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Cosmogenic Neutrinos from the Propagation of Ultra High Energy Cosmic Rays

N. G. BUSCA[1,2], D. ALLARD[1], A. OLINTO[1,2], M. AVE[2], E. PARIZOT[1]
[1] *APC, CNRS, Paris 7, Paris, France*
[2] *Kavli Institute for Cosmological Physics,The University of Chicago, Chicago IL, USA*
ngb@apc-paris7.in2p3.fr

Abstract: We calculate the flux of neutrinos generated along the propagation of ultra-high energy nuclei over cosmological distances. The propagation takes into account the interactions with the cosmic background radiations including the CMB and the most recent estimates of higher energy (infra-red, optical, and ultra-violet) backgrounds. We assume that the composition of ultra-high energy cosmic rays (UHECRs) at the source is the same as the observed one at low energies. We find that the neutrino flux in the mixed case has a high energy peak, mainly due to photopion production off CMB photons, of similar shape and amplitude to the proton case. At low energies both composition cases have a significant neutrino flux that extends down to 10^{12} eV. Detection of diffuse neutrino fluxes at ultra high energies is within reach of present experiments.

Introduction

The question of the origin of the highest energy cosmic rays (of energy above 10^{18} eV) remains unanswered. The understanding of the phenomenon will most likely require the precise measurement of several observables. The presence of spectral features at these energies, namely the ankle and the GZK cutoff constrain the possible theories but do not provide much discriminating power. While the GZK cutoff represents strong evidence for a cosmological origin of ultra-high energy cosmic rays (UHECR), the ankle feature can be interpreted as a pair production dip [1] or and indication of a transition from a Galactic to an extra Galactic origin [2, 3]. The dip models require an almost pure proton composition while the transition models allow for a heavier composition.

Composition data, such as the observation of the depth of shower maximum or muon counting, has discriminating power among these models. It can also strongly constrain bottom-up models and even unequivocally rule out top-down models in case a component heavier than protons is observed. On the other hand, an observation of a photon component at the highest energies would support such top-down models.

The flux of UHECR is expected to be accompanied by a flux of neutrinos. For top-down models, the decay or annihilation of super heavy particles naturally produce a flux of ultra-high energy neutrinos along with a flux of protons. For bottom-up models, neutrinos result from interactions of cosmic rays with background photons, either at the acceleration site or along their propagation path.

The flux of neutrinos produced along the propagation path of UHECR is often termed as *guaranteed*. This flux is expected to be present as long as cosmic rays propagate for cosmological distances before reaching the Earth. Recent estimates of this flux have been carried out for protons [4] and for several other nuclei primaries such as pure Fe [5, 6], He and O [6].

We report on the expected cosmogenic neutrino flux resulting from the propagation of UHECR in the context of the mixed composition model of [2]. According to this model, the source composition of cosmic rays after acceleration is the same as the one reconstructed using low energy cosmic ray data [7]. We use a Monte Carlo method to propagate nuclei and follow their secondaries, includign neutrinos, as they interact with the photon background. All relevant processes for nucleus-photon interactions are taken into account according to the current theoretical and experimental understanding [8, 9]. For the photon background we use the CMB and recent estimates of the infra-red, optical and ultra-violet backgrounds given in [10].

This paper is organized as follows. In section §2 we describe our Monte Carlo method, in section §3 we present our results and finally, in section §4 we present our conclusions.

Monte Carlo method

We use a Monte Carlo method to propagate primary protons or heavier nuclei from their source at redshift z to z=0. Following [2] we take the probability for a given primary of energy E to be proportional to $x_i A_i^{\alpha-1} E^{-\alpha}$, i indicates the species, A_i is the mass number, the coefficients x_i are given in [7], and α is the spectral index of the source. The choice of initial energy for the primary is done according to a power law distribution with index α. The power law distribution extends up to an energy $E_{max} = Z \times E^H_{max}$, where E^H_{max} is the maximum acceleration energy for protons.

