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NUCLEAR EXPERIMENTAL TECHNIQUE

Photocathodes for the Detection of Cerenkov Radiation in Deep-Water Neutrino Telescopes

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Abstract—The results from a comparative assessment of the applicability of various vacuum photodetectors with different types of photocathodes to next-generation neutrino telescopes are presented. It is shown how the spectrum of Cerenkov radiation is altered during its propagation through the waters of Lake Baikal and the Mediterranean Sea. The effect exerted by the dispersion of the medium on the duration of a Cerenkov light pulse is studied.

Experimental high-energy neutrino astrophysics has an almost 30-year history rich in achievements in experimental techniques and instruments for scientific studies. Despite the fact that no high-energy ($E_\nu > 100$ MeV) extraterrestrial neutrino has thus far been reliably detected (in contrast to the low-energy range $E_\nu < 100$ MeV), this field of experimental physics can rightly be considered as entering the period of its maturation.

The HT-200 neutrino telescope, the first deep-water Cerenkov detector in the world, has been successfully functioning for several years at Lake Baikal [1]. The AMANDA neutrino telescope has also been used to good advantage at the South Pole [2]. Neutrino telescopes with active volumes of ~1 km^3 are currently being constructed under the Mediterranean Sea (NESTOR [3], ANTARES [4], and NEMO [5]), at the South Pole (ICECUBE [6]), and at Lake Baikal (GVD [7]).

In all of the telescopes now in operation or being designed, high-energy neutrinos are detected by the Cerenkov radiation generated in water or ice by the products of their interactions with the substance (relativistic charged leptons and high-energy electromagnetic or hadronic showers). Cerenkov radiation is detected at distances of ≥100 m from a particle track or a shower. Because the attenuation of light is wavelength-dependent, the spectrum of the Cerenkov light is altered during its travel through the substance. As a consequence, photons with wavelengths for which the absorption and scattering of light are higher are suppressed more heavily as the distance from the light source to the photodetector increases.

In this paper, calculations are performed for the waters of Lake Baikal and the Mediterranean Sea in the approximation of a point directional source of light pulses. The scattering length in these waters is λ_{scatt} = 60–100 m, and the dispersion index is characterized by the mean cosine $\langle \cos\theta \rangle \sim 0.8$–0.9 [2, 8] (i.e., forward small-angle scattering dominates). Taking into account the foregoing considerations, plus the fact that high-energy electromagnetic and hadronic showers are to be detected at distances of ≥100 m while the scattering length remains virtually constant in the wavelength range under consideration, we infer that the effect of light scattering can be ignored.

In order to estimate the distortion of the spectrum of Cerenkov radiation during its passage through the water (with the scattering of light being ignored), we use the wavelength dependences of the absorption coefficients $k(\lambda)$ in the range of 350–600 nm [2, 8] (Fig. 1). The initial spectrum of Cerenkov radiation in this range of wavelengths is assumed to be as follows:

$$\Phi_i(\lambda) = \Phi_0 \lambda^{-2}. \qquad (1)$$

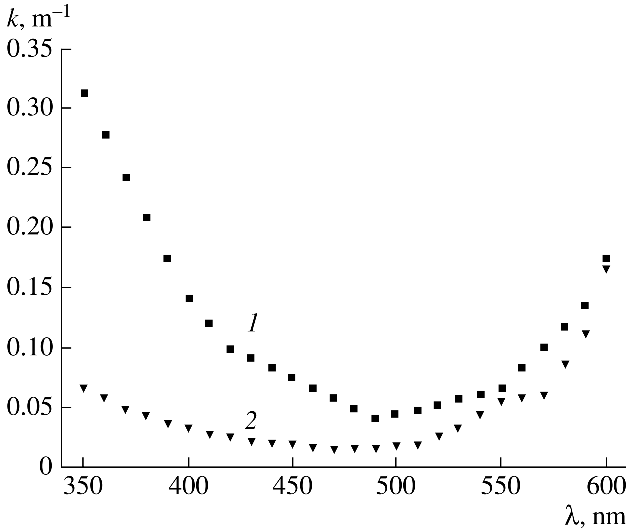

Fig. 1. Wavelength dependence of the light absorption coefficient in the waters of (*1*) Lake Baikal and (*2*) the Mediterranean Sea.

