JOINT INSTITUTE FOR NUCLEAR RESEARCH

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FINAL REPORT ON THE START PROGRAMME

Simulation of an electromagnetic calorimeter for registration of soft photons

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1 Abstract

The nature of soft photons is still unknown and the existing theoretical models do not explain the reason for the excess of their yield in hadron and nuclear interactions. The SPD detector will be used to study soft photons within the framework of the NICA experiment. For this experiment, we built a model of a calorimeter of the type "Shashlik", the simulation was carried out by the Geant4 program, and the results of the simulation were analyzed in the CERN Root framework.

2 Introduction

Getting into the scintillator crystal, the particle gives rise to a cascade process of secondary particles, such as electromagnetic and hadronic showers. The shower is absorbed in the volume of the calorimer and its energy is measured. These phenomena are well studied, but the question of the mechanism of formation of soft photons still remains open. Soft photons are not decay products of secondary particles and their characteristic energy does not exceed 50 MeV. In the experimental data, there is an excess of their yield in hadron and nuclear interactions.

The existing theoretical calculations cannot explain the reason for the excess of their yield in hadron and nuclear interactions.The nature of soft photons is still mysterious and scientists only offer various models based on experimental data and quantum chromodynamics. So far, the most successful model is based on the hypothesis of the formation of a cold quark-gluon system, which consists of quarks, antiquarks and gluons. They collide with each other and re-emit soft photons because they don't have enough energy to form hadrons. The main reactions are Compton scattering: $q + g \to q + \gamma$ and annihilation: $q + \overline{q} \to +\gamma$.

3 Calorimetry

Calorimetric methods imply the complete absorption of the energy of particles in the bulk of the material, followed by the measurement of the released energy. Passing through the material, this particle loses its energy mainly due to the ionization of atoms, while other contributions are negligible. On the other hand, high-energy photons, electrons and hadrons can interact with the medium, producing secondary particles, which leads to the development of a cascade shower with gradually decreasing energy. The particle energy is recorded as scintillations or as an electrical signal.

Thus, calorimeters are most widely used in high-energy physics for recording electromagnetic and hadron showers. Such detector systems are called electromagnetic and hadron calorimeters, respectively.Electromagnetic calorimeters are mainly used to measure the characteristics of electrons and photons through their electromagnetic interactions (eg bremsstrahlung), while hadron calorimeters are used to measure the characteristics of hadrons through their strong and electromagnetic interactions.

3.1 Electomagnetic calorimeters

The main interaction processes for spectroscopy in the MeV energy range are the photoelectric effect and the Compton effect for photons, and ionization and excitation for charged particles. At high energies, electrons lose their energy almost exclusively through bremsstrahlung, while photons lose their energy through the formation of electron-positron pairs. The most important properties of electronic stages can be understood using a simplified model. Let E0 be the energy of a photon incident on a bulk material. After one radiative length, a photon produces an e+ e- pair; electrons and positrons emit one bremsstrahlung photon through a different radiation length, which again turn into electron-positron pairs. When the particle energy drops below the critical value Ec, absorption processes such as ionization for electrons and Compton and photoelectric effects for photons begin to dominate. At this multiplication step, the position of the shower maximum is reached.

This simple model describes correctly the most important qualitative characteristics of electromagnetic cascades: to absorb most of the energy of the incident photon the total calorimeter thickness should be more than $10 - 15\ X_0$. The position of the shower maximum increases slowly with energy. Thus, the thickness of the calorimeter should increase as the logarithm of the energy. The energy leakage is caused mostly by soft photons escaping the calorimeter at the sides or at the back. 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.

3.2 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). 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.

4 Geant4 simulations

4.1 $BaBr_2$ scintillator

$BaBr_2$ is a high density scintillation material.It is one of the brightest available scintillators with an emission peak at 408 nm. The calorimeter model consists of 28 $BaBr_2$ plates with dimensions $100\times100\times3\ mm^3$ and 27 plates of W/Cu absorber ($100\times100\times2\ mm^3$).

The mass fraction was calculated using formula: $f_i = \frac{A_i v_i}{\sum_{i=1}^{N} A_k v_k}$

where, A = atomic mass in g/mole, v = valence.

