Advanced Laboratory Course

B22 Compton Effect [EN]

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Contents

1 Preparation

1.1 Abstract

In this experiment, by detecting absorption spectra of radioactive which went through different targets and angles, we measure Compton wavelength, determine cross section for photo effect and check Klein-Nishina cross-sectional formula.

Below we briefly describe the corresponding theory and our experiment, mostly following the task and the experimental description from [1].

1.2 Theoretical basics

1.2.1 Interaction between γ-rays and X-rays and matter

When photon goes through matter, several variants could appear. For the details see [5].

First, there is electron-pair production. The photon interacts with the nuclei of the atom and produce electron-positron pair. The energy of the photon then must be bigger than $2m_ec^2$. The cross-section section is, roughly speaking, proportional to $Z^2 \ln(E)$ (for high energy) , where Z is atomic number, and E is the energy of the photon.

Second effect is absorption of the photon by the electron or so-called photo effect. In this process the electron absorbs the photon and increase its energy. It is possible when energy of the photon is bigger than difference between the electron energy levels. The cross-section section is, roughly speaking, proportional to $Z^5/E^{7/2}$.

The third option is Compton Effect. The photon is scattered by the not moving electron, changing its trajectory. The cross-section section is, roughly speaking, proportional to $\frac{Z_{eff}}{E}\ln(E)$. Here $Z_{eff} = Z - 2$ due to the fact that K-electrons do not contribute [1].

1.2.2 Compton scattering formula

Consider scattering of a photon on an electron within the framework of relativistic mechanics. At the beginning, the electron e is at rest and the photon γ moves towards it. At the end there is a photon γ' and an electron e' with a different momentum.

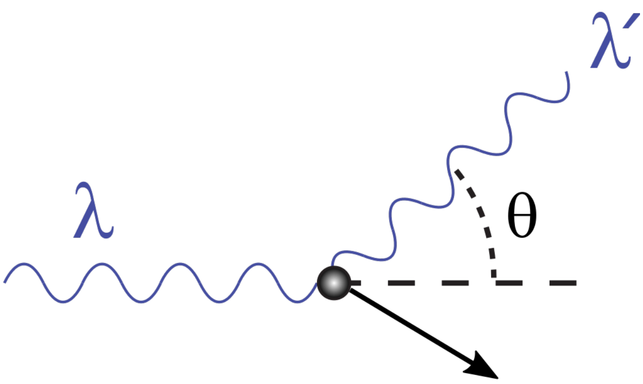

Figure 1: Compton effect. [4]

Conservation of total energy:

$$E_\gamma + m_e c^2 = E_{\gamma'} + E_e \tag{1}$$

Conservation of total space momentum:

$$\vec{p}_\gamma = \vec{p}_e + \vec{p}_{\gamma'} \tag{2}$$

Expressing the momentum of the electron and setting the scattering angle θ, we get:

$$p_{e'}^2 c^2 = (\vec{p}_{\gamma'} - \vec{p}_\gamma)^2 c^2 = p_\gamma^2 c^2 + p_{\gamma'}^2 c^2 - 2c^2 p_\gamma p_{\gamma'} \cos\theta \tag{3}$$

Using $E_{e'}^2 - p_{e'}^2 c^2 = m_e c^2$ and conservation of total energy, writing the photon energy as $h\nu$ frequency ν , we get:

$$\left(h\nu - h\nu' + m_e c^2\right)^2 - m_e^2 c^4 = (h\nu)^2 + (h\nu')^2 - 2h^2 \nu\nu' \cos\theta \tag{4}$$

Or,equally:

$$\frac{c}{\nu'} - \frac{c}{\nu} = \frac{h}{m_e c}(1 - \cos\theta) \tag{5}$$

In terms of corresponding wavelength $\lambda = \frac{c}{\nu}$:

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \tag{6}$$

For backwards scattered photons:

$$\Delta\lambda = \lambda' - \lambda = \frac{2h}{m_e c} \tag{7}$$

$\lambda_{Compton} = \frac{h}{m_e c}$ is called Compton wavelength.

1.2.3 Cross section

According to [2], consider A-flow which consists of particles type A colliding with B type particles B-target.

Let A have length ℓ_A with concentration of A-particles ρ_A. While B, moving with speed v, has length ℓ_B and particles type B concentration ρ_B. The contacting area of the target is A. See the figure.

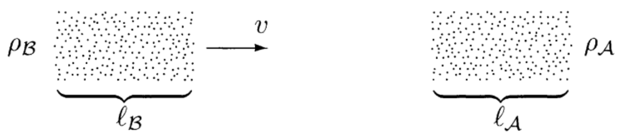

Figure 2: Colliding A with B, simple model [2].

Then, here cross section is defined as:

$$\sigma = \frac{\text{number of collisions}}{\rho_A \ell_A \rho_B \ell_B A} = \frac{\text{number of collisions}}{\text{the incoming flux over time and target particles number}} \tag{8}$$

This definition need to be generalized. In particular, takig into account the dependence on the angles of collision $\Omega = (\theta, \phi)$, we write:

$$d\sigma = \frac{\text{density of number of collisions per angles}(\theta,\phi)d\Omega}{\text{the incoming flux over time and target particles number}} \tag{9}$$

Differential $d\sigma$ is called differential cross. While total cross section is full integrated value, here defined as

$$\sigma = \int_\Omega d\Omega \frac{d\sigma}{d\Omega}. \tag{10}$$

1.2.4 Klein-Nishina formula

The cross section of Compton Effect can be calculated using Quantum Field Theory framework. The so-called Klein-Nishina formula [6] gives the leading order of the differential cross section:

$$\frac{d\sigma_{Compton}}{d\Omega} = \frac{\alpha^2\hbar^2}{2m_ec^2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'} + \frac{E'}{E} - \sin(\theta)\right) \tag{11}$$

Here α is fine-structure constant and E is the initial energy of the photon, while E' is its energy in the end, which is given, according to Compton scattering formula:

$$E' = \frac{E}{1 + \frac{E}{2m_ec^2}(1-\cos\theta)} \tag{12}$$

In terms of wavelength:

$$\frac{d\sigma_{Compton}}{d\Omega} = \frac{\alpha^2\hbar^2}{2m_ec^2}\left(\frac{\lambda}{\lambda'}\right)^2\left(\frac{\lambda'}{\lambda} + \frac{\lambda}{\lambda'} - \sin(\theta)\right) \tag{13}$$

$$\lambda = \frac{\lambda'}{1 + \frac{\lambda'}{2m_ec^2}(1-\cos\theta)} \tag{14}$$

1.2.5 Attenuation of radiation

According to the attenuation law [7], the change in the number of photons when passing through matter is given by

$$N(x) = N_0 e^{-\mu x}, \tag{15}$$

where x is the thickness of the material, N_0 is the initial number and μ is given by total cross section and concentration of the particles of the material:

$$\mu = \sigma_{total} n \tag{16}$$

The total cross section is a sum of all possible cross sections. Due to our experimental energy scale we take into account here only photo effect and Compton effect, so:

$$\sigma_{total} = \sigma_{Compton} + \sigma_{photo} \tag{17}$$

1.3 Experiment

1.3.1 Setup

According to [1], the physical part of the setup consists of radioactive sample, creating γ - ray radiation, plastic scintillator crystal as a target, NAI scincillator as a detector. The detection angle is variable. The scincillators outputs are connected with the electronics, as shown on the figure, using two PMA amplifiers (amplify the signals), two discriminators (convert the signal to a logical of a certain duration if it crosses a reference threshold), coincidence unit (passes only signals which both have peaks) , two delay units (delay the amplified signals for the duration of the passage of other signals) , ADC with three gates, converting the final output to the PC.

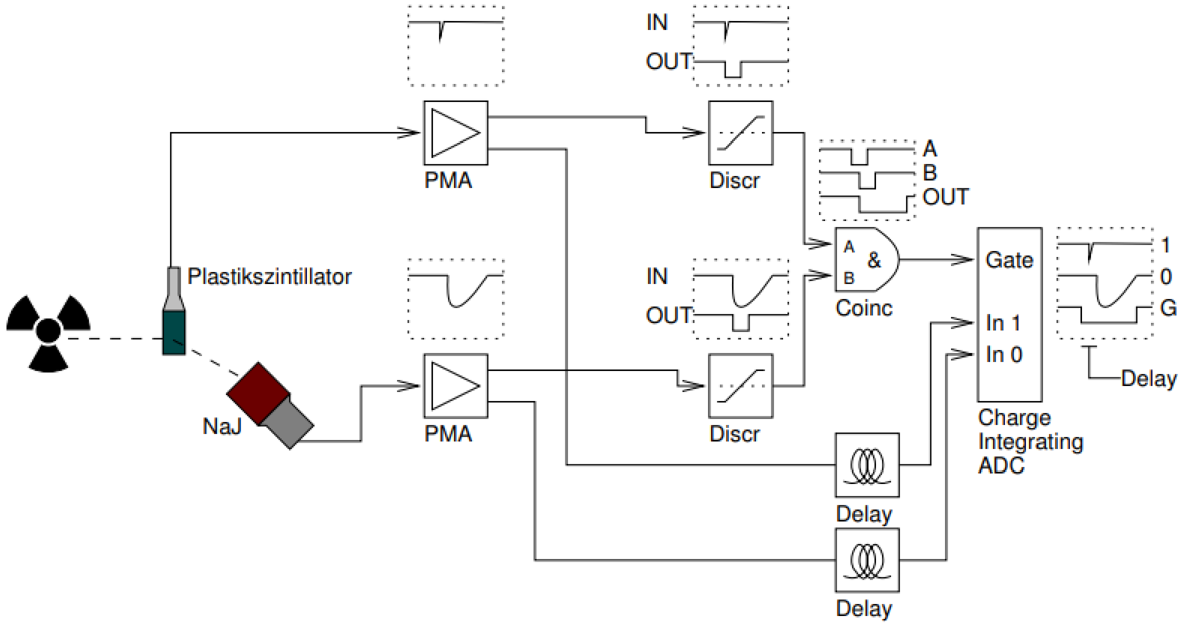

Figure 3: The setup of our experiment [1].

