ANGULAR DISTRIBUTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINOS IN ROCK

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At present, measurement of the upgoing muons flux, produced by cosmic ray neutrinos is aiming at:
i) search for neutrino oscillation,
ii) search for extraterrestrial neutrinos from local sources,
iii) search for any hypothetical neutral penetrating radiation different from neutrinos.
In this paper we analyze experimental data of Baksan underground telescope on intensity of upward muons for three years of living time, having in mind mainly neutrino oscillation.

1.EXPERIMENTAL DATA. Baksan neutrino experiment[1,2] is in operation from December 1978. To distinguish upward particles from downward ones time-of-flight method is used. Fig.1 shows distribution of recorded muons as a function of c/v (v-measured velocity of particles and c-velocity of light). Value of ratio c/v>0 correspond to downgoing muons and c/v<0 to upgoing ones. It is seen that time resolution of Baksan underground telescope allows to select upward muons with high reliability.

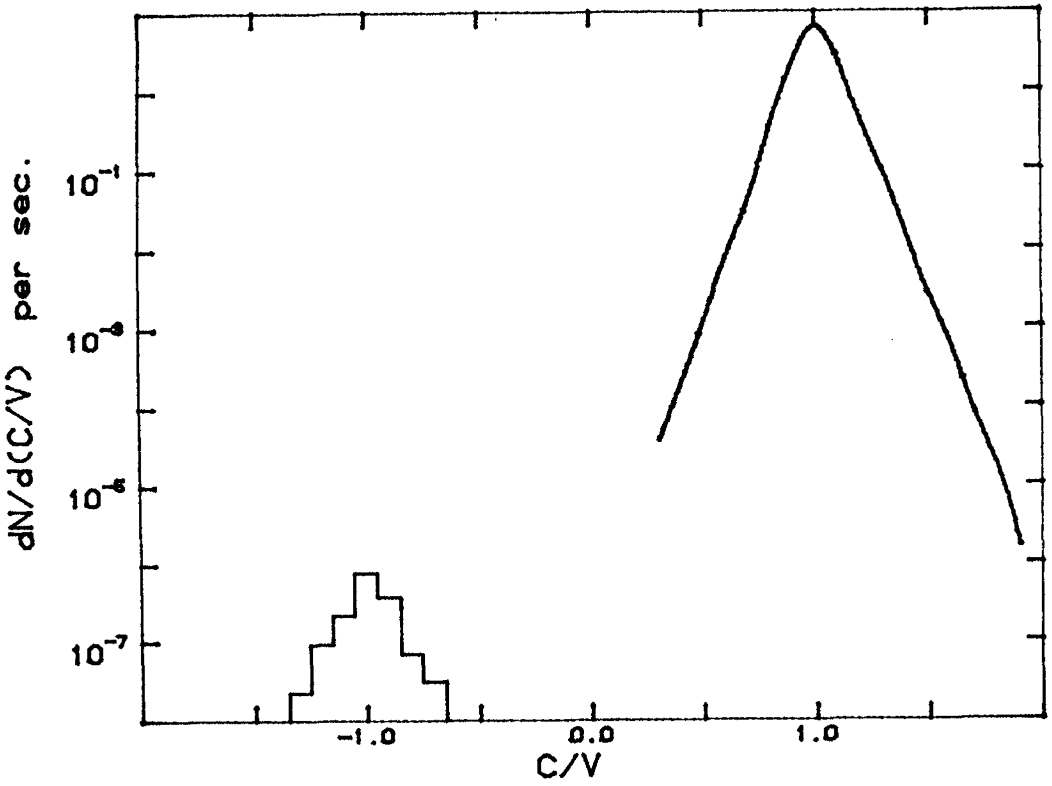

Fig.1 Separation of upgoing and downgoing muon trajectories.

371 events with zenith angles $\theta > 90^{\circ}$ have been recorded. However significant part of them, generaly near horizontal direction, arised due to scattering at large angles of atmospheric muons in surrounding rock. Calculations show that intensity of scattered muons rapidly decreases while zenith angle increases and for $\theta > 110^{\circ}$ is negligible. In zenith angle range $90^{\circ} < \theta < 110^{\circ}$ effect from scattering is very large only for half of total azimuth angle 2π and is negligible for another half. Taking this into account, we selected 150 events as neutrino muons. In 139 events the trajectory of penetrating particle was seen, which crossed $> 600 g/cm^2$ of matter. In 10 events muons stopped inside telescope and there is one cascade without penetrating particle (E 40GeV).

