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Very high energy antineutrinos from photo-disintegration of cosmic ray nuclei

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ABSTRACT

The photo-disintegration of cosmic ray nuclei by starlight leads to the production of secondary antineutrinos. We have assumed that the flux of the ultrahigh energy cosmic ray nuclei near the Galactic plane region is the same as that observed near the earth and calculated the antineutrino flux produced from their photo-disintegration. The IceCube detector has measured the neutrino/antineutrino flux in the TeV–PeV energy range. Our calculated secondary antineutrino flux in the energy range of 10–100 TeV is found to be much less compared to the flux detected by the IceCube collaboration. The upper limit on the intensity of the radiation field in the extragalactic medium is much lower than that near the Galactic center. If we extend our formalism to the extragalactic medium the contribution from the photo-disintegration of ultrahigh energy cosmic ray heavy nuclei remains insignificant due to their very low flux.

1. Introduction

The cosmic ray detectors of CASA-MIA [1], Tunka [2], GAMMA [3] and KASCADE-Grande [4] have measured the cosmic ray flux from the knee region at around 10^{17} eV which mostly contains iron nuclei. This is known as the “iron knee”. Beyond the knee there is a change in the composition of the cosmic rays from heavy to light nuclei.

The radiation field produced from the stars is most intense near the Galactic center region where the density of the stars is the highest and gradually decreases with the distance [5] from this region. The cosmic rays emitted from the Galactic and extragalactic sources interact with the interstellar radiation and matter during their propagation through the interstellar medium. Secondary neutrinos and gamma rays are produced from their interactions [6–9]. The pure hadronic interactions have negligible contribution to the observed neutrino events in the IceCube detector [10–13].

The photo-disintegration of cosmic ray heavy nuclei has been studied earlier analytically [14–16] and with Monte Carlo simulations [17]. More recently it has been suggested that the antineutrinos produced in the photo-disintegration [18] of some very high injected flux of ultrahigh energy cosmic rays (UHECRs) may explain the flux observed by the IceCube neutrino detector. In photo-disintegration protons and neutrons are produced almost equally. The neutrons decay to protons and antineutrinos. In this paper it has been assumed that 1–10% of the high energy protons produced in the decay of the high energy neutrons reach us due to magnetic shielding and their flux is the same as the observed cosmic ray proton flux in the energy range of $10^{8.5}$–$10^{9.5}$ GeV.

Parameterizations of the all particle cosmic ray spectrum are given in [19] for the following three population models (i) Hillas model (ii) global fit model. We have used their parameterizations of the diffuse cosmic ray flux to calculate the antineutrino flux produced in the photo-disintegration of cosmic ray heavy nuclei. According to the Hillas model the Galactic cosmic ray spectrum ends at the knee which mostly originates from supernova remnants. The contribution to the diffuse cosmic ray flux from the extragalactic sources is significant at the ankle. This scenario is based on the amplification of the magnetic fields in non-linear diffusive shock accelerations which determines the maximum energy of the cosmic rays produced in Galactic SNRs. In this model at least three populations of particles are needed to explain the observed cosmic ray flux. Many more populations may be introduced to explain the cosmic ray spectrum in much more detail. In the global fit model the fluxes of the individual cosmic ray nuclei measured by the CREAM experiment [20] are well explained. This model is also consistent with the “iron knee” observed by the KASCADE-Grande at 10^{17} eV [21]. In each population all the particles have the same maximum rigidity. Another important aspect is the higher energy populations can significantly contribute to the cosmic ray flux at lower energy. For more details on these models the readers may see [22].

Although, the radiation field depends on the Galactocentric radius R and the altitude above the Galactic plane z, a uniform background radiation field is assumed in this work near the Galactic plane region. The strength and spectral distribution of this radiation field are

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Table 1
Hillas Model: normalization constants a_{ij} and spectral indices γ_{ij} and cut-offs in -rigidity R_c [19].

