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N.I.Balalykin, I.A.Golutvin, O.I.Kochetov, V.D.Kuznetsov,
V.K.Makoveev, G.V.Myshinski, A.F.Novgorodov,
V.G.Shabratov, A.G.Volodko, V.S.Klimenko[1], A.S.Kurilin[2]

MEASUREMENT OF THE PLASTIC SCINTILLATOR RESPONSE IN THE MAGNETIC FIELD

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[1] Institute for Nuclear Research, Moscow
[2] National Scientific Center, Minsk, Belarus

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INTRODUCTION

Any modern high energy physics experiment, especially a collider experiment, uses the hadron calorimeter as the main part of its apparatus, and practically in any hadron calorimeter there is used a plastic scintillator for shower detection. All this is taken into account for light yield investigations of various organic scintillators for different incoming charged particles (electrons, muons, pions, etc.). In his original "classic" papers [1] J.B.Birks made the following statement: "Scintillating response **L** is a monatomic function of **dE/dx** and independent of the nature of the ionizing particle"

$$L(E)=\int_0^E \frac{1}{1+kB\bullet dE/dx}\,dE \ , \qquad (1)$$

where S and kB (Birks coefficient) are constants characterizing the scintillating material.

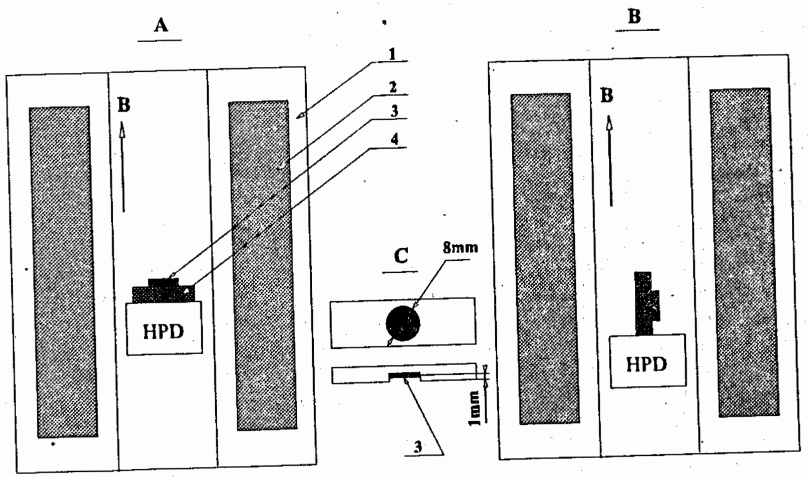
A series of investigations [2,3] have confirmed this conclusion.Resently a model [4] was formulated, which permits to make computing calculations of light response for different scintillating materials.It was found later light yield of plastic scintillators in magnetic field is dependent on the value of the field, but " this dependence is rather complex and has no clear explanation up to now".

In 1994-95 test beam runs with copper hadron calorimeter prototype for the CMS apparatus in H2 SPS CERN superconducting magnet (magnetic field up to 3 Tesla), dependences were found and measured of light yield *vs.* magnetic field for different particles (e, μ, π) not only on the value of this field but also on its orientation.These dependences differed for different field orientations—along or transverse to the shower directions, and for transverse magnetic field case these dependences are different for different particles. In the present work we tried to undertake more or less systematic investigations of the influence of the magnetic field value and direction on the light yield of plastic scintillators irradiated by different radioactive sources.

EXPERIMENTAL SET-UP AND MEASUREMENT PROCEDURE

The layout of our experimental set-up is shown in Fig.1. First of all it has a superconducting solenoidal magnet with the following parameters:

- acceptable "working" volume has 9 cm in diameter and 22 cm in length
- values of magnetic field are changed from 0 up to 3.8 Tesla with precision less than 1%
- nonuniformity of the magnetic field in "working" volume is less than 1% stability of the magnetic field is less than 0.01%.



