EXPLORING THE UNIVERSE BEYOND THE PHOTON WINDOW*

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In this talk I review how to identify cosmic ray accelerators that are high energy neutrino emitters. I also delineate the prospects for a new multi-particle astronomy: neutrons as directional pointers + antineutrinos as inheritors of directionality.

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1. Introduction

Conventional astronomy spans about 18 decades in photon wavelengths, from 10^4 cm radio-waves to 10^{-14} cm γ-rays of GeV energy. Because the universe is opaque to photons of TeV energy and above (see Fig. 1) [1], present studies focus on hadrons, neutrinos, and gravitational waves as messengers probing the high energy universe. The best candidates to serve as messengers in a new astronomy of the high energy behavior of distant sources are neutral particles. This is because the orbit of a charged cosmic ray can be substantially bent, both by extragalactic magnetic fields [2] and by the ambient magnetic field of our own Galaxy [3]; destroying the possibility of locating the source. The most promising messenger is the neutrino: it can be copiously produced in cosmic beam dumps and can traverse unscathed dense astrophysical environments. In this talk I delineate the prospects to identify high energy neutrino emitters.

2. Cosmic ray astronomy

For primary energy > 1 GeV, the observed cosmic ray intensity can be described by a series of power laws with the flux falling about 3 orders of magnitude for each decade increase in energy [4]. In recent years,

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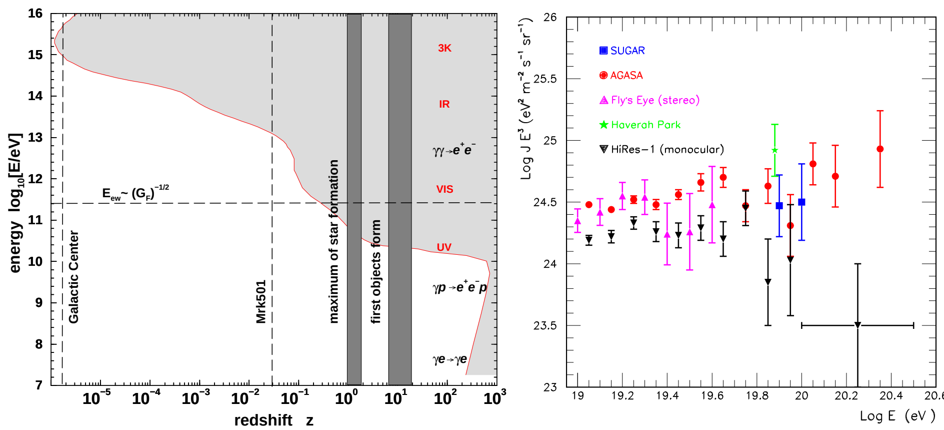

Fig. 1. Left: Mean interaction length for photons on the ultraviolet, visible, infrared and microwave backgrounds [1]. Right: Upper end of the cosmic ray energy spectrum as observed by 5 different experiments (for details see main text).

a somewhat confused picture *vis-à-vis* the energy spectrum and arrival direction distribution has been emerging. Since 1998, the AGASA Collaboration has consistently reported [5] a continuation of the spectrum beyond the expected Greisen–Zatsepin–Kuzmin (GZK) cutoff [6], which should arise at about $10^{10.9}$ GeV if cosmic ray sources are at cosmological distances. This theoretical feature of the spectrum is mainly a consequence of interactions of the primary cosmic ray with the microwave background radiation. In contrast, the most recent results from HiRes [7] describe a spectrum which is consistent with the expected GZK feature. The discrepancy between the 2 estimated fluxes is shown in Fig. 1 (for comparison, the intensity as seen by the Fly's Eye [8], the Haverah Park [9] and the SUGAR [10] experiments is also shown). This situation is suggestive of the challenge posed by systematic errors in these types of measurements. Further confusing the issue, the AGASA Collaboration reports observations of event clusters which have a chance probability smaller than 1% to arise from a random distribution [11], whereas the recent analysis reported by the HiRes Collaboration showed that their data are consistent with no clustering among the highest energy events [12]. In my opinion, it is *very important* to rigorously define the corresponding budget of statistical significance and search criteria *prior* to studying the data, since defining them *a posteriori* may inadvertently introduce an indeterminate number of "trials" and thus make it impossible to assign the correct statistical significance to the search result. In this direction, with the aim of avoiding accidental bias on the number of trials performed in selecting the angular bin, the original claim of the AGASA Collaboration was re-examined considering only those events observed after the original claim [13]. This study showed that the evidence for clustering in the AGASA data set is weaker than was previously supposed, and is consistent with the hypothesis of isotropically distributed arrival directions. The confusing experimental situation regarding the GZK feature should be resolved in the near future by the Pierre Auger Observatory [14], which will provide not only a data set of unprecedented size, but also the machinery for controlling some of the more problematic systematic uncertainties.

