“Signature” neutrinos from photon sources at high redshift

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Abstract. The temperature of the cosmic microwave background increases with redshift; at sufficiently high redshift it becomes possible for ultrahigh-energy photons and electrons to produce muons and pions through interactions with background photons. At the same time, energy losses due to interactions with radio background and intergalactic magnetic fields are negligible. The energetic muons and pions decay, yielding a flux of “signature” neutrinos with energies $E_\nu \sim 10^{17}$eV. Detection of these neutrinos can help understand the origin of ultrahigh-energy cosmic rays.

The origin of ultrahigh-energy cosmic rays [1] with energies beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2] remains an outstanding puzzle [3]. Most of the proposed explanations can be categorized in two main classes. In the *bottom-up/acceleration* scenarios, charged particles are accelerated to ultrahigh energies in giant astrophysical “accelerators”, such as active galactic nuclei and radio galaxies [4,5]. In the *top-down/decay* scenario on the other hand, massive objects such as topological defects (TD) [6–9] and superheavy relic particles [10–12] decay, emitting mainly ultrahigh-energy (UHE) photons. TD and relic particles can exist at much higher redshift than the astrophysical candidate sources, which are formed only after the onset of galaxy formation. To understand the origin of the ultrahigh-energy cosmic rays (UHECR), it is crucial to distinguish between these two different scenarios. In this talk we will show that the observation of a diffuse flux of “signature” neutrinos with energies $E_\nu \sim 10^{17}$eV [13] can provide evidence for UHE photon sources at high redshift — for members of the *top-down/decay* class.

At small redshift UHE photons lose their energy mainly through scattering off the radio background (RB), and in the subsequent electromagnetic cascade [14,3]. In addition, the cascade electrons lose energy through synchrotron radiation in the intergalactic magnetic field (IGMF). This picture changes completely at high redshift, where both radio background and magnetic fields are small. At redshift z the density of CMB photons is higher by a factor $(1+z)^3$, while the density of radio background is either constant or, more likely, lower. At some redshift z_R the scattering of high-energy photons off CMBR dominates over their scattering off RB.

Based on the analyses of refs. [15,16] we take $z_R \sim 5$. Also, before galaxy formation the IGMF is weak, and for $z > z_M \sim 5$ synchrotron losses are not significant.

But the absence of RB and IGMF at early times is not the only difference: at redshift z the temperature of the cosmic microwave background radiation increases by a factor $(1+z)$. Because of this, at high redshift the production of muons and pions in interactions of UHE photons and electrons with the CMBR becomes possible. Muons and charged pions decay into neutrinos, which can reach us today. The threshold for muon production is $\sqrt{s} > 2m_\mu = 0.21\text{GeV}$, or

$$E_{\gamma,e} > E_{\rm th}(z) = \frac{10^{20}\text{eV}}{1+z} \tag{1}$$

But will muons, and thus neutrinos, indeed be produced? To answer this question one has to look closely at the propagation of UHE photons at $z \gtrsim 5$. Photons scatter off CMB photons and, if their energy is above the threshold for muon pair production, given in eq. (1), they can either produce a muon pair, an electron pair or a double electron pair. Among these processes electron pair production (PP) has the highest cross section for photon energies $E_\gamma \lesssim 5 \times 10^{20}\text{eV}/(1+z)$. Since the energies of the two interacting photons are vastly different, either the electron or the positron from PP has energy close to that of the initial photon. At higher photon energies, double pair production (DPP) becomes more important [17]. Four electrons, each carrying about 1/4 of the initial photon energy, are produced in this reaction. Thus, after an initial $\gamma\gamma_{CMB}$ interaction one ends up with one or more UHE electrons.

These electrons in turn scatter off CMBR. For electron energies above the muon threshold, inverse Compton scattering is negligible compared to higher order processes [3], such as triplet production (TPP) $e\gamma_{CMB} \to e\, e^+e^-$ and muon electron-pair production (MPP) $e\gamma_{CMB} \to e\,\mu^+\mu^-$. For $\sqrt{s} > 2m_{\pi^\pm} = 0.28\text{GeV}$ charged pion production may also occur through $e\gamma_{CMB} \to e\,\pi^+\pi^-$. The TPP cross section is larger than that for MPP [18,19]. However, for center of mass energies $s \gg m_e^2$ the inelasticity for TPP is very small: one of the electrons produced in TPP carries 99.9% of the incoming electron's energy. It can interact once again with the CMBR. As a result, the leading electron can scatter many times before losing a considerable amount of energy; and with every scattering there is another chance to produce a muon pair. So instead of comparing cross sections, one should compare the *energy attenuation* length for TPP with the *interaction* length for MPP. As the latter is much larger, all electrons with energies above muon threshold will produce muons (or pions).

