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Photon detectors for neutrino telescopes

B K Lubsandorzhiev

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Contents

Abstract. **The tremendous success of neutrino telescopes witnessed today is primarily due to their 'workhorses,' photon detectors. Photon detectors used in neutrino telescopes are briefly reviewed, and various approaches to the development of these devices for suchlike applications are described. Prospects for the development of photon detectors for next-generation neutrino telescopes are discussed.**

Keywords: neutrinos, neutrino telescopes, photon detectors, photomultipliers

1. Introduction

Photomultiplier tubes play a fundamental role in neutrino telescopes. In all operating and planned neutrino telescopes, high-energy neutrinos are detected by Cherenkov radiation in water or ice induced by the products of interaction of neutrinos with matter — relativistic charged leptons and high-energy electromagnetic or hadron showers.

Cherenkov radiation is detected using highly sensitive, fast photon detectors, which play a special role in suchlike experiments. The invention by L A Kubetsky in the Soviet Union of the world's first vacuum photoelectron multiplier (photomultiplier) [1] gave a powerful impetus to the development of physical experiments in general. The same refers to the silicon photomultiplier, also invented in the USSR in the 1980s by Z Ya Sadygov and V M Golovin and colleagues [2]. Photon detectors occupy a special place in the success story of neutrino telescopes.

Almost 50 years ago, at the very beginning of discussions on the problem of deep underwater neutrino detection and the development of large-scale neutrino telescopes, great attention was paid to the development of photon detectors.

2. Photon detectors for deep underwater experiments in neutrino physics

In active discussions of projects for the first deep underwater neutrino experiments in the 1970s and 1980s, requirements for photon detectors for such experiments were formulated [3–5]. Here, we list only the main requirements with brief comments:

(1) High sensitivity to Cherenkov light in water and ice, which meant the need to use a bi-alkali photocathode, which was at that time the most sensitive in the blue region of the spectrum.

(2) Large sensitive area in a large solid angle, preferably $\sim 2\pi$, which led to the advent of photon detectors with a large hemispherical photocathode.

(3) The highest possible time resolution or the lowest possible level of photoelectron transit time spread. This is determined by the distribution of the photoelectron transit time of photoelectrons during single-photoelectron illumination of the photocathode of the photon detector. This requirement also favors hemispherical photon detectors.

(4) The best possible single-photoelectron resolution, which is determined by the charge distribution of single-photoelectron pulses. It is characterized by the full width at half maximum (FWHM) of this distribution. At that time, it was believed that a sufficiently good separation of peaks from one, two, etc. photoelectrons will make it possible to effectively suppress the count rate of background pulses, due primarily to the decays of K^{40} in ocean water.

(5) Low level of the photodetector's own dark current, which again leads to the use of a bi-alkali photocathode.

B K Lubsandorzhiev
Institute for Nuclear Research, Russian Academy of Sciences,
prosp. 60-letiya Oktyabrya 7a, 117312 Moscow, Russian Federation
E-mail: lubsand@rambler.ru

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(6) Fast photodetector response: a photodetector output pulse width of $\sim$ 10 ns or less. It was believed that this feature would make it possible to separate single muons from groups of muons.

(7) Insensitivity to Earth's magnetic field.

Of course, all of the listed requirements corresponded to the then level of knowledge of the aquatic environment, background conditions, the properties of the photon detectors themselves, etc., and, from today's perspective, they look largely naive, reminiscent of the general Olympic principles: *Citius, Altius, Fortius*. Translated into the language of photon detectors, this could mean that detectors should be faster, more sensitive, and 'smarter'. The last concept, which was introduced by S Flyckt, implies a fairly good single-photoelectron resolution, which enables clear separation of peaks in the charge spectrum of the output pulses of the photodetector that are due to one, two, three, and so on photoelectrons from the detector photocathode. It is surprising that, despite sounding somewhat naïve, these requirements remain relevant today.

