Nuclear Instruments and Methods in Physics Research A 345 (1994) 461-467
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Properties of the YAG : Ce scintillator

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(Received 31 January 1994)

Light yield, light pulse shape due to γ-rays and α-particles, energy resolution and time resolution of the new YAG:Ce scintillator were studied using a light readout by means of the XP2020Q photomultiplier and the S3590-03 photodiode. The light yield of 20300 ± 2000 photons/MeV was determined using three independent methods. The light pulse produced by γ-rays consists of two components with the decay time constants of 87.9 ns and 302 ns respectively. The light pulse measured for α-particles exhibits a faster and less intense fast component with the decay time constant of 68.4 ns. The energy resolution obtained was 11.1% and 11.7% for the 662 keV γ-rays from a ^{137}Cs source as measured with the photomultiplier and the photodiode readout, respectively. A time resolution of 1.3 ns was observed for ^{60}Co γ-rays (at 100 keV threshold) with the crystal coupled to the XP2020Q photomultiplier. The YAG:Ce scintillator with the peak emission at 550 nm is a good candidate to replace CsI(Tl) and BGO scintillators in detection of light charged particles when photodiode readout is of importance. The observed difference in the light pulse shape due to γ-rays and α-particles suggests good performance of the crystal in the pulse shape discrimination method for the particle identification.

1. Introduction

The rediscovery of the CsF scintillator [1,2] and the discovery of the fast component in BaF_2 [3,4] renewed interest for new scintillator materials [5–23]. Current application of the scintillators in high energy and nuclear physics, and particularly a recent demand of the future experiments at LHC and SSC accelerators stimulates the search for promising high density, fast and radiation hard scintillators [17]. The study covers a number of different materials [10] which allows to select several interesting new scintillators for a future application in different experiments. It may show prospect to find new scintillators with properties that fulfill requirements of special applications.

The detection of light- and heavy ions in nuclear [24–27] and atomic [28] physics experiments requires fast scintillators with a high stopping power. The high light yield, determining a good signal-to-noise ratio is of importance when a Si photodiode redaut is considered. The disadvantage of the commonly used CsI(Tl) and BGO crystals is the long decay time of the light pulses. To find alternative solution a comparison of a new GSO scintillator with BGO was recently carried out [24]. However, due to the peak emission of the GSO at 420 nm the expected advantages of GSO over BGO associated with the higher light yield and shorter decay time of the light pulse are not fully useable. The need of the photodiode with the extended sensitivity to shorter wavelengths for GSO crystal was thus concluded.

Within the newly proposed scintillating materials, YAP:Ce and YAG:Ce, developed earlier for laser application, are of interest [17]. Both the crystals are characterised by a high luminescence and a fast light pulses of 40 and 70 ns, respectively [29]. Moreover, the peak emission of YAG:Ce scintillator is at 550 nm and thus fits well to the sensitivity spectrum of Si photodiodes. The properties of the YAP:Ce were recently studied in comparison to BGO and GSO crystals [15]. This showed a higher light yield for YAP:Ce and good energy and time resolutions as measured for γ-rays. The information concerning YAG:Ce are limited. Some of them from ref. [17] and those given by the manufacturer [29] are collected in Table 1. Note a good light yield of YAG:Ce and fast light pulse with the decay time constant of 70 ns.

The aim of this work was to study the properties of the YAG:Ce scintillator as a detector for γ-rays and α-particles using the light readout by means of a photomultiplier as well as a photodiode. Particular attention was paid to the measurements of the light yield and the light pulse shape since these determines the properties

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SSDI 0168-9002(94)00176-8

Table 1
Properties of the YAG:Ce scintillator

Parameters	Ref. [29]	Ref. [17]
Density [g/cm^3]	4.55	4.56
Formula	$Y_3Al_5O_{12}$:Ce (0.15% CeO_2)	$Y_3Al_5O_{12}$:Ce (0.4 mol%)
Index of refraction	1.82	
Melting point [°C]	1970	
Max. of emission [nm]	550	550
Decay time [ns] constant	70	65
Light yield	125% of plastic	14000 photons/MeV

of the YAG:Ce crystal as a scintillator. Finally, the properties of the YAG:Ce scintillator for the energy and time spectroscopy were studied.