	Parameters	p	He	CNO	Mg–Si	Fe
Pop 1	a_{ij}	7860	3550	2200	1430	2120
$R_c = 4PV$	γ_{ij}	1.66	1.58	1.63	1.67	1.63
Pop 2	a_{ij}	20	20	13.4	13.4	13.4
$R_c = 30PV$	γ_{ij}	1.4	1.4	1.4	1.4	1.4
Pop 3	a_{ij}	1.7	1.7	1.14	1.14	1.14
$R_c = 2EV$	γ_{ij}	1.4	1.4	1.4	1.4	1.4

Table 2
Global fit Model: normalization constants a_{ij} and spectral indices γ_{ij} and cut-offs in rigidity R_c [19].

	Parameters	p	He	C	O	Fe
Pop 1	a_{ij}	7000	3200	100	130	60
$R_c = 120TV$	γ_{ij}	1.66	1.58	1.4	1.4	1.3
Pop 2:	a_{ij}	150	65	6	7	2.3
$R_c = 4PV$	γ_{ij}	1.4	1.3	1.3	1.3	1.2
Pop 3	a_{ij}	14				0.025
$R_c = 1.3EV$	γ_{ij}	1.4				1.2

assumed as given for $R = 0, 4$ kpc and $z = 0$ in Fig. 1 (bottom panel) of [5]. We have denoted the two cases by IR1 and IR2. In the first case (IR1) it is assumed that the Galactic plane region has a uniform radiation field, the same as the one given for $R= 0, z = 0$ in their paper. IR2 is the case corresponding to the radiation field equal to that given for $R = 4$ kpc, $z = 0$.

2. The cosmic ray flux near the galactic plane

The cosmic ray flux and its composition near the Galactic plane region are unknown. Even near the earth the composition of the UHECRs is not yet known. The measured flux near the earth has been fitted with the Hillas model and the global fit model earlier [19]. The all particle spectrum (GeV^{-1} m^{-2} s^{-1} sr^{-1}) in the three population models is

$$\frac{dN_{A_i}(E_{A_i})}{dE_{A_i}\, dS\, dt\, d\Omega} = \Sigma_{j=1}^{3} a_{ij} E_{A_i}^{-\gamma_{ij}-1} \times exp\left[-\frac{E_{A_i}}{Z_i R_{cj}}\right] \quad (1)$$

We have used the above cosmic ray flux in this work. The subscript $i = 1, 5$ runs over the standard five groups of particles p, He, CNO, Mg–Si and Fe. The three populations are denoted by $j = 1, 3$. Area has been denoted by S and charge of a nucleus by Z_i. For CNO and Mg–Si we have used the mean values of their charges. The values of the parameters are given in Tables 1, 2 for the Hillas model and the global fit model, respectively. Note that in Eq. (1) the energy E_{A_i} is the energy of the nucleus for the ith group, $E_{A_i} = A_i E_n$ where A_i is the average mass number for the ith group and E_n is the energy of each nucleon. In the Hillas model the fluxes of the heavy nuclei are higher compared to the global fit model. The population 3 in the global fit model contains only protons and iron nuclei whereas in the Hillas model proton, He, CNO, Mg–Si and iron fluxes are almost equal. In the next section we do not use the subscript i anymore to write the cosmic ray flux for the individual groups.

3. Secondary antineutrinos from the galactic plane region

The cross-section of photo-disintegration [23] for a medium or heavy nucleus of mass number A in the rest frame of the nucleus is

$$\sigma_A(\epsilon^*) = \sigma_{0A} \frac{(\epsilon^* \triangle)^2}{(\epsilon^{*2} - {\epsilon_0'}^2)^2 + (\epsilon^* \triangle)^2} \quad (2)$$

where the photon energy in the nuclear rest frame ϵ^* is below 30 MeV. Above 30 MeV the cross-section is energy independent with a smaller value of $A/8$ mb. The values of the constants are as follows, cross-section $\sigma_{0A} = 1.45A$ mb, the central value of GDR (Giant Dipole Resonance) $\epsilon_0' = 42.65A^{-0.21}$ MeV for mass number of nuclei $A > 4$ and width of the GDR $\triangle = 8$ MeV. The rate of photo-disintegration (R_{ph}) is calculated for the background radiation density per unit energy (IR) $\frac{dn(x)}{dx}$. The Lorentz factor of each nucleon of mass m_n and energy E_n is $\gamma_n = E_A/(A\, m_n)$.