Element	ν_i	Z	A, g/mol	ρ_i,g/cm^3	f$_i$	X$_0$	X$_0^i$
Ba	1	56	137.3277	3.500	0.46217	8.31	2.373
Br	2	35	79.9041	7.072*10^{-3}	0.53782	11.42	1615.

Table 1: Components properties of the BaBr$_2$

The composite density of the $BaBr_2$ crystal is calculated using the density and mass fractions of the component elements and it is given by:

$$\rho = 4,78\ g/cm^3$$

We consider that the absorber is made of 50 % W and 50 % Cu. Composite density is 11.187 g/cm^3 and radiation length is 0.56 cm.

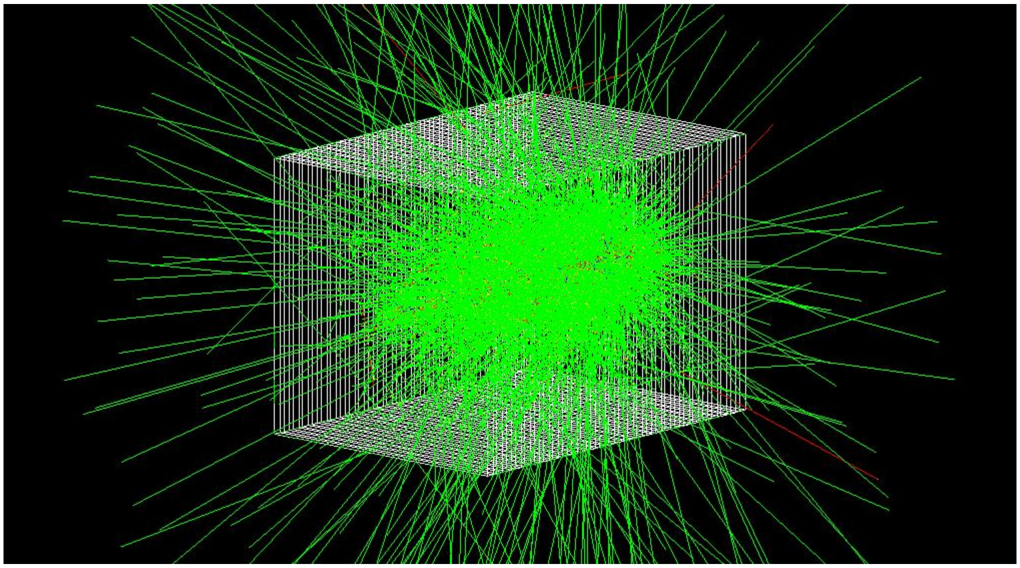

Figure 1: Simulation of electromagnetic shower in $\mathrm{BaBr_2}$"$Shashlik$"$calorimeter$

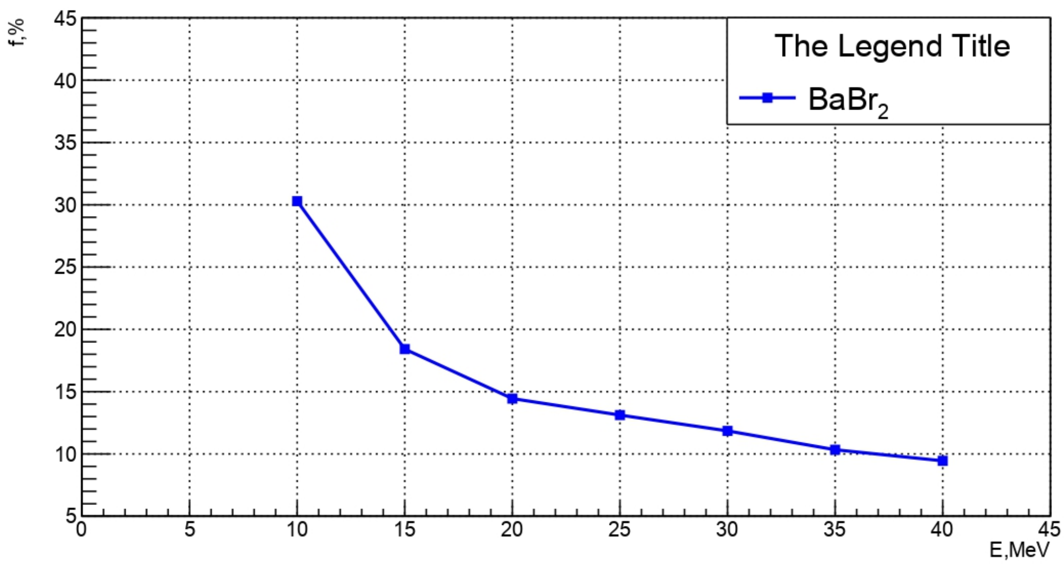

Figure 2: dependence of the energy resolution from energy for $BaBr_2$ scintillation crystal(40 MeV)

