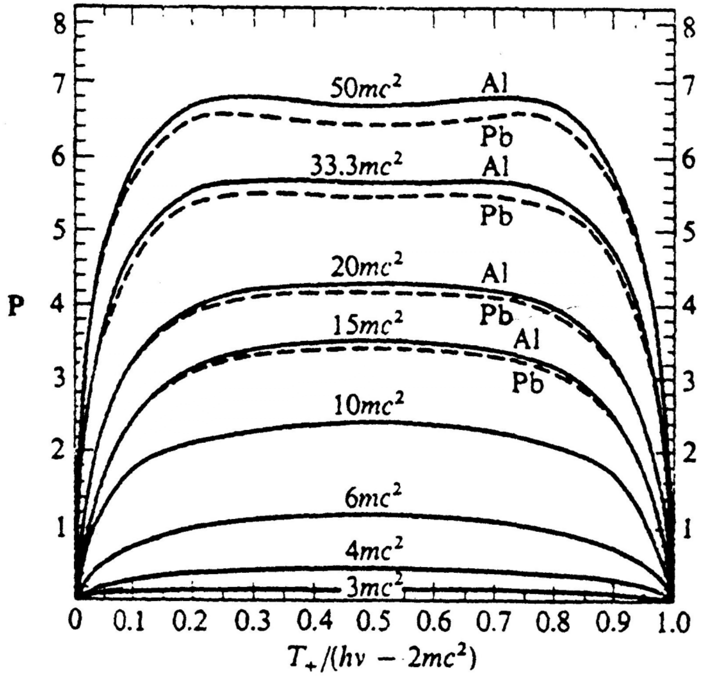
For $E_\gamma > 2\ m_e$ the photon can create an electron-positron pair; the cross section increases very fast with energy.



ABSORPTION COEFFICIENT:

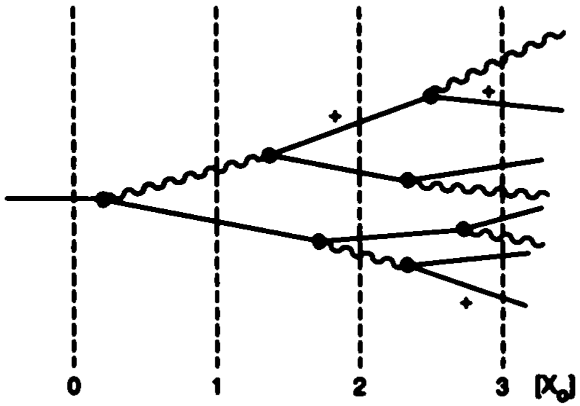


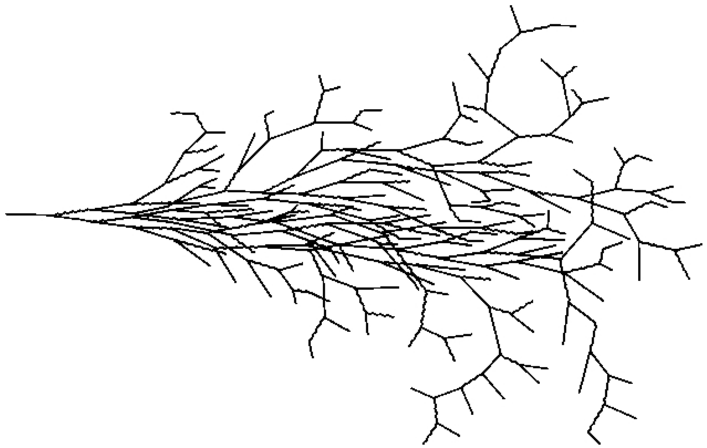
ENERGY SHARING BETWEEN e^+ and e^-
(Photon energy in terms of electron rest energy 0.511 MeV)



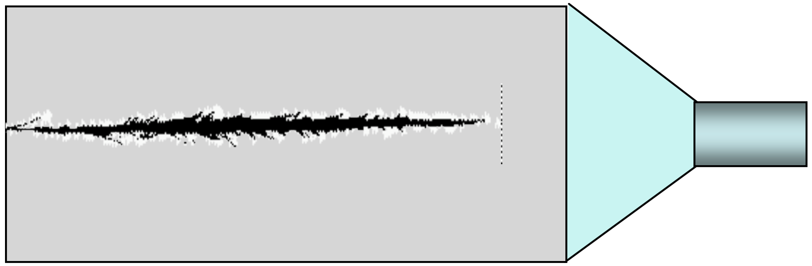
C.M. Davisson and R.D. Evans,Rev. Modern Phys. 20(1948)305

