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Flavor composition of the IceCube neutrinos: A quest for sterile neutrinos?

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Summary. — The identification of flavor content in the cosmic high-energy neutrinos recently observed by the IceCube collaboration could spread the light on the origin of these neutrinos. We study the expected fraction of muon tracks for different cases of the neutrino flavor composition at the sources taking into account uncertainties in the neutrino mixing angles and CP-phase. We show that in the frame of the three known neutrinos it is hard to explain the ν_μ fraction observed at IceCube. However if the cosmic component is produced in some hidden sector, in the form of sterile neutrinos which then oscillate into ordinary ones, a better agreement can be obtained. Especially, in a scenario when heavy dark matter with mass of few PeV decay into sterile neutrinos which then oscillate in ordinary neutrinos due to tiny mixing with the latter, it is possible to explain the low fraction of muon tracks in the events observed by IceCube in the energy region from 60 TeV to 2 PeV.

1. – Introduction

Discovery of high-energy neutrino events by the IceCube Collaboration [1] opened a new era of experimental high-energy neutrino astrophysics. Recently the collaboration published the complete data collected between 2010 and 2013 [2], they have 35 candidate events in the energy range from 30 TeV to 2 PeV, significantly over the expected background of 8.4 ± 4.2 for cosmic ray muon events and $6.6^{+5.9}_{-1.6}$ from atmospheric neutrinos from atmospheric muons and neutrinos, for an exposure of 3 years [2]. The evident excess of the observed events over the expected background excludes the purely atmospheric explanation at 5.7σ level [2] and indicates the presence of extraterrestrial (cosmic) neutrino component which seems to become dominant above 60 TeV or so. The origin of these cosmic neutrinos is not clear yet. They might have astrophysical origin, generated by cosmic rays accelerated in sites like supernova remnants [3], or they can be originated from the decay of dark matter particles with mass of few PeV [4, 5]. The study of flavor composition of the IceCube neutrino events can give useful hints for discriminating the origin of this cosmic component. One has to take into account that neutrino oscillations change the original flavor composition predicted in the high-energy neutrino production models, into another blend of neutrino flavors detected by IceCube detector, where the electron and tau neutrinos (or antineutrinos) typically produce a shower event while the muon neutrinos (and antineutrinos) ν_μ and $\bar{\nu}_\mu$ typically produce a weak shower with an evident accompanying muon track. Therefore, for understanding the flavor content one can study the fraction of ν_μ tracks in different regions of the spectrum also taking into account the background uncertainties. Several recent papers have been addressed to this issue [6-8]. Among 35 candidates with energies $> 30\,\mathrm{TeV}$ registered during 988 days of observations, only 7 events contain muon tracks, while the remaining 28 shower-like events are consistent with the neutrino charged current (CC) interactions ν_e-N or ν_τ-N. On the other hand, at least 10 track events are expected from the atmospheric muon and neutrino background. Hence, it seems that the observed number of tracks fully saturates the background expectation and thus a very little space is left for the cosmic ν_μ component. In addition, among 12 events detected at energies from 100 TeV to 2 PeV, where the background is practically vanishing, 11 are showers and only one event is a muon track. Hence, it seems that the flavor composition of the cosmic neutrinos is strongly dominated by ν_e or ν_τ, or by some blend of the latter, with a very limited admixture of ν_μ. Yet, due to limited statistics, it would be premature to draw any far-going conclusions.

2. – Standard neutrinos

This section is devoted to study predictions for the fraction of tracks $F(E,E')$ assuming only the three standard neutrinos and that they come from some distant Astrophysical source. Starting from different flavor composition at the source we will compute $F(E,E')$ expected at IceCube considering different power-law spectra ($\phi_\alpha(E) \propto E^{-\gamma}$) with spectral index γ running from 2 to 2.8 and the effective area of the detector. The expected tracks fraction in certain energy range can be expressed as

$$F(E,E') = \frac{N_t}{N_t+N_s} = \frac{\int_E^{E'} \mathrm{d}E \;\; \phi_\mu(E)\; A_\mu(E)}{\int_E^{E'} \mathrm{d}E \;\; \sum_\alpha \phi_\alpha(E)\; A_\alpha(E)} = \frac{r_\mu\, f_\mu}{f_e + r_\mu\, f_\mu + r_\tau\, f_\tau}, \tag{1}$$

