FINAL REPORT ON THE INTEREST PROGRAM

Soft photon study in nuclear and hadron interactions

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1 Introduction

For over 30 years there has been no comprehensive understanding of the mechanism of soft photons formation. Soft photons (SPh) are the direct products of high energy interactions. They are not decay products of secondary particles and their energy is smaller than 50MeV.

Experimental data indicate an excess of their yield in hadron and nuclear interactions. The existing theoretical calculations based on the quantum electrodynamics cannot predict and explain this excess. For a more thorough study of this phenomenon the building of the future accelerator complex NICA makes possible to carry out such studies in different interactions. [1]

Up to now the nature of SPh remains enigmatic. Apparently, they are formed in the region of non perturbative quantum chromodynamics and physicists build phenomenological models. The most successful model is based on the hypothesis of the cold quark-gluon plasma (QGP) formation. This model implies the formation of a quark-gluon system which consists of a few quarks, antiquarks and gluons (about 40 partons). These partons are encountering each other and reradiate soft photons because they do not have enough energy to produce hadrons, the main reactions being Compton scattering and pair annihilation. [2]

2 Project goals

- Getting accustomed to Geant4 packet and CERN Root open-source data analysis framework
- Data taking and data processing for different simulations
- Study of the operation of electromagnetic calorimeters of homogeneous and heterogeneous ('spaghetti') types

3 Interaction of radiation with matter

Particles can be detected only through their interactions with matter. There are specific interactions for charged particles which are different from those of neutral particles, such as photons. Every interaction process can be used as a basis for a detector concept. The main interactions of charged particles with matter are ionisation and excitation. For relativistic particles, *bremsstrahlung* - if the charged particles are decelerated in the Coulomb field of the nucleus, a fraction of their kinetic energy will be emitted in form of photons - energy losses must also be considered. Neutral particles must produce charged particles in an interaction that are then detected via their characteristic interaction processes. In the case of photons, these processes are the photoelectric effect, Compton scattering and pair production of electrons. The electrons produced in these photon interactions can be observed through their ionisation in the sensitive volume of the detector.

3.1 Radiation length (X_0)

It is a characteristic of a material related to the energy loss of high energy particles electromagnetically interacting with it.

$$X_0 = \frac{716.4 \cdot A[\text{ g/mol}]}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}} \text{ g/cm}^2 \tag{1}$$

The radiation length for a mixture of elements or a compound can be approximated by

$$X_0 = \frac{1}{\sum_{i=1}^{N} \frac{f_i}{X_0^i}}, \tag{2}$$

where f_i are the mass fractions of the components with the radiation length X_0^i.
The mass fraction can be calculated using the following formula

$$f_i = \frac{A_i v_i}{\sum_{i=1}^{N} A_k v_k}, \tag{3}$$

Where
A is atomic mass in g/mole
v is valence of atom in molecule

In order to obtain the radiation length expressed in cm we have to divide it by the density ρ of the considered material.

3.2 Critical energy (E_c)

Energy losses due to *bremsstrahlung* are proportional to the energy while ionisation energy losses beyond the minimum of ionisation are proportional to the logarithm of the energy. The energy, where these two interaction processes for electrons lead to equal energy losses, is called the critical energy E_c.

$$E_{\mathrm{c}} = \frac{610\mathrm{MeV}}{Z + 1.24} \tag{4}$$

In the case of compound systems, the critical energy can be calculated using the following formula,

$$E_{\mathrm{c}} = \frac{550\mathrm{MeV}}{Z_{eff}} \tag{5}$$

where Z_{eff} is given by,

$$Z_{eff} = \frac{\sum_{i=1}^{N} Z_i f_i}{\sum_{i=1}^{N} f_i} \tag{6}$$

3.3 Molière radius (R_M)

The lateral width of an electromagnetic cascade is mainly determined by multiple scattering and can be best characterised by the Molière radius. [3]

$$R_{\mathrm{M}} = \frac{21\mathrm{MeV}}{E_{\mathrm{c}}} X_0 \tag{7}$$

4 Calorimetry

Calorimetric methods imply total absorption of the particle energy in a bulk of material followed by the measurement of the deposited energy. High-energy photons, electrons and hadrons can interact with media producing secondary particles which leads to a shower development. Then the particle energy is deposited in the material much more efficiently. Thus calorimeters are most widely used in high energy physics to detect the electromagnetic and hadronic showers. Accordingly, such detector systems are referred to as electromagnetic and hadron calorimeters.