2. Experimental details

All the studies were carried out for a $10 \times 10 \times 2$ mm^3 YAG:Ce ($Y_3Al_5O_{12}$:Ce) crystal delivered by Preciosa Co (Turnov, Czech Republic) [29]. For the measurements with γ-rays the crystal was coated with a Teflon tape while for α-particles it was coated with a 3.3 μm thick aluminised Mylar foil.

In the measurements with photomultiplier the XP2020Q with the radiant photocathode sensitivity of 74 mA/W at 401 nm working with the B′ voltage chain [30] was used.

To study the performances of the YAG:Ce crystal with the photodiode readout the Hamamatsu S3590-03 diode was used with a radiant sensitivity of 320 mA/W, equivalent to a quantum efficiency of 72% at 550 nm [31]. The signal from the photodiode was fed into a charge sensitive preamplifier and further processed by a spectroscopy amplifier. Fig. 1 presents the energy spectrum for 59.6 keV γ-rays from ^{241}Am source measured with the photodiode itself. The energy resolution equal to 4.3 keV is typical for this type of photodiodes [33,34].

3. Results

3.1. Light yield

To determine the light yield of YAG:Ce scintillator the light readout using the XP2020Q photomultiplier and the S5390-03 photodiode were applied.

In the measurements with the XP2020Q the photoelectron yield of the YAG:Ce scintillator was measured by comparing the position of the 662 keV full energy peak from a ^{137}Cs source with that of the single photoelectron peak. The number of photoelectrons equal to 1200 ± 60 phe/MeV was determined as the mean value from three independent measurements.

To estimate the number of photons produced by the tested scintillator one has to consider the quantum efficiency of the photocathode at 550 nm, the efficiency of the photoelectron collection and the efficiency of the light collection in the scintillator. The quantum efficiency of the photocathode was estimated by assuming that the shape of the radiant sensitivity spectrum given by Philips Photonics for the XP2020Q photomultipliers [30] is valid for the applied photmultiplier in the presented measurements. Based on this spectrum normalised to 74 mA/W at 401 nm one can find the radiant sensitivity at 550 nm as 23.1 mA/W and afterwards the quantum efficiency equal to 5.2%. For the tested sample placed in the center of the photocathode one can easily assume 100% efficiency of the photoelectron collection. This is due to a very sophisticated focalisation system of the XP2020 photomultiplier and a low initial energy of the emitted photoelectrons due to the 550 nm photons. The last factor which can limit the accuracy of the estimated photon number is the light collection process in the tested sample. However, again in the 2 mm thick sample one can easily overpasses an attenuation of the light due to the selfabsorption and reflection in the crystal, thus assuming a full light collection.

Based on the above considerations the number of photons in the YAG:Ce crystal equal to 23000 ± 1150 photons/MeV was found from the measured number of photoelectrons.

The number of photons in the YAG:Ce scintillator can be determined independently by comparing the number of photoelectrons with that measured for the CsI(Tl) crystal. Note that the peak emission of the CsI(Tl) is at 560 nm thus approximately the same quantum efficiency of the XP2020Q can be assumed as

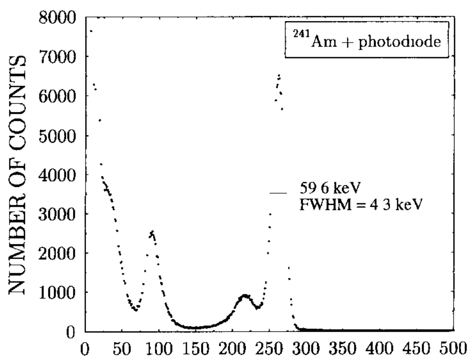

Fig. 1. The energy spectrum of the 59.6 keV γ-rays from a ^{241}Am source measured by the S3590-03 photodiode.

