Probing the 2-3 leptonic mixing at high-energy neutrino telescopes

Pasquale D. Serpico
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
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We discuss the possibility to probe leptonic mixing parameters at high-energy neutrino telescopes in a model-independent way, using astrophysical neutron and pion sources. In particular we show how the octant of the 2-3 mixing angle might be determined independently of prior knowledge of the source, even when current uncertainties on the other mixing parameters are included. We also argue that non-trivial neutrino oscillation effects should be taken into account when using high-energy flavor ratios for astrophysical diagnostics.

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I. INTRODUCTION

The physics of neutrinos is entering the precision era, where laboratory sources from reactors or accelerators are progressively replacing the natural ones (solar and atmospheric neutrinos) for the detailed determination of mixing angles and mass splittings. A parallel development is expected with the opening of a new observational window in astrophysics by the next generation of high-energy neutrino telescopes \[1\]. The hope is that these instruments will finally shed light on several open problems in cosmic-ray and gamma-ray astrophysics. It is well recognized that the value of neutrino oscillation parameters has a great impact on the expected fluxes. We just mention here that significant \(\nu_\tau\) fluxes from astrophysical sources are implied by the large mixing in the \(\nu_\mu-\nu_\tau\) sector, opening the interesting possibility to identify \(\nu_\tau\) events in both optical Cherenkov telescopes and in extensive air-shower experiments \[2\] \[3\] \[4\]. On the other hand, high-energy neutrinos are expected to come mainly from pion decays, with a flavor composition of \(\{\phi_\alpha : \phi_\mu : \phi_\tau\} \simeq \{1 : 2 : 3\} \) at the source. (We denote with \(\phi_\alpha\) the combined flux of \(\nu_\alpha\) and \(\bar{\nu}_\alpha\), where \(\alpha = e, \mu, \tau\).) Presently favored ranges for mixing parameters imply oscillated fluxes at the detector \(\phi_\alpha^D\) approximately in the ratios \(\{1 : 4 : 0\}\), almost independently from the details of neutrino mixing parameters \[5\] \[6\]. Astrophysical uncertainties and the expected low statistics would not justify deeper studies. This qualitative argument probably explains why the potential for neutrino mixing studies has remained largely unexplored.

However, the possibility to exploit the flavor content of neutrino fluxes for astrophysical diagnostics has been recently analyzed in greater detail. A change in neutrino flavor fluxes was shown to be important for diagnostistics of gamma ray bursts (GRB) \[7\]. As another example, the fraction of neutrinos produced in high-energy accelerators via the strongly isospin-asymmetric \(p\gamma\) process (as opposed to \(pp\) inelastic scattering) might also be measurable, at least around energies of 6.3 PeV \((1\text{ PeV} \equiv 10^{15}\text{ eV})\) \[8\] \[9\]. This idea is based on the fact that at this energy optical Cherenkov telescopes have an enhanced efficiency to single out \(\bar{\nu}_e\) showers, because of the Glashow resonant process \(\nu_e + e^- \rightarrow W^-\). The ratio \(R_G\) of such events to the \(\nu_\mu\) plus \(\nu_\tau\) charged current tracks in the same energy bin is a suitable observable to that purpose. The ratio \(R_G\) was shown to have a significant sensitivity to the mixing angles as well, in particular to the 1-2 mixing angle \(\theta_{12}\) \[9\]. In that respect, we also have discussed an interesting astrophysical target \[10\]. Neutron primaries generated in the photo-dissociation of nuclei (see e.g. \[11\]) would have the right properties to explain the excess of high-energy cosmic rays from the Galactic Plane at \(E \gtrsim 10^{18}\text{ eV}\), reported in \[12\]. If this model is correct, the initial flavor content of the neutrino flux from some galactic regions is close to \(\{1 : 0 : 0\}\). A sensitivity to \(\theta_{13}\) and to the leptonic CP-phase \(\delta_{CP}\) is achieved via the quantity \(R \equiv \phi_\mu^D/\phi_\tau^D\), that can be deduced in a neutrino telescope from the ratio of track to shower events \[13\] \[14\]. However, though physically plausible, this source is not guaranteed. The very existence of a significant anisotropy—at least towards the Galactic Center—is currently debated, in the light of the negative results of an analysis of preliminary Auger data \[14\].