5 Electromagnetic calorimeters

The dominating interaction processes for spectroscopy in the MeV energy range are the photoelectric and Compton effect for photons and ionisation and excitation for charged particles. At high energies, electrons lose their energy almost exclusively by *bremsstrahlung* while photons lose their energy by electron-positron pair production. The most important properties of electron cascades can be understood using a simplified model. Let E_0 be the energy of a photon incident on a bulk material. After one radiation length the photon produces an e^+e^-pair; electrons and positrons emit after another radiation length one *bremsstrahlung* photon each, which again are transformed into electron-positron pairs. When the particle energy falls below the critical value E_c, absorption processes like ionisation for electrons and Compton and photoelectric effects for photons start to dominate. At this step of multiplication, the position of the shower maximum is reached.

This very simple model describes correctly the most important qualitative characteristics of electromagnetic cascades:

a) To absorb most of the energy of the incident photon the total calorimeter thickness should be more than $10 - 15X_0$

b) The position of the shower maximum increases slowly with energy. Thus, the thickness of the calorimeter should increase as the logarithm of the energy

c) The energy leakage is caused mostly by soft photons escaping the calorimeter at the sides (lateral leakage) or at the back (rear leakage)

In reality the shower development is much more complicated, an accurate description of the shower development being a difficult task. However, due to the increase of the computer capacity, an accurate description is obtained from Monte Carlo simulations.

5.1 Homogeneous calorimeters

Homogeneous calorimeters are constructed from a material combining the properties of an absorber and a detector. It means that practically the total volume of the calorimeter is sensitive to the deposited energy. These calorimeters are based on the measurement of the scintillation light (scintillation crystals, liquid noble gases), ionisation (liquid noble gases) and the Cherenkov light (lead glass or heavy transparent crystals).

The main parameters of electromagnetic calorimeters are the energy and position resolution for photons and electrons. The energy resolution $\frac{\sigma_E}{E}$ is determined both by physical factors like the fluctuation of the energy leakage or photoelectron statistics and technical ones like nonuniformity of crystals.

5.2 Sampling calorimeters

A sampling calorimeter is a calorimeter designed as an array of thin counters separated by layers of absorbers and only a sample of the energy deposition is measured. As sensitive elements of sampling calorimeters are used: gas-filled chambers, liquid-argon ionisation detectors, 'warm' liquids and scintillators.

A normal sampling calorimeter of absorber plates and scintillator sheets can also be read out by wavelength-shifter rods or fibres running through the scintillator plates perpendicularly. The technique of wavelength-shifter readout allows to build rather compact calorimeters. The scintillation counters used in calorimeters must not necessarily have the form of plates alternating with absorber layers, they can also be embedded as scintillating fibres. They can either be read out directly or via light-guide fibres by photomultipliers ('spaghetti' calorimeter). [3][4] This type of calorimeter provides both high energy resolution and precise timing for photons due to the short decay time of the light flash of the plastic scintillator. The spaghetti concept also eliminates what is considered one of the main disadvantages of sandwich scintillator calorimeters, namely the poor position resolution. The fibre concept essentially allows one to choose any granularity one likes (and can afford), since one is free to connect any number of fibres to a readout element. Other major advantages are obtained if the fibres are running longitudinally, i.e. roughly in the direction of the particles that have to be detected. For example, one avoids in this way the dead space taken by WLS bars and module covers in a sandwich structure. Also, one can avoid the lateral inhomogeneities in light. The energy resolution $\sigma E/E$ is determined both by physical factors like the fluctuation of the energy leakage or photoelectron statistics and technical ones like nonuniformity of crystals. For all calorimeter types the common contribution to the energy resolution originates from fluctuations of the energy leakage and from fluctuations of the first interaction point. The energy resolution can be expressed as