The energy resolution for the $BaBr_2$ "shashlik" calorimeter is given by,

$$f = \frac{\sigma}{E}$$

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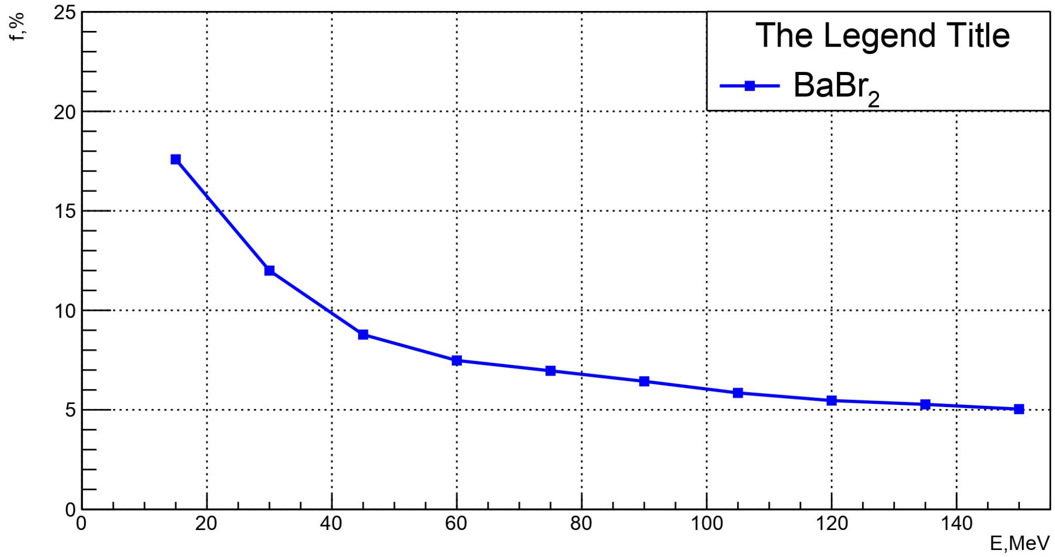

Figure 3: dependence of the energy resolution from energy for $BaBr_2$ scintillation crystal(150 MeV)

We get the energy resolution dependence from the initial photons energy.For the sake of completeness, we calculated energy resolution for cases of 40 MeV and 150 MeV photons: $f_{40MeV} = 9\%$, $f_{150MeV} = 5\%$.

4.2 $CsBa_2I_5$ scintillator

Another scintillation crystal that we have reviewed $CsBa_2I_5$. It has an emission peak at 430 nm. Light output is 80.000 ph/MeV.

Element	ν_i	Z	A, g/mol	ρ_i,g/cm^3	f$_i$	X$_0$	X$_0^i$
Cs	1	55	132.9054	1.873	0.12753	8.31	4.434
Ba	2	56	137.3277	3.500	0.46217	8.31	2.373
I	5	53	126.9044	4.930	0360889	8.48	1.720

Table 2: Components properties of the CsBa$_2I_5$

Having carried out similar calculations as in previous subsection we get:

$$\rho = 5,0\,g/cm^3$$

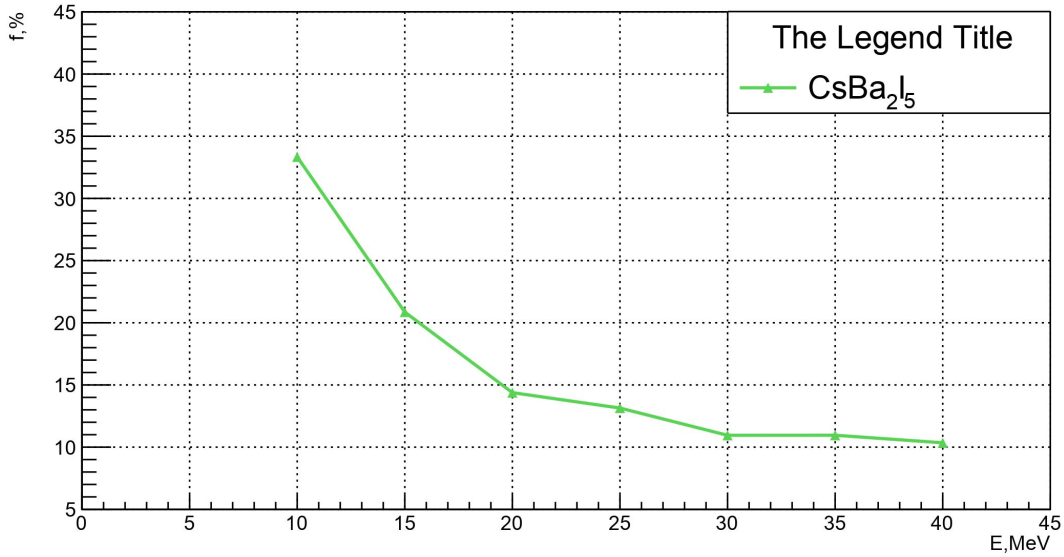

Figure 4: dependence of the energy resolution from energy for $CsBa_2I_5$ scintillation crystal(40 MeV)

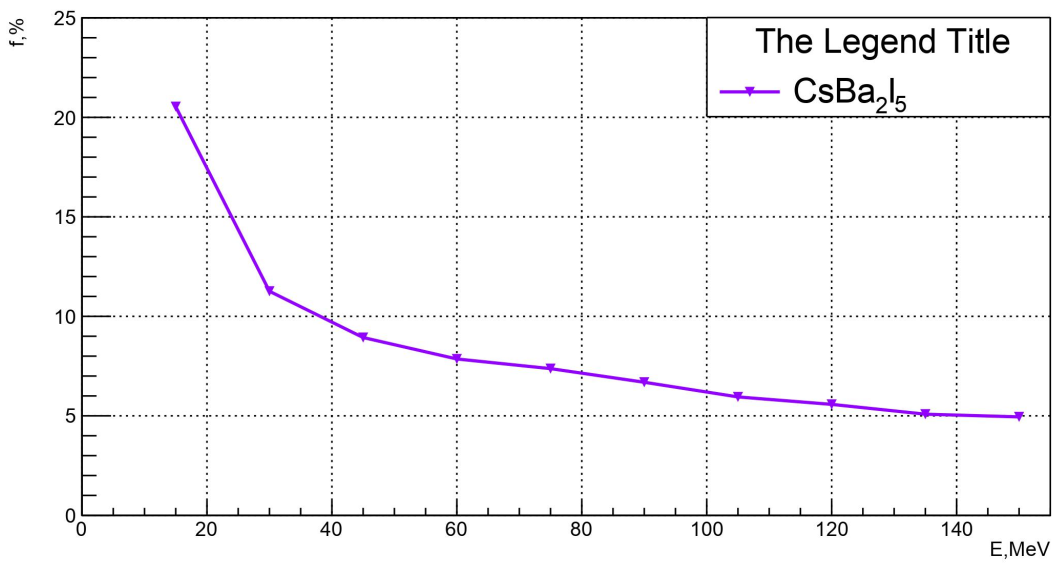

Figure 5: dependence of the energy resolution from energy for $CsBa_2I_5$ scintillation crystal(150 MeV)

We again get the dependence of the energy resolution on the initial photon energy. We calculate the energy resolution for cases of 40 MeV and 150 MeV photons: $f_{40MeV} = 10.2\%$, $f_{150MeV} = 5\%$.

4.3 $RbGd_2Br_7$ scintillator

The last scintillator in this work is $RbGd_2Br_7$. It has an emission peak at 430 nm. Light output is 56.000 ph/MeV.

Element	ν_i	Z	A, g/mol	ρ_i,g/cm^3	f$_i$	X$_0$	X$_0^i$
Rb	1	37	85.4678	1.532	0.08909	11.03	7.198
Gd	2	64	157.253	7.901	0.32784	7.48	0.9471
Br	7	35	79.9041	7.072*10^{-3}	0.53782	11.42	1615.

