

A liquid scintillator for thermal neutrons detection

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A novel gadolinium-loaded liquid scintillator based on linear alkylbenzene intended for use in a large-scale neutrino experiment Daya Bay has been studied. The study results show a high efficiency of thermal neutron detection using the novel liquid scintillator and make it possible to recommend this material in experiments on search for neutrino oscillations.

Исследован новый гадолинийсодержащий жидкий сцинтиллятор на основе линейного алкилбензола, предназначенного для использования в крупномасштабном нейтринном эксперименте Daya Bay. Полученные результаты свидетельствуют о высокой эффективности регистрации тепловых нейтронов новым жидким сцинтиллятором и позволяют рекомендовать его для использования в экспериментах по поиску нейтринных осцилляций.

The enhancement of detection efficiency of the nuclear reaction products is among the urgent topics in the experimental support of investigations in the fields of nuclear and neutron physics, elementary particle physics, neutrino physics, high energy physics, as well as in search for solution of numerous astrophysical and cosmological problems. Liquid scintillators having numerous advantages as compared to inorganic analogs are often used as bases for various detecting systems. A considerable interest in development and production of such materials is due to widening investigations in neutrino astronomy and neutrino oscillation observations. Many experiments [1–7] using the reactor neutrinos are based on the study of an electron antineutrino interaction with a proton:

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$

The neutron formed due to inverse β-decay is moderated in the scintillator up to thermal energy range and is captured by a proton under release of a 2.2 MeV gamma quantum. The detection of gamma radiation arising due to capture of a thermalized neutron by a proton is delayed with respect to the instantaneous release of the recoil energy of positron and neutron and two annihilation gamma quanta (E_γ = 0.511 MeV). This fact provides additional possibilities to observe the reaction. To reduce the lifetime of the thermal neutron and increase the energy of gamma quanta being released at its capture, gadolinium is introduced into the liquid scintillators at a mass fraction of about 0.1 %. The energy being released at the neutron capture on ^{155}Gd and ^{157}Gd nuclei is about 8 MeV. The thermal neutron capture cross-section of the natural gadolinium isotopic mixture is five decimal order higher than that of hydrogen (Table 1).

New Gd-loaded liquid scintillator (Table 2) based on linear alkylbenzene [9] has been developed in the framework of the collaboration on preparing to the DAYA BAY neutrino experiment.

Table 1. Thermal neutron capture characteristics by nuclei of some isotopes

Isotope	Natural abundance, %	Reaction	Capture cross-section, barn	Recording particles
^{1}H	99.985	(n,γ)	0.334	γ:2.224 MeV
^{235}U	0.7	fission	$5.8\cdot10^{2}$	Fission products: ≅200 MeV
^{6}Li	7.5	(n,α)	$9.4\cdot10^{2}$	α:2.05 MeV + ^{3}H:2.73 MeV
^{10}B	20	(n,α)	$3.8\cdot10^{3}$	α: 1.47 MeV + ^{7}Li:0.84 MeV + γ:0.48 MeV
^{3}He	0.01	(n,p)	$5.3\cdot10^{3}$	p:0.574 MeV + ^{3}H:0.191 MeV
^{113}Cd	12	(n,γ)	$2.0\cdot10^{4}$	γ-cascade:8 MeV
^{155}Gd	15	(n,γ)	$6.1\cdot10^{4}$	γ-cascade:8 MeV
^{157}Gd	16	(n,γ)	$2.6\cdot10^{5}$	γ-cascade:8 MeV

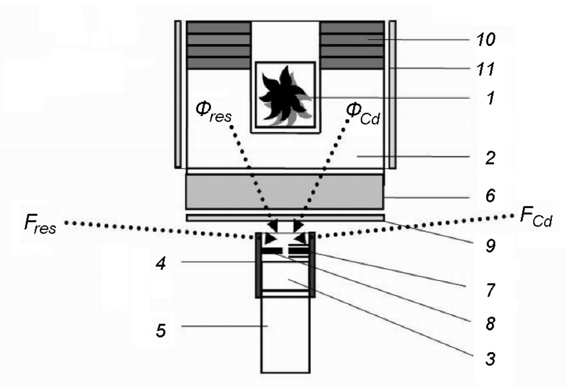

Fig. 1. Experimental setup for studies on thermal neutron detection efficiency in a LS.

The purpose of present work is to measure the detection efficiency of thermal neutrons by the novel Gd-loaded liquid scintillator (LS) intended to be used in the large-scale experiment on high-accuracy measurement of the neutrino mixing angle θ_{13}.

