Hands-on session: Radioactivity Laboratory

Spectrometry with NaI(Tl)

Prof. Giuseppe Iaselli
Dott. Dayron Ramos
Dott. Nicola Ferrara

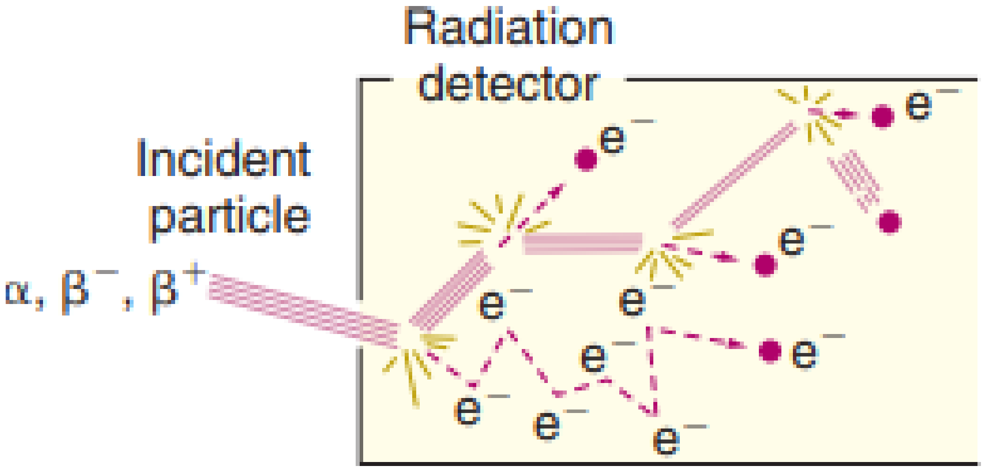
INFN
Istituto Nazionale di Fisica Nucleare

Politecnico di Bari

Gamma Spectrometry

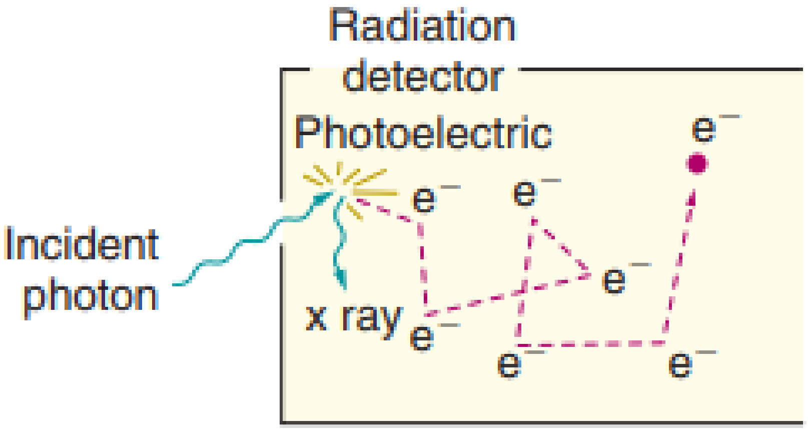
- Introduction to spectrometry
- NaI(Tl) photopeak detection
- Detection response
- Multi-Channel-Analysis
- Measurements

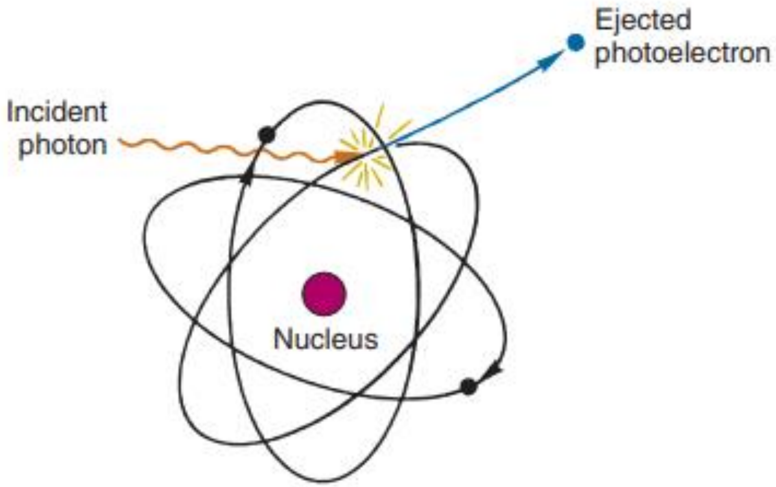
Basics of Pulse-Height Spectrometry



- Particles deposit energy into sensitive volume of detector
- Signal output proportional to particle energy
- Energy deposited outside the detector is not registered

Basics of Pulse-Height Spectrometry

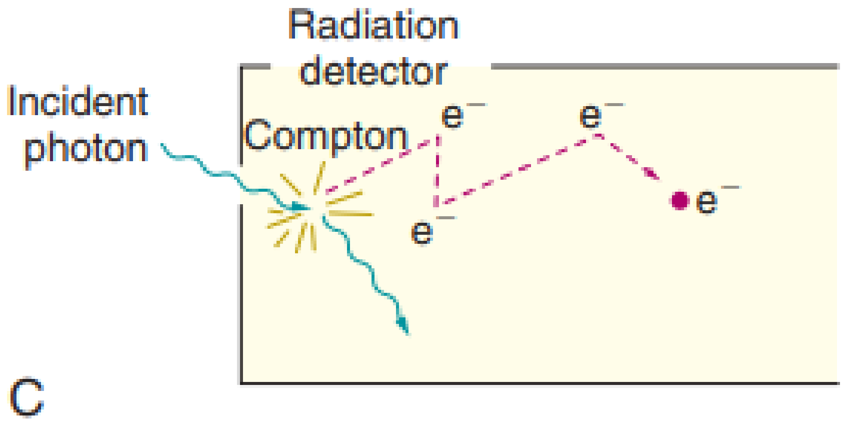


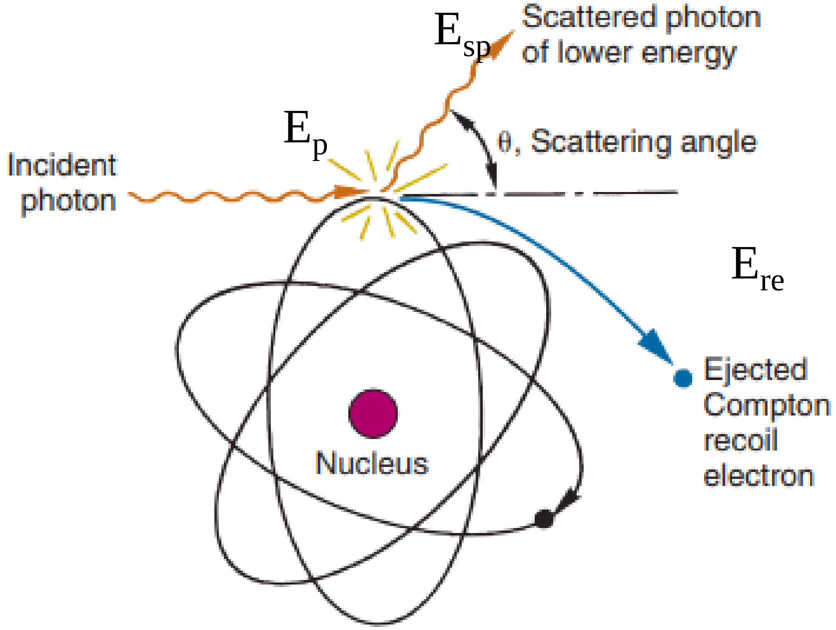


Photoelectric effect

- Energy of photon transferred to atom
- Atom ejects an electron
- Photon is absorbed
- $E_{pe} = h\nu - K_B$

Photoelectron ejection creates a vacancy in an orbital electron shell, which is occupied by an electron of higher shell, which in turns lead to emission of a x-ray or an emission of an Auger electron

