Advantages and Limitations of LSO Scintillator in Nuclear Physics Experiments

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Abstract

Light yield, light pulse shape due to γ-rays and α-particles, energy and time resolutions for three different samples of the LSO scintillator were studied using an XP2020Q photomultiplier and an S3590-03 photodiode. Light yields of 4200±200 phe/MeV and 18500±900 e-h pair/MeV were measured for the PM tube and the photodiode, respectively. The light pulse shape exhibits a pure exponential decay with a time constant of 47.2±1.3 ns for both γ-rays and α-particles. Energy resolutions of 10% and 14.6% for the 662 keV γ-rays from a ^{137}Cs source were obtained for the photomultiplier and the photodiode readout, respectively. A time resolution of 180 ns was observed for ^{60}Co γ-rays at 1 MeV threshold and 400 ps for 100 keV threshold. The study confirmed a number of advantages of the LSO scintillator for nuclear physics experiments, however, for small size samples. For larger volumes the natural radioactivity of the LSO, about 300 counts/s/cm^3, may limit possible applications. The high number of e-h pair produced in the photodiodes makes LSO very attractive for small compact scintillation probes.

1. INTRODUCTION

The rediscovery of the CsF scintillator [1,2] and the discovery of the fast component in a BaF_2 [3,4] triggered a growing interest for new scintillator materials [5-7]. Within the number of recently proposed new inorganic scintillators [5] the LSO ($Lu_2(SiO_4)O$:Ce) seems to be of great importance as a promising dense, fast and efficient scintillator. According to refs [8-12], it has a density of 7.4 g/cm^3, a fast decay time constant of the light pulse equal of about 40 ns and a high light yield of 75% of NaI(Tl) crystal. The presented properties of LSO and the fact that the peak of its emission spectrum, at 420 nm, fits well to typical photomultipliers suggest potential applications of the LSO in γ-ray spectroscopy in nuclear physics, nuclear medicine etc. However, due to the high cost of the raw material, a deeper evaluation of the expected advantages is required. The large detection efficiency of the LSO for γ-rays, the high light yield and fast light pulse makes LSO very attractive in experiments requiring a good timing. In this respect the LSO crystal may in the future replace BGO and even BaF_2 crystals. The γ-ray spectroscopy requires, in general, a rather large volume crystals. Thus the observed background coming from the natural radioactivity of lutetium [10,12] may limit possible applications.

Another potential field of application of the LSO crystal is detection of light charge particles, in particular, since a new scintillator characterised by a high light yield and a fast light pulse is required to replace CsI(Tl) or BGO crystals [7,13].

The aim of this work was to study the basic properties of the LSO crystal for γ-rays and α-particles. This was carried out for the LSO crystals coupled to the XP2020Q photomultiplier and the Hamamatsu S3590-03 photodiode. The application of the photodiode readout is of importance in the modern experiments. The peak of the LSO emission is on the limit of the sensitivity spectrum for typical Si photodiodes, however, its high light yield can make LSO still attractive in such application.

2. EXPERIMENTAL DETAILS

All the studies were carried out for three different LSO samples with the dimensions 15×15×1.5 mm^3, 10×10×2 mm^3 and 5×4×14.5 mm^3. The last sample was treated by additional annealing in order to improve its optical and scintillation properties. The LSO crystals were grown at the Lebedev Physical Institute in Moscow. The concentration of Ce in the studied LSO samples was 0.22%. For the measurements with γ-rays the crystals were coated with a teflon tape, while for α-particles the uncoated crystals or crystals coated with a 3.3 μm thick aluminised mylar foil were used. The tested LSO crystals showed a strong day light afterglow. It was necessary to keep them in a darkness at least for 24 hours in order to eliminate this effect.

In the measurements with the photomultiplier the XP2020Q with the radiant photocathode sensitivity of 74 mA/W working with the B' voltage chain [14] was used. To study the performances of the LSO crystal for the photodiode readout both the 10×10×2 mm^3 and 5×4×14.5 mm^3 samples

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were used coupled to the Hamamatsu S3590-03 and S2744-03 photodiodes with the 10×10 mm^2 and 20×10 mm^2 sensitive areas, respectively. Note that the typical quantum efficiency of both the photodiodes at 420 nm is equal to 50% [15] thus still acceptable for the LSO crystal. The signal from the photodiode was fed into a charge sensitive preamplifier and further processed by a spectroscopy amplifier. The energy resolution of the S3590-03 photodiode itself measured with 59.6 keV γ-rays from a ^{241}Am source was equal to 4.3 keV while that of the S2744-03 photodiode was 4.8 keV.

3. RESULTS

3.1. Light yield

To determine the light yield of the LSO scintillator two independent methods were applied. In the first one the light readout using the XP2020Q photomultiplier was used, while in the second, the S3590-03 photodiode was exploited.

In order to extract the photoelectron yield for the XP2020Q the position of the 662 keV full energy peak from a ^{137}Cs source was compared with that of the single photoelectron peak. The results of the measurements done for three LSO samples of the LSO are collected in Table I.

Table I Photoelectron yield for LSO scintillators (measured with the XP2020Q photomultiplier, S_{pc}=74mA/W).

