SCINTILLATION NEUTRON DETECTOR ON THE BASIS OF BORON-CONTAINING PLASTICS

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Main parameters are presented for plastic scintillators containing boron. These scintillators were obtained by the block polymerization method of polystyrene with luminescent dopants and allyldodecaborane. Sample dimensions: diameter 25 mm, height 25 mm. Parameters studied included light output, sensitivity to neutrons and time characteristics.

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1. INTRODUCTION

Plastic scintillators containing ^{10}B show many advantages over other neutron detectors, such as high detection efficiency and low intrinsic background, as well as high radiation stability.

Thermal neutrons are detected by such scintillators mainly as a result of exothermal reaction ^{10}B(n,αγ)^{7}Li (interaction cross-section δ=3840 barn):

$$^{10}_{5}B + {}^{1}_{0}n \rightarrow \begin{cases} {}^{7}Li(1.015\,\text{MeV}) + \alpha\ (E_{\alpha} = 1.777\,\text{MeV})\ \ (Q_p = 2.792\,\text{MeV}) \\ {}^{7}Li^{*}(0.840\,\text{MeV}) + \alpha\ (E_{\alpha} = 1.470\,\text{MeV})\ \ (Q_p = 2.310\,\text{MeV}) \end{cases}$$

$$^{7}Li^{*} \rightarrow {}^{7}Li + \gamma\ (E_{\gamma}=0.480\ \text{MeV})$$

In 93.7% of cases (in the neutron energy range from thermal to 0.2 MeV) ^{7}Li is formed in the excited state. In transition from the excited to the basic state, the lithium nucleus ($T_{1/2}=67.3\cdot10^{-15}$ s) emits a gamma-quantum of energy E_{γ}=0.480 MeV.

Detection of fast neutrons is possible by the recoil protons, as well by the reaction:

$$^{11}_{5}B + {}^{1}_{0}n \rightarrow {}^{8}_{3}Li + {}^{4}_{2}He$$

$$\beta^{-},\ 0.847\,s \longrightarrow {}^{8}_{4}Be \rightarrow 2\alpha\ ,\ 10^{-16}\,s$$

This reaction is endothermic, its threshold is 6.63 MeV, and the cross-section is $4\cdot10^{-26}$ cm^2. ^{8}Li nucleus with $T_{1/2}$=0.847 s is transformed into two α-particles of 1.5 MeV energy each, and one β-частицу of energy 13 MeV.

The light yield in a plastic scintillator due to capture of thermal neutrons from α-particles and ^{7}Li nuclei is equivalent to the yield from γ-quanta or electrons of energies from 65 to 480 keV.

At such lifetime, the detection probability of γ-quanta with E_{γ} =480 keV is rather high, which can noticeably affect the pulse discrimination by their shape. However, equipment of new generation, with time resolution of tens of picoseconds, allows us to approach the solution of this problem. The light yield resulting of thermal neutron capture from α-particles is equivalent to the yield from γ - quanta or electrons with energies from 65 to 160 keV.

2. EXPERIMENTAL AND RESULTS

In several papers, studies were reported on a possibility to use different boron-organic compounds in plastic scintillators (see, e.g., [1]). However, little attention has been paid to the problem of creation of efficient fast boron-containing plastic scintillators with maximum possible boron content and good transparence at the emission spectrum maximum for detection of neutrons with energies up to 10 MeV.

Attempts were made of introducing various boron-organic compounds into liquid scintillators [1], though efficient light output and a possibility of discrimination over pulse shape were shown only for trimethylborate. Boron content in trimethylborate was 9.7%. As detection efficiency of thermal neutrons depends of the introduced boron content, this compound has to be introduced into liquid scintillators in high concentrations (up to 50 mass %), which affects the scintillation properties of the material. Moreover, for trimethylborate, as well as for other boric acid esters, a problem is its low stability with respect to moisture, leading to hydrolysis, with boric acid (non-soluble in weakly polar organic media) being one of its products:

$$B(OR)_3 + 3\ H_2O \rightarrow B(OH)_3\downarrow + 3\ ROH$$

where R is an alkyl group. Formation of the precipitate of this compound leads to property degradation with time of the liquid scintillator; therefore, boric acid esters are hardly suitable for their use in plastic scintillators.

For neutron detection, we have developed specially made compositions of types Т-1 и Т-2 [2], which contain boron compounds enriched in $^{10}_{5}B$ isotope (its concentration in the natural boron is ~ 20%), lithium compounds enriched in $^{6}_{3}Li$, as well as ZnS(Ag). In most cases, boron and lithium are used in the form of oxides or fluorides. Introduction of the luminescent composition into the polymer was carried out either by the method of hot pressure compaction of the mixture of the composition and polymer dissolved in the monomer, or by polymerization. Polystyrene or polymethylmetacrylate was used as the polymeric basis.

