PHYSICAL REVIEW D **83**, 091301(R) (2011)

Heavy-neutrino decays at neutrino telescopes

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(Received 7 March 2011; published 19 May 2011)

It has been recently proposed that a sterile neutrino ν_h of mass $m_h = 40$–80 MeV, mixing $|U_{\mu h}|^2 \approx 10^{-3}$–$10^{-2}$, lifetime $\tau_h \leq 10^{-9}$ s, and a dominant decay mode $\nu_h \to \nu\gamma$ could be the origin of the experimental anomalies observed at LSND and MiniBooNE. Such a particle would be abundant inside air showers, as it can be produced in kaon decays. We use the Z-moment method to evaluate its atmospheric flux and the frequency of its decays inside neutrino telescopes. We show that ν_h would imply around 10^4 contained showers of energy between 0.1 and 100 TeV per year inside a 0.03 km^3 telescope like ANTARES or the DeepCore in IceCube, while the standard background is 100 times smaller. Therefore, although it may be challenging from an experimental point of view, a search there could confirm this heavy-neutrino possibility.

DOI: 10.1103/PhysRevD.83.091301 PACS numbers: 14.60.St, 13.35.Hb, 95.85.Ry

I. INTRODUCTION

The direct observation of neutrino interactions in different types of experiments [1] has been used to establish a basic picture of neutrino masses and mixings. From a model building point of view, this is arguably the most significant discovery in particle physics since the confirmation of the standard model in the early 1970s, as it reveals a scale that is (most likely) not electroweak. The picture, however, has faced some persistent anomalies in experiments with neutrino beams from particle accelerators. Basically, muon neutrinos of energy below 1 GeV seem to experience an excess of charged-current (CC) interactions with an electron in the final state. The interpretation of these events in terms of $\nu_\mu \to \nu_e$ oscillations is inconsistent with the mass parameters deduced from solar, atmospheric, and reactor neutrino observations.

In a recent analysis Gninenko [2] has made a very compelling case for a massive neutrino as the origin for all these anomalies:

(i) LSND [3] observed $\bar{\nu}_e$-like events ($\bar{\nu}_e p \to e^+ n$) with a gamma signal from neutron capture that seem to imply an excess of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. Gninenko shows that the events could be equally explained through ν_h production ($\nu_\mu^{12}C \to \nu_h n X$) followed by its radiative decay $\nu_h \to \nu\gamma$, with the final γ converted into a e^+e^- pair indistinguishable from an electron. This explanation would work for a large enough production cross section ($|U_{\mu h}|^2 \approx 10^{-3}$–$10^{-2}$ and $m_\nu < 80$ MeV) and a short enough decay length ($\tau_h \lesssim 10^{-9}$ s and $m_\nu > 40$ MeV). During the first years of data taking LSND also observed an excess of $\nu_e^{12}C \to e^- X$ events that were interpreted as $\nu_\mu \to \nu_e$ oscillations but are consistent as well with the ν_h hypothesis.

(ii) KARMEN [4], using a similar technique, did not confirm the LSND anomalies. The neutrinos at LSND, however, had an average energy of 100 MeV and a long high-energy tail, whereas the spectrum at KARMEN was a narrow peak around 20 MeV. Gninenko shows that a 40 MeV neutrino would be above the production threshold at KARMEN, which makes his hypothesis consistent with the data.

(iii) MiniBooNE [5] has observed an excess of electron-like events for ν_e energies between 200 and 475 MeV, with no significant excess at higher energies. Gninenko's fit exhibits also a good agreement with the data (higher-energy events are disfavored by an increase in the decay length and are hidden by the low statistics). More recently [6], this experiment has also reported an excess in $\bar{\nu}_\mu$ data for antineutrino energies in a wider range. Gninenko's fit is consistent as well, and could favor a Dirac nature for ν_h.