Sample	Number of photoelectrons [phe/MeV]
5x4x14.5mm^3	4200±300
10x10x2mm^3	4100±300
15x15x1.5mm^3	3100±200

Note that the measured number of photoelectrons of 4200 phe/MeV for the two better samples is only about 50% of that measured for a small high quality NaI(Tl) scintillator [16]. It is difficult to judge the reason of the discrepancy with the previous measurements [8,9] which reported the light yield of 75% of NaI(Tl). It could be associated with the technology of the LSO production used by different manufacturers. However, one has to pay attention to the different methods applied to measure the relative light yield. In refs [8] and [9] the relative light yield was determined from the emission spectra of both LSO and NaI(Tl) measured evidently in DC mode. Thus the measured light intensity takes into account all the components of the emitted light including phosphorescences. The observed strong afterglow of LSO crystal induced by the day light suggests that the measured emission spectrum of LSO in refs [8] and [9] can be enhanced by phosphorescence components which, in turn, are not taken into account in the measurement of the photoelectron yield by the spectrometry technique used in the present study. The above consideration strongly suggests that the light yield of LSO expressed in the photoelectron number is, in fact, lower than that reported in refs [8] and [9] and is about 50% of NaI(Tl).

The measured photoelectron yield of the LSO crystals coupled to the XP2020Q photomultiplier can be used to estimate the photon yield of the LSO using the method discussed in ref. [7]. It is assumed that the LSO emits light mainly around its peak wavelength. The quantum efficiency of the photocathode was calculated assuming that the shape of the radiant sensitivity spectrum given by Philips Photonics for the XP2020Q [14] is valid for the applied photomultiplier in the present measurements. Based on this spectrum normalised to 74 mA/W at 401 nm one can find the radiant sensitivity at 420 nm as 72 mA/W and afterwards the quantum efficiency equal to 20.8%. Since all the other remarks concerning the collection efficiency of photons in the crystals and photoelectrons in the photomultiplier given in ref. [7] are valid one can arrive to the photon yield of the LSO crystal of 20200±1000 photons/MeV. It corresponds to 53% of the light yield of NaI(Tl) as reported in ref. [17], confirming discussed above relatively lower LSO light yield.

The number of electron-hole pairs produced in the S3590-03 diode by the scintillating light was determined by comparing the 662 keV full energy peak position from a ^{137}Cs source detected in the LSO crystals with that of the 59.6 keV γ-rays from a ^{241}Am source detected directly in the photodiode. Since the energy required to produce an e-h pair in an Si diode is equal to 3.6 eV, the number of electron-hole pairs of 18500±900 $N_{e\text{-}h}$/MeV was determined.

To estimate the light yield of the LSO the radiant sensitivity quoted by the manufacturer for this type of the photodiode as 169 mA/W at 420 nm [15] or the quantum efficiency of 50% was used. It was assumed that the full charge is collected in the photodiode. Assuming a full scintillation light collection one can arrive to a number of photons equal to 37000±2000 ph/MeV. This is almost by a factor of two larger than that found above from the photomultiplier measurement. To get the agreement one has to assume a quantum efficiency of about 90% for the photodiode which seems rather unrealistic.The recent study of the light emission mechanism in LSO carried out by means of UV light shows two emission bands of the light at 420 nm and 460 nm [11]. Moreover, the latter one is extended into the longer wavelengths up to about 600 nm. This observation seems to explain observed above disagreement in the estimated light yield of LSO based on the measurements with the photomultiplier and the photodiode. Fig. 1 presents the comparison of the emission spectrum of LSO crystal measured with γ-rays [8,9], to the spectral quantum efficiency curves of the XP2020Q photomultiplier and the S3590-03 photodiode following refs [14] and [15]. The photomultiplier with the peak quantum efficiency at 400 nm is mainly sensitive to the 420 nm wavelength band of LSO. In contrary, the quantum efficiency of the photodiode is reduced in this region to 50% or even less and at longer wavelengths it reaches a saturation at about 75%. No doubt that the contribution of the wavelength band at 460 nm in the LSO emission is of the main importance when working with photodiode. Note that even assuming a

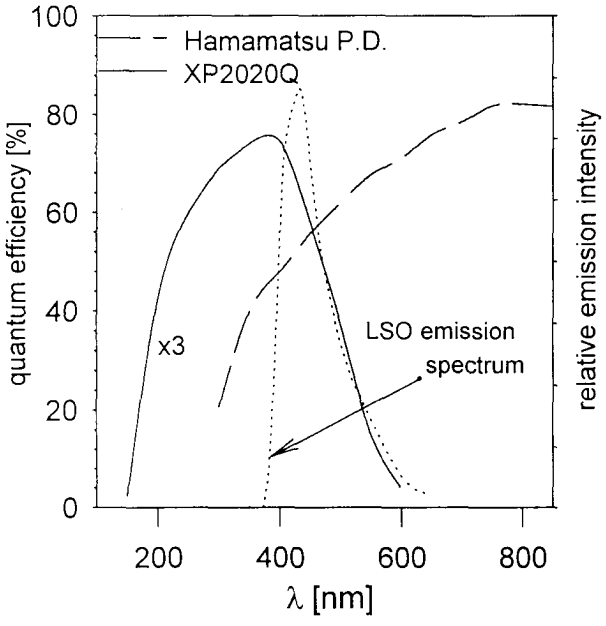

Figure 1. Comparison of the LSO scintillator emission spectrum according to refs. [8] and [9], with the spectral quantum efficiency curves following refs [14] and [15].

