ELEMENTARY PARTICLES AND FIELDS

Experiment

GUT-Monopole Searches by Means of Deep Underwater Baikal Neutrino Telescope

O. N. Gaponenko^{1)*}

Received August 25, 2020; revised September 14, 2020; accepted September 14, 2020

Abstract—The procedure for Grand Unified Theory (GUT) monopole searches by means of the NT200 Baikal neutrino detector is described. Event-selection and background-suppression algorithms are discussed in detail. Limits on the flux of slow monopoles are presented and are compared with theoretical predictions and with the results of other experiments.

DOI: 10.1134/S1063778821020083

1. INTRODUCTION

Searches for superheavy magnetic monopoles by means of deep underwater stationary Cherenkov detectors in the Lake Baikal have been performed since 1984. Limits on the flux of superheavy magnetic monopoles were obtained with the aid of the GIRLYANDA facility and its various modifications (see [1]), which were operated from 1984 to 1989 within the Baikal experiment. Photomultiplier tubes of the PMT-49B type with a photocathode diameter of 15 cm were used as a light-sensitive element in the GIRLYANDA-84, GIRLYANDA-86, and GIRLYANDA-86M facilities. The structure of the GIRLYANDA deep underwater facilities is shown in Fig. 1.

Since April 1993, the NT200 neutrino detector has been commissioned stage-by-stage in the Lake Baikal. The task of this deep underwater detector was to record high-energy neutrinos. The detector was also adapted to performing searches for slowly moving bright objects, such as monopoles of Grand Unified Theories (GUT). The NT36 neutrino detector, which is the first stage of NT deep underwater detector, was commissioned in April 1993. The data collected over one year by means of this Cherenkov detector permitted constraining the flux of slow magnetic monopoles at a level commensurate with the results of many years of operation of all preceding Baikal neutrino detectors (see [1, 2]). In subsequent years, the NT72, NT96, and NT144 Cherenkov detectors collected data in the Lake Baikal. In 1998, the NT200 detector featuring 192 QUASAR photodetectors and having a photocathode diameter of 37 cm was put into operation [2].

The NT200 deep underwater Cherenkov detector consists of eight vertical strings. Of them, seven are situated at the vertices of a regular heptagon with a side length of 21.5 m, while one string is positioned at its center (see Fig. 2). The strings are placed at a depth of 1.1 km and at a distance of 3.6 km from the shore. A signal from the detector is transmitted to the shore center via several underwater connection lines. In order to reduce the background, the optical modules used are combined into pairs. Dedicated electronics form a pulse, provided that triggering of both optical receivers of a pair occurs within 15 ns (so-called local trigger). Such a pair of optical modules forms an optical channel. Information about the times and number of local triggers is thereupon used to form a pulse that would trigger the detector master system in the monopole mode (master pulse). Each string in NT200 carries 12 optical channels. The distance between the uppermost and lowermost optical channels of a string is 68 m. Along each string, all channels, with the exception of the second from the top and the second from the bottom, which are oriented upward, are oriented downward (see Fig. 2). The upper and lower halves of a string form half-strings. In order to develop a muon trigger, it is required that not less than n , where n is usually chosen to be 3 to 4, local triggers be actuated within a 500 ns time window. For a monopole trigger it is required that not less than m (m is usually chosen to be 3) local triggers from any half-string be actuated within a specific time interval ΔT (usually $\Delta T = 500 \mu\text{s}$). In contrast to muon events, there is no transmission of information about the amplitudes of events for a monopole signal in the NT200 detector—the electronics records only the times and number of local triggers.

In the present article, we describe the algorithm of GUT monopole searches by means of the NT200 detector and the results of these searches. A high trans-

¹⁾Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia.

*E-mail: olgaponen@mail.ru

Fig. 1. Layout of the GIRLYANDA deep underwater facilities: (a) GIRLYANDA-84, (b) GIRLYANDA-86, and (c) GIRLYANDA-86M.

Fig. 2. NT200 deep underwater Cherenkov detector.

parency of water in Lake Baikal around the location of the detector, strongly anisotropic forward directed light scattering, a high sensitivity of photodetectors, and a large detector volume open unique possibilities for applications in these realms.