With the controversy over the GZK cutoff, one may have missed the fact that below 10^{10} GeV AGASA has revealed a correlation of the arrival direction of the cosmic rays to the Galactic Plane (GP) at the 4σ level [15]. The GP excess, which is roughly 4% of the diffuse flux, is mostly concentrated in the direction of the Cygnus region, with a second spot towards the Galactic Center (GC). The anisotropy signal spans a narrow energy window, from $10^{8.7}$ GeV to $10^{9.3}$ GeV. Evidence at the 3.2σ level for GP enhancement in a similar energy range has also been reported by the Fly's Eye Collaboration [16]. Interestingly, the full Fly's Eye data include a directional signal from the Cygnus region which was somewhat lost in an unsuccessful attempt to relate it to γ-ray emission from Cygnus X-3 [17][1]. Additionally, a 3.4σ excess from an extended region surrounding Cygnus X-3 has been reported by the Yakutsk Collaboration [19]. On the other hand, the existence of a point-like excess in the direction of the GC has been confirmed via independent analysis [20] of data collected with the SUGAR facility. This is a remarkable level of agreement among experiment using a variety of techniques.

Independent evidence may be emerging for a cosmic accelerator in the Cygnus spiral arm. The HEGRA experiment has detected an extended TeV γ-ray source in the Cygnus region with no clear counterpart and a spectrum

$$\frac{dF_\gamma}{dE_\gamma} = 4.7^{\pm 2.1}_{\pm 1.3} \times 10^{-13} \left(\frac{E_\gamma}{1 \text{ TeV}} \right)^{-1.9^{\pm 0.3}_{\pm 0.3}} \text{ cm}^{-2}\text{s}^{-1}\text{TeV}^{-1} \ , \tag{1}$$

not easily accommodated with synchrotron radiation by electrons [21]. Especially intriguing is the possible association of this source with Cygnus-OB2, a cluster of more than 2700 (identified) young, hot stars with a total mass of $\sim 10^4$ solar masses [22]. Proton acceleration to explain the TeV photon signal requires only 0.1% efficiency for the conversion of the energy in the stellar wind into cosmic ray acceleration. Also, the stars in Cygnus-OB2 could be the origin of time-correlated, clustered supernova remnants forming a source of cosmic ray nuclei. *An immediate consequence of this picture is the creation of free neutrons via nuclei photodisintegration on background photon fields.* These liberated neutrons are presumably responsible for the

[1] The complete isotropy at PeV energies revealed by KASCADE data [18] vitiate direction-preserving photons as primaries.

observed directional signals. *This implies that it may not be a coincidence that the signal appears first at energies where the neutron lifetime allows propagation distances of galactic scales, i.e., 10 kpc.*

3. Neutrino astronomy

Neutrinos can serve as unique astronomical messengers. Except for oscillations induced by transit in a vacuum Higgs field, neutrinos propagate without interactions between source and Earth, providing powerful probes of high energy astrophysics [23]. The deployment of under-ice/water telescopes in the Northern [24] and Southern [25] hemispheres will greatly increase the statistics required for the realization of such a program. In this section we study possible mechanisms for neutrino production in astrophysical sources and discuss how flavor oscillations can distort the initial injection spectra.