1. Cryostat
2. Superconducting solenoid
3. Radioactive source
4. Scintillator

Fig 1. *Lay-out of the experiment.*
A) - for longitudinal magnetic field measurements
B) - for transverse magnetic field measurements
C) - structure of the radioactive source

Secondly what makes our measurements mainly different from all the others that we used for the light detection a new type of the photodetector-HPMT (Hybrid Photomultiplier Tube) or HPD (Hybrid Photodiode)- which was checked and used at CERN in H2 Superconducting magnet . In all previous investigations physicists used the standard photomultipliers,therefore they had to use long (more than 1 meter) lightguides to avoid the magnetic field influence on PMT. Due to that the signals dropped strongly and it was impossible to receive the quantative , amplitude spectrum.These problems disappeared when one uses HPD , especially when the outer magnetic and inner electric field directions are parallel, as in our case. During our experiment the behavior of HPD was conrolled by the light generator (light diode AL-102A) via the long quartz fiber. Stability of the light diode peak position in common amplitude spectrum was better than 0.6%

with the amplitude resolution (FWHM) better than 3%. The signal from HPD was going to the low noisy preamplifier, developed at IHEP (Protvino) and working in the magnetic field too. After that the signals were going to the spectrometric amplifier SU-4K and finally to PC-386.

And last one - the following radioactive sources which were prepared had well defined energy peak structures in the amplitude spectra:

α-source - ^{241}Am (E_α^{peak} ~ 5479 keV) and

β-source - ^{137}Cs (E_e^{peak} ~ 630 keV)

β-source - ^{207}Bi (E_e^{peak} ~ 976 keV)

Electrons in these sources are produced via the inner conversion process. All these sources were prepared by the mass separation and mounted on the special lining (see Fig.1).The absolute activity of these sources was measured separately. It can be seen from Fig.1 that the solid angle for any source irradiation is a little bit less than 2π.

Sources and scintillators were checked without magnetic field on the spectrometric photomultiplier FEU-85.These original spectra are shown on Fig.2.Our measurements were made in the two configurations when the magnetic field was parallel (A) and perpendicular (B) to the main direction of the charge particle moment to the scintillator (see Fig.1). The preliminary results of this investigations were reported at the CMS Hadron Calorimeter Workshop in August 1995 (IHEP, Protvino).

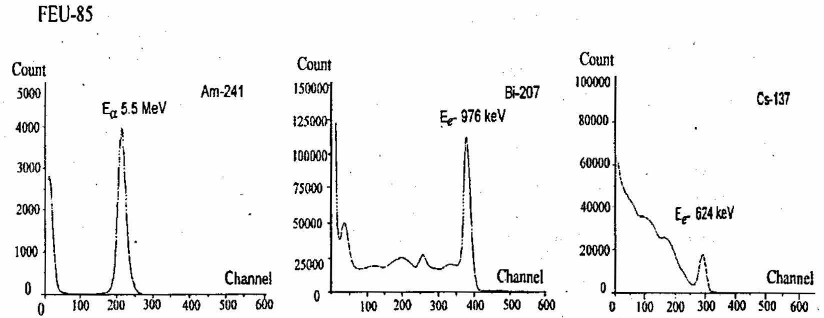


Fig 2. *Original spectra for ^{241}Am, ^{207}Bi and ^{137}Cs sources. (spectrometr in photomultiplier FEU-85).*

The measurement procedure was the following: from one setting of the radioactive source (magnetic field-along or perpendicular to irradiation) there was measured the amplitude spectrum as value of the magnetic field.The total number of events, the peak position and the number of events under peak were calculated.

It should be specially noted, absolutely all previous measurements were made in such a way that signals were detected above some threshold, which was defined by the properties of PM's , the length and characteristics of light guides , scintillators and radioactive sources itself.In our measurements we tried to avoid any uncertanties:HPD was controlled permanently, light guides were absent, well known **NE-110** scintillator was used for main measurements, radioactive sources were calibrated previously. Five minutes irradiation was selected for sufficient statistical accuracy.

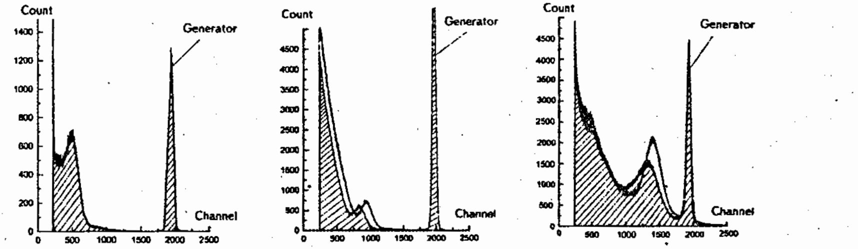
RESULTS

A. Longitudinal magnetic field

Fig.3 (a,b,c) shows the amplitude spectra for **^{241}Am (α-source)** , **^{137}Cs** and **^{207}Bi (β-sources)** at two different values of the magnetic field (0 and 3.8 Tesla),when the field direction is parallel to the main direction of the moving charged particles. Typical errors were ~ **0.7%**.One can see that for α-particles both the full energy spectrum, the peak position and intensity under peak do not practically change.