2. PROPAGATION OF A GUT MONOPOLE THROUGH THE DETECTOR MEDIUM

In 1931, Dirac proposed magnetic-charge theory [3]. Later, 't Hooft [4] and Polyakov [5] showed that magnetic charges should exist for a wide class

of theories involving spontaneously broken symmetries. Monopoles are also predicted by Grand Unified Theories (GUT monopoles). Their magnetic charge is an integral multiple of the Dirac magnetic charge, $g = ne\alpha/2$ (here e is the electron charge; α is the fine-structure constant; and $n = 1, 2, \dots$), while their mass may lie within a wide range of $M \cong 10^8 - 10^{21} \text{ GeV}/c^2$ (see, for example, [6]).

In 1981, Rubakov [7] arrived at the conclusion that baryon-number-violating processes may proceed in the presence of a GUT monopole. A similar conclusion was drawn in 1982 by Callan [8]. According to the results of those studies, the cross section for monopole-catalyzed baryon decay can be represented in the form

$$\sigma = \sigma_0/\beta, \quad (1)$$

where $\beta = v_{\text{mon}}/c$ is the monopole relative velocity and σ_0 is on the same order of magnitude as the strong-interaction cross sections, $\sigma_0 \cong 10^{-28} \text{ cm}^2$. The inclusion of the electromagnetic monopole-nucleus interaction leads to the appearance of an additional factor $G(\beta)$ in expression (1) (see [9, 10]),

$$G(\beta) = \begin{cases} 2.4 \times 10^7 \beta^{3.1} & \text{for } ^{16}\text{O nucleons,} \\ 0.17 \beta^{-1} & \text{for free protons.} \end{cases} \quad (2)$$

It is noteworthy that there are GUT versions where there is no catalysis of baryon decay or where this catalysis undergoes substantial suppression.

By employing relations (1) and (2), one can readily obtain the GUT monopole mean free path in a medium between two baryon-decay events. The mean free path λ_{cat} and the mean time τ_{cat} between two events of catalysis for a monopole moving in water are shown in Fig. 3 versus the velocity β . For water, the decay of hydrogen nuclei prevails up to $\beta = 6 \times 10^{-3}$ and only at higher velocities does the contribution of the decay of nucleons of the ^{16}O nucleus become substantial. The energy $m_p c^2$ released in monopole-catalyzed baryon decay is distributed among proton-decay products. Part of the decay energy is carried away by neutral particles, while the other part is spent on the production of charged particles, which emit Cherenkov light while moving in water. As was shown in [1], each proton-decay event involves the emission of $N_{\text{phot}} = 3 \times 10^4$ to 1.1×10^5 Cherenkov photons, on average, with a wavelength in the range of $300 < \lambda < 600 \text{ nm}$. These Cherenkov photons may be recorded by the optical modules of the detector, and this is interpreted as the appearance of a signal from the propagation of a GUT monopole in the working substance of the detector.

As is well known, light propagation in a medium is affected by absorption and scattering processes. In

the first case, light-radiation photons are absorbed in the medium, whereby the radiation intensity is weakened, while, in the second case, radiation photons are deflected from the initial direction. It is common practice to characterize the first process in terms of the absorption length λ_{abs} . This is the length over which the radiation-beam intensity becomes weaker by the factor e . For the second case, one applies, in addition to the mean scattering length λ_{scat} , the scattering function $\chi(\theta)$ in order to describe angular features. The mean cosine $\langle \cos(\theta) \rangle$ also provides useful information about angular characteristics of scattering. Many years of measurements of optical parameters of the aqueous medium at the location of the Baikal neutrino telescope (see, for example, [2, 11–16]) have shown that the absorption length changes only slightly over a year, and one can take, for different years, 21 m as a characteristic value of λ_{abs} in the wavelength range between 470 and 500 nm (that is, at the transparency maximum). On the contrary, the scattering length and the scattering function may change greatly from one month to another and from one year to another, but the effective scattering length defined as

$$\lambda_{\text{eff}} = \frac{\lambda_{\text{scat}}}{1 - \langle \cos(\theta) \rangle} \quad (3)$$

change slightly with time (a decrease in the scattering length λ_{scat} for natural water basins is likely due to the occurrence of processes involving strongly anisotropic forward scattering, in which case $\langle \cos(\theta) \rangle$ approaches unity—on the contrary, large values of λ_{scat} are characteristic of more isotropic scattering). In [12, 16], values between 450 and 640 m were obtained for λ_{eff} . Light scattering leads to the delay of the photon arrival time with respect to the case where there is no scattering. The investigations performed by the present author reveal that, for the NT200 neutrino detector, the arrival of light from detected particles is delayed because of light scattering in the aqueous medium of the detector by not more than 10 ns. Such delays may be of importance in detecting fast particles, such as relativistic muons, but, for the detection of slow monopoles (and this is the case that we consider in the following), they do not lead to substantial uncertainties. For example, the distance that a particle moving at a velocity β not higher than 10^{-2} travels over this time does not exceed 3 cm.

