ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2015. Т. 46. ВЫП. 2

THE TUNKA EXPERIMENT: FROM SMALL “TOY” EXPERIMENTS TO MULTI-TeV GAMMA-RAY OBSERVATORY

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The Cherenkov experiments developed, carried out, presently being operated and under development in the Tunka Valley are reviewed. We present the physics goals of the experiments covering a wide field of studies of cosmic rays in the energy range of 10^{15}–10^{18} eV to multi-TeV gamma-ray astronomy.

PACS: 95.55.Vj; 29.40.Ka; 96.50.S-

INTRODUCTION

The origin of cosmic rays and their acceleration mechanisms are among the most mysterious and intriguing problems existing in the contemporary physics. The energy spectrum of primary cosmic rays follows a power law over a very wide energy range. In the high-energy domain there is no possibility to study cosmic rays by direct methods in satellite experiments due to their extremely low intensity. One can only study such cosmic rays by using only ground-based experiments detecting extensive air showers (EAS) produced by primary cosmic rays in the upper part of the Earth atmosphere. It is possible to detect electromagnetic, hadronic and muonic components of EAS. One technique is to detect the Cherenkov light produced by EAS in the atmosphere. In this case, the atmosphere is used as a calorimeter due to its high transparency to the Cherenkov light.

Large area photodetectors allow a substantial decrease in the energy threshold of the EAS Cherenkov detectors, reducing the gap existing in experimental data on the primary cosmic rays energy spectrum provided by direct satellite and existing ground-based experiments. The Tunka experiment, located near Lake Baikal, is the only currently running EAS Cherenkov experiment working around the “knee” of the cosmic-ray spectrum in the energy range of 10^{15}–10^{17} eV.

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The Cherenkov experiments in the Tunka Valley started almost exactly twenty years ago in 1994. In fact, they started around two years earlier on the ice cover of Lake Baikal. By that time we had completed the development of the Quasar-370 large area hybrid phototube [1–3] discussed in the following section.

1. QUASAR-370G PHOTOTUBE

The Quasar-370 phototube was originally developed for the Baikal deep underwater neutrino experiment [4–7]. At that time we began to think about other applications for the phototube. For us it was quite natural to turn to extensive air shower experiments, since we realized that the larger the sensitive area of phototubes, the lower the energy threshold of the whole array. Of course there were many doubts concerning applicability of the phototube to such applications. We did not know if the phototube would withstand high light background of the night sky in comparison with Lake Baikal deep underwater environment, which is almost completely dark apart from faint fresh water luminescence [8]. We were not sure if the luminescent screen of the phototube would survive much the higher intensity of photoelectron bombardment. So, after some laboratory tests we developed a special modification of the phototube, called Quasar-370G [7, 9]. The extension "G" denoting "gamma" aimed at the detection of gamma-quanta initiated showers — a telescope based on the Quasar-370G phototubes.

The Quasar-370G is a hybrid phototube with luminescent screen (Fig. 1). Photoelectrons from large area hemispherical photocathode (37 cm in diameter) are accelerated in a 25-kV electric field and hit a luminescent screen — a thin

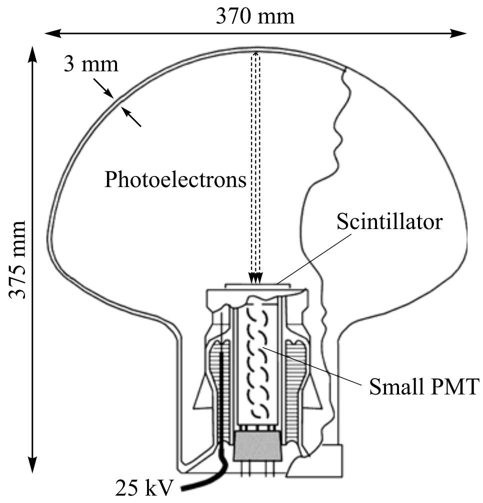

Fig. 1. Quasar-370G hybrid phototube

layer of a fast scintillator covered by aluminium foil to suppress light feedback. As a result, 25-keV photoelectrons produce light flashes in the scintillator, which are registered by small photomultiplier tube (PMT) placed near the luminescent screen. The small PMT is isolated by vacuum from the luminescent screen. Such an approach provides excellent amplitude and time resolutions [1–7, 9, 27], Figs. 2 and 3, respectively.

