



Neutrino, photon interaction in unparticle physics

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ABSTRACT

We investigate the impact of unparticle physics on the annihilation of relic neutrinos with the neutrinos identified as primary source of ultra high energy (UHE) cosmic ray events, producing a cascade of photons and charged particles. We compute the contribution of the unparticle exchange to the cross-sections $\nu\bar{\nu} \rightarrow \gamma\gamma$ and $\nu\bar{\nu} \rightarrow f\bar{f}$ scattering. We estimate the neutrino–photon decoupling temperature from the reaction rate of $\nu\bar{\nu} \rightarrow \gamma\gamma$. We find that the inclusion of unparticles can in fact account for the flux of UHE cosmic rays and can also result in the lowering of neutrino–photon decoupling temperature below the QCD phase transition for unparticle physics parameters in a certain range. We calculate the mean free path of these high energy neutrinos annihilating themselves with the relic neutrinos to produce vector, axial-vector and tensor unparticles.

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1. Introduction

High energy neutrino interactions are of great interest in astrophysics, cosmology and in high energy cosmic ray physics. Neutrinos have been considered as possible candidates of Ultra High Energy (UHE) cosmic rays as opposed to protons and photons on account of their ability to travel cosmic galactic distances without significantly degrading their energy. In comparison to protons and photons, neutrinos have relatively weaker interaction cross-section with relic neutrinos and CMBR. By the same token they present difficulty in initiating air showers. Weiler [1] proposed that if their energy could correspond to Z-resonance, i.e.,

$$E_\nu \approx \frac{m_Z^2}{2m_\nu} \simeq 10^{23} \text{ eV}, \quad (1)$$

they would have significant annihilation cross-section with relic neutrinos of mass consistent with the oscillation data. The difficulty in realizing this scenario is to identify the source of UHE neutrinos with their energy close to Z-resonance. Decay of super heavy relic particles $M_\chi \geq 10^{13}$ GeV has been proposed [2] to be the source of these highly energetic neutrinos that can explain cosmic ray events above the GZK cut off. There however, remains the problem of confining the production of these neutrinos in a spherical shell at red shift

$$Z = \left[\frac{M_\chi}{2 E_{\text{res}}} - 1 \right] = \left[\frac{M_\chi m_\nu}{m_Z^2} - 1 \right], \quad (2)$$

so that this energy near earth is close to Z-resonance energy for the $\nu\bar{\nu}$ annihilation cross-section on relic neutrinos to be large. If such a scenario is not realized in nature, we would require large neutrino–hadron cross-section in the millibarn (mb) region for the neutrinos to initiate showers high in the atmosphere. Current estimate of UHE neutrino–hadron cross-section in the Standard Model (SM) by Gandhi et al. [3] put the cross-section in the 10^{-4} – 10^{-5} mb range for $E_\nu \sim 10^{21}$ eV.

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We thus require anomalously large high energy neutrino interactions. In this context theories of n -extra dimensions with large compactification radius and TeV scale gravity [4] provide the possibility of enhancing neutrino interactions through the exchange of a tower of massive spin 2 bulk gravitons (Kaluza–Klein excitations). The contribution of Kaluza–Klein excitations and its impact on UHE cosmic ray physics has been discussed by several authors [5] in the literature.

The high energy neutrino–photon interactions are also of great interest in astrophysics and cosmology. Scattered photons on neutrinos through $\gamma\nu \rightarrow \gamma\nu$ are predominantly circularly polarized due to the left handed nature of neutrinos [6]. In the early universe, the photons and neutrinos decouple, i.e., the process $\nu\bar{\nu} \rightarrow \gamma\gamma$ ceases to occur at a temperature $T \sim 1.6$ GeV about one micro second after the big bang. If due to some enhanced neutrino–photon interaction, this temperature can be brought down to the QCD phase transition temperature, some remnants of circular polarization could perhaps be retained in the cosmic microwave background. In the SM these cross-sections are very small, due to the vector and axial vector nature of weak interaction and the leading term for massless neutrinos in fact vanishes due to Yang’s theorem [7]. The cross section for $\gamma\gamma \rightarrow \nu\bar{\nu}$ has been calculated in the SM [8] and shows an s^3 behavior upto $W^\pm$ pair production threshold beyond which it starts falling. The cross section is given by

$$\sigma(\nu\bar{\nu} \rightarrow \gamma\gamma) = \frac{s^3}{20\pi} \left(\frac{Ag^2\alpha_{\text{em}}}{32\pi m_W^4} \right)^2, \quad \text{where } A = 14.4. \quad (3)$$

The contribution of Kaluza–Klein excitations to these processes has been computed by Dicus et al. [9], who have shown that the contribution is not large enough to allow high energy neutrinos to scatter from relic neutrinos through $\nu\bar{\nu} \rightarrow \gamma\gamma$ but photon–neutrino decoupling temperature may in fact be lowered.

