SEARCH FOR UPWARD-GOING MUONS FROM NEUTRALINOS AT BAKSAN UNDERGROUND SCINTILLATOR TELESCOPE

M.M. BOLIEV, A.V.BUTKEVICH, A.E.CHUDAKOV, O.V.SUVOROVA, V.N.ZAKIDYSHEV
Institute for Nuclear Research Academy of Sciences of Russia; 60th October Anniversary Av. 7a; 117312 Moscow Russia

S.P. MIKHEYEV
Laboratorio Nazionale Del Gran Sasso dell'INFN; SS 17 bis Km 18+910; I-67010 Assergi (L'Aquila) Italy

Presented by O.Suvorova

The detection of upward-going muons with the Baksan Underground Scintillator Telescope has been carried out during almost two decades. We present here: (i) an analysis of upward through-going muon sample collected by the Baksan detector since December of 1978 for search for high energy neutrino signals from annihilations of massive neutralinos inside the Earth's core and the Sun; (ii) a discussion of effects of high energy neutrino passage through a thick layers of matter.

1 Introduction

The observation of energetic ($\geq$ GeV) upward-going muons by underground neutrino telescopes in the direction of the Earth's core and the Sun implies the indirect search for weakly interacting massive particles. According to the theory relic hypothetical supersymmetric neutralinos with the masses in GeV-TeV range accumulated inside the Earth's core and the Sun could produce detectable flux of high energy neutrinos. The neutrino yield could be due to decays of the neutralino annihilation products.

We do evaluated number of background muons induced by atmospheric neutrinos by means of full Monte Carlo simulations of the neutrino interactions, muon propagations, and the detector response. The signal to background ratio has been optimazed by an appropriate angular selection. The detailed angular analysis of the Baksan data has been presented in Ref. [1] and the parameter space excluded at the 90% c.l. by the Baksan experiment has been reported in previous note [2].

2 Experiment

The Baksan Underground Scintillator Telescope (North Caucasus, the altitude 1700m) is one of the first and oldest operating large installation for upward-going muons detection [3]. The detector is placed in the underground laboratory at the effective depth of $850 hg/cm^2$ where the atmospheric muon flux is reduced by factor of $5 \cdot 10^3$. The telescope itself is a fourfloor building with a shape of a parallelepiped ($17m \times 17m \times 11m$) with two horizontal planes at the distance of 3.6m and 7.2m from the bottom. So, there are four vertical and four horizontal planes separated from each other by $160 g/cm^2$ of absorber. In total the telescope consists of 3,150 liquid scintillator counters of standard type ($70cm \times 70cm \times 30cm$), which entirely cover all its planes.

The separation of upward and downward-going muons (the ratio is order 10^{-7}) is performed by means of the time-of-flight method. The time resolution of the telescope, measured with downward-going muons, is equal to 5 ns, therefore the value of $1/\beta$ can be measured with accuracy about 10%. The following convention is used: the positive value of $1/\beta$ around unit is expected for downward-going muons, while $1/\beta$ around -1 is expected for upward-going particles. The particle trajectories are determined by the positions of hitted tanks. For the preliminary rejection of downward-going atmospheric muons two hardware triggers are used (for more details see Ref. [4]). Trigger 1 covers the zenith angle range $95° \div 180°$, while trigger 2 selects horizontal muons in the range $80° \div 100°$. The efficiency of hardware triggers of 99% has been measured with the flux of atmospheric muons. The triggers give 0.1% of the initial rate, leaving of about 1,800 events per day for further processing. The upward-going muon candidates are selected by the off-line routine from reconstructed events if there is really only one single trajectory of penetrating particle and negative measured value of $1/\beta$. However all events with negative values of $1/\beta$ have been visual scanned to check possible misinterpretation.

The data used for this analysis have been collected from December of 1978 until June of 1995, with 11.94 live-years. It was found that 840 events survived these cuts. Having in mind an upward-going trajectories that could be mimicked by downward-going atmospheric muon interactions or multiple muons we have applied a few additional cuts to a single track. These cuts do exclude: (i) particles with energy below $\approx 1GeV$; (ii) downward-going muons with large scattering angles. (ii) particles which were produced or stopped inside the detector. Our approch to final events selection as well as estimations of systematic uncertainties and a possible background sources are in details discussed in Ref. [5]. In total 558 events survived all cuts. In Fig.1 solid histogram shows the zenith angular distribution of these events.