Table 3: Components properties of the RbGd$_2Br_7$

Density of a given scintillation crystal:

$$\rho = 4.8\ g/cm^3$$

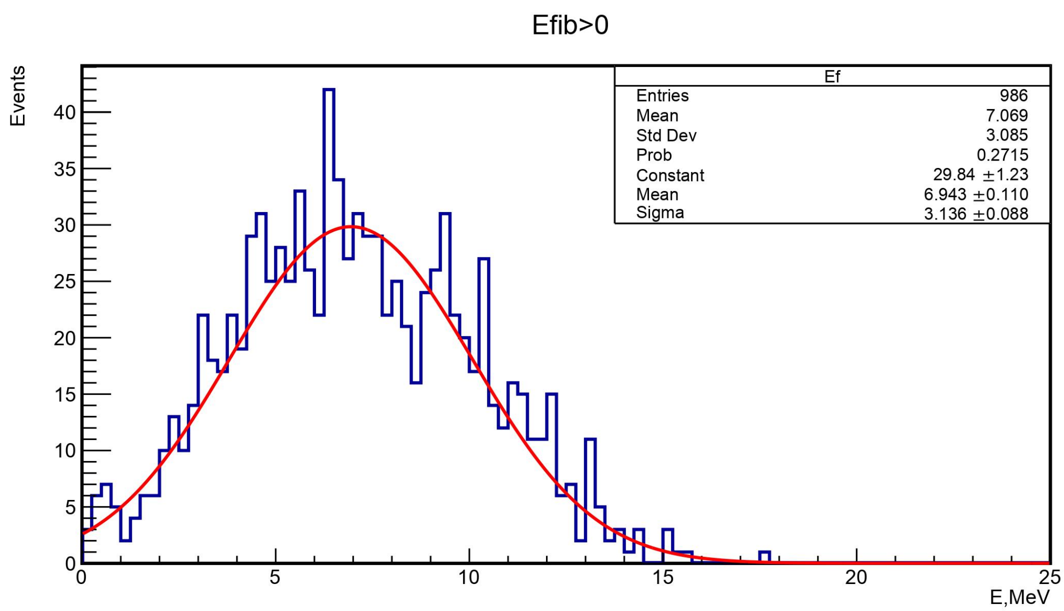

Figure 6: Energy resolution for $RbGd_2Br_7(20MeV)$

A histogram of the energy release in the calorimeter $RbGd_2Br_7$ "Shashlik" is also presented for incoming photons.

We get the dependence of the energy resolution on the initial photon energy. We calculate the energy resolution for cases of 40 MeV and 150 MeV photons: $f_{40MeV} = 10.3\%$, $f_{150MeV} = 4.9\%$.

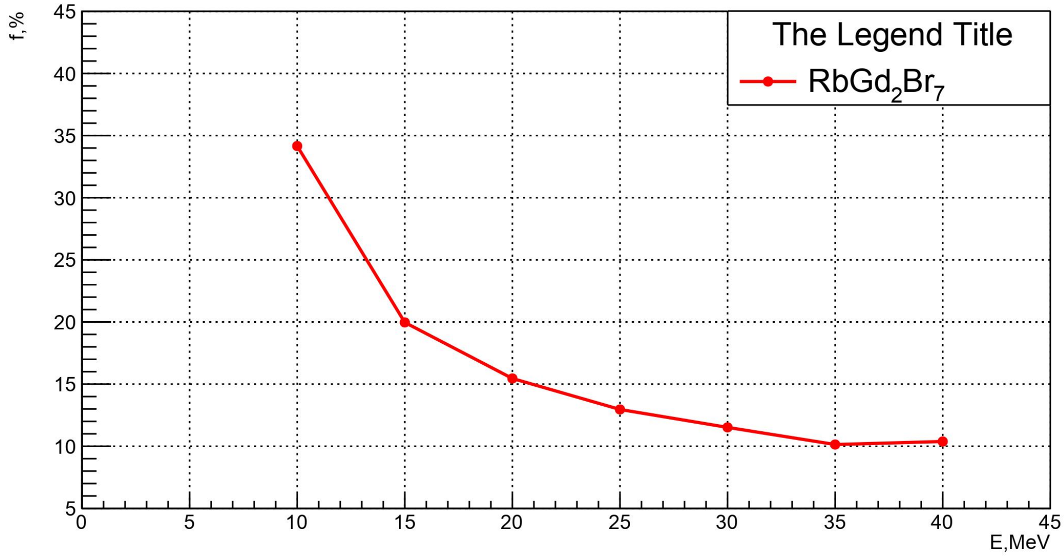

Figure 7: dependence of the energy resolution from energy for $RbGd_2Br_7$ scintillation crystal(40 MeV)

