Mass and Life Time of Heavy Dark Matter Decaying into IceCube PeV Neutrinos

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Abstract

Considering that the ultrahigh energy (UHE) upgoing muon neutrino events around the PeV energy region observed by the IceCube are due to the decay of super heavy dark matter to neutrinos, we constrain the mass of the decaying dark matter and its decay lifetime using the IceCube analysis of these neutrinos in the PeV region. The theoretical fluxes are computed by adopting the procedure given in the reference \cite{1,2}, where the DGLAP numerical evolutions of QCD cascades as well as electroweak corrections are included for evolving the decay process of the super heavy dark matter. Our results indicate that to explain the IceCube events around PeV region the decaying dark matter mass $m_{\chi}$ would be $\sim 5 \times 10^7$ GeV with the decay lifetime $\tau \sim 7 \times 10^{28}$ sec.

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1 Introduction

The origins of the ultra high neutrino events recorded by the IceCube Collaboration so far are not very clearly known. Although one multimessenger observation in terms of coincident gamma ray detection by the collaboration of Fermi-LAT, MAGIC, AGILE, HAWC, H.E.S.S. etc. and the high energy neutrino at IceCube-170922A point towards a flaring blazar TXS0506+056 \cite{3}. But the source of other UHE neutrino events at IceCube is by and large unknown. These also include the track events for the neutrinos in and around PeV region. In this work we explore an alternative possibility that these neutrinos could have been created by the rare or long leave decay of superheavy dark matter in the Universe \cite{4,21}. The superheavy dark matter could be created during a spontaneous symmetry breaking in Grand Unified scale and thus they were never in thermal equilibrium with the Universe. Thus their production is nonthermal in nature. Such particles can also be originated by the process of gravitational creation \cite{4} in the early Universe. After the discovery of PeV neutrinos at Icecube, the hypothesis of their dark matter origin gained lot of interest \cite{5}-\cite{20}. Here in this work, we consider the decay of the super heavy dark matter to interpret the neutrinos in and around the PeV region recorded by IceCube that includes the best fit region for muon neutrino track events given by IceCube in the same regime.

From the 2078 data sample, where 82 events had been detected by the IceCube collaboration, they have made a fit with these 82 events assuming these to have come from extragalactic diffuse UHE neutrino flux \cite{22}. They have fit the flux by adopting first an unbroken power law spectrum $\sim E^{-\gamma}$, $\gamma$ being the spectral index and $\gamma$ is obtained as $\gamma = 2.92^{+0.33}_{-0.29}$. But later analyses yielded a softer spectrum. Also from the upgoing muon events for high energy muon neutrino sample starting from an energy around 120 TeV the IceCube collaboration had obtained a different power law. The earlier single power law fit ($\gamma \sim 2.9$) which the IceCube collaboration referred to as HESE (high energy starting events) data differ from the fit of high energy muon neutrino data above 120 TeV. In the present work we consider the softer spectrum fit (from the track event) for the later data set above 120 TeV and argue that this UHE neutrino signals could have originated from the rare decay of very massive dark matter with mass $\sim 10^7$ GeV. The decay of such massive particles generally produces QCD cascade.

The decay of such massive particles much heavier than electroweak scale are discussed in the literature such as \cite{1,2,21,23}, where the decays of super heavy particles are considered to proceed via the cascading of QCD partons. It is argued that al-
though the QCD coupling is small the parton splitting is favoured by collinear parton emission \[2\]. Also these decay processes are enhanced by the electroweak radiative corrections at the TeV scale and above. Computer codes have been developed for the QCD decay cascade process of such decays where use have been made for Dokshitzer-Grivov-Lipatov-Altarelli-Parisi (DGLAP) equations \[24, 25\]. In order to treat the electroweak radiative corrections, evolution equations similar to DGLAP equations are developed valid for a spontaneously broken theory. The electroweak cascade experiences interactions of SU(3) × SU(2) × U(1) and the couplings are enhanced \[2\].

