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Search for relativistic magnetic monopoles with the Baikal neutrino telescope NT200

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We present a limit on the flux of relativistic monopoles obtained during 994 days of operation of the Baikal neutrino telescope NT200. The search for relativistic monopoles is based on the enormous amount of Cherenkov radiation emitted by these particles.

1. Introduction

Fast magnetic monopoles with Dirac charge $g = 68.5e$ are attractive objects to search for with deep underwater neutrino telescopes. The intensity of monopole Cherenkov radiation is ≈ 8300 times higher than that of muons. An optical module (OM) of the Baikal experiment could detect such an object from a distance up to hundred meters. Propagating through the Universe, a monopole could be accelerated by magnetic fields up to energies $10^{21} - 10^{24}$ eV [1] ,[2]. Hence, monopoles with mass below $10^{12} - 10^{14}$ GeV are expected to be relativistic. The monopole energy loss is about 10 $\frac{GeV \cdot cm^2}{g}$ for a Lorentz factor $\gamma < 10^3$, but rises significantly with energy (by a factor 1000 for $\gamma = 10^7$). Monopoles with such energy losses could not cross the Earth. Still, for a wide mass range of $10^7 - 10^{14}$ GeV one may search for relativistic monopoles from the lower hemisphere, with significant suppression of the background caused by very energetic atmospheric muons.

The monopole flux is limited by the Chudakov-Parker bound $F_{CP} < 10^{-15}$ cm^{-2}s^{-1}sr^{-1} which results from the requirement that galactic magnetic fields must be conserved. The strongest experimental bounds on relativistic monopoles ($\beta > 0.8$) have been obtained by large Cherenkov detectors: Baikal [3] and AMANDA [4].

In this paper we present the result of a search for relativistic monopoles with the Baikal neutrino telescope NT200, based on data taken in the years 1998-2001 (994 days).

2. Search strategy

The present stage of the telescope NT200 [5] takes data since April, 1998 and consists of 192 optical modules (OMs) at 8 strings. The OMs are grouped in pairs and each pair defines a channel. A trigger is formed by the requirement of $N_{hit} \geq 4$ fired channels within 500 ns. For such events amplitude and time of all fired channels within time window 2000 ns are digitized and sent to shore. The space-time pattern of light recorded from a monopole depends on the water optical characteristics. The absorption length of Baikal deep water is L_{abs}(480 nm) $= 20 \div 24$m and slightly varies during years. Scattering in Baikal water is characterized by a strongly anisotropic function $f(\theta)$ with a mean cosine of the scattering angle $\overline{cos(\theta)} = 0.85 \div 0.9$ and a scattering length $L_s = 15 \div 70$ m. The OM response to a fast monopole was calculated for a scattering length 30 m. OMs facing the monopole path record about one photoelectron at 85 m distance, OM turned away still see one photoelectron at 50 m. The uncertainty of the scattering length which varies between 15 m and 30 m leads to an uncertainty of nearly 20% for the effective area for fast monopole registration.

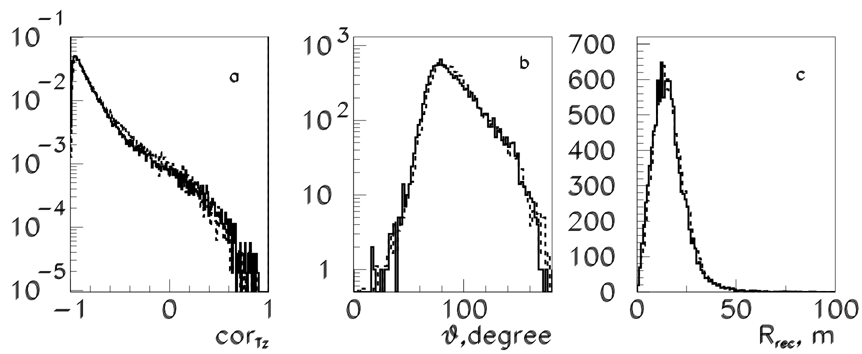

Figure 1. (a) cor_{Tz} distribution of experimental events with $N_{hit} > 30$ (solid) and simulated events from atmospheric muons (dashed); (b) Zenith angle distribution for events selected by cut 0; (c) R_{rec} distribution for events selected by cut 0

The processing chain for fast monopole starts with the selection of events with a high multiplicity of hit channels. In order to reduce the background from downward atmospheric muons we restrict ourself to monopoles coming from the lower hemisphere. For an upward going particle the times of hit channels increase with rising z-coordinates from bottom to top of the detector. To suppress downward moving particles, a cut on the value of the z – time correlation has been applied:

$$cor_{Tz} = \frac{\sum_{i=1}^{N_{hit}} (t_i - \overline{T})(z_i - \overline{z})}{N_{hit}\sigma_t\sigma_z} > 0 \qquad (1)$$

where t_i and z_i are time and z-coordinate of a fired channel, $\overline{T}$ and $\overline{z}$ 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.

The requirements $N_{hit} > 30$ and $cor_{Tz} > 0$ (cut 0) define the first selection stage and leave 0.015% of events that satisfy trigger $N_{hit} \geq 6$ on ≥ 3 strings. This cut reduces the effective area for monopoles with $\beta = 1$ by almost two times.

