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# Compton effect

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on the basis of PhD Przemysław Duda work

1. Objective ........................................ 2
2. Physical basis........................ **Błąd! Nie zdefiniowano zakładki.**
Introduction........................................ 2
Probability of occuring Compton effect ........................ 3
Relationship between gamma ray photon energy and scattering angle ........ 5
3. Experiment ........................................ 7
4. Addition: measurements conditions, equipment settings ........................ 9
5. Bibliography ........................................ 9

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## 1. Objective

The objectives of this exercise is to study the Compton effect by simulating and measuring angular distributions of intensity and energy of dispersed gamma rays.

## 2. Theory

### Introduction

The change in the X-ray wavelength that occurs as a result of elastic scattering on electrons is known as Compton's effect. A. H. Compton conducted an experiment in which he directed a beam of X-rays with a precisely defined wavelength to a graphite block and then measured the intensity of X-rays for different scattering angles, as a function of their wavelength. The diagram of the experiment and the results obtained is presented in Figure 1.

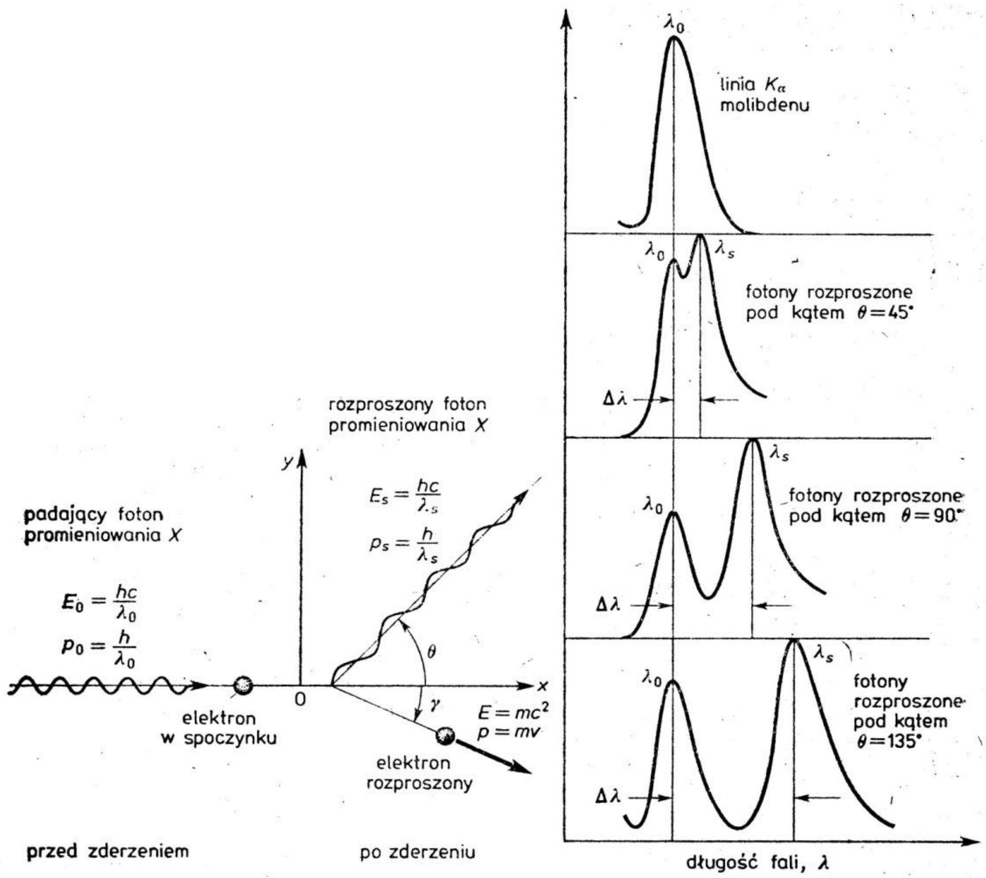


**Figure 1.** Compton scattering of the photon at free electron. The graphs on the right show how the length of Kα radiation of molybdenum dispersed on coal changes.

Although the incident beam contained one wavelength, $\lambda_0$, the scattered X-rays have a maximum of scattering at two wavelengths: initial $\lambda_0$ and additional wavelength $\lambda_s$, the value of which is close to $\lambda_0$. Secondary X-rays generated in the scattering process have the following properties:

- $\lambda_s$ is always greater than$\lambda_0$;
- $\lambda_s$ depends on the scattering angle θ, but does not depend on the scattering center.

