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Non-standard neutrino interactions in the earth and the flavor of astrophysical neutrinos

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ABSTRACT

We study the modification of the detected flavor content of ultra high-energy astrophysical neutrinos in the presence of non-standard interactions of neutrinos with the Earth matter. Unlike the case of new physics affecting the propagation from the source to the Earth, non-standard Earth matter effects induce a dependence of the flavor content on the arrival direction of the neutrino. We find that, within the current limits on non-standard neutrino interaction parameters, large deviations from the standard 3ν oscillation predictions can be expected, in particular for fluxes dominated by one flavor at the source. Conversely they do not give sizable corrections to the expectation of equalized flavors in the Earth for sources dominated by production via pion-muon decay-chain.

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1. Introduction

The detection of ultra-high energy neutrinos of astrophysical origin in IceCube [1–4] marks the begin of high energy neutrino astronomy. From the point of view of astronomy, the main open question resides in finding the sources of such neutrinos, an issue to which many suggestions have been contributed (for a recent review see Ref. [5]). More on the astrophysical front, one also questions what type of mechanisms are at work in those sources to produce such high energy neutrino flux. To address this question the measurement of the flavor composition of the observed neutrinos acquires a special relevance. For example, for the pion-muon decay chain, which is the most frequently considered, one expects $\phi^s_\mu = 2\phi^s_e$ while $\phi^s_\tau = 0$ [6] (denoting by ϕ^s_α the neutrino flux of flavor ν_α at source). Alternatively, if some of the muons lose energy very rapidly one would predict a single μ-flavor flux while $\phi^s_e = \phi^s_\tau = 0$ [7–11]. If neutrino production is dominated by neutron decay one expects also a single flavor flux but of electron neutrinos [8] so in this case $\phi^s_\mu = \phi^s_\tau = 0$. Decay of charm mesons contribute a flux with equal amounts of electron and muon neutrinos, $\phi^s_e = \phi^s_\mu$ and $\phi^s_\tau = 0$. If several of the above processes in the source compete, arbitrary flavor compositions of ϕ^s_e and ϕ^s_μ are possible but still with $\phi_\tau = 0$ [10]. If, in addition, ν_τ are also produced in the source [12–14], then generically $\phi^s_\alpha \neq 0$ for $\alpha = e, \mu, \tau$.

Neutrino oscillations modify the flavor composition of the neutrino flux by the time they reach the Earth. In the context of the well established framework of 3ν oscillations these modifications are well understood and quantifiable given the present determination of the neutrino oscillation parameters. Because of this several studies to quantify the flavor composition of the IceCube events, even with the limited statistics data available, have been presented [15–23] but the results are still inconclusive.

It is well-known that new physics (NP) effects beyond 3ν oscillations in the neutrino propagation can alter the predicted flavor composition of the flux reaching the Earth, thus making the task of elucidating the production mechanism even more challenging. Examples of NP considered in the literature include Lorentz or CPT violation [24], neutrino decay [25,26], quantum decoherence [27,28] pseudo-Dirac neutrinos [29,30], sterile neutrinos [31], non-standard neutrino interactions with dark matter [32], or generic forms of NP in the propagation from the source to the Earth parametrized by effective operators [33]. Besides modifications of the flavor ratios many of these NP effects also induce a modification of the energy spectrum of the arriving neutrinos.

In this paper we consider an alternative form of NP, namely the possibility of non-standard interactions (NSI) of the neutrinos in the Earth matter. Unlike the kind of NP listed above, this implies

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that neutrinos reach the Earth surface in the expected flavor combinations provided by the "standard" 3ν vacuum oscillation mechanism: in other words, NSI in the Earth affect only the flavor evolution of the neutrino ensemble from the entry point in the Earth matter to the detector. The goal of this paper is to quantify the modification of the neutrino flavor composition at the detector because of this effect within the presently allowed values of the NSI parameters. To this aim we briefly review in Section 2 the formalism employed and derive the relevant flavor transition probabilities from the source to the detector including the effect of NSI in the Earth. We show that the resulting probabilities are energy independent while they depend on the zenith angle arrival direction of the neutrinos, in contrast with NP affecting propagation from the source to the Earth. Our quantitative results are presented in Section 3, where in particular we highlight for which source flavor composition the Earth-matter NSI can be most relevant. Finally in Section 4 we draw our conclusions.

2. Formalism

Our starting point is the initial neutrino (antineutrino) fluxes at the production point in the source which we denote as ϕ^s_α ($\bar\phi^s_\alpha$) for $\alpha = e, \nu, \tau$. The corresponding fluxes of a given flavor at the Earth's surface are denoted as $\phi^\oplus_\alpha$ ($\bar\phi^\oplus_\alpha$) while the fluxes arriving at the detector after traversing the Earth are ϕ^d_α ($\bar\phi^d_\alpha$). They are generically given by

$$\phi^{\oplus}_{\beta}(E) = \sum_{\alpha} \int dE' \mathcal{P}^{s\to\oplus}_{\alpha\beta}(E,E')\phi^s_\alpha(E'),$$
$$\phi^{d}_{\beta}(E) = \sum_{\alpha} \int dE' \mathcal{P}^{s\to d}_{\alpha\beta}(E,E')\phi^s_\alpha(E') \tag{1}$$

and correspondingly for antineutrinos. $\mathcal{P}$ is the flavor transition probability including both coherent and incoherent effects in the neutrino propagation.