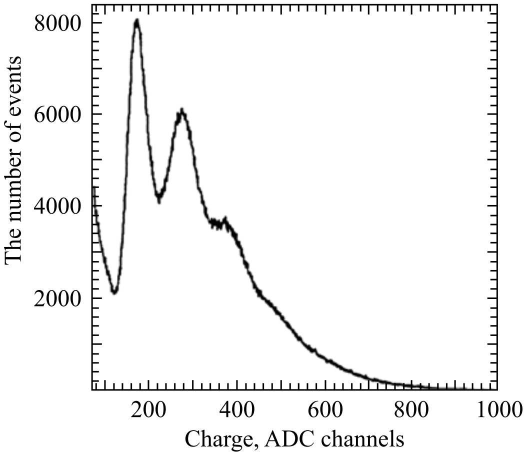

Fig. 2. Charge distribution of multi-photoelectron events of Quasar-370 [7]. Good separation of events due to one, two and three photoelectrons is clearly seen

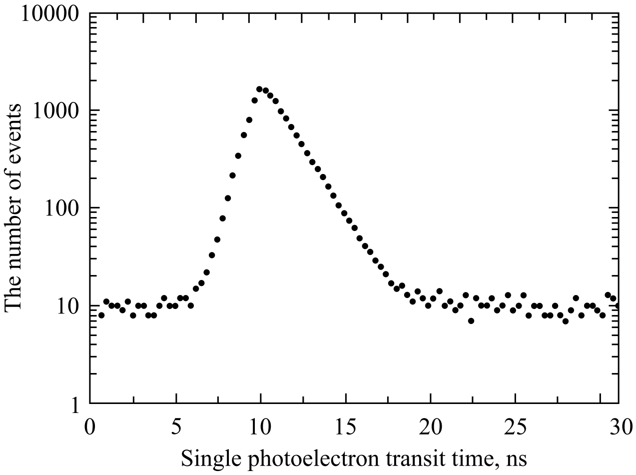

Fig. 3. Single photoelectron transit time distribution of the Quasar-370 ($t_{\mathrm{FWHM}} = 1.8$ ns) [22]

To withstand the high level of photoelectron bombardment, we developed special scintillators for luminescent screen — a Y_2SiO_5:Ce phosphor with a small addition of BaF_2 (2–3% by weight) ("YSO + BaF_2") and $ScBO_3$:Ce (SBO) [5, 7]. The scintillators provide very stable operation of the phototubes under night-sky background. Furthermore, to withstand the high anode DC current, a special small-size PMT was developed for use in the Quasar-370G phototube [7, 10]. The PMT has a 6-stage dynode system and 3 cm in diameter of photocathode with spectral sensitivity compatible with the emission spectrum of the scintillator in the luminescent screen. The PMT withstands up to 250 μA DC anode current.

2. TUNKA-4–TUNKA-25 CHERENKOV ARRAYS

The Cherenkov experiments in the Tunka Valley began with the Tunka-4 array [11, 12], which consisted of only four optical stations based on the Quasar-370G phototubes. The scheme of the optical station and its angular acceptance are shown in Fig. 4. The optical stations were arranged in a star configuration with three peripheral stations at distances of $\sim$ 100 m from the central station. The distances between optical stations were fixed with 10-cm accuracy. The angular resolution and energy threshold of the array were 0.5° and about 1 PeV, respectively. Its main achievement was being the first Cherenkov-only array to detect the classical "knee" in the energy spectrum of the primary cosmic rays at $\sim 3 \cdot 10^{15}$ eV [12]. The demonstrated capability of the Quasar-370G phototubes in this kind of application was another important result for the array.