At the very beginning of the development of deep underwater neutrino telescopes in the 1970s, active discussions began regarding possible designs of photoelectron multipliers (detectors). (What ideas were suggested!) It should be noted that a wide variety of designs were discussed [6]. But even then all the proposed designs were divided into two main groups. The first approach concentrated on the development of an optical module based on a single large-sized photomultiplier (one optical module — one photomultiplier), while the second approach consisted of using a large number of small photomultipliers in one optical module. The original idea of the Porcupine optical module, proposed at that time, was also associated with small photodetectors: it was proposed to collect light from a large area onto a small high-sensitivity photodetector using optical fibers. It should be mentioned that, based on this idea, Z Ya Sadygov started the development of a silicon photomultiplier at the Institute for Nuclear Research of the Russian Academy of Sciences.

Silicon photomultipliers have undergone rapid development over the past 20 to 25 years. It is described below that silicon photomultiplier tubes are again being discussed in connection with neutrino telescopes.

It is of interest that most of the ideas discussed at that time have been developed in neutrino telescopes in our time. This issue is discussed below in Section 3.

At that time, the first option prevailed: one optical module based on one large-sized photodetector. This approach, in turn, was divided into two branches. The first is classical photomultiplier tubes, which use a dynode system to multiply photoelectrons. Today, such photomultipliers are called Dynode PMTs.

The alternative approach was to use other methods of multiplying photoelectrons: microchannel plates, semiconductor diodes with and without internal amplification, transmission type secondary emitters, etc.

3. Photon detectors of first-generation neutrino telescopes

3.1 Photon detectors of the NT-200 neutrino telescope

At the first stages of the development of neutrino telescopes, photomultipliers used a venetian blind type dynode system, a representative example of which is the R2018 photomultiplier [7] with a 40-cm photocathode, developed for the first underwater experiments, DUMAND (Deep Underwater Muon And Neutrino Detector) [8], off the Hawaiian Islands in the Pacific Ocean.

Almost concurrently with US research in the Pacific Ocean, work in this area began in the USSR. A E Chudakov proposed to deploy a deep underwater neutrino telescope in Lake Baikal, prophetically pointing out the acceptable depth and transparency of the lake's water and the presence of reliable ice cover for 1.5 months, facilitating work to be carried out when setting up, assembling, and testing the elements of the neutrino telescope.

In 1983, G van Aller and his colleagues from Philips Laboratories proposed creating a large-sized hybrid photodetector for deep underwater neutrino telescopes based on an electron-optical preamplifier [9]. In this hybrid photodetector, a photoelectron from a large-area photocathode is accelerated by a potential difference of 20–30 kV, hits a thin small-sized luminescent screen, and produces flashes of light, which are detected by a small-sized conventional photomultiplier. This approach makes it possible to achieve high time and amplitude characteristics of a hybrid photo detector. In 1986, G van Aller and his colleagues developed XP2600, a full-fledged hybrid photomultiplier with a spherical photocathode 35 cm in diameter [10].

It should be noted that a similar idea was put forward earlier, in the 1950s, for example, by A E Chudakov [11]. D Winn and C Rubbia suggested an idea of a large barrel-shaped hybrid photodetector [12].

In 1984, the Institute for Nuclear Research, in collaboration with the Novosibirsk-based KATOD Design Bureau, began the development of QUASAR-370, a large-sized hybrid photomultiplier. This article is published in the year of the fortieth anniversary of this significant event, so this photon detector deserves additional discussion. First, luminescent screens and other structural elements were optimized using prototypes. The electron optics of the photomultiplier were meticulously calculated. Based on the calculations, the shape of the glass envelope and anode assembly was optimized to achieve the maximum possible collection of photoelectrons and the best time resolution.

Figure 1 shows a sketch of the QUASAR-370 photon detector [13–15], which we developed specifically for the world's first deep-underwater neutrino telescope, NT-200 [16], in Lake Baikal. This photon detector was a hybrid vacuum photodetector consisting of an electron-optical light pre-amplifier with a hemispherical photocathode 37 cm in diameter and a photomultiplier tube (PMT) of a classical type with a photocathode of small diameter ($\sim$ 3 cm). The shape of the photodetector glass envelope was optimized to minimize the difference in the transit time of photoelectrons along the photocathode. This approach makes it possible to obtain excellent time and amplitude parameters of the entire photodetector as a whole: the spread of photoelectron transit time for single-photoelectron illumination of the photocathode is 1.8–2.2 ns (FWHM) and the single-photoelectron resolution is 70–80% (FWHM). The difference in the photoelectron transit time along the photocathode is less than 1 ns. The design of the QUASAR-370 photon detector ensures its sensitivity in a solid angle of $\sim 2\pi$, while the inhomogeneity of the anodic sensitivity of the photodetector over the entire sensitive field of the photocathode does not exceed 10%. The Novosibirsk-based KATOD Design