Topological defects and relic particles emit UHE photons. One can parameterize the time-dependence of their photon production rate as $\dot{n}_\gamma = \dot{n}_{\gamma,0}(t/t_0)^{-m}$, where t_0 is the present time. For decaying relic particles $m = 0$, for ordinary strings, monopolonium and necklaces $m = 3$, and for superconducting strings $m \geq 4$ [6–8]. Integrating $\dot{n}_\gamma = \dot{n}_{\gamma,0}$ over time, taking redshift into account, yields a neutrino flux:

$$n_\nu = \xi \int_{z_{\rm min}}^{z_{\rm max}} dt\ \dot{n}_\gamma(z)\ (1+z)^{-4}$$

$$= \xi \frac{3}{-2a} \dot{n}_{\gamma,0}\, t_0 \left[(1+z_{\rm min})^a - (1+z_{\rm max})^a \right]. \tag{2}$$

Here $a = (3m-11)/2$, $z_{\rm min} = \max(z_R, z_M) \approx 5$ the minimum redshift at which both RB and IMGF are negligible, $z_{\rm max} \sim 3 \times 10^3$ the redshift at which the universe becomes transparent to UHE neutrinos [20], and ξ is the number of neutrinos produced per UHE photon. We take $\xi \approx 4$, as one UHE photon produces one UHE electron, which generates a pair of muons whose decay gives four neutrinos. This is probably an underestimate because DPP produces more than one UHE electron. Also, the electron produced alongside the muon pair in MPP may have enough energy for a second round of muon pair-production.

For $m < 11/3$, $a < 0$, and, according to eq. (2), most of neutrinos come from red shift $z \sim z_{\rm min} \approx 5$. All these neutrinos are produced by photons with energies $E_\gamma > E_{\rm min} = 10^{20}{\rm eV}/(1+z_{\rm min}) \sim 2 \times 10^{19}{\rm eV}$. If decaying TD or relic particles are the origin of the UHECR today, one can use the observed UHECR flux to fix the overall normalization constant $\dot{n}_{\gamma,0}(E > E_{\rm min})$. Using the photon fluxes calculated in [8,21,22], we get for the neutrino flux:

$$\phi_\nu \sim \begin{cases} 10^{-21}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}, & \text{relic particles}\,(m=0), \\ 10^{-18}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}, & \text{monopolonium}\,(m=3), \\ 10^{-16}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}, & \text{necklaces}\,(m=3). \end{cases} \tag{3}$$

The difference in the fluxes produced by monopolonium and by necklaces lies in their different clustering properties: whereas monopolonium (and relic particles) clusters in galaxies, necklaces are uniformly distributed throughout the universe.

The energy of these neutrinos can be estimated by

$$E_\nu \sim \frac{10^{20}{\rm eV}}{1+z} \times \frac{1}{4} \times \frac{1}{3} \times \frac{1}{1+z}. \tag{4}$$

As the photon spectrum of TD is a sharply falling function of energy, most neutrinos will come from photons with energies just above the threshold. In MPP, each muon produced gets about 1/4 of the incoming electron energy [19]. A muon decays into an electron and two neutrinos, each getting approximately 1/3 of the muon energy. Furthermore, the neutrino energy is redshifted by a factor $1/(1+z)$. As already noted before, most neutrinos come from $z \sim z_{\rm min} \approx 5$; their energy is $E_\nu \sim 10^{17}{\rm eV}$.

Neutrinos from slowly decaying relic particles or some other $m = 0$ source are too sparse to be detectable in the foreseeable future. However, the flux from $m = 3$ sources, especially from necklaces, may be detected soon. This flux exceeds the background flux from the atmosphere and from pion photo-production on CMBR at this energy [23–25], as well as the fluxes predicted by a number of models [26]. TD can produce a large flux of primary neutrinos. However, the primary flux peaks at $E_\nu \sim 10^{20}{\rm eV}$, while the secondary flux peaks at $E_\nu \sim 10^{17}{\rm eV}$ and creates a distinctive "bump" in the spectrum. Models of active galactic nuclei (AGN) have predicted a similar flux of neutrinos at these energies [5]. The predictions of these models have been a subject of debate [27]. However, everyone agrees that AGN cannot produce neutrinos with energies of 10^{20}eV. So, an observation of 10^{17}eV neutrinos accompanied by a comparable flux of 10^{20}eV neutrinos would be a signature of a TD rather than an AGN.

Rapidly evolving $m \geq 4$ sources, *e.g.* superconducting strings, have been ruled out as the origin of UHECR by the EGRET bounds on the flux of low-energy γ-rays [3]. Although their density today is constrained, in the early universe these sources might have existed in large enough numbers to produce a detectable flux of neutrinos. Neutrinos with $E_\nu \sim 10^{17}$eV are probably the only observable signature of such rapidly evolving sources that were active at high red shift but are "burned out" by now.

To conclude, we have shown that sources of ultrahigh-energy photons that operate at red shift $z \gtrsim 5$ produce neutrinos with energy $E_\nu \sim 10^{17}$eV. The flux depends on the evolution index m of the source. A distinctive characteristic of this type of neutrino background is a cutoff below 10^{17}eV due to the universal radio background at $z < z_{\rm min}$. Detection of these neutrinos can help understand the origin of ultrahigh-energy cosmic rays.

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