In addition to the properties of the medium where the signal propagates, it is also necessary to take into account the properties of the photodetectors used—that is, their amplitude, time, and angular features, as well as their detection efficiency. According to the investigations of the present author, the efficiency of signal detection by an optical module depends in complicated way on the state of the detector optical

Fig. 3. Mean free path and mean time between two baryon-decay events versus the velocity β of the monopole moving in water.

channel. For example, the optical-channel detection efficiency shows a trend toward a decrease in the course of a year and a trend toward the recovery of the original values after ascending and descending the telescope during mounting work. This behavior is likely due to the contamination of the detector optical surfaces with precipitations formed by the biological environment of the Lake Baikal. The detection efficiency also becomes lower in response to an increase in the channel load. This effect is especially pronounced in the summer–autumn period, which is characterized by a seasonal increase in the light background of the lake because of the enhancement of bioluminescent processes.

In order to determine the optical-channel detection efficiency, the author developed a dedicated procedure for precisely separating a signal generated by a special laser light source from background events. By employing a periodic character of laser bursts, vast statistics, and information about the triggering of all channels of the telescope, the present author formulated an algorithm for determining the detection efficiency for an individual channel with an uncertainty not exceeding 1%. According to the results of respective investigations, a typical value of the

detection efficiency for the usual signal amplitudes is $\text{Eff} = 0.95$ to 0.98 . In the ensuing calculations, we will everywhere use the lower boundary of $\text{Eff} = 0.95$ for the detection-efficiency value in order to avoid overestimating it in the cases of overloaded channels.

By way of example, Figs. 4 and 5 show the effective area of an optical channel for detecting a magnetic charge on the basis of the monopole trigger for which $\Delta T = 500 \mu\text{s}$, while the number of local triggers from this channel is not less than 14 (for more details concerning the choice of triggering conditions for the detection of a monopole signal, see the next section). The calculations illustrated in the figures were performed by means of a computer simulation. A specific direction of monopole motion was chosen for a fixed orientation of the optical channel, whereupon the plane was broken down by convention into rather small regions in such a way that each region was traversed by only one trajectory (the monopole angle α in Figs. 4 and 5 is reckoned from the vertical direction for monopole motion from top to bottom, the optical channel being oriented downward). The method of statistical tests (Monte Carlo method) was used to answer the question of whether a magnetic charge moving along this trajectory generates a given

trigger. After that, the tests were repeated many times in order to accumulate an adequate statistical data sample. The contribution of each region was taken into account with a weight proportional to the number of positive results of the tests. The tests were then repeated for different directions of monopole motion, as well as for various velocities β and cross sections σ_0 . The probability for triggering a photodetector at each point of the trajectory of monopole motion was calculated on the basis of the detection efficiency of the channel and its amplitude and angular features. In these calculations, the following possibilities were taken into account: (i) Both photodetectors of the pair are triggered immediately, and a local trigger is formed. (ii) One photodetector was triggered earlier within the time interval of a local trigger, while the other photodetector was triggered by the event being considered. (iii) By a given instant of triggering of photodetectors, a local trigger was not initiated in the respective time window. (iv) A local trigger was initiated by a background event. In those cases where a local trigger was initiated, the respective optical channel was switched off for $\tau = 15 \times 10^{-6}$ s, which corresponds to the dead time of the monopole system of the telescope. Further steps consisted in determining the next point of baryon decay on the monopole trajectory and in performing calculations until the monopole went away from the optical channel to a rather long distance. For the frequency of the local trigger from background events, we took $\nu = 1500$ Hz, which corresponds to the maximum possible counting rate from local triggers: not higher than 500 Hz under ordinary conditions and less than 1500 Hz within periods of the enhancement of bioluminescent processes. It is noteworthy that the results of the calculations depend only slightly on the exact value of this frequency. To demonstrate this, we note that, for the time interval of the monopole trigger, one would expect, at such frequencies, approximately one background event within $\Delta T = 500 \mu\text{s}$, and its effect would reduce the useful interval ΔT by the dead time associated with this background event. In more detail, the algorithm for suppressing background events in searches for monopole signals will be described in the next section.