ELECTROMAGNETIC SHOWERS

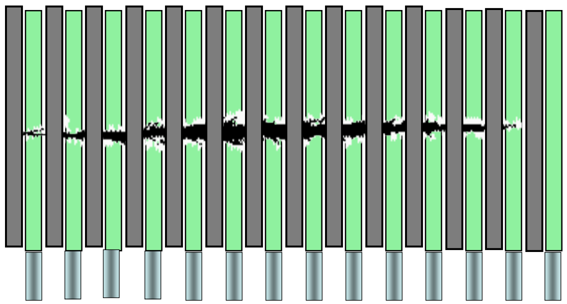




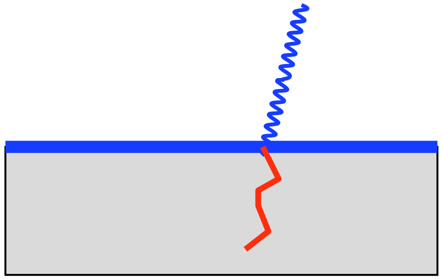
HOMOGENEOUS CALORIMETERS:



SAMPLING CALORIMETERS:

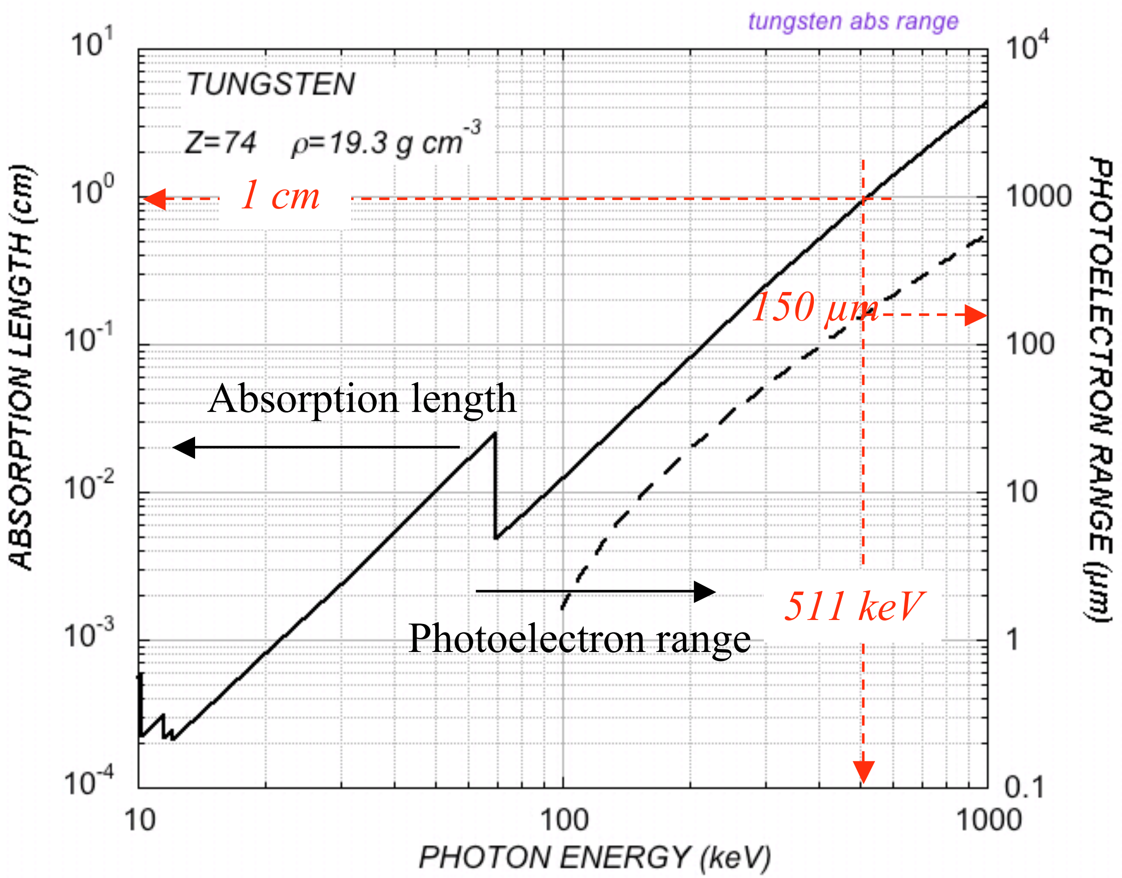


HARD X-RAYS: CONVERTERS AND DETECTION IN GASES



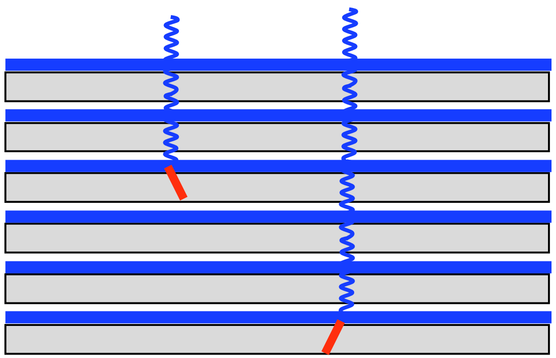
THICK FOIL:
- HIGHER CONVERSION EFFICIENCY