3.1. Flavor metamorphosis

In recent years, stronger and stronger experimental evidence for neutrino oscillations has been accumulating. Neutrino flavor change implies: *(i)* that neutrinos have nonzero masses, *i.e.*, there is a spectrum of 3 or more neutrino mass eigenstates that are analogues of the charged lepton mass eigenstate l_α ($\alpha = e, \mu, \tau$); *(ii)* leptonic mixing, *i.e.*, the weak interaction coupling the W boson to a charged lepton and a neutrino, can also couple any charged lepton mass eigenstate l_α to any neutrino mass eigenstate ν_j ($j = 1, 2, 3, \ldots$). The superposition of neutrino mass eigenstates produced in association with the charged lepton of flavor α

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle \ , \tag{2}$$

is the state we refer to as the neutrino of flavor alpha, where $U^*_{\alpha j}$ are elements of the neutrino mass-to-flavor mixing matrix, fundamental to particle physics.

Throughout this talk we consider 3 neutrino species. In this case, atmospheric data [26] indicate that ν_μ and ν_τ are maximally mixed and reactor data [27] points to $|U_{e3}|^2 \ll 1$. Thus, to simplify the discussion hereafter we use the fact that $|U_{e3}|^2$ is nearly zero to ignore CP violation and assume real matrix elements. With this in mind, one can define a mass basis as follows

$$|\nu_1\rangle = \sin\theta_\odot |\nu^\star\rangle + \cos\theta_\odot |\nu_e\rangle \, , \tag{3}$$

$$|\nu_2\rangle = \cos\theta_\odot |\nu^\star\rangle - \sin\theta_\odot |\nu_e\rangle \, , \tag{4}$$

and

$$|\nu_3\rangle = \frac{1}{\sqrt{2}}(|\nu_\mu\rangle + |\nu_\tau\rangle)\,, \tag{5}$$

where $\theta_\odot$ is the solar mixing angle and

$$|\nu^\star\rangle = \frac{1}{\sqrt{2}}(|\nu_\mu\rangle - |\nu_\tau\rangle) \tag{6}$$

is the eigenstate orthogonal to $|\nu_3\rangle$. Inversion of the neutrino mass-to-flavor mixing matrix leads to

$$|\nu_e\rangle = \cos\theta_\odot|\nu_1\rangle - \sin\theta_\odot|\nu_2\rangle \tag{7}$$

and

$$|\nu^\star\rangle = \sin\theta_\odot|\nu_1\rangle + \cos\theta_\odot|\nu_2\rangle\,. \tag{8}$$

Finally, by adding Eqs. (5) and (6) one obtains the ν_μ flavor eigenstate

$$|\nu_\mu\rangle = \frac{1}{\sqrt{2}}\left[|\nu_3\rangle + \sin\theta_\odot|\nu_1\rangle + \cos\theta_\odot|\nu_2\rangle\right]\,, \tag{9}$$

and by subtracting these same equations the ν_τ eigenstate.

The evolution in time of the ν_i component of a neutrino initially born as ν_α in the rest frame of that component is described by Schrödinger's equation

$$|\nu_i(\tau_i)\rangle = e^{-im_i\tau_i}|\nu_i(0)\rangle\,, \tag{10}$$

where m_i is the mass of ν_i and τ_i is the proper time. In the lab frame, the Lorentz invariant phase factor may be written as $e^{-i(E_it-p_iL)}$, where t, L, E_i, and p_i, are respectively, the time, the position, the energy, and the momentum of ν_i in the lab frame. Since the neutrino is extremely relativistic $t \approx L$ and $E_i = \sqrt{p^2+m_i^2} \approx p + m_i^2/2p$. Hence, from Eq. (2) it follows that the state vector of a neutrino born as ν_α after propagation of distance L becomes

$$|\nu_\alpha(L)\rangle \approx \sum_i U_{\alpha i}\, e^{-i(m_i^2/2E)\ L}\ |\nu_i\rangle\,, \tag{11}$$

where $E \approx p$ is the average energy of the various mass eigenstate components of the neutrino. Using the unitarity of U to invert Eq. (2), from Eq. (11) one finds that

$$|\nu_\alpha(L)\rangle \approx \sum_\beta \left[\sum_i U_{\alpha i}\, e^{-i(m_i^2/2E)\ L}\ U_{\beta i}\right] |\nu_\beta\rangle\,. \tag{12}$$