75% quantum efficiency of the photodiode typical for wavelength above 500 nm, one will find a photon number of 24700 ph/MeV, still larger than that found with the photomultiplier. This suggests that the intensity of the emission band at 460 nm in underestimated in the present measurements done mainly with photomultipliers. The high electron-hole pair number measured with the S3590-03 photodiode is certainly due to an intense emission of LSO at 460 nm band.

The above discussion shows clearly that at present it is difficult to determine the number of photons per energy unit emitted from LSO. The expected rather complex emission spectrum of LSO needs an analysis of both the emission spectrum and the sensitivity spectrum of the photosensitive detector. Thus, the estimation of the light yield based on the measurement with the photomultiplier can be only considered as a lower limit. More reasonable is to discuss the light yield of the LSO expressed in the number of photoelectrons as observed with photomultipliers.

3.2. Light pulse shape study

The light pulse shape studies were performed by means of the single photon method [18,19]. The XP2020UR photomultiplier was used to detect single photons. The uncoated LSO scintillator was optically coupled to the XP2020Q photomultiplier, to produce a reference signal, and was irradiated by γ-rays from a ^{137}Cs source or α-particles from a ^{241}Am source. The prompt time spectrum of the system was measured with the Cherenkov light produced in the photocathode glass window by a ^{60}Co γ-rays following the method used in ref. [20]. The measured FWHM of the prompt spectrum was equal to 500 ps. The measurements were carried out for all the LSO samples.

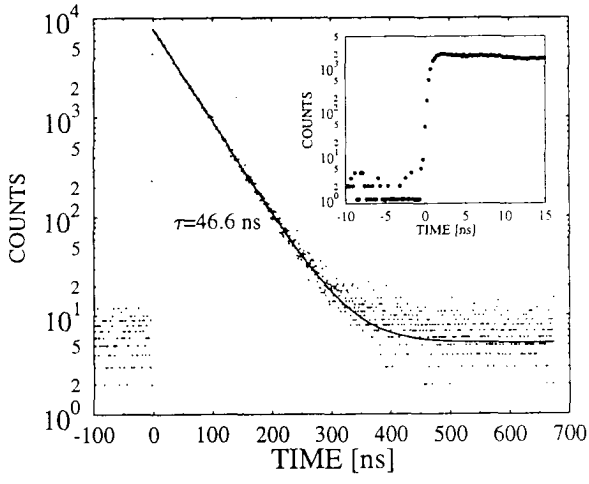

Figure 2 The time distribution spectrum of the light pulse measured with the 4x5x14.5 mm^3 LSO crystal for γ-rays. The solid line represents a fit of a one term exponential function. Note the absence of the 12ns fast component observed in refs [8] and [9]. In the insert the initial part of the light pulse is shown in an extended scale.

Fig. 2 presents the time distribution spectrum of the light pulse measured with the 4×5×14.5 mm^3 LSO sample for γ-rays. Note a pure exponential decay of the light pulse with the decay time constant of 46.6 ns found from the fit (the solid line in the fig. 1). In the contrary to the previous measurements [8,9] the faster component of 12 ns is not observed. Note that in the measurement presented in ref.[10] the fast component of 11 ns represents even 62% of light. The insert of fig.1 shows the initial rise of the light pulse from the LSO in the extended time scale. It reflects a very fast rise time of the light pulse described by the speed of the prompt response of the timing system (FWHM=500 ps). It is important to note an absence of the slow component in the LSO light pulse. The pure exponential decay is observed through three decades.

In the Table II the results of the measurements of the decay time constant from all the tested samples are collected. Note a very good agreement of the quoted numbers. The measurements of the light pulse carried out for α-particles show the same light pulse shape as that observed for γ-rays. The decay time constants collected in the table II presents no dependence on the type of particles. The average decay time constant of 47.2±1.3 ns is in a good agreement with the slower decay time component reported in refs. [8,9].

Table II Decay time constant of the light pulses from LSO crystals.

LSO sample	Decay time constant [ns]	
	γ-rays	α-particles
5×4×14.5 mm^3	46.6±1.4	46.4±1.2
10×10×2 mm^3	47.7±4.2	47.6±4.2
15×15×1.5mm^3	48.0±4.0	46.6±3.5

3.3. Energy spectra

Figures 3a and 3b present the energy spectra for the 662 keV γ-rays from a ^{137}Cs source measured with the 5×4×14.5 mm^3 and 15×15×1.5 mm^3 LSO crystals coupled to the XP2020Q photomultiplier. The full energy peaks with the FWHM of 10% and 12.6% correspondingly are seen. Note a high efficiency of the full energy peak in both the spectra in spite of the small volume of the LSO samples. It is associated with the high density of the LSO and a high atomic number of lutetium. In this respect the LSO is comparable to the BGO crystals. The peak-to-total fraction of about 25% found for the 5x4x14.5 mm^3 crystal is comparable to that of a 2.5 cm x 2.5 cm NaI(Tl) crystal [21].

In fig. 3c the background of the largest volume 15×15×1.5 mm^3 LSO crystal measured without the presence of radioactive source is shown. According to ref. [9] it originates from an admixture of the radioactive ^{176}Lu in the natural lutetium with an abundance of 2.6%. The spectrum is due to β-decay of ^{176}Lu and the main γ-rays with the energies of 89, 202 and 307 keV. The natural activity background was about 300 counts/cm^3. The observed background is rather of a minor importance for small crystals, however, extrapolated to larger volume scintillators leads to about 4000 c/s for 1"×1" crystal and about 100000 c/s for 3"×3" crystal.

