JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Simulation of an electromagnetic calorimeter for the soft protons investigation

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Participation period:
July 24 - September 03

Dubna 2022

Contents

1 Absract

Despite numerous experimental confirmations of the excess of the yield of soft photons in hadron and nuclear interactions, a comprehensive theory explaining this process has not yet been developed. This suggests the need for a more detailed study of soft photons(SP). We have simulated a 'shashlik' type calorimeter, which is planned to be used to study direct SP at the NICA accelerator complex, using three different scintillator crystals: $CeBr_3$, $YAG(Ce)$, $TLC(Ce)$. The energy resolution for each of these crystals was obtained and a comparative analysis was carried out.

2 Introduction

In the past several decades, experimental studies of the direct photon production in hadronic collisions have shown an excess of soft photons (SP) over the theoretical predictions by 5-8 times. Thus, the experiment using the Big European Bubble Chamber (BEBC) and an incident radio frequency (RF) separated beam, which was perfomed in 1984, indicated the presence of an excess γ cross section (4.5 ± 0.9 mb) over the contributions arising from hadron decays. This experiment was aimed at studying the production of photons in K^+p interactions at 70 GeV/c. [1].

Moreover, an excess of SP was obtained in proton-nucleus collisions [2],[3] by Helios Collaboration and in proton-proton interactions in the CERN experiment WA102 [4].

During the 2006 – 2010 years DELPHI collaboration in CERN was investigating the reaction $e^+e^- \to Z^0 \to hadrons + direct\ soft\ \gamma$ at LEP1 [5], [6], [7]. As a result the signal amplitudes obtained were close to the anomalous soft photon effects seen earlier in hadronic reactions at high energy.

It was obvious that classical theory of the bremsstrahlung radiation from the initial and final hadronic states couldn't explain such effects. Hence, new theoretical models were suggested. Formation of an intermediate parton system (IPS) composed of a form of cold quark-gluon plasma (CQGP) far from thermal equilibrium was one of these models. According to this qualitative model parts of the parton shower extend very far into the infrared domain and produce globs of ultrasoft partons, i.e. partons of very low momenta (50 MeV/c) in the glob restframe. As a result quark-antiquark annihilation and the Compton-like processes arise and they are proposed to account for the excess of inner bremsstrahlung [8], [9].

There are also several models based on the collective behavior of radiation sources, for instance Barshay's model [10]. According to these models the production rate of the anomalous photons should depend on the collective jet characteristics, jet net charge and mass. However, no such dependencies were found by DELPHI Collaboration [7].

It can be argued that up to now no comprehensive theoretical model has been developed describing the anomalous excess of SP. The creation of such a model requires a more thorough study of soft photons, and hence the improvement of calorimetry methods. That's why it was *the development of a calorimeter with a low registration threshold that became our main objective.*

Attention should also be drawn to the reasons why the emission of SP is essential. Soft photons forming an excess in the experiments described above are not the decay products of short-living particles (including resonances). They are called *direct* ones. Due to the fact that they interact with surrounding medium only electromagnetically they are useful for investigating strong interactions. Thus they give us an opportunity to study the soft gluon component of a nucleon and a stage of hadronisation. Direct SP are also an important tool for testing QCD.

3 Project goals

- To learn how to use Geant4 object-oriented detector simulation toolkit for the calorimeter simulations.
- Get experience in data analysis framework ROOT.
- To simulate a 'shashlik' type calorimeter using three different scintillator crystals: $CeBr_3$, $YAG(Ce)$, $TLC(Ce)$ and carry out a comparative analysis of the simulation results to identify the best conditions for the registration of soft photons.

4 Methods

A Geant4 toolkit was used to simulate the 'shashlik' calorimeter, which is planned to be used to study low-energy photons at the future NICA collider [11]. An open-source framework ROOT was used to analyze the data obtained during the simulation.