$$\sigma_{int}^2 = \sigma_1^2 + \sigma_r^2 + \sigma_l^2 + \sigma_b^2 \tag{8}$$

where σ_1 is determined by the fluctuations of the point of the first interaction, σ_r is the rear leakage, σ_l the lateral leakage and σ_b the leakage due to albedo fluctuations. The energy leakage is mostly due to low-energy (1–10 MeV) photons. The albedo is usually quite small (¡ 1% of the initial energy) and the induced contribution to the energy resolution is negligible. Based on partial deviations's depencies of energy, energy resolution of the CMS electromagnetic calorimeter can be approximated as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \tag{9}$$

where a stands for photoelectron statistics (sometimes called stochastic term), b for the electronics noise, and c appears due to the calibration uncertainty and crystal non-uniformity. All calculated energy resolutions were fitted to this formula. [4][5]

6 Detector construction

6.1 Homogeneous PWO calorimeter

The first crystal that is used to make calorimeter is PWO ($PbWO_4$). The main features of this crystal are high density, extremely short radiation length and small Moliere radius, allowing the realization of a homogeneous compact calorimeter with high granularity.

Element	Z	A (g/mole)	v	f	X_0 (g/cm^2)	ρ (g/cm^3)	$\tilde{X}_0$(cm)
Pb	82	207.2	1	0.455	6.31	11.35	0.556
W	74	183.9	1	0.404	6.77	19.84	0.341
O	8	16.0	4	0.141	34.46	1.141	30.202

Table 1: Properties of the component elements of PWO crystal

The mass fraction was calculated using formula (3) and the radiation length using formula (1).

The composite density of the PWO crystal is calculated using the denisties and mass fractions of the component elements and it is given by,

$$\rho^{PWO} = 8.28 \text{ g/cm}^3$$

In order to obtain the radiation length for the PWO crystal we employ formula (2) and obtain,

$$X_0^{PWO} = 0.89 \text{ cm}$$

The next step is to calculate the critical energy for the PWO crystal. Making use of the formulas (5) and (6) , we get

$$E_c^{PWO} = 7.92\text{MeV}$$

The Molière radius is computed using formula (7) and it has the following value,

$$R_M^{PWO} = 2.36 \text{ cm}$$

All the above calculations were used in simulating a homogeneous calorimeter based on a PWO crystal using Geant 4. The dimensions of crystal were 57x57x100 mm. The energies between 10 and 100 MeV with step of 10 MeV were assigned to 2000 gamma particles and standard deviations of fitted gaussian curve were calculated.

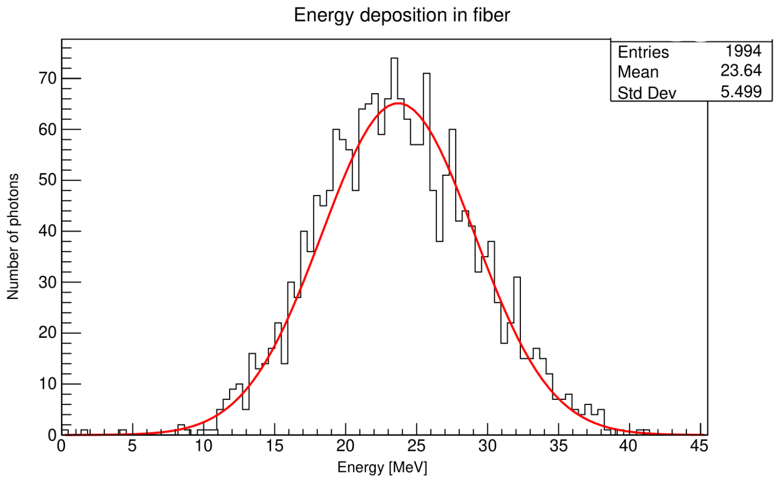

Figure 1: Energy deposition in fiber of homogeneous PWO calorimeter for beam energy E=50 MeV

