Search for relativistic magnetic monopoles with the Baikal neutrino telescope

V. Aynutdinov^a, A. Avrorin^a, V. Balkanov^a, I. Belolaptikov^d, N. Budnev^b, I. Danilchenko^a, G. Domogatsky^a, A. Doroshenko^a, A. Dyachok^b, Zh.-A. Dzhlkibaev^a, S. Fialkovsky^f, O. Gaponenko^a, K. Golubkov^d, O. Gress^b, T. Gress^b, O. Grishin^b, A. Klabukov^a, A. Klimov^h, A. Kochanov^b, K. Konischev^d, A. Koshechkin^a, L. Kuzmichev^c, V. Kulepov^f, E. Middell^e, S. Mikheyev^a, M. Milenin^f, R. Mirgazov^b, E. Osipova^{c,*}, G. Pan'kov^b, L. Pan'kov^b, A. Panfilov^a, D. Petukhov^a, E. Pliskovsky^d, P. Pokhil^a, V. Poleschuk^a, E. Popova^c, V. Prosin^c, M. Rozanov^g, V. Rubtzov^b, A. Sheifler^a, B. Shoibonov^d, A. Shirokov^c, Ch. Spiering^e, B. Tarashansky^b, R. Wischnewski^e, I. Yashin^c, V. Zhukov^a

^a Institute for Nuclear Research of the Russian Academy of Sciences, 60-the October Anniversary pr. 7a Moscow 117312, Russian Federation

^b Irkutsk State University, Irkutsk, Russian Federation

^c Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russian Federation

^d Joint Institute for Nuclear Research, Dubna, Russian Federation

^e DESY, Zeuthen, Germany

^f Nizhni Novgorod State Technical University, Nizhni Novgorod, Russian Federation

^g St. Petersburg State Marine University, St. Petersburg, Russian Federation

^h Kurchatov Institute, Moscow, Russian Federation

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ABSTRACT

We present results of a search for relativistic magnetic monopoles with the Baikal neutrino telescope NT200, using data taken between April 1998 and February 2003. No monopole candidates have been found. We set an upper limit $4.6 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for the flux of monopoles with $\beta_m = 1$. This is a factor of 20 below the Chudakov–Parker bound which is inferred from the very existence of large-scale galactic magnetic fields.

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1. Introduction

Magnetic monopoles have been introduced by Dirac [1] in 1931 in order to explain the quantization of electric charge. The magnetic charge of monopoles must obey the Dirac quantization rule $g = kg_D$, with $g_D = e/(2\alpha)$, $k = 1, 2, 3, \dots$, $\alpha \approx 1/137$ being the fine-structure constant and e the elementary charge.

The existence of magnetic monopoles is mandatory in many formulations of Grand Unified Theories [2,3]. Predicted monopole masses range from 10^7 to 10^{17} GeV, depending on the symmetry

group and unification scale of the underlying theory. GUT monopoles are topologically stable. Once created in early phases of the universe, they could have survived and can be searched for in cosmic radiation. Measurements and estimates of cosmic magnetic fields suggest that they could accelerate monopoles lighter than 10^{14} eV to relativistic velocities [4,5].

The large magnetic charge value leads to strong ionization and also strong emission of radiation. The monopole energy loss via ionization is about $10 \text{ GeV cm}^2/\text{g}$ for $g = g_D$, and dominates over energy losses due to the other electromagnetic processes for Lorentz factors of $\gamma_m < 10^3$ [6,7]. The energy losses due to e^+e^- -pair production and bremsstrahlung are proportional to γ_m . However, these processes are suppressed by factors of α^2 for pair production and

* Corresponding author.

E-mail address: osp@dec1.sinp.msu.ru (E. Osipova).

M^{-1} (where M is the monopole mass) for bremsstrahlung, and dominate the energy loss only for very large γ_m . It was shown [7], that the Earth is transparent for relativistic monopoles with $M \geq 10^7$ GeV, which could be detected with optical Cherenkov neutrino telescopes as upward moving bright particles.