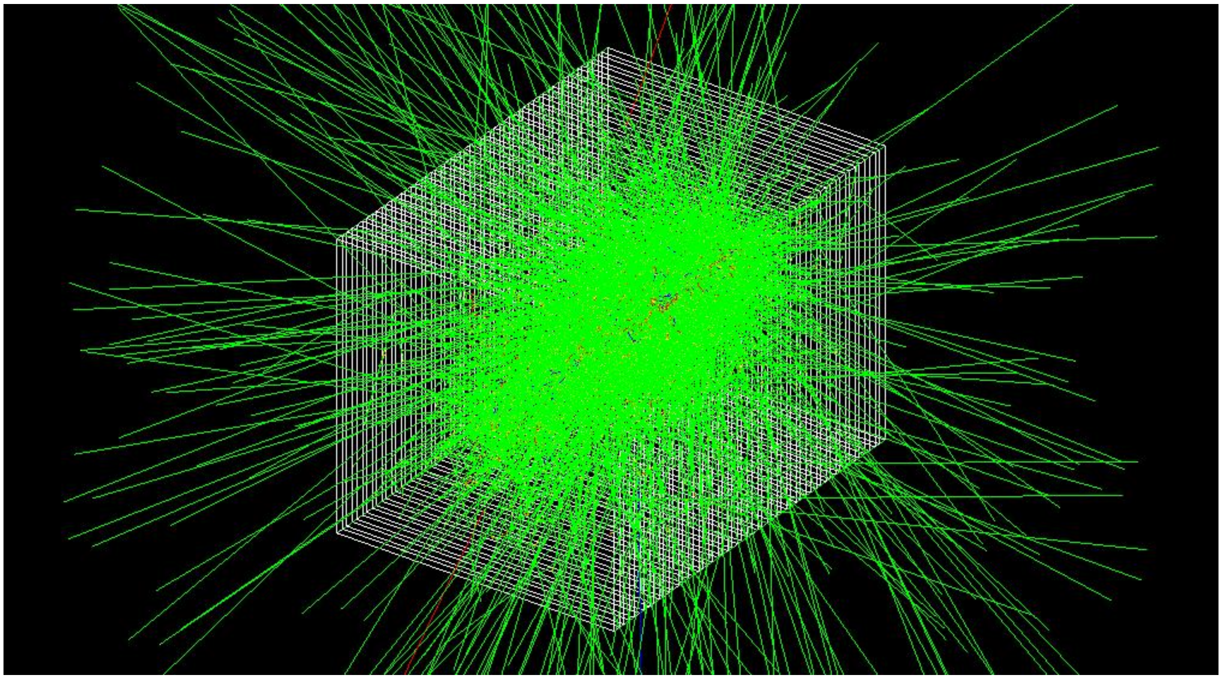

Figure 1: Geant 4 simulation of electromagnetic shower in YAG "shashlik" calorimeter (initial:beam of thousand 40 MeV photons)

5 Calorimetry

Calorimetric methods involve total absorption of the particle energy in a bulk of material followed by the measurement of the deposited energy.

Moreover, the interaction of high-energy photons, electrons and hadrons with the medium leads to the birth of secondary particles and as a result shower development. Then the particle energy is deposited in the material much more efficiently. Further we will discuss electromagnetic calorimeters which are used to detect the electromagnetic showers.

The dominating interaction processes for spectroscopy in the considered MeV energy range are the photoelectric and Compton effect for photons and ionisation and excitation for charged particles. At high energies (higher than 100 MeV) electrons lose their energy almost exclusively by bremsstrahlung while photons lose their energy by electron–positron pair production.

The angular distribution of the produced particles by bremsstrahlung and pair production is very narrow. That is why the lateral width of an electromagnetic cascade is mainly determined by multiple scattering and can be best characterised by the *Moliere radius.*

About 95% of the shower energy is contained in a cylinder around the shower axis whose radius is $R(95\%) = 2R_M$ almost independently of the energy of the incident particle [12].

The multiplication of the shower particles in calorimeter continues as long as $E_0/N > E_c$, where E_0 - initial energy, N - number of shower particles, E_c - critical energy. 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.

The most important qualitative characteristics of electromagnetic cascades mainly determine the construction of the calorimeter:

1. To absorb most of the energy of the incident photon the total calorimeter thickness should be more than 10–15 X_0, where X_0 - radiation length.
2. The position of the shower maximum increases slowly with energy. Hence, the thickness of the calorimeter should increase as the logarithm of the energy.
3. The energy leakage is caused mostly by soft photons escaping the calorimeter at the sides (lateral leakage) or at the back (rear leakage).

5.1 'Shashlik' calorimetry

Energy resolution for photons and electrons is one of the main calorimetric parameters. The energy resolution can be defined as σ_E/E and is determined both by physical factors (fluctuation of the energy leakage, photoelectron statistics) and technical ones (nonuniformity of crystals).

For our investigation we have chosen heterogeneous (or sampling) calorimeter as a simpler and more economical way to measure the photon energy compared to homogeneous one. From a large variety of currently existing sampling calorimeters, a 'shashlik' type calorimeter developed for the KOPIO experiment [13] was chosen. It is characterised by rather high energy resolution $4\%/\sqrt{E\{GeV\}}$ and consist of thin layers of scintillation counters separated by layers of absorbers. The scintillation counters used in this calorimeter have the form of fibres, so the readout is greatly simplified because the scintillating fibres can be bent rather strongly without loss of internal reflection. To obtain information from scintillating fibres all inner surfaces of the calorimeter are covered with photomultipliers.