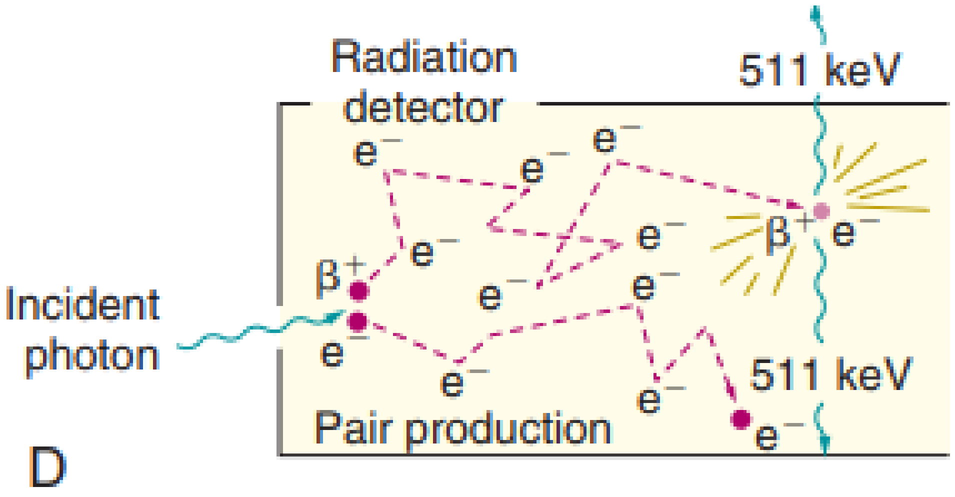


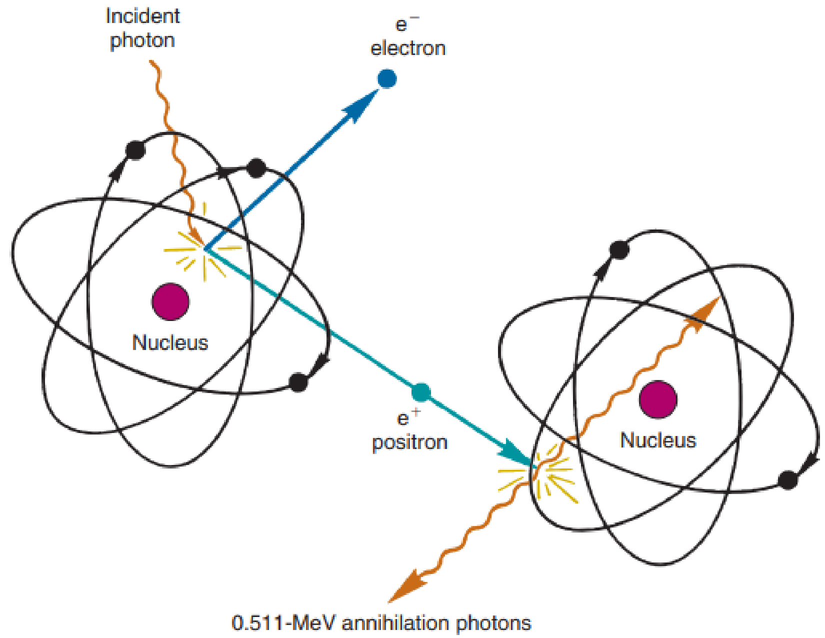


Basics of Pulse-Height Spectrometry

Compton effect:

- Energy of photon changes, because is transferred to electron
- Photon is not absorbed, but is deflected by θ angle
- $E_{sf} = \dfrac{E_f}{(1+\frac{E_f}{0.511}(1-cos\theta))}$
- E_{sf} energy of scattered photon
- E_f energy of incident photon





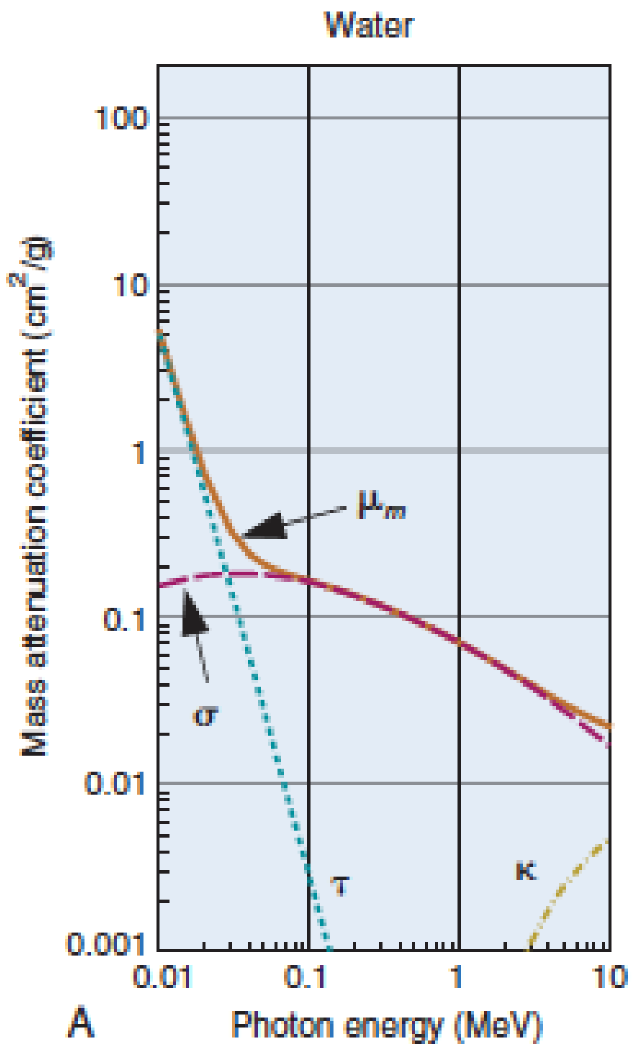
Basics of Pulse-Height Spectrometry

Pair production:

Photon undergoes pair production if energy is more than 1022 keV

Positron undergoes annihilation with an electron, producing two photons back-to-back

Basics of Pulse-Height Spectrometry



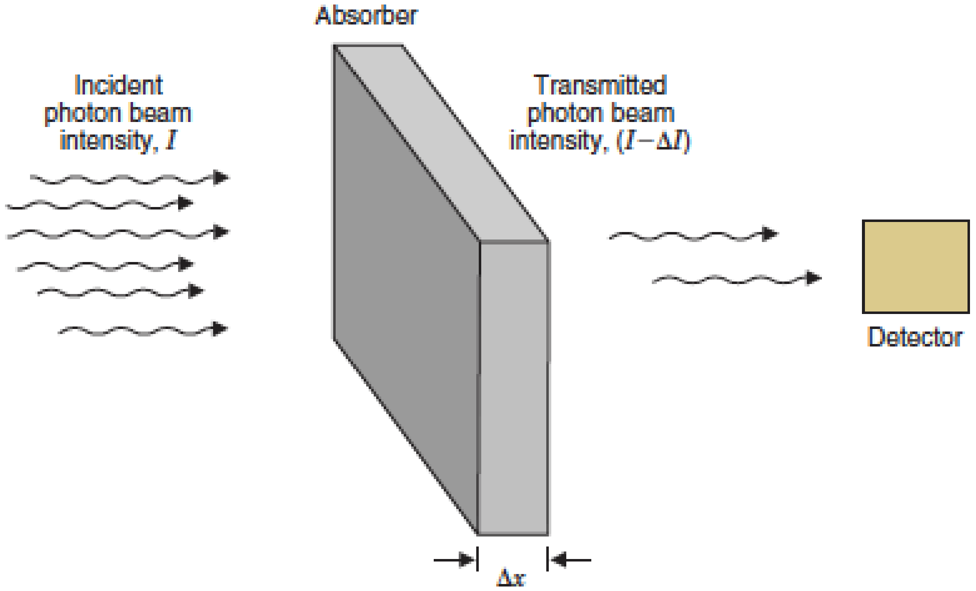
Attenuation coefficient:

$$N = N_0 e^{-\mu(E)x}$$

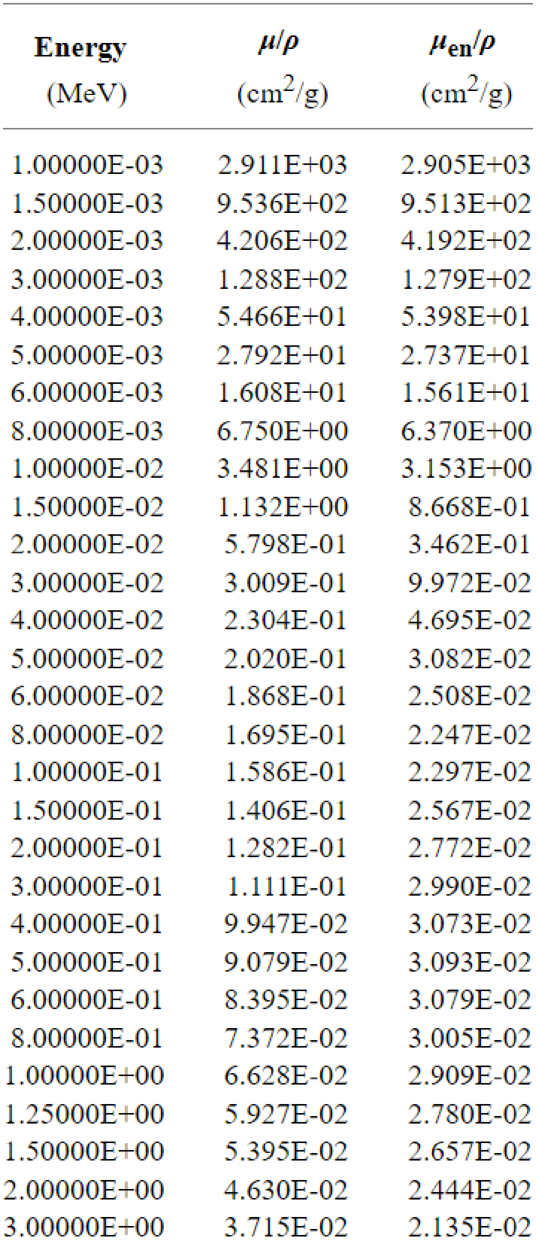
Mass attenuation coefficient:

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

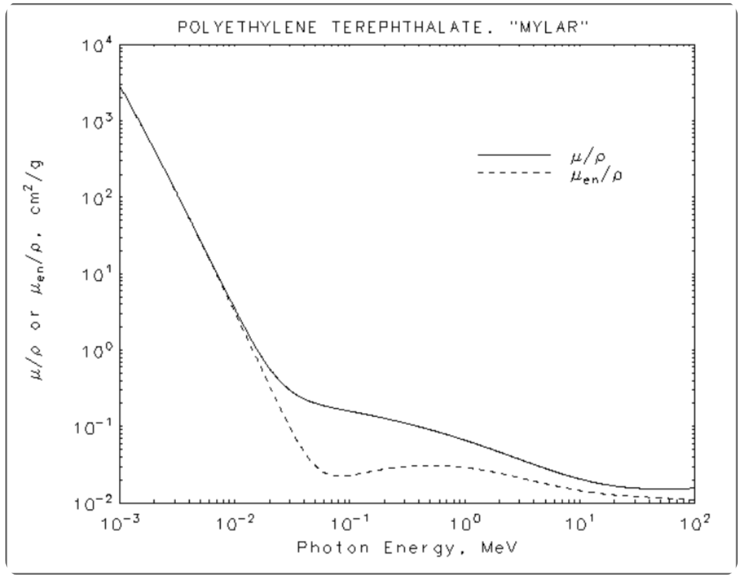
It depends on energy and on type of interaction



NIST database



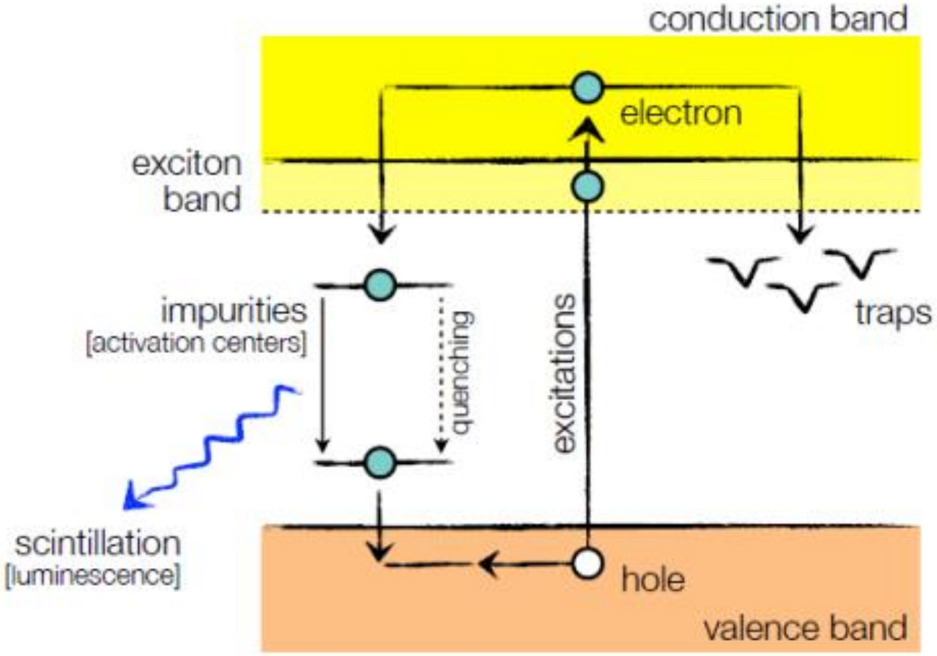
Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)
1.00000E-03	2.911E+03	2.905E+03
1.50000E-03	9.536E+02	9.513E+02
2.00000E-03	4.206E+02	4.192E+02
3.00000E-03	1.288E+02	1.279E+02
4.00000E-03	5.466E+01	5.398E+01
5.00000E-03	2.792E+01	2.737E+01
6.00000E-03	1.608E+01	1.561E+01
8.00000E-03	6.750E+00	6.370E+00
1.00000E-02	3.481E+00	3.153E+00
1.50000E-02	1.132E+00	8.668E-01
2.00000E-02	5.798E-01	3.462E-01
3.00000E-02	3.009E-01	9.972E-02
4.00000E-02	2.304E-01	4.695E-02
5.00000E-02	2.020E-01	3.082E-02
6.00000E-02	1.868E-01	2.508E-02
8.00000E-02	1.695E-01	2.247E-02
1.00000E-01	1.586E-01	2.297E-02
1.50000E-01	1.406E-01	2.567E-02
2.00000E-01	1.282E-01	2.772E-02
3.00000E-01	1.111E-01	2.990E-02
4.00000E-01	9.947E-02	3.073E-02
5.00000E-01	9.079E-02	3.093E-02
6.00000E-01	8.395E-02	3.079E-02
8.00000E-01	7.372E-02	3.005E-02
1.00000E+00	6.628E-02	2.909E-02
1.25000E+00	5.927E-02	2.780E-02
1.50000E+00	5.395E-02	2.657E-02
2.00000E+00	4.630E-02	2.444E-02
3.00000E+00	3.715E-02	2.135E-02



- Table shows mass attenuation coefficient at different energy for the polyethylene terephthalate

- Density=1.38 g/cm^3

Spectrometry with NaI(Tl)



Energy bands in impurity activated crystal

showing excitation, luminescence, quenching and trapping

- Inorganic scintillators are lab grown crystals.
- Pure crystals make bad scintillators:
  - the defined energy bands between valence band and excitation band means that energy emitted by the crystal get reabsorbed by the same lattice
  - There are only definite energy quanta allowing for the excitation of molecules
  - Adding impurity improves the behavior
  - There are more intermediate states between valence and excitation band that can be reached by the excited electron
  - The emitted light is not completely reabsorbed by the crystal lattice

Spectrometry with NaI(Tl)

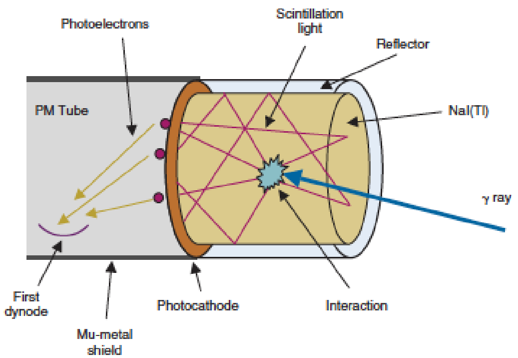


FIGURE 7-16 Arrangement of NaI(Tl) crystal and photomultiplier (PM) tube in a typical scintillation detector assembly.