Recently Georgi [10,11] has proposed that the scale invariance, which has been a powerful tool in physics, may indeed exist at a scale much above the TeV scale. He argued that at high energies there is a hidden sector with a non-trivial IR fixed point Λ_U , below which there is a scale invariance. At energies above Λ_U , there is a hidden sector operator $\mathcal{O}_{UV}$ of dimension d_{UV} much like the Banks–Zaks [12] scale invariant sector. This couples to SM operator $\mathcal{O}_{SM}$ of dimension d_{SM} through the exchange of high mass M_U particles.

$$\mathcal{L}_{\text{eff}} = \frac{\mathcal{O}_{SM}\mathcal{O}_{UV}}{M^{d_U+d_{SM}-4}}. \quad (4)$$

Below Λ_U , the hidden sector becomes scale invariant and the operator $\mathcal{O}_{UV}$ goes over to an operator $\mathcal{O}_U$ called an unparticle operator with a non-integral scale dimension d_U . The unparticle operator has a mass spectrum which looks like the mass spectrum of d_U number of massless particles. The unparticles have continuous mass spectrum. The unparticle operators can have different Lorentz structures and couple to the SM fields at low energies through an effective non-renormalizable Lagrangian

$$\mathcal{L}_U = C_U \frac{\Lambda_U^{d_{UV}-d_U}}{M^{d_{UV}-d_{SM}-4}} \mathcal{O}_{SM}\mathcal{O}_U \quad (5)$$

and C_U is the dimensionless coupling constant.

This unparticle sector can arise as stated in [10] from the hidden sector or from the strongly interacting magnetic phase of a specific class of supersymmetric theories [13] or from the hidden valleys model [14]. However, we also note that under a specific conformal invariance [15] the propagators for vector and tensor unparticle operators are modified.

In this Letter we study the attenuation of high energy neutrinos through interaction with the present density of relic neutrinos through $\nu\bar{\nu} \rightarrow U$, $\nu\bar{\nu} \rightarrow \gamma\gamma$ and $\nu\bar{\nu} \rightarrow f\bar{f}$ processes. The last two processes will proceed through the exchange of U unparticles and would directly produce a cascade of high energy photons and hadrons which could account for the flux of UHE cosmic rays. We also estimate the photon–neutrino decoupling temperature. In Section 2 we give the unparticle interactions with the SM fields and calculate the cross sections for the above processes. In Section 3 we give an estimate of the neutrino–photon decoupling temperature and the mean free path of neutrinos through intergalactic journey. This is followed by a discussion of our results in Section 4.

2. Neutrino–antineutrino annihilation

The effective interactions consistent with SM gauge symmetry for the vector and tensor unparticles with SM fields are given by

$$\frac{\kappa_1^V}{\Lambda_U^{d_U-1}} \bar{f} \gamma_\mu f \mathcal{O}_U^\mu, \quad \text{and} \quad \frac{\kappa_1^A}{\Lambda_U^{d_U-1}} \bar{f} \gamma_\mu \gamma_5 f \mathcal{O}_U^\mu \quad (6)$$

and for tensor unparticles the interactions are

$$\frac{-i}{4} \frac{\kappa_T}{\Lambda_U^{d_U}} \bar{f} (\gamma_\mu \overleftrightarrow{D}_\nu + \gamma_\nu \overleftrightarrow{D}_\mu) \psi_f \mathcal{O}_U^{\mu\nu} \quad \text{and} \quad \frac{\kappa_T}{\Lambda_U^{d_U}} \mathcal{F}_{\mu\alpha} \mathcal{F}_\nu^\alpha \mathcal{O}_U^{\mu\nu}, \quad (7)$$

where f stands for a SM fermion doublet or singlet, $\mathcal{F}_{\mu\nu}$ is electromagnetic field tensor and the dimensionless coupling constants κ_i ’s are related to the coupling constant C_U and the mass scale M_U through

$$\frac{\kappa_1^{V,A}}{\Lambda_U^{d_U-1}} = C_U^{V,A} \frac{\Lambda_U^{3-d_U}}{M_U^2} \quad \text{and} \quad \frac{\kappa_0^T}{\Lambda_U^{d_U}} = C_U^T \frac{\Lambda_U^{2-d_U}}{M_U^2}. \quad (8)$$

The neutrinos being left handed the scalar operator does not couple to them and therefore we consider only the vector and tensor operators. The unparticle propagator for the vector and tensor fields are given by [10,16]

$$[A_{\mathcal{F}}(P^2)]_{\mu\nu} = \frac{A_{d_U}}{2 \sin(d_U \pi)} (-P^2)^{d_U-2} \pi_{\mu\nu}(P) \quad \text{where } \pi_{\mu\nu}(P) = -g^{\mu\nu} + \frac{P^\mu P^\nu}{P^2}, \quad (9)$$

$$[A_{\mathcal{F}}(P^2)]_{\mu\nu,\rho\sigma} = \frac{A_{d_U}}{2 \sin(d_U \pi)} (-P^2)^{d_U-2} T_{\mu\nu,\rho\sigma}(P),$$

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