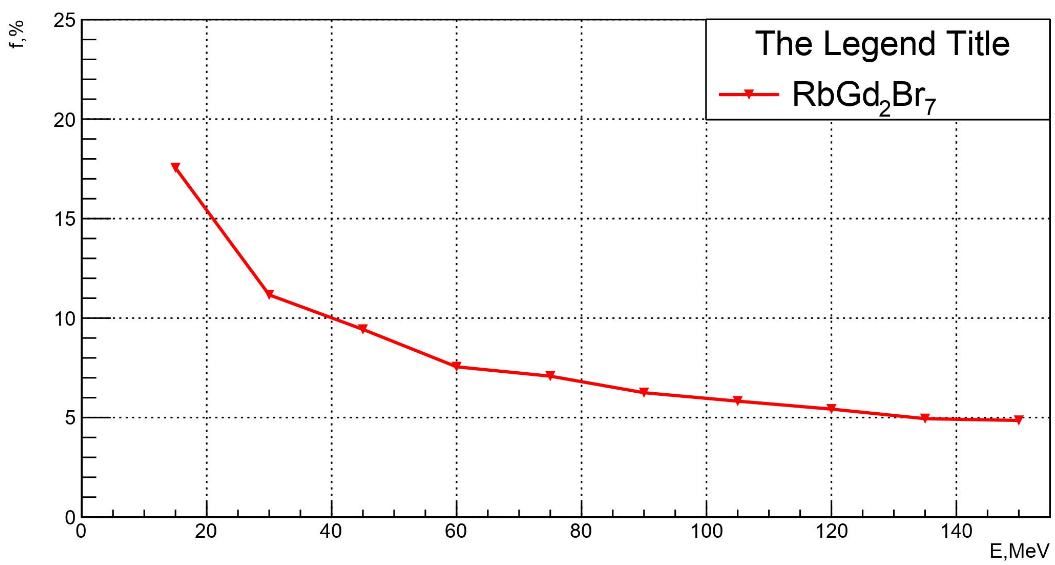

Figure 8: dependence of the energy resolution from energy for $RbGd_2Br_7$ scintillation crystal(150 MeV)

5 Conclusions

In our work, I simulated the model of the "Shashlyk" calorimeter, changed the scintillation crystals, and it was used W/Cu absorber. By calculating different parameters, such as: radiation length, critical energy, we were able to define the optimal calorimeter dimensions. After performing various simulations in Geant4, the obtained histograms were analyzed using CERN Root. We calculated for each calorimeter the energy resolution for 40 MeV amd 150 MeV photons coming in the z direction.

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
$BaBr_2$	4,78	49	408	2,200-slow
$RbGd_2Br7(Ce)$	4,8	56	430	45
$CsBa_2I_5(Eu)$	5,0	80	430	900