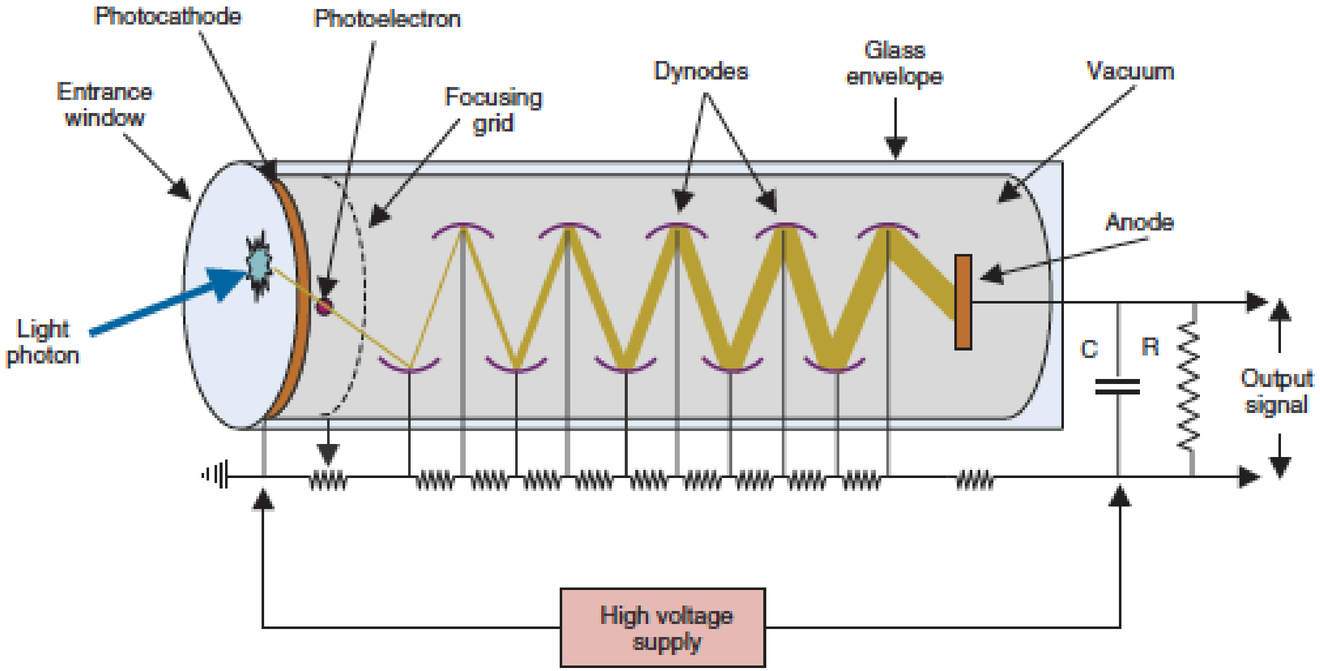
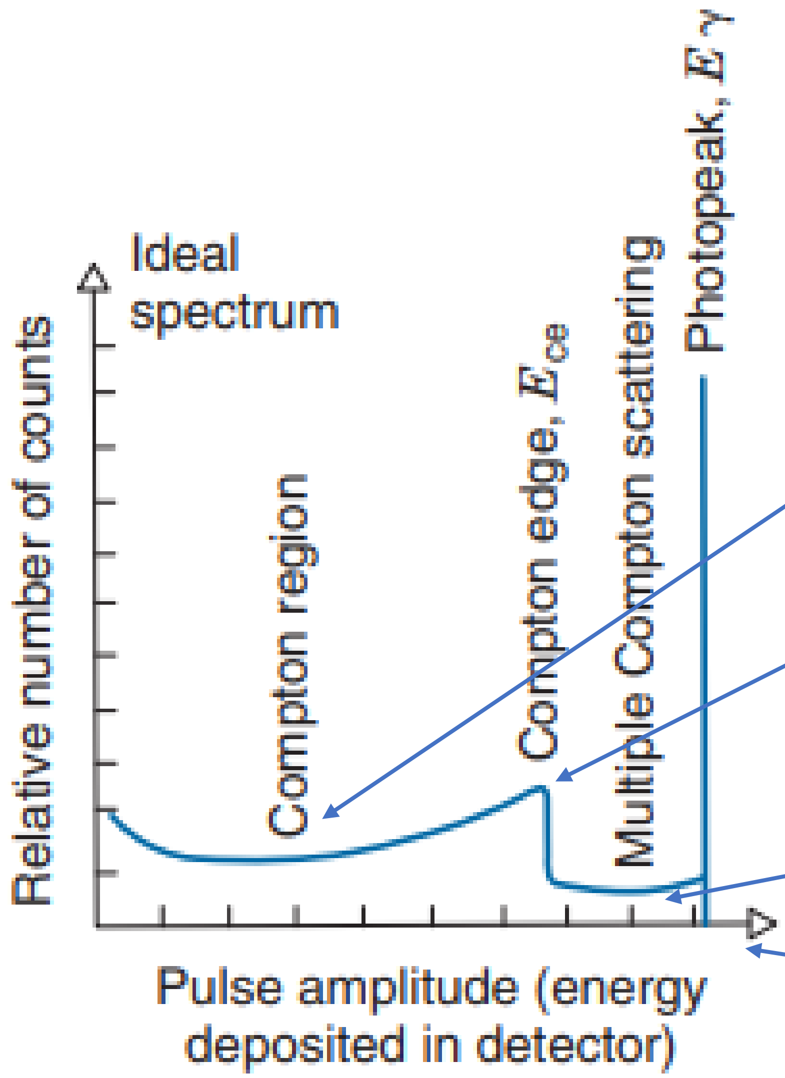


FIGURE 7-13 Basic principles of a photomultiplier tube.

- Good coupling with Photomultiplier by the use of light guide
- Multiplication of electrons, accelerated from a dynode to the other



Ideal spectrum

- Compton region:

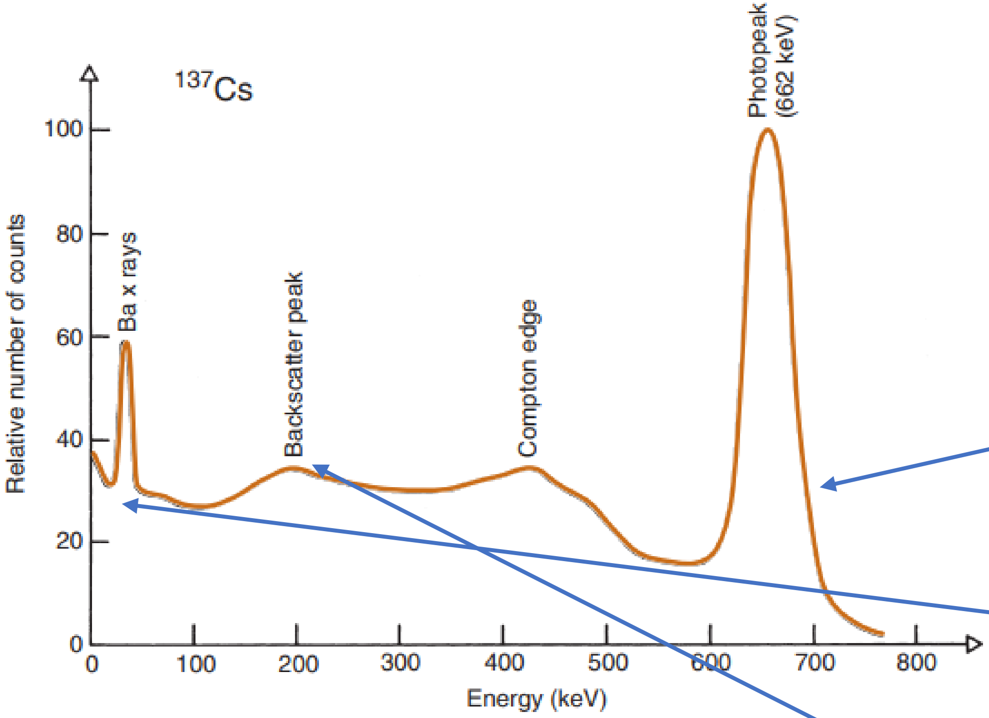
Electrons recoil at different angles

- Compton edge:

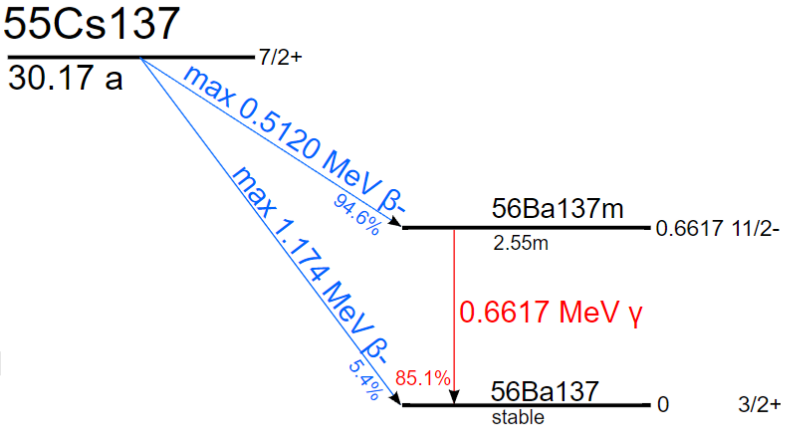
Electron recoiled at 180° degree, maximum energy transferred to electron and deposited in the scintillator

- Multiple Compton scattering
- Photopeak: photon deposits all energy by photoelectric mechanism