The energy spectra of the 5×4×14.5 mm^3 LSO crystal measured using a photodiode readout present somewhat worse energy resolution of 14.6%, see fig. 4, and comparable to that reported in ref. [22].

It is important to note here that the calculated energy resolution of the LSO due to photoelectron statistics equal to 4.5% is much better then the measured one. Thus, a contribution of the LSO itself of 8.4% can be estimated. This effect is typical for doped crystals and it was previously observed for NaI(Tl) and CsI(Tl) scintillators [23,24]. Similar estimation can be done based on the measurement with the photodiode. It leads to the LSO contribution of 9.8%, the value which is comparable to that estimated above. It suggests that a further improvement of the energy resolution of LSO crystals is mainly associated with the better homogeneity of the crystals.

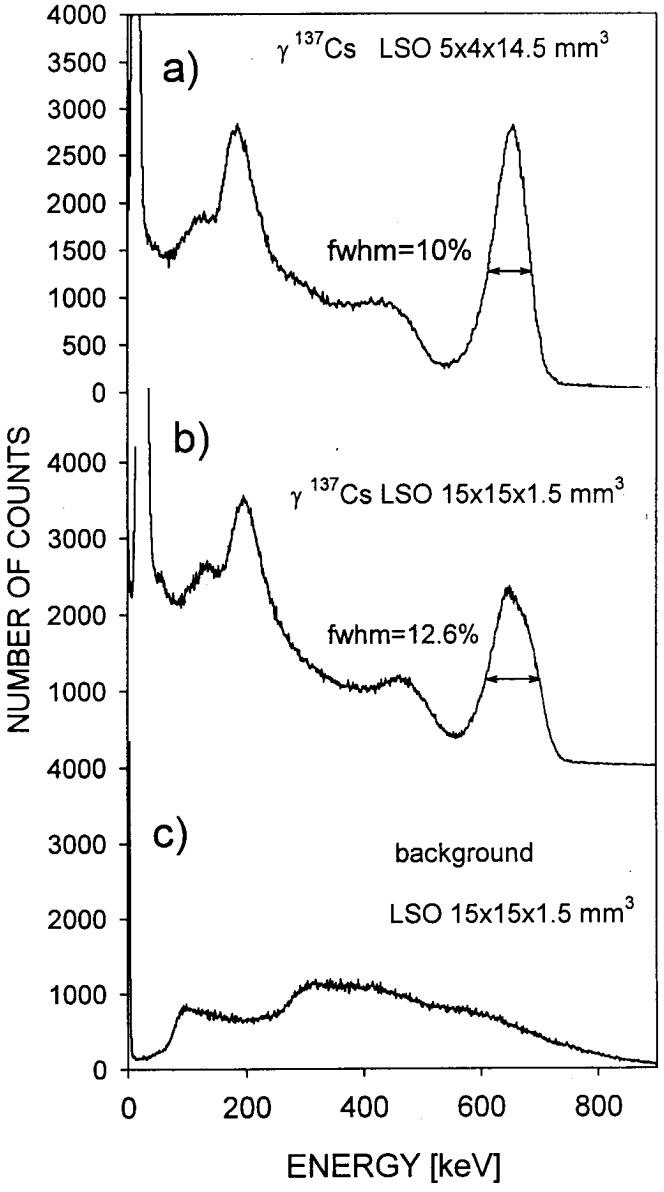

Figure 3. The energy spectra of the 662 keV γ-rays from ^{137}Cs source measured with the 5x4x14.5 mm^3 (a) and 15x15x1.5 mm^3 (b) LSO crystals coupled to the XP2020Q photomultiplier. The bottom spectrum (c) shows the background of the largest 15x15x1.5 mm^3 LSO crystal measured without radioactive sources.

Fig.5 presents the energy spectrum of α-particles from ^{241}Am source measured with the 4×5×14.5 mm^3 LSO crystal coupled to the XP2020Q photomultiplier. The measurement was carried out without vacuum, thus the energy of α-particles was attenuated by approximately 1 mm of air. To avoid further attenuation of the energy of α-particles uncoated crystals were used. The width of the peak is

certainly affected by the absorption in air (no collimation).

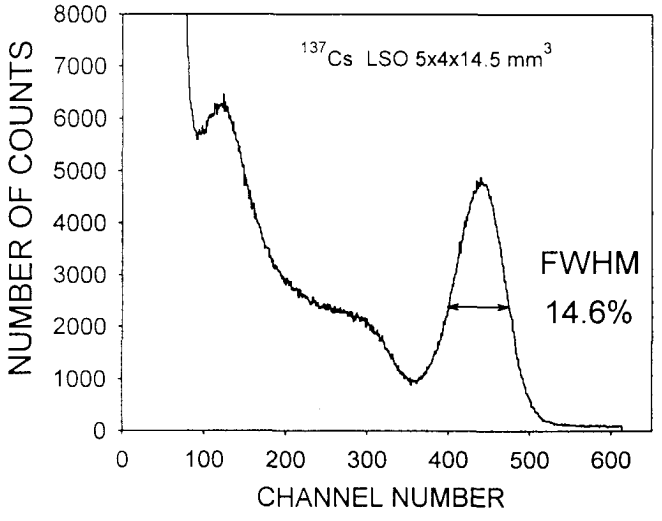

Figure 4 The same as in fig. 3a with the LSO scintillator coupled to the S2744-03 photodiode.

