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Galactic beta-beams as a tool to measure the neutrino 13-mixing angle and the CP-phase with neutrino telescopes

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The observed excess of high-energy cosmic rays from the Galactic plane in the energy range around 10^{18} eV may be naturally explained by neutron primaries generated in the photo-dissociation of nuclei. In this scenario, neutrons with lower energy decay before reaching the Earth and produce a detectable flux in a km^3 neutrino telescope. The initial flavor composition of these (anti)neutrinos, $\phi_e : \phi_\mu : \phi_\tau = 1 : 0 : 0$, offers the opportunity to perform a combined $\bar{\nu}_\mu/\bar{\nu}_\tau$ appearance and $\bar{\nu}_e$ disappearance experiment. The observable ratio of μ tracks over e and τ showers depends appreciably on the 13-mixing angle θ_{13} and the leptonic CP phase $\delta_{\rm CP}$, thus providing a new way to measure these quantities.

1. Introduction

The determination of the mixing parameters controlling the solar and atmospheric neutrino oscillations has already entered the precision era, but currently it exists only an upper limit for the 13-mixing angle θ_{13}, $\sin^2 2\theta_{13} < 0.1$ [1], while the CP-violating Dirac phase $\delta_{\rm CP}$ (the only one entering neutrino oscillation phenomenology) is completely unconstrained. Both the mixing angle θ_{13} and the phase $\delta_{\rm CP}$ are key features of a genuine three-flavour mixing scenario, but are observable in solar and atmospheric neutrino oscillation experiments only as small, sub-leading effects. Strong experimental efforts are planned to measure θ_{13} and eventually $\delta_{\rm CP}$, though the latter appears unlikely for the next generation of facilities [2].
It it then of primary interest to find other observables allowing to explore as soon as possible this "terra incognita" in the neutrino sector. In the following, we discuss the possibility to use high-energy neutrinos produced by decaying galactic neutrons to perform a measurement sensitive (in particular) to θ_{13} and $\delta_{\rm CP}$ at neutrino telescopes. Further details can be found in [3] and Refs. therein. If realized in Nature, such a source would have a similar potential for neutrino physics as a "β-beam" facility [4], with the main and non-negligible difference of being available for free. The other advantage is that it could be studied at observatories which will be build anyway for astrophysical purposes. We will estimate the relevance of the signal and the feasibility of the measurement in IceCube, which is the largest neutrino telescope under construction [5].

Neutron primaries have been invoked to explain an excess of high-energy cosmic rays (CRs) from two regions in the Galactic plane [6, 7]. This signal, in a limited energy range around 10^{18} eV, has been observed by several experiments with different techniques: the AGASA collaboration found a correlation of the arrival directions of CRs with the Galactic plane at the 4 σ level [8]. This excess, which is roughly 4% of the diffuse flux, is concentrated towards the Cygnus region, with a second hot spot towards the Galactic Center (GC) [9]. Such a signal has been independently confirmed by the Fly's Eye Collaboration [10] and by a re-analysis of the SUGAR data [11]. Complementary evidence for a cosmic accelerator in the Cygnus region comes from the detection of an extended TeV γ-ray source by the HEGRA experiment [12]. Similarly, multi-TeV γ-rays from the vicinity of the GC have been recently detected by HESS [13].

The excess from the Cygnus and GC region is seen at $E \approx 10^{18}$ eV, i.e. at energies where charged cosmic rays still suffer large deflections in the Galactic magnetic field so that only a neutral primary can produce a directional signal. Another evidence for neutrons as primaries is that the signal appears just at that energy where the neutron lifetime allows neutrons to propagate from a distance of several kpc.

Neutrons can be generated either in collisions of high-energy protons on ambient photons and protons, or in the photo-dissociation of nuclei. In the first case, the flux of $\bar{\nu}_e$ from neutron decays would be negligible compared to the neutrino flux from pion decays. Thus one expects a neutrino flavor composition of $\phi_e : \phi_\mu : \phi_\tau = 1 : 2 : 0$ before oscillations[1], typical for most sources of high-energy neutrinos. In contrast, photo-dissociation of nuclei produces a pure $\bar{\nu}_e$ initial flux. Since the energy fraction transferred to the $\bar{\nu}_e$ is of the order of 10^{-3} and only neutrons with $E \lesssim 10^{18}$ eV can decay on galactic distances, the neutrino flux from photo-dissociation is limited to sub-PeV energies. Moreover, the threshold for photo-dissociation on UV photons implies a lower cut-off at $E \sim$ TeV for the $\bar{\nu}_e$ energies.

In the following we use as our basic assumption that photo-dissociation of nuclei is the origin of the decaying neutrons. Some arguments supporting this scenario are discussed in [3]. We study the case where other neutrino sources contaminating the pure $\bar{\nu}_e$ initial flux can be neglected. Later on, we will relax this assumption, which is in any case experimentally falsifiable. To be specific, we use the model of Anchordoqui *et al.* in Ref. [6], who calculated the neutrino flux from the Cygnus region, which is in the field of view of the km^3 telescope IceCube. These authors estimated an integrated $\bar{\nu}_e$ flux from neutron decays of $\sim 2 \times 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $E > 1$ TeV by normalizing the neutron flux to the 4% anisotropic component observed by AGASA. This flux corresponds to ≈ 20 events (of all flavours) per year in IceCube.