for the YAG:Ce. The photon yield for the CsI(Tl) was measured with a good accuracy in Ref. [34] and found to be equal to 51 800 ± 2600 photons/MeV. The number of photoelectrons measured for the CsI(Tl) crystal with dimensions of $27 \times 14 \times 3$ mm^3 from Ref. [35] was used. The same consideration concerning the photoelectron and light collection efficiency can be applied for the studied sample of the CsI(Tl) crystal. The measured number of photoelectrons at 3 μs shaping of the amplifier (Ref.[34]) was equal to 3616 ± 180 phe/MeV. Thus the number of photons emitted in YAG:Ce equal to 17 200 ± 1000 photons/MeV was found. Note a pretty good agreement of this value with that found above from the direct measurement.

The third method applied for measurement of the light yield of the YAG:Ce scintillator utilises the S3590-03 photodiode. It is based on the radiant sensitivity quoted by the manufacturer for this type of the photodiodes as 320 mA/W at 550 nm [31]. In the present method the measured quantity is the number of electron–hole pair produced in the diode by the scintillating light. It was determined by comparing the 662 keV full energy peak position from a ^{137}Cs source detected in the YAG:Ce scintillator with that of the 59.6 keV γ-rays from an ^{241}Am source detected directly in the photodiode. Since the energy required to produce an e–h pair in a Si diode is equal to 3.6 eV, the number of electron–holes equal to 15 000 ± 750 e-h/MeV was found. It was assumed that the full charge is collected in the photodiode. Assuming now a full light collection from the scintillator one can arrive to a number of photons equal to 20 800 ± 1000 photons/MeV. Again a good agreement with those found above for the photomultiplier is observed.

All the presented methods are affected by different systematical errors as for example the utilisation of the typical characteristic of spectral sensitivity of the photodiode and photomultiplier instead of the calibrated photosensitive devices. However, based on the above measurements one can adopt the mean value of 20 300 ± 2000 photons/MeV as a good approximation for the photon yield for the YAG:Ce scintillator.

3.2. Light pulse shape study

The light pulse shape studies were performed by means of the single photon method [36,37]. The XP2020UR photomultiplier was used to detect single photons. The uncoated YAG:Ce scintillator was optically coupled to the XP2020Q photomultiplier, to produce a reference signal, and it was irradiated by γ-rays from a ^{137}Cs source or α-rays from an ^{241}Am source. The prompt time spectrum of the system was measured with the Cherenkov light produced in the photocatode glass window by a ^{60}Co γ-rays following the method used in Ref.[38]. The measured FWHM of the prompt spectrum was equal to 600 ps.

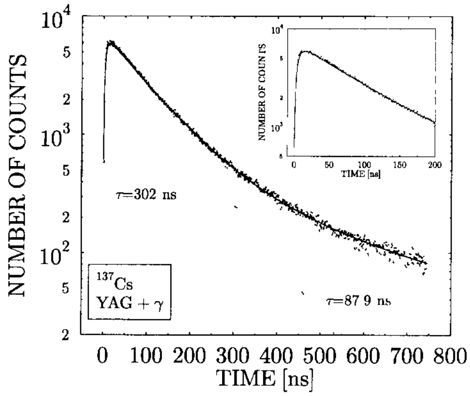

Fig. 2. Time distribution spectrum of the light pulse produced by the YAG:Ce scintillator for γ-rays. The solid curve presents the result of the fit of the Eq. (1). The dashed lines represent the decays of the fast and slow components of the light pulse. In the insert the initial part of the light pulse is shown in the extended time scale.