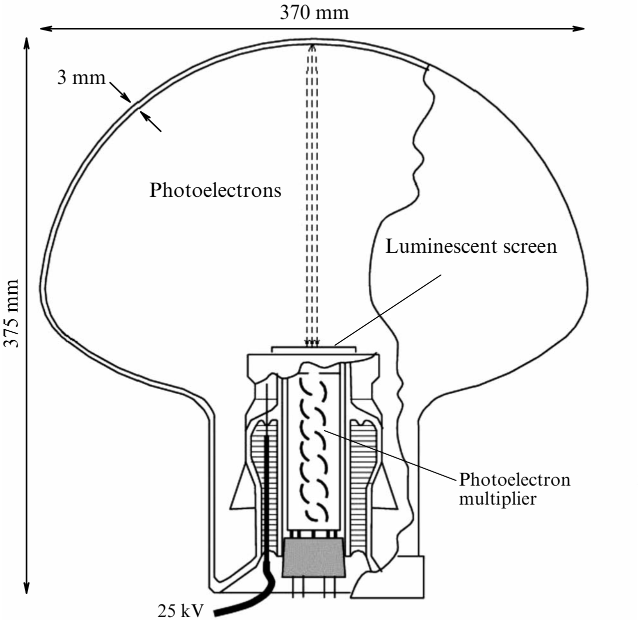

Figure 1. Hybrid photon detector QUASAR-370 [13–15].

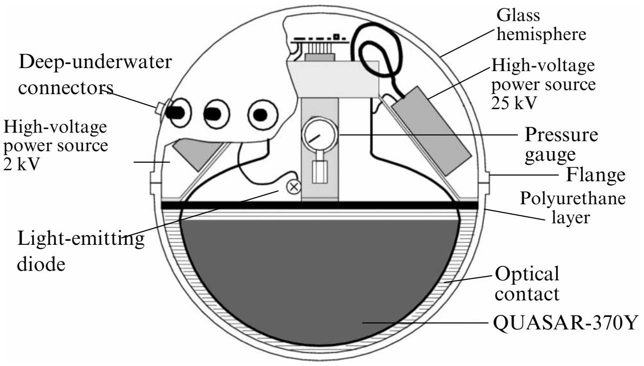

Figure 2. Optical module of NT-200 neutrino telescope [15].

Bureau produced QUASAR-370 photomultipliers in a small batches.

Based on the QUASAR-370 photon detector, in collaboration with a number of Russian enterprises and institutes, NT-200, the optical module [15] of the Baikal deep-underwater neutrino telescope, was designed and developed. Figure 2 displays a sketch of the optical module. The protective glass body of the module is made of potassium-free borosilicate glass S-49-1. Such a deep-underwater protective housing is used for all deep-underwater modules — both optical and electronic — of the NT-200 neutrino telescope. Optical contact of the QUASAR-370 photon detector with a protective glass sphere is set using chemically pure glycerin or optical gel. The NT-200 neutrino telescope consists of 192 optical modules.

To improve the parameters of the QUASAR-370 photon detector, some modifications were made. They involved, primarily, the use of new scintillation materials as part of the luminescent screen of the QUASAR-370 photon detector.

