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Neutral-to-charged current events ratio in atmospheric neutrinos and neutrino oscillations

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Abstract

The atmospheric neutrinos produce isolated neutral pions (π^0-*events*) mainly in the neutral current interactions. We propose to study the ratios involving π^0-*events* and the events induced mainly by the charged currents. This minimizes uncertainties related to the original neutrino fluxes, and in certain cases, also to the cross-sections. Experimental study of these ratios will allow one to check the oscillation solution of the atmospheric neutrino problem and to identify the channel of oscillations. Illustrative analysis of existing data is presented.

1 Introduction

Recent results from the Super-Kamiokande [1] and the SOUDAN 2 experiments [2] have confirmed the existence of the atmospheric neutrino problem [3, 4]. At the moment, it seems that neutrino oscillations are the only satisfactory solution of the problem [5, 6, 7]. Various possibilities of description of the data still exist depending on channel of oscillations. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillations give the most favorable solution [5, 6, 7]. The $\nu_\mu \leftrightarrow \nu_{\rm e}$ channel is restricted by the reactor data [8, 9, 10], especially by recent results from CHOOZ experiment [10] and it seems strongly disfavored by recent Super-Kamiokande results on the zenith angle dependence of the e-like and μ-like events. At low energies the oscillations to sterile neutrinos, $\nu_\mu \leftrightarrow \nu_{\rm s}$, [11, 12] lead to results which are similar to those in the $\nu_\mu \leftrightarrow \nu_\tau$ channel. The $\nu_\mu \leftrightarrow \nu_{\rm s}$ channel is of interest since it gives an additional freedom in reconciliation of different neutrino anomalies. Moreover, it allows one to keep usual hierarchical mass structure and small mixings for active neutrinos, while solving the atmospheric neutrino problem [13, 14]. Combined effect of different channels of oscillations is also possible [16].

Still a number of questions exists concerning the interpretation of the atmospheric neutrino data. They are related to consistency of the experimental results and to possible systematic errors. Therefore, the crucial task is to find new independent criteria for cross-checking the oscillation hypothesis, as well as for discrimination of different channels of oscillations. Recently several new attempts have been made along with this line [17].

Up to now studies of the atmospheric neutrinos were restricted, mainly, by events induced by the charged current (CC) interactions (e-like and μ-like events) which compose the bulk of the data. However, new high statistics experiments: the Super-Kamiokande, and later ICARUS, will allow one to get important information from samples of more rare events.

In this paper we will consider the possibility to use events induced by the *neutral currents*. The ratio of the neutral and charged currents events (NC/CC) can give an important information on the neutrino flavor oscillations. In the next Section we will consider properties of the neutrino fluxes relevant for the NC and CC reactions. In experiment one observes events of different type which do not correspond to certain NC or CC reactions. In this connection we identify (Sect. 3) the observables which represent closely the ratio NC/CC and study their sensitivity to different channels of oscilla-

tions. In Sect. 4 we confront predictions with the available Siper-Kamiokande data.

2 Flavour content of atmospheric neutrinos

In what follows we will consider the (relative) fluxes, $F_{\rm e}$, F_μ, and F_τ of the $\nu_{\rm e}$, ν_μ, and ν_τ neutrinos (and corresponding antineutrinos) with energies around 1 GeV that induce the "fully contained" events in the underground detectors.

The neutral current effects are determined by the total flux of the active neutrinos in the detector: $F_a \equiv F_{\rm e} + F_\mu + F_\tau$. For the ratio of this flux and the flux in absence of oscillations, $F_a^0 \equiv F_{\rm e}^0 + F_\mu^0$ (the predicted ν_τ-flux is negligibly small), we can write

$$\frac{F_a}{F_a^0} = \begin{cases} 1 & \nu_\mu \leftrightarrow \nu_{\rm e} \ \text{ and } \ \nu_\mu \leftrightarrow \nu_\tau \\ \dfrac{1 + r\,P}{1 + r} & \nu_\mu \leftrightarrow \nu_{\rm s} \end{cases} , \qquad (1)$$

where $r \equiv F_\mu^0/F_{\rm e}^0 \approx 2.1$ (in the energy range $E_\nu \sim 1$ GeV), and $P \equiv P(\nu_\mu \leftrightarrow \nu_\mu) \leq 1$ is the ν_μ survival probability averaged over the appropriate energy range. The ratio F_a/F_a^0 equals one in the no-oscillation case as well as in the case of flavor oscillations. It is smaller than one, if active neutrinos oscillate into sterile neutrinos, $\nu_{\rm e} \leftrightarrow \nu_{\rm s}$.