3. ALGORITHM FOR SEPARATING MONOPOLE EVENTS IN THE NT200 DETECTOR

As was shown in the preceding section, one background event, on average, appears within the time window ΔT of the monopole trigger. In order to separate a useful signal from the background of other events that trigger the photodetectors, one can make use of the following circumstance. Figure 3 shows

that the monopole mean free path to the next baryon-decay event does not exceed several centimeters (this mean free path is in inverse proportion to the cross section σ_0 , so that, at different values of σ_0 , this statement may turn out to be valid only within a specific range of β). In view of these circumstances, it is natural to expect that the propagation of a magnetic charge through the working volume of the detector will look like a sequence of multiple flares against the background of rare random events of triggering of photodetectors from alien signal sources. The number of events of triggering of an individual optical channel within the time ΔT that lapsed from the generation of a monopole trigger is bounded by the dead time τ of the monopole system. Therefore, a large number N_{loc} of local triggers from any channel within the master time interval ΔT , $N_{\text{loc}} \sim \Delta T/\tau \approx 30$, may serve as a signature of the monopole signal. Unfortunately, the implementation of this program is hampered by the fact that the number of digits in the counters of the number of local triggers initiated by monopoles in the master system of the NT200 telescope is 4, so that the maximum number of local-trigger events that can be conserved by the electronics within the master time interval ΔT is $2^4 - 1 = 15$. In addition, it is necessary to take into account the possible malfunctions in the operation of an individual channel. In dealing with events as rare as the appearance of a magnetic charge in the detector, their searches by means of only one optical channel would not be reliable for this reason. At the same time, the use of a large number of optical modules with the aim of suppressing the background may lead to the reduction of the effective area of the detector in searches for a useful signal. For example, a degradation of the optical channels with time, malfunctions in the operation of the electronics or some other reasons frequently lead to a situation where one urgently has to switch off individual channels or groups of channels until the next repair work conducted once a year from the ice of the lake Baikal. Because of this, operative channels of the detector sometimes alternate with the regions of channels switched off completely. It follows that the strategy adopted for background suppression should compromise between the requirement that the number of simultaneously triggered optical channels not be overly large and the requirement that it remove the background events completely. Figure 6 shows the number of background events versus the toughness of various background-suppression criteria. As a measure of the toughness of such criteria, we plot, along the abscissa, the number of local triggers in the master signal for the actuation of two, three, and four channels under the additional condition that the time interval between the generation of a signal by the telescope master system in response to the monopole

Fig. 4. Effective area of the optical channel in the NT200 detector for detecting a GUT monopole in the case of $\sigma_0 = 10^{-26} \text{ cm}^2$ and $\beta = 10^{-5}$.

signal for these channels does not exceed the time of propagation of the slowest monopole in our analysis through the detector volume (we have chosen $\beta_{\min} = 10^{-5}$ for the minimum monopole velocity and $L \sim 100 \text{ m}$ for the characteristic detector size).

From Fig. 6, one can see that, for the chosen data set (approximately 100 hours of data accumulation), the triggering of not less than four channels provides the background suppression in the case of $N_{\text{thresh}} \geq 5$; for three and more channels, N_{thresh} should not be less than 6, while for two and more channels, $N_{\text{thresh}} \geq 8$. In processing vaster data sets, still greater values of N_{thresh} should be chosen in order to avoid random occurrence of background events. As an appropriate criterion, we henceforth choose the triggering of not less than two channels, requiring that $N_{\text{thresh}} \geq 14$. The calculations reveal that this strategy is optimal and does not lead to a substantial reduction of the effective detection area in relation to criteria employing different values of N_{thresh} and requiring the actuation of a greater number of channels. As was indicated at the beginning of this section, this is because, in contrast to random background effects, the signal from the propagation of a monopole has a specific signature that consists in

the possibility of multiply triggering optical channels within the time of propagation of a magnetic charge through the detector volume. At the same time, the criterion chosen here does not require simultaneously triggering a large number of different channels.