Energy resolution of fitted gaussian for E=50 MeV is

$$\left(\frac{\sigma_E}{E}\right)_{PWO} = 10.72\%$$

6.2 Spaghetti PWO/WCu calorimeter

Spaghetti calorimeter was made by using previosly described PWO crystal as scintillator and 50%W-50%Cu composite as absorber. Fibers made of PWO were placed in WCu crystal in 11x11 grid. Dimensions of each fiber were 3x3x100 mm. Properties of WCu absorber were analysed in Table 2.

Element	Z	A(g/mole)	ρ (g/cm^3)	X_0 cm
W	74	183.84	19.30	0.35
Cu	29	63.55	9.96	1.44

Table 2: Properties of W and Cu

The radiation length for the W/Cu composite is given by

$$X_0^{W/Cu} = 0.8 \text{ cm}$$

and the density is

$$\rho^{W/Cu} = 11.19 \text{ g/cm}^3$$

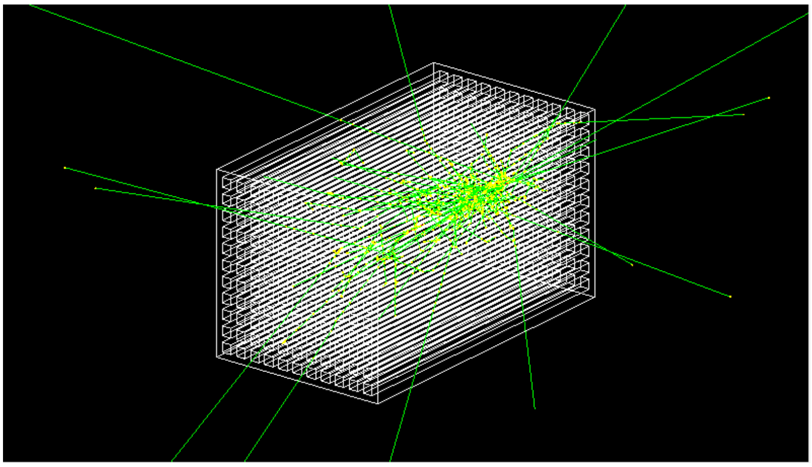

Figure 2: Graphic enviroment of 'spaghetti' calorimeter in GEANT4 program

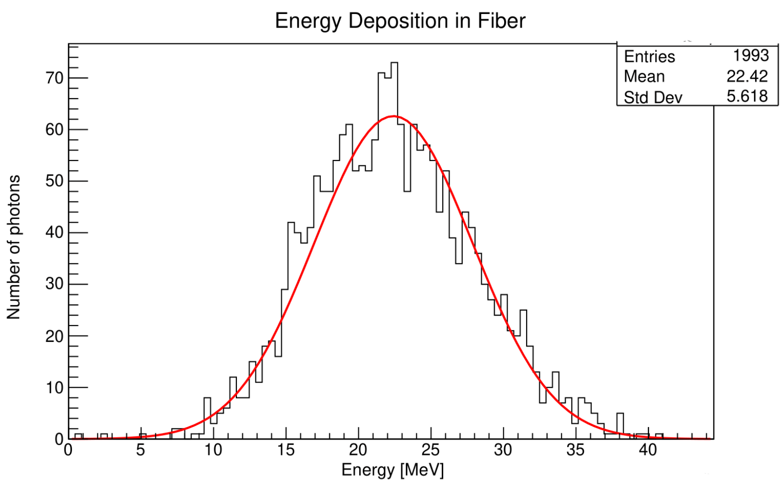

Figure 3: Energy deposition in fiber of PWO/WCu calorimeter for beam energy E=50 MeV