As mentioned in the present work, we are considering a super heavy particle with mass \(m_\chi \leq m_{\text{GUT}}\) that decays to produce νν̄ (\(\chi \rightarrow \nu \bar{\nu}\)) as the final product. Here for \(m_\chi >> m_W\) the electroweak cascade accompanies the usual QCD cascade. The numerical evolution of the DGLAP equations and Monte Carlo (MC) studies of such cascades yield the spectrum of the final product leptons. In the whole process one needs to consider two decay channels, one is the hadronic decay channel while the other is the leptonic decay channel. As mentioned in the hadronic decay channel, the decay proceeds through the QCD cascade whereby the decay of dark matter \(\chi\) to \(\bar{q}q\) (\(\chi \rightarrow \bar{q}q\)) is first produced which then hadronizes producing eventually the leptons as final decay products. The numerical evolution of DGLAP equations can also be used for the case of electroweak radiative corrections. These are studied for a spontaneously broken theory \[26\]. Similar procedure for electroweak cascade attributes to the leptonic decay channel. In this work, we compute the neutrino spectrum from the decay of super heavy dark matter using first the hadronic channel and then extend to the leptonic channel of dark matter decay to calculate the neutrino flux in the PeV region considered. We then make a \(\chi^2\) fit with the IceCube results to obtain the values of dark matter mass and its decay lifetime.

In Section. 2 we describe the formalism of our work. Section. 3 gives the calculations and the results. Finally a summary and conclusions are given in Section. 4.

## 2 Formalism

The final neutrino spectrum is written as \[1\]

\[
\frac{dN_\nu}{dx} = 2R \int_{xR}^{1} dy D^{\pm}_\pi(y) + 2 \int_{x}^{1} \frac{dz}{z} f_{\nu_1} \left(\frac{y}{z}\right) D^{\pm}(z),
\]

(1)
where $D^\pi(x,s)$ is defined as $D^\pi \equiv [D_q^\pi(x,s) + D_g^\pi(x,s)]$. $R = \frac{1}{1 - r}$, where $r = (m_\mu/m_\pi)^2 \simeq 0.573$ and the functions $f_{\nu_i}(x)$ are taken from the reference [27].

\begin{align*}
  f_{\nu_i}(x) &= g_{\nu_i}(x)\Theta(x - r) + (h_{\nu_i}^{(1)}(x) + h_{\nu_i}^{(2)}(x))\Theta(r - x), \\
  g_{\nu_i}(x) &= \frac{3 - 2r}{9(1 - r)^2}(9x^2 - 6 \ln x - 4x^3 - 5), \\
  h_{\nu_i}^{(1)}(x) &= \frac{3 - 2r}{9(1 - r)^2}(9r^2 - 6 \ln r - 4r^3 - 5), \\
  h_{\nu_i}^{(2)}(x) &= \frac{(1 + 2r)(r - x)}{9r^2}[9(r + x) - 4(r^2 + rx + x^2)], \\
  g_{\nu_e}(x) &= \frac{2}{3(1 - r)^2}(1 - x)(6(1 - x)^2 + r(5 + 5x - 4x^2)) + 6r \ln x, \\
  h_{\nu_e}^{(1)}(x) &= \frac{2}{3(1 - r)^2}[(1 - r)(6 - 7r + 11r^2 - 4r^3) + 6r \ln r], \\
  h_{\nu_e}^{(2)}(x) &= \frac{2(r - x)}{3r^2}(7r^2 - 4r^3 + 7xr - 4xr^2 - 2x^2 - 4x^2r) .
\end{align*}

In this work we compute Eq. (1) and obtained the neutrino spectrum for several values of $m_\chi$. We also found that for the chosen range of $m_\chi$ in this work the contribution to the neutrino spectrum due to the leptonic channel is not more than $\sim 10\%$. Therefore in this work we focus on the hadronic channel.

