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Enhancement of the Sensitivity of Neutrino-Telescope Optical Modules to Cerenkov Light

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Abstract—The results of studies of thin-film wavelength shifters developed for optical modules of large-scale neutrino telescopes are presented. The effect of such wavelength shifters is an increase in the sensitivity of an optical module of the AMANDA neutrino telescope to Cerenkov light of 48%.

One of the most important problems of modern high-energy physics, cosmic-ray physics, and astrophysics is the investigation of natural high-energy neutrino fluxes. Active works on the creation of large-scale neutrino telescopes are underway in many countries in order to succeed in this field. For example, the first HT-200 deep-underwater neutrino telescope in the world successfully operates in Lake Baikal [1]. Similar projects are being developed for the Mediterranean Sea: ANTARES [2], NESTOR [3], and NEMO [4]. At the South Pole (Antarctic), the AMANDA neutrino telescope operates for several years inside ice at a depth of 1–2 km [5]. Works on the development of a giant ICECUBE detector [6] with a working volume of ~1 km^3 were initiated in the same region.

In all the telescopes mentioned above, neutrinos are detected using Cerenkov light from products of interaction of neutrinos with matter. The Cerenkov light spectrum changes with the wavelength of the emitted light as λ^{-2}; consequently, the greater part of this radiation lies in the UV and blue regions. The spectral composition of light that falls on the optical module of a Cerenkov detector is determined by the spectrum of Cerenkov light and the medium transmission spectrum. In fresh lake and salt sea water, the short-wavelength portion of the Cerenkov radiation is efficiently absorbed and becomes inaccessible for neutrino telescopes. Another situation takes place for distilled water and, especially, ice (e.g., at a depth of >1 km in Antarctic).

Figure 1 shows the light absorption coefficient as a function of λ for water in Lake Baikal and the Mediterranean Sea, as well as for distilled water and ice at a depth of ~1 km at the South Pole. The experimental data are taken from [1, 7–9]. As is shown in this figure, the transparency of ice at such depths is high, down to $\lambda \sim 200$ nm. Note that distilled water is also rather transparent in this wavelength range. Thus, this work can be also interesting for underground Cerenkov neutrino detectors, such as SUPER-KAMIOKANDE [10], in which distilled water serves as a working substance. This is especially important to prepare for forthcoming restoration works on this detector and for currently conducted works on designing a giant UNO underground Cerenkov detector [11].

The sensitivity of optical modules is limited by the transparency of glasses and sensitivity of photocathodes of photodetectors (PDs) of optical modules at wavelengths of 200–300 nm. The sensitivity reaches a maximum at λ = 380–400 nm and abruptly falls almost to zero at λ = 300 nm. A typical dependence of the quantum efficiency η of the photocathode of a photomultiplier tube (PMT) of an optical module of the AMANDA neutrino telescope on the light wavelength λ and a transmission τ spectrum of the protecting spherical glass are shown in Figs. 2 and 3. According to these data, a considerable fraction of the emitted Cerenkov radiation remains undetected, eventually resulting in a decrease in the sensitive volume of the array as a whole and an increase in the particle detection energy threshold. Consequently, in order to enlarge the detector sensitive volume and to reduce the detection energy threshold, it is expedient to increase the sensitivity of the optical modules to Cerenkov light.

A possible solution to this problem is the use of film wavelength shifters described in detail in the literature [12–15]. Such wavelength shifters efficiently absorb Cerenkov radiation in the range of 200–300 nm and reemit light in the spectrum region in which the sensitivity of optical modules is high. Most of them were developed to be used in air, gases, or when operating with solid scintillators rather than in water or ice. The complexity of developing wavelength shifters in the two latter cases is explained by the comparatively small difference between the refractive indices of water/ice ($\simeq$1.35) and the glass of the optical module ($\simeq$1.48).

Scintillating additives for thin-layer wavelength shifters were selected taking into account the following factors: the high quantum efficiency at wavelength of