The purpose of the setup is to be able to obtain target and detector signals corresponding only to Compton Effect (when there were signal from both scintillators, this is advantage of the coincidence technique) on the screen of the PC with the help of which we can analyze the signals as numbers of detections depending on a channel corresponding an energy. This technique can be turned off while using only the detector without the target.

On the PC the program Gnuplot is used for creating the graphs.

1.3.2 Scintillator

Let us briefly describe here the working principle of the detection scintillator.

The high energy photon interacts with an electron from the scintillators material and it goes to a high energy level. Then, the electron moves to a lower levels, emitting a photons in the visible spectrum.

These photons hit the photocathode, which emits electrons. This electronic signal is then linearly increased by dynodes and goes to the anod.

See Figure 4. Fore more details see [3].

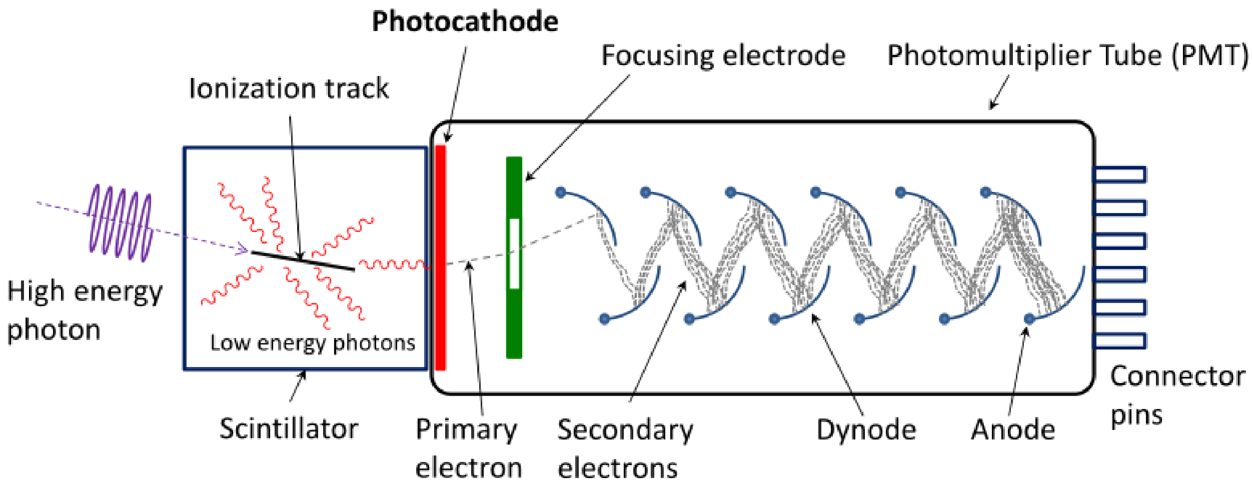

Figure 4: Scintillator, scheme [3].

As a result, the number of electrons supplied to the anode is directly proportional to the corresponding lost of photon energy.

The absorption of photons results in signals called photo peaks. With Compton scattering, the final signals related to the change of the photons energies are called the Compton continuum. Their maximum, corresponding to the back scattering, is called the Compton edge. See [8].

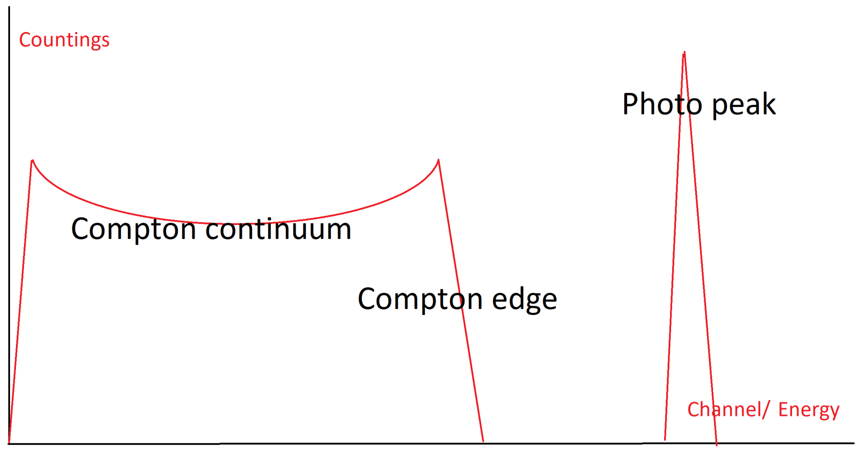

Figure 5: Qualitative sketch of the spectrum of a monochromatic radiation with the terms above.

1.3.3 Experimental plan

Here briefly describe the plan of our actions.

First, we do the calibration. We take ^{137}Cs, ^{133}Ba, ^{22}Na, ^{60}Co samples. We use observed photo peaks to correlate the channels with the energy, based on spectral line data of the samples. We also determine the photo detection efficiency of the scincillators as the number of observed photons devided by the number of expected photons.For this we use the known radioactive activity data of the samples to calculate the expected numbers. To determine Compton length we will also use the ^{137}Cs and ^{22}Na samples spectra.

Next, to measure the cross section for the photo effect for Al, Cu, Pb, we observe ^{137}Cs radiation attenuation through the different thickness of them, using ^{137}Cs - source, taking cross section of the Compton effect known.

Finally, we measure the wave length shift and check Klein-Nishina formula, using caesium source and active target with coincidence technique. We taking spectra varying the angle.

In addition, using an oscilloscope, we follow the way of the signal in the electronics. Their photos can be found in the appendix.

Also we determine all necessary values of the setup.

1.3.4 Source activity

The radioactive samples are described by an activity, the number of decays per time unit:

$$A(t) = A_0 e^{-(t/\tau)\ln 2} \tag{18}$$

Their data, initial registered activity A_0, half decay time τ, energies and relative intensities are given on the figure.

source	**Activity at 01.05.1999**	**HDT**	**decay**	**Energy**	**particle RI.**	**Energy**	**Photon RI.**
^{22}Na	$5,22 \cdot 10^5$ Bq	2,603 a	β^+, EC	0,545 MeV	90%	$0,511$ MeV $1,275$ MeV	Annihil. 100%
^{60}Co	$4,7 \cdot 10^5$ Bq	5,271 a	β^-	0,316 MeV	100%	1,173 MeV 1,333 MeV	100% 100%
^{133}Ba	$4,0 \cdot 10^5$ Bq	10,52 a	EC			0,276 MeV 0,302 MeV 0,356 MeV 0,383 MeV	7,16% 18,33% 62,05% 8,84%
^{137}Cs	$74 \cdot 10^6$ Bq $\star$	30,04 a	β^-	0,514 MeV (e^-) 1,176 MeV (e^-)	94% 6%	0,662 MeV	85,1%

Figure 6: Activities at 01.01.1994 , half decay time(HDT), energies and relative intensities(RI). [1]

2 Setup calibration

2.1 Peak analysis and calibration line

In this section, as it shortly described earlier, we find out some characteristics of the setup. At first we are interested in the relation between the energy and the channel. For this we use the measured spectra of the calibration samples, which peaks are fitted by the function

$$f(x) = \sum_i a_i \exp\left(-\left(\frac{x - x_i}{\sigma_i}\right)^2\right) + kx + m. \tag{19}$$

Below on the table 1 we present the fitting parameters of the curves. The corresponding graphs are on the Figure 7-10.

	^{133}Ba	^{60}Co	^{22}Na	^{137}Cs
x_1	51.7058 ± 0.0456	167.5610 ± 0.1117	73.1951 ± 0.1339	96.5906 ± 0.0322
x_2	42.9409 ± 0.1244	190.0660 ± 0.1512	184.1890 ± 1.3090	
a_1	5619.5000 ± 79.0900	470.3640 ± 13.2900	105.6030 ± 3.6910	6573.6500 ± 52.6800
a_2	2156.0000 ± 72.4500	411.5450 ± 23.5500	21.7854 ± 3.0830	
σ_1	3.5044 ± 0.0773	6.2540 ± 0.2098	5.0615 ± 0.2247	5.0203 ± 0.0510
σ_2	4.0067 ± 0.2014	7.1569 ± 0.4818	15.6333 ± 2.7170	
m	1095.7900 ± 136.5000	617.8410 ± 105.5000	74.6566 ± 4.5840	1392.0900 ± 150.4000
k	-9.1151 ± 3.2350	-2.8498 ± 0.6806	-0.3874 ± 0.0382	-10.5553 ± 1.4460

Table 1: Fitting parameters of the spectra, obtained by Gnuplot.