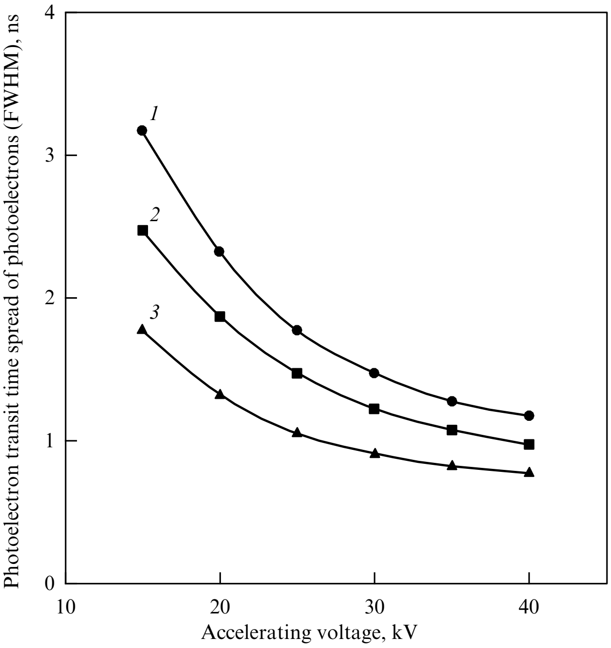

Figure 3. The photoelectron transit time spread for single-photoelectron illumination of photocathode of QUASAR-370 photon detector as a function of accelerating voltage [17–19].

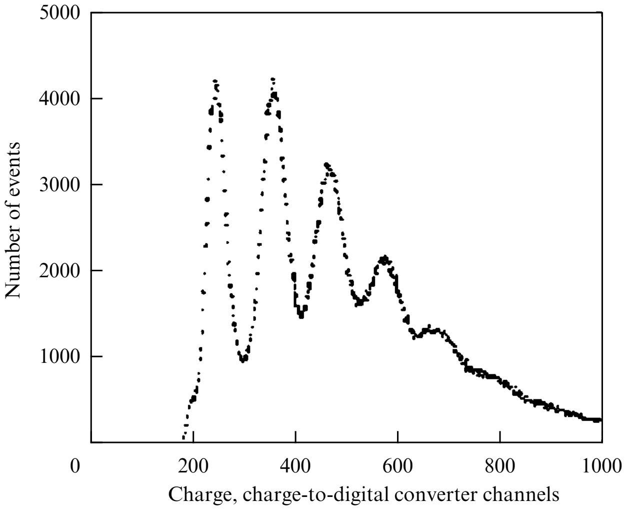

Figure 4. Charge distribution of multiphotoelectron pulses of the QUASAR-370 photon detector [18].

By now the best results have been achieved in modifications with the scintillators YAP, SBO, and LSO (QUASAR-370YAP, QUASAR-370SBO, QUASAR-370LSO, respectively) [17–19]: time resolution with a single-photoelectron illumination of $\sim 1-1.2$ ns (FWHM) and a single-photoelectron resolution of $\sim 30-40\%$ (FWHM). These photon detectors currently most fully meet the requirements for photodetectors for the next generation of neutrino telescopes. Figure 3 shows the dependence of the photoelectron transit time spread for single-photoelectron illumination of the photocathode on the accelerating voltage for various modifications of the QUASAR-370 photon detector. For the QUASAR-370LSO photon detector with a luminescent screen based on an LSO scintillator, photoelectron transit time spread is < 1 ns (FWHM).

The charge distribution of multiphotoelectron pulses of the QUASAR-370LSO photodetector is presented in Fig. 4. Single-photoelectron peak resolution is better than 30%, which provides excellent separation of peaks due to one, two, three, etc. photoelectrons in the charge spectrum.

The time resolution of vacuum photodetectors plays an important role in neutrino experiments. The main factors affecting the accuracy of time measurements with vacuum photodetectors are prepulses, late pulses, and afterpulses. Late pulses are the same as main pulses but delayed by approximately double the photoelectron transit time of the photoelectron in the cathode chamber. This is the fundamental difference between them and afterpulses. The occurrence of late pulses is explained by the backward, elastic or inelastic, reflection of photoelectrons from the first dynode, focusing electrodes, or PMT structural elements. The probability of the appearance of late pulses does not exceed $\sim 3-4\%$. The same late events are observed in microchannel plate photomultipliers (MCPs) and hybrid vacuum photodetectors. In QUASAR-370 photon detectors, prepulses are virtually absent, and the contribution of late pulses and afterpulses is significantly suppressed due to the design features of the detector.

It should be noted that the time and amplitude characteristics of QUASAR-370 photomultipliers still remain record-setting. There are practically no prepulses, and the probabilities of the appearance of late pulses and afterpulses are significantly suppressed compared to classical-type PMTs. The high uniformity of the anodic sensitivity of these photon detectors is achieved over a wide solid angle ($\sim 2\pi$). Finally, the characteristics of QUASAR-370 photon detectors do not depend on Earth's magnetic field. Due to these features, such photon detectors are the closest to an ideal photodetector [17, 19] for giant next-generation neutrino detectors, which have been actively discussed recently.