The isotropic extragalactic neutrino flux from the decay of such a heavy dark matter with mass $m_\chi$ is given as

\begin{equation}
  \frac{d\Phi_{EG}}{dE}(E_\nu) = \frac{1}{4\pi m_\chi \tau} \int_0^\infty \frac{\rho_0 c/H_0}{\sqrt{\Omega_m(1 + z^3) + (1 - \Omega_m)}} \frac{dN}{dE}(E(1 + z))dz .
\end{equation}

In the above equation (Eq. (3)), the proper radius of the Hubble sphere, which is known as the Hubble radius, is defined as $c/H_0$, where $c/H_0 = 1.37 \times 10^{28}$ cm. $\rho_0 = 1.15 \times 10^{-6}$ GeV/cm$^3$ signifies the average cosmological dark matter density at the present epoch (redshift $z = 0$), $\Omega_m = 0.316$ is the contribution of the matter density to the energy density of the Universe in units of the critical energy density.

The quantity $\frac{dN}{dE}$ in Eq. (3) describes the neutrino energy spectrum, which is obtained from the decay of super heavy dark matter ($\chi$) and this injected neutrino spectrum is considered as a function of the neutrino energy at redshift $z$, $E(z) = (1 + z)E$.

The galactic neutrino flux from similar decay is described by

\begin{equation}
  \frac{d\Phi_G}{dE}(E_\nu) = \frac{1}{4\pi m_\chi \tau} \int_{V} \frac{\rho_\chi(R[r])}{4\pi r^2} \frac{dN}{dE}(E,l,b)dv ,
\end{equation}

\section*{References}

[27]
where $\rho_\chi(R|r)$ is the dark matter density at a distance $R$ from the Galactic Centre and $r$ is the distance from the Earth. In our calculation, for the dark matter density we consider the Navarro-Frenk-White (NFW) profile. $l$ and $b$ are the galactic coordinates, where $l$ is the line of sight distance. $dN/dE(E,l,b)$ defines the neutrino spectrum decaying from the super heavy dark matter particle ($\chi$). We consider the Milky way halo over which the integration is taken over in our calculation and for which $R_{\text{max}}$ is chosen as 260 Kpc.

The total flux is obtained as

$$\phi^{\text{th}}_\nu(E_\nu) = \frac{d\Phi_{\text{EG}}}{dE}(E_\nu) + \frac{d\Phi_{\text{G}}}{dE}(E_\nu).$$

(5)

The total flux is defined as the theoretical flux $\phi^{\text{th}}_\nu$ at an energy $E_\nu$ of our analyses.

Also it is assumed that due to the oscillations of the neutrinos the neutrinos are reaching the earth with the flavour ratio 1:1:1. Using Eq. (1 - 5) we compute the total $\nu_\mu$ flux reaching at the IceCube detector and fit them with the data points from the pink band given by the IceCube analyses (Figure 2 of [22]).

3 Calculations and Results

We have considered the energy region from $\sim 10^5$ GeV to $\sim 5 \times 10^6$ GeV for UHE neutrinos for our analyses. As mentioned earlier, this region is obtained by the analyses of the IceCube collaboration for the UHE upgoing muon neutrino spectrum and shown as a pink band (for 1$\sigma$ uncertainties) in Figure 2 of reference [22]. For our analyses we have chosen all the three experimental points that are included in the pink band and have adopted several other points within the pink band along with their 1$\sigma$ spread (the bandwidth of the pink band at the position of the chosen band). The chosen data sets for the fit are given in Table 1.

The pink band as given by the fit are given in Table 1 along with the three observational points included in the band are reproduced in Figure 1.