3 Comparison with Monte Carlo simulations of atmospheric neutrinos

The shaded histogram in Fig.1 is a result of complete Monte Carlo simulations of upward through-going muons induced by atmospheric neutrinos with the calculated flux [6]. In total we have modeled 273184 neutrinos interactions in the surround rock, in which induced muons reached the detector. It corresponds to 100 runs of real data taking. In this calculation we have used the conventional expression for the cross-section of neutrino charged current deep-inelastic scattering off isoscalar targets and parton density functions given in Ref. [7]. The muon propagation has been simulated for Baksan rock using muon energy-loss parameterization given by Lohman et al. [8] and taking into account the multiple Coulomb scattering of muons on route to the detector. In simulations of the detector response the same requirements for hardware triggers and the same set of cuts as for real data have been applyed. The hardware triggers were produced for 29% of events. Finally we have found of 55692 generated events that survived all the cuts.

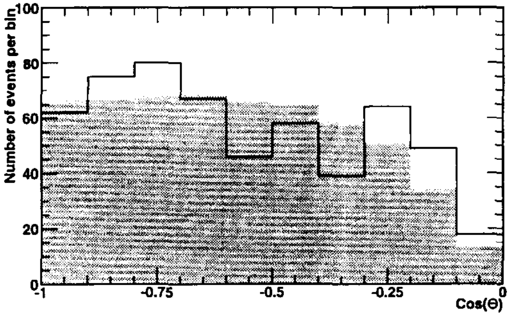


Figure 1: Distribution in $\cos(\theta)$ for upward-going muons observed with the Baksan Underground Scintillator Telescope. The shaded histogram is Monte Carlo simulations.

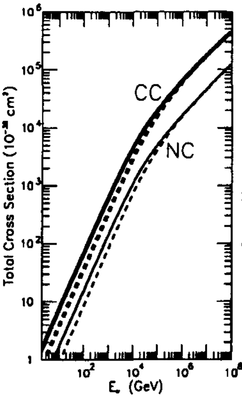
Although the shape of the experimental zenith angular distribution is different from the predicted one, we note that we don't observe any excess of the data in the vertical bins. Also in total number we found a good agreement between the data and Monte Carlo simulations. The ratio of the observed number of events to expected one is obtained to be $1.00 \pm 0.04(stat.) \pm 0.08(syst.) \pm 0.15(theor.)$. The systematic uncertainties have been evaluated by MC simulations of detector acceptance, varying the parameters relevant to the observation of upward-going particles [1),5)]. The theoretical uncertainties of 15% are mainly due to the absolute normalization of the atmospheric neutrino flux.

In general the neutrino and muon fluxes are in equilibrium while neutrino absorption can be neglected. However, in case of neutrino signal expected from neutralino annihilations inside high density of matter, we had to involve the opaque of medium for neutrino. The problem has been studied (see, e.g. [9]), but for strongly nonpower neutrino spectra, as we have, the result cannot be straightforwardly applied, and so we did a special calculations.

4 HE neutrinos propagation through the matter

With the growth of the energy as well as a target thikness, neutrinos interactions with the matter lead not only to the absorption of passing neutrino flux but due to neutral current reactions it would be generated a secondary neutrinos that resultes in modification of the neutrino spectrum shape. The energy dependences of neutrino (antineutrino) cross sections of scattering off isoscalar nucleon are shown in Fig.2. Here, our calculations based on parton distribution functions given by [10] according to modern information about the nucleon structure functions. Neutrinos generated inside the central space of the Sun with GeV-TeV energies would pass around $10^{12} g/cm^2$ of matter on the way to the surface and so would have a several interactions inside the Sun. The effect have been calculated by use the explicit expression for neutrino propagation through the solar matter [11]. Moreover the role of neutral current interactions becomes significant for the detection of upward-going muons induced by very high energies neutrinos ($\geq 10^6$ GeV). We have applied MC simulations to a monohromatic energy neutrinos passing through the terrestrial medium. Due to the secondary interactions these neutrinos should give a spectrum with a lower energies than initial one but quite enough yet to produce an observable muons at the exit of the depth. The upgoing muons yield can be found by solving the kinetic equation for muon propagation through the matter numerically.

Our final result for the probability $P_{\nu-\mu}$ that neutrino with primary energy E_ν produces a observable muon with energy exceeding energy threshold (for our detector $\approx 1 GeV$) is shown in Fig.3. There is $P_{\nu-\mu}$ as a function of neutrino energy for different arrival directions in comparison with a curves where absorption is accounted simply as an attenuation factor $K = exp(-h \cdot N_A \cdot \sigma_{tot})$: either with CC reaction only or with CC+NC reactions. The effect of the latter interaction is seen explicity.



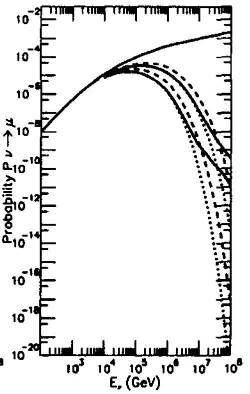


Figure 2: Charged current and neutral current cross sections for νN (solid line) and $\bar{\nu} N$ (dash) interactions.