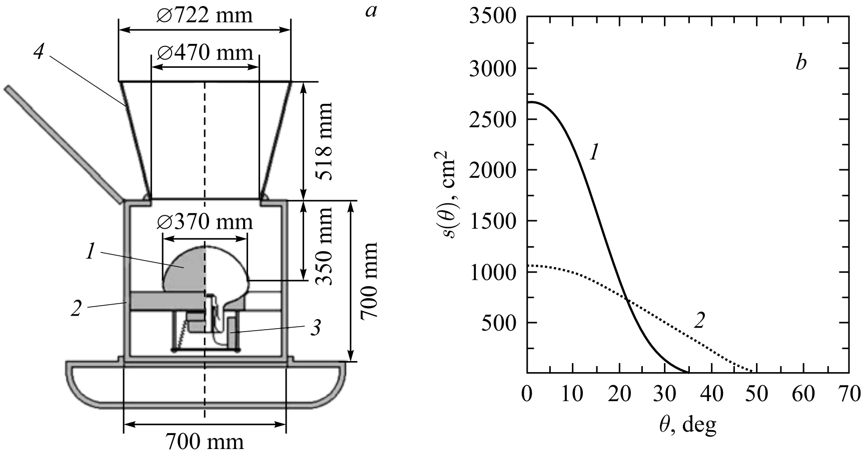

Fig. 4. Optical station of the Tunka-4–Tunka-25 arrays (*a*) and its angular acceptance (*b*)

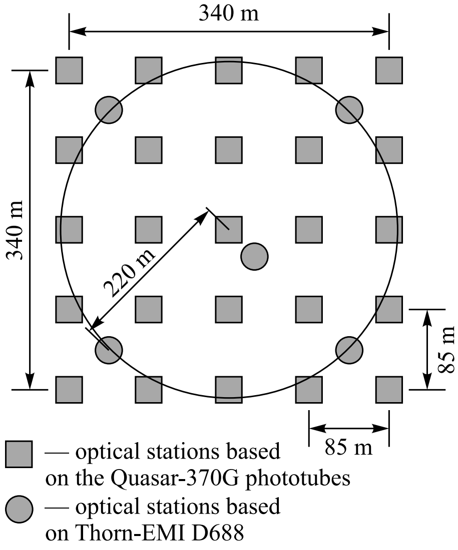

Fig. 5. The Tunka-25 array layout

The phototubes operated perfectly under night-sky light background, which was measured to be on average $2 \cdot 10^8$ photons $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$ at the experiment site [12]. The large sensitive area, coupled with precise time and amplitude resolutions of the phototube allowed us to develop the EAS Cherenkov arrays with competitive physics capabilities in the Tunka Valley. After the successful operation of the Tunka-4 array we steadily increased the number of optical station until completion of the Tunka-25 array at the same site.

The Tunka-25 array layout is shown in Fig. 5. It incorporated 25 optical stations based on the Quasar-370G phototube distributed over 340×340 m area. The distance between individual optical stations was 85 m. The array had 0.5° angular resolution and 1-PeV energy threshold and operated between 2000 and 2006. Using this array, we studied the energy spectrum and

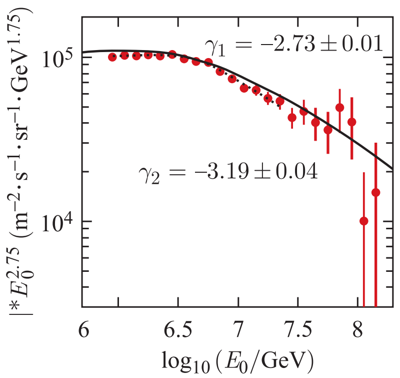

Fig. 6. Energy spectrum of primary cosmic rays measured by the Tunka-25 array [13]

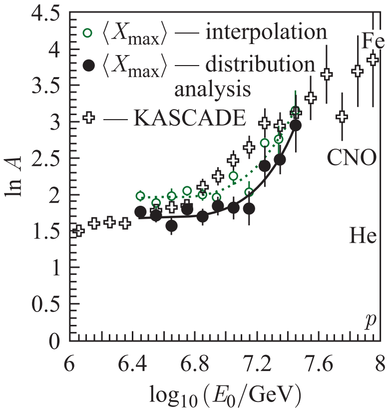

Fig. 7. Mass composition of primary cosmic rays in the energy range of 10^{15}–10^{17} eV measured by the Tunka-25 array [13]. ● — data based on analysis of $\langle X_{\max} \rangle$ distribution; ○ — data based on $\langle X_{\max} \rangle$ interpolation; ✙ — KASCADE data

mass composition of primary cosmic rays in the energy range of 10^{15}–10^{17} eV, as shown in Figs. 6 and 7, respectively [13]. The power index of the spectrum at $\sim 3 \cdot 10^{15}$ eV changes from $\gamma = -2.73 \pm 0.001$ to $\gamma = -3.19 \pm 0.04$, while the mass composition above the energy of 10 PeV steadily increases [13].