- LOWER PHOTOELECTRON EXTRACTION EFFICIENCY

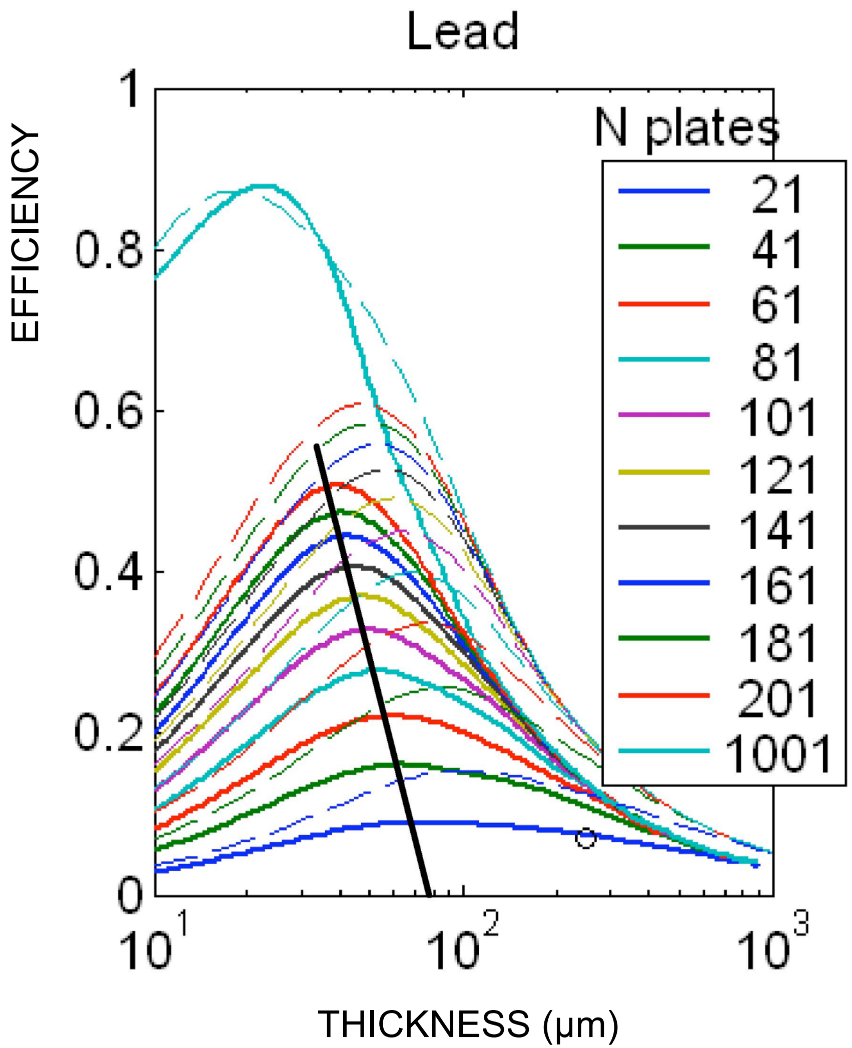
For 511 keV photons the 441 keV photoelectron (511-70) has a range in Tungsten of 150 µm. The optimum thickness of the converter is around 100 µm, ~ 1/100 of the absorption length, so the theoretical detections efficiency is ~ 1%.