5.2 Absorber

As an absorber a composite of 50% tungsten and 50% copper is used. The radiation length X_0 of this material is $0,56\,cm$, density ρ is equal to $12,24\,g/cm^3$, effective atomic number and atomic mass are $Z_{eff} = 56,16$ and $A_{eff} = 123,69$ respectively.

Based on the differences in densities of tungsten ($19,3\,g/cm^3$) and copper ($8,96\,g/cm^3$), in order to reduce the energy resolution it is possible to increase the concentration of copper relative to the concentration of tungsten.

5.3 Scintillation crystals

Selecting scintillation materials for the registration of low-energy photons, we focused on the following characteristics: high density ($\geq 5\,g/cm^3$), high light yield ($\geq 30\,ph/KeV$), wavelength of emission peak $300-550\,nm$ and short decay time. The decay time of a scintillator is defined by the time after which the intensity of the light pulse has returned to $1/e$ of its maximum value. The decay time is of importance for fast counting.

The table below demonstrates the crystals with the most suitable parameters [14]:

Formula	density, g/cm^3	light yield, ph/keV	emission peak, nm	decay time, ns
$Gd_3Al_2Ga_3O_{12}(Ce)$	6,63	54	520	50-150
Lu_2SiO_5	7,1	33	410-420	40
$CeBr_3$	5,1	60	380	19
$Y_3Al_5O_{12}(Ce)$	4,35	35	550	70
$Tl_2LaCl_5(Ce)$	5,31	76	383	36 (89%), 217 (6%),1500(%)

Table 1: Scintillator Crystal Properties

Gadolinium-gallium garnet ($GaGG$) and $LYSO$ crystals were already used in several investigations, for instance [11], therefore, our further work will be aimed at a detailed study of $CeBr_3$, $YAG(Ce)$ and $TLC(Ce)$ scintillation crystals.

In the next section, the results of simulating an electromagnetic shower using these scintillation crystals will be presented. Based on the fact that the properties of scintillation crystals to some extent determine the design of the calorimeter, it is necessary to know several characteristics of these crystals, such as:

1. Radiation length X_0. The radiation length of a mixture of elements or a compound can be approximated by

$$X_0 = \frac{1}{\sum\limits_{i=1}^{N} f_i/X_0^i} \tag{1}$$

where f_i are the mass fractions of the components with the radiation length X_0^i.

The mass fractions can be calculated as:

$$f_i = \frac{A_i v_i}{\sum\limits_{k=1}^{N} A_k v_k} \tag{2}$$

Where A-atomic mass [g/mole], v- valence.

2. The critical energy E_c (the energy, where brensstrahlung process and ionization for electrons lead to equal energy losses). For solids E_c can be described as:

   $$E_c = \frac{610MeV}{Z + 1.24} \tag{3}$$

   In the case of compound system the critical energy can be calculated as:

   $$E_c = \frac{550}{Z_{eff}} \tag{4}$$

   where Z_{eff} - effective atomic number, which can be obtained from the following equation ($i-$ for each of N elements in material):

   $$Z_{eff} \cdot (Z_{eff} + 1) = \sum_{i=1}^{N} f_i Z_i (Z_i + 1) \tag{5}$$

3. Moliere radius:

   $$R_M = \frac{21MeV}{E_c} \cdot X_0 \tag{6}$$

These characteristics will be calculated in the following section.

6 Simulation of electromagnetic shower for several types of scintillation crystals for 'Shashlik' calorimeter

6.1 $CeBr_3$ scintillator

Cerium Bromide ($CeBr_3$) scintillator crystals are now available on a commercial basis and have proven to be very capable detectors in X-ray and gamma-ray