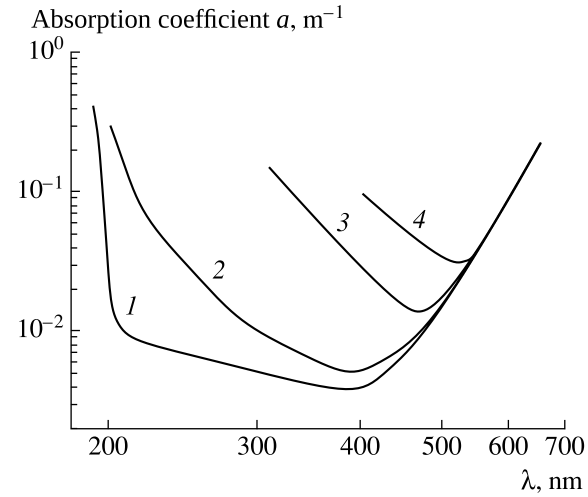

Fig. 1. The light absorption coefficient *a* as a function of wavelength λ: (*1*) for ice at a depth of ~1 km at the South Pole (Antarctic); (*2*) for distilled water used in the SUPER-KAMIOKANDE detector; (*3*) for water in the Mediterranean sea at the probable location of the ANTARES neutrino telescope; and (*4*) for water in Baikal at the location of the HT-200 neutrino telescope.

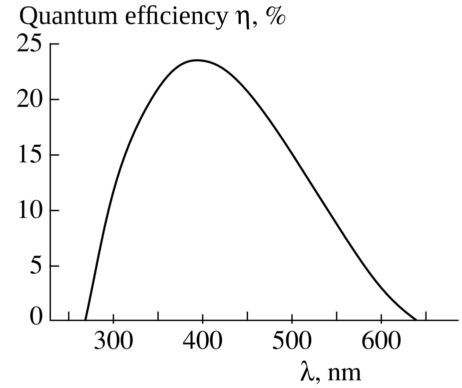

Fig. 2. Quantum efficiency η of the photocathode of the R5912-02 PD versus wavelength λ.

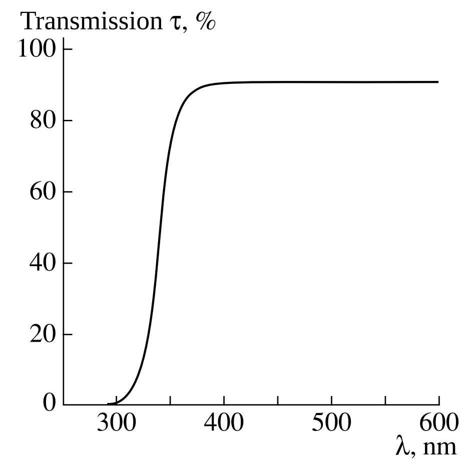

Fig. 3. Transmission spectrum τ for the glass of the protecting sphere of an OM of the AMANDA neutrino telescope.

200–350 nm, a considerable Stokes shift, a small anti-Stokes region; a peak of the light absorption spectrum between 200 and 330 nm, a peak of the emission spectrum between 360 and 400 nm, a short scintillation decay time, a good solubility in available organic solvents (toluene, dichloromethane, etc.), a good adhesion of the resulting film to the optical module glass, and stable optical and mechanical properties of films exposed to water. Table 1 lists the main characteristics of scintillating additives of phosphors used in experiments (the data from [16, 17]). Figure 4 shows the absorption and emission spectra of one of the used phosphors (Butyl PBD).

Figure 5 shows a block diagram of the test bench developed for studying the properties of thin-film wavelength shifters. Cerenkov radiation was radiated by a layer of distilled water ~10 cm thick located in a special conic metallic cell *C* attached to the optical module OM using a sealing ring *SR* and a system of elastic tension members (not shown in Fig. 5). The cell is covered by a cap *CP* made of a light-absorbing material for suppressing multiple light reflections. At such a thickness of the distilled water layer, the absorption of Cerenkov radiation in the range of 200–300 nm is still insignificant (see Fig. 1). Plastic scintillators S_1 and S_2 with dimensions of 50 × 50 × 1.5 cm each are located above and below the optical module under study, forming a muon telescope, which selects the muons with trajectories close to the vertical and intersecting the Cerenkov radiator. These scintillators are viewed by two PMTs (XP2020), whose anode pulses arrive at the inputs of a coincidence circuit *CC* (LeCroy 466) via fast amplifiers A_1 and A_2 (LeCroy 612AM) and discriminators D_1 and D_2 (LeCroy 621AL). The *CC* output pulses form gate signals for a charge-to-digital converter *CDC* (LeCroy 2249A). Via a delay line DL_1, the output pulses of the OM under study arrive at the *ADC* input, where they are digitized. The data are processed by a computer (IBM-PC/486DX2-66), which is interfaced with a CAMAC crate through a crate controller *CrC* (KK-009).