In other words, the propagating mass eigenstates acquire relative phases giving rise to flavor oscillations. Thus, after traveling a distance L an initial state ν_α becomes a superposition of all flavors, with probability of transition to flavor β, $|\langle\nu_\beta|\nu_\alpha(L)\rangle|^2$, given by

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} U_{\alpha i}\, U_{\beta i}\, U_{\alpha j}\, U_{\beta j}\, \sin^2 \varDelta_{ij}\,, \tag{13}$$

where $\varDelta_{ij} \sim \delta m^2_{ij} L/2E$, and $\delta m^2_{ij} = m_i - m_j$.

For $\varDelta_{ij} \gg 1$, the phases will be erased by uncertainties in L and E. Consequently, averaging over $\sin^2 \varDelta_{ij}$ one finds

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 2 \sum_{i>j} U_{\alpha i}\, U_{\beta i}\, U_{\alpha j}\, U_{\beta j}\,. \tag{14}$$

Now, using $2\sum_{1>j} = \sum_{i,j} - \sum_{i=j}$, Eq. (14) can be re-written as

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \delta_{\alpha\beta} - \sum_{i,j} U_{\alpha i}\, U_{\beta i}\, U_{\alpha j}\, U_{\beta j} + \sum_i U_{\alpha i}\, U_{\beta i}\, U_{\alpha i}\, U_{\beta i} \\ &= \delta_{\alpha\beta} - \left(\sum_i U_{\alpha i} U_{\beta i}\right)^2 + \sum_i U^2_{\alpha i} U^2_{\beta i}\,. \end{aligned} \tag{15}$$

Since $\delta_{\alpha\beta} = \delta^2_{\alpha\beta}$, the first and second terms in Eq. (15) cancel each other, yielding

$$P(\nu_\alpha \to \nu_\beta) = \sum_i U^2_{\alpha i}\, U^2_{\beta i}\ . \tag{16}$$

The probabilities for flavor oscillation are then

$$P(\nu_\mu \to \nu_\mu) = P(\nu_\mu \to \nu_\tau) = \frac{1}{4}\,(\cos^4\theta_\odot + \sin^4\theta_\odot + 1)\,, \tag{17}$$

$$P(\nu_\mu \to \nu_e) = P(\nu_e \to \nu_\mu) = P(\nu_e \to \nu_\tau) = \sin^2\theta_\odot\ \cos^2\theta_\odot\ , \tag{18}$$

and

$$P(\nu_e \to \nu_e) = \cos^4\theta_\odot + \sin^4\theta_\odot\ . \tag{19}$$

Now, let the ratios of neutrino flavors at production in the cosmic sources be written as $w_e : w_\mu : w_\tau$ with $\sum_\alpha w_\alpha = 1$, so that the relative fluxes of each mass eigenstate are given by $w_j = \sum_\alpha \omega_\alpha\, U^2_{\alpha j}$. From our previous discussion, we conclude that the probability of measuring on Earth a flavor α is given by

$$P_{\nu_\alpha\ \mathrm{detected}} = \sum_j U^2_{\alpha j}\ \sum_\beta w_\beta\, U^2_{\beta j}\ . \tag{20}$$

Straightforward calculation shows that any initial flavor ratio that contains $w_e = 1/3$ will arrive at Earth with equipartition on the three flavors.