with $r_{\mu,\tau} \equiv \left(\int_E^{E'} \mathrm{d}E \;\; E^{-\gamma}\; A_{\mu,\tau}(E)\right) \left(\int_E^{E'} \mathrm{d}E \;\; E^{-\gamma}\; A_e(E)\right)^{-1}$ where A_α are the effective areas for each flavor $\alpha = e, \mu, \tau$ and f_α are the corresponding flavor fraction at Earth whose can be evaluated from the source composition $\tilde{f}_\alpha$ taking into account the effect given by neutrino oscillation, since we assume that this neutrinos come from a very far source we have that the averaged oscillation probability is given by

$$P_{\alpha\beta} = \sum_i |V_{\alpha i}|^2 |V_{i\beta}|^2, \quad \text{with} \quad V = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix}, \tag{2}$$

where $V_{\alpha i}$ are the elements of the PMNS neutrino mixing matrix, and $i = 1,2,3$ is the mass eigenstate index. So, composition ad Earth is given by $f_\alpha = P_{\alpha\beta}\,\tilde{f}_\beta$. The matrix $P_{\alpha\beta}$ has 6 independent elements but they have to satisfy 3 bounds: $\sum_\alpha P_{\alpha\beta} = 1$ so we are left with only 3 independent elements we choose: P_{ee}, $P_{e\mu}$ e $P_{\mu\tau}$, but if we consider the case where $r_\mu = r_\tau = 1$ we have $F = f_\mu \simeq P_{e\mu}$ and so $P_{e\mu}$ is the key parameter.

TABLE I. – *Results for the calculation of $F(E, E')$, central values are given for $\gamma = 2.4$ and the central values of mixing angles and CP-phase, the upper and lower limit are given variating the oscillation probabilities according to the experimental uncertainties and the second variance is given variating the spectral index and it is expressed in terms of $\delta\gamma \in [-0.4; 0.4]$.*

E [Tev] $\rightarrow$	$60 < E < 2000$	$60 < E < 100$	$100 < E < 2000$
	$F_{IC} = 4/20$	$F_{IC} = 3/8$	$F_{IC} = 1/12$
$\frac{1}{3}\nu_e + \frac{1}{3}\nu_\mu + \frac{1}{3}\nu_\tau$	$.229 + .045\ \delta\gamma$	$.153 + .001\ \delta\gamma$	$.249 + .031\ \delta\gamma$
$\frac{1}{3}\nu_e + \frac{2}{3}\nu_\mu(\mathrm{Atm})$	$.235^{-.005}_{+.015} + .045\ \delta\gamma$	$.150^{-.005}_{+.013} + .001\ \delta\gamma$	$.245^{-.005}_{+.016} + .031\ \delta\gamma$
ν_e	$.156^{+.029}_{-.032} + .035\ \delta\gamma$	$.096^{+.019}_{-.020} + .001\ \delta\gamma$	$.174^{+.032}_{-.035} + .029\ \delta\gamma$
ν_μ	$.264^{-.025}_{+.046} + .046\ \delta\gamma$	$.185^{-.021}_{+.039} + .001\ \delta\gamma$	$.284^{-.025}_{+.047} + .032\delta\gamma$
ν_τ	$.279^{-.009}_{-.005} + .045\ \delta\gamma$	$.200^{-.004}_{-.007} + .001\ \delta\gamma$	$.298^{-.011}_{-.004} + .031\ \delta\gamma$
ν_1	$.106^{+.058}_{-.052} + .029\ \delta\gamma$	$.062^{+.035}_{-.031} + .001\ \delta\gamma$	$.120^{+.065}_{-.058} + .021\ \delta\gamma$
ν_2	$.278^{-.054}_{+.044} + .056\ \delta\gamma$	$.191^{-.039}_{+.034} + .001\ \delta\gamma$	$.300^{-.057}_{+.046} + .036\ \delta\gamma$
ν_3	$.341^{-.021}_{+.031} + .037\ \delta\gamma$	$.275^{-.019}_{+.028} + .001\ \delta\gamma$	$.355^{-.022}_{-.031} + .026\ \delta\gamma$