At that time, within the theory of waves, the mechanism of light scattering was considered as follows: a light wave falls on the electron, stimulating it to vibrate, the electron then vibrates and radiates a wave of the same frequency. This model was in line with the experiments with light waves - low frequency waves. For X and γ rays, however, it turned out to be insufficient - if the incident radiation is to be treated as an electromagnetic wave, it is not possible to understand the occurrence of a scattered wave.

A. H. Compton proposed in 1923 a bold hypothesis that the incident beam of X rays is not a wave, but a set of photons with energy E = hf, which are subject to elastic collisions with the free (weakly bound) electrons of the medium. The incident photon transfers some of its energy to the electron it collides with, so the photon scattered has an energy lower than the incident, and thus a lower frequency and a longer wavelength. The peak in the recorded spectrum corresponding to the unchanged wavelength comes from the collision of photons with electrons bound to the cores of carbon atoms (their effective mass is so large that the Compton shift is unobservable to them).

The Compton experiment was one of the first experiments to show the quantum nature of light. He confirmed the existence of a photon as a finite portion of energy. Compton was in 1927 for his work honored with the Nobel Prize.

The Compton phenomenon plays a fundamental role in the process of weakening γ rays in the energy range from 0,5 MeV to 10 MeV [1].

**Probability of occuring Compton effect**

As a result of Compton effect, the energy carried by the γ-ray beam is partially converted into the kinetic energy of the electrons and partly dispersed (the part taken by the photons). The ratio of these parts depends on the energy of the primary quanta. Thus, the total loss of energy of the γ-ray beam passing through the absorbent equals the sum of energy absorbed by the electrons and dispersed.

The total cross-section for Compton effect on the electron $\sigma_c$ equals the sum of the cross-section for absorption $\sigma_{abs}$ and for the dissipation of energy.

$$\sigma_{\mathrm{c}} = \sigma_{\mathrm{abs}} + \sigma_{\mathrm{rozpr}} \tag{1}$$

The cross-section for the electron equals the number of the part of the particle beam which caused the occurrence of a given phenomenon when the beam passes through a disc with a unit surface in which there is one electron. Fig. 2. shows the dependence of $\sigma_c$, $\sigma_{abs}$ and $\sigma_{rozpr}$ on the energy of the primary quantum.

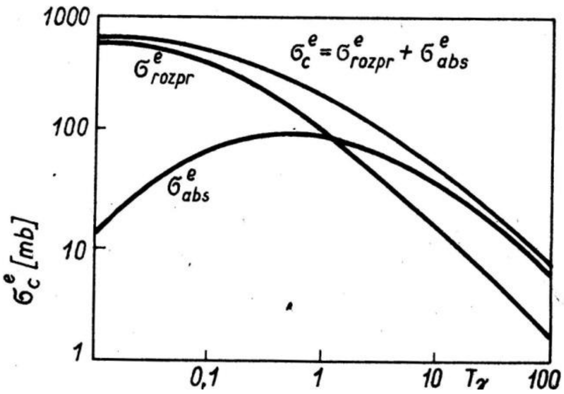


**Figure 2.** Dependence of cross-sections on the electron for the Compton effect on the energy of the original quantum γ [1].

- $\sigma_C^e$ - total cross-section for the Compton effect,
- $\sigma_{abs}^e$ - cross-section on the electron for energy absorption in the Compton effect,
- $\sigma_{rozpr}^e$ - cross-section on the electron for dissipation of energy in the Compton effect.

Differential cross-section for scattering quantum γ on electron was derived based on quantum mechanics by Klein and Nishina (1928):

$$\mathrm{d\sigma} = \frac{\mathrm{r}_0^3}{2}\left(\frac{\mathrm{f}}{\mathrm{f}_0}\right)^2\left(\frac{\mathrm{f}_0}{\mathrm{f}} + \frac{\mathrm{f}}{\mathrm{f}_0} - \sin^2\varphi\right)\mathrm{d\Omega} \tag{2}$$

gdzie:

- $r_0 = 2{,}28 \cdot 10^{-13} cm$ – classical electron radius,
- $f_0$ – frequency of primary $\gamma$ rays,
- $f$ – frequency of scattered $\gamma$ rays, depending on staterigng angle $\varphi$.
- $d\sigma$ – differential cross-section equals the probability of the fact that when the quantum γ passes through the absorbent containing 1 electron to 1 $cm^2$, the solid angle element $d\Omega$ will be scattered at an angle $\varphi$ with respect to the primary direction.