3.2 Photon detectors of the AMANDA neutrino telescope

Since the mid-1990s, large-sized vacuum photomultipliers have been using more efficient dynode systems with linear focusing and a large-area first dynode. This solved the problem of isochronism of the trajectories of photoelectrons and secondary electrons in the multiplying system, which made it possible to significantly improve the main parameters of large-sized vacuum photomultipliers. This solution, in turn, triggered the development of neutrino telescopes in sea water and Antarctic ice.

In the early 1990s, the development of AMANDA (Antarctic Muon AND neutrino Array), a neutrino telescope buried deep in the ice at the South Pole [20, 21], started. The optical modules of this telescope used eight-inch photomultipliers of the ET9350 series manufactured by ET Enterprises (UK) and R5912 manufactured by Hamamatsu Photonics. At that time, these were pioneering products. For the first time, a dynode system with linear focusing and a large-area first dynode was used in large-sized photomultipliers with a hemispherical photocathode. Acceptable single-photoelectron response and good time resolution were attained. The peak/valley ratio of the charge spectrum of single-photoelectron pulses was on average ~ 2, and the time resolution was 3 ns. Used as the photocathode of photomultipliers was a conventional bi-alkali photocathode (K_2CsSb) with a maximum sensitivity at wavelengths of 400 nm with a quantum efficiency of $\sim 25\%$. The counting rate of dark current pulses did not exceed 10^4 s^{-1} at 20 °C.

Due to the high transparency of deep Antarctic ice in the near ultraviolet region of the spectrum and the nature of the Cherenkov radiation spectrum, if such photocathodes are employed, most of the Cherenkov radiation remains undetected by photomultipliers. To enhance the efficiency of detecting Cherenkov radiation, we developed thin-film spectrum shifters [22] for the optical modules of the AMANDA telescope. Using such films increased the efficiency of detecting Cherenkov radiation by optical modules by ~ 1.5 times.

3.3 Photon detectors of the ANTARES neutrino telescope

Photomultipliers ET9350 and R5912 were a good foundation for the next step in the development of large-sized photomultipliers: the ten-inch photomultiplier R7081-02, which became the basis for the optical modules of the ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) neutrino telescope [23, 24] located in the Mediterranean Sea off Toulon, France. The photomultiplier photocathode is still conventional bi-alkali with the same parameters as those of R5912 and ET9350.

The single-photoelectron response is slightly better with a single-photoelectron charge spectrum peak/valley ratio of $\sim 2-2.5$. The photoelectron transit time spread for single-photoelectron illumination of the photocathode is ~ 3 ns (FWHM).

The number of large-sized photomultiplier tubes in the first generation neutrino telescopes was 192 in NT-200, 677 in AMANDA, and 900 in ANTARES. As for photomultipliers, the ANTARES neutrino telescope was a kind of connecting link between first- and second-generation neutrino telescopes, since the R7081 photomultiplier platform became virtually the basis for the photodetectors of second-generation neutrino telescopes.

4. Photon detectors of second-generation neutrino telescopes

4.1 Photon detectors of the ICECUBE and BaikalGVD neutrino telescopes

Currently, two second-generation neutrino telescopes are operating — IceCube at the South Pole [25–27] and GVD in Lake Baikal [28, 29]. In these facilities, the number of photon detectors already amounts to several thousand; for example, the IceCube telescope contains 5160 photomultipliers. The photon detectors in both telescopes are R7801 photomultiplier tubes of the same type as in ANTARES. However, IceCube uses a modification of such a photomultiplier R7801-20 with a conventional bi-alkali photocathode, while GVD employs the R7801-100 version with a so-called super bi-alkali high-sensitivity photocathode.