3. TUNKA-133 CHERENKOV ARRAY

In 2006, the experiments with Tunka-25 were concluded and the array was decommissioned. In the same year, the development of new array, Tunka-133, began. The Tunka-133 array has been operating to the present day. The Tunka-133 array consists of 175 wide-angle optical detectors placed to cover an area of 3 km^2 [14–17]. The detectors are grouped into 25 clusters, each with 7 detectors — six hexagonally-arranged detectors and one in the centre. The distance between the detectors in the cluster is 85 m. Nineteen clusters were installed in a circle of 500-m radius — the "inside" clusters — with 6 clusters placed at a distance 700–1000 m from the array centre — the "outside" clusters (Fig. 8).

An optical detector consists of a metallic cylinder of 50-cm diameter, containing the PMT (Thorn-EMI 9350 or Hamamatsu R1408) with a 20-cm diameter hemispherical photocathode. The container has a plexiglass top window heated

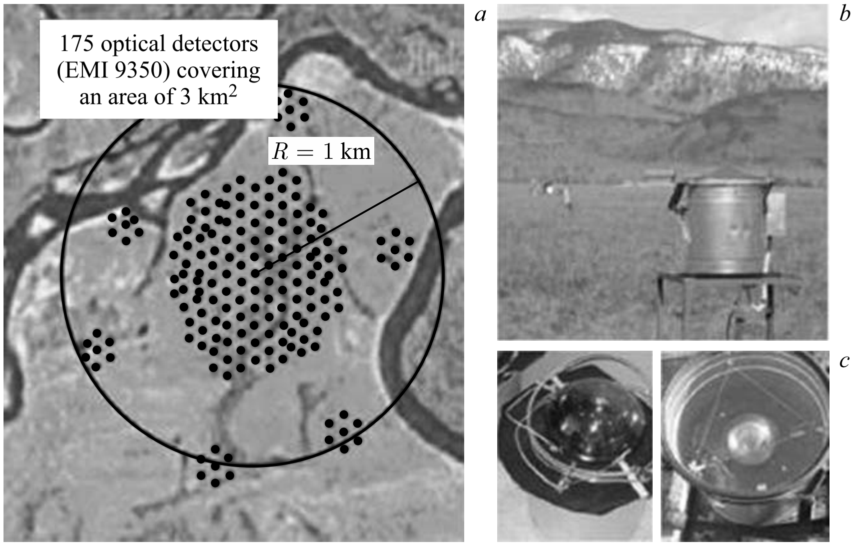

Fig. 8. The Tunka-133 array. *a* — the array layout, *b* and *c* — the array's optical stations [17]

against frost. The angular aperture is defined by geometric shadowing of the PMT. The detector is equipped with a remotely-controlled lid protecting the PMT from sunlight and precipitation. Apart from the PMT with its high-voltage supply and preamplifiers, the detector box contains a light emitting diode (LED) for both amplitude and time calibration, together with a controller. The controllers are connected with the cluster electronics via RS-485 twisted pairs. To provide the necessary dynamic range of $3 \cdot 10^4$, two analog signals, one from the anode and another from the dynode, are read out. They are amplified and then transmitted to the central electronics hut of each cluster. The ratio of amplitudes of these signals is about 30. It is not planned to heat the inner volume of the optical detector boxes, therefore all the detector electronics is designed to operate over a wide temperature range (down to $-40\,^{\circ}$C). The signals from PMTs are sent via 95-m coaxial cable RG58 from the detectors to the centre of each cluster. This leads to the broadening of signals, the minimum value of FWHM is around 20 ns.

