Hybrid Phototubes in Neutrino Telescopes: Experience and Perspectives

B. K. Lubsandorzhiev

Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia.

Kepler Center for Astro and Particle Physics, University of Tuebingen, Tuebingen, Germany

Postal address: pr-t 60th Anniversary of October, 7a, 117312 Moscow, Russia; phone: +7-495-1353161; fax: +7-495-1352268;
E-mail: lubsand@pcbai10.inr.ruhep.ru

Abstract

In this paper we review hybrid phototubes with luminescent screens used in deep underwater neutrino telescopes. The operational princliple and the main characteristics of the phototubes are described. Their advantages and disadvantages are discussed. It is shown that the phototubes suit very well to such kind of application.

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Key words: Neutrino telescopes; Cherenkov light; Photodetector, Hybrid Phototube, Luminescent Screen.

1.Introduction.

One of the most challenging tasks of present day experimental physics is to detect high energy neutrinos which come from the very deep space and are still very elusive. To solve the problem rather intense efforts have been done for the last more than four decades. Deep underwater high energy neutrino telescopes started their history in the middle of 1970s with the DUMAND [1, 2] project in the Pacific Ocean near Hawaii. The Baikal neutrino experiment [3, 4] commenced its activity a few years later in the great Siberian lake Baikal. These activities have been followed by a number of European projects in the Mediterranean Sea like NESTOR [5], NEMO [6] and ANTARES [7]. Despite of the very intense discussions on the development of such neutrino telescopes so far there are only two currently running deep underwater neutrino telescopes in the world - the Baikal and ANTARES neutrino telescopes.

Photodetectors play a crucial role in such projects. They should have high sensitivity to Cherenkov light in water, large view angle and low noise. They should be fast and immune to terrestrial magnetic field. All such requirements compelled to develop large area highly sensitive and fast hemispherical or spherical vacuum photodetectors.

From the very beginning of discussions on deep underwater neutrino detection two competing approaches in the photodetector development for such kind of application manifested themselves distinctly - classical photomultiplier tubes (PMTs) and hybrid phototubes. Vacuum hybrid phototubes are Hybrid Photodiodes (HPDs), Hybrid Avalanche Photodiodes (HAPDs) and Hybrid Phototubes with Luminescent Screens (HPLSs). HPD and HAPD are vacuum photodetectors with silicon diode and avalanche diode respectively as photoelectron multiplication elements. Classical PMTs have a number of shortcomings like poor collection and effective quantum efficiencies, poor time resolution, existence of prepulses, late pulses and afterpulses, susceptibility to terrestrial magnetic field. In many respects HPDs and HAPDs are free from all above mentioned disadvantages. They have excellent characteristics but at least one substantial drawback – they are too expensive because a transfer technique is necessary for their production. Furthermore their gain is still rather low. The hybrid phototubes with luminescent screens are free from shortcomings and disadvantages of PMTs, HPDs and HAPDs and they are relatively cheap.

2. Hybrid Phototubes with luminescent screens

2.1. XP2600 "smart" hybrid phototube

In the mid of 1980s Van Aller, Flyckt and Kuhl and their colleagues from PHILIPS Laboratories at that time (now PHOTONIS Group) had developed the "smart" 15 inch hybrid phototube with luminescent screen – XP2600 [8, 9], Fig.1.

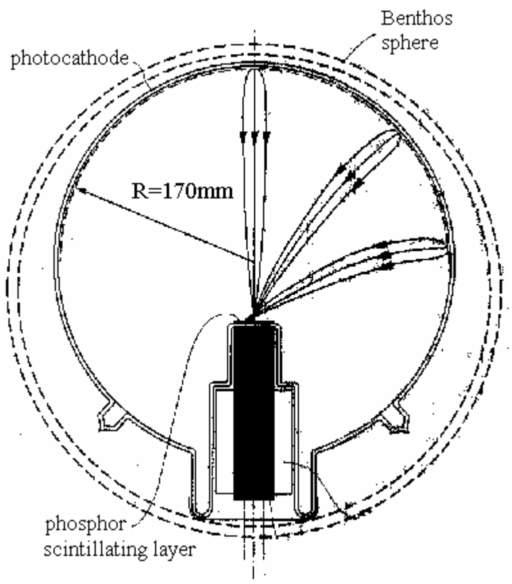

Fig.1. XP2600 hybrid phototube [9].