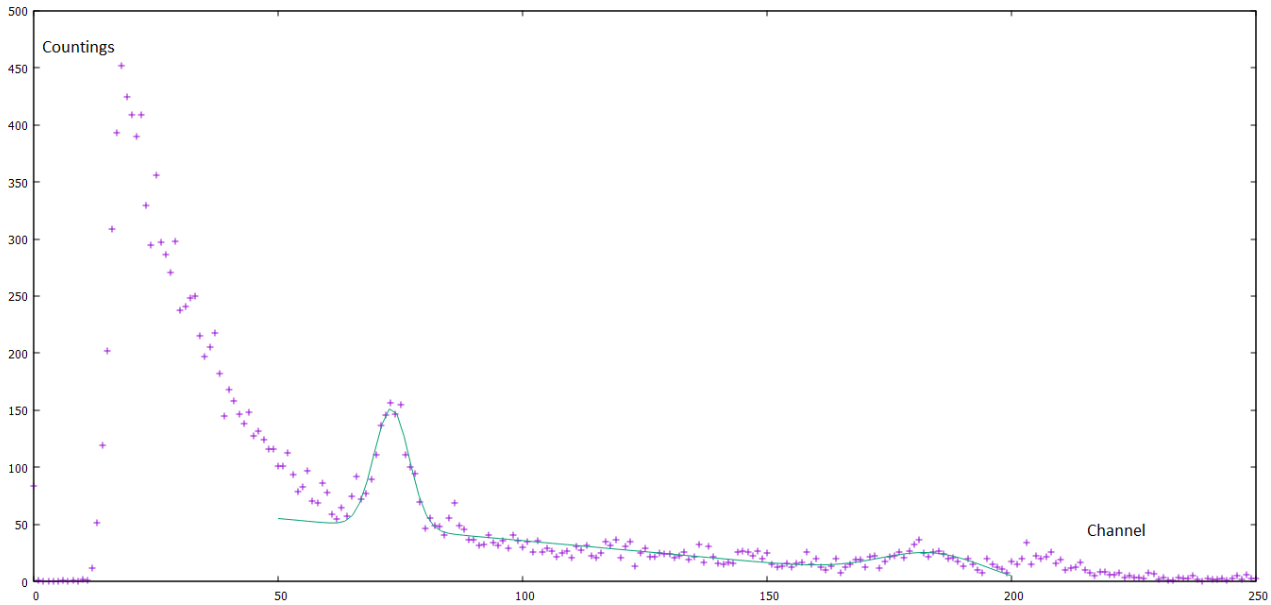

Figure 7: Natrium source spectrum. All two photo peaks are identified.

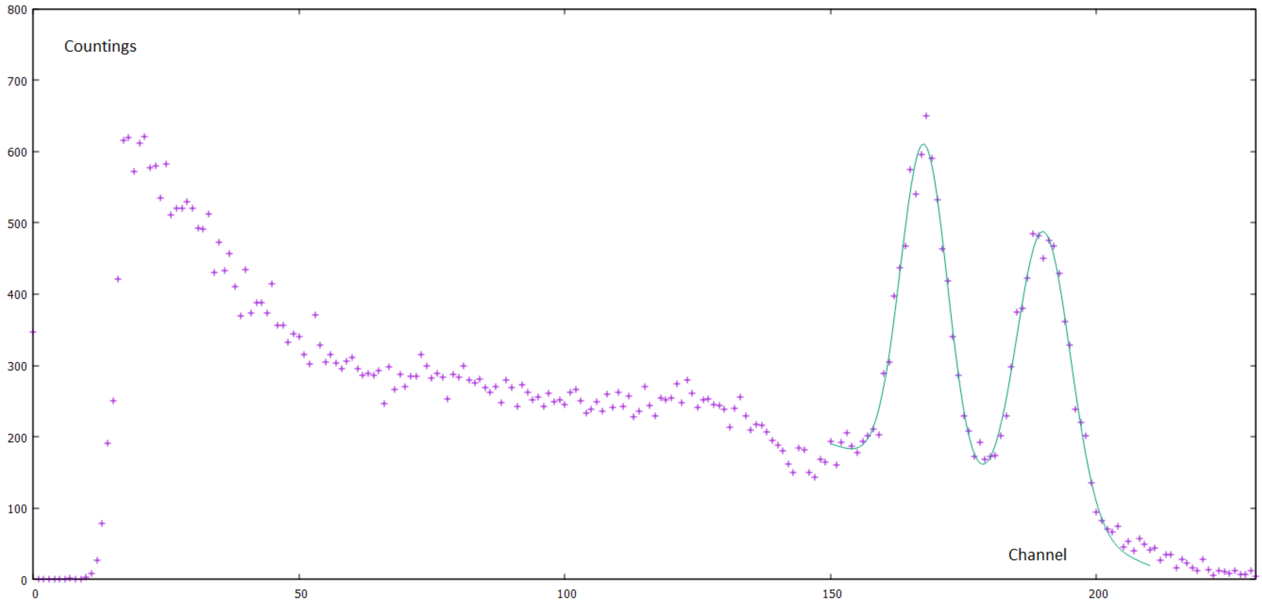

Figure 8: Cobalt source spectrum.All two photo peaks are identified.

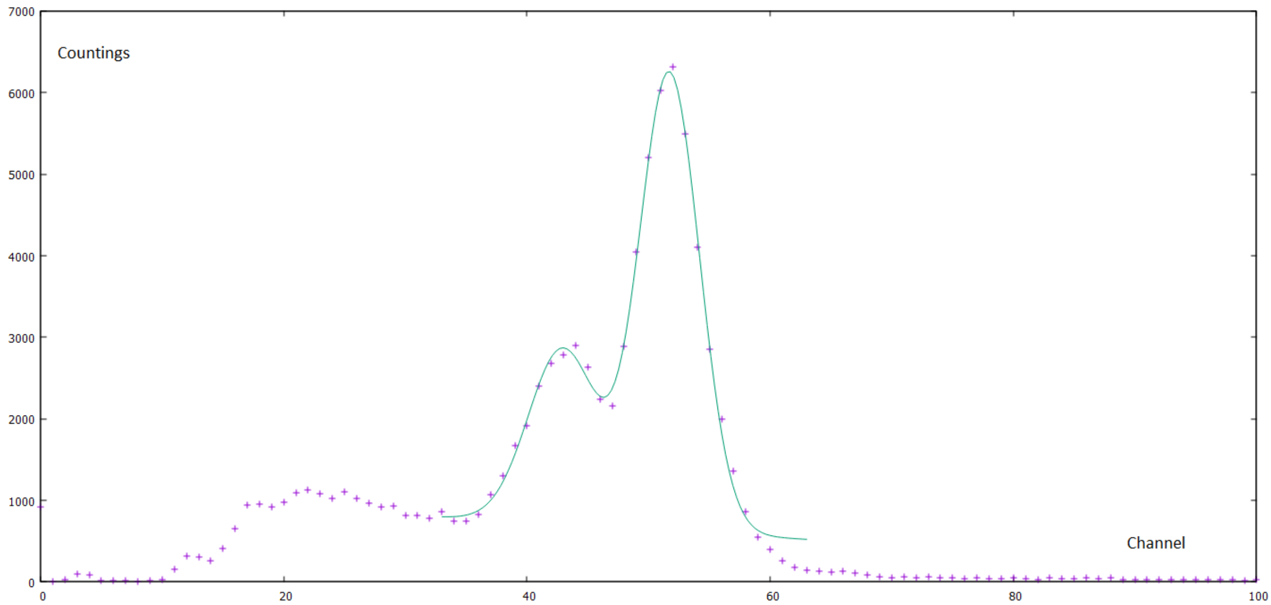

Figure 9: Barium source spectrum. The two most intense photo peaks are identified.