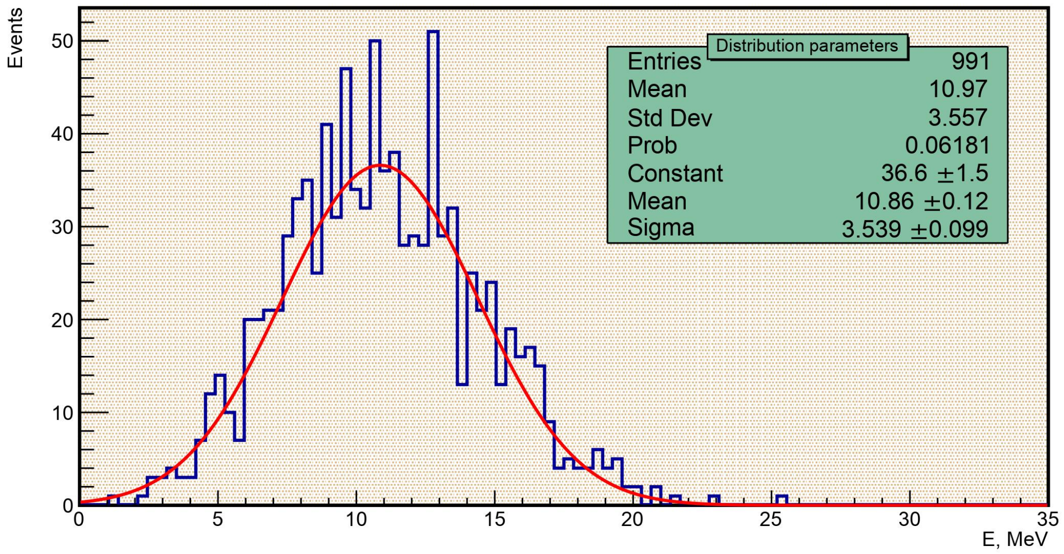

Figure 2: Histogram describing the energy distribution in scintillation crystal $CeBr_3$ approximated by Gaussian function (initial: beam of thousand 30 MeV photons)

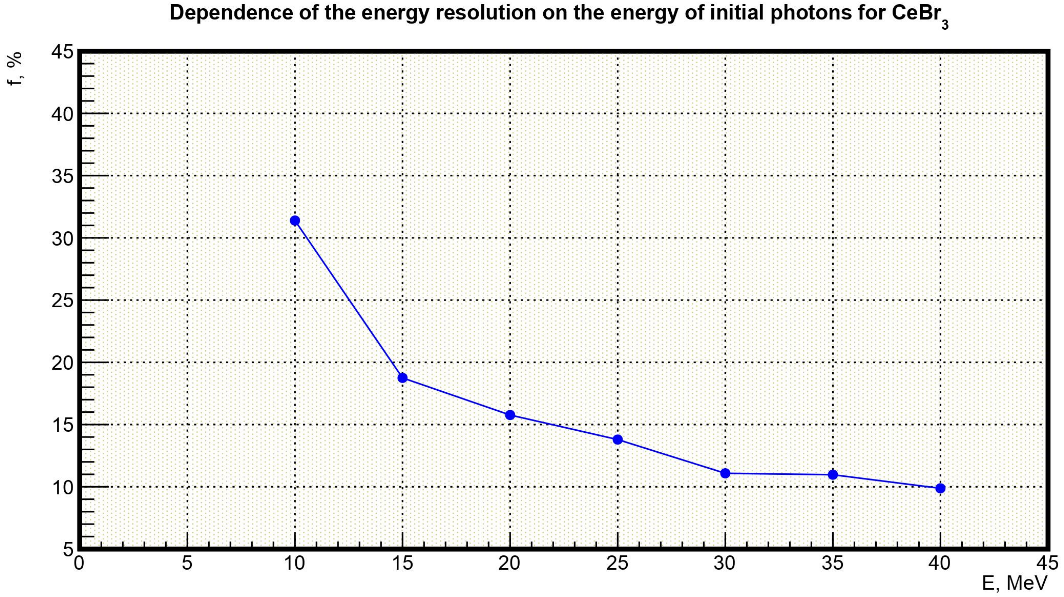

Figure 3: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for $CeBr_3$ scintillation crystal for the low registration threshold

spectroscopy applications. $CeBr_3$ crystals are hygroscopic but can be supplied both with and without encapsulation. The mass fractions were calculated using equation (2), radiation length and density were obtained from Lawrence Berkeley National Laboratory database [15]