3.2. The γ–ν connection

There are two principal mechanisms for TeV gamma ray production: *(i)* Electrons undergo bremsstrahlung in the magnetic field and/or inverse Compton scattering in the ambient photon sea or *(ii)* the gamma rays are directly traced to π^0 decay.[2] Only the second scenario can accommodate baryonic cosmic ray production. Since such cosmic rays are observed, it is reasonable to assume that at least some gamma ray sources operate according to the second mechanism.

Inelastic pp collisions lead to roughly equal numbers of π^0's, π^+'s, and π^-'s, hence one expects two photons, two ν_e's, and four ν_μ's per π^0. On average, the photons carry one-half of the energy of the pion. The average neutrino energy from the direct pion decay is $\langle E_{\nu_\mu}\rangle^\pi = (1-r)\,E_\pi/2 \simeq 0.22\,E_\pi$ and that of the muon is $\langle E_\mu\rangle^\pi = (1+r)\,E_\pi/2 \simeq 0.78\,E_\pi$, where r is the ratio of muon to the pion mass squared. Now, taking the ν_μ from muon decay to have 1/3 the energy of the muon, the average energy of the ν_μ from muon decay is $\langle E_{\nu_\mu}\rangle^\mu = (1+r)E_\pi/6 = 0.26\,E_\pi$. This gives a total ν_μ energy per charged pion $\langle E_{\nu_\mu}\rangle \simeq 0.48\,E_\pi$, with a total $\langle E_{\nu_\mu}\rangle^{\rm total} = 0.96\langle E_\gamma\rangle$ for each triplet of π^+, π^-, and π^0 produced. For simplicity, hereafter we consider that all neutrinos carry one-quarter of the energy of the pion.

The total number of γ-rays in the energy interval $(E_1/2,\, E_2/2)$ is equal to the total number of charged pions in the interval $(E_1,\, E_2)$ and twice the number of neutral pions in the same energy interval,

$$\int_{E_1/2}^{E_2/2} \frac{dF_\gamma}{dE_\gamma} dE_\gamma = 2\int_{E_1}^{E_2} \frac{dF_{\pi^0}}{dE_\pi} dE_\pi = 2N_{\pi^0}\ . \tag{21}$$

Additionally, since $N_{\pi^\pm} = 2\,N_{\pi^0}$, the number of ν_μ in the energy interval $(E_1/4,\, E_2/4)$ scales as

$$\int_{E_1/4}^{E_2/4} \frac{dF_{\nu_\mu}}{dE_\nu} dE_\nu = 2\int_{E_1}^{E_2} \frac{dF_{\pi^\pm}}{dE_\pi} dE_\pi = 2N_{\pi^\pm}\ . \tag{22}$$

Now, taking d/dE_2 on each side of Eqs. (21) and (22) leads to, respectively

$$\frac{1}{2}\frac{dF_\gamma}{dE_\gamma}\bigg|_{E_\gamma = E_2/2} = 2\,\frac{dF_\pi^0}{dE_\pi}\bigg|_{E_2} \quad \text{and} \quad \frac{1}{4}\frac{dF_{\nu_\mu}}{dE_\nu}\bigg|_{E_\nu = E_2/4} = 2\,\frac{dF_\pi^\pm}{dE_\pi}\bigg|_{E_2}\ . \tag{23}$$

[2] Pions can be produced in pp and/or $p\gamma$ collisions. In this talk we focus attention on the former; a generalization to the photopion production process is straightforward, see [28] for details.

