FLUX OF ANTINEUTRINOS FROM PHOTO-DISINTEGRATION OF COSMIC RAY NUCLEI NEAR THE GALACTIC PLANE

NAYANTARA GUPTA
Astronomy & Astrophysics, Raman Research Institute, Bangalore, 560080, India
(Dated: March 31, 2015)
Draft version March 31, 2015

ABSTRACT

The photo-disintegration of cosmic ray nuclei by star light leads to the production of secondary antineutrinos and gamma rays. We have calculated the antineutrino flux produced in this way from ultrahigh energy cosmic ray nuclei trapped close to the Galactic plane where the radiation field is intense. 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 28-100 TeV is found to be much less compared to the flux detected by the IceCube collaboration.

1. INTRODUCTION

The cosmic ray detectors of CASA-MIA (Glasmecher et al. 1999), Tunka (Berezhnev et al. 2012), GAMMA (Garyaka et al. 2008) and KASCADE-Grande (Antoni et al. 2005) 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 ray flux from heavy to light nuclei.

The radiation field produced from the stars is most intense near the Galactic plane where the density of the stars is the highest and gradually decreases with distance (Moskalenko, Porter & Strong 2006). 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 (Gupta 2012, 2013; Joshi, Winter & Gupta 2014; Ahlers & Murase 2014). The pure hadronic interactions have negligible contribution to the observed neutrino events in the IceCube detector (Aartsen et al. 2013a;2013b;2013c;2014).

The photo-disintegrations of cosmic ray heavy nuclei have been studied earlier analytically (Stecker 1969; Puget, Stecker & Bredekamp 1976; Balashov, Korotkikh & Moskalenko 1987; Karakula et al. 1994; Stecker & Salamon 1999; Hooper, Sarkar & Taylor 2008) and with Monte Carlo simulations (Hooper, Taylor & Sarkar 2005; Anchordoqui et al. 2007). More recently it has been shown that the antineutrinos produced in photo-disintegration (Anchordoqui et al. 2014) of ultrahigh energy cosmic rays during their propagation through the intergalactic and Galactic medium may explain the flux observed by the IceCube detector.

Parametrizations of the all-particle cosmic ray spectrum are given in the paper by Gaisser, Stanev & Tilav 2013 for the following three population models (i) Hillas model (ii) global fit model (Gaisser 2012). We have used their parametrizations of the diffuse cosmic ray flux to calculate the antineutrino flux produced in 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 (Ahn et al. 2009) are well explained. This model is also consistent with the “iron knee” observed by the KASCADE-Grande at $10^{17}$ eV (Antoni et al. 2005). 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 Gaissier, Stanev & Tilav 2013.

Although, the radiation field depends on the Galactocentric radius R and the altitude above the Galactic plane z, an uniform background radiation field is assumed in this work near the Galactic plane region. The strength and spectral distribution of this radiation field is taken as given for R=0,4kpc and z=0 in Fig.1.(bottom panel) of the paper by Moskalenko, Porter & Strong 2006. We have denoted the two cases by IR1 and IR2. In the first case (IR1) it is assumed that the Galactic plane region has an uniform radiation field 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=4kpc,z=0.

2. THE COSMIC RAY FLUX NEAR THE GALACTIC PLANE:

The cosmic ray flux and its composition near the Galactic plane region is unknown. Even near the earth the composition of the ultrahigh energy cosmic rays is not yet known. The measured flux near the earth has been fitted with the Hillas model and the global fit model earlier (Gaissier, Stanev & Tilav 2013). The all particle spectrum (GeV\(^{-1}\)m\(^{-2}\)sec\(^{-1}\)sr\(^{-1}\)) in the three population models is

\[
\frac{dN_A(E_A)}{dE_A dS dt d\Omega} = \sum_{j=1}^{3} a_{ij} E_A^{-\gamma_{ij}} \times \exp \left[ - \frac{E_A}{Z_i R_{c,j}} \right]
\]

We have used the above cosmic ray flux in this work. 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 Table 1 and Table 2 for the Hillas model and the global fit model respectively. 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. Note that in eqn.(1) the energy E_A is the energy of the nucleus, E_A = A E_n where A is the mass number and E_n is the energy of each nucleon. In the Hillas model the fluxes of 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.