Searches for magnetic monopoles with underwater neutrino telescopes are based on four different mechanisms:

- direct Cherenkov radiation of the monopole itself ($\beta_m > 0.75$),
- Cherenkov radiation of δ -electrons generated by the monopole ($\beta_m > 0.52$),
- water luminescence stimulated by the monopole ($\beta_m \geq 0.01$),
- Cherenkov radiation from nucleon decays catalyzed along the monopole path ($\beta_m \leq 10^{-3}$) [8–10].

Here $\beta_m = v_m/c$ denotes the speed of the monopole expressed in units of the speed of light in vacuum, c , and we assume $\gamma_m < 10^3$. The catalysis process is important in case of slow monopoles and is not discussed in this paper (see e.g. [10]).

For the *direct Cherenkov* radiation, the number of photons per path length and per photon wavelength emitted by a magnetic monopole with magnetic charge g passing through matter with index of refraction n is [11]:

$$\frac{d^2 n_\gamma}{d\lambda dl} = \frac{2\pi\alpha}{\lambda^2} \left(\frac{gn}{e} \right)^2 \left(1 - \frac{1}{\beta_m^2 n^2} \right). \quad (1)$$

Fig. 1 (curve labeled as 1) shows the direct Cherenkov light emission of a magnetic monopole with charge $g = g_D$ in water ($n = 1.33$) for the wave length range 350–650 nm as a function of β_m . For $\beta_m = 1$ the emission exceeds that of a minimum ionizing relativistic muon by a factor of 8300. This is equivalent to the brightness of a muon with an energy of about 10 PeV accompanied by cascades of secondary particles which would also emit Cherenkov light.

Estimations of radiation intensity from δ -electrons as well as from water luminescence are presented in Appendices A and B, respectively. In this analysis we search for fast magnetic monopoles with $g = g_D$ within the velocity range $\beta_m \geq 0.8$ and $\gamma_m < 10^3$. Also, the search criteria (see Section 4) accept only upward moving monopoles and at large distances from the detector center. Under these conditions, the contributions from δ -electrons, radio-luminescence of water as well as from pair production and bremsstrah-

lung processes to the total Cherenkov radiation are negligible (contribution to the systematic uncertainty of effective area for monopole detection is less than 1%).

The monopole flux is limited by the Chudakov–Parker bound $F_{CP} < 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [12] since otherwise monopoles would destroy galactic magnetic fields. The best experimental limits on the flux of relativistic monopoles have been obtained with the large water and ice Cherenkov detectors NT200 [13] and AMANDA [14]. The MACRO detector uses emulsions, scintillators and streamer tubes and has established monopole flux limits over many orders of magnitude in velocity [15]. In this paper we present the result of a search for relativistic monopoles with the Baikal neutrino telescope NT200, based on data taken between April 1998 and February 2003.

The paper is organized as follows: in Section 2 we describe the detector. Section 3 describes simulation and reconstruction of signal and background events and Section 4 the search strategy. Section 5 gives the results of the analysis and compares the obtained limit on the monopole flux to limits from other experiments. Section 6 summarizes the results and gives a short outlook on the improvement of the present search by more than another order of magnitude.

2. Detector and long-term performance

The Baikal neutrino telescope is operated in Lake Baikal, Siberia, at a depth of 1.1 km. The NT200 configuration consists of 192 optical modules (OMs) arranged pair-wise on eight strings, with 12 pairs per string. The height of the detector is 72 m, its diameter 42 m [16].

This configuration was preceded by smaller stages NT36 (three strings with six pairs per string) and NT96 (four strings with 12 pairs per string). NT36 has been operated in 1993/1994, NT96 in 1996/1997. NT200 takes data since 1998. In 2005 it was upgraded by additional three strings each 100 m away from the center. This configuration NT200+ is operated at present and also serves as a prototype cell for a later Gigaton volume detector [17,18].