Figure 5 shows the R7801-100 photomultiplier, prepared for use in BLNT (Baksan Large Neutrino Telescope) prototypes [30]. In such photocathodes, the quantum efficiency at maximum sensitivity exceeds 35%. In some samples of these photomultipliers, the maximum quantum efficiency of the photocathode even exceeds 40%. It should be noted that the sensitivity of photomultiplier tubes reaches a maximum at wavelengths of 360–380 nm, which further enhances their sensitivity to Cherenkov light. Figure 6 shows a typical dependence of the quantum efficiency of the photocathode of the R7801-100 photomultiplier tube measured for prototype BLNT samples [30].

Figures 7 and 8 present typical charge distributions and the distribution of photoelectron transit time for single-photoelectron illumination of the photocathode of R7801-100 photomultipliers [31]. The figures show that the photo-

Figure 5. Image of a 10-inch R7801-100 photomultiplier tube [30].

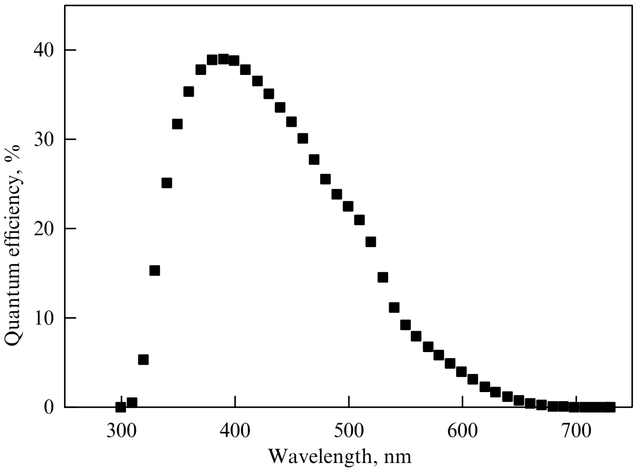

Figure 6. Quantum efficiency of R7801 photomultiplier photocathode as a function of wavelength [30].

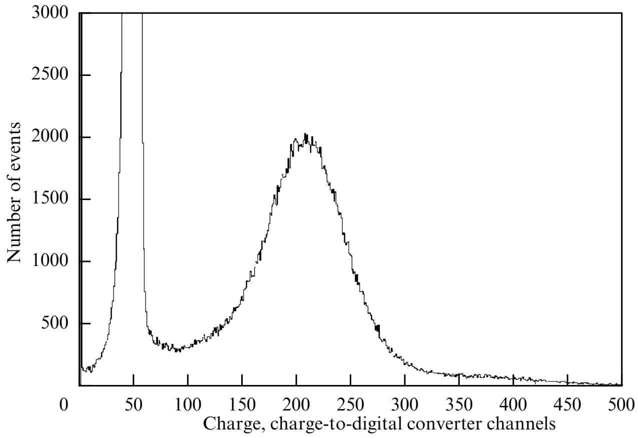

Figure 7. Charge distribution of single-photoelectron pulses for single-photoelectron illumination of photocathode of R7801-100 photomultiplier [31].

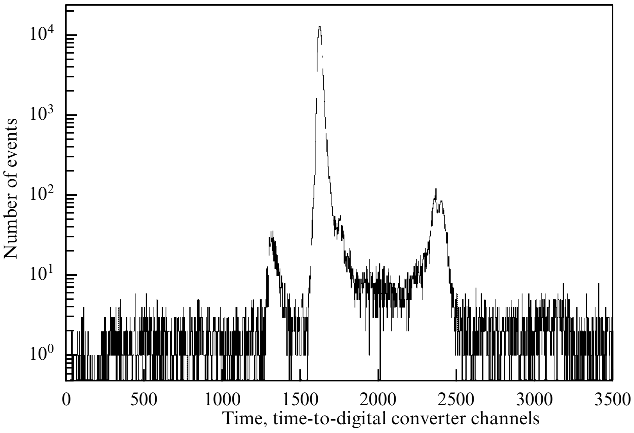

Figure 8. Distribution of photoelectron transit time for single-photoelectron illumination of R7801-100 photomultiplier photocathode [31].

Figure 9. Optical module of KM3NeT neutrino telescope [33].

multiplier features a good single-photoelectron response: peak/valley ratio $P/V > 3$ and single-photoelectron peak resolution of $\sim 50\%$ (FWHM). The distribution of photoelectron transit time is ~ 2.2 ns (FWHM). The probability of the emergence of afterpulses is less than 4% per photoelectron. The counting rate of dark current pulses does not exceed $3 \times 10^{-3}\ \text{s}^{-1}$ at a temperature of 20 °C.