Energy resolution of fitted gaussian for E=50 MeV is

$$\left(\frac{\sigma_E}{E}\right)_{PWO} = 10.92\%$$

In figure 4, energy resolutions for energies between 10 and 100 MeV for PWO and PWO/WCu were shown. For energies under 50 MeV (where soft photons are dominant), spaghetti calorimeter is showing better resolution than homogeneous. This effect can be explained by bigger critical energy of spaghetti calorimeter due to existance of absorber. For bigger energies, homogeneous PWO crystal is showing slightly better performances (Figure 5).

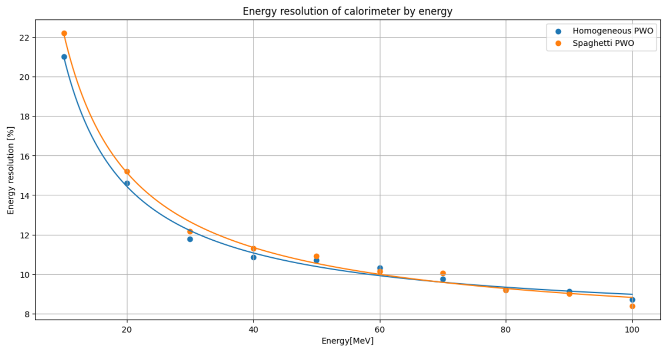

Figure 4: Energy resolution by energy for PWO and 'spaghetti' PWO/WCu crystal (10-100 MeV)

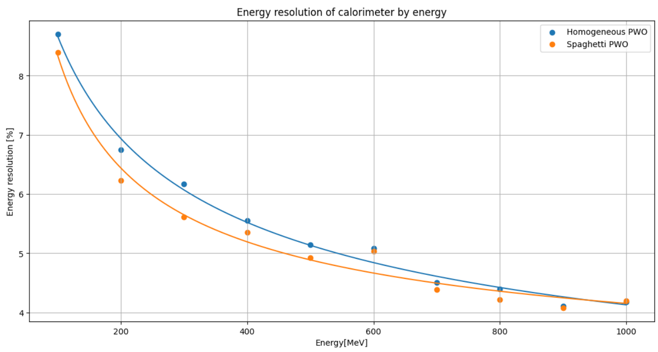

Figure 5: Energy resolution by energy for PWO and 'spaghetti' PWO/WCu crystal (100-1000 MeV)

6.3 Spaghetti NaI calorimeter

Sodium iodide (NaI) is a low-density and low-Z scintillator sensitive to low- and intermediate-energy gamma radiation with mild sensitivity to high-energy beta radiation. Many gamma-ray spectrometry applications use sodium iodide, and, due to its high radiopurity, it is attractive for dark matter research applications. Sodium iodide can be grown in various forms and sizes which makes it less costly to produce. It also exhibits high light output at short wavelengths, which means it is easily matched with various photomultiplier tubes. Since it can be grown in larger formats, it also offers good resolution and efficiency. Undoped sodium iodide has a smaller decay constant compared to doped sodium iodide, which makes it attractive for fast imaging applications. It is an alkali-metal halide that is hygroscopic and must be hermetically sealed to prevent deterioration. It is also susceptible to radiation and ultraviolet damage. [6] Properties of components of NaI are given in Table 3.