3. SECONDARY ANTINEUTRINOS FROM THE GALACTIC PLANE REGION:

We have used the cross-section (Stecker 1969) and the analytical formalism discussed in earlier papers (Anchordoqui et al. 2007) to calculate the antineutrino spectrum produced in the photodisintegration of cosmic ray heavy nuclei. The rate of photo-disintegration (R_{ph}) has been calculated (shown in our Fig.1.) using the radiation fields for R=0,z=0 (IR1) and R=4kpc,z=0 (IR2) given in Fig.1.(bottom panel) of the paper by Moskalenko, Porter & Strong 2006. We have considered a disc shaped region centered at the Galactic center of radius R = 10kpc and height z = 0.5 kpc having uniform intensity of radiation.

\[
R_{ph} = \frac{c \pi \sigma_0 \epsilon_0}{4 A \gamma_n^2} \int_{\gamma_n/2}^{\infty} \frac{dn(x)}{dx} \frac{dx}{x^2}
\]

The background photon density per unit energy in the Galactic plane region is denoted by \(\frac{dn(x)}{dx}\). The values of the constants are as follows, cross-section \(\sigma_0 = 1.45 \, \text{A} \, \text{mb}\) and the central value of GDR \(\epsilon_0 = 42.65 \, \text{A}^{-0.21} \, \text{MeV}\) for mass number of nuclei A > 4 and width of the GDR \(\Delta = 8 \, \text{MeV}\). The Lorentz factor of each nucleon with energy \(E_n\) is \(\gamma_n = E_A/(A m_n)\). The rate of photodisintegration is the highest for Fe and decreases with decreasing A (also see Fig.1. of Kundu & Gupta 2014) as shown in Fig.1. The spectrum of neutrons \([\text{GeV}^{-1}\text{cm}^{-2}\text{sec}^{-1}\text{sr}^{-1}]\) produced in photodisintegration is

\[
\frac{dN_{n_s}(E_n)}{dE_n dS dt dV} = 0.5 R_{ph}(E_n) \frac{dN_A(E_A)}{dE_A dS dt d\Omega}
\]

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 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 eqn.(3). This density flux \([\text{GeV}^{-1}\text{cm}^{-3}]\) is

\[
\frac{dN_A(E_n)}{dE_n dV} = 10^{-4} \frac{4\pi}{c(\text{cm/ sec})} \frac{A}{dE_A dS dt d\Omega}
\]

The neutron flux \([\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]\) is calculated for the disc shaped region. The geometrical correction is done following the formalism discussed in the paper by Joshi, Winter & Gupta.
The solid angle subtended by the Galactic plane to us is assumed to be \( \Omega_G = 1 \) sr. \( r \) is the distance of the site of neutron production from the earth. The effective radius is \( R_{\text{eff}} = \int \frac{dV}{4 \pi r^2} = 1.7 \) kpc as discussed in Joshi, Winter & Gupta 2014. The neutrons decay to antineutrinos with average energy \( \epsilon_n' = 0.48 \) MeV in the rest frame of the neutrinos. The secondary neutrons have a flux given by eqn. 4. The antineutrino flux \( (\text{GeV}^{-1} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}) \) produced from the decay of neutrons is

\[
J_{\bar{\nu}}(E_{\bar{\nu}}) = \frac{m_n}{2\epsilon_n} \int_{E_{\nu}^{max}}^{E_{\nu}^{max}} \frac{dN_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}} J_n(E_n) \quad (6)
\]

as given in eqn.(25) of Anchordoqui et al. 2007 where \( E_{\nu}^{max} \) is the maximum energy of the neutrons decaying to antineutrinos. The antineutrinos may take energy between 0 and \( \frac{2\epsilon_n'}{m_n} E_n \). We have assumed that the antineutrinos on the average have energy \( \frac{2\epsilon_n'}{m_n} E_n \) to simplify the calculations. The number of neutrons is equal to the number of antineutrinos if all the neutrons decay before reaching us. We apply the conservation of the total number of neutrons and antineutrinos to get the antineutrino flux. The antineutrino flux \( (\text{GeV}^{-1} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}) \) produced from the decay of neutrons of energy \( E_n \) and Lorentz factor \( \gamma_n \) is