In addition, the mass range $40 \leq m_h \leq 80$ MeV makes ν_h too heavy to be produced in pion decays and too light to distort the muon spectrum in kaon decays. The heavy neutrino is also produced when the muon itself decays, but he argues that a mixing $|U_{\mu h}|^2 < 10^{-2}$ makes it acceptable. Specific searches for unstable neutrinos put strong constraints on $|U_{\mu h}|$, but are based on decays with charged particles in the final state ($\nu_h \to ee\nu$, $\mu e\nu$, $\mu\pi\nu$), never on the decay $\nu_h \to \nu\gamma$ induced by a magnetic moment transition. Its large mass and short lifetime should keep ν_h also *safe* from bounds from supernovae and primordial nucleosynthesis [7]. Finally, a recent analysis [8] of muon capture with photon emission at TRIUMF finds that Gninenko's neutrino would imply a signal well above the 30% excess (versus the standard model value) deduced from the data [9]. One should notice, however, that the photon energy cut and the small size of the target volume at TRIUMF make this experiment very sensitive to the

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neutrino lifetime. A value $\tau_h \approx 3 \times 10^{-9}$ s could imply a consistent radiative capture rate there while explaining the data at LSND and KARMEN (which require $\tau_h \leq 10^{-8}$ s) and still having an impact at MiniBooNE.[1]

We find the heavy-neutrino hypothesis very interesting and will study here its implications in a different type of experiment. Our basic observation is that ν_h would be abundantly produced in the atmosphere through kaon decays. At energies around 1 TeV its decay length becomes $c\tau_h\gamma \approx 5$ km, which implies that ν_h can reach a neutrino telescope and then decay. The final photon would be seen there as a *pointlike* event, similar to the shower from $\nu_e N \to eX$ or from a neutral-current (NC) interaction of high inelasticity but clearly distinguishable from the muon track in $\nu_\mu N \to \mu X$.

II. NEUTRINO FLUXES AT SEA LEVEL

The atmospheric flux of any species can be easily estimated using the Z-moment method [10,11]. This method provides a set of coupled differential equations that describe the evolution with the atmospheric depth t (in $\mathrm{g/cm^2}$) of the fluxes of *parent* hadrons (ϕ_H with $H = p$, n, $\pi^\pm$, $K^\pm$, K_L) and of any particles that may result from their decay or their collision with an air nucleus. The generic equations for $\phi_H(E, \theta, t)$ are

$$\frac{\partial \phi_H}{\partial t} = -\frac{\phi_H}{\lambda^H_{\rm dec}} - \frac{\phi_H}{\lambda^H_{\rm int}} + \sum_{H'} S_{H'H}, \qquad (1)$$

where $\lambda^H_{\rm dec}$ ($\lambda^H_{\rm int}$) is the decay (interaction) length of H in the air and $S_{H'H}$ describe the sources. These equations can be solved analytically under some simplifying assumptions, namely,

(i) the all-nucleon primary flux has a constant spectral index $-\alpha$;
(ii) the energy distribution of particles from collisions and decays scales linearly with the energy of the parent hadron;
(iii) the hadronic interaction lengths $\lambda^H_{\rm int}$ do not change with the energy;
(iv) the contributions to the nucleon flux from meson collisions and to the pion flux from kaon collisions are negligible.

It follows that the nucleon fluxes ϕ_N keep the same spectral index $-\alpha$ at any depth, and that the source terms are reduced to

$$S_{NH} = \frac{\phi_N}{\lambda^N_{\rm int}} Z_{NH}, \qquad (2)$$

where the Z-factors

$$Z_{NH} = \int_0^1 {\rm d}x x^{\alpha-1} F_{NH} \qquad (3)$$

are constants (independent of E and the zenith angle θ) derived from the distribution $F_{NH}(x)$ of the fraction of energy taken by H after an N-air collision. The meson fluxes ϕ_M can then be easily derived in two different regimes. At low energies $\lambda^M_{\rm dec} = (E/m_M)c\tau_M\rho$ is much smaller than $\lambda^M_{\rm int}$ and meson interactions can be ignored, whereas at high energies the variations in ϕ_M are dominated by collisions with air nuclei (the air density ρ is a function of t and of θ). A simple interpolation can be used between these regimes. We take in our analysis the primary flux, the Z-factors, and the atmospheric model in [11] (see [12] for a discussion of the fluxes at higher energies). We obtain, for example, that the TeV charged-pion vertical flux reaches its maximum (a 4% of the initial nucleon flux) at a depth of 200 $\mathrm{g/cm^2}$, and that the kaon flux there is 7 times smaller.