The two 37-cm photomultipliers of a pair are switched in coincidence in order to suppress background from bioluminescence and dark noise. A pair of OMs defines a *channel*. The light arrival time assigned to a channel is the time of the OM that reported the earliest hit in the given event. The amplitude of a channel is measured for one of the two OMs (the one with superior amplitude resolution, as pre-selected at calibrating stage). A *trigger* is formed by the requirement of $\geq N_{\text{hit}}$ (with hit referring to a channel) within 500 ns. N_{hit} is typically set to 3 or 4. For these events, amplitude and time of all fired channels are digitized and sent to shore. For further details on detector and calibration methods (see [16,19–21]).

Temporal changes of the detector performance are mainly due to two factors: (a) changes in the detector configuration due to hardware failures and (b) temporal variations of the water parameters. The actual configuration of NT200 was changing with time, since it happened that OMs (or groups of OMs) failed over the year and have been repaired or replaced only in the next following deployment season, in March/April. For each of the temporal configurations a so-called base run was selected and subjected to all time-consuming calibration procedures, including also artificial light sources (lasers).

For muons at trigger-level, amplitude distributions of individual channels have been compared to Monte-Carlo results, and the ADC coefficients in the base run renormalized for best agreement. Then, all other runs belonging to this configuration were normalized with respect to the base run, using signals from atmospheric muons rather than dedicated laser calibrations. Calibration

Fig. 1. Light emission of a magnetic monopole with $g = g_D$ in water as a function of β_m . 1 – Direct Cherenkov radiation of the monopole; 2 – Cherenkov radiation of monopole induced δ -electrons; 3 – water luminescence induced by the monopole; 4 – direct Cherenkov radiation of a muon.

variables are the time differences between neighbouring channels and the amplitudes of individual channels. If the average time differences of one channel to its neighbours vary by more than 3 ns compared to the base run, corresponding timing corrections are applied. Similarly the ADC coefficient of a channel i is corrected if the muon amplitude distribution differs by more than 10% from that of the base run, i.e. if $|K_i - K_{i,0}|/K_{i,0} > 0.1$. Here K_i is the ADC coefficient for channel i in the current run, and $K_{i,0}$ that in the base run. Fig. 2 demonstrates typical variations of the average time differences between two neighbouring channels (ch.42 and ch.43) and typical variations of amplitudes ($K_i/K_{i,0}$ for ch.42) over one year. Eighty percent of channels are as stable as channel 42, within 3 ns w.r.t. timing and 20% w.r.t. amplitude. Fig. 3 shows the distribution of average time differences between all neighbouring channels and of the corrections in ADC coefficients for all channels and runs that have been included in data analysis, with an rms of 0.5 ns and 0.07, respectively.

Temporal changes of the water parameters are mostly related to the scattering of light. Variations of the absorption length $L_{\text{abs}}(480 \text{ nm}) = 20\text{--}24 \text{ m}$ are typically less than 10%. Scattering is characterized by a strongly anisotropic scattering function $f(\theta)$, with a mean cosine of the scattering angle $\overline{\cos}(\theta) = 0.85\text{--}0.9$ and

a scattering length of $L_s = 30\text{--}70 \text{ m}$. Both scattering length and $f(\theta)$ vary during the year.

3. Simulation and reconstruction

Monopoles have been simulated with velocities β_m between 0.8 and 1.0 and for an isotropic distribution over the lower hemisphere. The number of photons was calculated according to Eq. (1). The light emission angle, in an acceptable approximation for $\beta_m \geq 0.8$, was fixed to $\cos(\theta_{\text{cher}}) = 1/\beta_m n$. Light scattering in water is not negligible at those large distances over which the bright monopoles are visible. The scattering length has been fixed to the lower limit of 30 m. A conservative estimation of systematic errors due to occasionally smaller scattering lengths yields for even an extremely short scattering length of 15 m a reduction of only 20% for the effective area for $\beta_m = 1$.