Let us estimate the probability that the chosen criterion does not reject a background event. It was shown in [1] that, for the optical modules of the NT200 detector, the counting rate is described by the Poisson distribution. The probability P_1 that, within the master time of $\Delta T = 500 \mu\text{s}$, an optical channel will exhibit not less than 14 triggering events against a local trigger from background events characterized by the maximum frequency of $\nu = 1500 \text{ Hz}$ (see Section 2) is

$$P_1 = \sum_{n=14}^{\infty} \frac{(\nu \Delta T)^n}{n!} \exp(-\nu \Delta T) = 1 \times 10^{-13}. \quad (4)$$

The probability P_2 that a different channel will also generate thereupon a signal of actuation of the detector master system in the monopole mode within the time interval of $T = L/(\beta_{\min} c) = 0.0333 \text{ s}$ can be found in the following way. Within the time T , the second channel may generate $1, 2, \dots, T/\Delta T$ master

Fig. 5. Effective area of the optical channel in the NT200 detector for detecting a GUT monopole in the case of $\sigma_0 = 10^{-32} \text{ cm}^2$ and $\beta = 10^{-5}$.

triggers. The sought probability is then inverse with respect to the probability for generating no master trigger; that is,

$$P_2 = 1 - (1 - P_1)^N \approx NP_1, \quad (5)$$

where $N \cong T/\Delta T \approx 67$. Since the channels are equivalent, it is necessary to consider that the second channel may be triggered first. Ultimately, the probability for the triggering of two channels by a background event with allowance for the above circumstance has the form

$$\begin{aligned} P_{1:2} &= P_1 (NP_1) + P_1 (NP_1) - P_1 P_1 \\ &= P_1 P_1 (2N - 1) = 1.33 \times 10^{-24}. \end{aligned} \quad (6)$$

For the whole detector, the total probability P is inverse with respect to the probability that no pair of channels undergoes triggering; that is,

$$\begin{aligned} P &= 1 - (1 - P_{1:2})^{(N_{\text{chnl}}(N_{\text{chnl}}-1)/2)} \\ &\approx P_{1:2} \frac{N_{\text{chnl}}(N_{\text{chnl}} - 1)}{2}, \end{aligned} \quad (7)$$

where N_{chnl} is the number of optical channels in the NT200 telescope— $N_{\text{chnl}} = 96$. Substituting the numerical values from relations (4)–(6) into expression (7), we ultimately obtain $P = 6 \times 10^{-21}$. If one

interprets the probability as the ratio of successes to the total number of tests, $P = k/n$, then, for the above probability, there is one missed background event per total number $n = 1/P$ of tests. Considering that each such test lasts for the time T , we can readily see that, for the criterion being considered, background events can compete with a useful signal only over a time interval of about $T/P = 5.5 \times 10^{18} \text{ s} \approx 2 \times 10^{11} \text{ yr}$.

4. EFFECTIVE AREA OF DETECTION AND LIMITS ON THE FLUX OF GUT MONOPOLES FROM THE NT200 DETECTOR

The telescope effective area for the detection of a magnetic charge can be calculated by the same method as that which was used in Section 2 for one optical channel. However, a direct implementation of this method in practice involves substantial computational difficulties. From Figs. 3 and 4, one can see that the distance at which the telescope sees a GUT monopole reaches 140 m, while the monopole mean free path between events of monopole-catalyzed baryon decay may be 10^{-4} cm . In calculating, for

Fig. 6. Number of background events versus the toughness of various criteria for background suppression.

example, the contribution of only one such trajectory to the effective area by the Monte Carlo method, it is therefore necessary to take into account approximately $(140 + 68 + 140)/10^{-6} = 3.5 \times 10^8$ events of monopole interaction with water nucleons and to repeat thereupon the calculation many times in order to accumulate an adequate statistical data sample. Further, a similar calculation should be performed for other possible trajectories, velocities, and cross sections. In addition, it is necessary to consider that the telescope configuration may change from one run of data accumulation to another. Therefore, all calculations should be performed anew for each detector configuration. Experience shows that, even for the fastest of modern computers, the time spent on such calculations exceeds substantially the time of data accumulation in the telescope; therefore, we employ a simpler approximate method to calculate the detector effective area. An accurate calculation reveals that the error of this method does not exceed several percent. The basic idea underlying this method consists in replacing the optical channels of the telescope by regions whose dimensions correspond to mean effective detection areas for these channels (see Figs. 4 and 5). For a given direction of monopole motion, the effective area of the detector can be determined as the projection of the mean detection

areas for individual channels to a normal plane, only regions that consist of pairwise intersections of different projections satisfying the chosen selection criterion (which requires the triggering of at least two channels a preset number of times while the monopole traverses the detector volume). The sum of these intersection is taken to be the effective detection area for the telescope in a given direction. Since we do not expect a preferential direction of arrival for magnetic charges at the detector volume, it is also necessary to perform averaging over different directions. Knowing the effective area of the setup, one can readily obtain limits on the monopole flux.