$$R_{ph} = \frac{c}{2{\gamma_n}^2} \int_{\epsilon_{th}}^{2\gamma_n \epsilon_{max}} \epsilon^* \sigma_A(\epsilon^*) d\epsilon^* \int_{\epsilon^*/2\gamma_n}^{\epsilon_{max}} \frac{dn(x)}{dx} \frac{dx}{x^2}. \quad (3)$$

The threshold energy of photo-disintegration in the rest frame of the nucleus is $\epsilon_{th} \sim 2$ MeV and the maximum energy of the photons in the background radiation field is ϵ_{max}.

Eq. (3) is simplified after including the expression for the total cross-section of photo-disintegration. The cross-section corresponding to the GDR can be approximated by a delta function [16].

$$\sigma_A(\epsilon^*) = \pi \sigma_{0A} \frac{\triangle}{2} \delta(\epsilon^* - \epsilon_0') \quad (4)$$

The expression for the rate of photo-disintegration in the case of GDR is simplified to

$$R_{ph,GDR} = \frac{c\, \pi\, \sigma_{0A}\, \epsilon_0' \triangle}{4\, \gamma_n^2} \int_{\epsilon_0'/2\gamma_n}^{\infty} \frac{dn(x)}{dx} \frac{dx}{x^2}. \quad (5)$$

The constant cross-section of photo-disintegration above 30 MeV gives

$$R_{ph,const} = \frac{Ac}{16\gamma_n^2} \int_{30\,\mathrm{MeV}}^{2\gamma_n \epsilon_{max}} \epsilon^* d\epsilon^* \int_{(\epsilon^*/2\gamma_n)}^{\epsilon_{max}} \frac{dn(x)}{dx} \frac{dx}{x^2} \quad (6)$$

The contribution from the constant cross-section above 30 MeV is found to be low. We have considered a disc shaped region centered at the Galactic center of radius $R = 10$ kpc and height $z = 0.5$ kpc having uniform intensity of radiation. The rate of photo-disintegration is highest for Fe and decreases with decreasing A as shown in our Fig. 1. The spectrum of neutrons (GeV^{-1} cm^{-3} s^{-1}) produced in photo-disintegration is

$$\frac{dN_{n_s}(E_{n_s})}{dE_{n_s}\, dt\, dV} = 0.5 R_{ph}(E_{n_s}) \frac{dN_A(E_{n_s})}{dE_{n_s}\, dV} \quad (7)$$

Both neutrons and protons are stripped out from the nuclei. We have assumed 50% of the stripped nucleons are neutrons and denote them by n_s. The energy of the stripped neutrons is assumed to be the same as that of the parent nucleons. The steady state density of cosmic ray nuclei is $\frac{dN_A(E_n)}{dE_n\, dV}$ expressed in per nucleon energy in Eq. (7). This density flux (GeV^{-1} cm^{-3}) is

$$\frac{dN_A(E_n)}{dE_n\, dV} = 10^{-4} \frac{4\pi}{c(\mathrm{cm/s})} \frac{A\, dN_A(E_A)}{dE_A\, dS\, dt\, d\Omega} \quad (8)$$

The neutron flux (GeV^{-1} cm^{-2} s^{-1} sr^{-1}) is calculated for the disc shaped region. The geometrical correction is done following the formalism discussed in paper [8].

$$J_{n_s}(E_{n_s}) = \frac{1}{\Omega_G} \int \frac{dV}{4\, \pi\, r^2} \frac{dN_{n_s}(E_{n_s})}{dE_{n_s}\, dt\, dV} \quad (9)$$