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FINAL REPORT ON THE
SUMMER STUDENT PROGRAM

An approbation of methodology to measure scintillators' quench factor for alpha particles in comparison with electrons and muons

Supervisor:
Oleg Samoilov
Antoshkin Alexander
Student:
Velikanova Daria, Russia
Moscow State University

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Annotation.

This work describes the quenching of the light yield of scintillator, depending on the particle, that energizes it. Here we have described the main attributes of scintillators, the nature of quenching and the method of measuring the quenching factor. Here we present the results of measuring of quenching factors of α-particles in reference to electrons and muons of liquid and solid scintillators based on LAB and polystyrene.

Introduction.

Nowadays there are many different scintillators, which are used in experimental physics for the detection of radiation during the passing of radiation through the active substance. It is necessary to find the appropriate scintillator for experiments of any scope. Moreover, in order to interpret experiment results correctly we need to know attributes of the scintillator we use. This work is to research one of those attributes - quenching factor, which shows the variation of scintillator's light signal while applying different types of radiation.

The NOνA experiment is a good example: here we use two detectors for measurement, which are necessary for the reduction of indeterminacy in neutrino fluxes transverse cross section and effectiveness of sampling. The detectors are filled with liquid scintillator. The-far detector for NOνA is the main one, he is placed in order to detect the reaction between neutrino and "2Гэв" energy. The near detector is similar to the far detector, but its transverse cross section is a factor of 4 smaller relative to the far detector.

The NOνA detectors are highly segmented active tracking calorimeters. The size of the transverse cross section of the detector-s cells is about 6x4 cm. Every cell extends the entire width or height of the detector. It is possible to set the length of a cell to approximately 15 m for the far detector and to about 4 m for the close detector.

For measuring it is necessary to send a narrow (~10 μs) neutrino pulse for neutrino oscillations to both the far and close detectors. In both detectors cluster interacts nontrivially and leaves a topology, according to the mode of interaction between electron and muon neutrinos (neutral and charged currents)**.**

These are the main objects of this work.

1. Literature survey (attributes, types, etc.).
2. Working out the research method of quenching factor.
3. Measures with radioactive source.
4. Measures with cosmic muons.
5. The results of quenching factor calculations.
6. Detecting flaws of the method and improving it for researching liquid scintillator and quenching factor for α-particles and protons.

1. Literature survey.

1.1 Scintillators and their main attributes.

1.1.1. What is an scintillator?

One of the ways of detecting ionizing radiation in experimental physics is using scintillators. A charged particle passing through a substance leaves its energy inside. Part of this energy is for photon creation. For some substances (scintillators) this part is singnificant, so that the generated light can be detected and measured by photosensors or photodetection. The spectrum and intensity of the light signal depends on the intensity of energy release, and the type of passing particle and attributes of scintillator [1]-[3]. Many scintillators, depending on radiation length, are sencitive not only to charged particles, but also to gamma-radiation and neutrons.

These are the main attributes of scintillators:

1. Light yield
2. The spectral composition of radiation
3. Energy resolution.
4. Decay time.
5. Radiation resistance.
6. Radiation length.
7. Quenching factor.

1.1.2. Light yield.

Light yield is a relation of light flash energy in scintillator to quantity of energy: left by a charged particle. Light yield depends on many factors: the material scintillator is based on, production technology, scintillating doping and additive that shifts the spectrum and also on particles, passing through scintillator. [1][3][4].

$$\chi = \frac{\bar{n} h \bar{\nu}}{E} \qquad (1)$$

where χ −gives the light yield, $\bar{n}$ is the average number of photons: created in scintillator, $h\bar{\nu}$ is average of photon energy, E- is the energy-left by a passing particle [1][3][4].

A scintillator’s light yield is related to decay time this way:

$$L_R = \frac{1}{E_\gamma} \int_0^\infty I(t)dt = \frac{I(0)\tau}{E_\gamma}; \qquad (2)$$

where I −is the light intensity of photos per second, τ is constant luminescence decay, E_γ- is the energy of the radiation absorbed by a scintillator[10].