The acceptance A_{eff} for monopoles has been calculated for each temporary configuration of NT200 separately, depending on the number of operating channels and the chosen optimum values for rejection cuts (see below). The number of simulated monopole events for $\beta_m = 0.8, 0.9$ and 1 is 10^8 .

Fig. 2. Top: variation of average time-difference between channels 42 and 43 for all runs over one year. Bottom: variation of the coefficient $K_i/K_{i,0}$ for channel 42 over one year.

Fig. 3. Left: distribution of average time-difference variation between all neighbouring channels for all runs over one year. Right: distribution of the coefficient $K_i/K_{i,0}$ for all channels.

Uncertainties of the acceptances are mainly due to uncertainties on the optical water properties and on the sensitivity of the OMs. Compared to an earlier analysis [13], the present results are based on a more realistic description of light scattering. Sensitivities of the OMs itself have been tested by comparison of the experimental level-zero trigger rates with the ones calculated for atmospheric muons in each configuration of NT200. Note that, different to monopoles, minimum ionizing muons are visible only over short distances where light scattering is negligible. From this comparison, the uncertainties of the sensitivities of OMs are estimated as 15%. These uncertainties translate to 10% uncertainty for the effective area of monopole detection. Treating this and the error of 20% due to light scattering as independently, one arrives at an overall uncertainty of 23% for the monopole acceptance.

The main background in the monopole search – muon bundles and high-energy single muons – are due to cosmic ray air showers in the atmosphere above the detector. Air showers have been generated with CORSIKA [22]. We use the QGSJET1 model [23] and a primary composition according to [24]. The MUM program [25] is used to propagate muons through water. In the vicinity of the detector volume, processes of energy loss and light emission like pair production, bremsstrahlung and photonuclear interaction are explicitly simulated. In a final step, the response of the detector is simulated, taking into account the characteristics of the OMs and the measurement system. In total, 10^9 atmospheric muon events, which fulfill the experimental trigger condition $N_{\text{hit}} \geq 4$, have been generated. The ratio of number of simulated to experimental events is 3.3.

The trajectory of a muon is reconstructed by minimizing

$$\chi^2 = \frac{1}{(N_{\text{hit}} - 5)} \sum_{i=1}^{N_{\text{hit}}} \frac{(T_i(\theta, \phi, u_0, v_0, t_0) - t_i)^2}{\sigma_{ti}^2}. \quad (2)$$

Here, t_i are the measured times and T_i the times expected for a given track hypothesis. N_{hit} is the number of hit channels ($N_{\text{hit}} \geq 6$ for reconstruction, see [19]), σ_{ti} are the timing errors. A set of parameters defining a track hypothesis is given by θ and ϕ – the zenith and azimuth angle of the track, respectively, u_0 and v_0 – the two coordinates of the track point closest to the center of the detector, and t_0 – the time the muon passes this point.

The χ^2 defined above corresponds to a minimum ionizing muon. It implies the assumption that the photons along the muon path are emitted under the exact Cherenkov angle. The description worsens for higher muon energies due to electromagnetic cascades along the muon track: the direction of the secondary particles is smeared around the direction of the primary muon. The χ^2 as defined above also describes the Cherenkov radiation from a monopole with $\beta_m = 1$, which is just higher in amplitude than that from a muon but, for Lorentz factors smaller than 10^3 , has the same time pattern. Deviations from the model are mainly due to light scattering in water. For monopoles these deviations must be higher than for muons since they are visible over much larger distances than muons. Still, the impact of scattering on monopole track reconstruction is small. Our MC simulation demonstrates, that for 95% of events the χ^2 minimization for monopoles converges, for 94% even with a $\chi^2 < 3$.