The energy-bins dE scale with these fractions, and we arrive at

$$\begin{aligned}\left.\frac{dF_\gamma}{dE_\gamma}\right|_{E_\gamma=E_\pi/2} &= 4\left.\frac{dF_\pi}{dE_\pi}\right|_{E_\pi},\\ \left.\frac{dF_{\nu_e}}{dE_\nu}\right|_{E_\nu=E_\pi/4} &= 8\left.\frac{dF_\pi}{dE_\pi}\right|_{E_\pi},\\ \left.\frac{dF_{\nu_\mu}}{dE_\nu}\right|_{E_\nu=E_\pi/4} &= 16\left.\frac{dF_\pi}{dE_\pi}\right|_{E_\pi},\end{aligned} \tag{24}$$

for the total fluxes at the source, where π denotes any one of the three pion charge-states. In propagation to Earth a distance longer than all oscillation lengths, flavor changing amplitudes are replaced by probabilities. Using Eqs. (18), (18), and (19) one can check that the initial flavor ratio $1:2:0$ mutates in a nearly identical flux for each of the three neutrino flavors which is equal to [29]

$$\left.\frac{dF_{\nu_\alpha}}{dE_\nu}\right|_{E_\nu=E_\gamma/2} = 2\left.\frac{dF_\gamma}{dE_\gamma}\right|_{E_\gamma}. \tag{25}$$

IceCube is, perhaps, the most promising route for neutrino detection [25]. This telescope will consist of 80 kilometer-length strings, each instrumented with 60 10-inch photo-multipliers spaced by 1.7 m. The deepest module is 2.4 km below the ice surface. The strings are arranged at the apexes of equilateral triangles 125 m on a side. The instrumented detector volume is a cubic kilometer. A surface air shower detector, IceTop, consisting of 160 Auger-style Čerenkov detectors deployed over $A_{\rm eff} \approx 1$ km^2 above IceCube, augments the deep-ice component by providing a tool for calibration, background rejection and air-shower physics. Muons can be observed from 10^2 GeV to 10^9 GeV. Cascades, generated by ν_e, $\overline{\nu}_e$, ν_τ, and $\overline{\nu}_\tau$ can be observed above 10^2 GeV and reconstructed at energies somewhat above 10^4 GeV. For ν_μ's of TeV energy, the angular resolution $\approx 0.7°$ allows a point source search window of $\Omega_{1^\circ\times1^\circ} \approx 3\times10^{-4}$ sr.

The Crab Nebula is generally taken as the standard candle of steady TeV γ-ray emission. In the energy 1 TeV $< E_\gamma <$ 20 TeV, the Crab data can be fitted by a single power law [30],

$$\frac{dF_\gamma}{dE_\gamma} = 2.79^{\pm0.02}_{\pm0.5}\times10^{-7}\left(\frac{E_\gamma}{\rm TeV}\right)^{-2.59^{\pm0.03}_{\pm0.05}}\ {\rm m}^{-2}\,{\rm s}^{-1}\,{\rm TeV}^{-1}. \tag{26}$$

Even though the energy spectrum of the Crab Nebula as measured by the HEGRA system is in very good agreement with calculations of inverse Compton scattering [31], it is interesting and desirable to have an independent observational discriminator between these two scenarios. For $E_\nu^{\rm min} \simeq 1$ TeV, the number of $\nu_\mu + \bar{\nu}_\mu$ showers expected to be detected at IceCube is given by

$$\left.\frac{dN}{dt}\right|_{\rm signal} = A_{\rm eff} \int_{E_\nu^{\rm min}} dE_\nu \, \frac{dF_{\nu_\mu}}{dE_\nu}(E_\nu) \; p(E_\nu)\,, \tag{27}$$

where $p(E_\nu) \approx 1.3 \times 10^{-6}\,(E_\nu/{\rm TeV})^{0.8}$ denotes the probability (generic to ice/water detectors) that a ν (or $\bar{\nu}$) with energy E_ν on a trajectory through the detector produces a signal [23]. Using Eq. (25) straightforward calculation shows that $dN/dt|_{\rm signal} \sim 11\ {\rm yr}^{-1}$ [32]. The event rate of the atmospheric ν-background is

$$\left.\frac{dN}{dt}\right|_{\rm background} = A_{\rm eff} \int_{E_\nu^{\rm min}} dE_\nu \; J_{\nu+\bar{\nu}}(E_\nu) \; p(E_\nu) \; \Delta\Omega_{1^\circ\times 1^\circ} \approx 1.5\ {\rm yr}^{-1}\,, \tag{28}$$

where $J_{\nu+\bar{\nu}}(E_\nu)$ is the $\nu_\mu + \bar{\nu}_\mu$ atmospheric flux in the direction of the Crab region (about 22° below the horizon) [33]. We conclude that the neutrino signal can be easily isolated from background at IceCube. Therefore, the hadronic nature of the high energy emission from the Crab Nebula can be confirmed or disproved in a few years of operation.