By way of example, Fig. 7 shows limits on the flux of magnetic monopoles from an analysis of the data collected over approximately two years with the NT200 detector. For the sake of comparison, this figure also gives astrophysical constraints on the flux of magnetic charges: the Chudakov–Parker limit obtained from the condition of conservation of the observed strength of galactic fields and the cosmological limit based on the obvious requirement that the density of magnetic charges not be greater than the critical density of matter in the Universe, $4\pi F_{\text{mon}} M_{\text{mon}}/(c\beta) < \rho_0 = 10^{-29} \text{ g/cm}^3$.

From Fig. 7, one can see that the data obtained

Fig. 7. Limits on the flux of GUT monopoles: (solid curves) results of the present study at a 90% confidence level and (dashed curves) theoretical predictions.

over two years of NT200 operation yield, for a number of cross sections σ_0 and velocities β , limits that are substantially more stringent than the theoretical limits. We expect that, after the processing of all data accumulated to date by means of the NT200 detector and the data from the Baikal neutrino detectors of earlier generations, the experimental limits on the monopole flux in Fig. 7 will be improved by a factor of about ten.

Figure 8 illustrates a comparison of the results of the present study with limits on the monopole flux from other experiments (see [17–24]). This figure shows that, for many regions, the results of the present analysis yield limits that are several times superior to the analogous limits from other experiments.

5. CONCLUSIONS AND OUTLOOK

An algorithm of searches for slow GUT monopoles by means of the NT200 Baikal neutrino detector have been described. Limits on the monopole flux have been obtained from the data set accumulated over approximately two years of detector operation. For many values of the velocity β and the cross section σ_0 , these limits are substantially better than the analogous limits from other experiments. We also expect

an approximately tenfold improvement of the limits on the GUT-monopole flux after the completion of processing of all currently available data.

The large-scale Baikal Gigaton Volume Detector (Baikal-GVD) [25, 26] is a further extension of the NT200 detector. Unfortunately, this detector, which is under construction, is not equipped presently with electronics to be involved in searches for slow GUT monopoles. Figure 4 shows that the distance at which optical channels see slow GUT monopoles characterized by $\sigma_0 = 10^{-26} \text{ cm}^2$ exceeds 100 m. Therefore, the application of the new detector covering such scales of distances would make it possible to enlarge substantially the effective area for magnetic-charge searches in this cross-section range, whereas the NT200 detector, which has a more compact geometry, provides unique possibilities for GUT-monopole searches in the region of smaller values of the cross section σ_0 . We also hope that, in the future, the new electronics for GUT-monopole searches will have a substantially shorter dead time, with the result that we will be able to probe the region of higher values of β . The last comment is of importance since Fig. 3 shows that, at $\beta \sim 6 \times 10^{-3}$, the monopole mean free path between successive

Fig. 8. Experimental limits on the flux of magnetic monopoles at a 90% confidence level.

events of monopole-catalyzed baryon decay comes to decrease because of magnetic-charge interaction with oxygen nuclei.

ACKNOWLEDGMENTS

I am grateful to my colleagues G.V. Domogatsky, Ch. Spiering, L.A. Kuzmichev, Zh.-A. M. Djilkibaev, R. Wishniewski, E.A. Osipova, and V. V. Aynutdinov for their interest in this study and the useful discussions on its results.

OPEN ACCESS

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license

and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

REFERENCES

1. L. B. Bezrukov, I. A. Belolaptikov, E. V. Bugaev, N. M. Budnev, M. D. Gal'perin, Zh.-A. M. Djilkibaev, G. V. Domogatskiĭ, A. A. Doroshenko, V. L. Zurbanov, V. B. Kabikov, A. M. Klabukov, S. I. Klimushin, L. A. Kuz'michev, M. I. Nemchenko, A. I. Panfilov, Yu. V. Parfenov, et al., *Sov. J. Nucl. Phys.* **52**, 54 (1990).
2. I. A. Belolaptikov, L. B. Bezrukov, B. A. Borisovets, N. M. Budnev, E. V. Bugaev, A. G. Chensky, I. A. Danilchenko, J.-A. M. Djilkibaev, V. I. Dobrynin, G. V. Domogatsky, L. A. Donskykh, A. A. Doroshenko, G. N. Dudkin, V. Yu. Egorov, S. V. Fialkovsky, A. A. Garus, et al., *Astropart. Phys.* **7**, 263 (1997).
3. P. A. M. Dirak, *Proc. R. Soc. London, Ser. A* **133**, 60 (1931).
4. G. 't Hooft, *Nucl. Phys. B* **79**, 276 (1974).
5. A. M. Polyakov, *JETP Lett.* **20**, 194 (1974).
6. V. A. Rubakov, *Rep. Prog. Phys.* **51**, 189 (1988).
7. V. A. Rubakov, *JETP Lett.* **33**, 644 (1981).