In the following, we generalize previous considerations arguing that: (i) There could be neutron beam sources invisible to cosmic ray (an-)isotropy observations, and only detectable indirectly at neutrino telescopes. (ii) Other candidate targets useful for neutrino mixing studies at neutrino telescopes also exist, like muon-damped \(\nu_\mu\) sources from pion decays, that were recently discussed \[5\]. We shall motivate that both classes of sources could be not only identified at neutrino telescopes, but also used to infer non-trivial information on certain neutrino mixing parameters in a model-independent way, i.e. irrespective of astrophysical uncertainties. The argument still holds when presently allowed ranges for the other mixing parameters are taken into account. In particular, we shall show how a robust lower bound on \(\theta_{23}\) could be established, and thus a value of \(\theta_{23} > 45^\circ\) identified. Note that this information is non-trivial. The present 2\(\sigma\) range is \(36^\circ \leq \theta_{23} \leq 52^\circ\) \[15\], and a deviation from maximal mixing would be important for flavor symmetries and neutrino mass models \[16\].

Of course, our considerations could be invalidated if exotic mechanisms like neutrino decays are effective \[17\], but such scenarios seem to be at least disfavored by cosmological bounds \[18\] \[19\].
In Section II we treat generic neutron beam sources and focus on the octant of $\theta_{23}$ as a model-independent parameter possibly accessible at neutrino telescopes. In Section III similar considerations are developed for a pure $\nu_\mu$ beam from pion decay. In Section IV we conclude.

II. NEUTRON BEAM SOURCES

Neutrino fluxes detectable at neutrino telescopes, i.e. at $E \gtrsim 0.1$–1 TeV, might well originate in the decay of few PeV neutrons from sources which have characteristics similar to the ones detailed in [11], but whose neutron spectrum cuts-off at energies $E \ll 10^{18}$ eV. Since the decay length of a neutron is $d_n \approx 10$ pc ($E_n$/PeV), and typical galactic distances are of order 10 kpc, such a source would not show up as a cosmic ray anisotropy. The decay protons would rapidly lose directional information via deflection in the galactic magnetic field. The dominance of nuclei in the galactic cosmic ray spectrum is likely starting just above $10^{15}$ eV, and the spectrum of galactic cosmic rays is expected to extend at least up to few $\times 10^{19}$ eV (see e.g. 21 and Section 3.1 in 21): A situation suitable to the neutron beam production is conceivable in many regions of our Galaxy. Of course, such “hidden” neutron beams could only be revealed by neutrino observations, and are thus constrained only by the direct observational upper bounds at neutrino telescopes. Nonetheless, any standard pion-decay source would produce neutrinos with a ratio $R \approx 0.5$ (or larger, see Section III). By observing a ratio $R$ significantly lower than 0.5, one could claim both the discovery of an invisible neutron beam and put constraints on the neutrino mixing parameters, since any “background” (i.e., any additional flux not sharing the same flavor content) should push $R$ to higher values. More quantitatively, the flux flavor ratios $\phi_\alpha^D$ arriving at the detector are given in terms of the probabilities $P_{\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta)$ as $\phi_\alpha^D = \sum_{\beta} P_{\alpha\beta} \phi_\beta$, where $\phi_\alpha$ are the flux ratios at the source. Matter effects are negligible because of the extremely low densities of cosmic environments, and the interference terms sensitive to the mass splittings and to the sign of $\delta_{\text{CP}}$ (i.e., the CP-violating terms) average out because the galactic distances far exceed the experimentally known oscillation lengths. This also implies that the same probability formulae apply to neutrino and anti-neutrino channels. One then obtains