4.2 Photon detectors of the KM3NeT neutrino telescope

The KM3NeT neutrino telescope [32] is currently actively in operation and in scale can also be classified as a second-generation telescope. This facility can easily be called the successor of the ANTARES telescope. However, unlike its predecessor, it is planned to use in KM3NeT an optical module based on a large number of small photomultipliers [33], for example, R14374 (Hamamatsu Photonics) with a glass shell with a diameter of 76 mm ($\sim$ 3 inches). One optical module consists of 31 such photomultipliers. Figure 9 shows the optical module of the KM3NeT neutrino telescope.

Despite the difficulties of handling a large number of photomultipliers in one optical module, this approach provides a sensitivity of the module at a solid angle of almost 4π. Small-sized photomultipliers are discussed in more detail in Section 5 devoted to the next generation of neutrino telescopes.

Again, similar to its predecessor, the KM3NeT telescope creates a link between generations of telescopes. This time, the connection between second-generation neutrino telescopes and next generation telescopes is based on small photomultiplier tubes.

5. Photon detectors for next-generation neutrino telescopes

The next generation of neutrino telescopes is actively being developed; the effective volumes are an order of magnitude larger than those of existing telescopes. There are several such projects: expansion of the neutrino telescope at the South Pole, IceCube-Gen2 [34]; development of a neutrino telescope in the North Pacific Ocean off the coast of British Columbia, P-ONE [35]; and finally, the giant multi-cubic kilometer neutrino telescope TRIDENT [36] in the South China Sea. It is interesting that in all of these projects the concept of an optical module based on a large number of small-sized photomultipliers in one optical module is selected as preferable.

The IceCube-Gen2 project simultaneously considers several options for optical modules with three-, four-, and five-inch photomultipliers [37]. At the same time, the project continues to develop an optical module with the already mentioned 10-inch R7801-100 photomultiplier and an optical module with two eight-inch photomultipliers [38]. The total number of small-sized photomultipliers in the project can be 160,000 to 180,000.

The P-ONE neutrino telescope project is developing an optical module [39], the design of which is similar to that of the optical module of the KM3NeT telescope with 31 R14374 photomultipliers. The total number of photomultipliers in the project, 22,400, is quite modest compared to other projects.

Small-sized photomultipliers considered as candidates (for example, R14374, R15458-02, XP72B20, SFERA) are equipped with conventional bi-alkali photocathodes with quantum efficiencies of 25–30% at maximum sensitivity. Figure 10 displays R14374, XP72B20, and SFERA photomultipliers

The SFERA photomultiplier [40] developed at the Institute of Nuclear Research in collaboration with MELZ-FEU LLC is intended for use in Cherenkov and scintillation detectors of neutrino experiments.

Parameters of the SFERA photomultipliers — a good single-photoelectron response and acceptable time resolution — are not inferior to those of other photomultipliers. The peak/valley ratio of the charge distribution of single-photoelectron pulses is $P/V = 3.5$. The width of the distribution of photoelectron transit time is 2.5 ns (FWHM). The counting rate of dark current pulses does not exceed 400 s^{-1} at room temperature. The quantum efficiency of the photocathodes of prototypes of the SFERA photomultiplier at the maximum sensitivity at a wavelength of 390 nm is $\sim 28-33\%$. Unfortunately, it must be admitted that there are significant problems with the mass production of this photomultiplier.

Figure 10. Image of three-inch photomultiplier tubes. From left to right: XP72B20, R14374, and SFERA.

Figure 11. Optical module of the TRIDENT project [41].

A great potential for enhancing the sensitivity of three-inch photomultipliers to Cherenkov light is still available if a super bi-alkali photocathode is used.