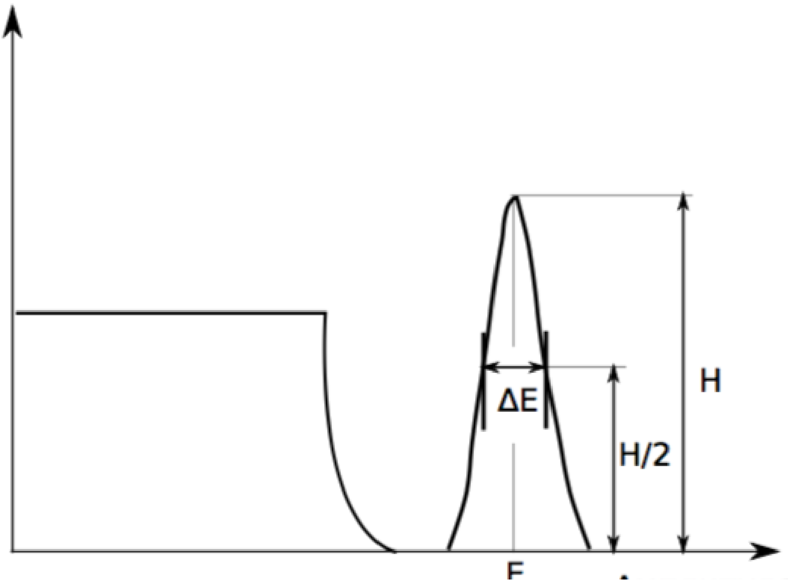
Usually scintillating detectors work at room temperature, although sometimes the range of temperatures changes drastically (research in space, for example). This can affect the scintillator requirements, as the light yield depends on temperature. This can lead to instability of readings. Temperature stability of scintillator is one of the most important properties of a scintillator[3][5].

1.1.3. Spectral composition of radiation.

The spectrum of photons, that leave scintillator should be coordinated with the photosencor's sensitivity in order to reduce the loss of light. If the spectrum is not coordinated with the photosencor's sencitivity, reading like signal intensity, resolution etc., may become inaccurate. For coordinating special additives that change the spectrum are added to organic scintillators. They convert the light from ultraviolet into a visible range. Organic dyes like POPOP are usually used for this purpose [1]-[3]

1.1.4. Energy resolution.

The primary aim of γ- spectrum measurement is the partition of γ $-$quanta into different energies. That is why the width of total absorption peaks in the amplitude spectrum is so important. If a detector and a scintillator could be perfect, a peak of total absorption could be described with δ-fuction. But in practice this peak has some finite width. Energy resolution is determined by the full width al half max of the total absorption peak spectrum(ΔE) of the scintillator (pic.1), related to a E-peak maximum. That shows: the lower is the quantity of energy resolution, the higher is the resolution of scintillator [5].



Pic. 1. Calculation of a scintillator's energy resolution with pulse amplitude spectrum. [10]

The pulse amplitude of the photosensor can differ even when scintillator is irradiated with the same particles with the same energy. It depends on:

- Quantity of scintillator's light signal;
- Scintillator's homogeneity;
- Homogeneity of process of collecting photons on a photodetector;

- Quality of optical contact with photosencor;
- Quantity of quantum efficiency of photocathode for different wavelengths.
- Quality and stability of the photodetector's amplification[5];

1.1.5. Decay time.

Decay time is a duration of the process of converting energy left in a scintillator by a particle into light radiation. A Flash decays according to a law. When the centers participating in luminescence are the same, a flash in scintillator decays according to exponential law.

$$I = I_0 e^{-t/\tau} \;, \qquad (3)$$

Where I_0– is an amplitude of light pulse, a τ – is decay time of scintillator's luminescence[3][5].

1.1.6. Radiation resistance.

For many experiments one of the most important attributes of the detector is the ability to retain its scintillation abilitiesy in harsh operating conditions. For example, in research within space thermal and vibration resistance are very importan. In geophysics resistance to temperature changes is also improtant. Radiation resistance is one of those attributes, it means that scintillator is able to keep its attributes while being ionized. It is important in nuclear physics, high energy physics and in electromagnetic calorimeters. In a calorimeter the scintillator should be able to keep its light yield constant for at least 10 years of work while enduring a radiation dose of 10^4 Gy.

These processes contribute to a scintillator's degradation.