The scintillators obtained by compaction in the form of pellets up to 10 mm in diameter were of milk-white color and low optical transparence. Using thermal polymerization, we succeeded in obtaining scintillators with relatively uniform distribution of the luminescent composition over its volume. However, the scintillator thickness should not be higher than 5 mm, as the optical transparence noticeably decreased with thicker samples.

In addition, during the polymerization process it is very difficult to keep the luminescent composition grains larger than 150 μm in suspended state over all the polymethyl-

metacrylate volume, because the density of polymethylmetacrylate is higher than that of luminescent composition.

As a result of mechanical treatment of the scintillator piece (cutting, grinding, polishing), luminescent composition grains were partially coming out to the polymer surface. These grains being hygroscopic (and, consequently, tending to change their chemical composition), it was not possible to obtain scintillators with uniform counting characteristics. Thus, reliability of thermal neutron measurements using such scintillators was not sufficiently high.

The presence of non-soluble (suspended) fraction of the luminescent composition decreases the light yield and increases light absorption in the bulk scintillator. Accounting for this, the detector should combine detection of fast neutrons over recoil protons (i.e., function of a conventional plastic scintillator) and the presence in it of boron compounds that cause the above-described reaction. The role of plastic scintillator included also detection of the formed heavy charged particles. This implies the requirement for homogeneity and high transparence of the whole scintillation system.

Consequently, the other way to obtain the required solid-state detector was to introduce a boron-containing compound – isopropenylcarborane – into a plastic scintillator containing luminescent dopants.

This substance has high stability characteristics with respect to various external factors, it is well soluble in non-polar and weakly polar organic media, displays no absorption bands in the visible spectral range, and, due to the presence of isopropenyl group, can be co-polymerized with vinyl monomers of aromatic series (styrene, vyniltoluene, vynilxylene, etc.).

However, isopropenylcarborane could be introduced in quantities not more than 5 mass %. Neutron detection efficiency of such scintillator is rather low [3]. There are also reports on the use of o-carborane in plastic scintillators [4], which contains somewhat larger quantity of boron (67 mass %) as compared with its isopropenyl derivative (49%). This substance was introduced into polystyrene with mass fraction of boron up to 5%.

Also known are boron-containing plastic scintillators where decaborane $B_{10}H_{14}$ was used as boron-containing compound [4]. However, such plastic scintillators, due to limited solubility of the introduced boron-organic compound, contained not more than 15 mass % of $B_{10}H_{14}$. This feature does not allow increasing absorption of the ionizing radiation, thus improving detection efficiency of thermal neutrons. Moreover, decaborane $B_{10}H_{14}$ is a toxic compound, easily oxidized in air, which substantially limits its possible use in production of plastic scintillators.

It seemed interesting for us to study plastic scintillators with yet another substance, which has not been used in plastic scintillator production - allyldecaborane:

$$(CH_2 = CHCH_2)B_{12}H_{12}$$

Due to its high solubility in the monomer, it can be introduced in amounts of up to 20 mass % of boron.

From the obtained pieces, we prepared samples 25 mm in diameter and 25 mm high. The light output of such detectors with respect to anthracene was 42%, effective light attenuation length is increased by 1.4 times, leading to substantial (by about 1.7 times) increase in detection efficiency of thermal neutrons. The α/β-ratio remains within the limits of 0.05-0.07.

3. CONCLUSIONS

Thus, high optical transparence allows fabrication of scintillators of different sizes and complex shapes, as well as combined detectors on the basis of gadolinium silicate and plastics. Detectors of small sizes allowed full realization of these advantages for pulse discrimination by shape and ensuring fast time characteristics.

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СЦИНТИЛЛЯЦИОННЫЙ НЕЙТРОННЫЙ ДЕТЕКТОР НА ОСНОВЕ БОРО-СОДЕРЖАЩИХ ПЛАСТМАССОВЫХ СЦИНТИЛЛЯТОРОВ

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В работе представлены основные параметры пластмассовых сцинтилляторов, содержащих бор. Эти сцинтилляторы получены методом блочной полимеризации полистирола с люминесцирующими добавками и аллилдодекабораном. Размеры образцов: диаметр 25 мм и высота 25 мм. Исследованы световой выход, чувствительность к нейтронам и временные характеристики.

СЦИНТИЛЯЦІЙНИЙ НЕЙТРОННИЙ ДЕТЕКТОР НА ОСНОВІ ПЛАСТМАСОВИХ СЦИНТИЛЯТОРІВ, ЯКІ МІСТЯТЬ БОР

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У роботі представлені основні параметри пластмасових сцинтиляторів, які містять бор. Ці сцинтилятори одержані за допомогою методу блочної полімеризації полістиролу з домішками, що випромінюють люмінесценцію та алилдодекабораном. Розміри зразків: Ø25х25 мм. Досліджені світловий вихід, чутливість до нейтронів та компоненти висвічування.