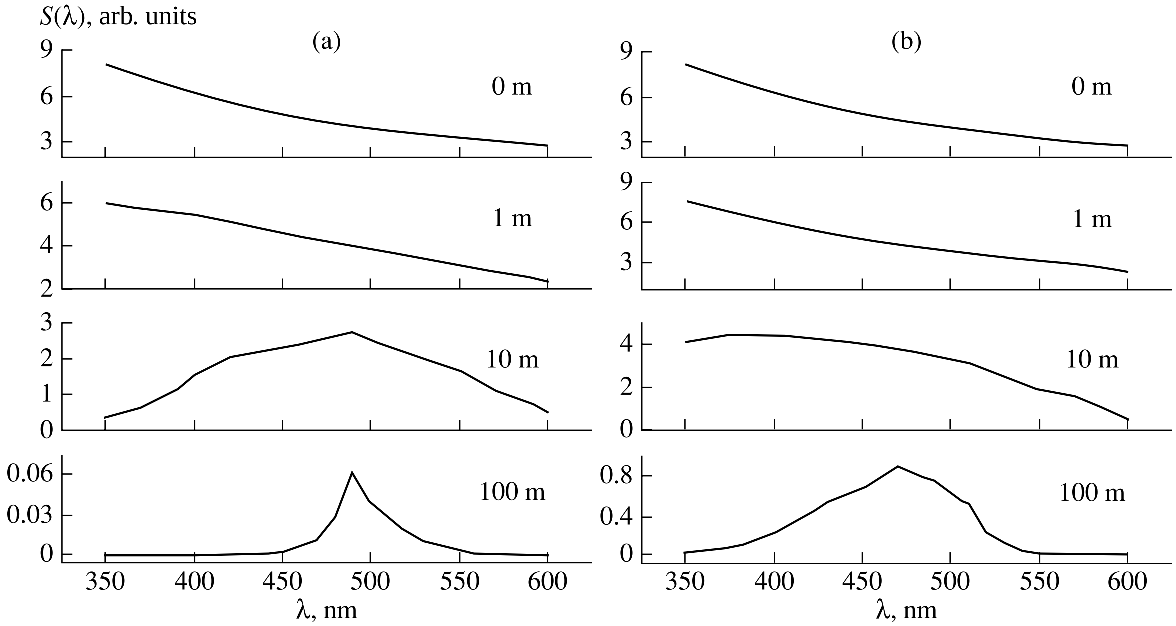

Fig. 2. Spectra of Cerenkov light in the waters of (a) Lake Baikal and (b) the Mediterranean Sea for different distances from the light source to the photodetector (numbers near the curves).

The final spectrum shape (i.e., the shape of the spectrum of Cerenkov radiation after its passage through a water layer of thickness R) is obtained from the formula

$$\Phi_k(\lambda) = \Phi_i(\lambda)\exp(-k(\lambda)R) \tag{2}$$

for three distances R equal to 1, 10, and 100 m. The spectra of the Cerenkov radiation that travels these distances in Lake Baikal and the Mediterranean Sea are shown in Fig. 2. As follows from the figure, the Cerenkov spectrum at a distance of 100 m from the source in the Mediterranean Sea is much wider than the analogous spectrum in Lake Baikal. This broadening is explained by the wider transparency window (Fig. 1).