Recently, the project of the TRIDENT neutrino telescope to be deployed in the South China Sea has been actively developed in China [36, 41]. This project promotes the concept of a hybrid optical module that includes 31 three-inch XP72B20 vacuum photomultiplier tubes (HZC/NNVT) and 20 PA3325-WB-0808 silicon photomultiplier arrays (KETEK) with a sensitive area of 7.2 cm^2 each. A general view of the optical module is displayed in Fig. 11 [41]. In total, 24,220 of these hybrid optical modules will be deployed. Thus, in implementing this project, more than 750,000 three-inch photomultiplier tubes will be operated in this neutrino telescope. Taking into account that each silicon photomultiplier assembly consists of 64 individual silicon photomultipliers with a sensitive area of 3×3 mm^2, the total number of silicon photomultipliers in the neutrino telescope will exceed 3,100,000. As mentioned above, the invention of silicon photomultipliers was largely inspired by the development of photon detectors for deep underwater neutrino experiments. What a remarkable second advent of silicon photomultipliers for neutrino telescopes!

6. Prospects for the development of photon detectors for neutrino telescopes

Paraphrasing Immanuel Kant, my teacher Alexander Chudakov liked to say that 'a photomultiplier is a thing in itself.' Through this saying, he was urging the study of the profound properties of photomultipliers, which would help in developing more advanced photomultipliers. Indeed, many areas of physics come together in photon detectors: solid state physics, surface physics, vacuum physics, etc. Almost all types of photon detectors have enormous potential for further development. Even conventional 'dynode' photomultipliers have undergone revolutionary changes over the past 20 years. For example, the development of a super bi-alkali photocathode yielded a sharp increase in the quantum efficiency of photomultiplier photocathodes in the blue and near ultraviolet region of the spectrum up to 40%, with some samples featuring a quantum efficiency of up to 50%. This spectral region is extremely important for Cherenkov detectors, which are neutrino telescopes per se. In the near future, we can expect the emergence of technology for the production of 'ultra bi-alkali photocathodes' with a quantum efficiency of 50% or more. Breakthrough achievements are possible in the development of highly efficient single-crystal photocathodes, for example, InGaN-based photocathodes with high sensitivity to Cherenkov radiation.

More accurate calculations of electron optics will significantly improve the spectrometric and timing parameters of photomultipliers. The appearance of a new eight-inch R14688-100 photomultiplier with a time resolution of ~ 1 ns, which is more than twice that of its predecessor R5912-100, is a clear confirmation of the enormous potential in the development of conventional photomultipliers. Other areas of advancement are the search for new, more efficient materials for the emitters of the dynode system, effective suppression of the ion feedback (afterpulses), etc.

All of the above arguments can also be applied to small-sized photomultipliers. Until now, all optical modules using small-sized photomultipliers have employed photomultipliers with conventional bi-alkali photocathode. The use of photomultipliers with super bi-alkali photocathodes with high quantum efficiency will significantly enhance the sensitivity of optical modules to Cherenkov radiation.

The same promising prospects are opening up for hybrid photomultipliers, especially in relation to the emergence of new efficient and fast inorganic scintillators. All this, combined with further improvements in electrovacuum technology and high-voltage compound technology, will make it possible to develop a large-sized hybrid vacuum photomultiplier, similar to the QUASAR-370 photon detector, with a time resolution of ~ 100 ps.

Huge potential is also seen in the use of silicon photomultipliers in neutrino telescopes, to which the emergence of silicon photomultipliers is largely due. Their return to this area is hailed. It is very interesting and useful to track how 'new' and 'old' ideas in photon detection are deeply interrelated in a dialectical sense [42].

The urgent need to revive developments and mass production of photomultipliers, both vacuum and silicon, in Russia should be especially stressed. It is regretful to admit that at present all attempts at such a revival are failing. This situation is especially sad since it is happening in Russia, which is the birthplace of vacuum and silicon photomultipliers and the first deep-underwater neutrino telescope.

7. Conclusions

After some lull in the 2000s, photon detectors are again rapidly developing today. An apt example of this is the development of photon detectors for neutrino telescopes.

It is vitally necessary to revive the development and mass production of vacuum and silicon photomultipliers in Russia.

It is very important in an experiment not to be content with only the options that are available but to strive to develop new, more advanced detectors. Should this be the case, the experiment will be more sensitive and more perfect and will open up new horizons in understanding the world.

Let me end with the words of Marcel Proust: "The real voyage of discovery consists not in seeking new landscapes, but in having new eyes." Photon detectors are the eyes of neutrino telescopes. Develop these eyes, and you will definitely see new, previously unimaginable landscapes!

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