The detection efficiency of thermal neutrons was measured using the setup presented in Fig. 1. A Pu–Be source (*1*) with the emission rate of $4.7\cdot10^{6}$ neutrons per second immersed in a paraffin moderator (*2*) was used to form the thermal neutron beam. The LS to be studied was placed in a cylindrical Teflon cell (*4*) of $\varnothing50\times47$ mm^3 size placed on a PMT (*5*) in the optical contact. To protect the scintillator against gamma quanta being formed in the neutron source and paraffin moderator, a massive lead barrier (*6*) was used.

Table 2. Characteristics of Gd-containing liquid scintillator based on linear alkyl benzene

Scintillator base	Linear alkyl benzene
Gd-containing additive	Gadolinium 3,5,5-trimethyl hexanoate
Gd concentration, g/L	1
Primary additive	PPO
PPO concentration, g/L	3
Spectrum shifter	Bis-MSB
Bis-MSB concentration, mg/L	15
Light yield, %, relatively to anthracene	53
Transparence (430 nm), m	15

The area under spectral curve of gamma quanta generated due to the thermal neutron capture is defined mainly by the flow density of thermal neutrons with <0.4 eV energy (Φ_{Cd}) as well as, to a less extent, by that of resonance neutrons with 0.4 to 10 eV energy (Φ_{res}) incident the LS. The comparison of the spectrum area associated with the thermal neutron detection and the flow density Φ_{Cd} provided the determination of the LS efficiency.

The flow density of thermal neutrons falling to the LS under study was determined using the activation technique. The gold-in-cadmium targets (*7*) and cadmium-free gold targets (*8*) were used for this purpose. The targets exhibit a large cross-section of ^{198}Au isotope formation (half-life-

Table 3. Thermal neutron detection efficiency of the LC based on linear alkyl benzene

Scintillator layer height, cm	Total detection efficiency of <0.4 eV thermal neutrons, %	
	Gd (1 g/L)	Gd-free
1	12±2	–
2	19±3	–
3.5	29±4	–
4.5	35±5	17±3

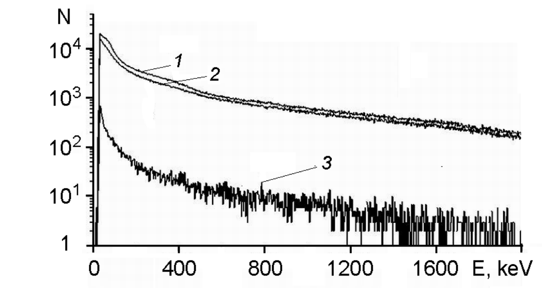

Fig. 2. Thermal neutron spectra recorded by the PMT for Gd-loaded LS at the layer height H = 2 cm: without (*1*) and with (*2*) ^{6}Li screen; (*3*) the background.

time 2.696 day) for thermal neutrons (σ_{Cd} = 95 barn) and the presence of a resonance integral (σ_{res} = 1570 barn) within the 0.4 to 10 eV energy range. By measuring the target gamma activity with and without cadmium being activated with and without the ^{6}Li screen (*9*), it was possible to discriminate the resonance component of the neutron flow density from the paraffin moderator as well as the thermal (F_{Cd}) and resonance (F_{res}) components of the external background. For its reduction, the moderator was screened by boron-containing polyethylene (*10*) and ^{6}Li (*11*). The fraction of the thermal neutron flow density (E_n < 0.4 eV) at the scintillator surface being absorbed by the ^{6}Li screen, as determined in that way, amounted Φ_{Cd} = (86±6) n/cm^2·s. Two such spectra (*1*, *2*) and the background spectrum (*3*) in the absence of the neutron source with gammas energy range up to 2 MeV for 2 cm height of scintillator's layer are presented in Fig. 2.

During the experiments, the spectra of 60 keV to 7 MeV gamma quanta that arise in the LS under interaction with thermal neutrons were measured for four samples of the Gd-loaded LS at the layer height of 1 cm to 4.5 cm as well for one Gd-free LS at the layer height of 4.5 cm. The experimental efficiency values for those samples are presented in Table 3.

The results obtained evidence a high efficiency of thermal neutron detection by the novel liquid scintillator and enable to recommend it for use in experiments on the search for neutrino oscillations.

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Рідкий сцинтилятор для реєстрації теплових нейтронів

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Досліджено новий гадолінійвмісний рідкийо сцинтилятор на основі лінійного алкілбензолу, призначеного для застосування у великомасштабному нейтринному експерименті Daya Bay. Отримані результати свідчать про високу ефективність реєстрації теплових нейтронів новим рідким сцинтилятором і дозволяють рекомендувати його для застосуванні у експериментах з пошуку нейтринних осциляцій.