The rates of the charged current events with appearance of the electrons or muons determine $\nu_{\rm e}$ or ν_μ fluxes separately[1]. The ratios of fluxes with and without oscillations equal:

$$\frac{F_{\rm e}}{F_{\rm e}^0} = \begin{cases} 1 & \nu_\mu \leftrightarrow \nu_\tau \ \text{ and } \ \nu_\mu \leftrightarrow \nu_{\rm s} \\ r - (r-1)\ P & \nu_\mu \leftrightarrow \nu_{\rm e} \end{cases} , \qquad (2)$$

and

$$\frac{F_\mu}{F_\mu^0} = \begin{cases} P & \nu_\mu \leftrightarrow \nu_\tau \ \text{ and } \ \nu_\mu \leftrightarrow \nu_{\rm s} \\ r^{-1} - (r^{-1}-1)\ P & \nu_\mu \leftrightarrow \nu_{\rm e} \end{cases} . \qquad (3)$$

[1]The τ lepton production by the oscillation-induced ν_τ is strongly suppressed because of the high energy threshold E_τ^{th}=3.4 GeV.

To avoid uncertainties related to the absolute normalization of theoretical fluxes let us introduce the double ratio $\mathcal{R}_{\nu/\mathrm{e}}$:

$$\mathcal{R}_{\nu/\mathrm{e}} \equiv \frac{(F_\mathrm{e} + F_\mu + F_\tau)/\,(F_\mathrm{e}^0 + F_\mu^0)}{F_\mathrm{e}\,/\,F_\mathrm{e}^0} \tag{4}$$

that compares the flux of active neutrinos with the flux of electron neutrinos at the detector normalized on the same ratio of fluxes without oscillations. Obviously, $\mathcal{R}_{\nu/\mathrm{e}} = 1$ in the absence of oscillations. We can rewrite the double ratio as

$$\mathcal{R}_{\nu/\mathrm{e}} = \frac{1 + r \cdot \mathcal{R}_{\mu/\mathrm{e}} + F_\tau/F_\mathrm{e}}{1 + r}, \tag{5}$$

where

$$\mathcal{R}_{\mu/\mathrm{e}} \equiv (F_\mu)/F_\mathrm{e})\,/\,(F_\mu^0/F_\mathrm{e}^0)$$

is the double ratio for the muon and electron neutrino fluxes. Experiment gives the double ratio of the μ-like and the e-like events

$$R_{\mu/\mathrm{e}} = (\mu/\mathrm{e})_{data}\,/\,(\mu/\mathrm{e})_{MC} = 0.61 \pm 0.05$$

instead of the expected value 1 which, as is known, composes the atmospheric neutrino problem. From this, up to small corrections due to misidentification of events, we can take $\mathcal{R}_{\mu/\mathrm{e}} \approx R_{\mu/\mathrm{e}} \approx 0.6$.

The double ratio $\mathcal{R}_{\nu/\mathrm{e}}$ (4) allows one to trace the effect of oscillations on the NC/CC ratios. Notice that once $\mathcal{R}_{\mu/\mathrm{e}}$ is fixed by experiment, the ratio $\mathcal{R}_{\nu/\mathrm{e}}$ depends on F_τ/F_e only. In particular, the minimal value of $\mathcal{R}_{\nu/\mathrm{e}}$ is attained for $F_\tau = 0$. The ratio $\mathcal{R}_{\nu/\mathrm{e}}$ increases with the flux of tau neutrinos in the detector (if F_e does not change). Using the definition of the $\mathcal{R}_{\nu/\mathrm{e}}$ (4) and assuming $F_a \leq F_a^0$, we get the inequality $\mathcal{R}_{\nu/\mathrm{e}} \leq F_\mathrm{e}^0/F_\mathrm{e}$. In turn, the ratio $F_\mathrm{e}^0/F_\mathrm{e}$ has at least 20% theoretical uncertainties, and its values smaller than unity (but compatible with unity) are experimentally preferred. This leads to the inequality $\mathcal{R}_{\nu/\mathrm{e}} \lesssim 1$.

Let us consider the influence of oscillations which give a solution of the atmospheric neutrino problem (that is, reproduce $\mathcal{R}_{\mu/\mathrm{e}} = 0.6$) on the double ratio $\mathcal{R}_{\nu/\mathrm{e}}$. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillations imply that $F_\mathrm{e} = F_\mathrm{e}^0$, and the total flux of active neutrinos is unaffected; therefore we have $\mathcal{R}_{\nu/\mathrm{e}} = 1$.