Element	Z	A(g/mole)	ρ (g/cm^3)	X_0 cm
Na	11	23.0	0.968	28.9
I	53	126.9	4.933	1.752

Table 3: Properties of Na and I

Density of NaI composite is calculated using the densities and mass franctions,

$$\rho^{NaI} = 3.67 \text{ g/cm}^3$$

For the NaI composite we calculate the radiation length using formula (2) and obtain,

$$X_0^{NaI} = 2.59 \text{ cm}$$

The next step is to calculate the critical energy for the NaI crystal. Making use of the formulas (5) and (6), we get

$$E_c^{NaI} = 11.81\text{MeV}$$

The Molière radius is computed using formula (7) and it has the following value,

$$R_M^{NaI} = 16.9 \text{ cm}$$

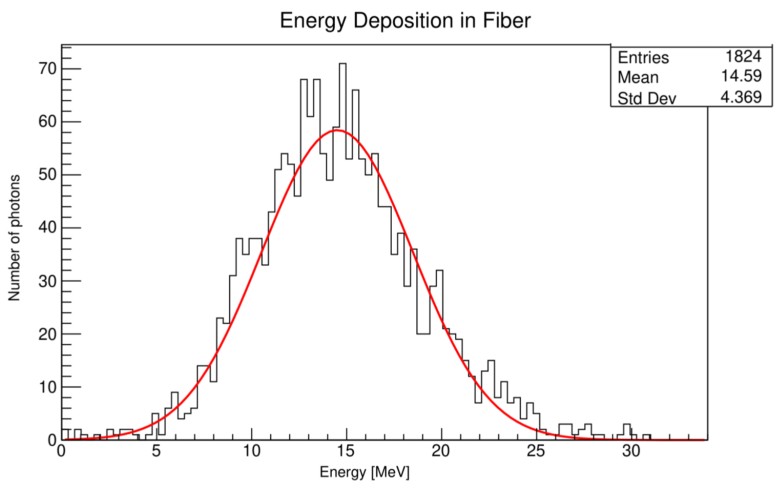

Figure 6: Energy deposition in fiber of NaI calorimeter for beam energy E=50 MeV

Energy resolution of fitted gaussian for E=50 MeV is

$$\left(\frac{\sigma_E}{E}\right)_{NaI} = 7.96\%$$

Firstly, the crystal was implemented as fiber material with WCu absorber and thickness of crystal $Z = 100mm$. Due to larger value of radiation length than PWO crystal, lesser energy resolution is expected. The condition of minimal thickness of crystal of $10X_0$ is not met and in Figure 6 we can see that only 91% of photons is absorbed. Therefore, thickness of crystal was extended to 250mm (approximately $10X_0$) and the measurings are shown in Figure 8.