4. Search strategy

The most natural first step in the search for extraordinary bright objects is the selection of events with a large number of fired channels N_{hit} . However, events with many hits are dominated by bundles of downward moving muons or by bremsstrahlung showers along downward muon tracks. The most radical rejection of that background is achieved by accepting only tracks from the lower

hemisphere. This naturally sets a lower limit on the allowed masses of monopole candidates since only monopoles with masses greater than 10^7 GeV can cross the Earth. This luckily coincides with the lower mass bound suggested by GUT theories. Note that such a condition also eliminates a possible background from extra-terrestrial neutrinos, since neutrinos capable to produce muons with equivalent light emission (corresponding to 10 PeV muon energy) are absorbed by the Earth. All background tracks from energetic neutrinos should therefore come from the upper hemisphere or from around the horizon.

For upward moving particles, the time values of hit channels should increase from bottom to top of the detector, and hence the correlation coefficient

$$\text{cor}_{tz} = \frac{\sum_{i=1}^{N_{\text{hit}}} (t_i - \bar{T})(z_i - \bar{z})}{N_{\text{hit}} \sigma_t \sigma_z} \quad (3)$$

should be positive. Here, t_i and z_i are time value and z-coordinate of the fired channel i , $\bar{T}$ and $\bar{z}$ are mean values for times and z-coordinates of the event, σ_t and σ_z the root mean square errors for time and z-coordinates.

Therefore, next to our level-zero cut for all standard analyses – $N_{\text{hit}} \geq 6$ and $N_{\text{string}} \geq 3$ – a first dedicated cut (**cut1**) for the monopole search was defined: $N_{\text{hit}} > 30$ and $\text{cor}_{tz} > 0$. It leaves 1.5×10^{-4} of the events passing level zero and reduces the effective area for monopoles with $\beta_m = 1$ by only a factor of 2.

Distributions in cor_{tz} and N_{hit} after **cut1** show consistency of experimental data with simulated background events. Fig. 4 compares experimental data with Monte-Carlo events from atmospheric muons and simulated monopoles with $\beta_m = 1$.

Preparing further background suppression beyond **cut1**, we first applied a full χ^2 minimization according to Eq. (2). Fig. 5 shows the distributions of the closest radial distance of the track to the detector center R_{rec} , and of the zenith angle θ . Again, experimental data are well described by background MC events. Most reconstructed muons cross the geometrical volume of the detector with its 21 m radius.

In contrast, monopoles are well visible up to about 80 ms.

Starting from this distance, even for the bright monopole tracks the detection efficiency decreases and becomes negligible above 90 m. Nearly horizontal monopole tracks passing the detector outside its geometrical volume are slightly shifted toward the center. This explains the difference in true and the reconstructed radial distances of monopoles as shown in Fig. 5. Nevertheless a cut on the reconstructed distance allows distinguishing the background of atmospheric muons from the bulk of far monopole events.

Based on the parameters derived from the full χ^2 reconstruction, we apply a series of further sequential cuts, checking at each level the agreement between experimental data and background events and making sure that the reduction of the acceptance for relativistic monopoles is small.

- **cut2**: χ^2 minimization converges and $N_{\text{hit}} > 35$,
- **cut3**: $\chi^2 < 3$,
- **cut4**: reconstructed zenith angle $\theta > 100^\circ$,
- **cut5**: closest distance to detector center $R_{\text{rec}} > R_{\text{rec}}(\text{min})$, with the optimum $R_{\text{rec}}(\text{min})$ ranging between 10 and 25 m, depending on the actual detector configuration (number of operating channels),¹
- **cut6**: correlation coefficient $\text{cor}_{tz} > \text{cor}_{tz}(\text{min})$, with the optimum $\text{cor}_{tz}(\text{min})$ ranging between 0.25 and 0.65, depending on the actual configuration of operating channels.

¹ We note good agreement between MC-generated and reconstructed distances: cutting on R_{true} leaves only 3% more events.