The lepton fluxes from meson decays can also be incorporated. In particular, standard neutrinos do not interact nor decay in the atmosphere and their flux equations will only depend on source terms of type

$$S_{M\nu}(E) = B(M \to \nu) \int_0^1 {\rm d}x x^{-1} \frac{\phi_M(E/x)}{\lambda^M_{\rm dec}(E/x)} F_{M\nu}(x), \qquad (4)$$

where $B(M \to \nu)$ is the branching ratio of a given decay mode, $F_{M\nu}(x)$ is again the distribution of the fraction of energy taken by the neutrino in that decay, and the dependence on t and θ is implicit. We obtain that, although kaons are less abundant than pions in air showers, a lower ratio $\lambda^M_{\rm dec}/\lambda^M_{\rm int}$ makes them the main source of neutrinos at energies above 100 GeV. The TeV flux at sea level is dominated by muon neutrinos, with $\phi_{\bar\nu_\mu} \approx 0.42\phi_{\nu_\mu}$, $\phi_{\nu_e} \approx 0.036\phi_{\nu_\mu}$, and $\phi_{\bar\nu_e} \approx 0.023\phi_{\nu_\mu}$.

Heavy neutrinos ν_h will be mainly produced in charged-kaon decays. The branching ratio is

$$B(K^+ \to \mu^+\nu_h) \approx B(K^+ \to \mu^+\nu) \times |U_{\mu h}|^2 \bar\rho_h, \qquad (5)$$

where $B(K^+ \to \mu^+\nu) = 0.64$ and the kinematic factor for $m_h = 40$–80 MeV is $\bar\rho_h \approx (1 + m_h^2/m_\mu^2)$ [13]. The fraction of energy x taken by ν_h will have a flat distribution (a constant $F_{Kh}(x)$) between $x_{\rm min}$ and $x_{\rm max}$,

$$x_{\substack{\rm min\\ \rm max}} = \frac{1}{2}\left(1 + \frac{m_h^2 - m_\mu^2}{m_K^2}\right) \mp \sqrt{\frac{1}{4}\left(1 + \frac{m_h^2 - m_\mu^2}{m_K^2}\right) - \frac{m_h^2}{m_K^2}}. \qquad (6)$$

There will be smaller contributions from $K^+ \to \pi^0\mu^+\nu_h$ and $K_L \to \pi^-\mu^+\nu_h$, plus the analogous K^- and K_L decays into $\bar\nu_h$ (the heavy neutrino may be a Dirac or a Majorana particle; see discussion in [2]). The equation defining $\phi_h(E, \theta, t)$ is

[1]A global fit including TRIUMF would certainly constrain further the parameter space in Gninenko's model.

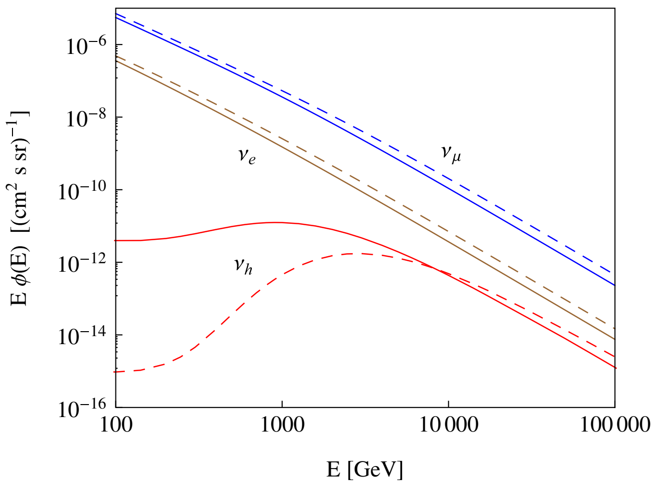

FIG. 1 (color online). Neutrino fluxes ($\nu_i + \bar{\nu}_i$) at sea level for $\theta = 0$ (solid lines) and $\theta = 60^\circ$ (dashed lines).

$$\frac{\partial \phi_h}{\partial t} = -\frac{\phi_h}{\lambda^h_{\rm dec}} + \sum_K S_{Kh}, \quad (7)$$

where the source terms take the form in Eq. (4), $\lambda^h_{\rm dec} = (E/m_h) c\tau_h \rho$, and the sum runs over the decay modes that produce ν_h. In Fig. 1 we plot the total heavy neutrino flux at sea level from inclinations $\theta = 0^o, 60^o$. We have taken the central values $m_h = 60$ MeV and $|U_{\mu h}|^2 = 0.005$, with $\tau_h = 10^{-9}$ s. At 1 TeV 73% of the flux comes from K^+ decays, K^- contributes a 25%, and K_L just a 2%. Finally, notice that the photons produced in the air through ν_h decays are together with other photons and muons *inside* the parent shower and are therefore nonobservable.