☐ - *3.8 Tesla*

▨ - *no magnetic field*



a. b. c.

Fig 3. *Amplitude spectra for (a) ^{241}Am, (b) ^{137}Cs and (c) ^{207}Bi at two values (0 and 3.8 Tesla) longitudinal magnetic field.*

For the β-spectra the picture is different.Beginning from the very small field value (~10 Gauss) both **^{137}Cs** and **^{207}Bi** peaks move to the right side (to bigger values of the light output).The full intensities and intensities under the peak are rising also. In Table 1 are given the behavior of the peak position full intensities and intensities under peak via magnetic field values for **^{241}Am**, **^{137}Cs** and **^{207}Bi** respectively. We think that the intensitiy rising has a simple explanation because the longitudinal magnetic field twists the electron trajectory around field direction and "involves" into the scintillator particles, which would escape the detector without field (the source is 1 mm away from the scintillator).

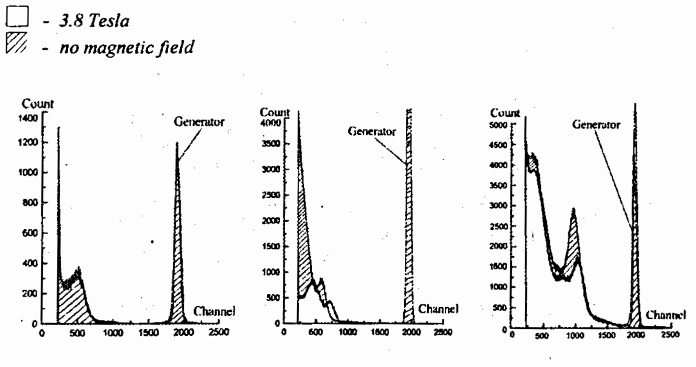
Table 1.

Magnetic field **B** (Gauss)	^{241}Am			^{137}Cs			^{207}Bi		
	$\frac{P-P_0}{P_0}$ (%)	$\frac{S-S_0}{S_0}$ (%)	$\frac{I-I_0}{I_0}$ (%)	$\frac{P-P_0}{P_0}$ (%)	$\frac{S-S_0}{S_0}$ (%)	$\frac{I-I_0}{I_0}$ (%)	$\frac{P-P_0}{P_0}$ (%)	$\frac{S-S_0}{S_0}$ (%)	$\frac{I-I_0}{I_0}$ (%)
10	-	0.7	-	0.7	0.1	-0.5	0.7	-1.4	-0.4
40	-	-	-	0.5	-2.1	-0.1	0.5	0.9	0
100	-	-	-	0.7	0.4	-1.0	0.7	1.1	0
400	-	-	-	1.1	-2.6	-0.8	1.1	0.9	0
10000	-	-	-	5.5	4.3	10.3	5.1	4.6	-0.2
15000	-0.006	-0.001	-0.001	-	-	-	-	-	-
20000	-	-	-	5.7	26.1	17.0	5.3	20.9	1.5
30000	-0.015	-0.007	-0.006	5.9	48.0	16.9	6.4	28.4	1.4
38000	-0.004	-0.001	-0.001	6.3	59.0	18.3	6.2	38.0	2.1

Where: *P - center of peak position at zero field;*
P_0 - center of peak position at current field;
S - intensities under peak at zero field;
S_0 - intensities under peak at current field;
I - full intensities peak at zero field;
I_0 - full intensities peak at current field;

B. Transverse magnetic field

Fig.4 (a,b,c) shows the amplitude spectra for ^{241}**Am** , ^{137}**Cs** and ^{207}**Bi** at two values of the magnetic field (0 and 3.8 Tesla), when the field direction is perpendicular to the main directions of the charge particle movements. It is seen that for α-particles the behavior of the full spectrum, the peak position and intensity under peak are practically the same, as in the case of the longitudinal magnetic field.In Table 2 are given the behavior of the peak position, full intensities and intensities under peaks via magnetic field values for ^{241}**Am**, ^{137}**C** and ^{207}**Bi**,respectively.



a. b. c.