\[
J_{\bar{\nu}}(E_{\bar{\nu}}) = \frac{m_n}{\epsilon_n'} J_n(E_n) \quad (7)
\]

where \( E_{\bar{\nu}} = \gamma_n \epsilon_n' \). We note that the antineutrino fluxes calculated using eqn. 5 and eqn. 7 differ by a factor of \( 2^{n-1}/\alpha \) where \( \alpha \) is the spectral index of the stripped neutron spectrum. For \( \alpha \) in the range of 1 to 4 one gets accurate results within a factor of 2 using our eqn. 7.

4. DISCUSSION:

We have used the three population models (i) Hillas model (ii) global fit model of cosmic rays to calculate the flux of antineutrinos produced in the photo-disintegration of cosmic ray heavy nuclei near the Galactic plane region. The CNO, Mg-Si and Fe cosmic ray nuclei are included in our study. The radiation field is assumed to be uniform within the disc shaped region of radius 10 kpc and height 0.5 kpc. The spectral intensities of the field corresponding to \( R=0, z=0 \) and \( R=4 \) kpc, \( z=0 \) given in Fig.1. (bottom panel) of the paper by Moskalenko, Porter & Strong 2006 have been used in the present work.

If we increase the halo size the effective radius increases (please see Table 1: of Joshi, Winter & Gupta). The antineutrino flux is directly proportional to the effective radius so it also increases. The intensity of radiation decreases if \( R \) and \( z \) increase hence increasing the size of the region is not justified. One may consider a smaller region near the Galactic plane in that case the effective radius will be smaller.

Our calculated rates of photo-disintegration for iron and oxygen nuclei are shown in Fig.1. The energy dependence of the rate of photo-disintegration can be explained from the energy dependence of the background radiation field. The higher energy cosmic ray nuclei can be photo-disintegrated by the lower energy photons in the radiation field.

The IceCube collaboration has given the best fit power law for the observed total isotropic flux of neutrinos and antineutrinos \( E_{\nu}^2 dN(E_{\nu}) = 1.5 \times 10^{-8} (E_{\nu}/100 \text{TeV})^{-0.3} \) GeV cm\(^{-2}\) sec\(^{-1}\) sr\(^{-1}\) in the energy range of 28 TeV to 2 PeV (Aartsen et al. 2014). We have shown our calculated antineutrino fluxes in Fig.2. in the energy range of 28 TeV to 100 TeV. The average length traversed by neutrinos before decaying to antineutrinos increases with energy. At 10\(^8\) GeV this length is 1 kpc. We do not expect antineutrinos at very high energy as their parent ultrahigh energy neutrons will not decay before reaching us.

Some of the antineutrinos oscillate to neutrinos while reaching us. In the present work we do not distinguish between antineutrinos and neutrinos.

In the other regions of the Galaxy the radiation field is significantly low so photo-disintegration of heavy nuclei is not so important in those regions. IceCube collaboration has not found any anisotropy in the neutrino flux. Hence neutrinos/antineutrinos can not be overproduced in any direction. Our result shows that the flux of antineutrinos expected from the photo-disintegration of heavy nuclei near the Galactic plane is very low compared to the flux detected by the IceCube collaboration.

5. CONCLUSION:

The three population models are used to calculate the antineutrino flux produced in the photo-disintegration of CNO, Mg-Si and Fe nuclei near
TABLE 1: Hillas Model: normalisation constants $a_{ij}$ and spectral indices $\gamma_{ij}$ and cut-offs in rigidity $R_c$ (Gaisser, Stanev & Tilav 2013).

| Parameters | $a_{ij}$ | $\gamma_{ij}$ | Pop 1: $R_c = 4PV$ | Pop 2: $R_c = 30PV$ | Pop 3: $R_c = 2 EV$ |
|------------|---------|---------------|---------------------|---------------------|---------------------|
| $He$       | 7860    | 1.66          | 3550                | 2200                | 1430                |
| $CNO$      | 1.58    | 1.63          | 1.63                | 1.67                | 1.63                |
| $Fe$       | 1.7     | 1.4           | 1.4                 | 1.4                 | 1.4                 |