The cluster electronics [14] includes a cluster controller, 4 four-channel FADC boards, an adapter unit for connection with the optical modules and a temperature controller. The 12-bit and 200-MHz sampling FADC boards are based on the AD9430 fast ADCs and the XILINX Spartan XC3S300 FPGA. The cluster controller consists of an optical transceiver, a synchronization module, a local time clock and a trigger module. The optical transceiver operating at 1000 MHz is responsible for data transmission and the formation of a 100-MHz synchronization signal for the cluster clocks. The cluster trigger (the local trigger) is formed by the coincidence of at least three pulses from optical detectors exceeding the threshold within a time window of 0.5 μs. The time stamp of the local trigger is fixed by the cluster clock.

The accuracy of the time synchronization between different clusters is about 10 ns. Each cluster electronics is connected to the DAQ centre with a 4-conductor power cable and fibre-optical cables (multimode fibres for inside clusters and single mode for outside clusters).

The central DAQ station consists of several DAQ boards synchronized with a single 100-MHz oscillator. On each board 4 optical transceivers are installed, allowing one board to operate with 4 clusters. The full number of boards may be increased to 20 (presently only 7 are used), giving a DAQ capacity of 80 clusters. The boards are connected to the master PC by 100-MHz Ethernet lines.

Each optical detector is equipped with remotely-controlled fast LED driver [18] with ultrabright blue GNL-3014BC LED. This LED driver is fixed near optical detectors PMT and used mainly for amplitude calibrations of the optical detectors. The LED driver provides light yield changeable in a wide range of 0–10^9 photons per pulse and pulse width of 3–10 ns. Time synchronization of the arrays optical detectors is a more complicated experimental task. To solve the problem, a dedicated calibration system has been developed.

The advent of ultrabright InGaN/GaN blue, violet and UV LEDs provides wide opportunities for development of calibration light sources for the Cherenkov and scintillator detectors [19–21]. Relatively new high-power blue LEDs open new possibilities for design of the Cherenkov detectors calibration systems. They are very bright and can withstand up to 1 A DC current. For the Tunka-133 experiment we have developed powerful nanosecond light source based on high-power LED XR7090 produced by Cree Company. The maximum of light emission spectrum of the LED is reached at 450 nm, the so-called “Royal Blue” LED. To get high-light yield of the light source staying still in a few nanoseconds time domain, the LED is driven by specially-designed driver using a pair of avalanche transistors ZTX415 switched consecutively. The light source is stable over wide range of repetition rate up to 1 MHz, although in the calibration system of the Tunka experiment the rate is quite low — ~ 5 Hz. The light yield of the light source measured by an integrating sphere is $\sim 10^{12}$ photons per pulse [22]. The width of light pulses of the source is ~ 3.5 ns (FWHM). The light source emits photons into 100° of full angle. The LED driver is enclosed into a metallic box with $40 \times 40 \times 25$ mm sizes.

Two approaches have been conceived to make time synchronization of the Tunka-133 arrays optical detectors using the above-described light source. The concept of the first approach can be seen in Fig. 5. In this approach, the light source is fixed on a helium balloon or a pilotless helicopter and raised at the height of ~ 400 m above the array. In this case, one needs to use GPS units and XBee radio units to know with a good accuracy the coordinates of the light source. In this approach, it is enough to use only one light source, because the light yield of the source and its emission angular distribution allow one to illuminate from 400-m height all optical detectors of the array. Implementation of the approach is hindered by the fact that so far it is unclear with which precision the coordinates of the light source on the balloon or helicopter can be maintained.

Based on the described light source, we have developed a system for calibration of the Tunka-133 array from balloon or helicopter. The system is equipped with a pulse generator with repetition rate of 5 Hz and power supply with batteries. The total weight of the system should be no more than 1 kg.

In the second approach, the light source is raised above the array using 2–3 m long pole or scaffolding. The optical detectors of the array have 50° half-angle of angular acceptance. So, in this case, there is a necessity to use light reflectors attached to the edge of the optical detectors.