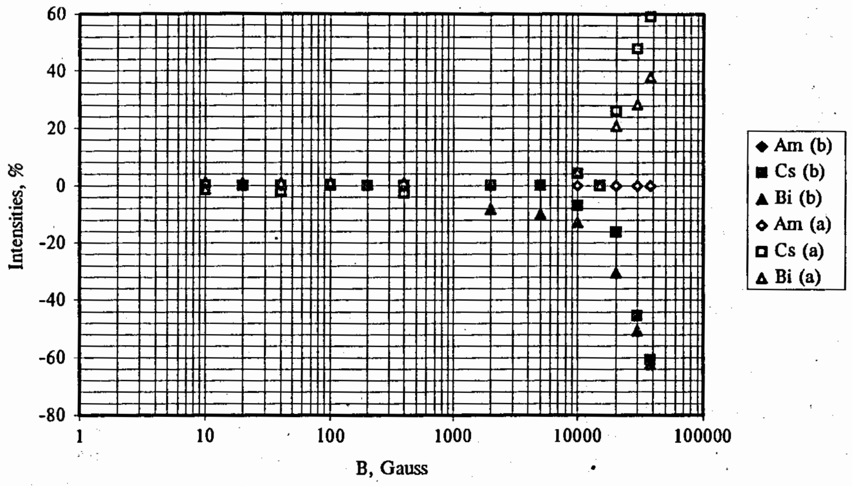
Fig 4. *Amplitude spectra for (a)* ^{241}*Am , (b)* ^{137}*Cs and (c)* ^{207}*Bi at two values (0 -3.8 Tesla) transverse magnetic field.*

Table 2

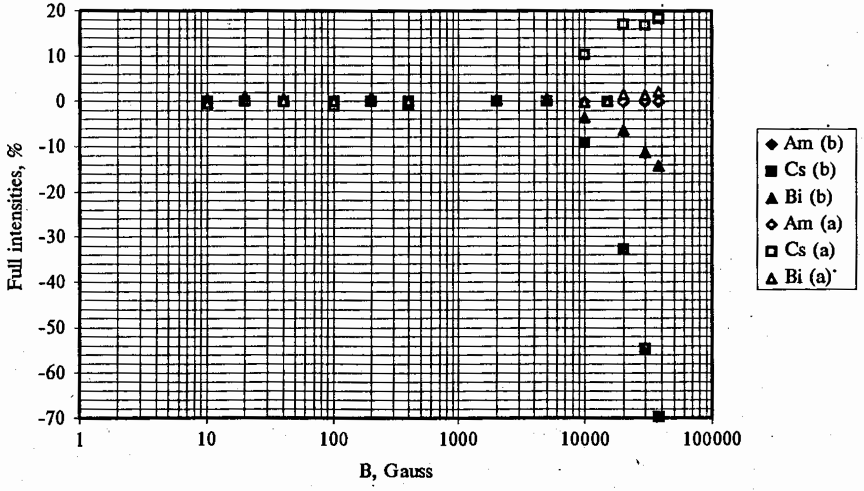
Magnetic field B (Gauss)	^{241}Am			^{137}Cs			^{207}Bi		
	$\frac{P-P_0}{P_0}$ (%)	$\frac{S-S_0}{S_0}$ (%)	$\frac{I-I_0}{I_0}$ (%)	$\frac{P-P_0}{P_0}$ (%)	$\frac{S-S_0}{S_0}$ (%)	$\frac{I-I_0}{I_0}$ (%)	$\frac{P-P_0}{P_0}$ (%)	$\frac{S-S_0}{S_0}$ (%)	$\frac{I-I_0}{I_0}$ (%)
10	-	-	-	-	-	-	0.1	1.2	0.5
20	-	-	-	-	-	-	0.6	0.9	1.1
40	-	-	-	-	-	-	0.8	0.3	0.6
100	-	-	-	-	-	-	1.0	0.5	0.3
200	-	-	-	-	-	-	1.0	0.3	0.9
400	-	-	-	-	-	-	1.1	-0.3	0.0
2000	-	-	-	-	-	-	3.7	-8.3	0.4
5000	-	-	-	-	-	-	4.2	-10.0	0.6
10000	-	-	-	6.3	-7.0	-9.1	6.3	-13.0	-3.6
20000	0.016	-0.2	-0.16	5.6	-16.2	-32.9	6.4	-30.5	-6.4
30000	0.08	-0.2	-0.15	5.8	-45.4	-54.6	6.1	-50.6	-11.3
38000	0.02	-0.24	-0.21	5.9	-60.8	-69.8	5.9	-62.4	-14.4