Given this, to take into account experimental uncertainties on neutrino mixing angles we choose to marginalize every $P_{\alpha\beta}$ matrix element with the combination of 1σ interval extremes that maximize or minimize $P_{e\mu}$: $P^{\pm}_{\alpha\beta} = P_{\alpha\beta}(\theta^{\pm}_{23}, \theta^{\mp}_{13}, \theta^{\mp}_{12})$. We can test many possibilities for source flavor composition: atmospheric production given by π and μ decay that gives $\tilde{f} = (1/3 : 2/3 : 0)$ but depending on the energy of the meson we could also have $(0 : 1 : 0)$ or $(1 : 0 : 0)$, the latter can be given also by neutron decay. We will also test more exotic case such as the symmetric case $(1/3 : 1/3 : 1/3)$ or the ν_τ production $(0 : 0 : 1)$. Is it interesting that after oscillation the atmospheric case reduces to the symmetric one which does not variate so much due to oscillations. It is also possible to think of more exotic production mechanism such as neutrinos from Dark Matter direct decay, which can produce neutrino Mass Eigenstate: ν_1, ν_2 and ν_3 which are not affected by oscillation and so flavor composition at Earth is given by projecting the mass eigenstate in the flavor eigenstate base: $f_\alpha = |V_{\alpha i}|^2$.

Now we have all the ingredients to compute $F(E, E')$, we are interested in the area above 60 TeV and especially in the two sub-regions where 60 TeV $< E <$ 100 TeV (Low Background) and 100 TeV $< E <$ 2 PeV (No Background); results are listed in table I and shown in fig. 1. Is it easy to see that none of these scenarios can explain the flavor content observed at IceCube in both the Interesting Energy region.

3. – Sterile neutrinos

In this section we consider the case in which these cosmic neutrinos were created in some Hidden Gauge Sector as Sterile Neutrinos. One can think of some kind of Heavy Dark Matter ($m_{DM} \sim$ PeV) that decades into neutrinos of that sector which are Sterile for us. Then, they oscillate with small probabilities ($P \sim 10^{-10}$) into our neutrinos: $\nu_s \rightarrow \nu_e$, ν_μ, ν_τ, which are then detected by IceCube. In a scenario where there

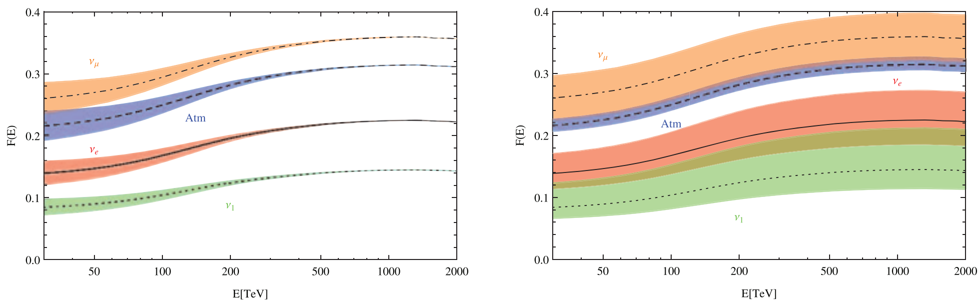

Fig. 1. – Results for $F(E, E')$ for some scenarios with standard neutrinos as a function of E choosing $E' = 2\,\mathrm{PeV}$ variating spectral index in the left panel and oscillation parameters in the right panel.

is an extra sterile neutrino with small mixing angles s_i with our neutrinos, oscillation probabilities between the three ordinary neutrinos remain the same, on the other hand for oscillation between active and sterile neutrinos we have

$$(3) \qquad P_{s\alpha} = |V_{\alpha 4}|^2 + \sum_{i=1}^{3} |V_{si}|^2 |V_{\alpha i}|^2, \quad \text{with} \quad V = \left(\begin{array}{ccc|c} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} \\ \hline V_{s1} & V_{s2} & V_{s3} & 1 \end{array}\right) + O(s_i^2),$$

where $|V_{si}| \ll 1$. One can think about different mixing pattern between active and sterile neutrinos. An interesting case is when only one of the three mixing angles is different from zero. As an example we can choose: $s_2 = s_3 = 0$ e $s_1 = s$ this will led for oscillation probabilities to

$$(4) \qquad P_{se} = s^2 \left[1 + P_{ee}\right], \quad P_{s\mu} = s^2 P_{e\mu}, \quad P_{s\tau} = s^2 P_{e\tau}.$$

Now assuming that only this sterile neutrinos are produced $\tilde{f} = (0:0:0:1)$ and that they undergo to a power-law spectra for the ν_μ fraction, we have

$$(5) \qquad F(E, E') = \frac{s^2\, r_\mu\, \left(1 + P_{e\mu}\right)}{s^2 \left(1 + P_{ee} + r_\mu\, P_{e\mu} + r_\tau\, P_{e\tau}\right)},$$

which is independent of the active-sterile mixing angle.