An OM of the AMANDA neutrino telescope was used in measurements [18]. The module consists of a protecting borosilicate-glass sphere (produced by Benthos) and a PMT (R5912 by Hamamatsu) [19]. The optical contact between the protecting sphere and PMT is implemented using a SEMICOSIL-912 optical compound with an average layer thickness of ~1 cm in the OM.

The R5912-02 PMT with a hemispherical bialkaline (K_2CsSb) photocathode ~20 cm in diameter was developed for the use in large-scale Cerenkov and scintillation neutrino detectors. It contains a highly efficient boxlike large-area first dynode and a subsequent trough-shaped dynode system. The total number of stages (14) in the anode system made it possible to achieve a gain $G \geq 10^8$ and, as a consequence, not to use

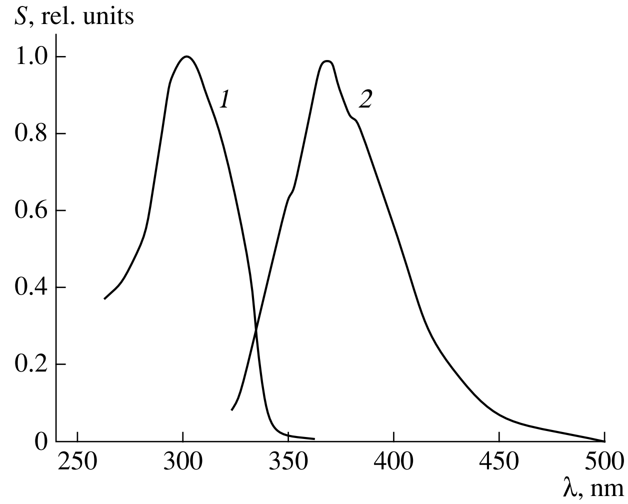

Fig. 4. (*1*) Absorption and (*2*) emission spectra of the Butyl PBD phosphor.

preamplifiers of PD output signals in the OM. Anode signals and the high supply voltage of the PMT are fed through the same coaxial cable. This PMT has a time resolution of ~3 ns. The PMT gain was set at $\sim 10^7$ for the measurements of the charges of PMT output pulses to be conducted in the linear region of its pulse light characteristic.

Table 1

Phosphor	$\lambda_{a\,\max}$, nm	$\Delta\lambda_a$, nm	$\lambda_{e\,\max}$, nm	$\Delta\lambda_e$, nm	ξ, %	t_d, ns
PPO	310	80	360	70	2–3	1.4
PTP	275	50	340	55	5	1.0
PQP	295	60	360	60	11	0.8
BBD	315	80	380	80	0.3	–
TMI	295	60	375	70	11	6.5
Butyl–PBD	302	60	368	60	5	0.8
Bis–MSB	350	75	415	80	8	1.4
POPOP	358	75	410	80	6.5	1.5
PBD	302	60	360	60	4	<1
Naphthalene	275	40	325	40	–	~100
BMQ	275	70	357	70	9	0.9
DPS	340	70	406	70	11	1.2
QUI*	310	65	390	70	11	–
TBS*	320	60	390	60	11	1.8

Note: $\lambda_{a,\max}$ is the wavelength at which the phosphor absorption spectrum reaches its maximum; $\Delta\lambda_a$ is the FWHM of the phosphor absorption spectrum; $\lambda_{e,\max}$ is the wavelength at which the phosphor emission spectrum reaches its maximum; $\Delta\lambda_e$ is the FWHM of the phosphor emission spectrum; ξ is the quantum efficiency of the phosphor; and t_d is the phosphor fluorescence decay time constant. Asterisks indicate the additives not used in this work.

We manufactured the wavelength shifters according to a conventional procedure described in [12, 14, 15]. Granulated plastic Paraloid B72 (produced by ROTH Gmb) was utilized as a binding base of the film. This material features a good transparency in the wavelength of interest (200–300 nm) and a short (~1 ns) scintillation decay time for scintillators based on it. The spectral transmission curve for a ~1-mm-thick film of this material measured in [12] is shown in Fig. 6. For comparison, this figure also presents the transmission curves for polymethyl metacrylate (PMMA) and polystyrene (PS), which are widely used for the production of plastic scintillators. PMMA- and PS-based scintillators have long fluorescence decay times compared to Paraloid B72-based scintillators [12, 13, 20].