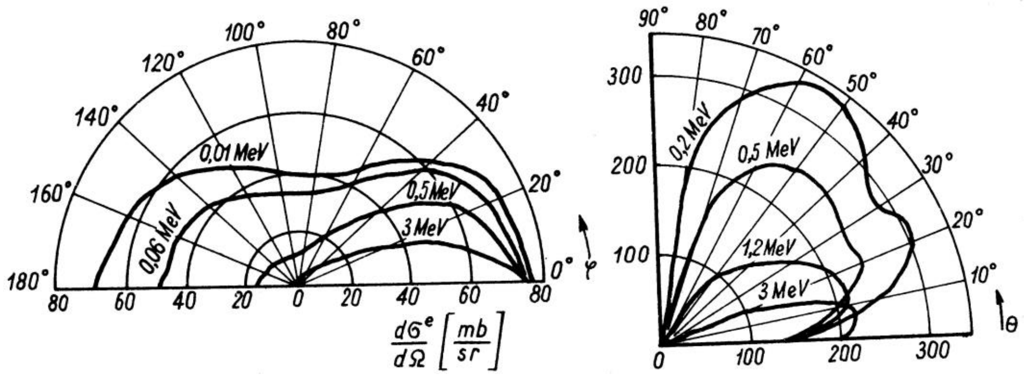


**Figure 3.** Left panel: polar differential cross-sections shown for the Compton effect. It can be seen that with the increase of primary quantum energy, the number of quanta scattered at small angles increases. Right panel: angular distribution of recoil electrons in the Compton effect for different primary quantum energies. Source [1].

The differential electron cross-section calculated on the basis of equation (2), which we do not include here, is quite complicated (see [1], p. 65).

### Relationship between gamma ray photon energy and scattering angle

Photon energy (particles with a rest mass equal to zero) is $E = pc$, on the other hand it is known that photon energy can be written as $E = hf$, where $f$ is the frequency. Thus, the photon's momentum is equal to:

$$p = \frac{hf}{c} = \frac{h}{\lambda} \quad (3)$$

The energy of quantum scattered as a result of Compton depends on the angle of scattering is expressed by the following formula:

$$\mathrm{E_{k'}} = \frac{\mathrm{E_k}}{1+\frac{\mathrm{E_k}}{m_e c^2}(1-\cos\theta)} \quad (4)$$

where $\mathrm{E_k}$ i $\mathrm{E_{k'}}$ mean energy of incident and scattered radiation.

With a given quantum energy hitting the diffuser, there is an unambiguous relationship between the energy of the scattered quanta and the angle of their propagation θ. In turn, the principle of energy conservation requires that the sum of the scattered quantum energy and the recoil electron be equal to the quantum energy of the incidenting one. In implies that if the radiation source emits monoenergetic γ quanta, then the coincidences registered at a given angle θ correspond to the recoiled electrons of the same energy. If the radiation source emits several monoenergetic quantum groups, the spectrum of the electrons of the recoil should contain maxima, each corresponding to a different energy of the falling quanta. Knowing the energies of recoil electrons, which coincide with quantum scattered at an angle θ, one can determine the energies of dissipated quanta.

Figure 4 presents cross sections for gamma and electrons obtained using an applet simulating the Compton effect.