TABLE 2: Global fit Model: normalisation constants $a_{ij}$ and spectral indices $\gamma_{ij}$ and cut-offs in rigidity $R_c$ (Gaisser, Stanev & Tilav 2013).

| Parameters | $a_{ij}$ | $\gamma_{ij}$ | Pop 1: $R_c = 120TV$ | Pop 2: $R_c = 4PV$ | Pop 3: $R_c = 1.3 EV$ |
|------------|---------|---------------|----------------------|-------------------|----------------------|
| $He$       | 7000    | 1.66          | 3200                 | 100               | 0.025                |
| $C$        | 1.58    | 1.4           | 1.4                  | 1.3               | 1.4                  |
| $O$        | 1.4     | 1.3           | 1.3                  | 1.2               | 1.2                  |

Fig. 1.— Rate of Photo-disintegration of cosmic ray iron and oxygen nuclei plotted for the assumed radiation fields IR1 ($R=0,z=0$) and IR2 ($R=4 kpc, z=0$) from Fig.1.(bottom) of Moskalenko, Porter & Strong 2006.

the Galactic plane region. The radiation field is assumed to be uniform with the intensity similar to that given in Fig.1. (bottom panel) of Moskalenko, Porter and Strong 2006 for the two cases IR1 ($R=0,z=0$) and IR2 ($R=4 kpc, z=0$). In all cases it is found that the antineutrino flux is much less than the flux measured by the IceCube detector.

6. ACKNOWLEDGMENT

The author is thankful to the referee for constructive comments which improved the paper significantly.

REFERENCES

Aartsen M. G. et al., 2013a, arXiv:1312.0101.
Aartsen M. G. et al., 2013b, Phys. Rev. Lett., 111, 021103.
Aartsen M. G. et al., 2013c, Science, 342, 124856.
Aartsen M. G. et al., 2014, Phys. Rev. Lett., 113, 101101.
Ahlers M. & Murase K., 2014, Phys. Rev. D, 90, 023010.
Ahn H. S. et al., 2009, ApJ, 707, 593.
Anchordoqui L. A. et al., 2007, Phys. Rev. D, 76, 123008.
Anchordoqui L. A., 2015, Phys. Rev. D 91, 027301.
Antoni T. et al. (Kascade Collaboration), 2005, Astropart. Phys., 24, 1.
Fig. 2.— Antineutrino fluxes calculated in the energy range of 28 TeV to 100 TeV for the Hillas model and the global fit model assuming uniform radiation fields for the two cases IR1 and IR2.

Balashev V. V. et al., 1987, Moscow University Physics Bull. 42, 93
Berezhnev S. F. et al. (Tunka Collaboration), 2012, NIM A, 692, 98.
Gaisser T. K., Stanev T. & Tilav S., 2013, FrPhys, 8, 748.
Gaisser T. K., 2012, Astropart. Phys., 35, 801.
Glasmacher M. A. K. et al., 1999, Astropart. Phys., 10, 291.
Garyaka A. P. et al., 2008, J. Phys. G: Nucl. Part. Phys., 35, 115201.
Gupta N., 2012, Astropart. Phys., 35, 503.
Gupta N., 2013, Astropart. Phys., 48, 75.
Hooper D., Sarkar S. & Taylor A. M., 2008, Phys. Rev. D, 77, 103007.
Hooper D., Taylor A. and Sarkar S., 2005, Astropart. Phys., 23, 11.
Joshi J., Winter W. & Gupta N., 2014, MNRAS, 439, 3414; Erratum 2015, MNRAS, 446, 892.
Karakula S. et al., 1994, ApJS, 92, 481.
Kundu E. & Gupta N., 2014, JCAP, 04, 030.
Moskalenko I. V., Porter T. & Strong A. W., 2006, ApJ Lett., 640, 155.
Puget J. L., Stecker F. W. & Bredekamp J. H., 1976, ApJ, 205, 638.
Stecker F., 1969, Phys. Rev., 180, 1264.
Stecker F. W. & Salamon M. H., 1999, ApJ, 512, 521.