2. Flavor composition after oscillations and discrimination in a neutrino telescope

Even at PeV energies, the galactic distances far exceed the experimentally known oscillation lengths. Thus the interference terms sensitive to the mass splittings $\Delta m^2_{(i)}$ in the usual oscillation formulas average-out. Moreover, the extremely low density of the interstellar medium allows to neglect matter effects, so the relevant probabilities $P_{\alpha\beta} \equiv P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ can be written solely in terms of the *vacuum* mixing matrix U. The fluxes ϕ^D_β arriving at the detector are then given by

$$\phi^D_\beta = \sum_\alpha P_{\alpha\beta}\phi_\alpha = P_{e\beta}\,\phi_e = \left[\delta_{e\beta} - 2\sum_{j>k} \mathrm{Re}(U^*_{\beta j}U_{\beta k}U_{ej}U^*_{ek})\right]\phi_e\,, \tag{1}$$

where we have inserted $\phi_\alpha = (\phi_e, 0, 0)$, and greek (latin) letters are flavor (mass) indices. The following properties also hold: P_{ee} is independent from θ_{23} and $\delta_{\rm CP}$, $P_{e\mu}$ and $P_{e\tau}$ depend on $\delta_{\rm CP}$ only via $\cos\delta_{\rm CP}$, and $P_{e\mu} = P_{e\tau}(\theta_{23} \to \theta_{23} + \pi/2)$.

Let us now recall briefly the flavor-discrimination possibilities in a neutrino telescope [14]. For the TeV-PeV energies relevant here, the charged-current interactions of ν_e and ν_τ are distinguishable in principle by the different muon content in electromagnetic (e.m.) and hadronic showers. Since this measurement is experimentally challenging, we shall conservatively consider ν_e and ν_τ as indistinguishable in a neutrino telescope. By contrast, in ν_μ charged-current interactions the long range of muons ensures that the muon track is always visible and allows the identification of these events. In the following, we will also neglect neutral current events (see the discussion in [3]) and consider the combined $\bar{\nu}_e$ and $\bar{\nu}_\tau$ flux $\phi^D_{e+\tau}$ and the $\bar{\nu}_\mu$ flux ϕ^D_μ as our two observables. If no prior information on the absolute source flux ϕ_e is assumed, the only measurable quantity sensitive to mixing parameters is the flux ratio $R \equiv \phi^D_\mu/\phi^D_{e+\tau}$. Under these assumptions, this probe *alone* does not allow the simultaneous measurement of both θ_{13} and $\delta_{\rm CP}$. In Fig. 1, we show the expected ratio R as a function of θ_{13} for three representative values of θ_{23}, each curve for the two extreme cases of $\delta_{\rm CP} = 0°$ and $\delta_{\rm CP} = 180°$. In all the cases we fix the value of the solar mixing angle to the best fit value $\theta_{12} = 32.5°$. First notice how the three sets of curves show a clear sensitivity to the octant of the angle θ_{23}. Moreover, in the best

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[1] We denote with ϕ_α the combined flux of ν_α and $\bar{\nu}_\alpha$.