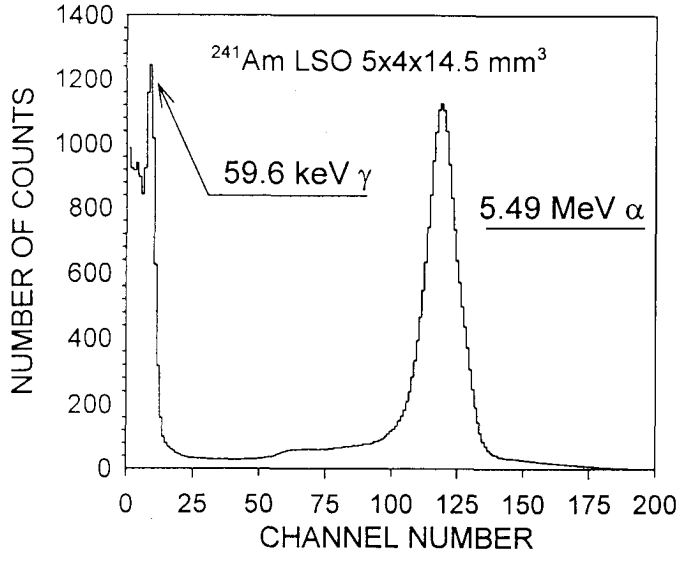

Figure 5 The 5×4×14.5 mm^3 crystal energy spectrum of the 5.49 MeV α-particles from a ^{241}Am source.

Note the peak at lower channels due to the 59.6 keV γ-rays from the ^{241}Am source. The extracted α/γ ratio of the light intensities is 0.105. To recheck this rather low value, similar measurements were done for a ThC source, where the energy degradation of α particles in air is practically avoided. The positions of the two α peaks due to 8.77 MeV and 6.05 MeV were compared to the γ-peak of 238 keV in the decay of ^{212}Pb (see fig. 6). The α/γ ratio equal to 0.125 found from this measurement confirms the previous value. Similar measurements done with the 10×10×2 mm^3 LSO crystal coupled to the S2744-03 photodiode exhibits even lower α/γ ratio, i.e. 0.09.

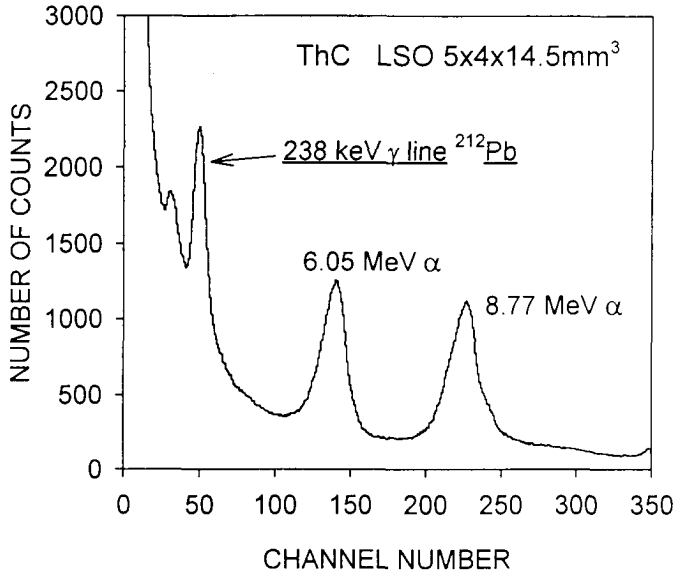

Figure 6 The 5×4×14.5 mm^3 crystal energy spectrum of α-particles from the ThC source.

The α/γ ratio found for the LSO is much lower than those measured before for CsI(Tl) and NaI(Tl) crystals, equal to 0.5 and 0.45, respectively [24,25]. It is also lower than that of 0.3 found recently for the YAG:Ce crystal [7]. This suggests a rather strong quenching of the light in LSO for light charged particles or a rather thick nonscintillating ("dead") surface layer discussed in ref. [24] for a CsI(Tl) crystal, which may limit a potential application of LSO for their detection. Recently measured light output of several new inorganic scintillators for light charged ions [26] with the energy of 3-20 MeV/nucleon shows a high quenching of the light for LSO crystal. However, due to its high light output the LSO is one of the best crystals for this type of application.

The presented above energy spectra of α-particles were measured with the best 5×4×14.5 mm^3 LSO crystal. Fig. 7 presents the same spectra measured with the 15×15×1.5 mm^3 and 10×10×2 mm^3 LSO samples. Note that both crystals exhibit double peaks for α-particles emitted from ^{241}Am as well as ThC source. The second peak usually with lower intensity is shifted up by approximately 15÷20% depending on the crystal and energy of the detected α particles. Similar splitting of the full energy α peak was observed also for the 15×15×1.5 mm^3 and 10×10×2 mm^3 crystals with the photodiode readout (see fig.8). The careful chemical cleaning of the crystals proved that this effect is not due to the α particle energy attenuation in the impurities deposited on the crystal surface. Moreover, a closer inspection of fig. 3b, where the energy spectrum of 662 keV γ-rays from ^{137}Cs source measured with the 15×15×1.5 mm^3 LSO crystal is presented, suggests that the same effect is observed for γ-rays. The full energy peak seems to be affected by the second component shifted up, however, with lower magnitude. One should keep in mind that the 5÷9 MeV α-particles are