Using the data about our radioactive samples, we can associate channels with the corresponding energies. This leads to the following linear dependence:

$$E(\text{channel}) = (6920.79 \pm 86.63)\text{eV} \times \text{channel} - (1178.89 \pm 7944.00)\text{eV} \qquad (20)$$

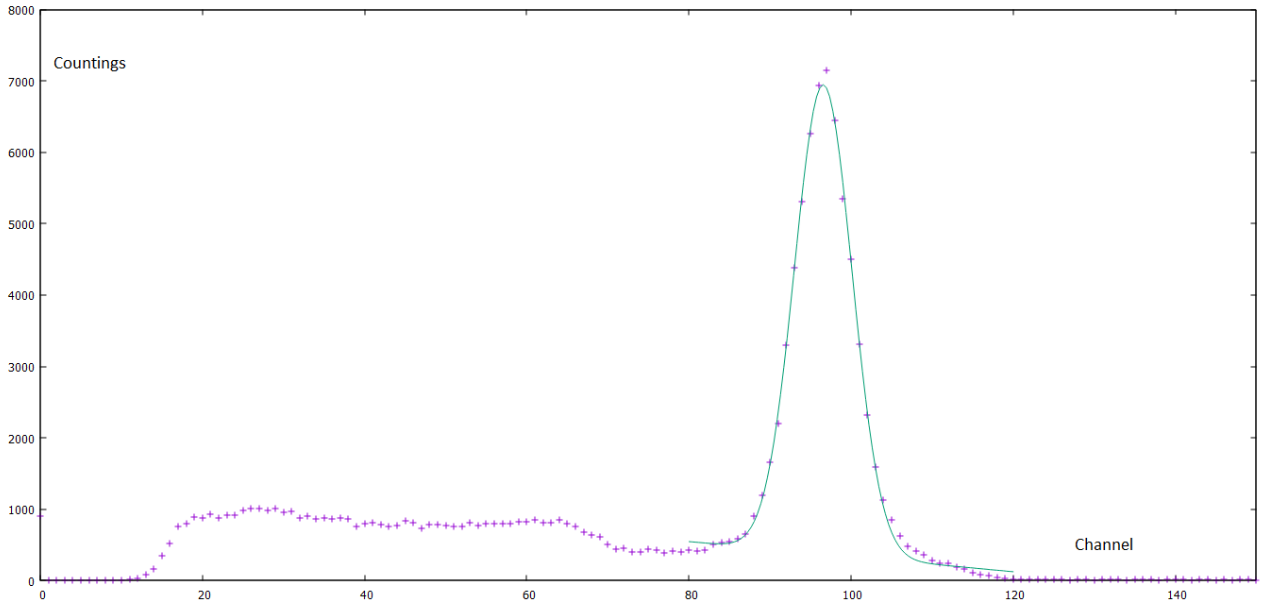

Figure 10: Caesium source spectrum. The photo peak is identified.

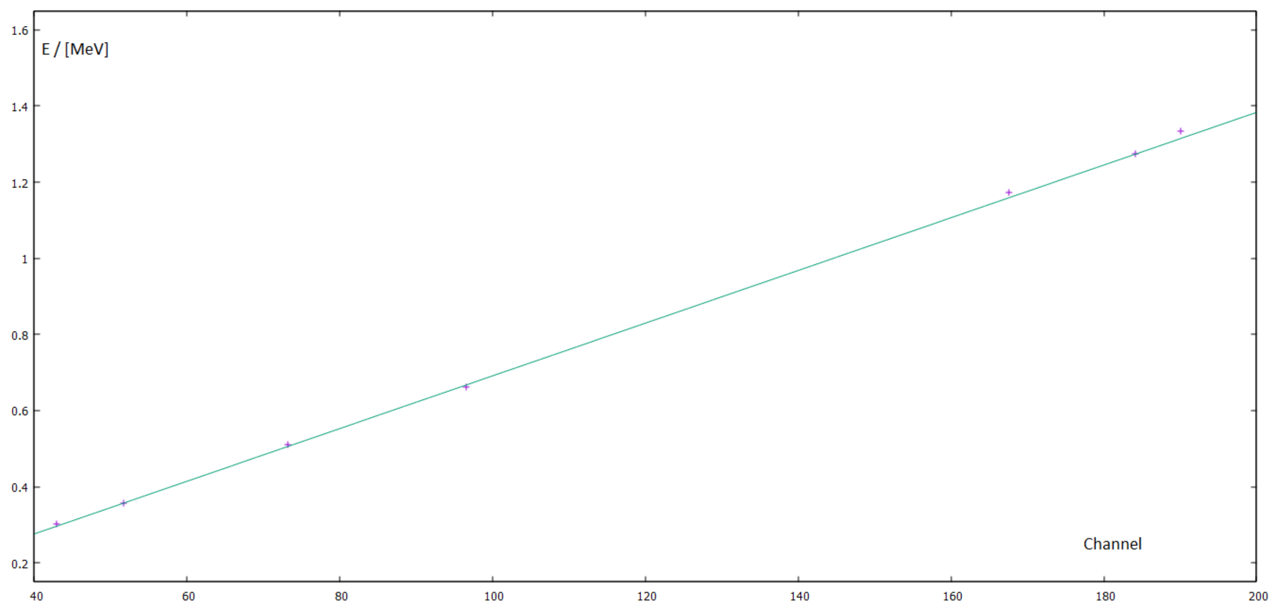

Figure 11: Energy dependence on the channel.

2.2 Detector efficiency

The efficiencies of the detector can be calculated as measured number divided by expected number of photons:

$$\zeta = \frac{N_{meas}}{N_{exp}} \tag{21}$$

We estimate N_{meas} corresponding to peak i as

$$N_{meas\,i} = \sqrt{\pi}\sigma_i a_i \tag{22}$$

and N_{exp} corresponding to energy level from source data as

$$N_{exp} = A(t)\Delta t f_{\mathrm{RI}} \frac{\Omega}{4\pi} \tag{23}$$

where Δt is the time of the measurements (here 50s for all except 30s for ^{137}Cs), the solid angle Ω is estimated as $\frac{6.5\times1.5\pm0.7}{(5\pm1)^2}$ for all except $\frac{6.5\times1.5\pm0.7}{(58.5\pm1.5)^2}$ for ^{137}Cs, based on the measured and known data about our experimental setup, the factor f_{RI} is the multiplication of the RI from the table with the source data according to transition processes.

Due to the dependence the scattering cross sections as $E^{-7/2}$, we expect similar dependence of the efficiency on energy.

We plot the dependence of efficiency on energy and fit it with the corresponding curve. See the figure.

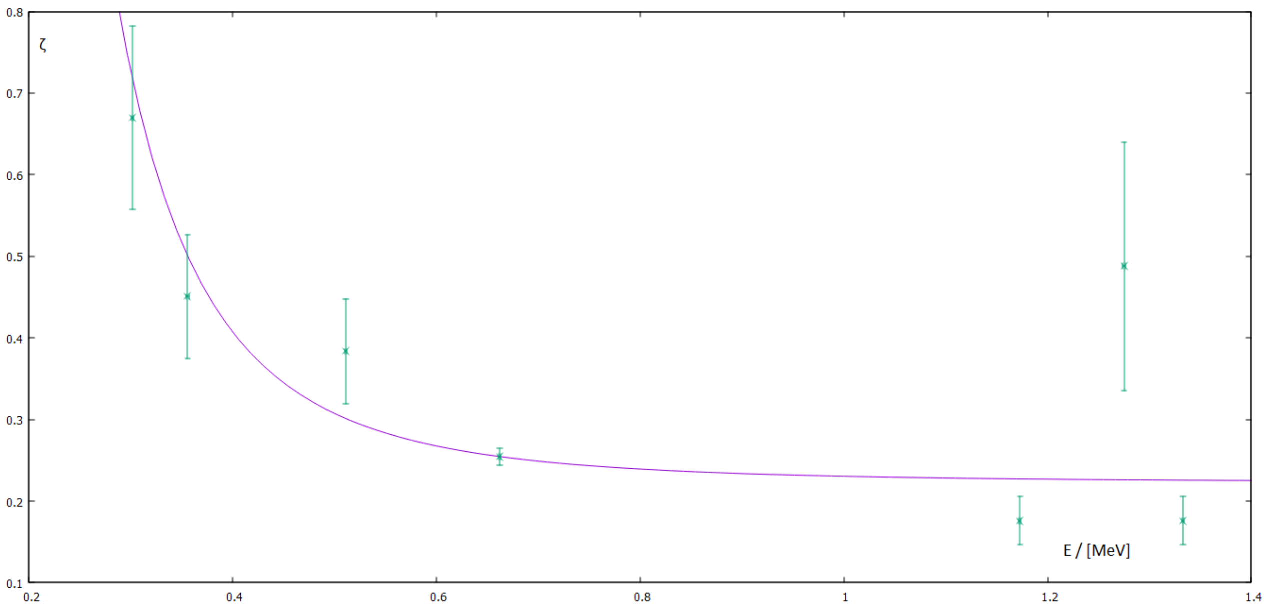

Figure 12: Efficiency dependence on the energy.

The fitting curve:

$$\zeta(E) = \frac{(0.00748 \pm 0.00203)}{(E/[\mathrm{MeV}])^{7/2}} + 0.2229 \pm 0.0089 \tag{24}$$

The dependence is recognizable from the measured data, but the deviation of one of the points is quite strong. The large error in this measurement is due to the smallness of the second Natrium peak, so it merges more with the background and its recognition is not precise enough.

Otherwise, the points are close to the curve, the errors of the coefficients are not too large, and we consider the obtained dependence to be satisfactory.

3 Measurements

3.1 Compton length using ^{137}Cs and ^{22}Na spectra

Here we roughly determine the Compton wavelength from the compton edges obtained from the spectra of the ^{137}Cs and ^{22}Na samples.