- When absorbing ion radiation a scintillator forma the colour centers, that create absorption bands, which decrease transparency of a material and lower the light yield.
- Luminescence centers, that are responsible for scintillation, may reorganize or change due to the absorption of high energy quanta.
- Polynomial trapping centers appear in scintillators, which leads to an increased contribution of afterglow.
- Heavy crystals after being irradiated by neutrons, protons, etc. may become radioactive, which can change the quality of measurements[5].

1.1.7. Radiation length.

Unlike charged particles, that have a constant passing range, γ-rays change their intensity *I* exponentially when passing through substance lay with thickness X:

$$I = I_0 \, e^{-x/x_0} \quad . \qquad (4)$$

Diminution speed depends on substance density (ρ) and on the average atomic number (Z) . The bigger these quantities are, the more efficiency of interaction between radiation and substance. It is often described as so called radiation length - coefficient - X_0, within in the exponent (4) and being responsible for intensity change. So, radiation length matches the thickness of substance lay. When it passes through the lay, the radiation intensity decreases, being divided by *e* times.

1.1.8. Quenching factor.

Particles, that are different by their nature, but having the same energy, give different light pulses while passing through scintillator. Heavy particles (protons, α-particles, heave ions) give fewer (in comparison with electrons and muons etc.) photons. Quenching factor is the relation of these type of particles to light yield for electrons.

The classic explanation of this phenomenon is situated in work of J. Birks written in 1951 [10]. Later it was discussed in works [11] and [12]. The phenomenon is the following:

Any particle, passing through a scintillator, energizing some quantity of excitons (quasi-particles - elementary excitations), that makes luminescent additive generate light after passing through. Light particles (electrons, muons) that pass through scintillators, create excitons without damaging the molecules around. Unlike light particles, heavy particles passing through scintillator material not only create excitons, but also damage molecules along the way. So a locally damaged section is created. One property of damaged molecules is that they intensively absorb excitons while not creating light. So, higher ionizing ability of particles lead to suppressing light pulse.

Quenching factor is a very important attribute of any scintillator. If we don’t know the quenching factor, we can not say what kind of particle passed through the scintillator and what kind of energy it had. So, for example, in large neuitrino experiments (Daya-Bay, JUNO, NOvA, DANSS) it is very important to know the accurate value of quenching factor for the scintillator.

1.2. Types of scintillators.

1.2.1. Inorganic scintillators.

It’s possible to have a higher average atomic number in inorganic crystals, so they are used more often for detecting γ-radiation.

These are the most popular inorganic scintillators:

- NaI(Tl)
- CsI(Tl)
- BaF_2
- BGO
- $PbWO_4$
- LSO

Their main attributes are shown in tab. 1.

NaI(Tl) has the best light yield (40000 photons per 1 MeV of energy), but it is very hygroscopic (requiers a sealed body). In spectrum with a peak of 415 nm works well with spectral sensitivity of most photomultipliers [3].

CsI(Tl) has good light yield, it’s easy to work with and not so hygroscopic. The spectrum of its radiation has a peak of 515 nm and works well with silicium photodiodes.

BaF_2 is the quickest of inorganic scintillator and has two temporal components. One with decay time 0,9 nsec, the other one - with 630 nsec. $\gamma-$quant activate the fast component, and $\alpha-$particles activate the slow one, which allows it to identify both particles.The radiation spectrum of BaF_2 has 2 peaks: one in ultraviolet range (about 200 nm), and the second in the border (about 320 nm) [3].

BGO ($Bi_4Ge_3O_{12}$) has a better density and smaller radiation length X_0 =1,12 cm, not hygroscopic and is easy to work with. The peak in its radiation spectrum is about 480and it works well with silicium photodiodes. [3][4].

$PbWO_4$ has the highest tensity (radiation length X_0=0,89 cm) and very little decay time (5-15 nsec) [3][7]

LSO has a high density, good light yield andsmall decay time, but it has a ^{176}Lu isotope, which makes it radioactive.[3][6].

Table 1. Physical and scintillation characteristics of some scintillators [6].

