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Review of modern inorganic scintillation materials

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Abstract

The paper presents an overview of modern developments in the field of inorganic scintillation materials. The most promising scintillators can be applied in science, medicine and industry are shown. Presents such basic properties as: light yield, decay time, resolution and density of the material. Today the most common are Ce-doped scintillators. Materials such as $Tb_3Al_5O_{12}$: Ce, $TlMgCl_3$: Ce and $LiCaAlF_6$ have been recently obtained and their properties are not fully understood. The incorporation of Na into Eu-doped $LiCaAlF_6$ is a promising method for increasing light yield. Scintillatorы $LaBr_3$:Ce and $CeBr_3$ are most effective and have found their application in nuclear medicine. Scintillator $Gd_3Al2Ga_3O_{12}$:Ce has the largest decay time, however, it has found wide application in the nuclear industry.

Keywords: Scintillator, light yield, decay time, doping, application;

1. Introduction

The development of modern technologies is directly related to the possibility of their practical application. Ionizing radiation is widespread in various fields of science. Accordingly, a detector was needed which is sensitive to both "soft" and "hard" radiation to register the full range of energies. The most suitable substances for these tasks were scintillators. Scintillators- are materials that can convert ionizing radiation energy into light. The main advantage of the scintillator is the high registration efficiency for almost any type of radiation. To date, the sensitivity and possible speeds of electronic registration systems have reached such a level that the main factors limiting the capabilities of modern detectors are the parameters of the used scintillators. Thus, the development of scintillators with improved characteristics is an important practical task.

The first scintillation detector, called the spinthariscope, was a screen with a thin layer of ZnS. The flashes occurred when charged particles hit it and recorded with a microscope. Since 1944, light flashes from the scintillator recorded by photomultiplier tubes (PMT). Later, photodiodes were used for this purpose also. The first modern detector based on NaI-T crystal was developed by Robert Hofstadter. Despite the presence of an impressive list of candidates for promising scintillators, for a long-time only cesium iodide crystal with thallium and sodium and calcium fluoride, activated by europium ions, as well as some tungstates in specific applications, were widely used. Today, more and more new materials are opening, with characteristics close to ideal [11].

Today there are a large number of scintillators that are fundamentally different from each other. The scintillator can be organic (crystals, plastics or liquids) or inorganic (crystals or glasses). Gaseous scintillators are also used. Anthracene ($C_{14}H_{10}$), stilbene ($C_{14}H_{12}$), and naphthalene ($C_{10}H_8$) are often used as organic scintillators [6]. Liquid scintillators are commonly known by brand names (for example, NE213).

There are a number of factors that determine the suitability of a scintillator for a particular application. There are a number of factors that determine the suitability of a scintillator for a particular application. The greater the density and attenuation coefficient of the material, the greater the absorption of incident photons. Light yield indicates the number of scintillation photons that would be expected from a given energy input (affected strongly by scintillator composition) — the more scintillation photons produced, the easier a single X- or gamma ray event is to detect and the better the theoretical limit for energy resolution. Peak emission wavelength and refractive index affect the efficiency with which a given detector can detect scintillation photons [2]. An important limiting factor is the hygroscopicity of the material - the ability of some substances to absorb water vapor from the air. All scintillators based on iodides, chlorides and bromides are hygroscopic. This leads to their degradation or complete destruction.

Scintillation detectors are used not only to register ionizing radiation, but also to detect quanta and neutrons. In these cases, the scintillation detector registers not the photons and neutrons themselves, but the ionizing particles arising from their collisions with the scintillator atoms: electrons, recoil nuclei and fragments of split nuclei. Thus, scintillation detectors register all types of radioactive radiation, and the detection efficiency of high-energy γ-quanta can be very large in scintillators (50 or even 100%). Due to the high temporal resolution, direct measurements of the lifetime of short-lived excited states of nuclei, positrons and mesons became possible. A scintillation detector can be not only a counting device that records the number of particles, but also a spectrometer — a device for measuring energy, because the amplitude of the pulse at the output of the photomultiplier is uniquely related to the amount of energy that a particle loses in the scintillator. The listed properties of scintillation detectors make it possible to use scintillation counters very widely not only in experimental physics, but also in radiochemistry, oil production, astrophysics, radiobiology, medicine, safety systems and geology. The most common scintillation detector applications in medicine are visualization (PET, X-ray CT, SPECT)