Fig. 2 presents the time distribution spectrum of the light pulse measured with γ-rays. The decay of the light pulse consists of two components and a certain slowing down of the rise of the pulse is seen. Thus to fit a whole spectrum with the finite rise time a three component exponential function was used:

$$i(t) = A_1 \exp(-t/\tau_1) - A_2 \exp(-t/\tau_2) + A_3 \exp(-t/\tau_3), \quad (1)$$

where τ_1 is the decay time constant of the fast component, τ_2 the rise time constant of the fast component, and τ_3 the decay time constant of the slow component.

The solid curve in Fig. 2 is the result of the fit of Eq. (1). In the fit the contribution of the prompt spectrum of the timing system was neglected since its FWHM is below one channel. The measured spectrum was only corrected for an uniform (random) background. The dashed lines represent the decays of both the components with a decay time constants of 87.9 ± 3.9 ns and 302 ± 10 ns respectively. Note that the decay time constant for the fast component is significantly longer than those given by manufacturer [29] and cited in Ref. [17]. The decay time constant for the YAG:Ce was recently studied in Ref. [39] using a laser excitation. The excitation wavelengths were on the long wavelength side of the lowest 5d absorption band of Ce to prevent any complications arising from photoionisation of cerium ions. The measured value of 59.1 ns is not far from those given in Refs. [17,29]. However, the same method applied to the YAP:Ce crystal shows the decay time constant of 18 ns, which is much lower than the values quoted in Refs. [15,17,29] and based on the measurements with a nuclear radiation. Thus, the observed difference in the decay time constant for the YAG:Ce scintillator may be associated with the way of excitation. On the other hand, it was shown in Ref. [7] that the decay time constant for a GSO crystal depends strongly on the concentration of the Ce dopant. The concentration of Ce in the delivered sample of the YAG:Ce crystal, according to the manufacturer, is equal to 0.15% of CeO_2 [29]. It is equivalent to 0.52 mol% concentration of Ce itself, thus it is slightly higher than that given in Ref. [17]. This would suggest rather a reduction of the decay time constant if assuming this same mechanism as observed in GSO. The above discussion seems to suggest that the observed difference in the decay time constant is associated with the way of the excitation. The calculated integral intensities of the fast and slow components from the fit are equal to $72 \pm 4\%$ and $28 \pm 1.4\%$, respectively. Note a much larger intensity of the slow component than that observed for the YAP:Ce.

The insert of Fig. 2 presents the initial part of the light pulse. The solid curve represents the pulse shape according to the Eq. (1). The rise time constant of 4.9 ± 0.7 ns was obtained from the fit. A similar finite rise time of the light pulses was observed in the case of GSO [7] as well as for the other yttrium compound YOP (YPO_4:Ce) and was interpreted as a slowdown of the lattice-to-activator energy transfer [22].

Fig. 3 shows the light pulse shape due to α-particles. Note a reduced intensity of the fast component in comparison to that measured with γ-rays. Moreover, the rise time of the light pulse is much faster. The solid curve in Fig. 4 is a result of a fit using a sum of two exponentials plus uniform background. The dashed lines represent the decays of both of the components with the decay time constant of 68.4 ± 4.2 ns and 247 ± 7.5 ns, respectively. Note that both the decay time constants are shorter than those measured for γ-rays. It is interesting that the decay time constant of

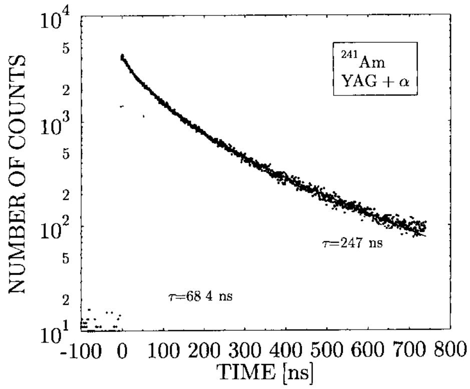

Fig 3. The same as in Fig. 2, but measured with α-particles.