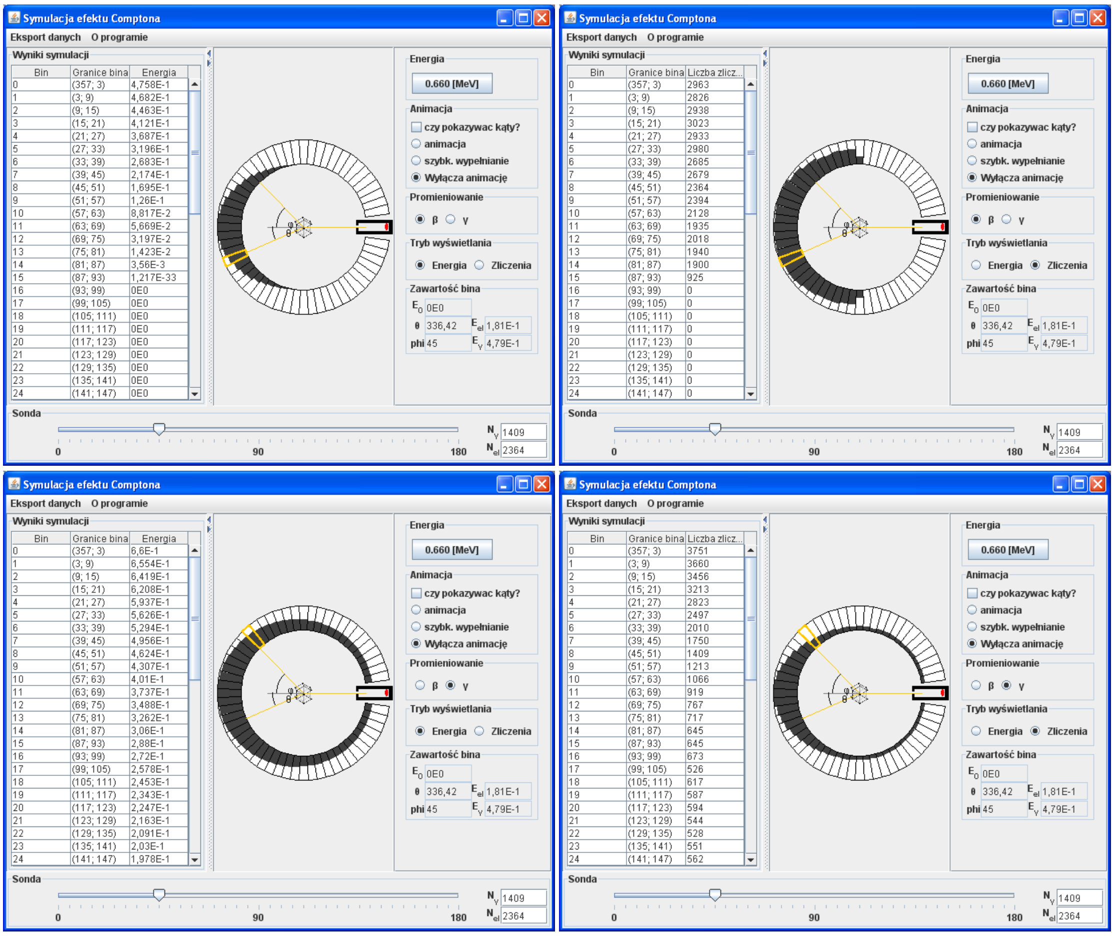

**Figure 4.** Results of simulations of angular energy distributions (left) and cross-section (right side) as a result of Compton interaction for 45 ° angle. The upper part of the drawing refers to recoiled electrons, lower part – scattered gamma.

## 3. Experiment

The purpose of this exercise is to measure angular distributions of scattered quanta emitted from a source with energy of incident radiation of approx. 662 keV.

The task will be to determine the spectra for a number of angles θ. The positions of the maxima in these spectra will allow to determine the energies of the quanta scattered at appropriate angles.

<u>Instrumentation used in the exercise to collect individual spectra (Figure 5):</u>

1. NIM-BIN cassette (62,2,24 V), 230 VAC (model 2100-2, 150W 12 NIM positions)
2. NaI (Tl) detector, 2 "x2" (model 802-2x2) - 2 pieces
3. Preamplifier for scintillation detectors (model 2007) - 2 pieces
4. Advanced spectrometric amplifier (model 2026, shaping of the triangle/Gauss; PUR/LTC)
5. Dual (independent) high voltage power supply 0-5 kV, supplying the photomultiplier in a scintillation counter (model 3125) - the system detecting the rising edge of the peak and sending the signal to the converter, is controlled by the coincidence system
6. Coincident analyzer (model 2040) - coincidence detection system
7. Multichannel 2-track pulse amplitude analyzer (model MP2-2E MultiPort II, Ether-net and USB, 2 inputs) containing 2 independent 16K ADC work in PHA and MCS modes dual NIM module, 14-bit (11 bit in the experiment - the energy range is divided into 2048 channels)
8. Spectrometer software (Genie-2000 Basic Spectroscopy - Multi Input)

In addition, there is a mechanism for setting the probe angle: the system includes a multi-turn potentiometer, stepper motor and control system via RS232, and application software (diesIrae.exe) enabling communication with the amplitude analyzer through batch and C / C ++ programs.