Real spectrum

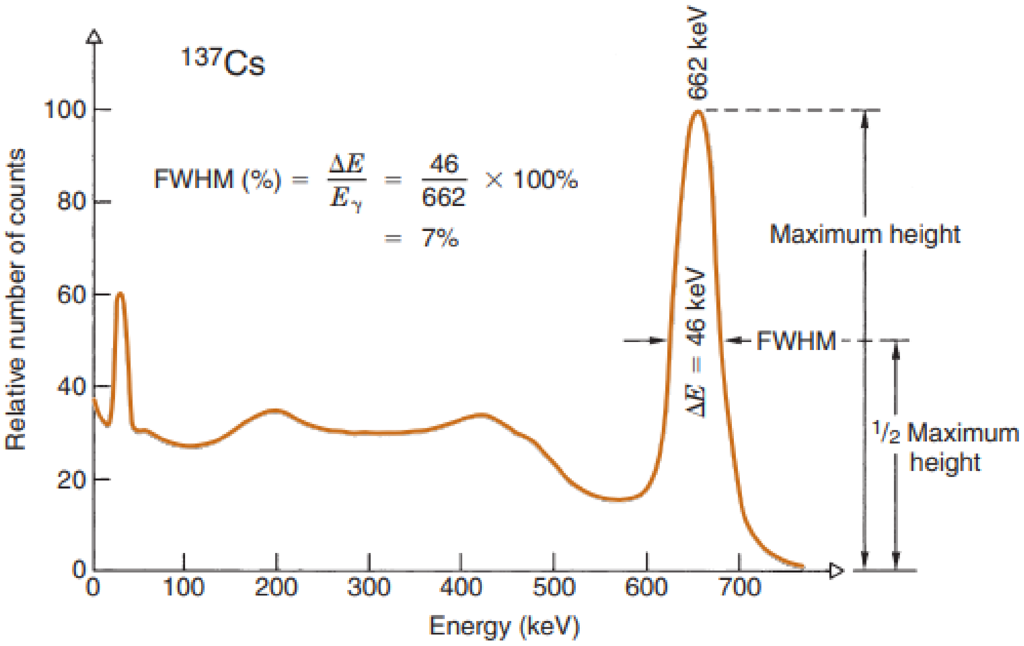


^{137}Cs decay emitting 662 keV gamma rays:



- Photopeak
- X-rays of Ba
- Backscattered peak

Spectrometry with NaI(Tl)



- Gaussian shape peak, instead of narrow-line.
- The width of the photopeak, ΔE, measured across its points of half-maximum amplitude is the energy resolution. This is referred to as the full width at half maximum.

$$FWHM(\%) = \frac{\Delta E}{E_\gamma} * 100\%$$

Detector efficiency

Efficiency with which detectors converts emission of a source into signal

$$\xi\left(\frac{\gamma\ rays}{sec}\right) = A\left(\frac{dis}{sec}\right) * \ \eta\left(\frac{\gamma\ rays}{dis}\right)$$

$$R = D\ \xi$$

Parameters:

- ξ rate of emission
- A activity
- η gamma per disintegration
- R rate of counts
- D efficiency

Multi-channel analyzer

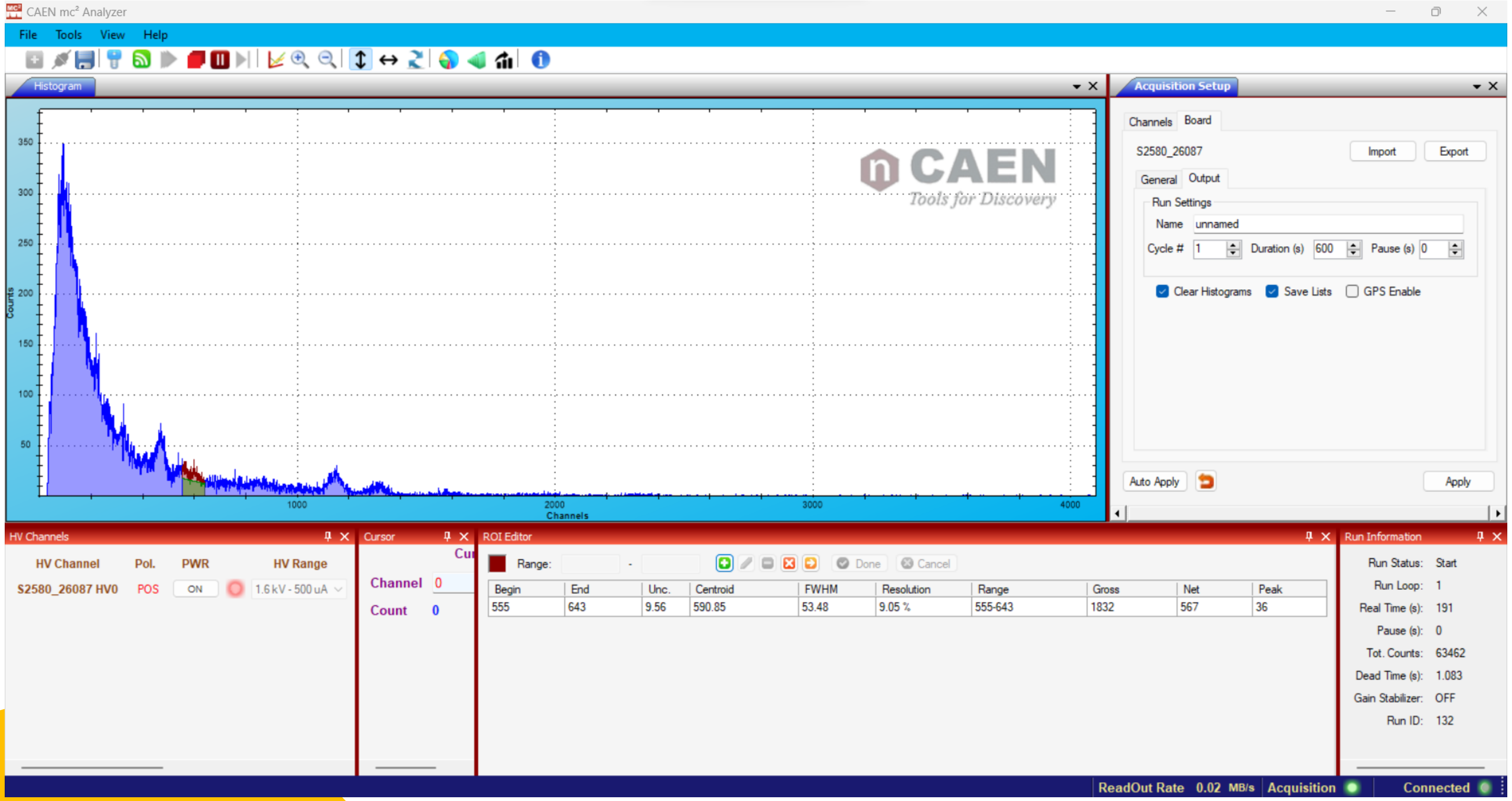
Energy selection is made by multichannel analyser, allowing the entire spectrum to be analysed

- Multi Channel Analyzer:

1. Receives in input PMT output signals
2. ADC digitizes the signals
3. Produces the pulse-height histogram = plot of number of events from the PMTs as function of output amplitude

Channel = specific energy range → number of channels can be >1000 → complete energy spectra produced

Gamma laboratory with MCA



S2580_26087

Run Settings

Name: unnamed

Cycle #: 1 Duration (s): 600 Pause (s): 0

☑ Clear Histograms ☑ Save Lists ☐ GPS Enable

HV Channel	Pol.	PWR	HV Range
S2580_26087 HV0	POS	ON	1.6 kV - 500 uA

Channel 0

Count 0

Range: -

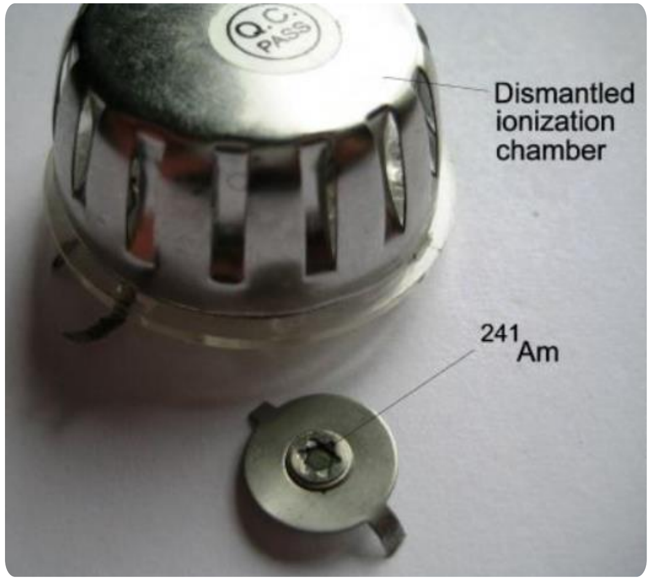
Begin	End	Unc.	Centroid	FWHM	Resolution	Range	Gross	Net	Peak
555	643	9.56	590.85	53.48	9.05 %	555-643	1832	567	36

Run Status: Start
Run Loop: 1
Real Time (s): 191
Pause (s): 0
Tot. Counts: 63462
Dead Time (s): 1.083
Gain Stabilizer: OFF
Run ID: 132