In the case of the $\nu_\mu \leftrightarrow \nu_\mathrm{e}$ and $\nu_\mu \leftrightarrow \nu_\mathrm{s}$ oscillation solutions no ν_τ-flux is produced, and according to (5) we get

$$\mathcal{R}_{\nu/\mathrm{e}} = \frac{1 + r \cdot \mathcal{R}_{\mu/\mathrm{e}}}{1 + r} = 0.73. \tag{6}$$

That is, $\mathcal{R}_{\nu/\mathrm{e}}$ reaches its minimal value. Let us underline that $\nu_\mu \leftrightarrow \nu_\mathrm{e}$ and $\nu_\mu \leftrightarrow \nu_\mathrm{s}$ oscillations as solutions of the atmospheric problem lead to the same value of ratio $\mathcal{R}_{\nu/\mathrm{e}}$, although they modify neutral current effects differently.

In the general case, when both $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_\mathrm{s}$ channels contribute to the deficit of the ν_μ-flux simultaneously, the ratio $\mathcal{R}_{\nu/\mathrm{e}}$ can take any value in the interval

$$0.73 \leq \mathcal{R}_{\nu/\mathrm{e}} \leq 1. \tag{7}$$

Here the right (left) value would signal the presence (absence) of an induced flux of tau neutrinos (for sufficiently small F_e/F_τ, the ratio in formula (5) can be even bigger than one, although this possibility is disfavored experimentally, as discussed above.) From (7) we conclude that better than 10% accuracy in measurements of $\mathcal{R}_{\nu/\mathrm{e}}$ is needed to disentangle different solutions at 3σ level.

The quantities $\mathcal{R}_{\mu/\mathrm{e}}$ and $\mathcal{R}_{\nu/\mathrm{e}}$ are (double) ratios of fluxes. In real experimental situations one deals with the numbers of events of certain type. For instance, in the water Cherenkov detectors (the IMB, Kamiokande and Super-Kamiokande) one observes μ-like and e-like events as the sharp and diffuse single-rings respectively. In a calorimetric detector, like SOUDAN, μ-like and e-like events are identified as tracks and showers *etc.*. Moreover, a number of criteria is also implemented to select samples of events, like suitable cuts on the momenta and absence of hits in the cosmic muons veto shield. Therefore, in calculations of numbers of events, the fluxes are folded with cross-sections, efficiencies of detection, misidentification functions *etc.*. As a result the observed events of different type do not correspond to certain underlying reactions. In particular, both the charged and neutral current reactions can contribute to the same sample of events. This makes the analysis of the NC/CC ratio more complicated. In next Sections we will identify the samples of events which represent the ratio NC/CC closely.

Notice that in principle, it should be possible for the experimental collaborations to perform the unfolding of the neutrino fluxes. Such a type of analysis was performed by the Fréjus collaboration [18].

3 Neutral current induced events

Let us discuss the possibility to detect the neutral current induced events.

The simplest option would be a study of the elastic scattering of the neutrino:

$$\nu_\ell \; N \to \nu_\ell \; N, \tag{8}$$

where $N = n$, p and $\ell =$e, μ, τ. A recoil proton can be used to track this reaction. In water Cherenkov detectors, however, the majority of the recoil protons originated from the interactions of atmospheric neutrinos is below the threshold for Cherenkov radiation. Calorimetric detectors do not have this shortcoming, but here the problem is in small statistics. In fact, only 26 *proton events* (isolated, highly-ionizing short tracks), with no coincident hits in the veto shield, had been collected at SOUDAN 2 during 2.83 Kton-years of exposure [19] [2]. As follows from the simulations [19], the hypothesis that the *proton events* are due to neutral current reaction, and there is no oscillation effect is in agreement with data. However, small statistics does not allow one to discriminate oscillation scenarios.

At present, the most promising possibility to track the neutral current effects is to study the reaction with production of one neutral pion:

$$\nu_\ell \; N \to \nu_\ell \; N \; \pi^0. \tag{9}$$

It can be identified as appearance of the isolated π^0 without any accompanying signal (unless the recoil nucleon is visible). The decay $\pi^0 \to \gamma\gamma$ gives two electromagnetic cascades which can be detected as two diffuse rings in the water Cherenkov detectors or two showers in the calorimeter detectors.