In accordance with the described definition of Compton edge energy E_{Compton} and photo peak E_{photo} , there is formula for the Compton wavelength:

$$\lambda_{\text{Compton}} = \frac{hc}{2}\left(\frac{1}{E_{\text{photo}} - E_{\text{edge}}} - \frac{1}{E_{\text{photo}}}\right) \tag{25}$$

Below we present the results for each spectrum:

	^{137}Cs	^{22}Na, 1 peak	^{22}Na, 2 peak
$E_{\text{photo}}/[\text{MeV}]$	0.662	0.511	1.275
$E_{\text{edge}}/[\text{MeV}]$	0.471 ± 0.035	0.339 ± 0.035	1.106 ± 0.035
$\lambda_{\text{Compton}}/[\text{pm}]$	2.31 ± 0.42	2.39 ± 0.49	3.19 ± 0.66

Table 2: The energies and obtained Compton wavelengths.

We calculate the final value as an average:

$$\lambda_{\text{Compton}} = 2.63 \pm 0.93\,\text{pm} \tag{26}$$

Comparing this result with the CODATA value $\lambda_{\text{Compton}} = 2.42631023867\text{pm}$ [9], we can conclude that our measurement, up to an error, gives the correct value.

3.2 Obtaining photo effect cross section

Here we measure the total cross section for photo effect using the measurement of the exponential decay of the measured number of particles under the peaks in the materials depending on the thickness. We use the theoretical formula of the scattering cross section for the Compton effect and calculate the cross section for the photo effect.

Total cross section for Compton effect in leading order is given as:

$$\sigma_{\text{Compton}} = Z_{eff} 2\pi \frac{\alpha^2\hbar^2}{m_e^2 c^2}\left\{\frac{1+k}{k^2}\left[\frac{2(1+k)}{1+2k} - \frac{\ln(1+2k)}{k}\right] + \frac{\ln(1+2k)}{2k} - \frac{1+3k}{(1+2k)^2}\right\} \tag{27}$$

Here $k = \frac{E_{\text{photo}}}{m_e c^2}$. Substituting the energy for ^{137}Cs photo peak, we get:

$$\sigma_{\text{Compton}} \approx Z_{eff} 0.256\text{b} \tag{28}$$

The data for each material of each measured thickness are also fitted by same Gaussian-type function

$$f(x) = a\exp\left(-\left(\frac{x-x}{\sigma}\right)^2\right) + kx + m. \tag{29}$$

The quantity of particles corresponding to the peak can be estimated as

$$N = \frac{\sqrt{\pi}\sigma a}{\zeta(E_{\text{photo}})}. \tag{30}$$

By default, we always use this estimate in our report.

All fitted initial measured data graphs can be found in the appendix.

In the table below we present the final results for each material and each length:

Al , $x/[\text{cm}]$	Al , $\lg(N/N_0)$	Cu , $x/[\text{cm}]$	Cu , $\lg(N/N_0)$	Pb , $x/[\text{cm}]$	Pb , $\lg(N/N_0)$
0.5	-0.0132 ± 0.0121	0.12	-0.0628 ± 0.0122	0.16	-0.0432 ± 0.0118
1.0	-0.0758 ± 0.0122	0.14	-0.1109 ± 0.0123	0.36	-0.1697 ± 0.0127
1.5	-0.1192 ± 0.0118	0.26	-0.1520 ± 0.0130	0.50	-0.2412 ± 0.0128
2.0	-0.1568 ± 0.0123	0.50	-0.2004 ± 0.0122	0.66	-0.3198 ± 0.0124
2.5	-0.1783 ± 0.0122	0.62	-0.2568 ± 0.0150	0.70	-0.3378 ± 0.0139
3.0	-0.2425 ± 0.0130	0.76	-0.3657 ± 0.0136	0.86	-0.4133 ± 0.0139

Table 3: The thickness and log of the relative photon number for each material.

For each material we fit these data with the dependence $\lg(N/N_0) = -\frac{\mu}{\ln 10}x$ (the $\ln 10$ factor is useful for technical reasons, it is not important) .

Here are the final results with the corresponding figures:

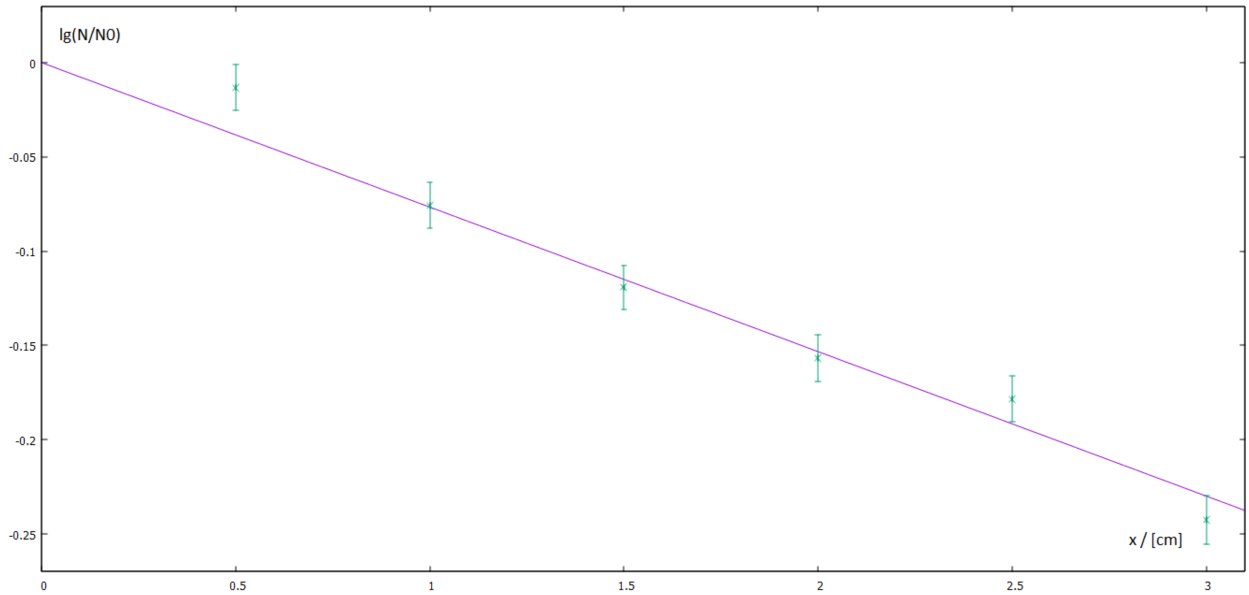

Figure 13: Decreasing of the relative number of photons with the thickness for the Al sample.

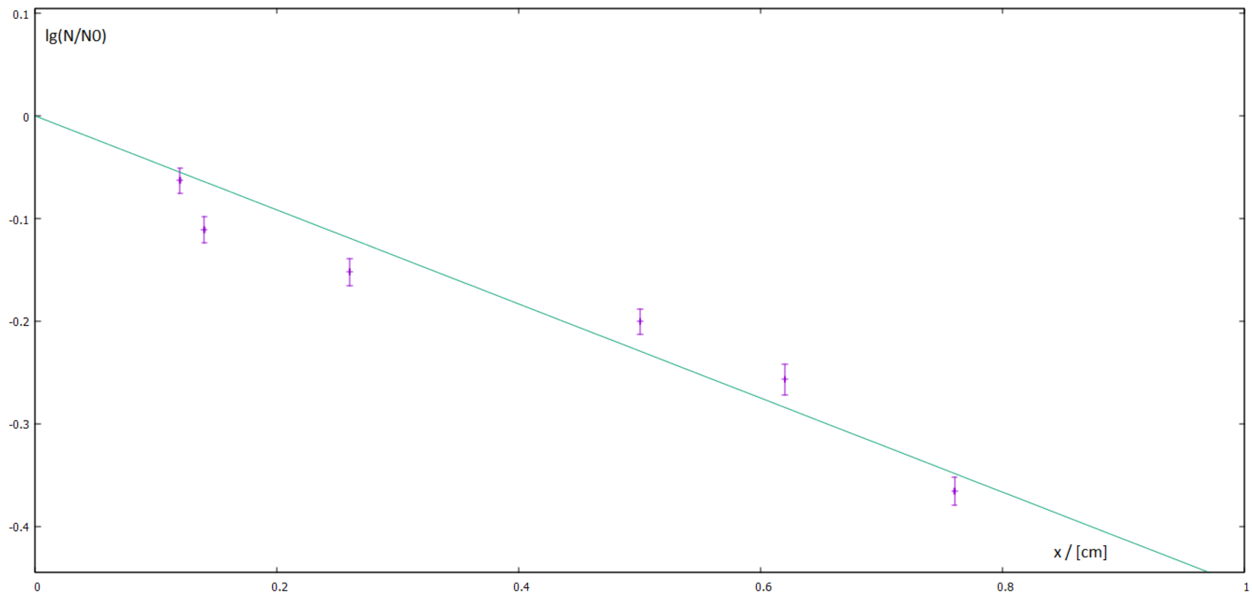

Figure 14: Decreasing of the relative number of photons with the thickness for the Cu sample.