Fig. 4. Distribution of the correlation coefficient cor_{tz} (left) and the number of hits N_{hit} (right) for events passing cut1. Left: experimental data (solid histogram) are compared to simulated atmospheric muons (dashed histogram) and monopoles (dotted histogram). Right: experimental data (points), simulated atmospheric muons (solid histogram) and monopoles (dotted histogram). Hatched area indicates the uncertainty in muon MC simulation.

Fig. 5. Distributions of the closest radial distance of the track to the detector center R_{rec} (left), and of the reconstructed zenith angle θ (right) after cut1. Experimental data (solid line) are compared to simulated atmospheric muons (dashed line) and monopoles with $\beta_m = 1$. For the radial distances of monopoles, the dotted line gives the reconstructed value R_{rec} and the dashed-dotted line the generated value R_{true} .

The distributions of the correlation coefficient for the background from atmospheric muons and for the observed events passing cut4 and cut5, as well as the multiplicity N_{hit} after cut5 are presented at Fig. 6. The agreement between MC background and experimental data is fairly good even for very rare events.

5. Results

Within 1003 days live time (between April, 1998 and February, 2003), 20,943 events satisfying cut0 have been selected. Passing rates versus cut level for experimental and simulated events are

shown in Fig. 7. For MC events the statistical errors in suppressing factor are considerably less than the systematic errors. Passing rates for the experimental sample fairly well follow the passing rates for simulated background events. The Monte-Carlo statistics for background events exceeds that of experimental data by about factor of three. The efficiency of monopole registration is only reduced to 0.55 going from cut1 to cut6.

No events from the experimental sample pass cut6. The number of background events passing cut6 is 3.9 ± 2.2 , where 2.2 is the total systematic and statistical uncertainty in background estimation.

Fig. 6. Distribution of the correlation coefficient cor_{tz} for events passing cut4 (a), passing cut5 (b) and distribution of the N_{hit} for events passing cut5 (c). Histograms – simulated background atmospheric muons; triangles – experimental events.

Fig. 7. Passing rates versus cut level for experimental data (triangles), MC for atmospheric muons (asterisk), MC for monopoles (squares). Errors shown are the sum of statistical and systematic errors.

With zero observed events and 3.9 ± 2.2 expected background events for a 90% confidence level an upper limit on the number of signal events of $n_{90\%} = 2.4$ is obtained according to Conrad et al. [26] with the modified Feldman–Cousins ordering [27,28].

From that and from the non-observation of candidate events in the earlier stages NT36 and NT96, a 90% confidence level upper limit of $4.6 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ is derived for the flux of relativistic monopoles with $\beta_m = 1$.

Table 1 gives the time integrated acceptances and flux upper limits for magnetic monopoles with $g = g_D$ and $\beta_m = 1, 0.9$ and 0.8 . Acceptances are given separately for NT200 data and for data taken with the early configurations NT36 and NT96 in the years 1993–1997. Inclusion of NT36 and NT96 data improves the limit by a few percent.

Fig. 8 shows our 90% C.L. upper limit as a function of β_m and compares it to the published limits from the experiments Ohya [29], MACRO [15] and limits from AMANDA [14] and [30] (the lat-

Table 1
Time integrated acceptance $A_{\text{eff}} \times T$ and 90% C.L. upper limits on the flux of fast monopoles

	$\beta_m = 1$	$\beta_m = 0.9$	$\beta_m = 0.8$
NT200: $A_{\text{eff}} \cdot T$ ($\text{cm}^2 \text{ s sr}$)	4.84×10^{16}	3.48×10^{16}	1.23×10^{16}
NT36 + NT96: $A_{\text{eff}} \cdot T$ ($\text{cm}^2 \text{ s sr}$)	0.37×10^{16}	0.25×10^{16}	0.094×10^{16}
90% C.L. upper flux limit ($\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$)	4.6×10^{-17}	6.5×10^{-17}	1.83×10^{-16}

Fig. 8. Upper limit (90% C.L.) on the monopole flux obtained in this work (BAIKAL), compared to other experiments.

ter preliminary limit having recently been presented at ICRC 2007). At $\beta_m = 1$, our limit is a factor of 20 below the Chudakov–Parker bound which is inferred from the very existence of large-scale galactic magnetic fields.