The choice of initial redshift of the particle is done according to a given distribution redshift of cosmic ray sources. We took four different assumptions. The first is to assume that sources do not evolve with redshift (hereafter called uniform distribution). The second is to assume a redshift dependence that follows the old estimate of the star formation rate of (hereafter oSFR), which evolves as $(1+z)^n$ for $z < 1.9$, followed by a constant 2.9^n up to z=2.7, followed by an exponential cutoff $2.9^n \exp(1-z/2.9)$. We take $n = 3$ as assumed by most previous cosmogenic neutrino flux calculations. The third is to take instead a more recent estimate of the star formation rate following (hereafter new SFR or nSFR), which evolves as $(1+z)^3$ for $z < 1.3$, followed by a constant 2.3^3 up to z=6, followed by sharp cutoff. The fourth is to assume a stronger source evolution (hereafter strong evolution) favored by the recent infra-red survey of the Spitzer telescope [11]. We use the following parametrization: $(1+z)^4$ for $z < 1$, followed by a constant rate between $1 < z < 6$ followed by a sharp cutoff.

Once the choices of energy, particle identity and redshift are made, the particle is propagated from its initial redshift to redshift z=0. The propagation is done on steps in redshift. The steps are sampled from an exponential distribution with an interaction length λ such that $1/\lambda = \sum_i 1/\lambda_i$, where the sum runs over all the possible interaction processes. These include redshift, pair production and photopion losses for all particles and photoerosion losses for all nuclei heavier than protons. For the case of redshift and pair production losses an effective interaction length is used, equal to about a thousandth of the respective attenuation length. This choice ensures that the steps are small enough to correctly treat the evolution of the interaction lengths with energy.

The calculation of the individual λ_i is done using recent theoretical calculations of the giant dipole resonance cross sections (GDR) taken from [8] or experimental data for quasi-deuteron (QD) and barionic resonances (BR) as reported in [9]. For the photon background we took into account the CMB and recent estimations of the infra-red, optical and ultra-violet backgrounds (which we will generically refer to as IRB) taken from [10]. Examples of the λ_i for an Fe nucleus are shown figure 1. Figure 2 shows the IRB background for different values of redshift.

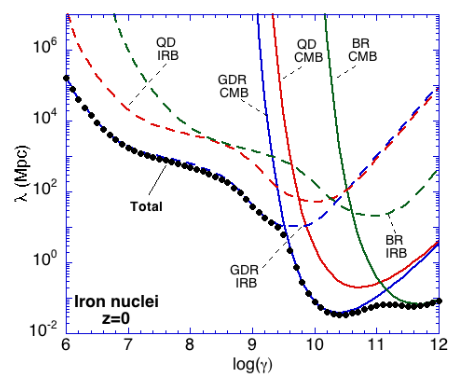

Figure 1: Interaction lengths for different processes for an Fe nucleus interacting with the CMB or IRB.

After each propagation step the interaction process is chosen with a probability proportional to $1/\lambda_i$ (including redshift and pair production losses as described in the previous paragraph). The energy is then updated according to the given interaction

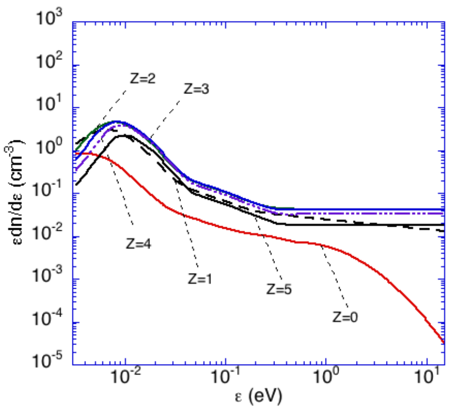

Figure 2: IRB energy density for different values of redshift.

process and a new propagation step is obtained using the updated energy. When a photoerosion process occurs, all daughter nuclei are followed.

Neutrinos are produced by two kinds of processes: isospin changing barionic resonances and neutron decay. For the case of barionic resonances we only considered the single pion production through the Δ resonance ($N+\gamma \rightarrow N'+\pi$). The contrubutions from higher energy resonances and multipion production have a higher threshold and are suppressed by the steep source spectrum (tipically of spectral index of at least 2). For nuclei, the cross section for the Δ resonance is even more prominent relative to the other resonances. Our results in the case of protons agree very well with more the detailed calculation of reference [4], validating this approximation.

The single pion production through the Δ resonance leads to a probability 1/3 of isospin flip of the initial particle. In this case, a charged pion is produced and, after its decay chain, contributes three neutrinos.