For this calibration system we have developed a complex light source consisting of 4 light sources identical to the one described in Sec. 1 of the paper. All sources are fixed on one plate orthogonally to their neighbours. So, in such a geometry, the whole source emits photons into 2π angle in azimuth. All individual sources are triggered simultaneously from one pulse generator. The light sources including cables and all other connections are tuned between themselves in such a way that the accuracy of simultaneousness of the light pulses from all individual light sources is better than 50 ps.

The energy spectrum of cosmic rays in the range of $6{\cdot}10^{15}$–10^{18} eV has been reconstructed using data from three winter seasons of measurements with the Tunka-133 array. The spectrum demonstrates the existence of the knee at $\sim 3\cdot 10^{17}$ eV, at this energy point the spectrum power law index changes by 0.3: from $\gamma = 2.97 \pm 0.01$ before the knee to $\gamma = 3.3 \pm 0.11$ at higher energies, Fig. 9 [17]. The spectrum steepening at $3\cdot 10^{17}$ eV could be interpreted as a

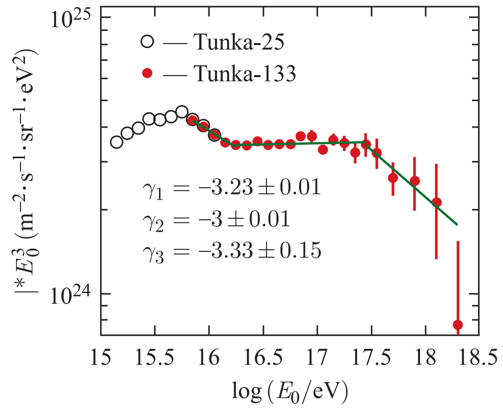

Fig. 9. Energy spectrum of primary cosmic rays measured by the Tunka-133 array [17]

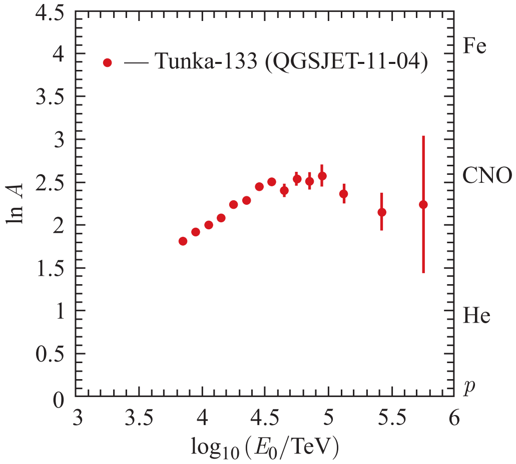

Fig. 10. Mass composition of primary cosmic rays in the energy range of 10^{15}–10^{18} eV measured by the Tunka-133 array [17]

"second knee" in the energy spectrum related to a transition from galactic to extragalactic cosmic rays. The decrease of the mean logarithm of atomic number or lightening of mass composition at energies above 10^{17} eV (Fig. 10) also points to such a transition to extragalactic cosmic rays.

4. TUNKA–HiSCORE CHERENKOV ARRAY

The development of the Tunka-HiSCORE wide-angle Cherenkov array [23, 24] began in 2010. The array is intended to study gamma-quanta fluxes from the known local sources and unknown new sources at the energies exceeding 20–30 TeV. Optical stations will be put at the distances of 150–200 m from each other and will consist of several PMTs with large area photocathodes ($\sim 20-30$ cm in diameter). Presently, we use Hamamatsu R5912 8-inch PMTs together with ET9352KB and PMT R7081-100 10-inch models in the optical stations. The effective area of the PMT in the optical stations will be increased by a factor of 4 using the Winston cones, which will in turn decrease the energy threshold by a factor of 2. The observational solid angle will be approximately 0.6 ster. Local trigger signals are formed from analog summation of the PMTs in each optical station. Such an approach will result in an additional decrease of energy threshold by $n^{1/2}$ times, where n is the number of PMTs in a station. In autumn of 2012, the first three optical stations (Fig. 9) were deployed for joint operation with the Tunka-133 array. As of February 2014, nine optical stations are in operation [25].