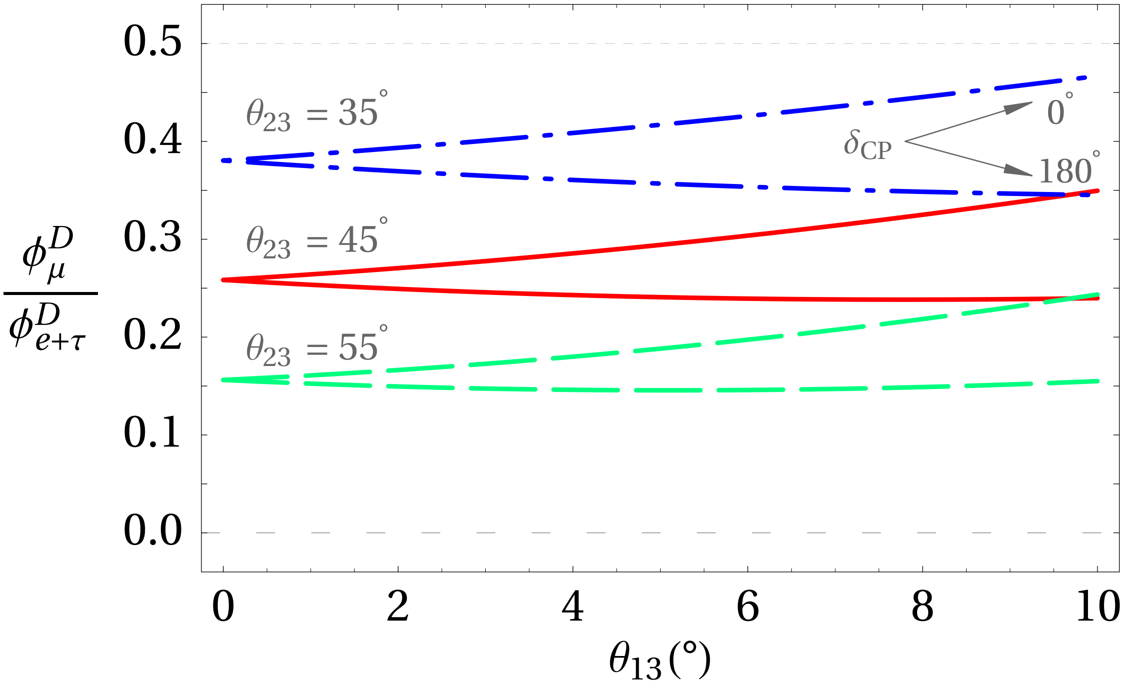

Figure 1. Flux ratio $R = \phi_\mu^D/\phi_{e+\tau}^D$ at Earth (for initial fluxes $\phi_e : \phi_\mu : \phi_\tau = 1 : 0 : 0$) as a function of θ_{13} for $\theta_{23} = 35^\circ, 45^\circ$, and 55°, each one shown for the two extreme values, $\cos\delta_{CP} = \pm 1$. The ratios $R = 0.5$ and 0.0 expected respectively for standard astrophysical sources and in case of no oscillations are also shown for comparison.

case of $\delta_{CP} = 0^\circ$, R varies by $\sim 50\%$ in the interval $0^\circ \leq \theta_{13} \leq 10^\circ$ and differs in the extreme by a factor of three from the standard value, $R = 1/2$, expected by a typical astrophysical source. Finally, varying δ_{CP} in the interval $0^\circ \leq \delta_{CP} \leq 180^\circ$ the ratio R can change up to 40% (in the best case $\theta_{13} \approx 10^\circ$). This effect obviously disappears when $\theta_{13} \to 0$.

3. Event rates in IceCube

The excellent angular resolution of 0.7° expected for IceCube applies only for muon induced showers, while for ν_e and ν_τ events the resolution is only about 25° [14]. From the estimate in Ref. [6] one easily derives that, in a 0.7° radius around the Cygnus region, one expects roughly ≈ 2.3 events per year ($E >$1 TeV), to be compared with about $4\,\bar{\nu}_\mu$ yr^{-1} signal events ($\theta_{23} = 45^\circ$, $\theta_{13} = 0$). A 2 σ detection of the $\bar{\nu}_\mu$ flux is then within 1 yr capability of IceCube. Rescaling this background number to a cone of 25° opening angle, one expects about 2900 ν_μ background events and 145 background showers[2]. The resulting statistical fluctuation of the background shower number is $\sqrt{N} \approx 12$. Thus integrating one year the ≈ 16 yr^{-1} rate from Cygnus one expects a 1.3 σ signal hint, or equivalently a 4.2 σ measurement in a decade.

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[2] Here we used the fact that the atmospheric neutrino background has a flavor ratio of $\phi_e : \phi_\mu : \phi_\tau \approx 0.05 : 1 : 0$ in the energy range of interest, 10^{11} eV $\lesssim E \lesssim 10^{14}$ eV [15].

Obviously, the poor angular resolution for ν_e and ν_τ events is the most serious obstacle to improve this measurement. Theoretical predictions for the neutron spectrum at the source could also be used to optimize the detection strategy: for example, for a $\bar{\nu}_e$ spectrum harder than the atmospheric neutrino background, the signal to background ratio could be improved by an increase of the threshold energy.

Let us now comment on the case where we add to our signal some contamination from conventional pion decay source. A 10% (100%) flux "pollution"[3] would led to an upward shift of 0.01 (0.1) in the flux ratio R. Note that, since the background from pion decay always pushes R towards $1/2$, a detection of $R < 1/2$ would in any case constrain the mixing parameter space, in particular if complementary information from terrestrial experiments will be available. If neutrons would be generated *mainly* in *pp* or $p\gamma$ collisions, a much larger flux of neutrinos from pion decays, with $R = 1/2$, is expected. This would simplify the detection of these galactic point sources by neutrino telescopes, though the θ_{13} and $\delta_{\rm CP}$ searches discussed here would be probably hopeless. In this case, however, one could still exploit the information for astrophysical source diagnostics as well as for CR composition studies.

In summary, it has been argued that the excess of high-energy cosmic rays from the Galactic Plane in the energy range around 10^{18} eV is caused by neutron primaries generated in the photo-dissociation of nuclei. If this model is correct, we showed that these sources could be used as "galactic beta beams" in neutrino telescopes, providing in particular a tool to measure θ_{13} and $\delta_{\rm CP}$ via the observable ratio of track to shower events. Obviously, a better theoretical modeling of sources as well as more experimental studies are highly desirable. Especially worthwhile would be a confirmation of the anisotropy by the Auger observatory [16] and more detailed chemical composition studies by the Kascade-Grande experiment [17].

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[3] A contamination of $\mathcal{O}(10\%)$ is indeed what is expected for the model of [6].