III. EVENTS AT A NEUTRINO TELESCOPE

As neutrinos enter the ground their sources disappear and they just experience two types of processes: heavy neutrinos ν_h may decay into $\gamma\nu_\mu$, whereas ν_μ and ν_e may have neutral- or charged-current interactions with matter. At a depth d the sea-level fluxes $\phi_i(E, \theta, 0)$ become

$$\phi_h(E, \theta, d) = \phi_h(E, \theta, 0) \exp\left(\frac{-d}{\lambda^h_{\rm dec} \cos\theta}\right);$$
$$\phi_\nu(E, \theta, d) = \phi_\nu(E, \theta, 0) \exp\left(\frac{-d}{\lambda^\nu_{\rm int} \cos\theta}\right), \quad (8)$$

where d and the decay/interaction lengths are given in meters and we have neglected the curvature of the Earth (a good approximation for $\theta \leq 85^o$). At 1 TeV we obtain $\lambda^h_{\rm dec} \approx 5$ km, whereas $\lambda^\nu_{\rm CC} \approx 2 \times 10^6$ km and $\lambda^\nu_{\rm NC} \approx 8 \times 10^6$ km (the interaction lengths decrease with the energy as $1/\sigma_{\nu N}$). This means that the decay of a ν_h crossing a neutrino telescope is 10^6 times more probable than the interaction of a standard neutrino. In addition, CC ν_μ interactions will be clearly different from ν_h decays, as the final muon will produce a track hundreds of meters long [14]. The electromagnetic shower from a ν_h decay will be pointlike (it develops in a few meters), similar to the one produced by a NC interaction or a ν_e CC process. These standard events, however, are suppressed by the lower ν_e fluxes ($\nu_\mu \to \nu_e$ oscillations at $L \leq 100$ km and $E \geq 100$ GeV are negligible) and the inelasticity distribution ($\propto 1/y$ [15]) in ν-N collisions.

Let us be more specific. To estimate the number of events per unit time that occurred inside a telescope one needs to calculate the total flux (ingoing plus outgoing neutrinos) through the surface containing the detectors. We model this region as a cylinder of section A and length H starting at a depth d_0 (i.e., d goes from d_0 to $d_0 + H$). For a fixed angle $\theta \lesssim 85^o$ the neutrino flux only depends on the depth d. Therefore, the total flux through the lateral surface of the detector will be zero (given θ, the flux through any lateral $d\vec{S}$ is equal to the flux leaving the detector through an opposed lateral surface $-d\vec{S}$; see Fig. 2). The number of heavy-neutrino events inside the detector in an interval of energy and solid angle per unit time can then be calculated as the difference between the fluxes through its upper and its lower sections,

$$N_h = \int_{\Delta E} dE \int_{\Delta\Omega} d\Omega \int_A dS \cos\theta [\phi_h(E, \theta, d_0) - \phi_h(E, \theta, d_0 + H)]. \quad (9)$$

An analogous expression can be obtained to estimate the number N_ν of interactions inside the detector produced by neutrinos from those directions. In Fig. 3 we plot in dashes the energy distribution of the neutrinos that interact (ν_μ and ν_e) or decay (ν_h) per year inside a detector like ANTARES [16] ($A = 0.1$ km^2, $d_0 = 2.2$ km, $H = 0.3$ km) or the DeepCore [17] in IceCube (of similar size and depth). The energy of the initial neutrino, however, is not the most relevant parameter for observation; as in NC interactions only a small fraction y may be deposited in the detector. In a ν_h decay only the photon energy is *visible* (we will assume an isotropic decay [2]), whereas in ν_e-CC interactions all the energy carried by the neutrino goes to the contained shower. If the inelasticity y in the event has a distribution $F_{\nu{\rm sh}}(y)$, then the energy distribution of the cascades inside the detector will be

$$\frac{dN_{\rm sh}}{dE}(E) = \int_0^1 dy y^{-1} \frac{dN_\nu}{dE}(E/y) F_{\nu{\rm sh}}(y). \quad (10)$$

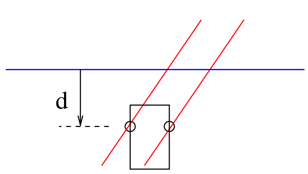

FIG. 2 (color online). The total flux through the lateral surface of the detection region cancels if $R_T \gg d/\cos\theta$ (we take $\theta \leq 85^\circ$).