The hybrid phototube with a luminescent screen is a combination of an electro-optical preamplifier or light preamplifier with a large hemispherical photocathode and a small conventional PMT. Photoelectrons produced by photons impinging on the large hemispherical photocathode of the electron-optical preamplifier with more than 2π viewing angle are accelerated by high electric field of ~25 kV and hit the luminescent screen which is mechanically fixed near the center of the glass envelope. The luminescent screen is a thin layer of a fast, high light yield scintillator covered by an aluminum foil. Light pulses produced by photoelectrons in the scintillator are registered by a small conventional type PMT. As a result one photoelectron from the photocathode of the optical preamplifier engenders 20-30 photoelectrons in the small PMT. The combination of the luminescent screen and the small PMT's photocathode can be likened to the first stage of a conventional PMT dynode system. This high gain first stage results in an excellent single photoelectron resolution and together with high accelerating electric field allows keeping low the time jitter of the phototube. The scintillator in the luminescent screen is Y_2SiO_5:Ce monocrystal with 40-50 ns decay time and light yield of ~10^4 photons per MeV. Single photoelectron resolution is ~80%. The photoelectrons transit time spread is ~2.2ns (FWHM). The maximum of photoelectron transit time difference is ~5ns. The last value is due to the fact that the phototube has a photocathode of clear spherical geometry.

The first samples of XP2600 have been successfully tested in the lake Baikal in 1987-88. They demonstrated very good sensitivity to cosmic ray muons in the deep Baikal water [10].

2.2. QUASAR-370 hybrid phototube

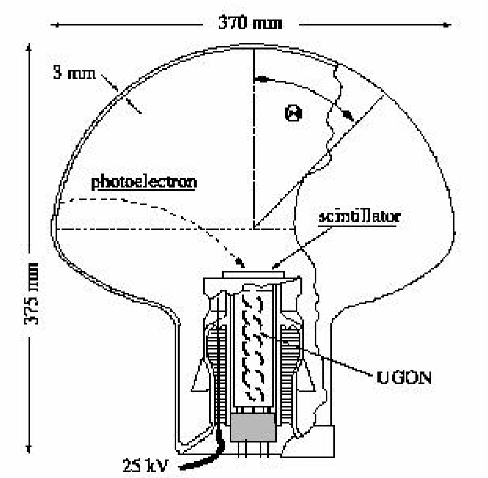

Fig.2. QUASAR-370 phototube

The QUASAR-370 hybrid phototube has been developed by close collaboration of INR in Moscow and KATOD Company in Novosibirsk especially for the lake Baikal neutrino experiment following the basic design of the "smart" phototube. The phototube has a mushroom shaped 37 cm in diameter hemispherical photocathode, Fig.2, in contrary to XP2600 to provide more isochronic phototelectron trajectories. A detailed description of the phototube is given in [11-13].

Due to the mushroom shape of the glass bulb the maximum transit time difference for photoelectrons over photocathode area is ~0.8 ns. The QUASAR-370 is equipped with a fast, efficient scintillator (Y_2SiO_5:Ce phosphor for the basic version of the phototube) which yields ~25 pe's in the small PMT for 1 pe from the preamplifier photocathode for 25 kV accelerating electric field. The phototube has on average a single photoelectron resolution of 80% (FWHM) and photoelectron transit time spread of 2 ns (FWHM). The QUASAR-370 has no pre-pulses and late pulses, and the level of after-pulses is less than 1%. Pre-pulses and late pulses are inherent phenomena in classical PMTs originating from direct photoelectric effect and photoelectron backscattering in a phototube electron multiplication system respectively. Afterpulses are another inherent thing plaguing vacuum phototubes. They are largely due to light ion feedback. We refer the reader to e.g. [14-16] and all references therein for more details on prepulses and late pulses. The phototube has ~2000 cm^2 sensitive area in $\geq 2\pi$ solid angle. Its parameters are immune to the terrestrial magnetic field. Modified versions of the QUASAR-370 with new scintillators have photoelectron transit time spread of 1 ns (FWHM) and 35-40% single photoelectron resolution (FWHM) [17-19]