Table 4: Scintillator Crystal Properties

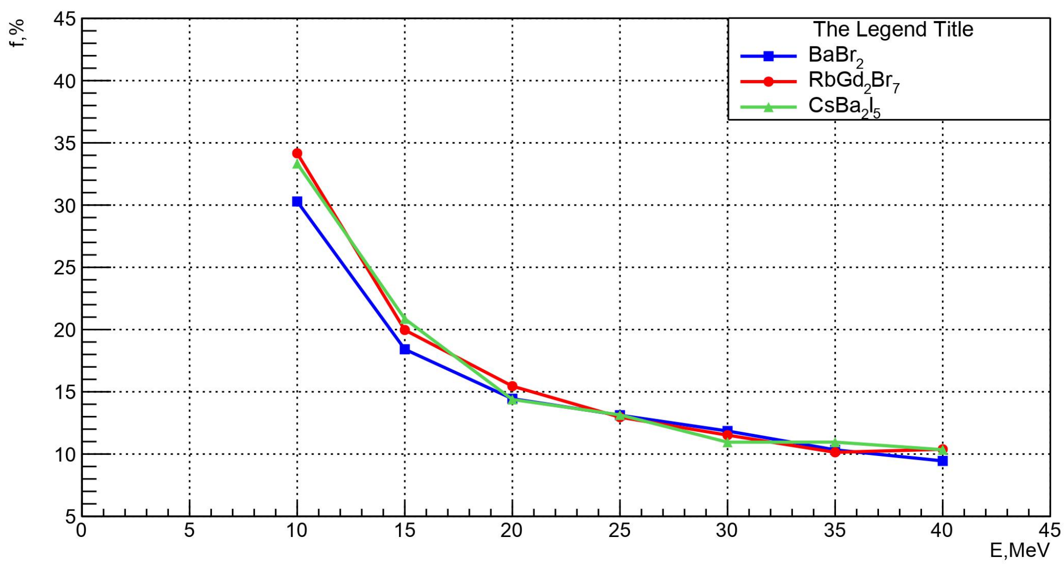

Figure 9: Energy resolution for $BaBr_2$, $CsBa_2I_5$, $RbGd_2Br_7$

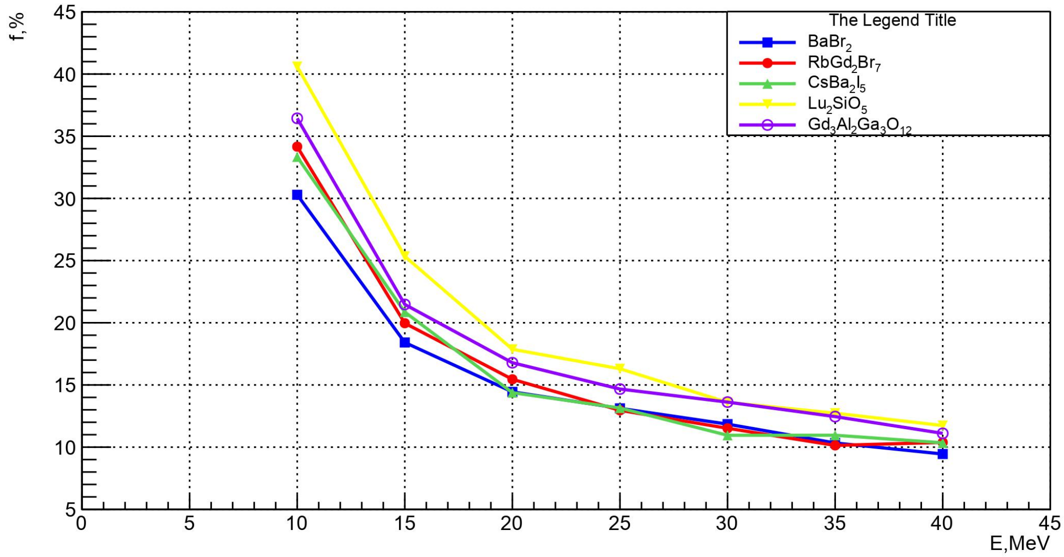

Figure 10: Energy resolution for $Gd_3Al_2Ga_3O_{12}(Ce)$, Lu_2SiO_5 ,$BaBr_2$, $CsBa_2I_5$, $RbGd_2Br_7$

We can observe that the best energy resolution at energies of 40 MeV, required for soft photons, is obtained in a crystal $BaBr_2$. But these crystals are very expensive. We compared the crystals that I proposed and the crystals that have already been modeled. The crystals I proposed are better in resolution, but lose in price. The main task was to find the optimal design for the registration of soft photons.Thus, it can be used in future experimental studies of soft photons at the Nuclotron facility at JINR.

6 Bibliography

[1] Claus Grupen and Boris Shwartz. Particle Detectors. 2nd ed. Cambridge University Press, 2008.

[2] P. Lichard and L. Van Hove. The cold quark-gluon plasma as a source of very soft photons in high energy collisions.1990.

[3]David Cockerill. Introduction to Calorimeters. Southampton Lecture, 4 May 2016.

[4] Elena Kokoulina et al. "Study of soft photon yield in pp and AA interactions at JINR". In: XLIX International Symposium on Multiparticle Dynamics (ISMD 2019). 2020.

7 Acknowledgments

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