2.RESULTS AND DISCUSSION. Fig.2 shows the ratio of observed intensity to calculated one versus zenith angle. It is seen that there is no discrepancy between observation and prediction for zenith angle range $> 130^{\circ}$, which is most sensitive to neutrino oscillations. Solid curves 1 and 2 were calculated for vacuum neutrino oscillations[3] with maximal mixing of two type of neutrinos ($\sin^2 2\theta = 1$) and for difference of square masses 10^{-2} and 10^{-3} eV^2 correspondingly. Neutrino flux[4] and accelerator data on neutrino cross section was used for calculation. Upper limit $m^2 < 2 \cdot 10^{-3} eV^2$ (90% c. l.) follows from comparison of observed rate of neutrino events with predicted one for zenith angle $\theta > 130^{\circ}$.

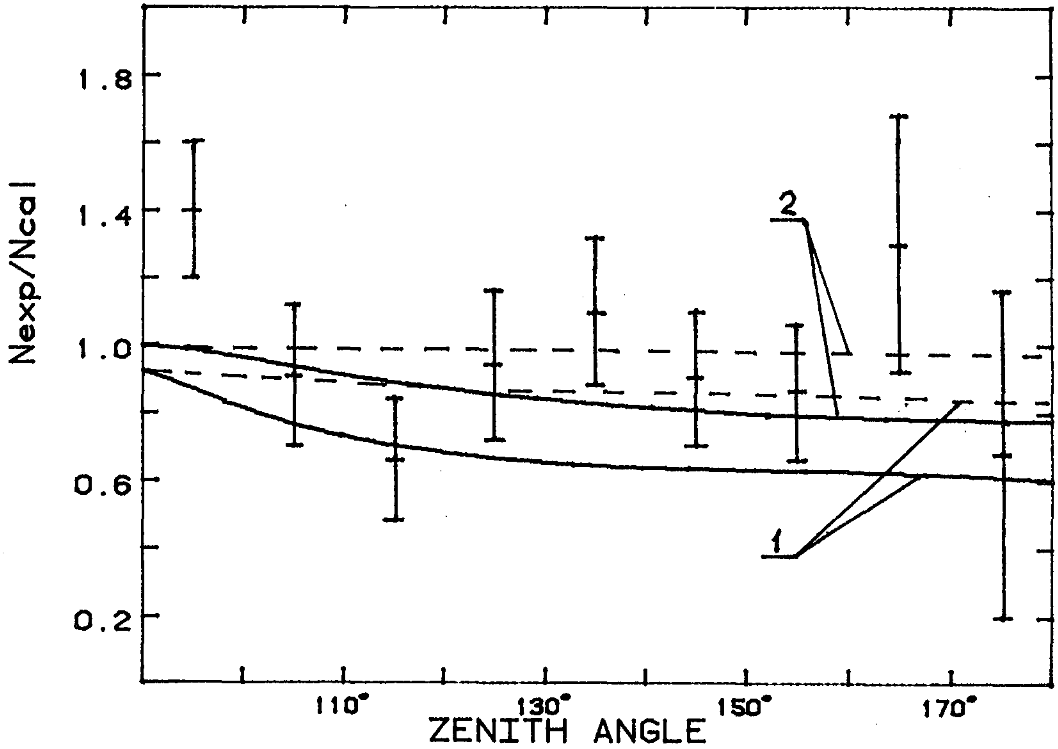

Fig.2 Angular distribution of neutrino induced events.

However, neutrinos pass through a large distance of terrestrial matter before interactions. It was shown[5] that matter can modify vacuum oscillation significantly at distance of the order of the size of the globe. The basis of this phenomena is that index of neutrino refraction in matter can produce an important change of phase. There are two possibilities to apply this idea: i) neutrinos are massive and vacuum oscillations exist; ii) neutrino are massless (vacuum oscillations are impossible).

First consider matter effect on vacuum oscillations[6]. The matter modifies vacuum oscillations because of difference in the amplitudes of elastic forvard scattering of ν_e and ν_μ which is due to charge current ν_e-scattering on electrons. In this case parameters of neutrino oscillations are:

$$\mathrm{Sin}^2 2\theta_m = \frac{\mathrm{Sin}^2 2\theta}{(1-2\cdot L_v/L_o\cdot \mathrm{Cos}2\theta + L_v^2/L_o^2)} \qquad (1)$$

$$L_m = \frac{L_v}{(1-2\cdot L_v/L_o\cdot \mathrm{Cos}2\theta + L_v^2/L_o^2)^{1/2}} \qquad (2)$$

Here $L_v = 4\pi E/\Delta m^2$ is the oscillation length in vacuum and $L_o = 1.77\cdot 10^7 \mathrm{m}/\rho$ is characteristic length for 2π change of phase which depends on matter density (ρ) only. From (1) we see that for maximal mixing ($\mathrm{Sin}^2 2\theta = 1$) of neutrinos in vacuum the parameter $\mathrm{Sin}^2 2\theta_m$ is less than 1 for any values of the oscillation length in vacuum. So, in this case matter effect results in suppression of vacuum oscillations. Dashed curves on Fig.2 were calculated for the same oscillation parameters as solid curves but matter effect was taken in account. One can see that impact of neutrino oscillations on the flux of neutrino induced muons is significantly less in this case. Therefore our limit on Δm^2 for $\nu_\mu - \nu_e$ oscillations changes to $2\cdot 10^{-2} \mathrm{eV}^2$. Note that if oscillations $\nu_\mu - \nu_e$ occur and probability of transitions is suppressed then previous limit on Δm^2 holds.