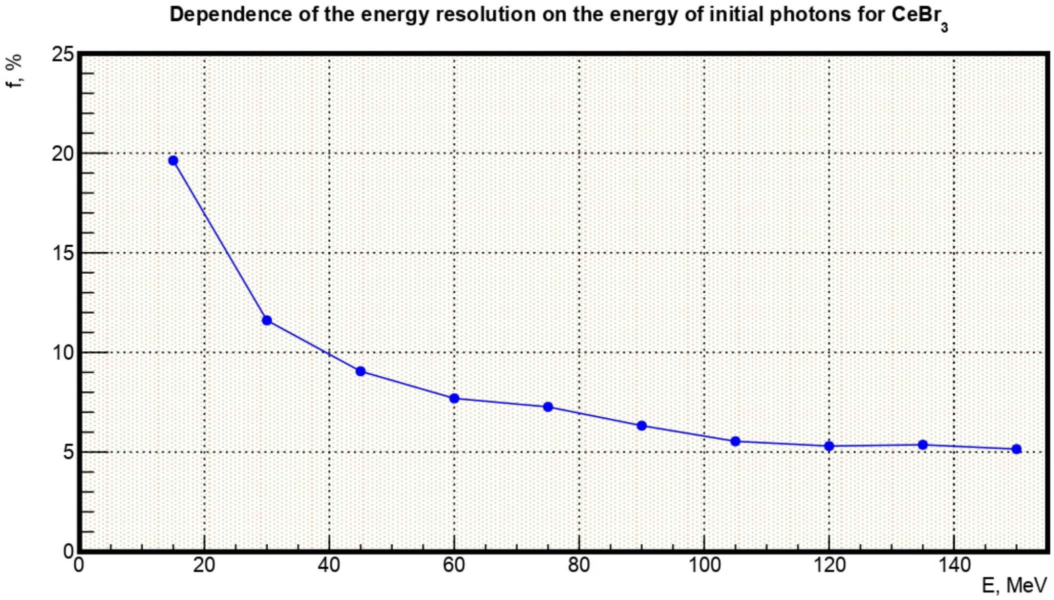

Figure 4: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for $CeBr_3$ scintillation crystal for the whole energy range

Element	ν_i	Z	A, g/mol	ρ_i, g/cm^3	$f_i(2)$	X_0, g/cm^2	X_0^i, cm
Ce	1	58	140,1161	6,770	0,368893	7,96	1,175
Br	3	35	79,9041	3,103	0,631107	11,42	3,681

Table 2: Component properties of the $CeBr_3$

Using (1) equation we can obtain the radiation length for the $CeBr_3$ crystal:

$$X_0 = 2.06015\,cm$$

The critical energy for the $CeBr_3$ crystal can be calculated by equation (4):

$$E_c = 12,25956\,MeV$$

The Moliere radius according to (6) equation is equal to:

$$R_M = 3,52893\,cm$$

With the help of the Geant4 toolkit the interaction of 1000 gamma-quantum beam with the material of 'shashlik' calorimeter with $CeBr_3$ crystal in the energy range 10-150 MeV was simulated. The simulation results were analyzed with the help of ROOT CERN toolkit. Histogram describing the energy distribution in scintillation crystal $CeBr_3$ was approximated by Gaussian function. This made it possible to obtain the value of the standard deviation and subsequently determine the energy resolution of the crystal.

6.2 YAG(Ce) scintillator

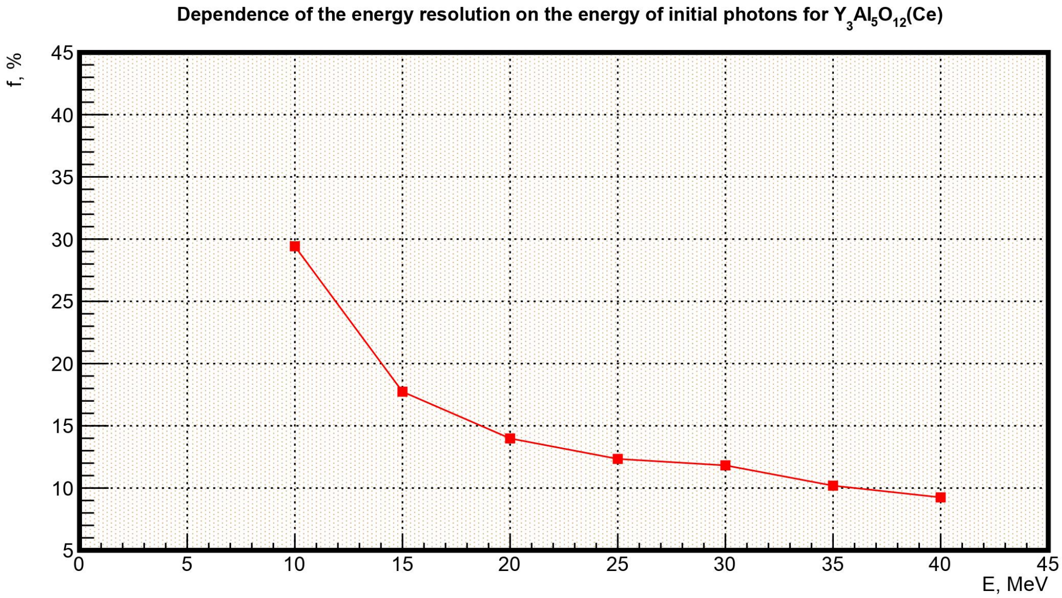

Figure 5: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for YAG scintillation crystal for the low registration threshold