2.1. Coherent effects

Let us start by considering first only the coherent evolution of the neutrino ensemble. In this case, the flavor transition probabilities from the source (s) to the Earth entry point ($\oplus$) and to the detector (d) can be written as

$$\mathcal{P}^{s\to\oplus}_{\alpha\beta}(E,E') = P^{s\to\oplus}_{\alpha\beta}(E)\,\delta(E-E'), \quad \text{with} \quad P^{s\to\oplus}_{\alpha\beta}(E) = \left|A^{s\to\oplus}_{\alpha\beta}(E)\right|^2 \tag{2}$$

$$\mathcal{P}^{s\to d}_{\alpha\beta}(E,E') = P^{s\to d}_{\alpha\beta}(E)\,\delta(E-E'), \quad \text{with}$$
$$P^{s\to d}_{\alpha\beta}(E) = \left|A^{s\to d}_{\alpha\beta}(E)\right|^2 = \left|\sum_\gamma A^{s\to\oplus}_{\alpha\gamma}A^{\oplus\to d}_{\gamma\beta}\right|^2, \tag{3}$$

where we have introduced the flavor transition amplitude from the source to the Earth surface $A^{s\,\to\,\oplus}$ and from the Earth surface to the detector $A^{\oplus\,\to\,d}$.

Generically these amplitudes are obtained by solving the neutrino and antineutrino evolution equations for the flavor wave function $\vec\nu(x) = \{\nu_e(x), \nu_\mu(x), \nu_\tau(x)\}^T$

$$i\frac{d\vec\nu(x)}{dx} = H^{s\to\oplus}_\nu\,\vec\nu(x), \qquad i\frac{d\vec{\bar\nu}(x)}{dx} = H^{s\to\oplus}_{\bar\nu}\,\vec{\bar\nu}(x) \tag{4}$$

for evolution between the source and the Earth surface and

$$i\frac{d\vec\nu(x)}{dx} = H^{\oplus\to d}_\nu\,\vec\nu(x), \qquad i\frac{d\vec{\bar\nu}(x)}{dx} = H^{\oplus\to d}_{\bar\nu}\,\vec{\bar\nu}(x), \tag{5}$$

for evolution in the Earth matter.

In this work we are interested in standard vacuum oscillation dominating the propagation from the source to the detector but allowing for new physics in the interactions of the neutrinos in the Earth matter. In this case

$$H^{s\to\oplus}_\nu = (H^{s\to\oplus}_{\bar\nu})^* = H_{\text{osc}} = UD_{\text{vac}}U^\dagger \quad \text{with}$$
$$D_{\text{vac}} = \frac{1}{2E}\,\text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \tag{6}$$

and U is the leptonic mixing matrix [34,35]. While

$$H^{\oplus\to d}_\nu \simeq H_{\text{mat}}, \qquad H^{\oplus\to d}_{\bar\nu} \simeq -H^*_{\text{mat}} \tag{7}$$

where the $\simeq$ corresponds to neglecting vacuum oscillations inside the Earth which is a very good approximation for the relevant neutrino energies ($\gtrsim$ 1 TeV).

The standard theoretical framework for the NP considered here is provided by non-standard interactions affecting neutrino interactions in matter [36]. They can be described by effective four-fermion operators of the form

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}(\bar\nu_\alpha\gamma^\mu\nu_\beta)(\bar f\gamma_\mu Pf), \tag{8}$$

where f is a charged fermion, $P = (L, R)$ and $\varepsilon^{fP}_{\alpha\beta}$ are dimensionless parameters encoding the deviation from standard interactions. NSI enter in neutrino propagation only through the vector couplings, so in the most general case the non-standard matter Hamiltonian can be parametrized as [37]

$$H_{\text{mat}} = \sqrt{2}G_F N_e(r)\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$
$$+\sqrt{2}G_F\sum_{f=e,u,d}N_f(r)\begin{pmatrix}\varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau}\end{pmatrix}. \tag{9}$$

The standard model interactions are encoded in the non-vanishing ee entry in the first term of Eq. (9), while the non-standard interactions with fermion f are accounted by the $\varepsilon^f_{\alpha\beta}$ coefficients with $\varepsilon^f_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$. Here $N_f(r)$ is the number density of fermions f in the Earth matter. In practice, the PREM model [38] fixes the neutron/electron ratio to $Y_n = 1.012$ in the Mantle and $Y_n = 1.137$ in the Core, with an average $Y_n = 1.051$ all over the Earth. Thus we get an average up-quark/electron ratio $Y_u = 3.051$ and down-quark/electron ratio $Y_d = 3.102$. We can therefore define:

$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d}\left\langle\frac{Y_f}{Y_e}\right\rangle\varepsilon^f_{\alpha\beta} = \varepsilon^e_{\alpha\beta} + Y_u\,\varepsilon^u_{\alpha\beta} + Y_d\,\varepsilon^d_{\alpha\beta} \tag{10}$$

so that the matter part of the Hamiltonian can be written as:

$$H_{\text{mat}} = \sqrt{2}G_F N_e(r)\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix} \equiv WD_{\text{mat}}W^\dagger \tag{11}$$

where

$$D_{\text{mat}} = \sqrt{2}G_F N_e(r)\,\text{diag}(\varepsilon_1, \varepsilon_2, \varepsilon_3). \tag{12}$$

where W is a 3 × 3 unitary matrix containing six physical parameters, three real angles and three complex phases. So without loss of generality the matter potential contains eight parameters, five real and three phases (as only difference of ε_i enter the flavor transition probabilities, only differences in the $\varepsilon_{\alpha\alpha}$ are physically relevant for neutrino oscillation data).

Altogether the flavor transition probabilities from a source at distance L are

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