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Ultra High Energy Cosmic Rays and Neutrinos

Roberto Aloisio

Gran Sasso Science Insitute (INFN), viale F. Crispi 7, 67100 L'Aquila, Italy
INAF/Osservatorio Astrofisico di Arcetri, largo E. Fermi 5, 50125 Firenze, Italy

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Abstract

We discuss the production of ultra high energy neutrinos coming from the propagation of ultra high energy cosmic rays and in the framework of top-down models for the production of these extremely energetic particles. We show the importance of the detection of ultra high energy neutrinos that can be a fundamental diagnostic tool to solve the discrepancy in the observed chemical composition of ultra high energy cosmic rays and, at the extreme energies, can unveil new physics in connection with the recent cosmological observations of the possible presence of tensor modes in the fluctuation pattern of the cosmic microwave background.

Keywords: Ultra High Energy Cosmic Rays, Ultra High Energy Neutrinos, Super Heavy Dark Matter

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1. Introduction

Ultra High energy Cosmic Rays (UHECR) are the most energetic particles observed in nature, with energies up to 10^{20} eV. The experimental and theoretical study of UHECR have brought several important results, such as [1, 2, 3]: (i) UHECRs are charged particles, with limits on neutral particles up to 10^{19} eV at the level of few percent for photons and well below for neutrinos [4, 5, 6], (ii) the spectra observed on Earth show a slight flattening at energies around 5×10^{18} eV (called the ankle), with (iii) a steep suppression at the highest energies around 10^{20} eV.

One of the key informations in the physics of cosmic rays in general and UHECR in particular is the composition of this radiation. In this respect, experimental observations are still not conclusive. The Pierre Auger Observatory (Auger) [7], far the largest detector devoted to the observation of UHECR, points toward a mixed composition with light (proton and He) elements dominating the low energy tail of the spectra and a heavier composition at the highest energies, that starts around energies 5×10^{18} eV. On the other hand, Telescope Array (TA) [8], even if with 1/10 of the Auger statistics, claims a proton dominated composition at all energies up to the highest observed.

The actual chemical composition of UHECR is a key information in order to understand the physical mechanisms responsible for the acceleration of this particles and, ultimately, to tag their sources. The production of secondary particles, such as neutrinos or gamma rays, is due to the interaction of UHECR with astrophysical backgrounds during propagation and, being strongly tied with UHECR chemical composition, can be of paramount importance to solve the alleged contradiction between Auger and TA observations. In this paper we will review secondary neutrino production bracketing the expectations connected with different assumption on chemical composition.

On more general grounds, the fraction of neutrinos (and gamma-rays) observed in the spectra of UHECR at energies till 10^{19} eV, as stated above, is extremely small with only upper limits and no direct observations. Nonetheless, the observations of Auger and TA at the highest energies are still affected by a reduced number of events. For instance, Auger, with the highest statistics, has only 5 events at energies around 10^{20} eV [9]. This energy range is of paramount importance in order to unveil possible top-down mechanism in the production of UHECR connected with new physics at the in-

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flation scale.

The recent claim by BICEP2 of a substantial contribution of tensor modes to the fluctuation pattern of the Cosmic Microwave Background, even if reconsidered after the combined analysis with Planck and Keck array [10], boosted the possible explanation of the Dark Matter problem in terms of Super Heavy Dark Matter, i.e. relic particles created by rapidly varying gravitational fields during inflation (see [11] and reference therein). One of the key expectations of this kind of models is the huge amount of neutrinos (and gamma-rays) produced at energies $\gtrsim 10^{20}$ eV [12]. In the present paper we will review recent results that link cosmological observations to the fluxes of neutrinos expected at the highest energies, also assessing the detection capabilities of future UHECR and neutrino observatories.

2. Secondary cosmogenic neutrinos

The physics of UHECR propagation is well understood [13, 14, 15]. During their journey from the source to the observer UHECR experience interactions with astrophysical backgrounds[1], namely the Cosmic Microwave Background (CMB) and the Extragalactic Background Light (EBL). The propagation of UHECR protons[2] is affected almost only by the CMB radiation field and the processes that influence the propagation are: (i) pair production and (ii) photo-pion production [15, 16]. On the other hand, the propagation of heavier nuclei is affected also by the EBL and the interaction processes relevant are: (i) pair production and (ii) photo-disintegration [13, 14, 17, 18].

The interaction processes that involve UHECRs with background photons are important not only as mechanisms of energy losses affecting the behaviour of the propagating particles but also being the source of secondary particles such as neutrinos, gamma-rays and electron-positron pairs. Here we will focus mainly on the production of secondary neutrinos. The main source of these particles is certainly the process of photo-pion production. A nucleon (N), whether free or bounded in a nucleus, with Lorentz factor $\Gamma \gtrsim 10^{10}$ interacting with the CMB photons gives rise to the photo-pion production process:

$$N + \gamma \to N' + \pi^0 \qquad N + \gamma \to N' + \pi^{\pm}. \tag{1}$$

At lower energies $\Gamma < 10^{10}$, even if with a lower probability, the same processes can occur on the EBL field. In the case of UHE protons propagating in the CMB, the photo-pion production process involves a sizeable energy loss producing the so-called GZK cut-off [19, 20], a sharp suppression of the flux of protons expected on Earth at $E \simeq 6 \times 10^{19}$ eV.

The photo-pion production process holds also for nucleons bound within UHE nuclei, being the interacting nucleon ejected from the parent nucleus, but this process is subdominant with respect to nucleus photo-disintegration except at extremely high energies [15].

UHE nuclei propagating through astrophysical backgrounds can be stripped of one or more nucleons by the interactions with CMB and EBL photons, giving rise to the process of photo-disintegration:

$$(A, Z) + \gamma \to (A - n, Z - n') + nN \tag{2}$$

n (n') being the number of stripped nucleons (protons). In the nucleus rest frame the energy involved in such processes is usually much less than the rest mass of the nucleus itself, therefore in the laboratory frame we can neglect the nucleus recoil.

Let us now concentrate on the unstable particles (pions, free neutrons and unstable nuclei) produced by the propagation of UHECRs through photo-pion production and photo-disintegration. In most cases the decay length of such particles is much shorter than all other relevant length scales, so these particles decay very soon giving rise to secondary neutrinos.

There are two processes by which neutrinos can be produced in the propagation of UHECRs:

- the decay of charged pions produced by photo-pion production, $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$, and the subsequent muon decay $\mu^{\pm} \to e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e)$;
- the beta decay of neutrons and nuclei produced by photo-disintegration: $n \to p + e^- + \bar{\nu}_e$, $(A, Z) \to (A, Z-1) + e^+ + \nu_e$, or $(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$.

These processes produce neutrinos in different energy ranges: in the former the energy of each neutrino is around a few percent of that of the parent nucleon, whereas in the latter it is less than one part per thousand (in the case of neutron decay, larger for certain unstable nuclei). This means that in the interactions with CMB photons, which have a threshold around $\Gamma \gtrsim 10^{10}$, neutrinos are produced with energies of the order of 10^{18} eV and 10^{16} eV respectively.

Interactions with EBL photons contribute with a much lower probability than CMB photons, affecting

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[1] We will not consider here the interaction with extragalactic magnetic fields, whose presence is not clear and yet under discussion.

[2] Hereafter discussing freely propagating UHE nucleons we will always refer only to protons because the decay time of neutrons is much shorter than all other time scales involved [13, 14, 15].