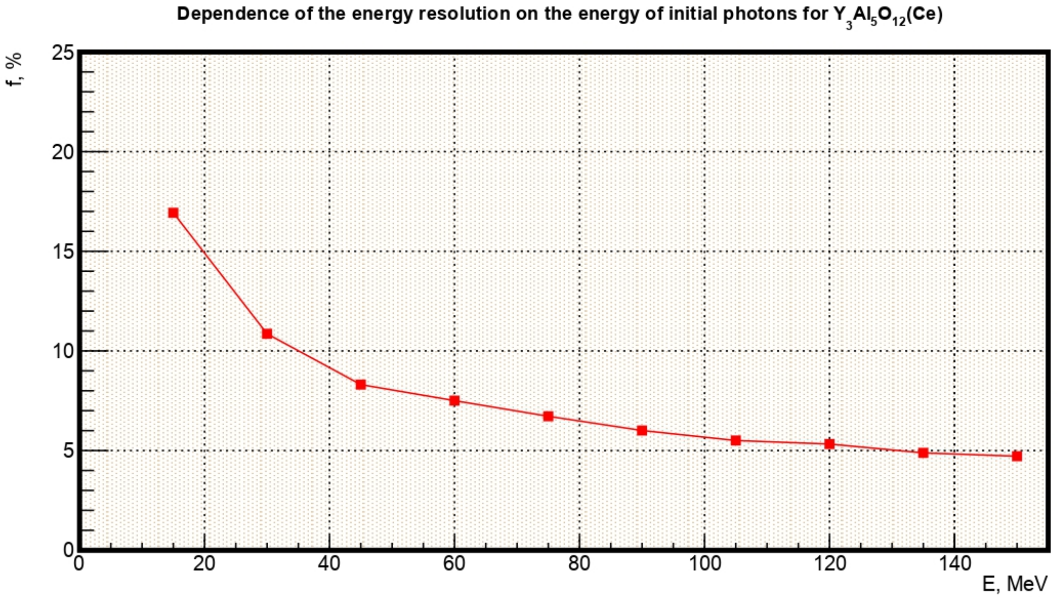

Figure 6: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for YAG scintillation crystal for the whole energy range

Yttrium Aluminium Granate activated with Cerium - $YAG(Ce), Y_3Al_5O_{12}(Ce)$ - is a highly effective gamma-ray absorber as a result of its high density and high Z

characteristics. $YAG(Ce)$ has stable scintillating characteristics up to $\approx 100\,rad$ and is non hygroscopic material.

Element	ν_i	Z	A, g/mol	ρ_i, g/cm^3	f_i	X_0, g/cm^2	X_0^i, cm
Y	3	39	88,9058	4,469	0,449309	10,41	2,329
Al	5	313	26,9815	2,699	0,227264	24,01	8,897
O	12	8	15,9993	$1,332 \cdot 10^{-3}$	0,323427	34,24	$2,571 \cdot 10^4$

Table 3: Component properties of the $Y_3Al_5O_{12}(Ce)$

The mass fractions were calculated using equation (2), radiation length and density were obtained from Lawrence Berkeley National Laboratory database [15]

Using (1) equation we can obtain the radiation length for the $YAG(Ce)$ crystal:

$$X_0 = 4,57717\,cm$$

The critical energy for the $YAG(Ce)$ crystal can be calculated by equation (4):

$$E_c = 20,24033\,MeV$$

The Moliere radius according to (6) equation is equal to:

$$R_M = 4,74896\,cm$$

With the help of the Geant4 toolkit the interaction of 1000 gamma-quantum beam with the material of 'shashlik' calorimeter with $YAG(Ce)$ crystal in the energy range 10-150 MeV was simulated. The simulation results were analyzed with the help of ROOT CERN. The analysis algorithm was given in the previous subsection.

6.3 TLC(Ce) scintillator

Thallium lanthanum chlorine scintillator activated with Cerium ($Tl_2LaCl_5(Ce)$) or TLC is rather new scintillator with very good energy resolution. Due to the high Z_{eff} of 70 and density of $5.31 g/cm^3$ TLC can be characterised as an efficient gamma-ray absorber in comparison with scintillators currently in use.

The mass fractions were calculated using equation (2), radiation length and density were obtained from Lawrence Berkeley National Laboratory database [15]

Using (1) equation we can obtain the radiation length for the $TLC(Ce)$ crystal:

$$X_0 = 0,851569\,cm$$

Element	ν_i	Z	A, g/mol	ρ_i, g/cm^3	f_i	X_0, g/cm^2	X_0^i, cm
Tl	2	81	204,3820	11,720	0,563863	6,42	0,548
La	1	57	138,9055	6,145	0,191611	8,14	1,324
Cl	5	17	35,4532	$2,980 \cdot 10^{-3}$	0,244527	10,21	3425

Table 4: Component properties of the $Tl_2LaCl_5(Ce)$

The critical energy for the $TLC(Ce)$ crystal can be calculated by equation (4):

$$E_c = 8,30362\,MeV$$

The Moliere radius according to (6) equation is equal to:

$$R_M = 2,15363\,cm$$

With the help of the Geant4 toolkit the interaction of 1000 gamma-quantum beam with the material of 'shashlik' calorimeter with $TLC(Ce)$ crystal in the energy range 10-150 MeV was simulated. The simulation results were analyzed with the help of ROOT CERN. The analysis algorithm was given in the previous subsection.

