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Abstract

The background produced by isolated neutrons in Cherenkov detectors studying the atmospheric neutrinos is discussed. The neutrons are generated in nuclear showers initiated by muons in the rock surrounding the detectors. It is shown that the taking into account of the detection of π^0 events from reactions of $nA \rightarrow \pi^0 X$, which look like the ν_e detection, results in the observed $I(\nu_\mu)/I(\nu_e)$ ratio being close to the expected one for the energy range of 0,2-5 Gev.

During the last few years the neutrino experiments performed with Cherenkov detectors [1-3] have focused attention on the low value of the obtained ratio of μ -like events to e -like compared to the expected one. The value of $R = \frac{(\mu/e)_{\text{data}}}{(\mu/e)_{\text{MC}}}$ increases with the depth [4-6], becoming 1 for the depth of $H > 4000$ m.w.e. This gives a basis to think that there is a source of a background decreasing with the depth in the experiments detecting atmospheric electron neutrinos. As the detectors have large anticoincidence shields, only neutral particles, namely neutrons, could be a source of the background.

Our previous studies have dealt both with the dependence of the muon produced neutron component on depth and with the measurement of the flux and the energy spectrum of isolated neutrons (coming from nuclear showers, generated by muons, individually) in the kinetic energy range of 18-92 Mev at the depth of 570 m.w.e. [7-13]. Monte Carlo simulations performed in these references and by other authors [14] show that energy distributions of nuclear-active particles with energies of 0.02-5 Gev outside the core of the nuclear shower and especially in the direction perpendicular to the shower axis do not depend practically on the shower energy for $E_{\text{sh}} > 20$ Gev. Calculated energy spectra of neutrons and $\pi^\pm$ behind 250g cm^{-2} absorber are seen in figure 1. The energy spectrum of the neutrons produced in the showers has a shape of $dT_n/T_n (T_n \leq 200 \text{ Mev})$ and $dT_n/T_n^2 (T_n > 200 \text{ Mev})$. Here T_n is the kinetic energy of the particles. It should be noted that the shapes of the spectra of Fig. 1 depend very weakly on neutron incidence angle and on the absorber thickness from 100 to 500g cm^{-2} [14].

The flux densities of neutrons entering through the lateral surface of the detector at an arbitrary depth can be calculated rather accurately. For this we should:

1. use the neutron flux density with energies of 18-92 Mev obtained at the depth of 570 m.w.e., $N_n(570)$, [9,11];
2. take into account the depth-intensity curve for muons, $I_\mu(H)$;
3. take into account the dependence of N_n on a depth of H and on the average muon energy at the depth, $\bar{E}_\mu(H)$, [7, 8, 10, 12, 13];
4. have the spectra of Fig.1 [14].

Thus we find,

$$N_n(H) = \frac{I_\mu(H)}{I_\mu(570)} \frac{\bar{E}_\mu^{-0,75}(H)}{\bar{E}_\mu^{-0,75}(570)} N_n(570).$$

The results of the calculation of the isolated neutron flux densities with energies of $T_n > 200 \text{ MeV}$, expressed as the number of neutrons per 1 m^2 of the lateral surface area per year for depths of 1570, 2700, 3300, 4000 and 5300 m.w.e. are shown in table I.

Table I

H (m.w.e.)	1570	2700	3300	4000	5300
$I_n(\text{n/yr per } 1\text{m}^2)$	230	65	25	7	3

The energy spectrum of $\pi^\pm$ from Fig. 1 is very close to the spectrum of events in the detector due to the fact that the average pions multiplicity for $T_n < 1 \text{ GeV}$ and for light nuclei is $\bar{N}_\pi < 1$ [15]. Many of the produced $\pi^\pm$ undergo nuclear interactions with ^{16}O nuclei and lose their energies down below the threshold of Cherenkov light. The estimates show that for $200 \text{ MeV} < T_n < 1,5 \text{ GeV}$ no more than 8-10% of $\pi^\pm$ could be seen as μ -like events, their visible energy being less than 500 MeV. π^0 , on the contrary, decaying into 2γ , could imitate e-like events in more than 30% of the events. The percentage of imitation increases with π^0 energy (the visible energy) because the minimal angle between the photons decreases with π^0 energy $\left(\sin \frac{\Psi_{\min}}{2} = \frac{m_{\pi^0}}{E_{\pi^0}} \right)$. In the case of $\pi^\pm$ the probability

of the μ -like event imitation with the visible energy higher than 1 GeV is insignificant. So, we can conclude that $nA \rightarrow \pi^0 X$ reactions are the additional channel of the e-like event production and the background for the atmospheric ν_e detection up to the energy of $\sim 5 \text{ GeV}$.

Considering the lateral distribution of the false events we should keep in mind that angular distributions of pions with $T_\pi < 1 \text{ GeV}$ produced in the (nA)-reactions with $T_\pi/T_n < 0,5$ are very close to isotropic ones [15,16]. Due to this reason a significant part of γ 's generated by π^0 decay near the boundary of a fiducial volume gives the signal in an anticoincidence system. Fully contained events are those originated in the central part of the detector at the distance greater than 1,5 m from the boundary of the fiducial volume, and those originated near the boundary with γ 's flying into the detector center.

Table 2 shows the result of the estimate of background events in the fiducial volumes, the data from a 7,7 kton yr exposure of the IMB-3 detector, and those from a 6,18 kton yr exposure for $E < 1,33 \text{ GeV}$ and a 8,2 kton yr exposure for $E < 1,33 \text{ GeV}$ at Kamiokande. The experimental and calculated ratios of μ -like events to e-like ones are also given with and without background subtraction.

Table 2

	DETECTOR					
	IMB		Kamiokande (E<1,33 GeV)		Kamiokande (E>1,33 GeV)	
	experim.	backgr.	experim.	backgr.	experim.	backgr.
Single ring events:						
Total	610	~250	389	~54	195	
showering (e-like)	378	210	191	46	98	~40
nonshowering (μ -like)	232	<40	198	<8	31	
(μ/e)data:						
without taking into account the background	0,61		1,04		0,32	
taking into account the background	~1,1		~1,4		0,53	
(μ/e) _{MC} [1-3]	1,1		1,6		0,57	

These estimates have the accuracy within $(30 \pm 40)\%$, but they indicate that the background for the e-like event detection is appreciable and, the taking of it into account, results in the value of $R = \frac{(\mu / e)_{\text{data}}}{(\mu / e)_{\text{MC}}}$ close to 1.

The angular distribution of background events with $E > 1,3$ GeV should be very similar to the angular distribution of neutrons incident on the detector [15]. As the probability for isolated neutrons to come into the fiducial volume near the vertical is very small, the background of higher energy should be absent in that direction.

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Fig. 1 - Energy spectra of neutrons and $\pi^{\pm}$ behind shielding of 250g cm^{-2} thickness, T -the kinetic energy.