ReadOut Rate 0.02 MB/s Acquisition Connected

1. Calibrate MCA with sources
2. Measure activity
3. Attenuation coefficient measure

Source

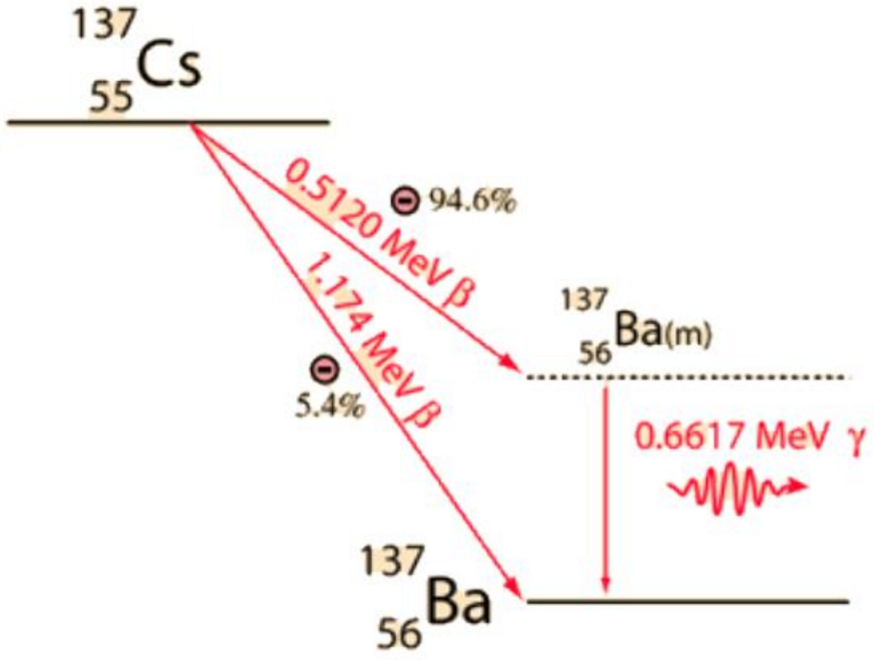


^{241}Am

Americium-241 is the most important radioisotope of americium from the point of view of the occurrence in environment. The other long-lived isotope ^{243}Am is produced in nuclear reactors in smaller activity compared to ^{241}Am. The activity of ^{242m}Am (half-life 160 years) that originated in nuclear weapons tests was nearly six orders of magnitude lower in comparison with ^{241}Pu activity from which ^{241}Am in-grows. Americium-241 is produced in nuclear power plants during activation of ^{239}Pu and ^{240}Pu by neutrons, which is followed by beta decay of ^{241}Pu ($T_{1/2}$ = 14.35 years).

Americium -241 is used in many smoke detectors for homes and business, for measure levels of toxic lead in dried paint samples, to ensure uniform thickness in rolling processes like steel and paper production, and to help determine where oil wells should be drilled.

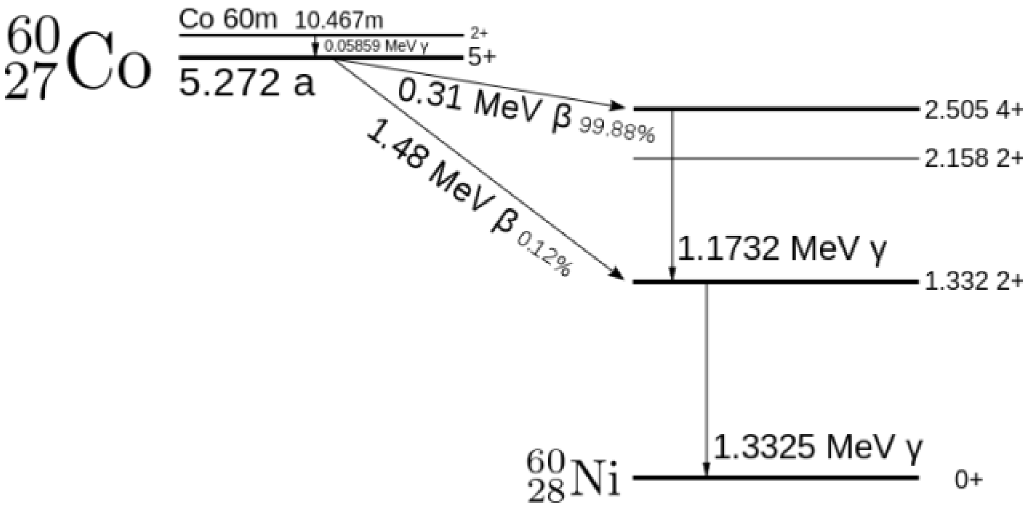
Source



^{137}Cs

Cesium-137 (Cs-137), or radium cesium is a radioactive isotope of cesium which is formed as one of the most common fission products from fission nuclear uranium-235 and other fissile isotopes in nuclear reactors and weapons nuclear. It is among the most problematic of the fission products with a medium-short half-life because it spreads easily in nature, due to the high water solubility of the most common chemical compounds of cesium. Small quantities of cesium-134 and cesium-137 were released into the environment during nearly all nuclear weapons tests and some nuclear accidents. Cesium 137 has a half-life of approximately 30.17 years. About 95 percent decays by beta emission to a nuclear isomer barium metastable: barium-137m (Ba-137m). The rest populate directly the ground state of barium-137, which is stable. Ba-137m has a half-life of approximately 153 seconds and is responsible for all emissions of gamma rays in cesium-137 samples. One gram of cesium-137 has a activity of 3,215 terabecquerels (TBq). The photon energy of Ba-137m is 662 keV

Source

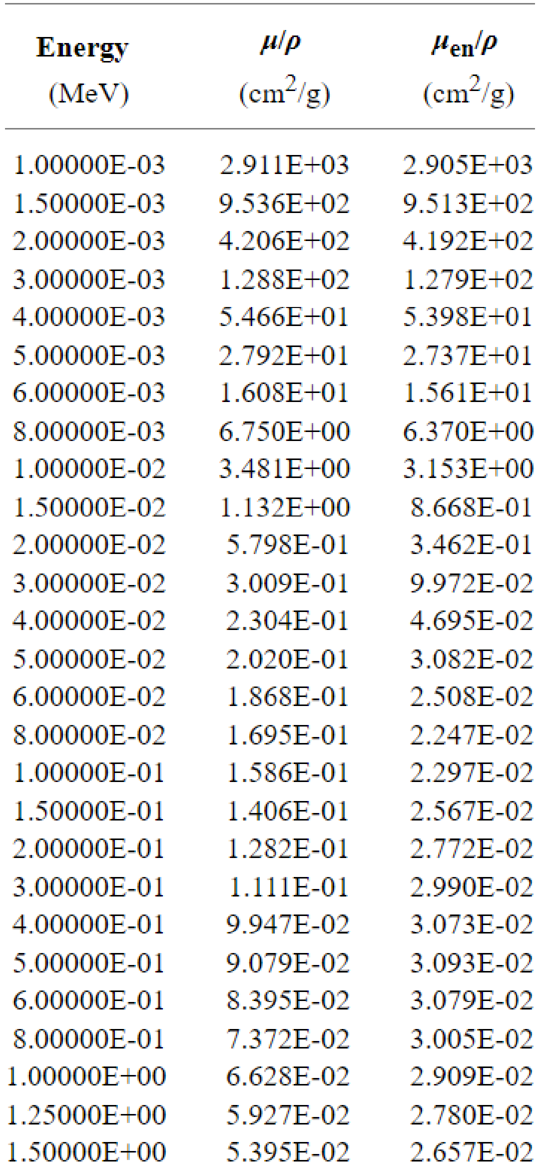


^{60}Co

Cobalt-60 is a synthetic radioactive isotope of the metal cobalt. Due to its short average life of 5.27 years, cobalt-60 is not found in nature. It is produced artificially by activation neutronics of cobalt-59. Cobalt-60 decays by beta decay negative in the stable isotope nickel-60. The energized nickel-60 core emits two beams gamma with energies of 1.17 and 1.33 MeV per become nickel-60 stable

NIST database

- Table shows mass attenuation coefficient at different energy for the polyethylene terephthalate