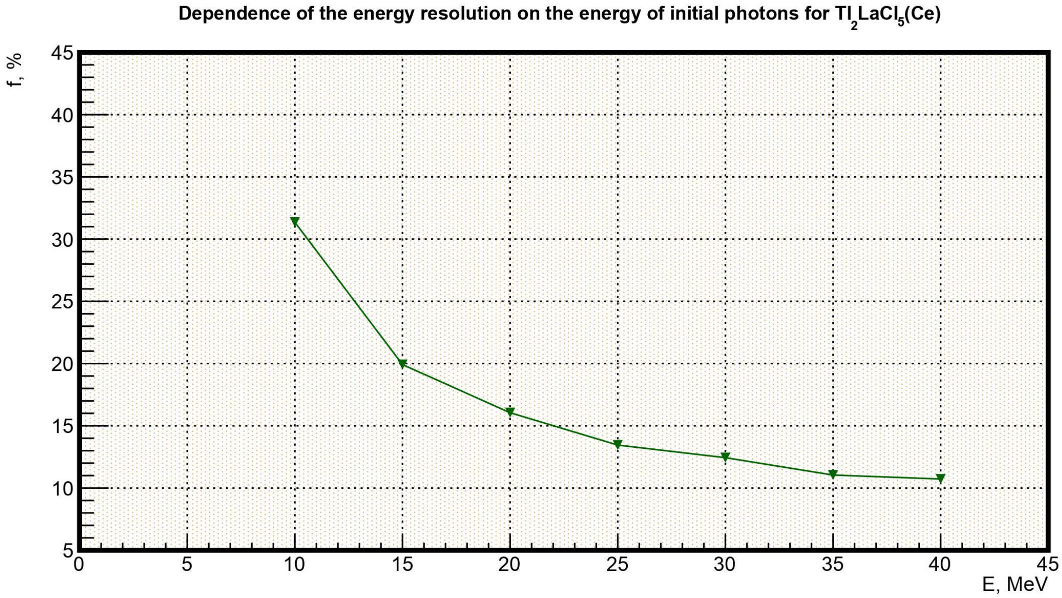

Figure 7: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for TLC scintillation crystal for the low registration threshold

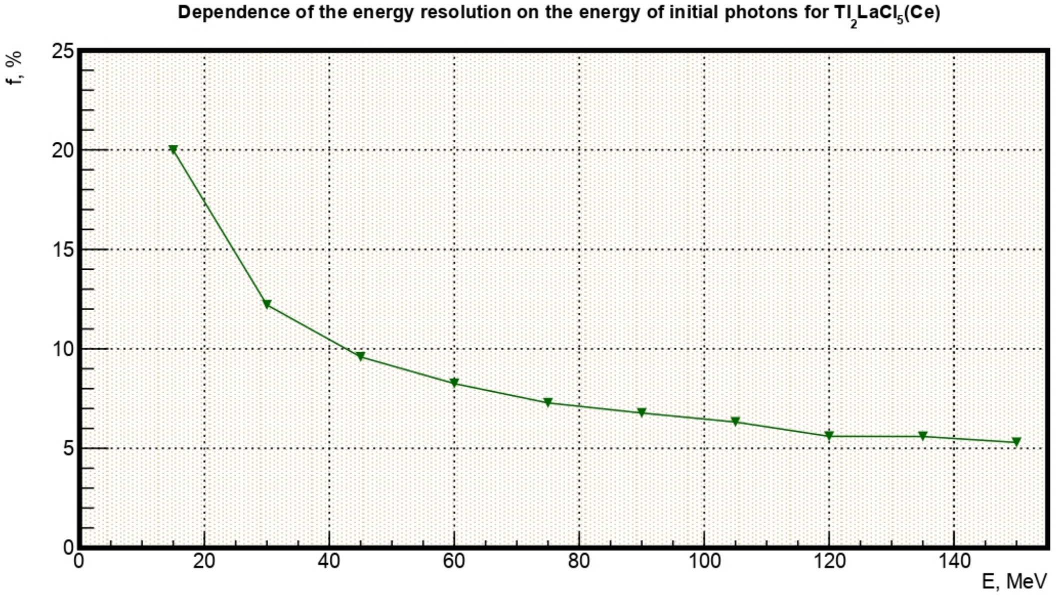

Figure 8: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for TLC scintillation crystal for the whole energy range

7 Conclusions

Summing up, we carried out a simulation of a 'shashlik' type calorimeter for the study of soft photons. A compound from copper and tungsten was used as an absorber, $YAG(Ce)$,$CeBr_3$, $TLC(Ce)$ were used as three different scintillation crystals. The analysis of the data obtained during the simulation allowed us to gain the dependences of the energy resolution of these crystals on the energy. When compared, it turned out that the crystal $YAG(Ce)$ has the highest resolution (Fig. 8) and that's why is recommended to be used in further investigations. Although $YAG(Ce)$ is more expensive than more common in use $GaGG$ and $LYSO$ scintillators, it improves energy resolution on the average by $2-3\%$ (Fig. 9), that will most likely prove critical in the study of direct soft photons.