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 2 \sum_{j>k} \text{Re}(U_{\beta j} U_{\alpha k}^* U_{\alpha j} U_{\beta k}^*),$$

where $U(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}})$ is the neutrino mixing matrix 22 and greek (latin) letters are used as flavor (mass) indices. For a neutron beam source, the parameter $R$ can be expressed in terms of oscillation probabilities $P_{\alpha\beta}$ as

$$R \equiv \frac{\phi_\mu^D}{\phi_e^D + \phi_\tau^D} = \frac{P_{e\mu}}{P_{e\mu} + P_{e\tau}} = \frac{P_{e\mu}}{1 - P_{e\mu}},$$

the last equality following from unitarity, $P_{e\mu} + P_{e\tau} = 1$. An useful approximation for $P_{e\mu}$, obtained as first order expansion in the small quantity $\sin \theta_{13}$, is

$$P_{e\mu} = \frac{1}{2} \sin^2 2\theta_{12} \cos^2 \theta_{23} + \frac{1}{2} \sin \theta_{13} \cos \delta_{\text{CP}} \sin 2\theta_{12} \cos 2\theta_{12} \sin \theta_{23} + O(\theta_{13}^3).$$

The extremes of the ratio Eq. 3 for a fixed $\theta_{12}$ and $\theta_{23}$ are obtained for maximal allowed value of $\theta_{13}$ and the cases $\cos \delta_{\text{CP}} = \pm 1$, as the linear approximation of Eq. 3 suggests. In Fig. 1 it is clearly shown that, also including current $2\sigma$ uncertainties on mixing parameters, observations of an extremely low value for $R$, say $R \lesssim 0.21$, could only be reconciled with $\theta_{23} > 45^\circ$.

Until now we have focused on neutron beams from galactic sources, because they are motivated targets having a chance of detection. On the other hand, it should be stressed that extra-galactic sources that have suitable conditions also exist. Even when one turns to the most...
reliable of the extra-galactic neutrino sources, the cosmogenic neutrino flux, one easily realizes that at energies around $10^{18}$ eV a secondary peak almost purely made of $\nu_e$ should be present \cite{24, 25}. This is formed after neutron decays, both in the case of proton and heavy nuclei primaries. In the latter case a relatively larger contribution is expected because of the additional free-neutrons produced in photo-dissociations \cite{24, 25}. Of course, this flux is so low that a detection is challenging, and maybe prevented even in principle by the larger contributions from “canonical” diffuse fluxes from other extra-galactic sources.

### III. MUON DAMPED SOURCES

We now turn to another class of sources producing a non-trivial flavor content at neutrino telescopes, i.e. sources optically thick to muons (lifetime $\simeq 2.2 \times 10^{-8}$ s) but not to pions (lifetime $\simeq 2.6 \times 10^{-8}$ s), which would mainly emit neutrinos in the flavor ratios $\{0 : 1 : 0\}$.

\[ P_{\mu\mu} = 1 - 2 \cos^2 \theta_{23} \left[ \sin^2 \theta_{23} + \frac{1}{4} \sin^2 2\theta_{12} \cos^2 \theta_{23} + \frac{1}{2} \sin \theta_{13} \cos \delta_{\text{CP}} \sin 2\theta_{12} \cos 2\theta_{12} \sin 2\theta_{23} \right] + \mathcal{O}(\theta_{13}^2). \]  

\[ R = \frac{\phi^D_{\mu} - \phi^D_{e}}{\phi^D_{\mu} + \phi^D_{e}} = \frac{P_{\mu\mu}}{1 - P_{\mu\mu}}, \]  

where we used the unitarity condition $P_{\mu e} + P_{\mu\tau} = 1 - P_{\mu\mu}$. For illustrative purpose we report here a first order expansion of $P_{\mu\mu}$ in the small quantity $\sin \theta_{13}$.