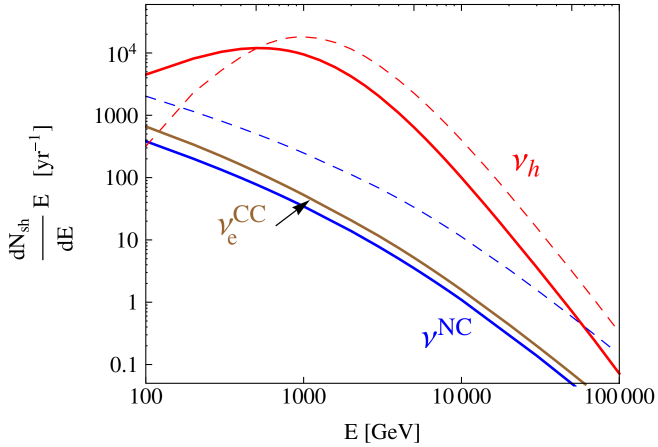

FIG. 3 (color online). Energy distribution of the contained showers from $\nu_h \to \nu_\mu \gamma$, $\nu N \to \nu X$, and $\nu_e N \to eX$ at ANTARES. We also plot (dashed lines) the energy distribution of the parent neutrino in each case.

Figure 3 shows in solid lines the main result of our analysis. The number of standard showers of energy above 100 GeV from down-going neutrinos inside ANTARES is around 1300 per year (60% from ν_e-CC interactions and 40% from NC interactions). For the central values $m_h = 60$ MeV and $|U_{\mu h}|^2 = 0.005$ the heavy neutrino would provide 26 000 extra events. If the energy threshold is set at 500 GeV the number of standard events is reduced to 220 per year, whereas the number of events from ν_h decays is just cut to 14 000.

IV. SUMMARY AND DISCUSSION

Telescopes like ANTARES or IceCube are designed to observe upward-moving muons produced in neutrino interactions near the detector. These events are *clean*, in the sense that no particles except for neutrinos can reach the detector after crossing the Earth. Telescopes can also observe the contained showers produced in NC interactions or in ν_e-CC processes. Since their development takes just a few meters, these events are pointlike, and the only sign indicating whether they are caused by an upward- or a downward-going neutrino is that in the latter case they may come together with muons.

In this paper we have shown that the decay of a long-lived neutral particle produced in the atmosphere could change drastically (by over a factor of 100) the number of TeV-contained showers in these experiments. In particular, we have analyzed Gninenko's heavy neutrino, that appears as a possibility well motivated by the results at LSND, KARMEN, and MiniBooNE. We find remarkable that its mass, mixing, and lifetime optimize the *distortion* introduced in TeV-neutrino telescopes: below ≈ 100 GeV ν_h does not reach the telescope, and above 100 TeV its decay length becomes too large and the signal vanishes (notice that $\lambda^h_{\rm dec}$ grows with the energy while $\lambda^\nu_{\rm int}$ decreases).

The heavy neutrino would be produced through kaon decays inside air showers together with a muon of similar energy. A crucial question is then whether these decays can be disentangled from the muon bundle associated with the parent shower. ANTARES or the DeepCore in IceCube are more than 2 km deep, and as the zenith angle grows all muon effects will decrease. In contrast, the zenith-angle dependence of the ν_h events up to 85° is very mild (especially at larger energies), since these neutrinos do not lose energy in their way to the detector. Therefore, the TeV-contained showers should appear as a clear anomaly that may be accompanied by muons in vertical events but that *persists* at higher zenith angles (slant depths). The large number of events that we obtain could allow for specific searches. For example, events with lower-energy muons in the upper part of the detector followed by a contained TeV shower below, or other topologies that would otherwise be discarded.

If a heavy neutrino is the explanation of the LSND and MiniBooNE anomalies, our results show that it will reach effectively the core of neutrino telescopes and will decay there at a high rate. A Monte Carlo simulation of individual showers, including all the muon backgrounds and the response of the detector, should then provide the best strategy in the search for an observable signal that confirms or excludes this heavy-neutrino possibility.

ACKNOWLEDGMENTS

We would like to thank Juande Zornoza for discussions. This work has been partially supported by MICINN of Spain (FPA2006-05294, FPA2010-16802, FPA2010-16696, Consolider-Ingenio Multidark CSD2009-00064, and CPAN CSD2007-00042) and by Junta de Andalucía (FQM 101, FQM 437, and FQM 3048).

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