The main background for monopole signatures are muon bundles and single high energy muons. The simulation chain of such muons starts with cosmic ray air showers generated with CORSIKA [6]. We use the

Table 1. Rejection coefficient for experimental events and simulated downgoing atmospheric muons, as well as the reduction coefficient K_A for the effective area of monopole registration, after application of cuts 1-4

Cuts	EXPERIMENTAL EVENTS	MC atmospheric muons	K_A for monopole (β=1)
1	$0.017 \pm 1.22 \cdot 10^{-3}$	$0.015 \pm 8.4 \cdot 10^{-3}$	0.53
2	$2.6 \cdot 10^{-3} \pm 4.7 \cdot 10^{-4}$	$3.3 \cdot 10^{-4} \pm 4.1 \cdot 10^{-4}$	0.43
3	$1.1 \cdot 10^{-3} \pm 3.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-3} \pm 2.5 \cdot 10^{-4}$	0.42
4	$< 2.1 \cdot 10^{-4}$ 90% C.L.	$2.88 \cdot 10^{-4} \pm 1.2 \cdot 10^{-4}$	0.38

QGSJET model [7] and a primary composition according to [8]. The MUM program [9] is used for muon propagation through water. In fig.1 we compare experimental data (solid curve) and simulated atmospheric muon events (dashed curve) with respect to all parameters which have been used for background rejection. One sees that the simulation describes experimental data quite well, even on the level of those rare events.

Within 994 days live time, about $3 \cdot 10^8$ events with $N_{hit} > 4$ have been recorded, with 20943 of them satisfying cut 0 ($N_{hit} > 30$ and $cor_{Tz} > 0$). All events have been reconstructed according to the standard algorithm [10]. For further background suppression we use additional cuts, which essentially reject muon events and at the same time only slightly reduce the area for registration of relativistic monopoles.

1. $N_{hit} > 35$ and $cor_{Tz} > 0.4 \div 0.6$
2. The χ^2 determined from reconstruction has to be smaller than 3 ($\chi^2 < 3$)
3. Reconstructed zenith angle $\theta > 100$ deg
4. Reconstructed track distance from the center of NT200 $R_{rec} > 20 \div 25$ m.

NT200 took data in various configurations, due to the different numbers of temporarily operating channels. The different cuts on cor_{Tz} and R_{rec} correspond to different configurations of NT200. In Table 1 the rejection coefficient, i.e. the ratio of events passing cuts 1-4 to those passing cut 0, is presented (for a subset of configurations representing 50% of full statistics). Also shown is the reduction factor for the monopole effective area K_A. No events from the experimental sample pass cuts 1-4.

The acceptances A_{eff} for monopoles with $\beta = 1, 0.9, 0.8$ have been calculated for each configuration of NT200 (17 configurations) separately depending on the number operating channels and the concrete values for the rejection cuts. For the time periods included, it varies between $3 \cdot 10^8$ and $6 \cdot 10^8 \text{cm}^2\text{sr}$ ($\beta = 1$).

From the non-observation of candidate events in NT200 and the earlier stages NT36, NT96 [3], an upper limit on the flux of fast monopoles on the 90% confidence level is obtained . The cumulative acceptances $A_{eff} \cdot T$ as well as the 90% C.L. upper limits are presented in Table 2.

In fig.2, the 90% C.L. upper limit obtained with the Baikal neutrino telescope for an isotropic flux of fast monopoles is compared to the final limits from the underground experiments Ohya [11] and MACRO[12] and to the published limit of the underice detector AMANDA[4].

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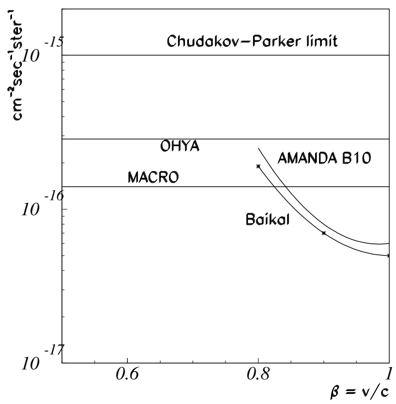

Figure 2. 90% C.L. upper limits on the flux of fast monopoles

Table 2. $A_{eff} * T$ and 90% C.L. upper limits on the flux of fast monopoles

	$\beta = 1$	$\beta = 0.9$	$\beta = 0.8$
NT200 $A_{eff} \cdot T$ $cm^2 \cdot sec \cdot sr$	$4.53 \cdot 10^{16}$	$3.22 \cdot 10^{16}$	$1.18 \cdot 10^{16}$
NT36+NT96 $A_{eff} \cdot T$ $cm^2 \cdot sec \cdot sr$	$0.37 \cdot 10^{16}$	$0.25 \cdot 10^{16}$	$0.9 \cdot 10^{15}$
90 % C.L. upper flux limit $cm^{-2} \cdot sec^{-1} \cdot sr^{-1}$	$0.5 \cdot 10^{-16}$	$0.67 \cdot 10^{-16}$	$1.97 \cdot 10^{-16}$

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