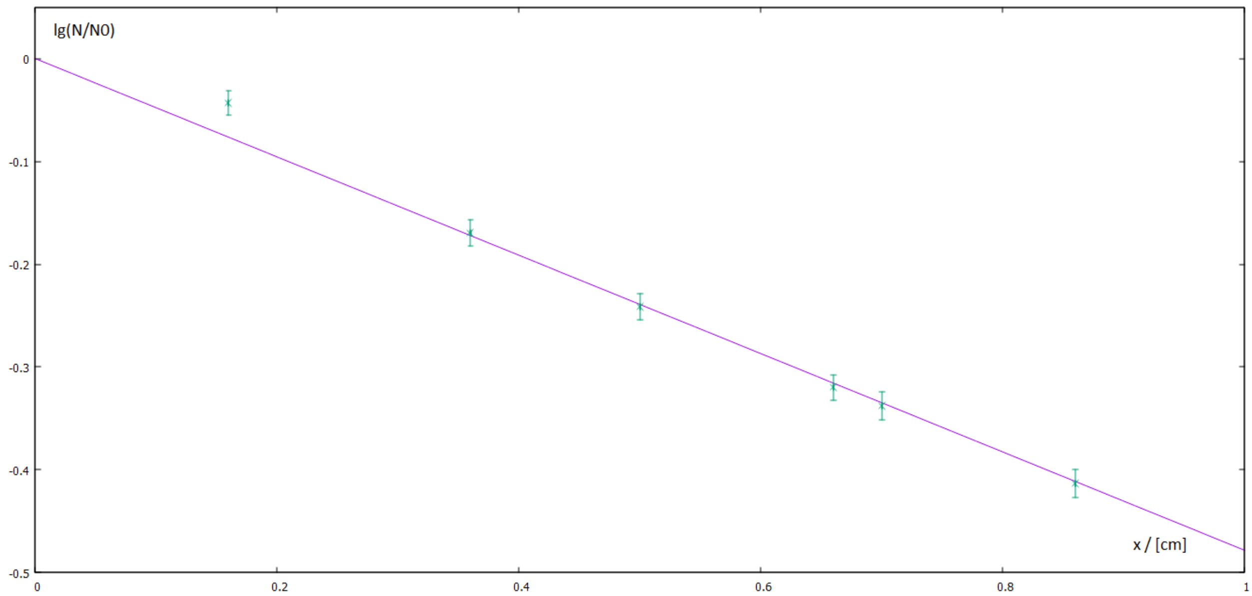

Figure 15: Decreasing of the relative number of photons with the thickness for the Pb sample.

	$\frac{\mu}{\ln 10}/[\mathrm{cm}^{-1}]$	$n/[10^{23}\mathrm{cm}^{-3}]$	$\sigma_{\mathrm{Compton}}/[\mathrm{b}]$	$\sigma_{\mathrm{photo}}/[\mathrm{b}]$
Al	0.07664 ± 0.00301	0.5783	2.816	0.295 ± 0.012
Cu	0.45824 ± 0.02982	0.8529	6.912	5.458 ± 0.355
Pb	0.47827 ± 0.01185	0.3298	20.480	12.912 ± 0.320

Table 4: Decadic attenuation coefficient, concentrations of atoms in the material, Compton and photo effect cross sections.

3.3 Compton scattering formula and Compton wavelength check

Next, as previously described, we measure the spectra after the radiation is scattered by the target at various angles.

The initial data with the fitting can be found in the appendix.

Here we present the table with the angles, calculated scattered photon energies and wavelengths.

$\theta/[^\circ]$	$E'/[\mathrm{MeV}]$	$\lambda'/[\mathrm{pm}]$
0 ± 1	0.660 ± 0.008	1.883 ± 0.024
10 ± 1	0.610 ± 0.008	2.035 ± 0.026
20 ± 1	0.576 ± 0.007	2.158 ± 0.027
30 ± 1	0.532 ± 0.007	2.335 ± 0.029
40 ± 1	0.486 ± 0.006	2.557 ± 0.032
50 ± 1	0.430 ± 0.005	2.887 ± 0.036
60 ± 1	0.381 ± 0.004	3.263 ± 0.041
70 ± 1	0.343 ± 0.004	3.623 ± 0.045
80 ± 1	0.308 ± 0.004	4.030 ± 0.051
90 ± 1	0.278 ± 0.003	4.467 ± 0.056

Table 5: The angle, the scattered photon energy and wavelength.

According to the previously described theory, the wavelength shift is given by:

$$\lambda(\theta) - \lambda(\theta = 0) = \lambda_{Compton}(1 - \cos(\theta)) \tag{31}$$

Fitting the data with these formula, we get:

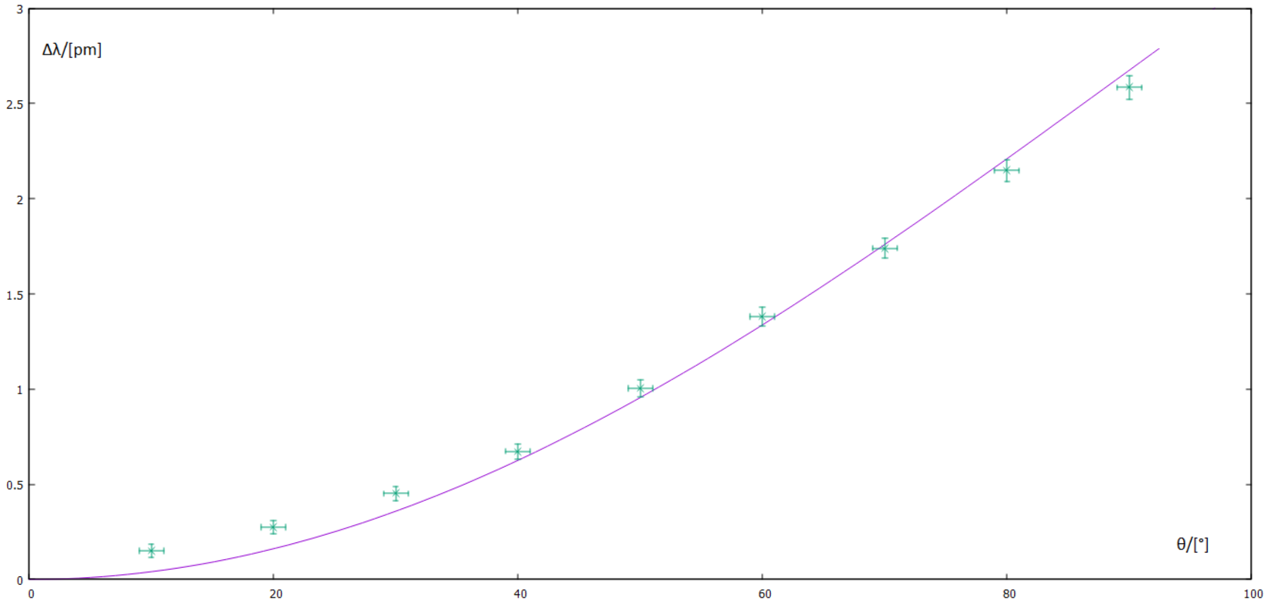

Figure 16: Wavelength shift dependence on the angle.

$$\lambda_{Compton} = 2.67431 \pm 0.07948\text{pm} \tag{32}$$

Knowing now the Compton wavelength, we can calculate the mass of the electron:

$$m_e = \frac{h}{c\lambda_{Compton}} = (8.259 \pm 0.246)10^{-31}\text{kg} \tag{33}$$

Comparing these values with the CODATA data: $\lambda_{\text{Compton}} = 2.42631023867\text{pm}$ [9], $m_e = 9.1093837015 \times 10^{-31}\text{kg}$ [10] we can conclude that our measurement of the Compton wavelength, up to an error, gives the correct value, but electron mass is not, however, it is still close.

3.4 Klein-Nishina formula check

The differential Compton effect cross section measured with our data can be estimated as:

$$\frac{d\sigma}{d\Omega} \approx \frac{\Delta\sigma}{\Delta\Omega} = \frac{N}{\Delta t}\frac{1}{J}\frac{1}{\rho d}\frac{\text{Am}_\text{u}}{\text{Z}}\frac{1}{\Delta\Omega} \tag{34}$$

Here N is the number of measured particles (obtained using fitting the peaks and taking into account the efficiency, as described earlier) over the time of the measurements $\Delta t = 500\text{s}$, m_u is the atomic mass unit.ρd is density of the target multiplied by its thickness, it is 1.032g/cm^2, Z/A, ratio of the chemical numbers of the target, is known as 0.54 [1] . The solid angle of the measurements $\Delta\Omega$ is estimated as $\frac{6.5\times1.5\pm0.7}{\pi(48.5\pm1.5)^2}$, while the incoming to the target number of photons per second J as $A(t)\frac{\pi 0.475^2}{4\pi(10)^2}$.