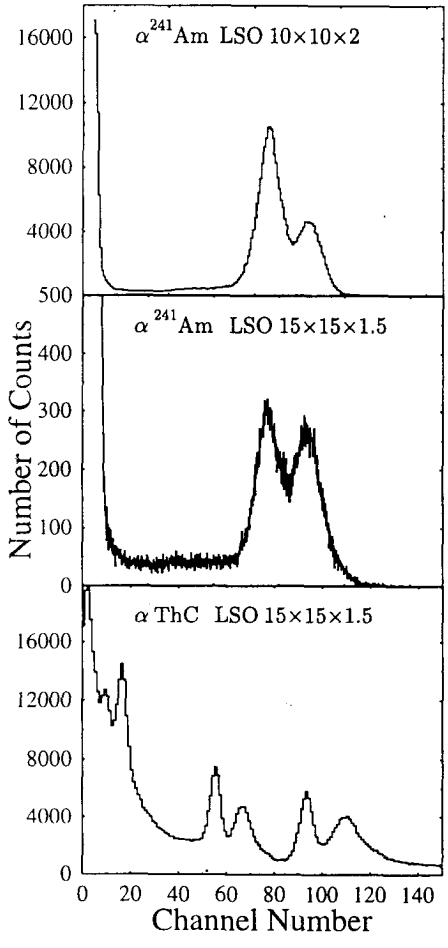

Figure 7 The same spectra as in figs 5 and 6 but measured with the 15x15x1.5 mm^3 and 10x10x2 mm^3 LSO samples.

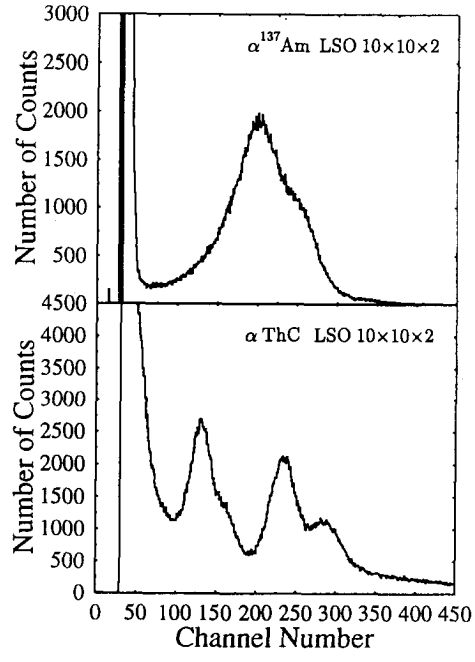

Figure 8 The same spectra as in fig.7 but measuerd with the 10x10x2mm^3 LSO coupled to the S3590-03 photodiode. A similar spliting of the α-peaks is observed.

stopped in a surface layer of ≈50μm, while the 661.6 keV photons interact in the whole crystal volume. The effects of full energy peak splitting for both the γ and α-particles can be therefore explained assuming imperfect crystal structure or inhomogeneous Ce doping in the surface layer of samples, which were not treated by the additional annealing.

3.4 Timing studies

The timing studies of the LSO scintillator were carried out with the 4x5x14.5 mm^3 crystal coupled to the XP2020Q photomultiplier. The time resolution measurements were performed for a ^{60}Co source with an energy threshold set at 1 MeV and 100 keV, respectively. The reference counter consisted of a NE111 plastic 2.5 cm in diameter and 1 cm in height coupled to the XP2020UR photomultiplier. Its time resolution for a narrow energy window set at 1 MeV of ^{60}Co γ-spectrum was equal to 80 ps [20]. The time spectra measured with the LSO crystal were compared to that observed with the 2.5 cm in diameter and 1 cm thick BaF_2 crystal.

Fig. 9 presents the comparison of the time spectra measured with LSO and BaF_2 crystals for the energy thresholds set at 1 MeV. To compare both the scintillators the measured values of 180 ps for LSO and 123 ps for BaF_2 has to be corrected for the contribution of the reference counter. It leads to a time resolution of the respective counters of 160 ps and 93 ps. The ratio of the measured time resolutions is equal to 1.7. The same ratio can be estimated taking into account the decay time constants and photoelectron numbers of both the scintillators. Note that the FWHM of the time spectrum is approximately proportional to the square root of decay time and inversely proportional to the square root of the number of photoelectrons [27]. It allowed to find ratio of 2.1 which is not far from the measured one.

It is worthy to note that the time resolution measured with larger volume BaF_2 crystals is strongly affected by the time spread introduced by the light collection process in the crystal, see ref. [3]. In the case of the LSO one can expect a lower degradation of time resolution with the volume of the crystal. The time resolution of the LSO is mainly contributed by the decay time of the light pulse, which is much longer than that of the BaF_2 crystal. Thus the slowing down of the light pulse by the light collection process less affects the slow pulse from LSO than the very fast of BaF_2. This remark is of importance for a future application of larger volume LSO crystals. Moreover, to get the same detection efficiency as that of the LSO one has to use a larger volume BaF_2 crystal more affected by the light collection process.

Table III Comparison of the LSO with other scintillators.