Material	ρ, [г/см^3]	X_0, [см]	Y, [фотон/МэВ]	τ, [нс]	λ, [нм]
CsI	4,51	2,43	16800	10	515
BGO	7,13	1,12	8200	300	480
$PbWO_4$	8,28	0,89	200	6	420
LSO	7,4	1,1	27000	40	420

1.2.2. Organic scintillators.

As they consist of light atoms, their Z number is not big, so they are mostly used for detecting charged particles. In experimental physics plastic and liquid organic scintillators are used more often than the crystal variety.

Organic plastic scintillators have a small decay time (2-4 nsec), good light yield) and they can be created in any size or form. Scintillators based on aromatic hydrocarbon compounds are often used. They have a weak light yield and are not very transparent to their own radiation. To make a scintillator out of it, we must shiftheir radiation from the ultraviolet to the visible spectrum. They usually have 3 components: the base (polystyrene), luminescent additive (p-terphenyl) and a spectrum shifter (POPOP) [3][7][8].

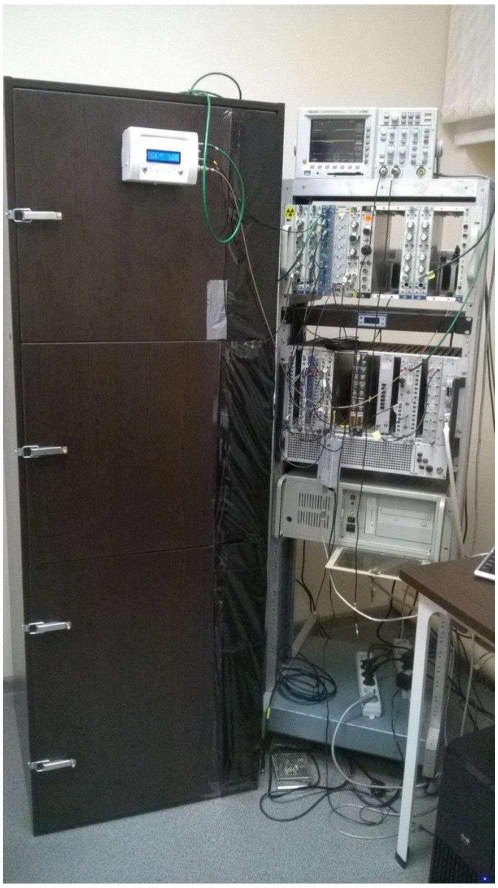
In liquid organic scintillator are often used solvents like toluene, xylan, benzene, alkylbenzene, luminescent additive p-terphenyl ($C_{18}H_{14}$), PBD ($C_{20}H_{14}N_2O$), butyl-PBD ($C_{24}H_{22}N_2O$) and spectrum shifter POPOP ($C_{24}H_{16}N_2O$). Liquid organic scintillators have a little decay time (1-10 nsec). While working with them, it’s important to isolate the substance away from O_2.

2. Experimental part.

2.1. Measure stand.

2.1.1. Mechanic works.

Not only radioactive sources, but also cosmic muons were measured. Muons are created after the decay of charged pions, that are created in the higher layers of atmosphere by the primary cosmic rays. Muon levels in the room, where measurement wasconducted was 100-150 muons per m^2, and they enter mostly from the upward direction. For using them was created a telescope and muon detectors that are situated higher and lower than the sample. That is shown on the pic.3.



Pic. 3. Impermeable closet.

All the connections of the closet are shielded from the light. By the perimeter of each door, there’s a hard skirting to limit background light as well. There are 2 scintillating plates of telescope and PMT Air waveguide in upper and lower sections. The size of plates is 500x500x50 mm. The central section is for placing radioactive sources and the samples.

2.1.2. Protection from random opening.

There is a double defense on each section :

1. In order to protect from accidental opening in each section there is an auto-switch that breaks the chain if the door is opened. (Pic. 4a).

2. There is also there is a special hole for the LEMO interblock connector, which is a socket for 50*Ω* charge, it looks like a plug (Pic. 4б). The lock cannot be opened until you remove the plug our and break the chain.