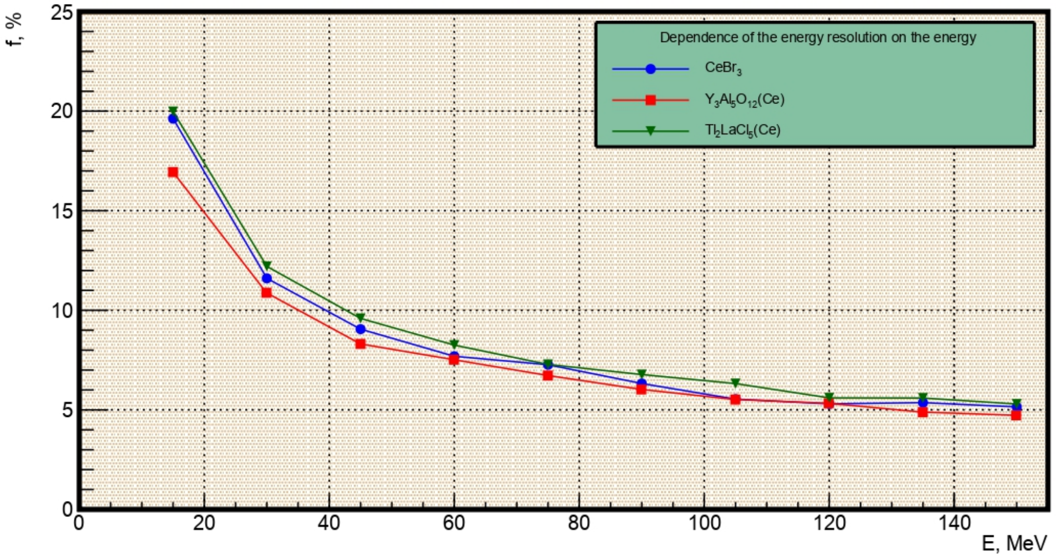

Figure 9: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for several scintillation crystal

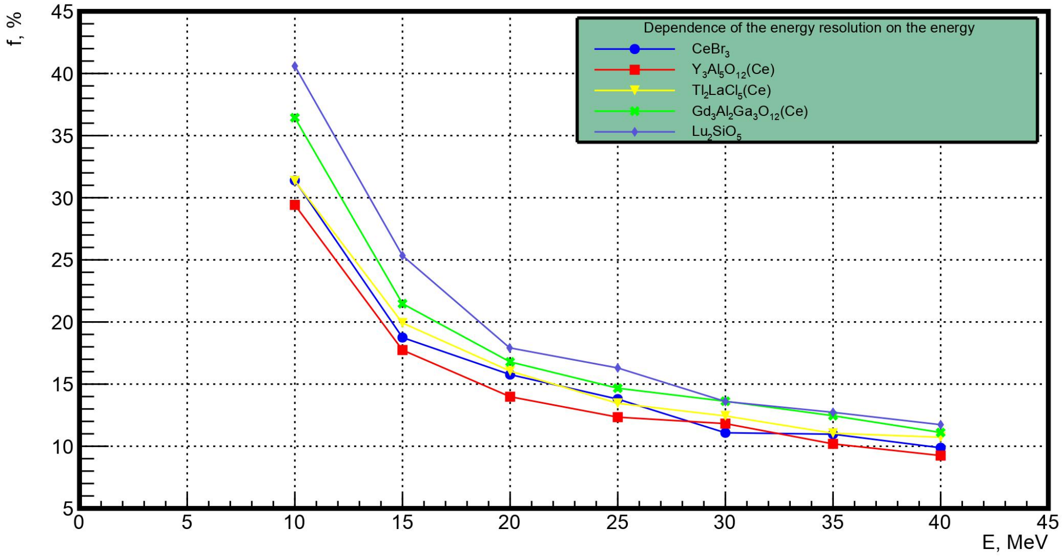

Figure 10: The dependence of the energy resolution (%) on the energy of initial photons (MeV) for several scintillation crystal

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9 Acknowledgments

I would like to express my gratitude to my supervisor, Professor Elena Kokoulina, who guided me throughout this project and gave me all opportunities for deep understanding of calorimetry simulations using Geant4 and analysis using ROOT framework. I also wish to acknowledge with gratitude the START team for performing interesting events and helping to resolve all organizational issues.