Parameters	NaI(Tl)	CsI(Tl)	BGO	BaF_2	GSO	YAP:Ce	YAG:Ce	CsF	LSO
Number of phe [phe/MeV]	9000[a] 12000[b]	7000[b]	940[c]	2500[d]	1600[c] 2840[b]	2700[c]	1200[e]	660[f]	4200
Number of e-h pairs [e-h/MeV]	20000[g] 12300[b]	39000[g] 35900[b]	6150[g] 5070[h]		6320[h] 5860[b]	6000[h]	15000[e]		18500
τ_γ [ns]	230	900	300	0.6 620	43[c] 341[c]	31[c] 245[c]	88[e] 302[e]	1.85[h]	47
τ_α [ns]		600			45		68 247		47
λ[nm]	415	560	480	220 320	430	380	550	390	420
ρ [g/cm^3]	3.67	4.51	7.13	4.88	6.7	5.35	4.55	4.64	7.4
α/γ	0.45	0.5					0.3[e]		0.12
ΔE/E[i] [%]	6	5.5[j]	11	9[d]	10[k]	6.7% 511keV	11.1[e]	18[n]	10
Time resolution[l] E>1 MeV [ps] E>100 keV [ps]	350[m] 800[e]		1050[e] 1300[e]	93[n], 75[d]			1180[e]	212[f] 312[n]	160 410

a) see ref. [16], b) see ref. [28], measured with the R1306 photomultiplier working in the photodiode mode and with the Hamamatsu S1790-02 photodiode respectively, c)see ref. [29], d) see ref. [30], e) see ref. [7], f) see ref [2], g)estimated using data on the light yield quoted in ref. [17] and the quantum efficiency characteristic of the S3590-03 photodiode [15],h) estimated using data on the light yield quoted in ref. [28] and the quantum efficiency characteristic of the S3590-03 photodiode [15], i) for ^{137}Cs source, j) measured with the photodiode, see ref. [31], k) see ref. [32], l) for one counter, measured with ^{60}Co source, m) see ref. [33], n) this work.

Fig. 10 presents the time spectrum measured with the LSO crystal for the energy threshold set at 100 keV. A broadening of the spectrum, FWHM=410 ps, is enhanced by the slow decay of the light pulse.

The presented results of the timing study show that the LSO belongs to the fastest inorganic scintillators. Its good timing properties and a high efficiency for γ-rays detection make them very attractive in several applications in nuclear physics experiments and applied physics.

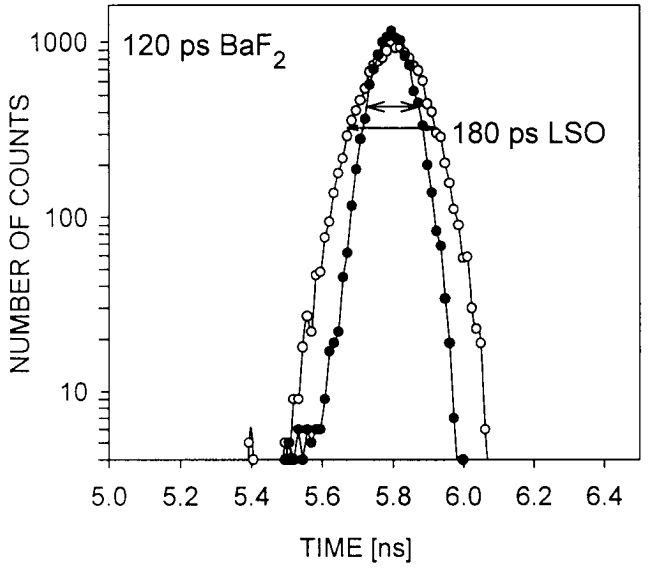

Figure 9 Comparison of the time spectra measured with the LSO (4x5x14.5 mm^3) and BaF_2 crystals for ^{60}Co γ-rays and the energy threshold set at 1 MeV.

The potential advantages of LSO crystal in positron emission tomography were pointed out in ref. [12]. The presented above results of the time resolution study seems to suggest the time-of-flight PET to be possible with LSO crystals. Thus, taking into account a high detection efficiency of LSO for γ-rays, it will join advantages of high resolution PET's built utilising small BGO scintillators with those of the time-of-flight PET built based on BaF_2. The high speed of the light pulse, absence of slow components would also allow to increase counting rate in PET to make possible a dynamic study in medicine.

4. DISCUSSION

The properties of the LSO scintillator are summarised in Table III, as compared to those of the mostly used and recently proposed new scintillators. The light yield of all the crystals is expressed in the numbers of photoelectrons, as measured with bialkaline photocathode photomultipliers, and in the number of e-h pairs measured or estimated for Si photodiodes. Excluding NaI(Tl) and CsI(Tl) crystals, the LSO exhibits the highest light yield for both the photomultipliers and the photodiodes. Moreover, the LSO belongs to the fastest crystals. The decay time constant of 47 ns is the same as that of GSO and slightly longer than that of YAP. Finally, the density of the LSO and the high atomic number of lutetium places it together with BGO and GSO among scintillators with the highest detection efficiency for γ-rays.