During the production of wavelength-shifter films, the binding agent was solved in dichlormethane (CH_2Cl_2) or toluene (C_7H_8) in a concentration of ~20 mg/ml. The selected scintillating dopants were added to this solution, which was deposited onto a preliminarily degreased surface of the OM by the technique of precipitation from a solution [14, 15]. The average film thickness was ~0.1 mm. Double layers were used in some cases. The deposited layer was dried in air under natural conditions for 1.5–2 h, and only then measurements began. The total number of prepared and investigated versions of wavelength shifters was 45 (the combinations of scintillating additives and their relative concentrations were varied).

The efficiency of utilizing wavelength-shifter films was determined by measuring the charge distribution of the OM output pulses generated due to Cerenkov radiation upon passage of muons in the water radiator. The mean value of the charge distribution Q_f for an OM with a deposited wavelength shifter was compared to a similar quantity Q_0 for the OM without a wavelength shifter. The efficiency A was determined from the formula

$$A = ((Q_f - Q_0)/Q_0) \times 100\%, \quad (1)$$

where the Q_f and Q_0 values are taken after the pedestal subtraction.

Table 2 presents the data of measurements with wavelength shifters whose efficiency is at least 25%. The highest efficiency (~48%) is observed with the following wavelength shifters: Paraloid + 5% TMI + 0.1% POPOP in CH_2Cl_2 and Paraloid + 5% Butyl PBD + 0.1% POPOP in CH_2Cl_2 (weight concentrations of the scintillating additives with respect to the binding agent are given). The use of a film with the TMI additive is limited by its comparatively high cost compared with Butyl PBD and a rather long (~6.5 ns) scintillation decay time. The relative concentrations of the binding substance and scintillating additives are taken from [12, 14, 15]. The efficiency as a function of the relative weight concentration of the Butyl PBD additive was measured for a wavelength shifter including this additive as a component (Fig. 7). As we see, the efficiency (light yield) already saturates at a 4–5% concentration

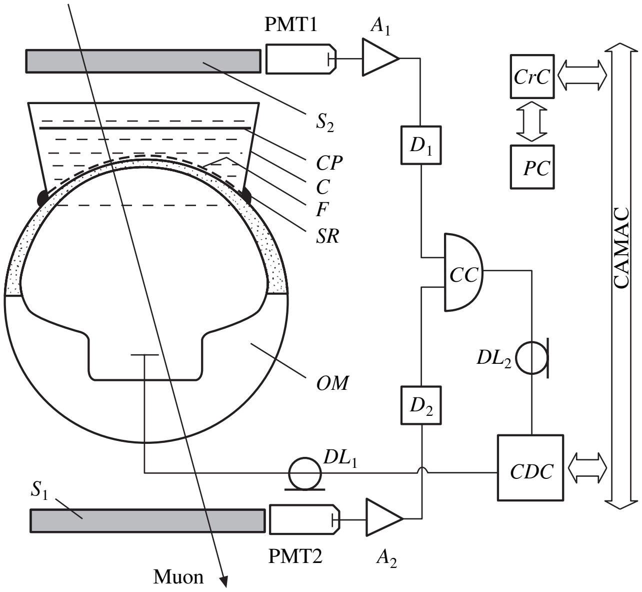

Fig. 5. Functional diagram of the measurement bench: (OM) optical module of AMANDA neutrino telescope; (*C*) cell with distilled water; (*F*) wavelength-shifter film deposited onto the OM; (*CP*) cap of a light-absorbing material; (*SR*) sealing ring; (S_1, S_2) plastic scintillators; (A_1, A_2) LeCroy 612AM fast scintillators; (D_1, D_2) LeCroy 621AL integral discriminators; (*CC*) LeCroy 466 coincidence circuit; (DL_1, DL_2) delay lines; (*ADC*) LeCroy 2249A charge-to-digital converter; (*CrC*) KK-009 crate controller; and (*PC*) IBM PC/486DX2-66 personal computer.

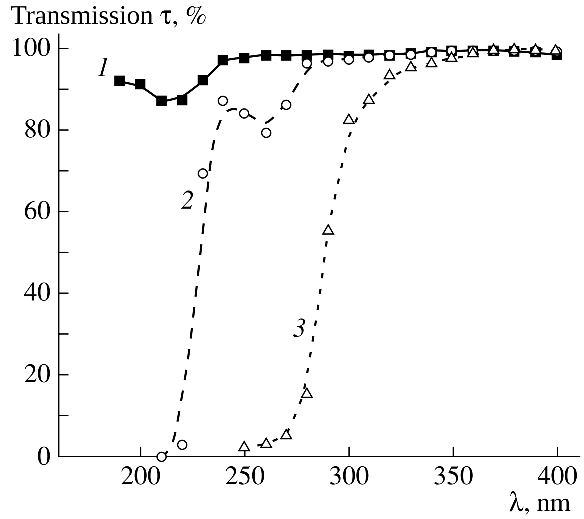

Fig. 6. Transmission spectra τ of (*1*) Paraloid B72, (*2*) polystyrene, and (*3*) polymethyl methacrylate films.