The number (the rate of production) of isolated π^0 can be compared *e.g.* with the number of the e-like (or μ-like) events produced by charged currents: $R_{\pi^0/\mathrm{e}} \equiv (\pi^0/\text{ e-like})_{data}/(\pi^0/\text{ e-like})_{MC}$, that minimizes the theoretical uncertainties in the neutrino fluxes. Here $(\pi^0/\text{ e-like})_{MC}$ is the predicted ratio. In ideal situation $R_{\pi^0/\mathrm{e}}$ represents the ratio of the fluxes discussed in previous Section, so that $R_{\pi^0/\mathrm{e}} \sim \mathcal{R}_{\nu/\mathrm{e}}$. In reality one can not exactly identify a sample of events which corresponds to reaction (9). Let us consider this problem for water Cherenkov detectors.

The reaction (9) can be detected as the "π^0-*event*" which is determined in the following way:

[2] The evaluation of the background is essential, and requires the study of the depth distribution of the events. If we estimate the background as a 10% fraction of *proton events* with shield hits, as for analysis of the *track* and *shower* data samples, the neutral current signal reduces to just 10 events approximatively.

(1) Two isolated electromagnetic cascades should be detected as two diffuse rings. At high energies the two rings tend to merge, therefore an upper cut on the total momentum permits to optimize the rings separation. In particular the Super-Kamiokande collaboration implements the momentum cut $p_\pi < 400$ MeV.

(2) The invariant mass of the two identified photons should be in certain interval around the mass of the pion, say, in the interval between 100 and 200 MeV.

To study the oscillation effects one should find separately the *partial* contributions (in absence of oscillations) to the total rates of events of different type from the neutral current reactions: N^{NC}, from the charged current reactions induced by $\nu_{\rm e}$: $N^{CC{\rm e}}$, and from the charged current reactions induced by ν_μ: $N^{CC\mu}$. In presence of oscillations these contributions will be modified by the flux suppression factors determined in (1, 2, 3).

The reaction (9) gives the main contribution to the π^0-*events* sample. However, contributions from other reactions are also relevant. Let us consider them in order.

The reaction of multi-pion production by the neutral currents: $\overset{(-)}{\nu}_\ell \; N \to \overset{(-)}{\nu}_\ell \; n\,\pi \; N$ gives π^0-*event* if only one π^0 is detected, whereas all charged pions are below the Cherenkov threshold, and moreover, they do not produce secondaries which lead to an observable signal. The contribution from these reactions is roughly three times smaller than that from (9). Also the neutral current reaction $\overset{(-)}{\nu}_\ell \; N \to \; \overset{(-)}{\nu}_\ell \; \pi^\pm N'$ leads to π^0-*event* if the $\pi^\pm$ undergoes the charge exchange. This contribution is, however, small. Let us denote by $N^{NC}_{\pi^0}$ the sum of all contributions from the NC reactions.

There is a substantial contribution to π^0-*event* sample from the CC reactions. In particular,

$$\overset{(-)}{\nu}_\mu \; N \to \mu^\mp \, \pi^0 N', \tag{10}$$

leads to the π^0-*event* if the muon energy is below the Cherenkov threshold, and subsequent muon decay does not produce an observable signal. Smaller contribution comes from reaction $\overset{(-)}{\nu}_\mu \; N \; \to \; \mu^\mp \; \pi^\pm N$, where the pion exchanges the charge in subsequent nuclear interactions, and the muon is not detected. Small contribution comes from the CC multi-pion reaction. Let us denote the sum of all ν_μ CC contributions by $N^{CC\mu}_{\pi^0}$.

There are similar CC-reactions induced by $\nu_{\rm e}$. Due to low Cherenkov threshold, the probability for the electron to be undetected is smaller and

the contribution from these reactions to π^0-*event* sample, $N_{\pi^0}^{CC\mathrm{e}}$, is also small: $N_{\pi^0}^{CC\mathrm{e}} \ll N_{\pi^0}^{CC\mu}$.

The total rate of the π^0-*events* in absence of oscillations equals

$$N_{\pi^0}^0 = N_{\pi^0}^{NC} + N_{\pi^0}^{CC\mu} + N_{\pi^0}^{CC\mathrm{e}}$$

and the relative partial contributions can be estimated as

$$N_{\pi^0}^{NC} : N_{\pi^0}^{CC\mu} : N_{\pi^0}^{CC\mathrm{e}} \approx 0.80 : 0.18 : 0.02. \tag{11}$$

Notice that this result depends on features of specific experiment and event selection criteria. The numbers in (11) have been obtained using the Table 5 from Kajita review [20] and correspond roughly to the Kamiokande sub-GeV sample. We estimate their uncertainties as $N_{\pi^0}^{CC\mu} \sim 0.18 \pm 0.05$ and $N_{\pi^0}^{CC\mathrm{e}} \sim 0.02 \pm 0.01$. Similar results are expected for the Super-Kamiokande. In what follows we will use (11) for illustrative purpose, mainly, to estimate the sensitivity of the method. Detailed comparison with experimental data requires recalculation of these numbers by experimental collaborations.