2. Materials

In the article [12] for achievement of achieve higher performance, the authors propose several methods for obtaining inorganic scintillating materials. The first method is a combination of an insulator host and a doped emission center. Namely, they are studying the Ce-doped garnet materials. The authors found that Ce-doped $Tb_3Al_5O_{12}$ (TAG) has very promising scintillation properties: decay time of 38 ns and a high light yield of 57,000 ph/MeV. This discovery will open a new possibility to be considered as a host of garnet scintillators. The second method is related to search for non-hygroscopic halide scintillators. And they have been developed non-hygroscopic halide scintillators, including Tl- and In-doped CsCl [10], $TlCdC_{l3}$ [4], Tl- and Ce-doped Cs_2HfC_{l6} [8], Rb_2HfC_{l6} [9], Ce-doped $CsCaC_{l3}$[5] and $TlMgC_{l3}$ [3]. Of these, the best properties showed $TlMgC_{l3}$. It has a relatively fast decay (60 ns), high energy resolution (5% at 662 keV) and a high light yield (46 000 ph/MeV). The third method can be considered the development in the direction of enhancing the light yield by co-doping with alkali metal elements of the crystal scintillators.

They proposed the inclusion of Na to Eu-doped $LiCaAlF_6$. With this method, the scintillation light yield is enhanced by 12 000 ph/n.

In the paper [1], the authors propose three inorganic scintillation crystals that have very fast decay times (τ_d = 16– 25 ns). Of these**,** $LaBr_3$:Ce has the best energy resolution due to the presence in its composition of ^{138}La radionuclide. $YAlO_3$:Ce (YAP) has a relatively low light yield (L_Y = 20-25 photons/keV), but it is the only scintillator that has no dependence of light yield on secondary electron energy at energies above 15 keV. And the $CeBr_3$ scintillator, which has not only a small decay time and a weak dependence of light yield on temperature, but also a high resolution and high efficiency of γ-quanta registration.

Another type of inorganic scintillation crystals is cerium-doped oxide gadolinium aluminum gallium garnet ($Gd_3Al_2Ga_3O_{12}$:CE) [7]. Although this material has a higher decay time (88 ns) compared to the previous crystals, it has a sufficiently high light yield.

In Table 1 presents the main characteristics of the scintillators under consideration.

Table 1. Characteristics of the scintillators under consideration

Materials	Luminosity (ph/MeB)	Decay time (ns)	Energy resolution (% at 662 keV)	Density, (g/cm^3)
$Tb_3Al_5O_{12}$:Ce	57000	38	-	
$TlMgC_{l3}$:Ce	46000	60	5	
$LiCaAlF_6$	-	50	-	-
$LaBr_3$:Ce	63000	16	2,9	5,08
$YAlO_3$:Ce	25000	25	4,4	5,37
$CeBr_3$	68000	17	3,8	5,2
$Gd_3Al_2Ga_3O_{12}$:Ce	57000	88	5,2	6,63

3. Application

The presented inorganic scintillators have a fairly wide spread over the decay time and light yield although they are considered to be the most effective. This is due to the difference in their fields of their application.

$Tb_3Al_5O_{12}$, $TlMgCl_3$ and $Gd_3Al_2Ga_3O1_2$:Ce scintillators are designed for x-ray and α-ray detectors. The main application is medical imaging (PET).

A $LiCaAlF_6$ scintillator is designed to detect thermal neutrons, and the advantage of it is a high scintillation light yield when Eu^{2+} and a non-hygroscopicity. Pulse-shape discrimination is possible when Ce^{3+} is doped.

Scintillators $LaBr_3$:Ce, $YAlO_3$:Ce and $CeBr_3$ are gamma spectrometers for nuclear power plants. But $LaBr_3$:Ce is not suitable for hard γ-ray spectrometry where large scintillator sizes are required to provide the required recording efficiency. $YAlO_3$:Ce is preferred in the soft (X-ray) region of γ-radiation energies. And $CeBr_3$ for measuring the characteristics of high-power γ-fields, and for conducting low-background studies.

4. Conclusion

The work is devoted to the review of modern developments in the field of inorganic scintillation materials. The most promising scintillators that are used in science, medicine and industry are shown. Presents such basic properties as: light yield, decay time, resolution and density of the material. It is revealed that today the most common are Ce-doped scintillators. It has been shown that materials such as $Tb_3Al_5O_{12}$: Ce, $TlMgC_{l3}$: Ce and $LiCaAlF_6$ have been recently obtained and their properties are not fully understood. It is noted that the inclusion of Na into Eu-doped $LiCaAlF_6$ is a promising method for increasing light yield. $LaBr_3$: Ce and $CeBr_3$ are most effective, which have found their application in nuclear medicine. Scintillator $Gd_3Al2Ga_3O_{12}$:Ce has the largest decay time, however, it has found wide application in the nuclear industry.

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