The calculated results:

$\theta/[°]$	$E'/[\text{MeV}]$	$\frac{\Delta N}{\Delta t}/[\text{s}^{-1}]$	$\frac{d\sigma}{d\Omega}/[\text{b}]$
0 ± 1	0.660 ± 0.008	4.980 ± 0.310	0.151 ± 0.824
10 ± 1	0.610 ± 0.008	1.949 ± 0.174	0.059 ± 0.049
20 ± 1	0.576 ± 0.007	5.099 ± 0.395	0.154 ± 0.127
30 ± 1	0.532 ± 0.007	10.084 ± 0.660	0.305 ± 0.252
40 ± 1	0.486 ± 0.006	9.029 ± 0.496	0.273 ± 0.225
50 ± 1	0.430 ± 0.005	7.194 ± 0.368	0.217 ± 0.179
60 ± 1	0.381 ± 0.004	6.284 ± 0.412	0.190 ± 0.157
70 ± 1	0.343 ± 0.004	5.142 ± 0.306	0.156 ± 0.128
80 ± 1	0.308 ± 0.004	4.034 ± 0.272	0.122 ± 0.101
90 ± 1	0.278 ± 0.003	3.393 ± 0.241	0.103 ± 0.085

Table 6: The angle, the scattered photon energy, number of measured photons per second, differential cross section.

Klein-Nishina formula and the obtained data are both plotted on Figure 17.

We see that, up to errors, the obtained values satisfy the theoretical formula.

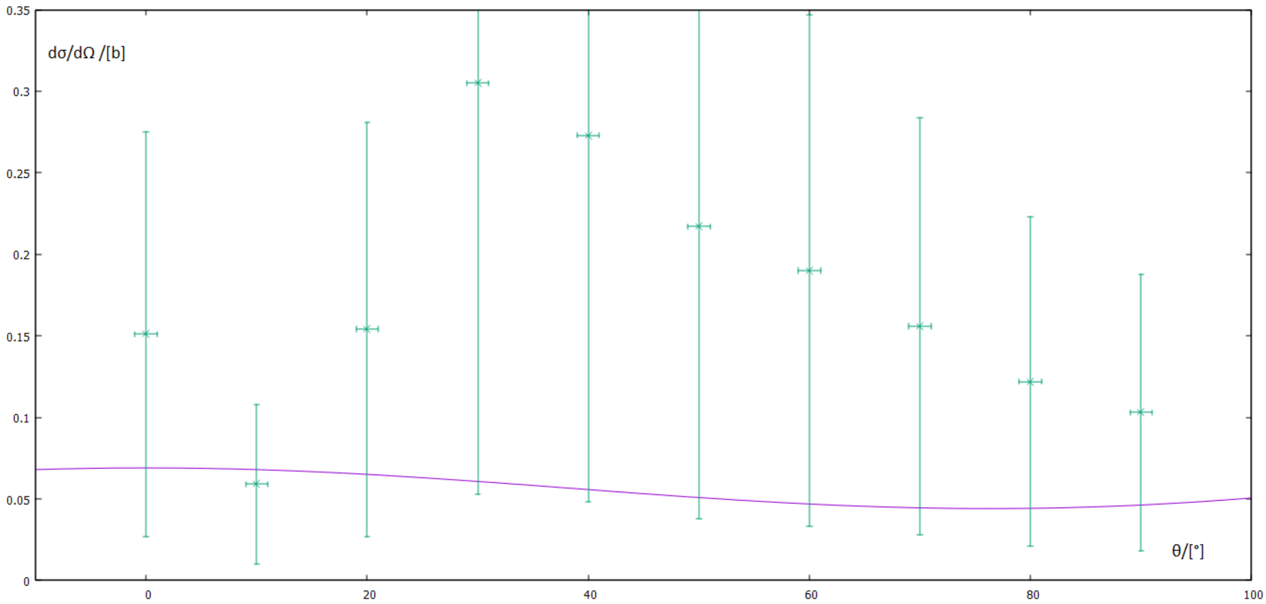

Figure 17: Differential cross section measurements and Klein-Nishina formula.

4 Conclusion

In this experiment, we were able to measure the Compton wavelength and the electron mass, determine cross section for photo effect for three different materials and roughly check Klein-Nishina cross-sectional formula.

The obtained values of the Compton wavelength gives the correct result within the limits of errors, the form of the dependence of the wavelength shift is also fully confirmed. The electron mass is close to the correct value, but the deviations are stronger than the expected error. The obtained photo effect scattering cross sections seem to be realistic based on the scale of other cross sections. Measurements of the differential scattering cross section have large deviations and large errors, strictly speaking, they do not confirm or refute the formula Klein-Nishina, being in agreement with it.

The leading mistakes were probably caused by the background noise and inaccurate estimation of the solid angles.

In particular, the accuracy could be improved by using more precise setup geometry, longer measurement times, and noise filtering techniques.

A Initial measured data

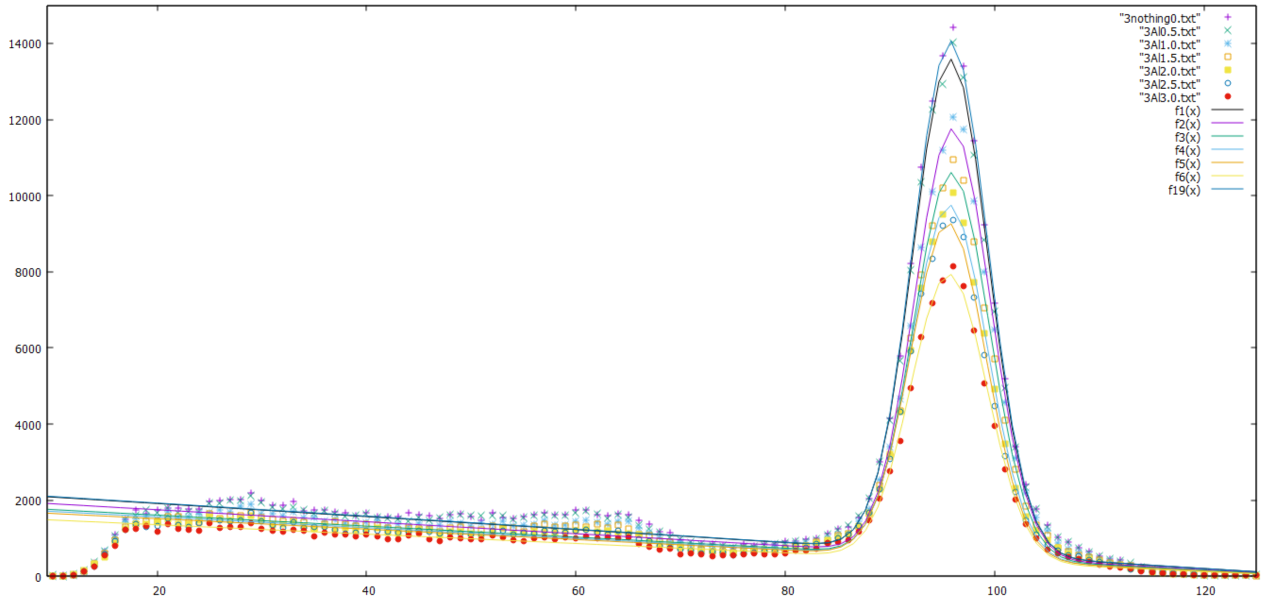

Figure 18: Spectra (countings dependence on channel) with the Al sample of various thicknesses and the fitting curves. The thickness corresponds to the name of the data file. $\Delta t = 60$s.

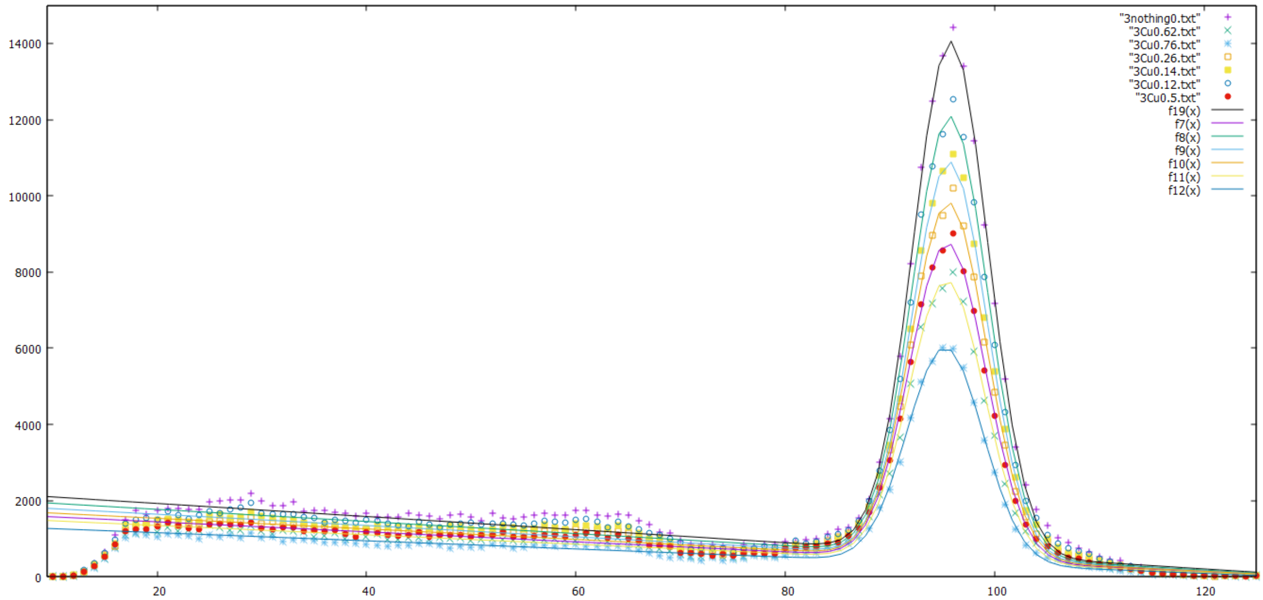

Figure 19: Spectra (countings dependence on channel) with the Cu sample of various thicknesses and the fitting curves. The thickness corresponds to the name of the data file. $\Delta t = 60$s.