6. Conclusion

The neutrino telescope NT200 in Lake Baikal is taking data since April 1998. We performed a search for relativistic magnetic monopoles with $M \geq 10^7 \text{ GeV}$, $\gamma_m < 10^3$ and magnetic charge $g = g_D$ for $0.8 < \beta_m < 1$. From the non-observation of candidate events in NT200 and the early stages NT36 and NT96, a 90% C.L. upper limit on the flux of fast monopoles of $4.6 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for $\beta_m = 1$ is obtained.

The search for bright objects is presently continued with the NT200+ array. This is an extension of NT200 by three external strings spaced at 100 m distance from the center [18]. Each external string contains 12 OMs arranged in six pairs, in analogy to NT200. NT200+ enables better identification of high energy bremsstrahlung cascades along muon tracks, the main source of background for monopole searches. This will result in softer cuts on N_{hit} and in a factor of 2 increase the effective area for fast magnetic monopoles compared to NT200. NT200+ represents a first step toward the construction a neutrino telescope with an effective volume about 1 km^3 (Gigaton Volume Detector, GVD). A design study of the new telescope GVD has started recently [17]. According to present plans, GVD will consist of 90–100 strings, with 12–16 OMs on each string and an instrumented length of strings of 300–350 m. Following our pilot simulations we estimate a sensitivity to fast monopoles on the flux level of $\sim 1 \times 10^{-18} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ after a 1 year of data taking.

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Appendix A. Cherenkov radiation of δ -electrons accompanying magnetic monopoles

The energy loss of a magnetic monopole in the velocity range $0.5 < \beta_m < 1$ reaches a value of several GeV/cm in water. Part of the lost energy is transformed into kinetic energy of δ -electrons. The maximum kinetic energy of δ -electrons is:

$$T_m^{\text{max}} = 0.69 \cdot T^{\text{max}} = 0.69 \cdot 2m_e(c\beta_m\gamma_m)^2. \quad (\text{A.1})$$

The factor 0.69 [31] takes into account the lower limit of the impact parameter due to the diameter of the electron wave packet in the atom. As can be derived from Eq. (A.1), the monopole velocity corresponding to the Cherenkov threshold of δ -electrons in water ($T_{\text{ch}} = 0.264 \text{ MeV}$) is $\beta_m = 0.52$.

The number of δ -electrons with energy T_e , generated per unit length by a monopole is given by:

$$\frac{d^2 n_e}{dT_e dl} = \frac{2\pi N_e e^2 g^2}{m_e c^2 T_e^2} f(T_e), \quad (\text{A.2})$$

$$f(T_e) = \left(\frac{d\sigma}{d\Omega} \right)_{\text{KYG}} / \left(\frac{d\sigma}{d\Omega} \right)_R,$$

where N_e is the electron number density in water, $(d\sigma/d\Omega)_R$ is the classical Rutherford scattering cross section of a free electron by a

fixed monopole and $(d\sigma/d\Omega)_{\text{KYG}}$ the quantum mechanical scattering cross-section [32,33].

The difference between Rutherford and KYG cross-sections is important only for scattering angles ψ larger than 70° , i.e. for scattering with large energy transfer to the electron in the laboratory frame. This corresponds to values $T_e/T^{\text{max}} \geq 0.3$.