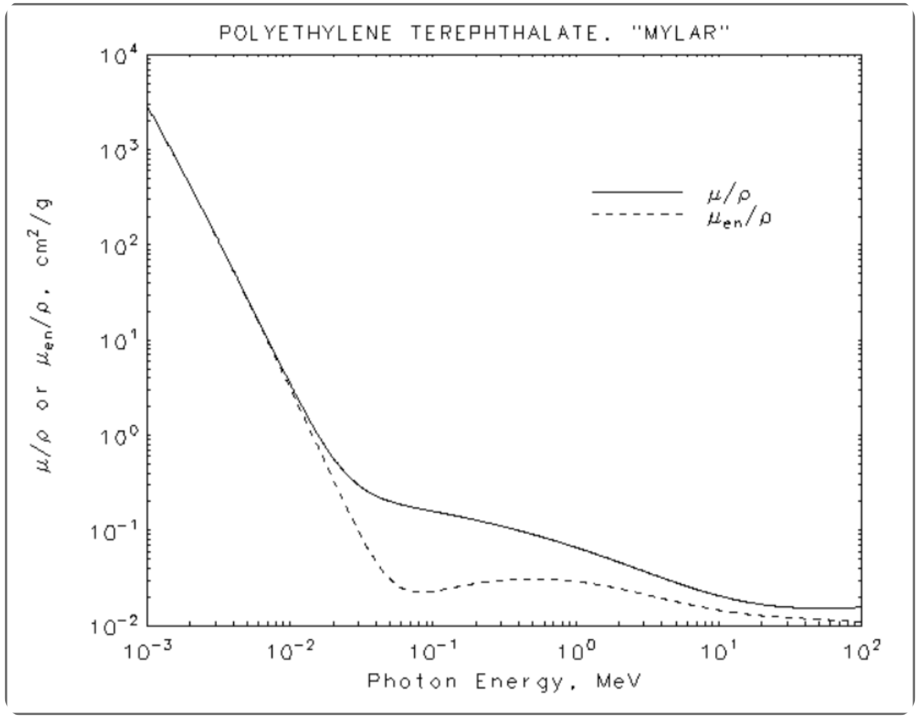


Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)
1.00000E-03	2.911E+03	2.905E+03
1.50000E-03	9.536E+02	9.513E+02
2.00000E-03	4.206E+02	4.192E+02
3.00000E-03	1.288E+02	1.279E+02
4.00000E-03	5.466E+01	5.398E+01
5.00000E-03	2.792E+01	2.737E+01
6.00000E-03	1.608E+01	1.561E+01
8.00000E-03	6.750E+00	6.370E+00
1.00000E-02	3.481E+00	3.153E+00
1.50000E-02	1.132E+00	8.668E-01
2.00000E-02	5.798E-01	3.462E-01
3.00000E-02	3.009E-01	9.972E-02
4.00000E-02	2.304E-01	4.695E-02
5.00000E-02	2.020E-01	3.082E-02
6.00000E-02	1.868E-01	2.508E-02
8.00000E-02	1.695E-01	2.247E-02
1.00000E-01	1.586E-01	2.297E-02
1.50000E-01	1.406E-01	2.567E-02
2.00000E-01	1.282E-01	2.772E-02
3.00000E-01	1.111E-01	2.990E-02
4.00000E-01	9.947E-02	3.073E-02
5.00000E-01	9.079E-02	3.093E-02
6.00000E-01	8.395E-02	3.079E-02
8.00000E-01	7.372E-02	3.005E-02
1.00000E+00	6.628E-02	2.909E-02
1.25000E+00	5.927E-02	2.780E-02
1.50000E+00	5.395E-02	2.657E-02
2.00000E+00	4.630E-02	2.444E-02
3.00000E+00	3.715E-02	2.135E-02

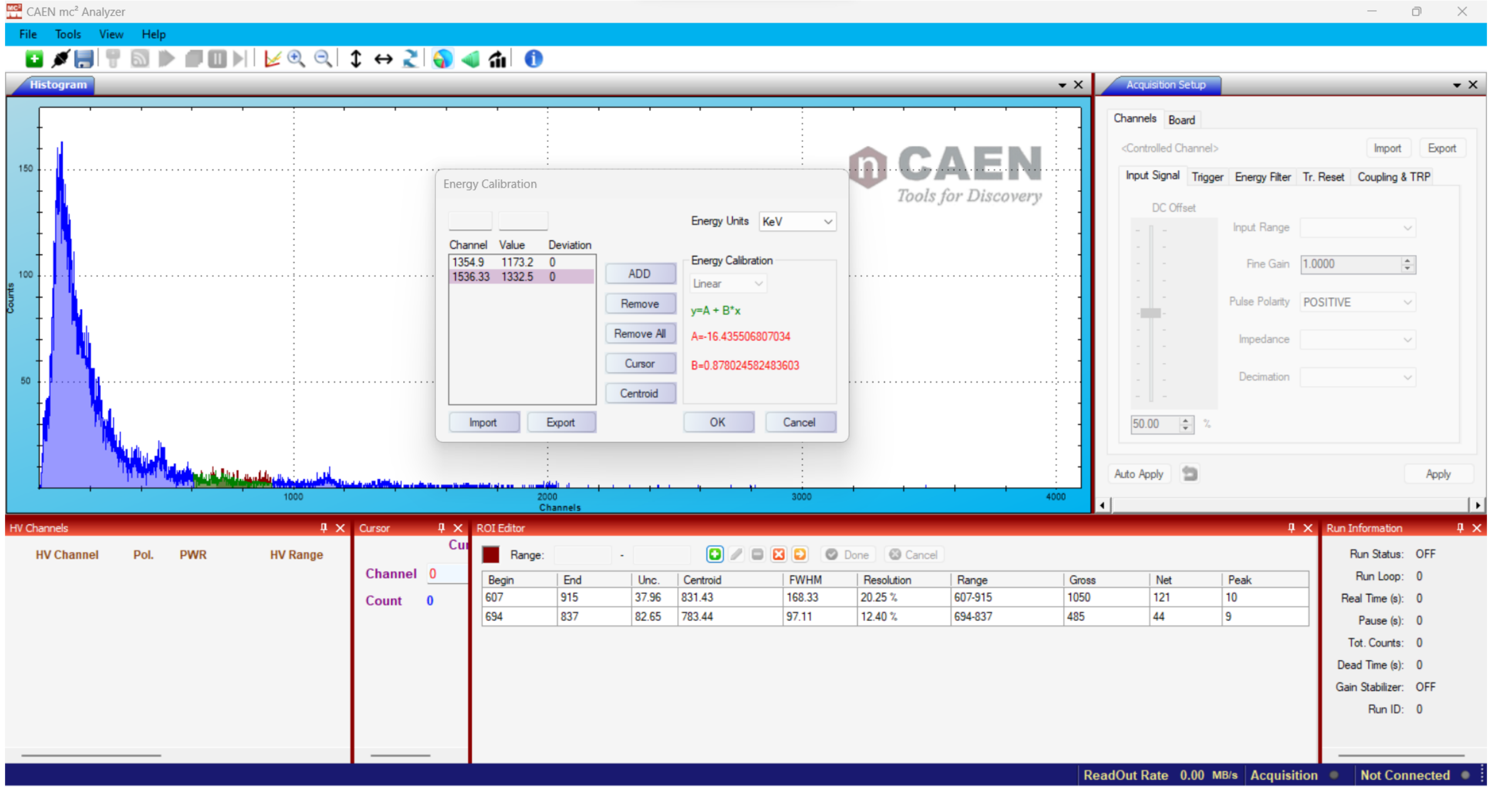
Americium → 6.00000E-02

Cesium → 6.00000E-01

Cobalt → 1.25000E+00



Calibration setup



Energy Calibration

Channel	Value	Deviation
1354.9	1173.2	0
1536.33	1332.5	0

Energy Units: KeV

Energy Calibration: Linear

y=A + B*x

A=-16.435506807034

B=0.878024582483603

<Controlled Channel>

DC Offset: 50.00 %

Input Range:

Fine Gain: 1.0000

Pulse Polarity: POSITIVE

Impedance:

Decimation:

Channel: 0

Count: 0

Range: -

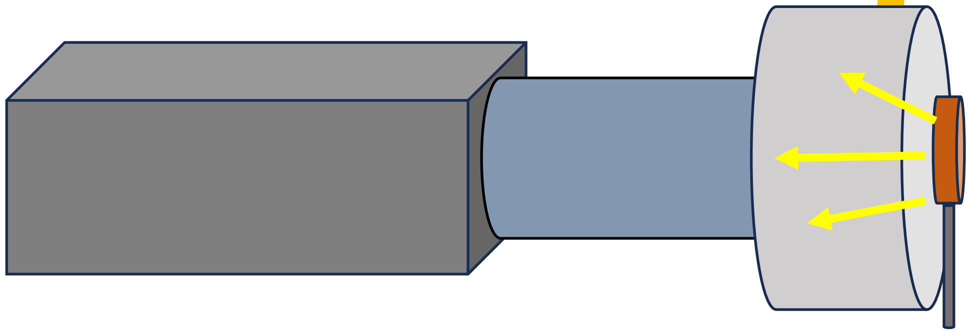
Begin	End	Unc.	Centroid	FWHM	Resolution	Range	Gross	Net	Peak
607	915	37.96	831.43	168.33	20.25 %	607-915	1050	121	10
694	837	82.65	783.44	97.11	12.40 %	694-837	485	44	9

Run Status: OFF
Run Loop: 0
Real Time (s): 0
Pause (s): 0
Tot. Counts: 0
Dead Time (s): 0
Gain Stabilizer: OFF
Run ID: 0