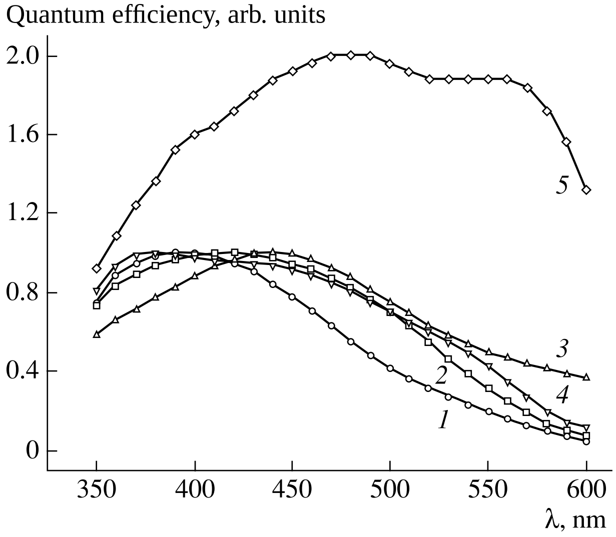

Fig. 3. Spectral dependences of the quantum efficiencies of different photocathode types: (*1*) K_2CsSb (OAO MELZ), (*2*) Rb_2CsSb (AOOT KATOD); (*3*) Na_2KCsSb (OAO MELZ), (*4*) K_2CsSb (Electron Tubes), and (*5*) GaAsP (HAMAMATSU).

As was pointed out in [9], the simulating of a Cerenkov neutrino telescope requires that the group velocity of light be used instead of the phase velocity, since dispersion in water gives rise to a difference in the velocity of photons with different wavelengths: $V_{gr} = c/n_{gr}$, where V_{gr} is the group velocity of light, c is the velocity of light in open space, and $n_{gr} = n - \lambda\partial n/\partial\lambda$ is the medium's group index of refraction.

As follows from the behavior of the dependences $n(\lambda)$ and $n_{gr}(\lambda)$ in the wavelength range of 350–600 nm in water, photons with longer wavelengths travel with a higher velocity than those with shorter wavelengths. For example, the difference (caused by the dispersion in water) in transit time between green photons with $\lambda = 525$ nm and violet photons with $\lambda = 370$ nm is ~10 ns when they travel a distance of 100 m [10].

The change in the duration of a Cerenkov light pulse after its passage through a water layer of thickness R is estimated from the finite length of the Cerenkov spectrum $\Phi_k(\lambda)$ for three values of R (1, 10, and 100 m) with due account of the photocathode's quantum efficiency $Y(\lambda)$. The spectrum shape in view of the quantum efficiency $Y(\lambda)$ is derived from the formula

$$\Phi_\eta(\lambda) = \Phi_k(\lambda)Y(\lambda). \tag{3}$$

Using the dependence $n_{gr}(\lambda)$ presented in [9, 10], we determined the differences in the refractive indices Δn_{gr} for the wavelengths corresponding to the opposite

Table 1

R, m	$\Delta\lambda$, nm		Δn_{gr}		Δt, ns	
	lake	sea	lake	sea	lake	sea
K_2CsSb (OAO MELZ)						
1	335–470	330–460	1.4125–1.368	1.416–1.37	0.15	0.15
10	385–504	340–475	1.3875–1.3635	1.409–1.3675	0.8	1.4
100	480–502	407–497	1.367–1.364	1.3805–1.365	1.0	5.2
Rb_2CsSb (AOOT KATOD)						
1	330–500	320–490	1.416–1.364	1.425–1.3655	0.17	0.2
10	390–525	340–505	1.386–1.361	1.409–1.3635	0.83	1.5
100	480–502	418–504	1.367–1.364	1.3775–1.3635	1.0	4.7
Na_2KCsSb (OAO MELZ)						
1	330–510	320–510	1.416–1.363	1.425–1.363	0.18	0.21
10	395–530	345–510	1.384–1.36	1.406–1.363	0.8	1.4
100	480–503	420–505	1.367–1.364	1.377–1.3635	1.0	4.5
K_2CsSb (Electron Tubes)						
1	335–495	320–480	1.4125–1.365	1.425–1.367	0.16	0.19
10	390–530	340–505	1.386–1.36	1.409–1.3635	0.87	1.5
100	480–502	420–505	1.367–1.364	1.377–1.3635	1.0	4.5
GaAsP (HAMAMATSU)						
1	340–580	330–575	1.409–1.354	1.416–1.3545	0.18	0.205
10	407–557	350–545	1.3805–1.357	1.403–1.358	0.78	1.5
100	480–505	430–510	1.367–1.3635	1.375–1.363	1.2	4.0