Let us now consider the influence of different modes of oscillations on the rate of the π^0-*events*. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillations suppress $\nu_\mu CC$ contribution only:

$$N_{\pi^0} = N_{\pi^0}^{NC} + N_{\pi^0}^{CC\mathrm{e}} + P \cdot N_{\pi^0}^{CC\mu}, \tag{12}$$

and the ratio of the rates with and without oscillations can be written as

$$N_{\pi^0}/N_{\pi^0}^0 = 1 - (1-P) \cdot N_{\pi^0}^{CC\mu}/N_{\pi^0}^0. \tag{13}$$

Since $N_{\pi^0}^{CC\mu}$ does not exceed 20 - 25 %, one expects the decrease of the π^0-*event* rate due to oscillations by 10 % at most.

For $\nu_\mu \leftrightarrow \nu_\mathrm{e}$ oscillations we get according to (1, 2, 3)

$$N_{\pi^0} = N_{\pi^0}^{NC} + (rP - (r-1)P) \cdot N_{\pi^0}^{CC\mathrm{e}} + (r^{-1} - (r^{-1}-1)P) \cdot N_{\pi^0}^{CC\mu}. \tag{14}$$

So the oscillations suppress the rate of π^0-*events* at most by 5 %.

In contrast, for the oscillations to the sterile neutrinos $\nu_\mu \leftrightarrow \nu_\mathrm{s}$ we have

$$N_{\pi^0} = \frac{1+rP}{r+1} \cdot N_{\pi^0}^{NC} + N_{\pi^0}^{CC\mathrm{e}} + P \cdot N_{\pi^0}^{CC\mu}. \tag{15}$$

and the suppression is larger than 30 %.

To avoid the uncertainties related to the absolute values of the neutrino fluxes we will study the double ratios involving the π^0-*events* and the e-like (or μ-like) events:

$$R_{\pi^0/\mathrm{e}} \equiv \frac{N_{\pi^0}/N^0_{\pi^0}}{N_{\mathrm{e}}/N^0_{\mathrm{e}}}. \tag{16}$$

The rate of the e-like events without oscillations equals

$$N^0_{\mathrm{e}} = N^{CC\mathrm{e}}_{\mathrm{e}} + N^{NC}_{\mathrm{e}} + N^{CC\mu}_{\mathrm{e}}, \tag{17}$$

where $N^{CC\mathrm{e}}_{\mathrm{e}}$, N^{NC}_{e}, and $N^{CC\mu}_{\mathrm{e}}$ are the partial contributions from the $\nu_{\mathrm{e}}CC$, NC and $\nu_\mu CC$ reactions correspondingly. The relative contributions at the Super-Kamiokande in the sub-GeV events sample are:

$$N^{CC\mathrm{e}}_{\mathrm{e}} : N^{NC}_{\mathrm{e}} : N^{CC\mu}_{\mathrm{e}} \approx 0.90 : 0.08 : 0.02. \tag{18}$$

The comparison of different Monte Carlo simulations allow us to estimate possible spread of predictions: $N^{NC}_{\mathrm{e}} = 0.08 \pm 0.03$ and $N^{CC\mu}_{\mathrm{e}} = 0.02 \pm 0.01$.

In presence of oscillations the contributions in (17) are modified by the flux suppression factors (1, 2, 3). In particular, for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations we get

$$N_{\mathrm{e}}/N^0_{\mathrm{e}} = 1 - (1 - P) \cdot N^{CC\mu}_{\mathrm{e}}/N^0_{\mathrm{e}}. \tag{19}$$

Using Eqs. (13) and (19) we find $R_{\pi^0/\mathrm{e}}$. Similarly one can find the double ratios for other modes of oscillations.