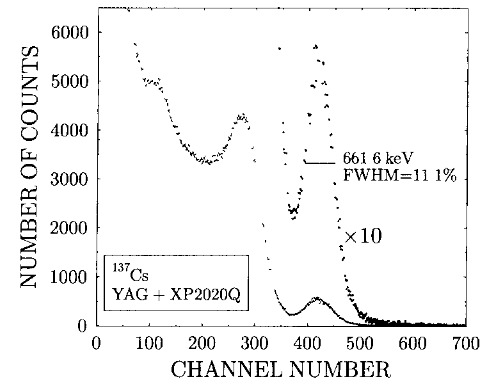

Fig. 4. The energy spectrum of the 662 keV γ-rays from a ^{137}Cs source measured with the XP2020Q photomultiplier

the fast component found for α-particles agrees pretty well with that measured for laser excitation [39] and cited in the literature [17,29]. It seems to confirm the conclusion given above that the decay time constant of the light pulse produced by the YAG:Ce scintillator depends on the way of excitation. The calculated intensities of the fast and slow components from the fit done for the light pulse due to α-particles are equal to $34 \pm 3.1\%$ and $66 \pm 5\%$, respectively, thus they are reversed in relation to those found for γ-rays.

The data on the decay times and the intensities of the fast and slow components of the light pulses due to γ-rays and α-particles are summarised in Table 2. The observed large difference in the light pulse shape between γ-rays and α-particles can be easily utilised in the pulse shape discrimination method of the particles identification.

3.3. Energy spectra

Fig. 4 presents the energy spectrum of the 662 keV γ-rays from a ^{137}Cs source measured with the YAG:Ce crystal coupled to the XP2020Q photomultiplier. A well defined full energy peak with the energy resolution of 11.1% is seen. The same spectrum measured using the photodiode readout presents somewhat worse energy resolution of 11.7%, see Fig. 5. Note a rather low efficiency of the full energy peak in both spectra. It

Table 2
The fast and slow components of the light pulse due to γ-rays and α-particles

	Fast component		Slow component	
	τ [ns]	Intensity [%]	τ [ns]	Intensity [%]
γ-rays	87.9 ± 3.9	72 ± 4	302 ± 10	28 ± 1.4
α-particles	68.4 ± 4.2	34 ± 3.1	247 ± 7.5	66 ± 5

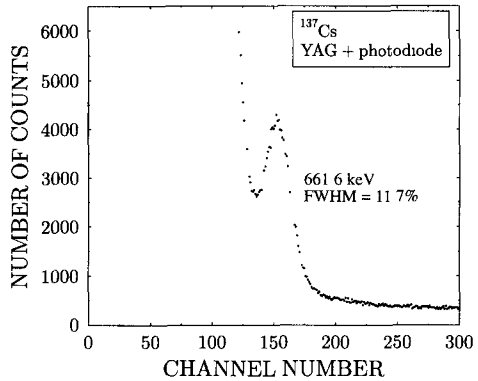

Fig. 5. The same as in Fig. 4, but measured with the S3590-03 photodiode

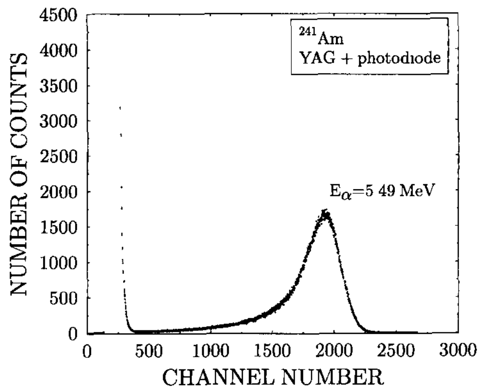

Fig. 7. The same as in Fig. 6, but measured with the S3590-03 photodiode.

is associated with a small volume of the tested sample and a rather low atomic number of yttrium ($Z = 39$) as compared to other new scintillators.