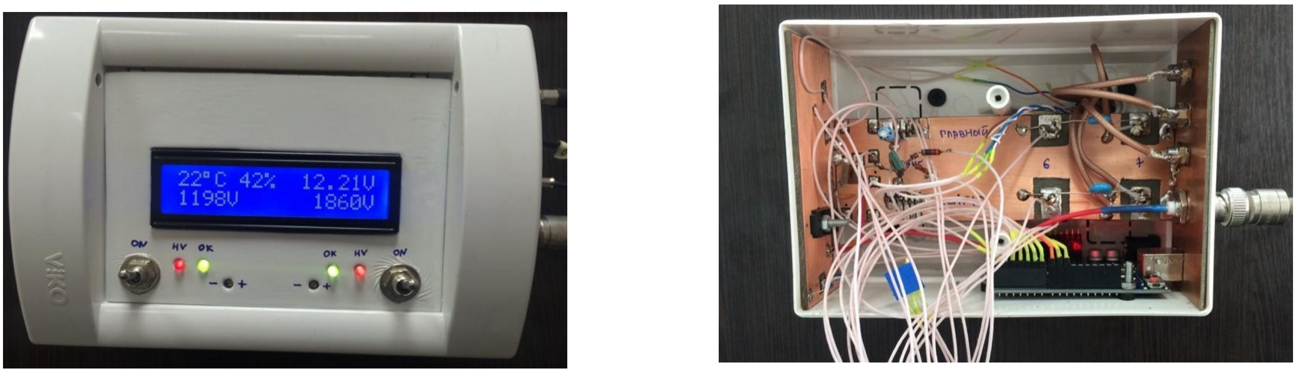
Pic. 4(a). Autoswitch.

Pic 4(б). A lock with a plug

2.1.3. Indication block.

In order to improve the installation, there is a control block (pic. 5), that is set on the closet. It has a control panel for the charge transformer and can monitor such attributes:

- Input charge;
- Output charge of every transformer;
- Central camera temperature;
- Central camera humidity;
- Regulation of output charge of every transformer;
- Indication of permission for giving high charge;

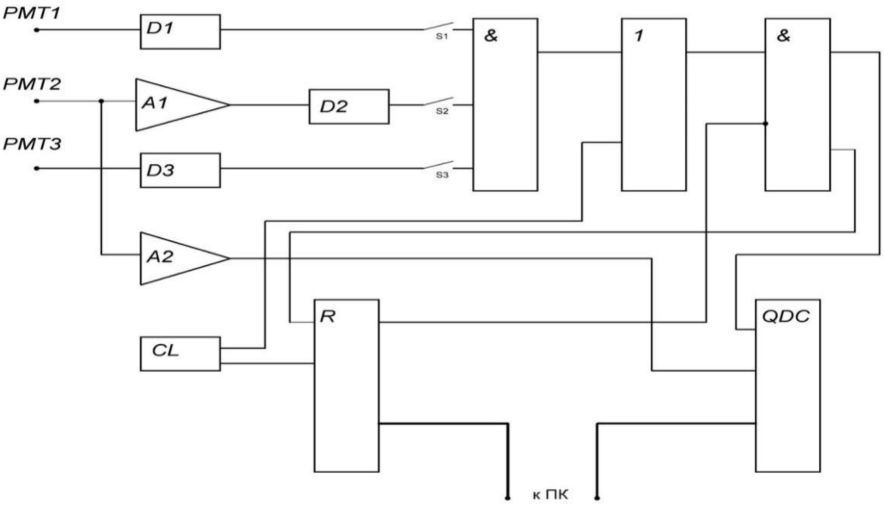


Pic 5.Control block outside and inside.

2.1.6.Outter electronics and connection to PC.

The control block had 3 signals output from the PMT. Before sending a signal to the analog-to-digital converter we need to form a signal and a logical scheme (pic. 7), that would control the ADC. The following are used in the scheme:

- Controller
- Input register
- Discriminator
- Analog-to-digital converter
- Signal amplifier
- Scheme AND
- Scheme OR
- 50Ω cables



Pic. 7. Block scheme of outer electronics (D– discriminator, A– amplifier, 1 – scheme OR, > – scheme AND, CL – pulse generator, QDC – Analog-to-digital converter, R – Input register).

2.2. Measurement process.

We have a solid organic scintillator, with diameter is 73.7 mm, which suits our PMT input box.