Note: "Lake" denotes Lake Baikal; "sea" is the Mediterranean Sea.

edges of the spectra $\Phi_\eta(\lambda)$ at their half-height. The change in the duration of a pulse was estimated from the formula $\Delta t = (R/c)\Delta n_{gr}$. This estimation was made for a bialkali Rb_2CsSb photocathode (AOOT KATOD), bialkali K_2CsSb and multialkali Na_2KCsSb photocathodes (OAO MELZ), a bialkali K_2CsSb (Electron Tubes) photocathode, and a photocathode based on a A_3B_5 compound (GaAsP) (HAMAMATSU). The dependences of the quantum efficiency of these photocathodes on the wavelength of incident light are shown in Fig. 3.

The results of these calculations are presented in Table 1. The effect of an increase in the pulse duration is more pronounced for the Mediterranean Sea; however, this increase is itself insignificant in terms of absolute value. For Lake Baikal, the duration of a Cerenkov signal is 1 ns longer after it passes 100 m; whereas in the Mediterranean Sea, this increase is ~5 ns for the same distance.

We also estimated the relative amplitude of signals in photodetectors with different photocathodes in response to a pulse of Cerenkov light that has traveled different distances in the waters of Lake Baikal and the Mediterranean Sea. The relative pulse height was

$$A = \int \Phi_\eta(\lambda) d\lambda,$$

where $\Phi_\eta(\lambda)$ is determined from Eqs. (1), (2), and (3) as

$$\Phi_\eta(\lambda) = Y(\lambda)\Phi_0\lambda^{-2}\exp(-k(\lambda)R).$$

The maximum quantum efficiency $Y(\lambda)$ of each photocathode was taken equal to unity, except for the GaAsP photocathode, whose maximum quantum efficiency is a factor of ~2 higher than the analogous value for the

Table 2

R, m	K_2CsSb (OAO MELZ)	Rb_2CsSb (AOOT KATOD)	Na_2KCsSb (OAO MELZ)	K_2CsSb (Electron Tubes)	GaAsP (HAMAMATSU)
Lake Baikal					
0	82.55	93.0	93.2	96.8	204.5
1	71.3	81.3	82.3	84.4	182.6
10	24.7	31.0	33.2	31.7	78.4
100	0.10	0.16	0.17	0.16	0.44
Mediterranean Sea					
0	82.55	93.0	93.2	96.8	204.5
1	79.6	89.8	89.9	93.35	196.8
10	58.2	66.6	66.3	68.5	142.9
100	5.3	6.75	7.0	6.7	15.0

other traditional photocathodes. In terms of absolute values, this is ~25 and ~50%, respectively.

The results of these calculations are given in Table 2. The highest sensitivity was shown by the GaAsP photocathode, but the very small (~20 mm) sensitive area of this photocathode attainable at present renders it unsuitable for neutrino telescopes. The other photocathodes have approximately the same (within the limits of 10–15%) sensitivity. Note that the relative amplitudes of the signals for the multialkali and GaAsP photocathodes should be somewhat higher, because the spectral response of these photocathodes ranges up to 600 nm and over. However, the available absorption coefficients that we had at our disposal corresponded to a range of 350–600 nm, and, hence, we used the spectral response in the same wavelength range.

An important result of this simulation is that, among traditional photocathodes, the multialkali photocathode from OAO MELZ appears to be the most sensitive to Cerenkov radiation at large distances in water; moreover, it compares favorably with the bialkali photocathodes at small distances as well. This fact should be taken into account when designing photodetectors for next-generation neutrino telescopes.

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