Where: P *- center of peak position at zero field;*
P_0 *- center of peak position at current field;*
S *- intensities under peak at zero field;*
S_0 *- intensities under peak at current field;*
I *- full intensities at zero field;*
I_0 *- full intensities at current field;*

As in the case of longitudinal magneic field, one can observe practically the same shifts of the peak positions via magnetic field values. The full intensities and intensities under peaks in the β-spectra are decreasing visibly with the arising magnetic field values, especially in the soft parts of spectra. This is quite so because magnetic field turns electrons so strongly that they avoid the detector (1mm distance between the source and the scintillator). Fig.5 (a,b) shows the behavior of full intensities and intensities under peaks measured values for longitudinal and transverse magnetic fields.



a)



b)

Fig 5. *Intensity under peak (a) and full intensity (b) for* ^{241}*Am,* ^{137}*Cs and* ^{207}*Bi vs magnetic field value.*

DISCUSSION

From our measurements we can conclude that there exist , as minimum, two effects for magnetic field influence on the light output of the plastic scintillators. First one is connected with the changing of the detecting intensity, especially in the case when magnetic field is perpendicular to the charge particle trajectory and the irradiating source is outside of the detector. This effect must vanish for the 4 -detector. Later we propose to check this conclusion.

Second effect—the growth of the light output on ~**7%** at the magnetic field value more than 1.0-1.5 Tesla, is connected with only the magnetic field value and independent from the field direction.We made measurements of the light output with other types of plastic scintillators (made in Kharkov,Protvino) and received practically the same results.On Fig.6 are shown our data for the "movement" of peaks in amplitude spectra together with previous investigations /5,6,7,8,9/ . From this picture we can conclude that in this measurements due to "threshold conditions", as it was mentioned above, it is detected exactly our "peak-movement"effect.In papers /7,8/ it was checked the connection of this effect with the excitation of fluorescence levels, but UV-irradiation of these levels does not confirm the such proposition. Anyway we propose to check light irradiation later.

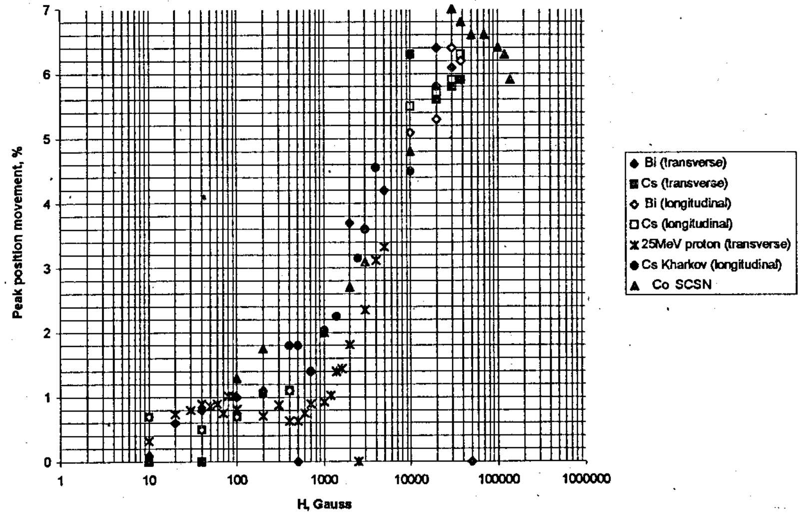


Fig 6. *Accumulated data for light field vs magnetic field value.*

More attractive it seems the model of the light output proposed in papers /11,12/, so called M & D-model.This model assumes that the light-emitting process in a scintillator is induced by the electrons scattered by the charge particle along its path. Limited by their linear penetration,these Coulomb scattered electrons deposit their energy in the vicinity of the charge particle trajectory. The luminescence **dL** produced along a differential sector of the length **dx** (measured along trajectory) is assumed to be proportional to the number of electrons penetrating a transverse area, i.e