8. C. G. Callan, Phys. Rev. D **26**, 2058 (1982).
9. V. A. Rubakov and M. S. Serebrjakov, Nucl. Phys. B **218**, 240 (1983).
10. J. Arafune and M. Fukugita, Phys. Rev. Lett. **50**, 1901 (1983).
11. L. B. Bezrukov, N. M. Budnev, M. D. Gal'perin, and Zh.-A. M. Dzhilkibaev, Okeanologiya **30**, 1022 (1990).
12. B. A. Tarashchanskii, O. N. Gaponenko, and V. I. Dobrynin, Opt. Atmosf. Okeana **7**, 1508 (1994).
13. B. A. Tarashchanskii, R. R. Mirgazov, and K. A. Pocheikin, Opt. Atmosf. Okeana **8**, 771 (1995).
14. O. N. Gaponenko, R. R. Mirgazov, B. A. Tarashchanskii, Opt. Atmosf. Okeana **9**, 1069 (1996).
15. V. Balkanov, I. Belolaptikov, L. Bezrukov, A. Chensky, N. Budnev, I. Danilchenko, Z.-A. Dzhilkibaev, G. Domogatsky, A. Doroshenko, S. Fialkovsky, O. Gaponenko, A. Garus, T. Gress, A. Karle, A. Klabukov, A. Klimov, et al., Appl. Opt. **38**, 6818 (1999).
16. O. N. Gaponenko, Opt. Spectrosc. **128**, 620 (2020).
17. Baksan Collab. (E. N. Alexeyev et al.), in *Proceedings of the 21st International Cosmic Rays Conference ICRC, Adelaide, 1990*, Vol. 10, p. 83.
18. S. Orito, H. Ichinose, S. Nakamura, K. Kuwahara, T. Doke, K. Ogura, H. Tawara, M. Imori, K. Yamamoto, H. Yamakawa, T. Suzuki, K. Anraku, M. Nozaki, M. Sasaki, and T. Yoshida, Phys. Rev. Lett. **66**, 1951 (1991).
19. The MARCO Collab. (M. Ambrosio et al.), Eur. Phys. J. C **25**, 511 (2002).
20. M. Cozzi, Phys. At. Nucl. **70**, 118 (2007).
21. BAIKAL Collab. (V. Aynutdinov et al.), Astrophys. J. **29**, 366 (2008).
22. ANTARES Collab. (S. Adrián-Martinez et al.), Astropart. Phys. **35**, 634 (2012).
23. IceCube Collab. (M. G. Aartsen et al.), Eur. Phys. J. C **76**, 133 (2016).
24. IceCube Collab. (M. G. Aartsen et al.), Eur. Phys. J. C **79**, 124 (2019).
25. A. V. Avrorin, A. D. Avrorin, V. M. Aynutdinov, R. Bannasch, Z. Bardáčová, L. A. Belolaptikov, V. B. Brudanin, N. M. Budnev, A. R. Gafarov, K. V. Golubkov, N. S. Gorshkov, T. I. Gres', R. Dvornický, G. V. Domogatsky, A. A. Doroshenko, J. A. M. Dzhilkibaev, et al., Instrum. Exp. Tech. **63**, 551 (2020).
26. A. V. Avrorin, A. D. Avrorin, V. M. Aynutdinov, R. Bannasch, I. A. Belolaptikov, V. B. Brudanin, N. M. Budnev, A. A. Doroshenko, G. V. Domogatsky, R. Dvornický, A. N. Dyachok, Zh.-A. M. Dzhilkibaev, L. Fajt, S. V. Fialkovsky, A. R. Gafarov, K. V. Golubkov, T. I. Gres, H. Honz, et al., Bull. Russ. Akad. Sci.: Phys. **83**, 921 (2019).