Figure 3: Probability that a neutrino with primary energy E_ν produces a muon which arrives at the detector with energy exceeding 1 GeV. Three example directions: horizontal (no interactions), vertical and 150°. Absorption with MC simulations (solid line) and analytic calculations (dashes for CC reactions only; dots for CC+NC).

5 Upper limits on the indirect neutralino signals

As far as events coming from near the core of the Earth and the Sun are studied as a possible high energy neutrino signal from dark matter annihilations, in Fig.4 we present the angular distributions of the number of observed events (solid histogram) in the direction of the Earth's core and the Sun in comparison with expected one from atmospheric neutrinos (shaded histograms). In the case of the Earth's core the expected histogram has been obtained in same way as in Fig.1, and in the case of the Sun the background has been evaluated from the data itself, considering fake "Suns" which have the same acceptance as true Sun but shifted at some hour angle.

Since the observed distributions are consistent with the expected from atmospheric neutrinos, the upper limits on number of upward-going muons from the direction of the Earth's core and the Sun can be obtained. Dash-dotted histograms in Fig.4 show upper limit at the 90% c.l. as a function of size of angular window.

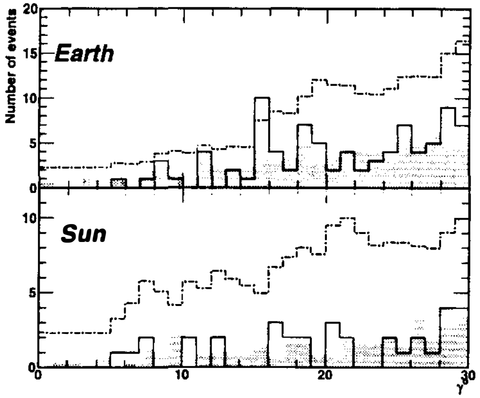


Figure 4: Distribution in γ for upward-going muons from directions of the Earth's core and the Sun. Solid histogram is data and shaded one is expectation for atmospheric neutrinos. Dash-dotted histogram is upper limits at 90% c.l. on number of upward-going muons produced by neutrinos nonatmospherc origin as a function of cone opening angle γ.

We have extensively studied the detector response for neutralino signals using the same Monte Carlo generator as above, except neutrino spectrum from neutralino annihilation has been inserted into generator. In our analysis we based on the phenomenological approch to MSSM with variation of model parameters in the following ranges: $\tan\beta = (2 \div 32)$, mass of pseudo-scalar Higgs boson $m_A = (50 \div 10^3)GeV$, neutralino mass $m_\chi = (10 \div 5 \cdot 10^3)GeV$, and gaugino fraction of neutralino $P = (0.01 \div 0.99)$. In the calculations for all allowed neutralino annihilation channels[12] we have computed neutrino yields considering two body decays down to fermions and following application the same approach as in Ref. [13] with parameterization[14]. Modification of the neutrino spectra inside the Sun (the discussion above) and an angular distribution due to neutralino space spread inside of the Earth's core have been taken into account. For each set of parameters we have collected 1000 events that survived all experimental cuts. We have resulted in a functions of neutralino mass for two detector dependent values: an angular window size (γ) containing 90% of events and a muon detection probability (P_μ^A) per one neutralino pair annihilation both for the Earth and the Sun cases. As we have found in the studied range of neutralino masses the values of γ and P_μ^A vary within approximately 30% with variation of another model parameters except masses around W-boson mass, where the spread of the detection probability is obtained much higher[1].

The obtained dependenses offer to set an upper limit on annihilation rate Γ_A that is more adequate for the indirect neutralino search, we believe. Indeed, an upper limit on annihilation rate can be written as

$$\Gamma_A = \frac{N_{90\%c.l.}(\gamma)}{T \cdot \varepsilon_\gamma} \times \frac{1}{P_\mu^A},$$

where $N_{90\%c.l.}(\gamma)$ is 90% c.l. experimental limit on number of events for given angular window γ, T is an observation time, and ε_γ is a fraction of total number of events are containing within of angular window γ. In our analysis we have used $\varepsilon_\gamma = 0.9$. With this definition the limit on Γ_A is completely detector independent while the limit on muon flux depends on detector energy threshold, which is not always well defined.

The upper limits on annihilation rate for several values of neutralino masses are presented in Table 1. Also we show limits on flux of muons with energy ≥ 1 GeV. Here, in order to derive limit we have used averaged value of γ and P_μ^A for each neutralino mass.