Fig. 6 shows the energy spectrum of α-particles from the ^{241}Am source measured with the photomultiplier. The energy dissipated in the scintillator is reduced by about 2 mm of air and the reflecting Mylar foil and corresponds to 3.94 MeV, as it was checked with a Si spectrometer. The width of the α-peak is mainly determined by the absorption in air and the reflecting mylar foil (no collimation). Note the peak at lower channels due to the 59.6 keV γ-rays from the ^{241}Am source. It made possible to extract the α/γ ratio of the light intensity as 0.3. This value was confirmed by the independent measurement done for γ-rays with the ^{137}Cs source.

Fig. 7 presents the same spectrum of α-particles measured with the photodiode readout. In this case the 59.6 keV γ-peak is within the noise component. However, the threshold for the detection of α-particles corresponds to about 0.5 MeV.

3.4. Timing studies

The timing properties of the YAG:Ce scintillator were tested with the crystal coupled to the XP2020Q photomultiplier. The measurement with the photodiode was considered rather not interesting since the time resolution is limited by the noise and low signal from the photodiode. Thus it is expected to be of a few tens of nanosecond.

The time resolution measurement was done with a ^{60}Co source with the energy threshold set at 100 keV. The anode pulse from the photomultiplier was sent to the 1512 Constant Fraction Discriminator [40]. The reference counter consisted of a NE111 plastic coupled to a XP2020UR photomultiplier. Its time resolution

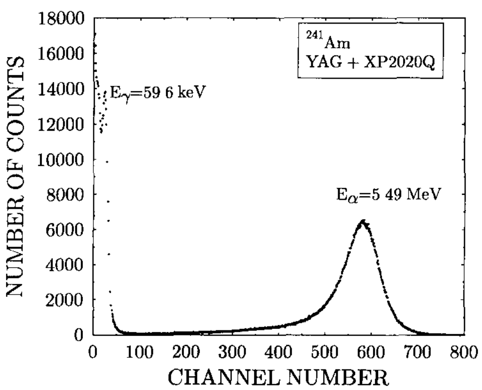

Fig. 6. The energy spectrum of the 5.49 MeV α-particles from a ^{241}Am source. Note that the energy dissipated in the crystal is reduced to 3.94 MeV due to absorption in about 2 mm of air and 3.3 μm Mylar foil. The width of the peak is mainly determined by absorption in air and Mylar foil.

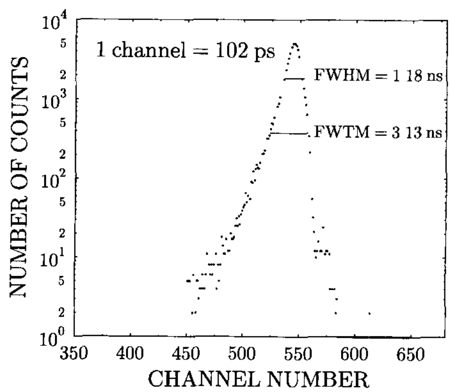

Fig. 8. The time spectrum measured with the γ-rays from a ^{60}Co source. Start channel: YAG:Ce coupled to the XP2020Q, stop channel NE111 plastic coupled to the XP2020UR photomultiplier. The energy thresholds in both of the channels were set to 100 keV.

Table 3
Comparison of the YAG:Ce scintillator with the CsI(Tl), BGO, GSO and YAP:Ce crystals

Parameters	CsI(Tl)	BGO	GSO	YAP:Ce	YAG:Ce
Light yield [ph/MeV]	51800 [a]	8200 [a]	11500 [b]	19700 [c]	20300
α/γ	0.5				0.3
τ_γ [ns]	900	300	43 [d]	31 [e]	88 302
τ_α [ns]	600		45 [f]		68 247
λ_{peak} [nm]	560	480	430	380	550
ρ [g/cm^3]	4.51	7.13	6.70	5.35	4.55
n_{e-h} [c] [e–h/MeV]	39000	6150	6320	~ 6000	15000