Oscillations of massless neutrinos. In this case oscillations can arise due to nondiagonal neutral current interactions. In neutral current interactitions ν_μ states can change into ν_e or ν_τ. Probability to observe ν_μ after traversing distance x of constant density is given by

$$P = 1 - \mathrm{Sin}^2 2\theta \cdot \mathrm{Sin}^2(\pi \cdot \rho \cdot x/L)$$

where in case of $\nu_\mu - \nu_\tau$ oscillation $\mathrm{Sin}^2 2\theta = 1$, $L = 1.77\cdot 10^7 \mathrm{m}/(g_p+g_e+g_n)\mathrm{Sin}\alpha$; and for $\nu_\mu - \nu_e$

$$\mathrm{Sin}^2 2\theta = \frac{4\cdot \mathrm{Sin}^2\alpha (g_p+g_e+g_n)^2}{1+4\cdot \mathrm{Sin}^2\alpha (g_p+g_e+g_n)^2}$$

and

$$L = \frac{1.77\cdot 10^7 \mathrm{m}}{\sqrt{1+4\cdot \mathrm{Sin}^2\alpha (g_p+g_e+g_n)^2}},$$

$\mathrm{Sin}\alpha$ is the contribution of nondiagonal neutral current in interactions. In usual theories of neutral current interactions this parameter is zero. However it is impossible to exclude $\mathrm{Sin}\alpha \neq 0$ because of invisibility of final states of neutrinos. In standard model of electroweak interactions $|g_p+g_e+g_n| = 0.5$. Contrary to the vacuum oscillations, this kind of oscillations do not depend on energy of neutrinos. These oscillations, if they occur, can change strongly angular dependence of cosmic ray neutrinos traversing the Earth. On Fig.3 curves calculated for Sinα=0.1, 0.2 and 0.3 are shown. Comparison of observed angular distribution of neutrino events with calculated ones for this type of oscillations permits to set upper limit on Sinα as 0.2 (90%c.l.)

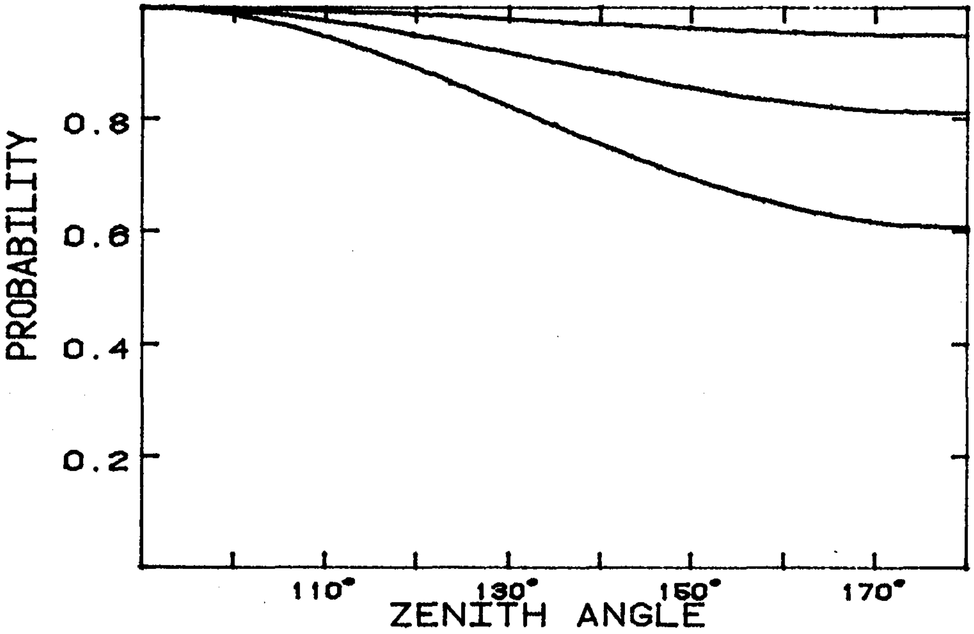

Fig 3. The probabilities of remaining muon neutrinos after traversing the Earth.

3.CONCLUSION. In this paper we assumed maximal mixing of two types of neutrinos. Obviously, if mixing decreases effect of neutrino oscillations decreases too. So there is no hope to see oscillations with small mixing using cosmic ray neutrinos. Moreover, matter effect reduces by an order of magnitude the sensitivity of underground neutrino experiments to vacuum neutrino oscillations. However, this kind of experiments is, apparently, a single possibility to search another type of oscillation arising due to nondiagonal neutral current.

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