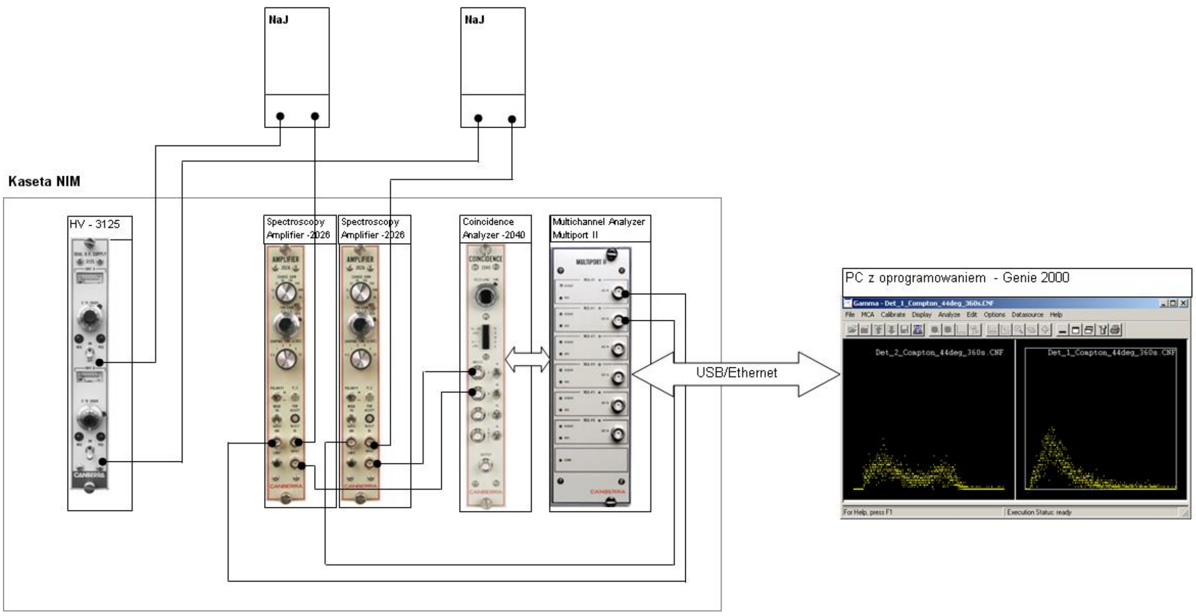


**Figure 5.** The measuring equipment allows the collection of individual spectra.

Measurements are made with two movable and immobile NaI scintillation detectors (see Figures 6 and 7).

Compton electrons created in a scintillator (element 3 in Fig. 6) generate flashes (scintillations) and are recorded by a photomultiplier, while scattered γ rays with high probability can leave the scintillator. The second, mobile probe (element 2 in Figure 6) has the task of registering these quanta. Both probes work in coincidence. The simultaneous appearance of impulses at the outputs of both detectors with a high level of confidence allows coincidence to be considered an act associated with the Compton effect. The use of coincidence technology significantly reduces the background of measurements.

<u>The idea of measurements in coincidence</u>

Their essence is to register only simultaneously (in practice at an interval less than the coincidence time) impulses appearing on both detectors: impulse on a immobile scintillator derived from the Compton electron and impulse on a moving scintillator from the scattered quantum γ.

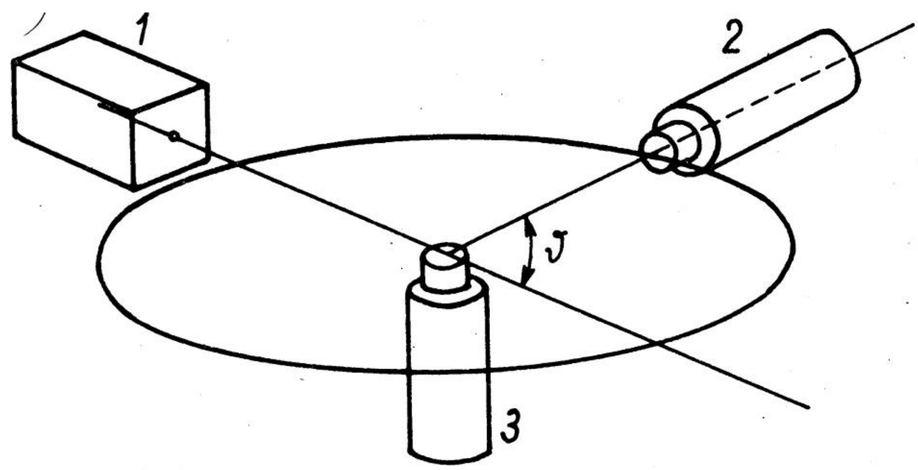


**Figure 6.** Measurement geometry: 1 - container with a radiation source and collimator, 2 - mobile probe, 3 - fixed probe [1].