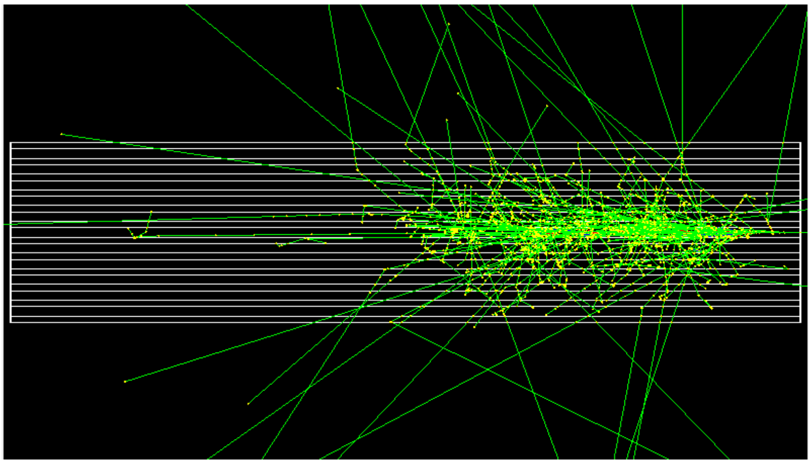

Figure 7: Graphic environment of long crystal in GEANT4

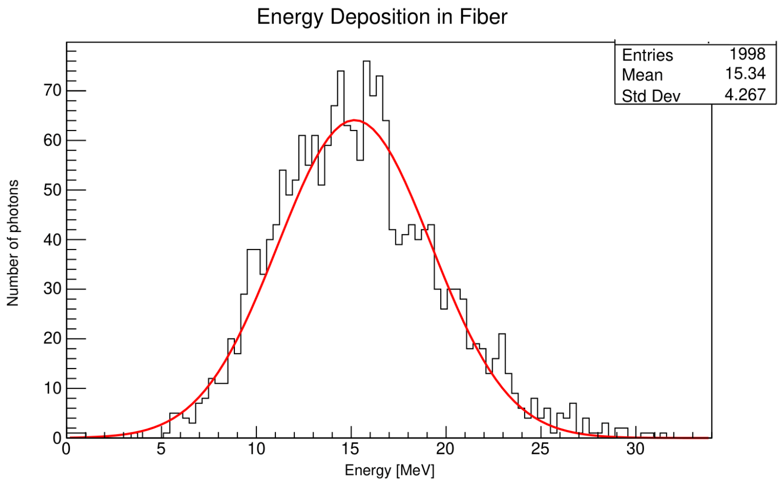

Figure 8: Energy deposition in fiber of long NaI calorimeter for beam energy E=50 MeV

Energy resolution of fitted gaussian for E=50 MeV is

$$\left(\frac{\sigma_E}{E}\right)_{NaI} = 8.1\%$$

In Figure 9, energy resolutions are compared between short and long NaI crystal. It can be seen that there is not much difference between values of resolution, but the number of photons is 10% bigger in case of long crystal, which makes it more accurate measurement.

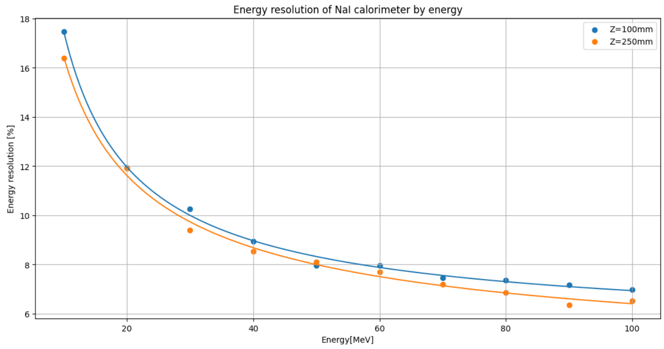

Figure 9: Energy resolution by energy for short and long NaI (10-100 MeV)

7 Conclusions

In our study we constructed three different types of calorimeteres: a homogeneous one based on a PWO crystal, a 'spaghetti' sampling calorimeter having as a fiber material PWO crystal scintillator and as an absorber WCu and a 'spaghetti' sampling calorimeter having as a fiber material NaI crystal and as an absorber WCu. By calculating different parameters, such as: radiation length, critical energy and Molière radius, we were able to establish the dimensions of the calorimeters in the z direction on which the photons are sent and on the transverse direction.

After performing various simulations in GEANT4, the obtained histograms were analyzed using CERN Root. We calculated for each calorimeter the energy resolution in the cases of $10 - 100$MeV photons coming in the z direction, and for PWO-based calorimeters $100 - 1000$MeV. We saw that the best energy resolution for soft photon energy range (10-50 MeV) is obtained in the 'spaghetti' PWO/WCu crystal. For NaI-based calorimeters it was discussed if short crystal was suitable for accurate measurements, but low level of photons in fibers denied it.

Our main task was to make simulations of different calorimeters and to find the optimal construction for registering soft photons. Thus, the 'spaghetti' calorimeter with NaI as a scintillator and WCu as an absorber is a good choice in the study of soft photons since it has a good energy resolution compared to a crystalline calorimeter, but it is more advantageous when we consider the price we need to pay for building the calorimeters. The NaI crystal with larger thickness would be the best solution. It can be used in future experimental studies of photon beams at the Nuclotron facility in JINR.

8 Bibliography

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9 Acknowledgments

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