Results and Discussion

The values of the spectral index α and the maximum energy (E^0_{max}) and an overall normalization are chosen to reproduce the measurements of AGASA or HiRes. It is possible to find good values of α and E^0_{max} for the four different models of source evolution considered. The overall normalization automatically provides also a normalization for the neutrino flux. A comparison between the propagated spectrum and the data from HiRes is shown in figure 3, for three source evolution hypothesis (nSFR is very similar to oSFR and is not shown) and the corresponding best values of the spectral index and E_max^0. For the three cases shown, the value $E^0_{max} = 10^{20.5}$ compares well with the data. A similar fit to AGASA data yields the same values but a higher normalization by a factor of about 1.8.

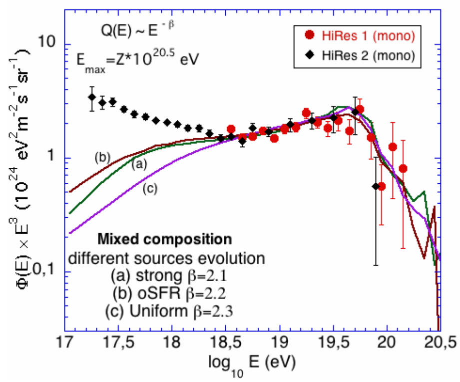

Figure 3: Comparisson between propagated spectrum and data for the mixed composition model.

The resulting flux of neutrinos is shown in figure 4 for the case of the strong source evolution model. It exhibits a high energy peak at around 10^{18} eV, a lower energy peak at around $10^{14.5}$ eV and continues to increase down to 10^{12} eV. This overall structure is maintained for the other three source evolution models considered. The uniform evolution, however, results in a lower neutrino flux by about an order of magnitude, illustrating the fact that source evolution is an important parameter for the neutrino flux.

It is interesting to note that the high energy peak is the same regardless of the primary composition assumed. It results from photopion interactions of individual nucleons (either primaries or resulting from photoerossion processes of nuclei) off the CMB photons. The lower energy structure has a larger dependence on composition. It is mainly due to neutron decay and interactions of individual nucleons off IRB photons.

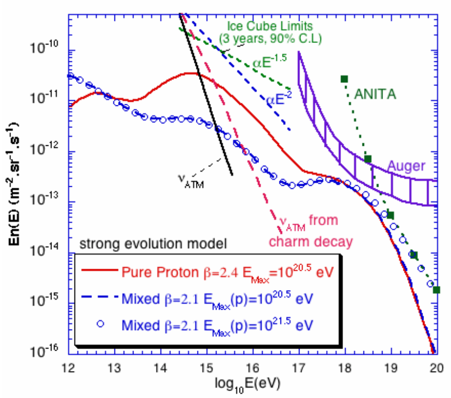

Figure 4: Flux of neutrinos for pure proton and mixed composition models. Also shown are the current experimental limits for ICE CUBE, ANITA and Auger.

Conclusions

In the present paper we report on the diffuse neutrino flux that results from the propagation of UHECR from cosmological sources in the context of the mixed composition hypothesis of [2]. Our calculations include the CMB and recent estimations of the infra-red, optical and ultra-violet photon backgrounds (IRB) as well as updated estimations of photonuclear cross sections.

We find a neutrino flux that extends from 10^{12} to 10^{19} eV. Such an extended energy range, as compared with predictions from previous works, is mainly due to the inclusion of the IRB. This flux exhibits a peak at high energies (centered at around 10^{18} eV) comparable to that obtained for a pure composition hypothesis (assuming pure protons or heavier nuclei). This peak results from the interaction of individual nucleons (either primaries or secondaries that follow photoerosion processes) with CMB photons. Such a robust prediction constitutes a signature of the cosmogenic origin of such a neutrino flux. On the other hand, the structure at lower energies, and in particular the relative height of the lower energy peaks to the high energy one, depends on composition and the IRB. For a well constrained IRB the low energy structure of the neutrino flux could provide information on composition.

The obtained flux of neutrinos, and in particular the high energy peak, are within reach of Auger or other neutrino observatories such as ANITA or ICE CUBE in the near future.

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