3. Deep underwater neutrino telescopes using hybrid phototubes

3.1. The DUMAND neutrino experiment

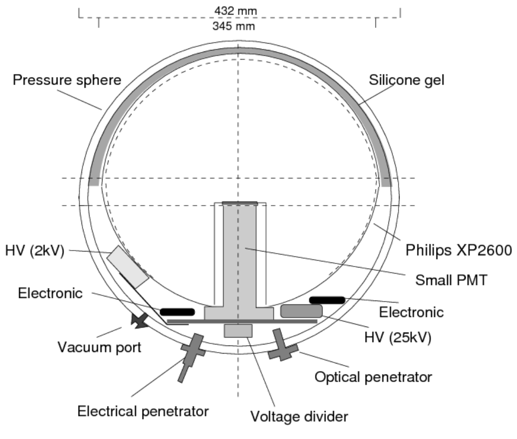

Fig.3. European optical module of DUMAND [21].

The first neutrino telescope project was DUMAND (Deep Underwater Muon and Neutrino Detector) [1, 2]. The experiment site was near the Hawaiian island Hawaii ~30 km offshore at the depth of 4800 m. Two versions of optical modules were developed for that project. The DUMAND 'Japan optical module' (JOM) was based on R2018 16" hemispherical classical PMT especially developed for the project by Hamamatsu and named the "DUMAND PMT" [20]. The 'European optical module' (EOM) [21] based on the XP2600, Fig. 3, was developed during the final stages of DUMAND project – DUMAND II [22]

Overall 13 EOMs were built and only 6 of them were incorporated into the TRIAD array which was attempted to deploy at the depth of ~4800 m in December 1993. The array consisted of 72 optical modules attached at 3 strings. Unfortunately, DUMAND project was terminated and didn't get further development; see [2, 21] for more details.

3.2. The lake Baikal neutrino telescope.

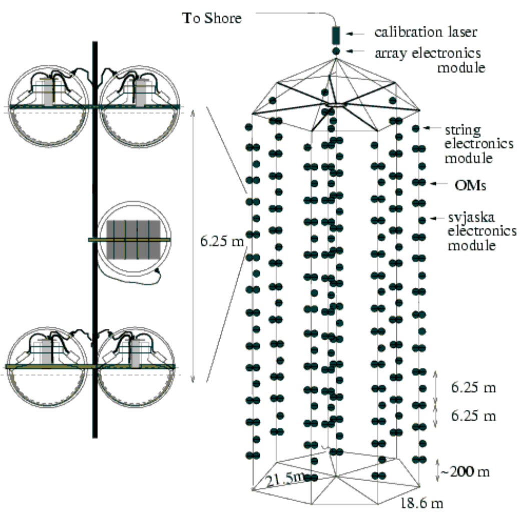

Fig.4. The lake Baikal Neutrino Telescope NT-200 and optical modules based on the QUASAR-370 phototubes.

The lake Baikal Neutrino Telescope NT-200 [3, 4] is located 3.6 km from the shore and at a depth of 1.1 km. The schematics of NT-200 and the optical modules attached to a detection string are shown in Fig.4. The telescope consists of 192 optical modules (OMs) grouped pair-wise on 8 vertical strings, which are fixed to an umbrella-like frame. The detector is operated from the shore station by four underwater cables: three electrical cables and one fibre-optic cable.

The telescope has been built using step-by-step ideology. In 1993 the first stage of the project, NT-36, started to operate with 36 QUASAR-370 tubes at 3 strings. Further through NT-72, NT-96 and NT-144 stages the neutrino telescope NT-200 has been put into full operation in April 1998. Afterwards the telescope was extended by three distant sparsely instrumented strings and it is still operating with overall 228 OMs. For the latest developments of the experiment see [23].