$$\frac{dL}{dx} \approx \int_{r\min}^{r\max} I(r)dr \qquad (2)$$

where **I(r)** is the electron flux distribution in the radial direction (r), perpendicular to the particle trajectory. The electrons scattered with kinetic energy below the average ionization energy of the scintillator are confined to radial distances $\mathbf{r} < \mathbf{r}_{\min}$ .The light emitted within this small region is neglected by the model. The $\mathbf{r}_{\max}$ integration limit is associated with the range of electrons having the maximum transferred energy from particle-electron Coulomb scattering.

In this model the concept of saturation of luminescence centers is introduced by the requiring that the density of penetrating electrons does not exceed a maximum value ρ_{sat}.This condition defines a critical radial distance $\mathbf{r}_c$ below which the light output reaches a maximum (constant) value.Thus, assuming that **dL/dx** remains approximately constant along a small finite segment of the particle trajectory, the corresponding light output is taken to be

$$\frac{\Delta L}{\Delta X} = K\left[\pi\left(r_c^2 - r_{\min}^2\right)\rho_{sat} + \int_{rc}^{r\max} I(r)dr\right] \qquad (3)$$

with $\mathbf{K} = \boldsymbol{\sigma}.\mathbf{n}$, where $\boldsymbol{\sigma}$ -represents the cross-section for luminescence production and **n** is the number of scintillation sites per unit volume.Need to note that in this model **r** is directly connected with the electron energy **r = k .E**.

We propose that in the outer magnetic field case, this field, from some value, turns scattered electrons back and therefore "flux" of them arises up to the moment when all scintillation sites in the trajectory vicinity are excited(saturation effect). We think that the magnetic field value for our plastic scintillator saturation is around **1.0 - 2.0 Tesla**, and according to such model this effect is independent of the magnetic field direction but must be dependent on the scintillation sites concentration.

For the α-particle irradiation due to very short α-particle range (few **μm**) and the scattered electron density the saturation is produced immediately without any field. For **25 MeV** protons /7/ (measureble ranges) the effect was detected approximately the same as for electrons from sources (see Fig.6).Later the M & D model was successfully developed for other scintillating materials in the high energy physics .Thus the high light yield, which was detected for hadron calorimeter in the transverse magnetic field /9/ is connected probably with the primary particle nature (the type of shower) and with the rise of secondary shower particle lengthes in the scintillator media and therefore must be directly connected with the shower and field mutual orientation.

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Балалыкин Н.И. и др. E1-96-239
Измерение световода пластических сцинтилляторов
в магнитном поле

Представлены результаты измерений зависимостей световода пластических сцинтилляторов от величины и направления магнитного поля. Величина магнитного поля изменялась от нуля до 3,8 Тесла. Сцинтилляторы облучались электронами (^{137}Cs и ^{207}Bi) и альфа-частицами (^{241}Am). При облучении электронами регистрируемые световые спектры показывали две зависимости: одна из них — зависимость спектра только от величины магнитного поля, а вторая — от его направления в том случае, если радиоактивный источник находится вне сцинтиллятора. Величина и поведение первой зависимости согласуются с результатами предыдущих работ.

Для случая альфа-частиц световоды практически не зависят ни от величины, ни от направления магнитного поля.

Работа выполнена в Лаборатории сверхвысоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1996

Balalykin N.I. et al. E1-96-239
Measurement of the Plastic Scintillator Response
in the Magnetic Field

We present the results of measurements of the light yield dependences for the plastic scintillators on magnetic field value and operation. The magnetic field value was changed from 0 up to 3.8 Tesla. Scintillators were irradiated by electrons (^{137}Cs and ^{207}Bi) and by alpha-particles (^{241}Am). The detected light spectra in the electron irradiating cases show two dependences: the first one is the dependence on the magnetic field value only and the second — light output is dependent on the magnetic field orientation when the radioactive source is outside of the scintillator. The value and behavior of the first dependence agree with the data published earlier.

Under alpha-particle irradiation the light output does not depend on the magnetic field value and orientation practically.

The investigation has been performed at the Laboratory of Particle Physics, JINR.

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