In Fig. 1 we show the predictions for different modes of oscillations in the $R_{\pi^0/\mathrm{e}} - R_{\mu/\mathrm{e}}$ plot. We have used the above formulas with relative contributions according (11, 18). Notice that the curves for $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{\mathrm{s}}$ differ, whereas the curves for $\nu_\mu \leftrightarrow \nu_{\mathrm{s}}$ and $\nu_\mu \leftrightarrow \nu_{\mathrm{e}}$ oscillations coincide in this plot. Indeed, as follows from discussion in Sect. 2, the value of $R_{\pi^0/\mathrm{e}}$ changes only if there is a ν_τ component in the atmospheric neutrino flux. This statement is not changed even if efficiencies of detection and misidentification of the samples are taken into account. Clearly, it will be possible to disentangle the case of $\nu_\mu - \nu_\tau$ oscillations from $\nu_\mu - \nu_{\mathrm{s}}$ using these ratios, although the difference is smaller than in the ideal case of fluxes. For $R_{\mu/\mathrm{e}} = 0.6$ we get from the Figure $R_{\pi^0/\mathrm{e}} = 0.93$ and $R_{\pi^0/\mathrm{e}} = 0.72$ for $\nu_\mu - \nu_\tau$ and $\nu_\mu - \nu_{\mathrm{s}}$ oscillations correspondingly. The ratio of the values of $R_{\pi^0/\mathrm{e}}$ in the two cases is 0.77, to be compared with 0.73 for $\mathcal{R}_{\nu/\mathrm{e}}$ (6).

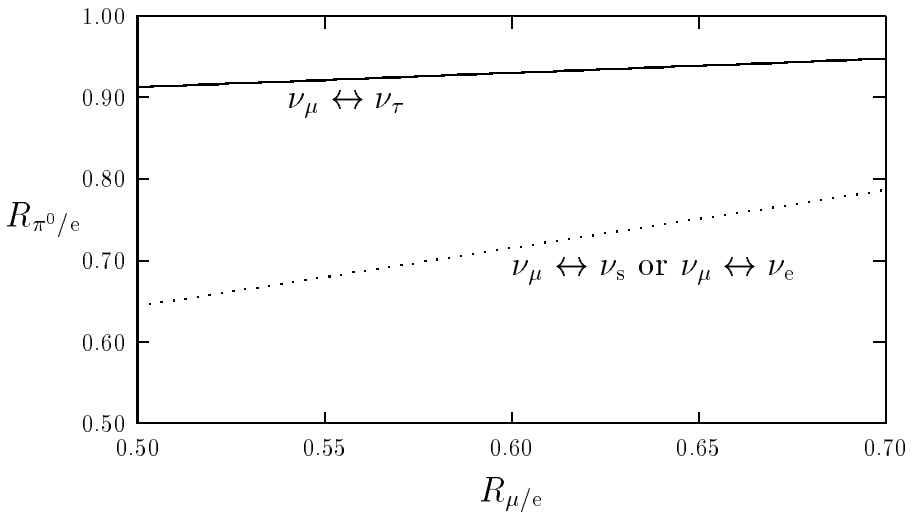

Figure 1: Theoretical dependence on $R_{\mu/\mathrm{e}}$ of the NC/CC events ratio $R_{\pi^0/\mathrm{e}}$, under different hypotheses of oscillation.

Alternatively, one can consider the double ratio $R_{\pi^0/\mathrm{m.r.}}$ in which the π^0-*events* are compared with the multi-ring events. "Inclusive" data subsets are numerically rich, but their interpretation is generally less simple.

Other samples of data can be used in tracking detectors with better identification of events (SOUDAN or ICARUS). Let us consider the samples of two prong events: with two showers (SS-events), with two μ-like tracks (MM-events), and with one shower and one μ-like track (SM-events). These events are generated mainly by one pion production reactions. SS events are due to NC reaction (9), SM and MM events are due to the charged current reactions:

$$\overset{(-)}{\nu}_\ell \, N \to \ell^\mp \, N \, \pi^\pm, \qquad \ell = \mathrm{e}, \, \mu. \tag{20}$$

A partial cancellation of the uncertainties in the cross-sections takes place in the double ratio:

$$R_{\pi^0/SM} \equiv \frac{(\pi^0 \,/\, SM)_{data}}{(\pi^0 \,/\, SM)_{MC}} \tag{21}$$

and in the analogous ratio $R_{\pi^0/MM}$. These quantities can be alternatively used to estimate the neutral-to-charged-currents ratio. Moreover, some uncertainties related to nuclear effects are cancelled in this ratios at low energies, where

Δ production mechanism dominates. Such a sample can be selected by imposing upper bound on the total visible energy. A diagnostic of this method is the study of the double ratio $R_{MM/SM} = (MM/SM)_{data}/(MM/SM)_{MC}$, that in the ideal case should correspond to the usual double ratio $R_{\mu/\mathrm{e}}$.