The optical module of the lake Baikal neutrino telescope is based on the QUASAR-370 phototube, Fig.5. It is particularly noteworthy that there are more than a dozen of QUASAR-370 phototubes which have been continuously operating since 1993 without any repair and replacement.

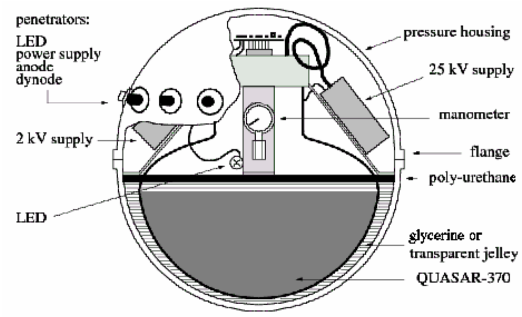

Fig.5. Optical module of the lake Baikal Neutrino experiment.

Relative angular sensitivity of the optical module measured with wide plane light wave in water is shown in Fig.6 [24]. It is seen how the OM sensitivity profits from the wide viewing angle of the phototube.

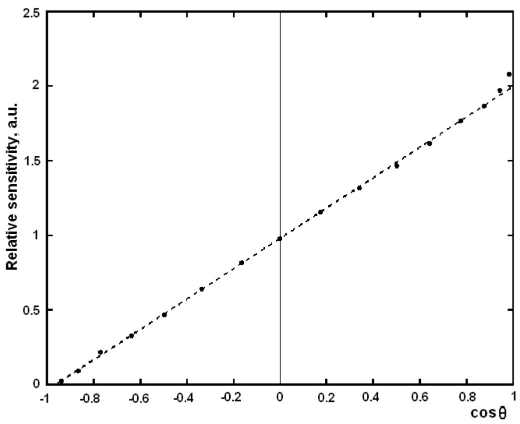

Fig.6. Angular sensitivity of optical module based on hybrid phototubes with luminescent screen.

Apart from remarkable physics results reached with NT-200 neutrino telescope, the QUASAR-370 phototube's excellent performance made possible to carry out very interesting environmental studies in the lake Baikal. Seasonal variation of water luminescence and strong deep water currents have been discovered [25, 26], moreover the practical absence of after pulses in XP2600 and QUASAR-370 allowed us to discover the existence of low rate multi-photon light pulses in the deep lake Baikal water [27].

4. Problems and perspectives of hybrid phototubes with luminescent screens

The main problem of the hybrid phototubes with luminescent screen stems from rather long decay time and relatively low light yield of their scintillators. Despite excellent time resolution the phototubes have slow time response due to the scintillators decay time. New scintillators with high light yield and short decay time, like ZnO:Ga, along with new high quantum efficiency photocathodes and new high voltage techniques (HV compounds, cablings, vacuum surface cleanings etc) would make a "dream" phototube of 21^{st} century.

5. Conclusion

So far hybrid phototubes with luminescent screens have been successfully exploited in two pioneering deep underwater high neutrino experiments. Moreover up to now hybrid phototubes with luminescent screens are the only type of hybrid phototubes which have been used in astroparticle physics experiments. Several XP2600 phototubes had been used in the DUMAND experiment. The QUASAR-370 phototubes are the basic photodetectors of the lake Baikal neutrino telescope, which is currently running. Modifications of the QUASAR-370 phototube, known as QUASAR-370G, are being used in the wide-angle EAS Cherenkov experiment TUNKA. A successful operation of the lake Baikal neutrino experiment proves the phototubes high performances, reliability and robustness. The experience accumulated during exploitation of the hybrid phototubes demonstrates their high suitability for deep underwater neutrino telescopes. The phototubes high performances along with immunity to the Earth's magnetic field and large, more than 2π, angular acceptance, make them very attractive as prototypes for developments of photodetectors for coming projects of the next generation deep underwater neutrino telescopes.

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