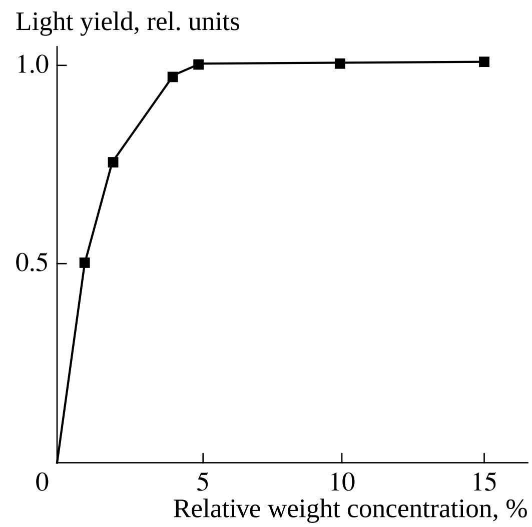

Fig. 7. Efficiency of the Paraloid B72-based wavelength-shifter film versus relative weight concentration of the Butyl PBD scintillating additive.

of the additive relative to the binding agent. Introducing a slight amount (~0.1%) of the second scintillating additive POPOP results in a small (~3%) increase in the efficiency. A certain amount of naphthalene added to the composition helps additionally increase the efficiency by several percent, but, in this case, the time resolution of the OM appreciably deteriorates because of the long decay time of naphthalene (~100 ns, see Table 1) and the adhesive ability of the film degrades (the film peels off the OM glass after being in water for one day).

The results of the measurements performed show that the most efficient wavelength shifter for OMs of neutrino telescopes is Paraloid + 5% Butyl PBD + 0.1% POPOP. When this composition is used, the sensitivity of OMs to Cerenkov radiation in distilled water increases by ~48%. When using a deuterium lamp as a light source simulating Cerenkov radiation in accordance with the technique described in [21], the OM sensitivity in air increased by ~140%.

Table 2

Composition of wavelength shifters	Efficiency, %	Notes
Paraloid B72 + 10% PTP	25	Transparent film covered by a grid
Paraloid B72 + 25% PPO	30	Transparent film
Paraloid B72 + 5% TMI	45	Transparent film
Paraloid B72 + 5% TMI + 0.1% POPOP	48	Transparent film
Paraloid B72 + 5% Butyl PBD	45	Transparent film
Paraloid B72 + 5% Butyl PBD + 0.1%POPOP	48	Transparent film

It should be noted that the optical parameters of the obtained film were not investigated in this study. The use of multilayer films with thoroughly selected optical parameters will allow for a more significant increase in the sensitivity of OMs of neutrino telescopes to Cerenkov radiation in ice and distilled water. A search for new efficient scintillating additives is also necessary. Unfortunately, the QUI and TBS phosphors, whose characteristics (Table 1) are promising for the use in thin-film wavelength shifters, were unavailable during this investigation.

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APPENDIX

The following abbreviations are used in this paper:

Paraloid B72—methylacrylate and ethylmethacrylate copolymer.

PMMA—polymethyl methacrylate.

CH_2Cl_2—dichlormethane.

C_7H_8—toluene.

PPO—2,5-diphenyloxazole.

PTP—*p*-terphenyl.

PQP—*p*-quartephenyl.

BBD—2,5-bis-(4-biphenyl)-1,3,4-oxadiazole.

TMI—2,5,2'''',5''''—Tetramethyl-*p*-quinquephenyl.

PBD—2-(4-Biphenylyl)-5-phenyl-1,3,4-oxadiazole.

Butyl PBD—2-(4-Biphenyl)-5-(4-*t*-butylphenyl)-1,3,4-oxadiazole.

Bis-MSB—*p*-bis(*o*-methylstyryl)-benzene.

POPOP—1,4-di[2-(5-phenyloxazolyl)]-benzene.

BMQ—2.2'''-dimethyl-*p*-quarterphenyl.

QUI—3,5,3,'''',5''''–Tetra-*t*-butyl-*p*-quinquephenyl.

TBS—3,5,3,'''',5''''–Tetra-*t*-butyl-*p*-sexiphenyl.

DPS—4,4'-diphenylstylbene.

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