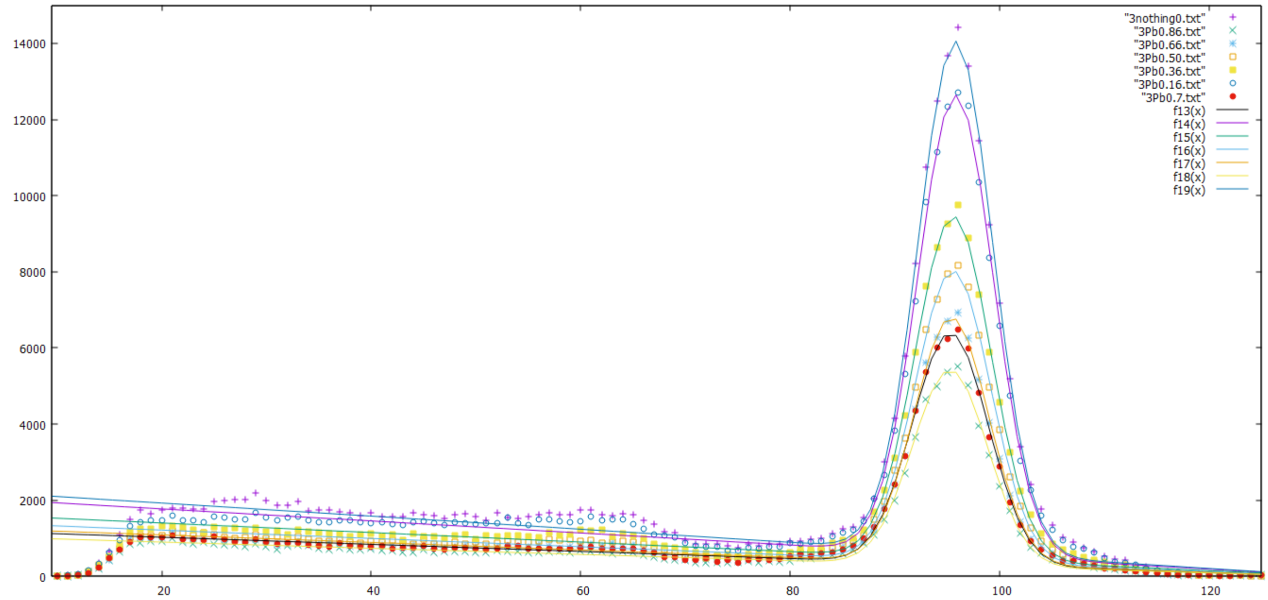

Figure 20: Spectra (countings dependence on channel) with the Pb sample of various thicknesses and the fitting curves. The thickness corresponds to the name of the data file. $\Delta t = 60\text{s}$.

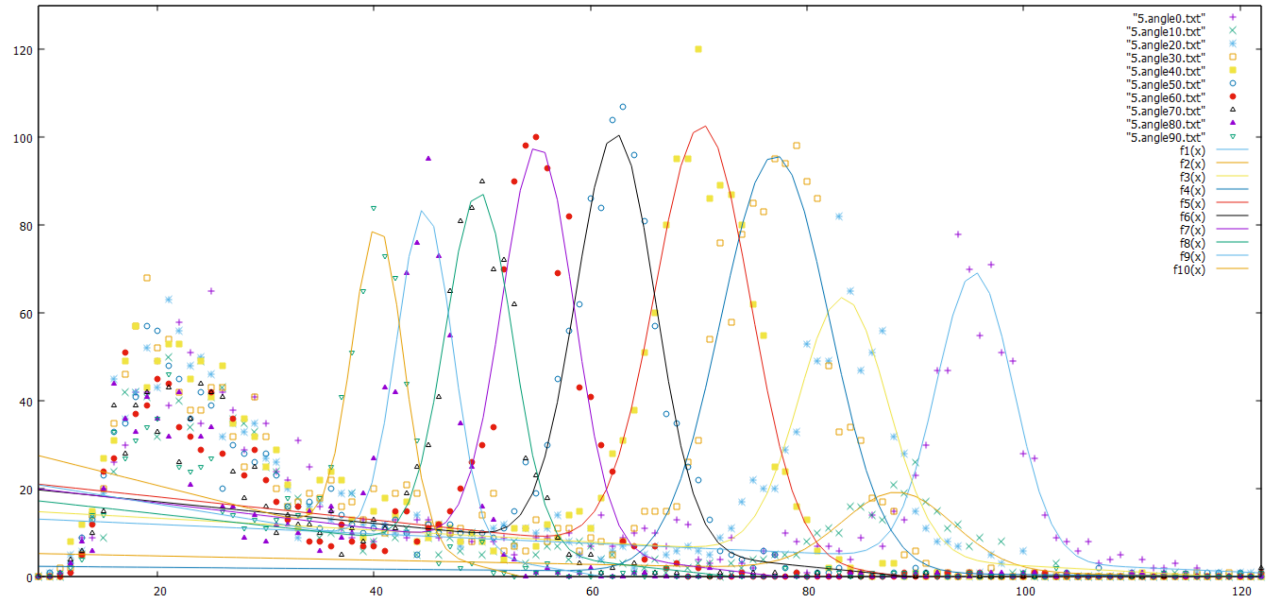

Figure 21: Spectra (countings dependence on channel) of various angles of the scattering and the fitting curves. The angles corresponds to the name of the data file. $\Delta t = 500\text{s}$.

B Signals from electronics

Figure 22: Signal from the detector output.

Figure 23: Logical signal from the discriminator and the referral signal. This corresponds to low energy photon.

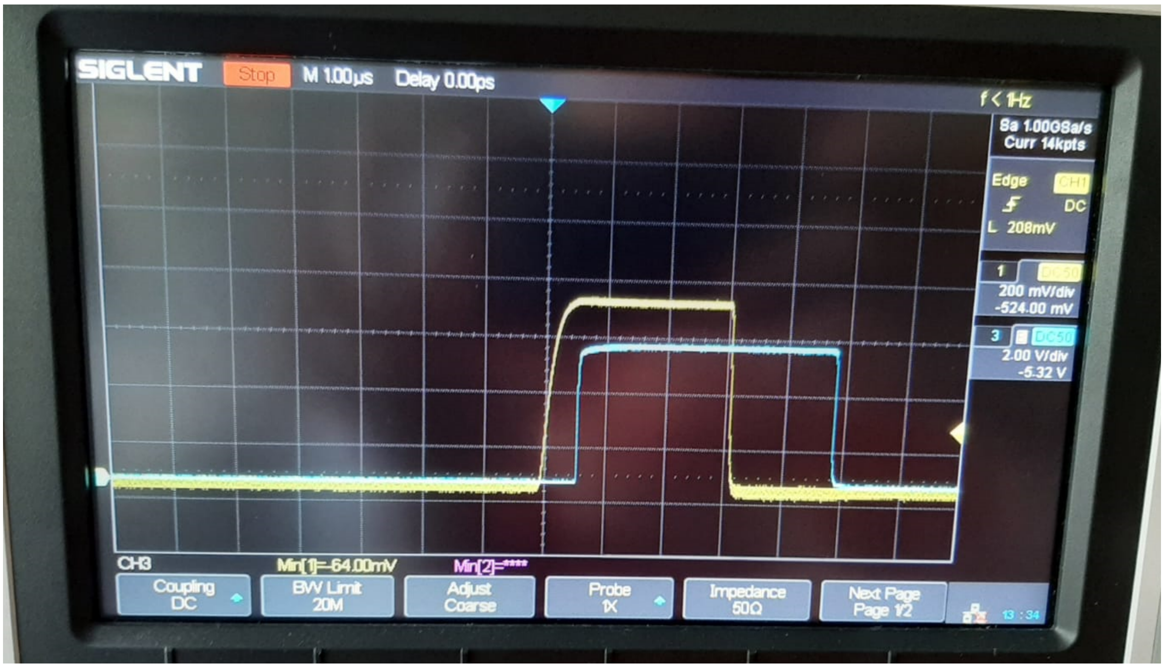

Figure 24: Logical signal from the discriminator and the referral signal. This corresponds to high energy photon.

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