We now compute the $F(E, E')$ fraction for three different scenarios: when the sterile neutrino is mixed with only one of the standard neutrinos: $\mathcal{M}_{s\alpha} : \nu_s \leftrightarrows \nu_\alpha$. Results of the calculation are shown in table II and in fig. 2 From the results it is clear that in the No Background region the flavor ratio observed at IceCube can be reconstructed by assuming that sterile neutrinos are mixed only with ν_e, on the other hand in the Low Background region IceCube flavor ratio is well reproduced assuming that the sterile neutrino is mixed only with ν_μ.

4. – Model

An ideal scenario to explain this flavor content is to have a mechanism that creates two flavors of ν_s, one mixed with ν_e of energy above 100 TeV and the other ν_s mixed

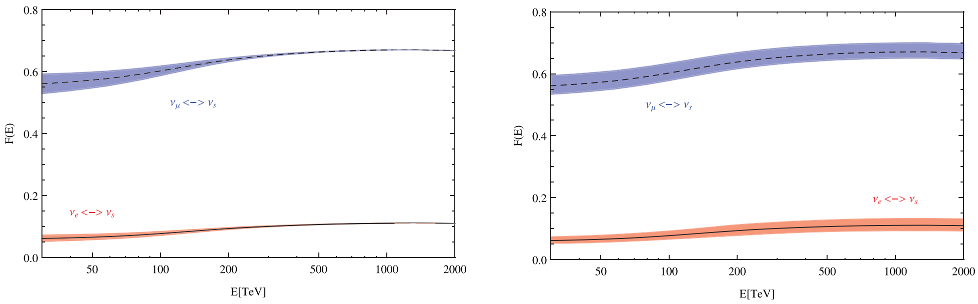

Fig. 2. – Results for $F(E, E')$ for the two interesting scenario with sterile neutrinos as a function of E choosing $E' = 2\,\mathrm{PeV}$ variating the spectral index in the left panel and the oscillation parameters in the right panel.

with ν_μ with energies from 60 to 100 TeV. We can think of two different species of Dark Matter with different masses and different decay modes which as decay product have two different kinds of sterile neutrinos. This can be naturally obtained in the framework of Asymmetric Mirror Dark Matter (For a review on this topics see [9]) as proposed in [5]. Assuming that: ν'_e are mixed only with our electron neutrino and ν'_x superposition prefers to oscillate in our muon neutrino, we can compute the Tracks Fraction using the spectra from [5]. In the low background region we get $0.456^{-0.022}_{+0.036}$ ($F_{IC} = 0.375$) and in the zero background region we get $0.122^{+0.021}_{-0.024}$ ($F_{IC} = 0.083$).

5. – Conclusions

It is hard to explain IceCube neutrino events in the framework of known Neutrino Physics and Astrophysics. A better agreement is possible if we take into account Sterile Neutrinos in particular we propose that these Neutrinos could be produced from Dark Matter decay in an Hidden Gauge Sector, then they Oscillate into our active neutrinos with small probabilities. This can be naturally obtained in the framework of Asymmetric Mirror Dark Matter. The validity of our model will be tested with increasing statistic by the IceCube Collaboration.

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Table II. – *Results for the calculation of $F(E, E')$ in the case of sterile neutrinos the limits follows the same philosophy as table I.*

E [Tev]	$60 < E < 2000$	$60 < E < 100$	$100 < E < 2000$
	$F_{IC} = 4/20$	$F_{IC} = 3/8$	$F_{IC} = 1/12$
$\mathcal{M}_{se}$	$.071^{+.012}_{-.014} + .021\,\delta\gamma$	$.040^{+.007}_{-.008} + .001\,\delta\gamma$	$.080^{+.014}_{-.016} + .016\,\delta\gamma$
$\mathcal{M}_{s\mu}$	$.572^{-.019}_{+.032} + .058\,\delta\gamma$	$.457^{-.023}_{+.038} + .002\,\delta\gamma$	$.596^{-.017}_{+.031} + .039\,\delta\gamma$
$\mathcal{M}_{s\tau}$	$.137^{-.005}_{-.002} + .022\,\delta\gamma$	$.101^{-.003}_{-.002} + .001\,\delta\gamma$	$.145^{-.005}_{-.001} + .016\,\delta\gamma$

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