Tab. 2

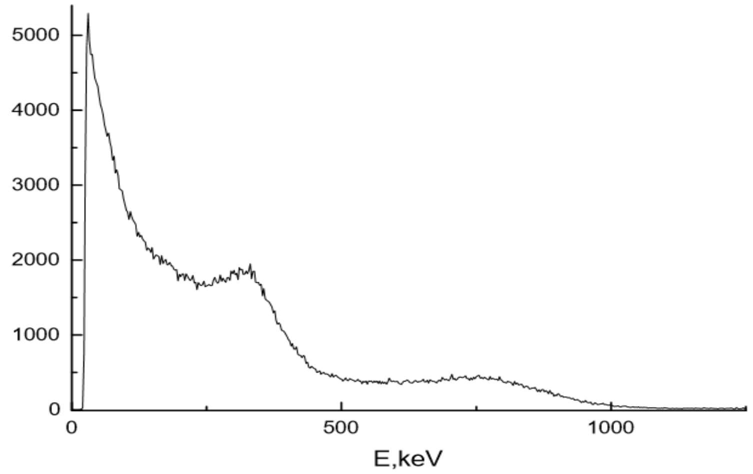
Sample	The target thickness $\frac{[г}{см^2]}$	State of aggregation	Chemical composition
Polystyrene scintillator	1,05	Solid	2 % - paraterphenyl 0.05 % - POPOP 97 % - polystyrene

Procedure:

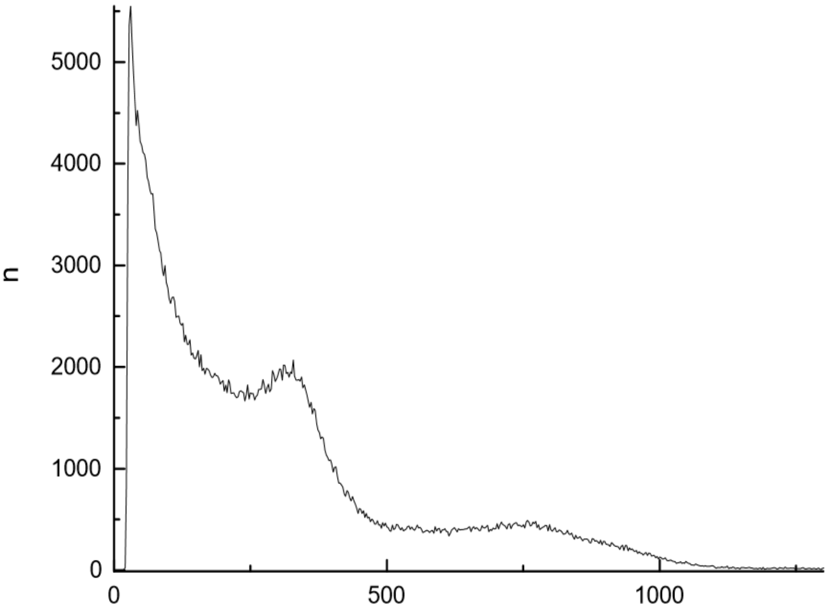
1. Measure the target thickness of a sample – the sample it weighed and its mass is divided by plate area.
2. We place a radioactive ^{207}Bi -5,11 cm above the target.
3. The first measurement was made with an absorber (10 mm of teflon), that was situated between the target and the source for electron absorption. The spectrum we have detected consists of γ-rays only. (pic 7)
4. The second measurement was also with ^{207}Bi, but without the absorber and without changing conditions. This spectrum registers γ-rays and electrons which convert within the interior of (pic. 8)
5. By deduction we obtained a difference spectrum corresponding to electrons. (pic. 9).
6. By this spectrum we made energy calibrations for detector: spectrum from the generator was taken as 0, and for known energy we take center of mass of a multiplet (4).