ReadOut Rate 0.00 MB/s Acquisition Not Connected

Open calibration setup and set ^{60}Co peaks channels

Activity measure



$$R = D\ \mathrm{A}$$

$$\mathrm{N} = D\ \mathrm{A}\Delta t$$

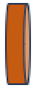
$$\frac{\mathrm{N}}{D\Delta t} = A$$

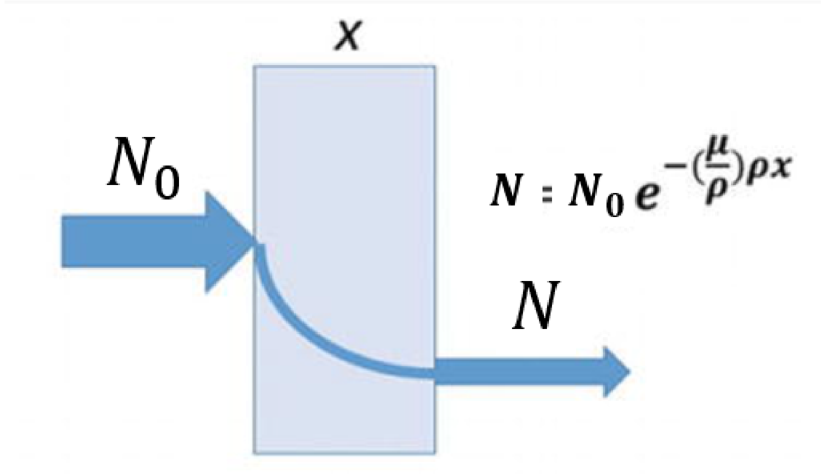
If we assume D is equal to 50% because of geometry, obtain A

Theory

Lambert-Beer Law

Source





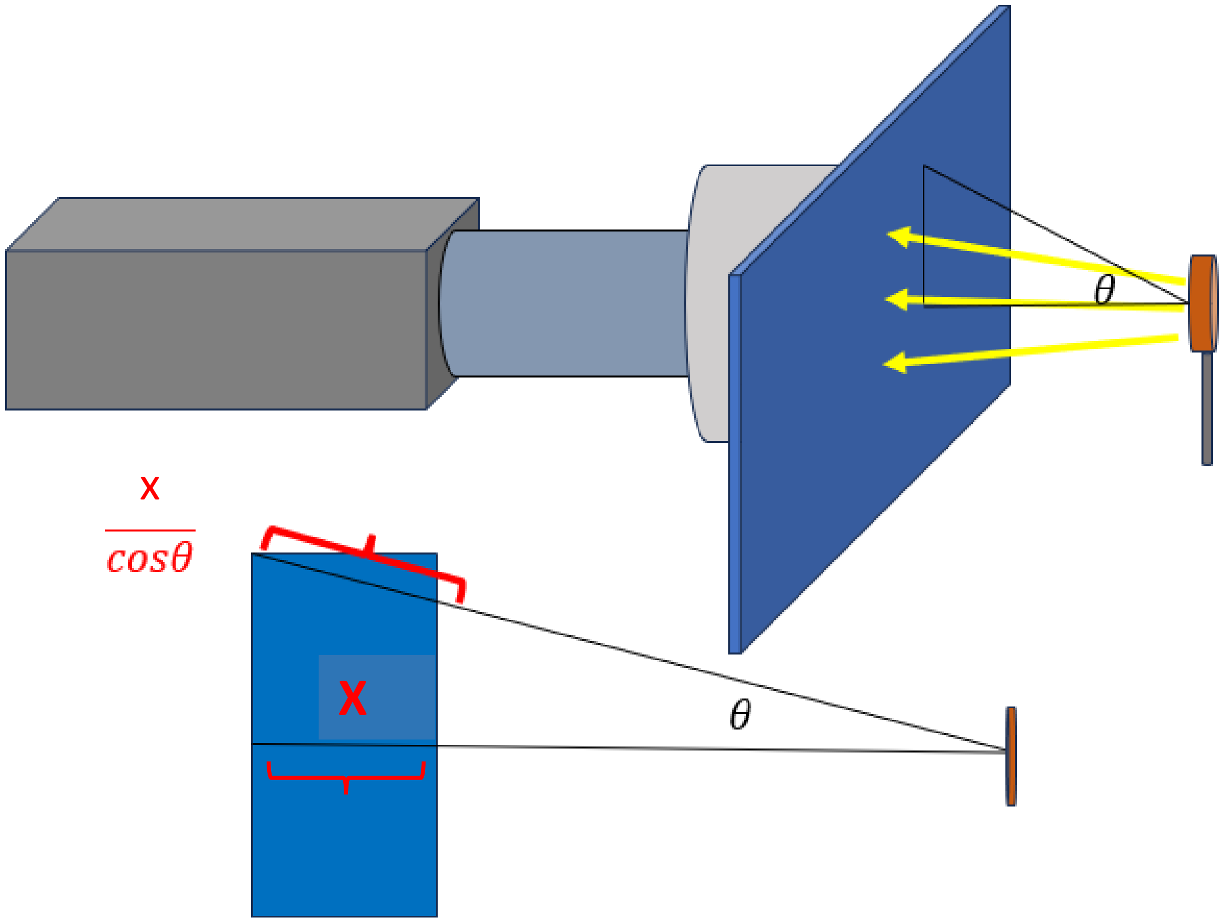
$N = N_0 e^{-\mu x}$

$N = \#gamma\ trasmitted$

$N_0 = \#gamma\ from\ source$

$x = thickness \qquad \mu = attenuation\ coefficient$

Measurements

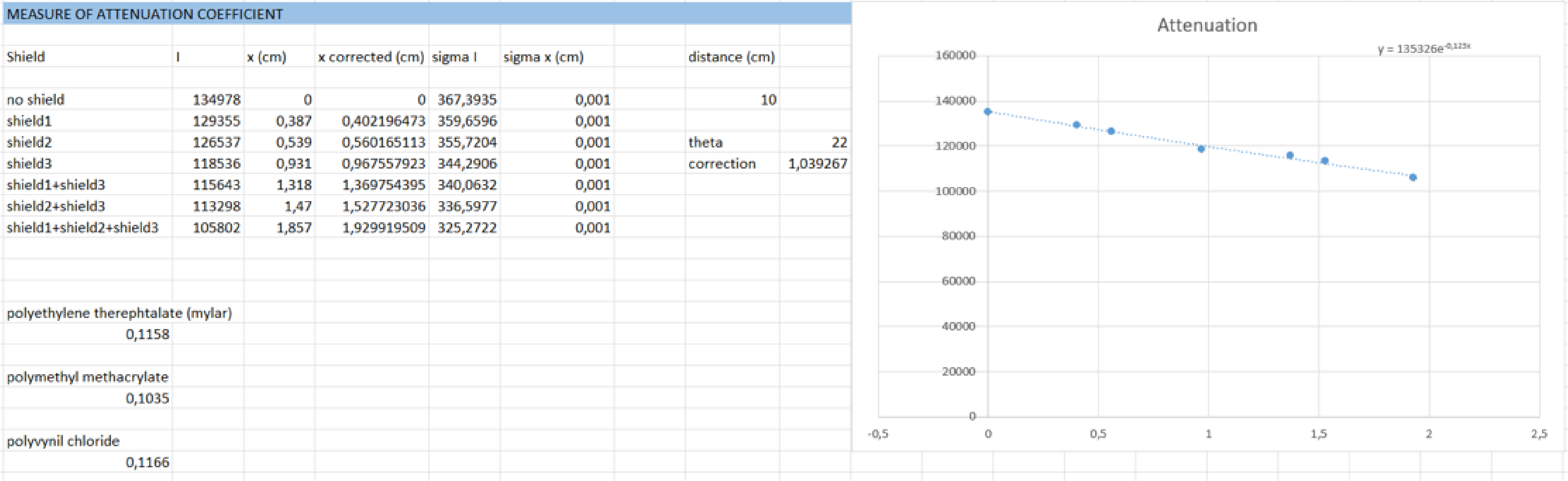


Measure the distance from the source to the detector, measure the thickness of the slice, position the slice in front of the detector

Measure the angle between the the source and the edge of the detector, like in figure.

$$\langle X\rangle = \frac{1}{2}\left(1+\frac{1}{cos\theta}\right)$$

Analysis



MEASURE OF ATTENUATION COEFFICIENT

Shield	I	x (cm)	x corrected (cm)	sigma I	sigma x (cm)		distance (cm)	
no shield	134978	0	0	367,3935	0,001		10	
shield1	129355	0,387	0,402196473	359,6596	0,001			
shield2	126537	0,539	0,560165113	355,7204	0,001		theta	22
shield3	118536	0,931	0,967557923	344,2906	0,001		correction	1,039267
shield1+shield3	115643	1,318	1,369754395	340,0632	0,001			
shield2+shield3	113298	1,47	1,527723036	336,5977	0,001			
shield1+shield2+shield3	105802	1,857	1,929919509	325,2722	0,001			

polyethylene therephtalate (mylar)
0,1158

polymethyl methacrylate
0,1035

polyvynil chloride
0,1166

Try with and without correction factor equal $\langle X\rangle = \frac{1}{2}\left(1+\frac{1}{cos\theta}\right)$