5. TOWARDS MULTI-TeV GAMMA-RAY ASTRONOMY

In 2012–2013, a very ambitious new project was initiated with aim of developing and constructing a high-energy gamma-ray observatory in the Tunka Valley. The main physics goals of the project are studies of the origin of cosmic rays combined with multi-TeV gamma-ray astronomy above the energy threshold of 20–30 TeV. The project called TAIGA [26] (Tunka Advanced Instrument for cosmic rays and Gamma Astronomy) will include the Tunka–HiSCORE array and a new net of narrow-angle Imaging Atmospheric Cherenkov Telescopes — the Tunka–IACTs. The new telescopes will incorporate relatively inexpensive matrices of photosensors with 8–10 m^2 area mirrors and a field of view of 8 by 8 deg. Matrices will consist of 400 PMTs of 25-mm diameter with corresponding data acquisition and control electronics. It is planned to build the Tunka–IACT array with telescopes of this type. Preliminary simulation results show that joint operation of the Tunka–HiSCORE wide-angle Cherenkov array and a net of relatively small Tunka–IACTs should be an effective, relatively inexpensive and quick way to penetrate the so far unexplored field of super high-energy gamma-ray astronomy [26]. The Tunka–HiSCORE and Tunka–IACT will complement each other, each measuring different parameters of EAS showers with high accuracy. The reconstruction of EAS core position and arrival direction provided by the Tunka–HiSCORE array (expected accuracies of core position location 5–6 m and arrival direction 0.1° [23, 24]) will be used for data processing. The total number of measurement channels and corresponding cost of such a complex array will be several dozen times lower than the cost of a gamma-ray telescope of the same area built using only classical narrow-angle IACT detectors.

The main feature of the new project is the combination in one array of detectors of different types: wide-angle Cherenkov detectors (non-imaging technique), narrow-angle Cherenkov detectors with photosensor matrices (imaging technique), and muon detectors. Apart from its main goal (search for and study of local sources of gamma quanta), the array will study gamma-quanta absorption on cosmic background radiation (infrared and microwave) and search for photon–axion transitions.

CONCLUSION

The history of the Cherenkov experiments in the Tunka Valley already spans more than twenty years. These developed from a small “toy” experiment with four photodetectors to a 3-km^2 array. Presently, these developments received a new impetus through a new giant Cherenkov array project with an area scalable up to 100 km^2, having ambitious physics goals including the solution of the century-long mystery of the origin of cosmic rays.

Aknowledgements. The work was supported by the Russian Federation Ministry of Education and Science (G/C 14.B25.31.0010), the Russian Foundation for Basic Research (Grants 13-02-00214, 13-02-12095 and 13-03-12451-ofi-m).

REFERENCES

1. *Bagduev R. I. et al. (Baikal Collab.).* Quasar-370 Large Area Hybrid Phototube // Izv. AN, Ser. Fiz. 1993. V. 57, No. 4. P. 135.
2. *Bezrukov L. B. et al. (Baikal Collab.).* The Optical Module of the Baikal Neutrino Telescope NT-200 // Proc. of the 23rd ICRC, Calgary, Canada, 1993. V. 4. P. 581.
3. *Bagduev R. I. et al. (Baikal Collab.).* The Optical Module of the Baikal Deep Underwater Neutrino Telescope // Nucl. Instr. Meth. A. 1999. V. 420. P. 138.
4. *Belolaptikov I. A. et al. (Baikal Collab.).* The Baikal Underwater Neutrino Telescope: Design, Performance and First Results // Astropart. Phys. 1997. V. 7. P. 263.