$$E = \frac{E_k * k + E_l * l + E_m * m}{k + l + m}; \qquad (4)$$

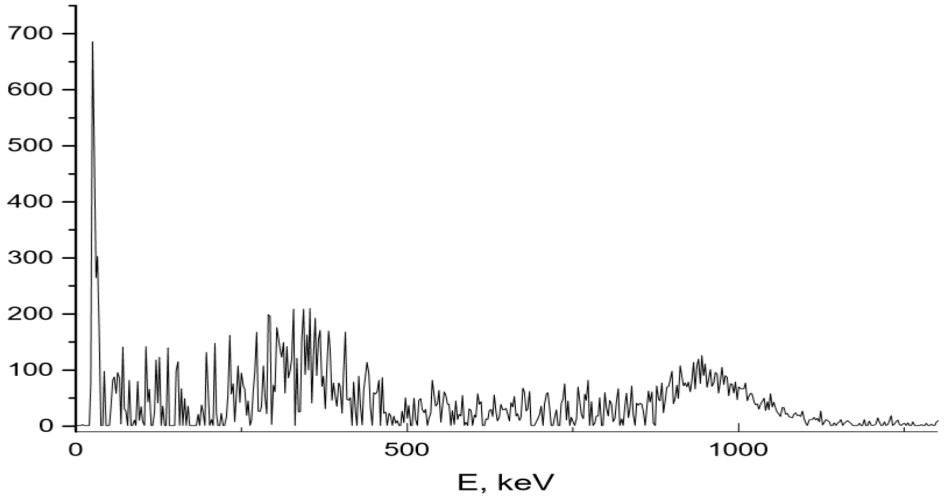
where E_k is energy of electrons of k shell, $E_l -$ energy of electrons of l shell, $E_m -$energy of electrons of m shell, k,l,m are weights.



Pic. 8 γ only

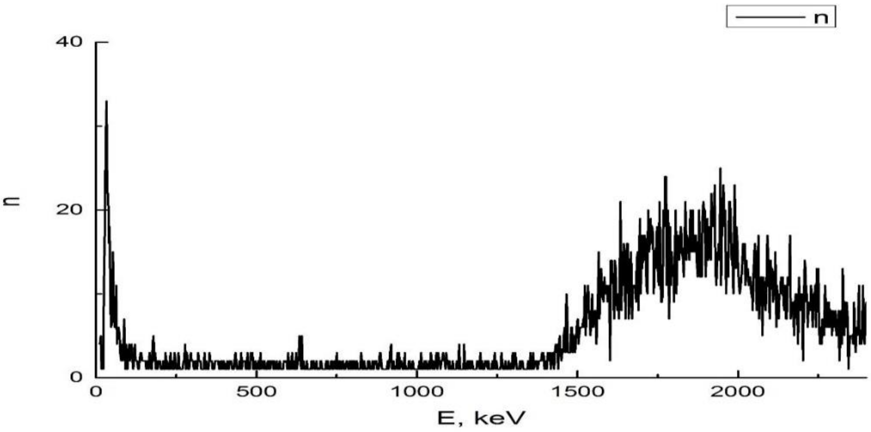


Pic. 9 γ and electrons



Pic. 9 Electrons only

Next we performed measurements with cosmic muons. For this we turn on the scheme of matching from 2 plates, which allowed us to accept the vertical muons. The spectrum we have is a spectrum of relative muons, their energy emission looks like a Landau distribution (Pic. 10). For this spectrum we've calculated the median of distribution. The energy we've measured was compared with theoretical data obtained by Monte-Carlo method [24].



Pic10.Energetical distribution of a singal from muons in a polystyrene scintillator.

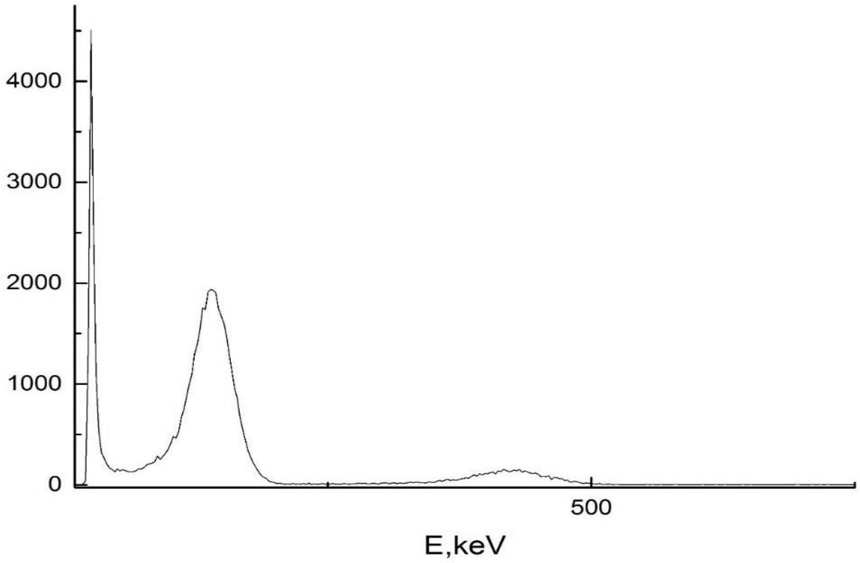
2.2.2. Measurements with α-particles.