Table 1: The size of angular windows and upper limits at 90% confidence level on annihilation rates and fluxes of upward-going muons for neutralino annihilation in the Earth's core and the Sun.

	Earth			Sun		
m_χ (GeV)	γ (o)	Γ_A s_{-1}	F_μ $cm^{-2}s^{-1}$	γ (o)	Γ_A s_{-1}	F_μ $cm^{-2}s^{-1}$
12.8	25	$4.8 \cdot 10^{17}$	$3.2 \cdot 10^{-14}$	16	$1.3 \cdot 10^{26}$	$2.4 \cdot 10^{-14}$
32.6	18	$3.6 \cdot 10^{16}$	$2.1 \cdot 10^{-14}$	13	$1.4 \cdot 10^{25}$	$2.1 \cdot 10^{-14}$
82.8	10	$1.5 \cdot 10^{13}$	$9.3 \cdot 10^{-15}$	6.5	$6.6 \cdot 10^{21}$	$1.1 \cdot 10^{-14}$
210.0	7.0	$2.1 \cdot 10^{12}$	$6.2 \cdot 10^{-15}$	4.7	$8.6 \cdot 10^{20}$	$6.5 \cdot 10^{-15}$
535.0	5.0	$3.1 \cdot 10^{11}$	$5.4 \cdot 10^{-15}$	3.6	$1.8 \cdot 10^{20}$	$6.4 \cdot 10^{-15}$
1358.0	4.5	$7.1 \cdot 10^{10}$	$5.2 \cdot 10^{-15}$	3.0	$6.2 \cdot 10^{19}$	$6.4 \cdot 10^{-15}$
3454.0	4.0	$1.6 \cdot 10^{10}$	$5.2 \cdot 10^{-15}$	2.7	$3.4 \cdot 10^{19}$	$6.4 \cdot 10^{-15}$

The obtained upper limits on muon fluxes are comparable with the recent MACRO analysis [15]. Although, at the almost the same statistics of the observed upward through-going events and with the similar energy threshold there is significant deficit in the vertical bins in MACRO experiment.

6 Conclusions

Baksan data don't show any excess of upward-going muons from the direction of the Sun and the Earth's core. We have got the upper limits at the 90% c.l. on annihilation rates of neutralinos pairs inside Earth's core and the Sun and on fluxes of upward through-going muons from it in dependence on neutralino mass. We take note of a significant role of neutral current neutrino interactions in the case of detection of upward going muons induced by very high energy neutrinos of nonatmospheric origin ($\geq 10^6$ GeV) or neutrinos with energy of a few hundred GeV after crossing $\geq 10^{11} g/cm^2$ of matter.

Acknowledgments

O.S. would like to express her deep gratitude to the organizers of the Rencontres de Moriond and Chairman Prof. J.Tran Thanh Van for the invitation and for the financial support by grant; her thanks also to S.Loucatos, T.Hill and A.Nicolaidis for helpful discussions.

References

1. Boliev M.M. et al., Proc. of the first Int. Workshop on Dark Matter in Astro- and Particle Physics, Heidelberg, *World Sci. Publ.* p.711 (1997).
2. Boliev M.M. et al., *Nucl. Phys.* B (Proc. Suppl.) **48**, 83 (1996).
3. Alexeyev E.N. et al., Proc. of the 16th ICRC, Tokyo, v.10, p.276 (1979).
4. Boliev M.M. et al., Proc. of the 3rd Int. Workshop on Neutrino Telescopes, p.235 (1991). Boliev M.M. et al., Proc. of the 24th ICRC, Roma, v.1, p.686 (1995).
5. Boliev M.M. et al., in press *Nucl. Phys.* B (Proc. Suppl.) (1998).
6. Agrawal V., Gaisser T.K., Lipari P., and Stanev T., Preprint hep-ph-9509423 (1995)
7. Morfin J.G. and Tung W.K., *Z. Phys.* C **52**, 13 (1991).
8. Lohmann W. et al., CERN Yellow report 85-03, (1985).
9. Nicolaidis A. and Taramopoulos A., *Phys. Lett.* B **386**, 211 (1996).
10. Martin A.D., Stirling W.J. and Roberts R.G., *Phys. Rev.* D **50**, 6734 (1994).
11. Bugaev E.V., Mikheyev S.P., Suvorova O.V., Proc. of the 24th ICRC, v.1, p.666 (1995).
12. Drees M. and Nojiri M.M., *Phys.Rev.* **D47**, 376 (1993).
13. Ritz S. and Seckel D., *Nucl.Phys.* **B304**, 877 (1988).
14. Mori M. et al., *Phys.Rev.* **D48**, 5505 (1993).
15. Montaruli T. (MACRO Collaboration), Proc.of the 25 ICRC, Durban, v.7, p.185 (1997).