3.3. The n–$\overline{\nu}$ connection

Cosmic ray experiments have identified an excess from the region of the GP in a limited energy range around 10^9 GeV. This is very suggestive of neutrons as candidate primaries, because the directional signal requires relatively-stable neutral primaries, and time-dilated neutrons can reach the Earth from typical Galactic distances when the neutron energy exceeds 10^9 GeV. In what follows we show that if the Galactic messengers are neutrons, then those with energies below an 10^9 GeV will decay in flight, providing a flux of cosmic antineutrinos above a TeV which would be *observable* at IceCube.

The basic formula that relates the neutron flux at the source (dF_n/dE_n) to the antineutrino flux observed at Earth $(dF_{\overline{\nu}}/dE_{\overline{\nu}})$ is [34]:

$$\begin{aligned} \frac{dF_{\overline{\nu}}}{dE_{\overline{\nu}}}(E_{\overline{\nu}}) \; &= \; \int dE_n \, \frac{dF_n}{dE_n}(E_n) \left(1 - e^{-\frac{D\, m_n}{E_n\, \overline{\tau}_n}}\right) \int_0^Q d\varepsilon_{\overline{\nu}} \, \frac{dP}{d\varepsilon_{\overline{\nu}}}(\varepsilon_{\overline{\nu}}) \\ & \quad \times \int_{-1}^{1} \frac{d\cos\overline{\theta}_{\overline{\nu}}}{2} \; \delta\left[E_{\overline{\nu}} - E_n\, \varepsilon_{\overline{\nu}}\,(1+\cos\overline{\theta}_{\overline{\nu}})/m_n\right]\,. \end{aligned} \tag{29}$$

The variables appearing in Eq. (29) are the antineutrino and neutron energies in the lab ($E_{\overline{\nu}}$ and E_n), the antineutrino angle with respect to the direction of the neutron momentum, in the neutron rest-frame ($\overline{\theta}_{\overline{\nu}}$), and the antineutrino energy in the neutron rest-frame ($\varepsilon_{\overline{\nu}}$). The last three variables are not observed by a laboratory neutrino detector, and so are integrated over. The observable $E_{\overline{\nu}}$ is held fixed. The delta-function relates the neutrino energy in the lab to the three integration variables. The parameters appearing in Eq. (29) are the neutron mass and rest-frame lifetime (m_n and $\overline{\tau}_n$). Finally, $dP/d\varepsilon_{\overline{\nu}}$ is the normalized probability that the decaying neutron produces a $\overline{\nu}$ with energy $\varepsilon_{\overline{\nu}}$ in the neutron rest-frame. Note that the maximum $\overline{\nu}$ energy in the neutron rest frame is very nearly $Q \equiv m_n - m_p - m_e = 0.71$ MeV. Integration of Eq. (29) can be easily accomplished, especially when two good approximations are applied. The first approximation is to think of the β-decay as a $1 \to 2$ process of $\delta m_N \to e^- + \overline{\nu}$, in which the neutrino is produced mono-energetically in the rest frame, with $\varepsilon_{\overline{\nu}} = \varepsilon_0 \simeq \delta m_N (1 - m_e^2/\delta^2 m_N)/2 \simeq 0.55$ MeV, where $\delta m_N \simeq 1.30$ MeV is the neutron–proton mass difference. In the lab, the ratio of the maximum $\overline{\nu}$ energy to the neutron energy is $2\varepsilon_0/m_n \sim 10^{-3}$, and so the boosted $\overline{\nu}$ has a flat spectrum with $E_{\overline{\nu}} \in (0, 10^{-3}\, E_n)$. The second approximation is to replace the neutron decay probability $1 - e^{-Dm_n/E_n\overline{\tau}_n}$ with a step function $\Theta(E_n^{\rm max} - E_n)$ at some energy $E_n^{\rm max} \sim \mathcal{O}(D\, m_n/\overline{\tau}_n) = (D/10 \text{ kpc}) \times 10^9$ GeV. Combining these two approximations we obtain