5. *Lubsandorzhiev B. K. et al. (Baikal Collab.).* Development of High-Sensitive Light Detectors for Underwater Neutrino Telescopes // Proc. of the 25th ICRC, Durban, 1997. V. 7. P. 269.
6. *Lubsandorzhiev B. K.* New Developments of Photodetectors for the Lake Baikal Neutrino Experiment // Proc. of the ICATPP-7, Villa Olmo, Como, Italy, 2001. World Sci. Publ. Co. Pte. Ltd, 2002. P. 79.
7. *Lubsandorzhiev B. K. et al. (Baikal and Tunka Collabs.).* Photodetectors for Lake Baikal Neutrino Experiment and TUNKA Air Cherenkov Array // Nucl. Instr. Meth. A. 2000. V. 442. P. 368.
8. *Bezrukov L. B. et al. (Baikal Collab.).* On Luminesce of Baikal Lake // Dokl. AN SSSR. 1984. V. 227, No. 5. P. 1240.
9. *Lubsandorzhiev B. K. et al. (Baikal Collab.).* Phototube Quasar-370 // Pribory i Tekhnika Eksperimenta. 2001. V. 3. P. 155.
10. *Bezrukov L. B. et al. (Baikal Collab.).* Photomultiplier for Cherenkov Detectors of Atmospheric Showers // Pribory i Tekhnika Eksperimenta. 2000. V. 1. P. 164.
11. *Antonov R. A. et al. (Tunka Collab.)* // Proc. of the 23rd ICRC, Calgary, Canada, 1993. V. 2. P. 430.
12. *Bryancki S. V. et al. (Tunka Collab.).* The Energy Spectrum of Primary Cosmic Rays by the Data of Tunka Cherenkov Array // Proc. of the 24th ICRC, Rome, 1995. V. 2. P. 724.
13. *Budnev N. et al. (Tunka Collab.).* Tunka-25 Air Shower Cherenkov Array: The Main Results // Astropart. Phys. 2013. V. 50–52. P. 18.
14. *Bezrukov L. B. et al.* Large Area Photodetectors for Astroparticle Physics Cherenkov Arrays: PMTs vs. HPDs // Nucl. Instr. Meth. A. 2011. V. 639. P. 42.
15. *Berezhnev S. F. et al. (Tunka Collab.).* Tunka-133: Primary Cosmic-Ray Mass Composition in the Energy Range $6 \cdot 10^{15}-10^{18}$ eV // Proc. of the 32nd ICRC, Beijing, 2011. V. 1. P. 197.
16. *Berezhnev S. F. et al. (Tunka Collab.).* The Tunka-133 EAS Cherenkov Light Array: Status of 2011 // Nucl. Instr. Meth. A. 2012. V. 692. P. 98.
17. *Berezhnev S. F. et al. (Tunka Collab.).* Tunka–HiSCORE — A New Array for Multi-TeV γ-Ray Astronomy and Cosmic-Ray Physics // Nucl. Instr. Meth. A. 2013. V. 732. P. 281.
18. *Lubsandorzhiev B. K. et al. (Tunka Collab.).* A LED Flasher for TUNKA Experiment // Proc. of the 30th ICRC. 2007. V. 5. P. 1117–1120.
19. *Vasiliev R. V., Lubsandorzhiev B. K., Pokhil P. G.* // Instr. Exp. Tech. 2000. V. 43(4). P. 570–572.
20. *Vyatchin Ye. E., Lubsandorzhiev B. K.* // Instr. Exp. Tech. 2004. V. 47(4). P. 493–498.
21. *Lubsandorzhiev B. K. et al.* LED-Based Powerful Nanosecond Light Sources for Calibration Systems of Deep Underwater Neutrino Telescopes // Nucl. Instr. Meth. A. 2009. V. 602. P. 220–223.

22. *Shaibonov B.A. (Jr.).* Event Selection in Muon and Neutrino Cascades in Baikal Neutrino Experiment. Ph. D. Thesis. Moscow: INR, 2011.

23. *Tluczykont M. et al. (HiSCORE Collab.).* HiSCORE: The Hundred-i Square-km Cosmic Origin Explorer // AIP Conf. Proc. 2012. V. 1505(1). P. 821.

24. *Tluczykont M. et al. (HiSCORE Collab.).* The HiSCORE Experiment and Its Potential for Gamma-Ray Astronomy // J. Phys. Conf. Ser. 2013. V. 409. P. 012120.

25. *Kunnas M. et al. (Tunka–HiSCORE Collab.).* Hardware and First Results of TUNKA–HiSCORE // Nucl. Instr. Meth. A. 2014. V. 742. P. 269.

26. http://dec1.sinp.msu.ru/ tunka/

27. *Lubsandorzhiev B. K., Combettes B.* The Quest for the Ideal Scintillator for Hybrid Phototubes // IEEE Trans. Nucl. Sci. 2008. V. 55, Iss. 3, Part 2. P. 1333.