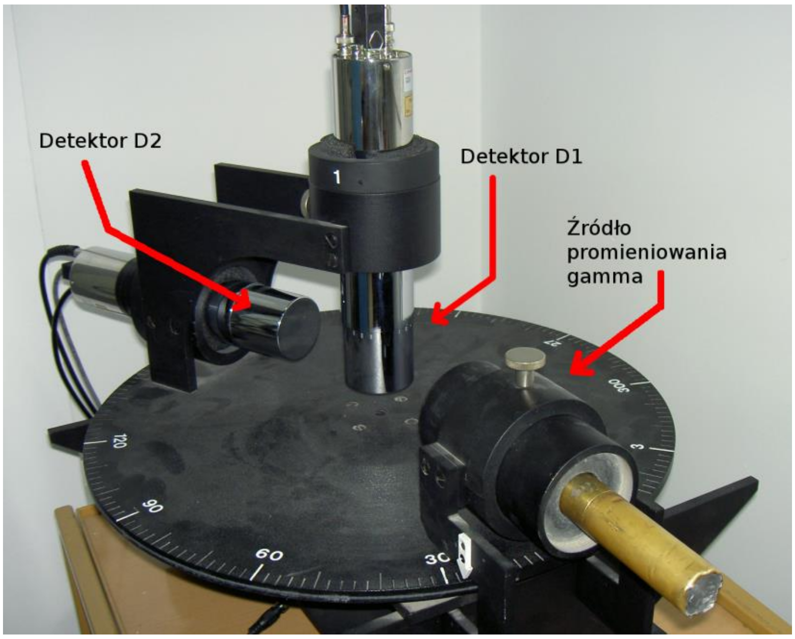


**Figure 7.** Photography of the mechanical part of the system together with detectors [2]. In the D1 detector the Compton effect occurs, the scattered quantum gamma leaves the detector, while the electron will be registered by the scintillation counter. Detector D2 can be rotated around the detector D1. The detectors work in a coincidence system.

Signals from both scintillation counters go to the inputs of spectrometer amplifiers. Each amplifier has two outputs: analogue and digital.

The amplifier identifies the pulse coming from the scintillator based on the shape of impulse. If the impulse is identified as coming from the desired phenomenon, the signal is processed further. Through the digital input to the coincidence detector there is a signal that scintillation has been observed in a given detector. At the same time, the amplifiers increase the amplitudes of the recorded peaks and give them a more favorable shape for further processing, and then the signals (analogue) are connected to the Multiport A/D converter.

In the coincidence detector a decision is made whether coincidence occurred or not - the difference in time between occurrences of peaks on both detectors must be within the range called coincidence time. If the coincidence has occurred, information about this is sent to the A/D converter and analog signals from the amplifiers are processed. The signal from the A/D converter is sent to a PC computer. The collected data are analyzed using dedicated software

Performing measurements

The measuring equipment is operated using dedicated software (application dieslrae.exe) available at the measurement stand.

Measurements with isotope $^{137}Cs$ should be performed at angles $\theta$: $45°$, $60°$, $90°$, $120°$, $135°$. For technical reasons, when changing the position of the mobile probe, enter negative angles.

## 4. Addition: measurements conditions, equipment settings

- Energy of γ rays of the source used (Cs-137, activity $100\ \mu Ci$): 662 keV.
- The coincidence time during measurements is set to range (0,5 – 5) $\mu s$.
- Photomultiplier power supply: 1 kV.
- Electron bond energy on which quanta are scattered ~2 eV.

## 5. Bibliography

**[1]** Janusz Araminowicz, Krystyna Małuszyńska, Marian Przytuła; „Laboratorium Fizyki Jądrowej"; Warszawa 1978, PWN

**[2]** Jacek Bzdak; Oprogramowanie ćwiczenia „Badanie efektu Comptona" – praca inżynierska wykonana pod kierunkiem dr. P. Dudy; Warszawa 2009