The intensity of Cherenkov photons emitted by δ -rays along the monopole trajectory can be described by the following expression:

$$\frac{dn_\gamma}{dl} = \int_{T_{\text{ch}}}^{T_{\text{max}}} \frac{d^2 n_e}{dT_0 dl} dT_0 \int_{T_{\text{ch}}}^{T_0} \frac{dn_{\text{ch}}}{dl_e} \left| \frac{dE}{dl_e} \right|^{-1} dE \quad (\text{A.3})$$

where dE/dl_e is the ionization loss of electrons in water:

$$\frac{dE}{dl_e} = \frac{2\pi N_e r_e^2 m_e c^2}{\beta_e^2} \left(\ln \frac{2m_e c^2 \beta_e^2 \gamma_e^2 W_{\text{max}}}{I_{\text{water}}^2} - \beta_e^2 \right) \quad (\text{A.4})$$

$$W_{\text{max}} = \frac{m_e (c\beta_e \gamma_e)^2}{2(1 + \gamma_e)}, \quad I_{\text{water}} = 74 \text{ eV},$$

where r_e is the classical electron radius and dn_{ch}/dl_e the number of Cherenkov photons per unit length emitted by an electron at wavelengths between λ_{min} and λ_{max} :

$$\frac{dn_{\text{ch}}}{dl_e} = 2\pi\alpha \left(\frac{1}{\lambda_{\text{min}}} - \frac{1}{\lambda_{\text{max}}} \right) \left(1 - \frac{1}{n^2 \beta_e^2} \right). \quad (\text{A.5})$$

In the following we use $\lambda_{\text{min}} = 3.5 \times 10^{-5} \text{ cm}$ and $\lambda_{\text{max}} = 6.5 \times 10^{-5} \text{ cm}$. This wavelength interval is determined by the spectral dependencies of the absorption coefficient of water and of the quantum efficiency of the optical sensor. With the KYG cross section tabulated in [33], using Eqs. (A.4) and (A.5), and integrating Eq. (A.3), one gets the dependence of dn_γ/dl on the monopole velocity as shown in Fig. 1 (curve labeled as 2). The intensity of Cherenkov photons generated by δ -electrons rapidly rises with the monopole velocity and reaches the order of 10^4 cm^{-1} at $\beta_m = 0.75$. With the sharp rise of direct monopole Cherenkov radiation above $\beta_m = 0.75$, δ -electrons contribute less than 5–8% of the total Cherenkov light intensity of monopoles for $\beta_m \geq 0.8$. The dependency given in Fig. 1 has been derived by us 10 years ago, but circulated only as an internal Baikal report (see also [34]). They have also been derived in a recent PhD work in the ANTARES collaboration [35].

The angular distribution of δ -electrons generated by a monopole (in the approximation $f(T_e) = 1$) is the same as that of a relativistic muon. So, the normalized angular distribution of the δ -ray generated Cherenkov radiation for a monopole is the same as that of a muon. For δ -electrons with energy $T_e < 20 \text{ MeV}$, i.e. for the majority of them, the photons are emitted preferentially along the monopole trajectory, in the same way as for δ -electrons generated by relativistic muons – and in contrast to direct Cherenkov photon emission of the monopole itself.

Appendix B. Radio-luminescence of water stimulated by a magnetic monopole ($\beta_m > 0.01$)

The energy loss of electrically charged objects passing through water stimulates molecular excitations, which can be dissipated

by emission of light in the optical range. In 1990, measurements have been performed in Lake Baikal at the site of the NT200 array, in order to determine the strength of radio-luminescence stimulated by 5 MeV α -particles. The number of photons generated by α -particles passing through Baikal water was measured as:

$$G \cong 2 \times 10^{-7} (\gamma/\text{eV}). \quad (\text{B.1})$$

Down to $\beta_m \approx 0.01$, this value can be used as a conservative estimate for the amount of light generated by a monopole passing through water. Taking into account the energy loss of magnetic monopoles [6] and using (B.1), one finds the radio-luminescence light yield plotted in Fig. 1 (curve 3). This radiation intensity allows to search for monopoles with $\beta_m \geq 0.01$ –0.03 in underwater Cherenkov neutrino telescopes.

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