[a] See Ref. [34].
[b] See Ref. [15], recalculated to the number of photons based on the light yield of BGO
[c] Recalculated from the light yield using the typical spectral sensitivity characteristic of the S5390-03 photodiode, see Ref. [31].
[d] See Ref. [15], Ce concentration about 1 mol%.
[e] See Ref. [15].
[f] See Ref. [7], Ce concentration 0.95 mol%.

studied in Ref. [38] is below 100 ps, thus negligible in relation to the expected time resolution of the YAG:Ce crystal. Fig. 8 presents the measured time spectrum with the YAG:Ce crystal in the start channel. Its FWHM equal to 1.18 ns and FWTM equal to 2.87 ns reflect rather good timing properties. Note a small spike at the late slope of the measured time spectrum. It was identified, by reducing the energy threshold, as due to Cherenkov light produced in the photocathode glass window [41].

4. Discussion

The properties of the YAG:Ce scintillator are summarised in Table 3, as compared to those of the BGO, CsI(Tl), and GSO crystals considered recently to be used to detect charged particles with the photodiode readout. The properties of the YAP:Ce scintillator are added in Table 3 in spite of the fact that its emission spectrum is at the limit of the spectral sensitivity of the photodiode. However, a direct comparison of both the YAG:Ce and YAP:Ce scintillators seems to be interesting.

The highest light yield is observed for the CsI(Tl), equal to 51800 ph/MeV. Both the YAG:Ce and YAP:Ce produce the same number of photons of about 20000 ph/MeV. The third group represents the heaviest crystals BGO and GSO with about 10000 ph/MeV. All the new scintillators produce much faster light pulses with the decay time constant well below 100 ns. The application of the photodiode readout for the scintillation light introduces a further limitation in the selection of the best crystal. Within the three crystals showing the peak emission of the light well fitting the sensitivity spectrum of the Si photodiodes e.g. CsI(Tl), BGO and YAG:Ce, only CsI(Tl) and YAG:Ce exhibit a high light yield. This is reflected in the measured (or estimated) number of electron–hole pairs for all the discussed crystals. The highest value represents CsI(Tl), however, its light pulse is one order of magnitude slower than that of the YAG:Ce. Thus the present study suggests strongly that the YAG:Ce scintillator is a good candidate to replace CsI(Tl) or BGO in detection of light charged particles when a photodiode readout is of importance.

The comparison of the YAG:Ce and YAP:Ce shows approximately the same light yield for both crystals. The YAP:Ce produces a faster light pulse with the decay time constant of 31 ns. However, because of the peak emission at 380 nm it can be used only with photomultipliers. In γ-ray spectroscopy both crystals are less applicable due to the lower mean atomic number as compared to CsI(Tl), BGO or GSO scintillators.

The study of the light pulse shape from the YAG:Ce shows a number of interesting observations. The light pulse of the YAG:Ce exhibits an intense slow component, much stronger than those observed with the other Ce doped crystals. This difference is particularly large in comparison to YAP:Ce crystal. Only 2% contribution of the slow component was reported in Ref. [15] for the YAP:Ce crystal. The decay time constant of the fast component for γ-rays excitation equal to 88 ns is significantly longer than that measured for the laser excitation [39] and for α-particle excitation. Moreover, the intensity of the fast component due to α-particles is lower than that of γ-rays. Further studies are necessary to better understand the properties of the YAG:Ce scintillator. However, a possible application of the YAG:Ce scintillator for a light charged particles identification by a pulse shape discrimination method can be considered at present.

5. Conclusions

The present study showed that the YAG:Ce scintillator is a good candidate to replace CsI(Tl) and BGO scintillators in detection of the light charged particles when a photodiode readout is of importance. Its light yield equal to 20300 ± 2000 photons/MeV for γ-rays is more than a factor of two lower than that for CsI, however, it assures detection of α-particles above 0.5 MeV with the photodiode readout. An important advantage of the YAG:Ce crystal over CsI(Tl) is the much faster light pulse.

The observed difference in the light pulse shape due to γ-rays and α-particles suggests good performances of the YAG:Ce crystal in the pulse shape discrimination method for the particles identification.

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