We summarize the relevant reactions, the topology of the corresponding events and the rates in the Table 1. The rates were computed for neutrino-

Reaction	Type of event	Rate
$\overset{(-)}{\nu}_{\mu}\ N \to \mu^{\mp}\ \pi^{\pm}\ N$	MM	1.00
$\overset{(-)}{\nu}_{\mathrm{e}}\ N \to \mathrm{e}^{\mp}\ \pi^{\pm}\ N$	SM	0.43
$\overset{(-)}{\nu}\ N \to\ \overset{(-)}{\nu}\ \pi^{0}\ N$	π^0-$events$	0.27
$\overset{(-)}{\nu}\ N \to\ \overset{(-)}{\nu}\ \pi^{+}\ \pi^{-}\ N$	MM	0.09
$\overset{(-)}{\nu}_{\mu}\ N \to \mu^{\mp}\ \pi^{0}\ N'$	MSY	0.28
$\overset{(-)}{\nu}_{\mathrm{e}}\ N \to \mathrm{e}^{\mp}\ \pi^{0}\ N$	SSY	0.12
$\overset{(-)}{\nu}_{\tau}\ N \to \tau^{\mp}\ X$	M, S ...	0.05

Table 1: Reactions of pion production by the atmospheric neutrinos and their rates normalized to the rate of reaction $\nu_{\mu}\ N \to \mu^{\pm}\ \pi^{\mp}\ N'$, $Y = S$ or nothing.

nucleon scattering using the fluxes and the cross-sections from the reports [21] and [22]. No efficiencies of detection have been taken into account.

According to the Table 1 there are two contributions to SS events (in assumption of good efficiency of detection): from π^0 production by the NC (reaction 3) and from $\nu_{\mathrm{e}}CC$ reaction with production of the π^0 (reaction 6), when π^0 is detected as one showering event. The latter reaction has more than two times smaller rate and its contamination can be further suppressed by imposing the invariant mass criteria and the upper cut on visible energy. The SM sample also has two contributions: from $\nu_{\mathrm{e}}CC$ production of the charged pion (reaction 2) and from $\nu_{\mu}CC$ production of the π^0 (reaction 5), when π^0 is detected as one showering event. Again the latter contribution can be suppressed by an upper cut of the visible energy. Using the numbers from the Table 1 we conclude that the double ratio $R_{\pi^0/SM}$ indeed can represent the ratio of NC/CC provided the products of reactions are well identified.

However in tracking detectors with ^{40}Ar (ICARUS) or iron (SOUDAN) as targets, nuclear effects should be taken into account. Charge exchange leads to further mixture of samples, moreover, if production of Δ occurs in heavy nuclei, the emission of pions is mainly a surface phenomenon. Certainly, more studies are needed to show the validity of the method for complex nuclei target with nonzero isospin.

4 Neutral Pions at Super-Kamiokande

Let us perform a tentative analysis of NC/CC ratios using available experimental data. The Super-Kamiokande has already collected a good statistics of *single* π^0 *events*, defined as the events with (1) only two rings, both of electromagnetic type (SS-events), (2) reconstructed vertex in the fiducial volume, (3) total momentum smaller than 400 MeV [23]. The study of the distributions in the invariant mass m_{π^0} was performed in order to calibrate the energy measurements at the Super-Kamiokande [1].

Additional criteria could be implemented to diminish the contribution of the CC reaction (10) to the π^0-*event* sample. This reaction gives a π^0-*event* if the muon is below the Cherenkov threshold. This muon can still be observed if it decays in the detector. Thus one can require an absence of the μ-decay in appropriate time window.

In what follows, we will use the results from the 20 Kton-year exposure and from the Monte Carlo simulations which correspond to 224.6 Kton-year [23]. Let us compare the observed number of neutral pion with the expectations. We will use narrower window of the invariant mass of two photons: $m_{\pi^0} = 100 - 200$ MeV. From Fig. A3 in [23] we get in this window the numbers: $N_{\pi^0}^{exp} = 72$ observed π^0-*events* events and $N_{\pi^0}^{MC} = 55$ expected events (the Monte Carlo data have been normalized to the same exposure time as observations). Extrapolating the distribution of events from the regions outside the peak to the peak region we can subtract the background. The above numbers of events become: $N_{\pi^0}^{exp} = 58$ and $N_{\pi^0}^{MC} = 41.6$. That is, the number of observed π^0-*events* exceeds the expected number.