DETECTION AND LOCALIZATION OF 511 keV PHOTONS

MULTILAYER CONVERTERS-
GAS DETECTORS





GEANT4 Calculation by P. Fonte (Imaging 2006)

DETECTION OF NEUTRONS WITH GAS DETECTORS

Neutrons are detected through the products of their nuclear interaction with matter. Interaction cross sections depend on energy and material; possible reaction products are:

n + nucleus --> { *recoil nucleus*, *proton*, *alpha particle*, *triton*, *fission fragments* }

TYPES OF DETECTORS:

- With thin converter foil, exploiting the reactions:

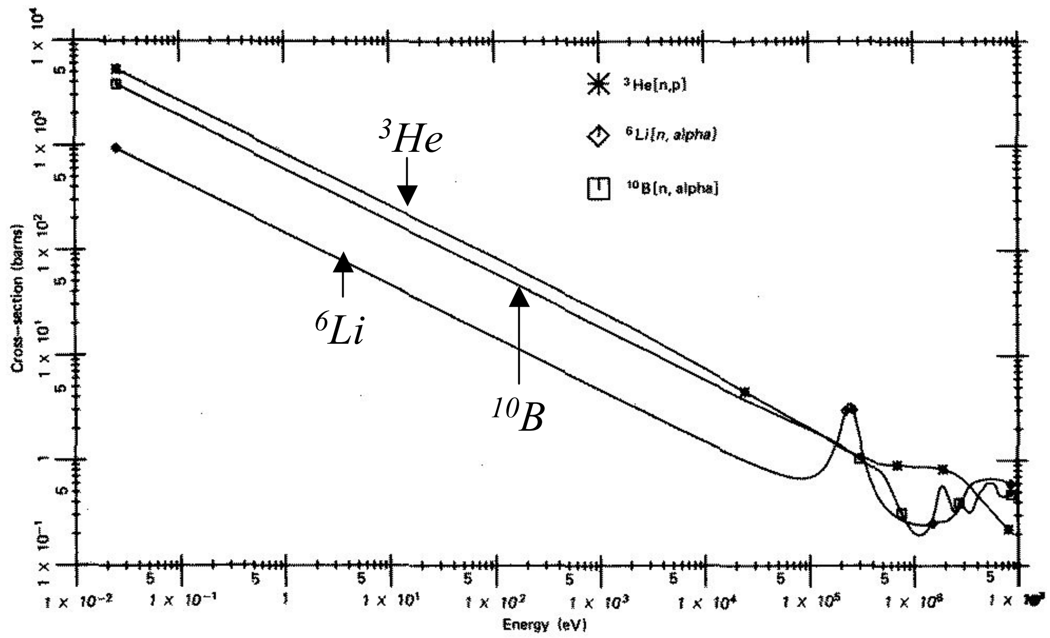
$${}^{10}_{5}B + n \rightarrow {}^{7}_{3}Li + \alpha$$
$${}^{6}_{3}Li + n \rightarrow {}^{3}_{1}H + \alpha$$

- With direct reaction on the gas (^{3}He):

$${}^{3}_{2}He + n \rightarrow {}^{3}_{1}H + p$$

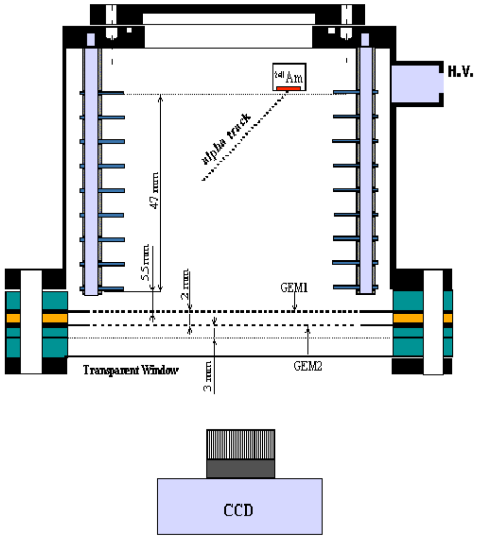
The charged prongs are then detected by their ionization in the medium.

NEUTRON CROSS SECTIONS`:



G. Knoll, Radiation Detection and Measurements (Wiley, New York 2000)

OPTICAL IMAGING CHAMBER FOR NEUTRON DETECTION



F.A.F. Fraga et al, Nucl. Instr. and Meth. A478 (2002) 357