One feature of α-particles is a small penetrating distance. For α-particles with energy of 6 MeV the penetrating distance in air is 4,6 cm. We've measured it in another geometry in order to decrease the effect of air. Both α-particles and ^{207}Bi were set over the sample at a distance of 1-2mm. It wasn't a flawless geometry. α-particles irradiated a very small park of the scintillator, while electrons may go deeper and deposit energy over the full depth (not full square though). As a result, the light from the α-particle passes to the PMT though a greater distance than the light from the electron. That leads to weakening of an α-particle signal and strengthening of quenching factor if transparency is less than 100%. In order to decrease the error we need to spread α-activity though the entire scintillator, which is not possible at the moment.

The measurement took 5 minutes without changing the position of a plate on PMT input box.

Source	Radiation type	Energy [keV]	decay part [%]	center of mass [keV]
^{148}Gd	α-particles	3182,69	100	3182,69
+				
^{244}Cm	α-particles	5762,64 5804,77	23,1 76,9	5795,04

The spectrum has a peak in energy. After energy calibration we can calculate the energy of that peak and compare it to the theoretical one. The difference will be due to the of quenching factor we are looking for.



Pic. 11 spectrum of α-source, detected on polystyrene scintillator

2.2.3. The results of quenching factor for α-particles.

Tab. 3

source	theoretical energy, [keV]	experimental energy, [keV]	quenching factor*
Сцинтиллятор на основе полистирола			
^{244}Cm	5795.04	423,1 ± 2.6	13.6
^{148}Gd	3182.69	139,4 ± 1	22,8

As we can see, quenching factor for α-particles is about 10-25, and it is increasing when the energy decreases. This correlate with theoretical calculation of J. Birks. This may be show even greated role of energy loss in the air.

2.2.4. The results of quenching factor for muons.

Tab. 4

Measure length, [sec]	Median of theoretical energy, [keV]	Median of experimental energy, [keV]	quenching factor
Polystyrene scintillator			
57600	2.2148	2.011	0.91

Unlike α-particles, muons should have no quenching (its quenching factor shoul be 1), although all the measured meanings were less than 1

There are some explanations. Part of the electron energy is lost in a dead body of a source, another portion is wasted on passing through air lay between the source and the scintillator (5,11 cm), and yet another portion is wasted in a dead lay of scintillator. That is why we see at signal not of their base energy (993.789 keV), but of a lesser energy. Moreover, compton scattering of gamma rays have an can affect as well.

3. Conclusion

We've made a literature survey of scintillator and their basic attributes in the work. We've calculated quenching factor of some scintillators, basing on that data. Our experimental data correlates well with that theories of J. Birks.

It is worth mentioning that our geometry is not perfect. α-particles irradiate small part of the scintillator in depth and area, while electrons can go much deeper and give energy emission in all the depths (although not of all the area). As a result, the light from the α-particle passes to the PMT through a greater distance than the light from the electron. That leads to weakening of an α-particle signal and strengthening of quenching factor if transparency is less than 100%. In order to decrease the error we need to spread α-activity though the entire scintillator, which is not possible at the moment.

At this stage, we have a variety of problems, the solving of which could have improved our results and would allow us to increase the accuracy of an experiment. The main problem is the instability of the environment, which is evidenced by the experiment with liquid scintillator. So, we have some suggestions:

1. Make the cell diameter for the experiment is less than the parameters of the PMT.
2. The cell should either connect to the PTM with a necessity to invent and cleaner and filler for this cell or the cell should be removable, but it should have ports on its circle, where we should pour liquid to provide the complete absence of air between the cell and the PMT.
3. For α-particles we should make the square of a source the same as the cell in order to get better research

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