In the Table 2 we present the data-to-Monte Carlo ratios for the events of different type with and without oscillations. The MC predictions in presence of oscillations have been calculated according to formulas (12, 14, 15, 19). For π^0-*events* we used relative elementary contributions from $\nu_\mu CC$, $\nu_e CC$

data/MC	no oscill.	$\nu_\mu \leftrightarrow \nu_\tau$	$\nu_\mu \leftrightarrow \nu_{\rm s}$
e-like	1.21	1.22	1.24
μ-like	0.77	1.25	1.27
multi-ring	0.89	1.07	1.20
π^0-*events*	1.31	1.42	1.86
π^0-*events*, bkgr. subtr.	1.39	1.51	1.98

Table 2: Data-to-Monte Carlo event ratios under different hypotheses of oscillation.

and NC reactions from Eq. (11), and for e-like, μ-like and multi-ring events we have taken the elementary contributions from [24]. The flux suppression factors were evaluated for $P = 0.6$ which permits to account for the double ratio $R_{\mu/{\rm e}}$.

According to Table 2 in absence of oscillations there is a shortage of μ-like and an excess of e-like events; the latter excess however could be explained by theoretical uncertainties in the normalization of the flux. The number of observed π^0-*events* exceeds the numbers expected under any hypothesis, moreover the oscillations, especially $\nu_\mu \leftrightarrow \nu_{\rm s}$ even enhance the difference.

The double ratios are presented in Table 3. As follows from the Table, the best agreement with the data is obtained under the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis (with a 15-25% excess of π^0-*events*). Let us estimate uncertainties in this analysis. The experimental (statistical) errors is related mostly to the small number of observed π^0-*events*. With present data it is about 15%, and it will decrease with the accumulation of statistics. The theoretical

	no oscill.	$\nu_\mu \leftrightarrow \nu_\tau$	$\nu_\mu \leftrightarrow \nu_{\rm s}$
$R_{\pi^0/{\rm e}}$	1.08 (1.15)	1.16 (1.24)	1.50 (1.60)
$R_{\pi^0/{\rm m.r.}}$	1.47 (1.56)	1.33 (1.41)	1.55 (1.56)
$R_{\mu/{\rm e}}$	0.64	1.02	1.02

Table 3: Double ratios under different hypotheses of oscillation. In bracket we present the values after the subtraction of the background for the π^0-*events*.

uncertainties are much larger. The results of two calculations of the neutrino-induced single-π production cross-sections by Fogli-Nardulli [25] and Rein-Sehgal [26] differ by 20% [21]. Using the results in Sec. 3.2 of [21] we estimate the uncertainties related to the nuclear effects as being about the 20% . So, the overall uncertainty could be around 35-40%. Already this uncertainty is larger than the differences in Eq. (7) or in Fig. 1, which means that at present it is impossible to exclude different channels of oscillations.

On top of this there is a possible neutron-induced background [27] which can contribute significantly to the π^0 data. This background is more important for π^0 sample than for e-like sample considered in [28] for two reasons: (1) smaller statistics of the π^0 events; (2) the absence of suppression which exists for the e-like events, since only in 17% of the cases the neutron-produced neutral pions can fake an electron [28]. The neutron background at Kamiokande was below 30% . Due to large size of the detector and the possibility to use central parts of the detector, the Super-Kamiokande can reduce possible effect of neutrons up to desired level.

5 Conclusions and Perspectives

The study of neutral current observables, and in particular of the π^0-*events*, can provide deeper insights in to the atmospheric neutrino problem. This study will give not only new independent check of the oscillation hypothesis, but also will allow one to discriminate between different channels of oscillations.

An exciting perspective is related to the Super-Kamiokande operations. Already to the end of 1998 it will collect more that 300 π^0-*events* [30]. Our tentative analysis of the recent SK data on neutral pions indicates a slight preference of the hypothesis of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, even though (as was emphasized) the uncertainties are large.

Further data taking at the Super-Kamiokande will lead to desired decrease of the experimental errors. As far as predictions are concerned, the progress could come not only from new updated series of calculations [29] but also from the future experimental studies of the neutrino induced single pion emission reactions at GeV energies. These studies will be possible with the two front detectors of the K2K experiment [31], that will start to operate in the beginning of 1999 [32]. The K2K collaboration plans also to search

for the oscillation effects using π^0-*events* directly [31]. The ratio of events (π^0/μ-like) in the front detector and in the Super-Kamiokande detector will be measured. However, it is not guaranteed that oscillation effects will be observable with the range of values of Δm^2 preferable now [1, 32].

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