The results of the presented study and the data collected in the table III confirms conclusions of refs [8-12] that LSO is a valuable scintillator for several applications. Combination of a high detection efficiency for γ-rays, high light yield and

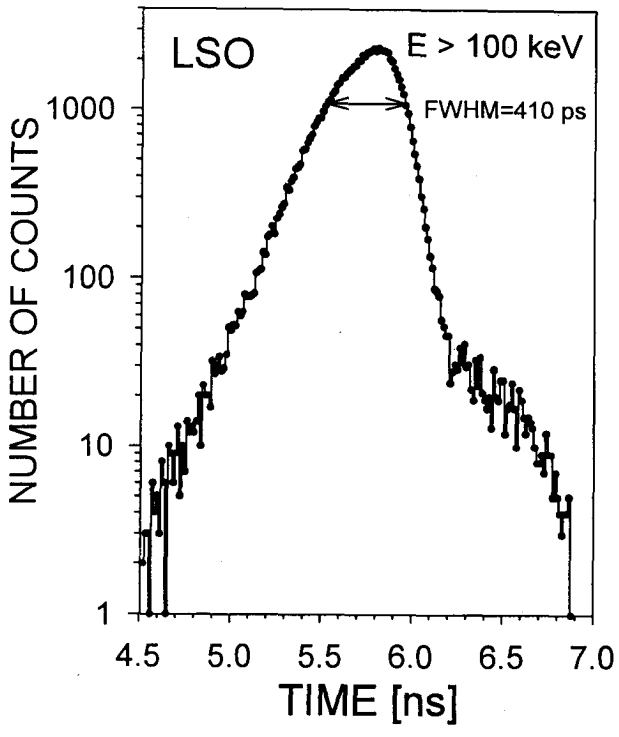

Figure 10 The same time spectrum as in fig.9 but for the energy threshold set at 100 keV.

fast light pulses result in a good energy spectra with a high peak-to-total ratio and a very good time spectra. The fast pulse with the decay time of 46 ns, free of slow component, allows to count up to about 10^6 c/s. Altogether suggest that LSO could replace BGO in several applications and very often even BaF_2. However, the observed background coming from the natural radioactivity of lutetium of about 300 c/s/cm^3 limits possible application. Thus the LSO can be recommended for the experiments when small size scintillators are sufficient and for those with high counting rates. In both the cases the natural background of the LSO can be neglected. No doubt that the LSO can be used in the future positron tomographs replacing the BGO crystals. A possible application of the LSO scintillators in the time-of-flight positron tomographs has to be further studied.

The other field of potential application of the LSO is due to its good results for the photodiode light readout. The high number of the e-h pairs measured for the LSO crystal coupled to the Hamamatsu photodiodes suggest an attractive design of a small compact scintillation probes for γ-rays spectroscopy.

In spite of the fact that the rather high quenching of the light for light charged particles is observed in LSO, this crystal is also attractive as particle detector. The high light yield of LSO, a good results with photodiodes, the high speed of the light pulse and the high stopping power make LSO the crystal of choice.

The data collected in the table III allow to return to the problem of the light yield of LSO discussed in sect. 3.1. Note that three scintillators listed in the table III exhibit almost the same wavelength of the peak emission, eg. NaI(Tl) at 415 nm, GSO at 430 nm and LSO at 420 nm. The number of photoelectrons measured with LSO is equal to 47% of NaI(Tl) and to 263% of GSO. In contrast, the measurements carried out with Si photodiodes show that the number of e-h pairs for LSO is comparable to that of NaI(Tl), while compared to GSO presents within about 10% accuracy the same scaling factor. No doubt that the observed excess of e-h pairs for LSO is due to an emission band at longer wavelengths, as it was discussed in sect. 3.1. Note that according to refs. [11] and [34] the emission spectra of GSO and LSO are comparable, which is manifested by the same ratio of the numbers of photoelectrons and e-h pairs.

It is important to point out that the light pulse of LSO does not exhibit a slow component which limits the high counting rate performances. Within the fast scintillators listed in the table III, with the decay time constant below 100 ns, only CsF is much better because of the fastest light pulse free of the slow component [1]. It is interesting that LSO exhibits the same light pulse, within a high accuracy, for both γ-rays and α-particles. It suggest a simple and efficient light generation process. It is not clear why the present study does not confirm the existence of the faster component (12 ns) reported by Melcher and Schweitzer [8-10]. Note that it was also not observed in the study of the emission spectra in the UV excitation [11].

The energy resolution measured for 662 keV γ-rays from a ^{137}Cs source does not follow the high light yield of LSO crystal, see also refs. [8-10]. Note the much poorer energy resolution than that of YAP:Ce crystal and comparable to those of BGO, BaF_2, GSO and YAG:Ce. All of them showed much lower photoelectron numbers, see table III. It suggests that further efforts are required to improve the quality of the LSO scintillators in that respect.

5. CONCLUSIONS

The presented study confirms conclusions of refs [8-10] for the LSO crystal as a very interesting scintillator for several applications. In particular the large detection efficiency for γ-rays, high light yield and fast pulse makes the LSO very attractive for γ-ray spectroscopy at high counting rates. The fast pulse with the decay time constant of 47 ns allows a counting rate up to 10^6 c/s. The observed background of about 300c/s/cm^3 originating from the natural radioactive lutetium limits possible applications. Thus the LSO can be recommended for the experiments when small size scintillators are sufficient and for those with high counting rates.

The good results for the LSO crystal with Si photodiodes suggests a wide application of LSO in small compact scintillation probes for γ-spectroscopy, as well as, in detection of light charge particles. The rather strong

quenching of the light for charged particles observed in LSO is compensated by the high light yield.

The very good timing properties places LSO within scintillators recommended for coincidence experiments. In this respect LSO may very often replace even BaF_2 crystals. No doubt that LSO is a good candidate to be used in the positron tomographs.

There are still some open questions concerning the crystal structure of LSO. This was indicated by some of the results from the present studies, like for example the low values for the α/γ ratio or the double peak structure for samples not treated by additional annealing. One may hope that further progress in this field will result in new, high quality LSO crystals.

6 ACKNOWLEDGEMENTS

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