In Fig. 2 we show that any observation of a ratio $R \gtrsim 0.78$ would not only point to a muon-damped source, but would also constrain the octant of $\theta_{23}$, i.e. $\theta_{23} > 45^\circ$. This result is irrespective of the uncertainties on the other mixing parameters, as well as of known backgrounds from (undamped) pion chain or even neutron beams, which could only contribute to lower the value of $R$. Note also that in both Figs. 1 and 2 special regions in the parameter space exist that are only compatible with very specific values of the mixing parameters, and in particular $\theta_{13}$ and $\delta_{\text{CP}}$. For example, if one establishes independently that $\theta_{23} < 45^\circ$, a detected value of $R \gtrsim 0.7$ would only be compatible with a relatively large $\theta_{13}$ and a non-vanishing $\delta_{\text{CP}}$.

The prospects of forthcoming laboratory experiments for the determination of the octant of $\theta_{23}$ have been analyzed in \cite{27}, and more in general for neutrino oscillation parameters in \cite{28}. To give a quantitative example of the possibilities of neutrino telescopes, for a benchmark flux of muon neutrinos of $E^2 dN/dE = 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$, IceCube \cite{28} could determine the flavor ratio at the 15% level after 1 year \cite{13}. In this case, IceCube would be sufficiently sensitive to detect the effects described above. Moderately lower fluxes could be compensated by a larger integration time. Remarkably, in any kind of extraterrestrial flux, even a diffuse one, one could look for an energy range with peculiar flavor ratios. Moreover, adding complementary information from forthcoming laboratory experiments would improve the chances to identify e.g. the effect of $\theta_{23} > 45^\circ$ at neutrino telescopes.

### IV. CONCLUSION

We have argued that the role of neutrino mixing at high-energy neutrino telescopes is not trivial, and that
forthcoming observations are potentially interesting for neutrino mixing phenomenology. If sources like neutron or pion beams exist, we showed that: (i) They can be identified unambiguously at neutrino telescopes; (ii) They may allow a model-independent determination of crucial qualitative features of neutrino mixing parameters, like the octant of $\theta_{23}$ or the existence of a non-vanishing $\{\theta_{13}, \delta_{CP}\}$ sector.

From a complementary perspective, accurate laboratory measurements of neutrino mixing parameters are of primary importance to perform astrophysical diagnostics: Since the flux flavor ratios depend on mixing angles, degeneracies with astrophysical parameters may arise. For example, although the main emphasis in [2] was on the sensitivity of the ratio $R_G$ to $\theta_{12}$ (which is relatively well determined from solar neutrino experiments), we remark that varying $\theta_{13}$ in the allowed experimental range can have an impact as large as $\approx 15\%$ on $R_G$. This effect alone might affect the extraction of astrophysical parameters.

Throughout this paper, we have conservatively assumed that only the ratio $R$ can be determined at neutrino telescopes. At energies larger than a few PeV, and in particular around 6.3 PeV where the observable $R_G$ can be used, one might expect to measure or to constrain the $\tau$ flavor fraction as well, since $\nu_{\tau}$-specific signatures such as lolly-pop or double bang events can be detected [13]. It is clear that the chance for a multichannel observation offers a more powerful tool.

We conclude that the usual assumption of a canonical flavor equipartition at neutrino telescopes is too simplistic: Peculiar astrophysical sources may offer complementary constraints to laboratory measurements or, conversely, a more accurate experimental determination of mixing parameters may help to shed light on the properties of cosmic accelerators. After the pioneering era of the discovery of the solar neutrino deficit and of the atmospheric neutrino anomaly, observations at the highest energies will be sensitive to new astrophysical sources, that might still offer opportunities for neutrino oscillation studies.

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[30] The quantity $R$ approaches the ratio of track to shower events in the limit in which sub-leading neutral-current events are neglected, and if both channels are detected with the same efficiency. Typical size of track to shower ratio is of several, since the km-long muon range ensures a larger effective target volume for the tracks. This is however a technical point inessential to our considerations, since it could be accounted for in refined predictions and for a specific experimental setup.