$$\frac{dF_{\overline{\nu}}}{dE_{\overline{\nu}}}(E_{\overline{\nu}}) = \frac{m_n}{2\,\varepsilon_0} \int\limits_{\frac{m_n\, E_{\overline{\nu}}}{2\,\varepsilon_0}}^{E_n^{\rm max}} \frac{dE_n}{E_n}\, \frac{dF_n}{dE_n}(E_n)\,. \tag{30}$$

Normalization to the observed "neutron" excess at $\sim 10^9$ GeV leads via Eq. (27) to about 20 antineutrino showers per year [34].

A direct $\overline{\nu}_e$ event in IceCube will make a showering event with poor angular resolution. Fortunately, neutrino oscillations rescue the signal. Since the distance to Cygnus OB2 ($D \approx 1.7$ kpc) greatly exceeds the $\overline{\nu}_e$ oscillation length $\lambda_{\rm osc} \sim (E_{\overline{\nu}}/\text{PeV}) \times 10^{-2}$ parsecs (taking the solar oscillation scale $\delta m^2 \sim 10^{-5}\text{eV}^2$), the antineutrinos decohere in transit. Replacing into Eq. (18) the most recent SNO result for the solar mixing angle $\theta_\odot \simeq 32.5^\circ$ [35], it is easily seen that the arriving antineutrinos are distributed over flavors, with the muon antineutrino flux $F_{\bar\nu_\mu}$ given by the factor $\sin^2(2\,\theta_\odot)/4 \simeq 0.20$ times the original $F_{\bar\nu_e}$ flux. The $\bar\nu_\tau$ flux is the same, and via Eq. (19) the $\bar\nu_e$ flux is 0.6 times the original flux. The Cygnus region is about 40° below the horizon, hence straightforward calculation yields a yearly atmospheric background of 1.5 events. Finally, on the basis that HEGRA observations given in Eq. (1) emerge from pion decay, one can first estimate the accompanying neutrino flux using Eq. (25), and then through Eq. (27) verify that the event rate associated with the unidentified HEGRA source is even smaller than the atmospheric background.

In summary, in a few years of observation, IceCube will attain 5σ sensitivity for discovery of the Fe$\rightarrow n \rightarrow \overline{\nu}_e \rightarrow \overline{\nu}_\mu$ cosmic beam, providing the "smoking ice" for the GP neutron hypothesis.

4. Concluding remarks

We have analyzed the possibility of detecting the neutrino counterparts of TeV γ-ray observations in a model where γ-rays originate through π^0-decay at the source. We have found that IceCube will attain sensitivity to observed neutrinos from the Crab Nebula. The discussion presented here can be easily generalized to other sources (see *e.g.,* [29, 36]). Indeed the AMANDA-II experiment has already achieved the sensitivity to probe the blazar Mrk 501 in its 1997 flaring state if the neutrino and γ-ray fluxes are equal [37]. We have also estimated the "essentially guaranteed" $\overline{\nu}$ flux originated in the decay of neutrons emitted by the Cygnus OB association. The expected event rate above 1 TeV at IceCube is $dN/dt|_{\rm signal} \sim 20$ yr^{-1} antineutrino showers (all flavors) and a 1° directional signal of 4 $\overline{\nu}_\mu$ events, well above atmospheric background.

The detection of (anti)neutrinos pointing towards TeV γ-ray sources or to the 10^9 GeV intriguing directional signals would not only provide a final answer to the origin of these particles, but also confirm the acceleration of protons/nuclei to ultrahigh energies.

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