The purpose of this work is to find the best fit value of the mass of the super heavy dark matter ($m_\chi$) and its decay lifetime ($\tau$) that on its decay produce the UHE neutrinos in the region considered. The $\chi^2$ for our fit is defined as

$$\chi^2 = \sum_{i=1}^n \left( \frac{E_i^2 \phi^{\text{th}}_i - E_i^2 \phi^{\text{Ex}}_i}{\text{err}_i} \right)^2,$$

(6)

where $n(=12)$ is the number of chosen points (Table 1) and $E_i(i = 1, .., n)$ are the energies of the chosen points. In Eq. (6) $\phi^{\text{th}}_i(E_\nu)$ (and hence $E_i^2 \phi^{\text{th}}_i(E_\nu)$), the
Table 1: The data points (12 in all) used for the $\chi^2$ fit. First three points (marked with “*”) are the observed events by IceCube as shown in Figure 1. See text for details.

| Energy (in GeV) | Neutrino Flux ($E_\nu^2 d\Phi_{E_\nu} dE$) (in GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$) | Error |
|----------------|---------------------------------------------------------------------------------|-------|
| 2.51189e+06*  | 4.16928e-09*                                                                     | 8.2726e-09* |
| 1.19279e+06*  | 5.03649e-09*                                                                     | 7.5383e-09* |
| 2.68960e+05*  | 7.50551e-09*                                                                     | 8.1583e-09* |
| 3.54813e+06   | 5.25248e-09                                                                       | 4.1258e-09 |
| 2.30409e+06   | 5.71267e-09                                                                       | 4.1600e-09 |
| 1.52889e+06   | 6.21317e-09                                                                       | 3.9882e-09 |
| 1.05925e+06   | 6.61712e-09                                                                       | 3.7349e-09 |
| 7.18208e+05   | 7.04733e-09                                                                       | 3.9777e-09 |
| 4.46684e+05   | 7.66476e-09                                                                       | 3.6478e-09 |
| 2.86954e+05   | 8.16308e-09                                                                       | 4.1571e-09 |
| 1.90409e+05   | 8.87827e-09                                                                       | 6.2069e-09 |
| 1.43818e+05   | 9.65612e-09                                                                       | 6.8856e-09 |
Theoretical flux is obtained from Eq. (5) where $E_2^2 \phi_i^E(E_{\nu}) (= E_{\nu}^2 \frac{d\Phi}{dE})$ corresponding to experimental data are given in Table 1 and $(err)_i$ is the $i^{th}$ chosen experimental points (Table 1).

Choosing a range of $m_{\chi}$ and the decay time $\tau$ we compute the $\chi^2$ and one obtained the best fit values of $m_{\chi}$ and $\tau$ by minimizing the $\chi^2$ and the minimum $\chi^2$ denoted as $\chi^2_{\text{min}}$. The 1$\sigma$, 2$\sigma$ and 3$\sigma$ ranges for $m_{\chi}$ and $\tau$ are also obtained. As the present $\chi^2$ fit is a two parameter fit, the 1$\sigma$, 2$\sigma$ and 3$\sigma$ regions are obtained by adopting the range of $\chi^2$ to be $\chi^2_{\text{min}} + 2.30, \chi^2_{\text{min}} + 4.61, \chi^2_{\text{min}} + 9.21$ respectively. The results are shown in Figure 2.

The best fit value of $m_{\chi}$ and $\tau$ from our analyses are obtained as $m_{\chi} = 5.2 \times 10^7$ GeV, $\tau = 7.05 \times 10^{28}$ sec. This is denoted by a point in Figure 2. The 1$\sigma$, 2$\sigma$ and 3$\sigma$ are also shown in Figure 2 by different shades. From this analysis it can be said that in case the UHE neutrinos of the chosen energy range, adopted from IceCube experimental results, are generated from the decay of super heavy dark matter then the mass of such dark matter will be $\sim 5 \times 10^7$ GeV undergoing the rare decay with decay lifetime $\sim 7 \times 10^{28}$ sec. In Figure 3 we show the neutrino flux in the PeV region calculated with these best fit values.

In order to explore the effect of the decay of the super heavy dark matter via the leptonic channel on the IceCube results we fix the mass $m_{\chi}$ at its best fit value obtained above ($m_{\chi} = 5.2 \times 10^7$ GeV). The neutrino spectrum due to the leptonic channel for $m_{\chi} = 5.2 \times 10^7$ GeV is evaluated from the formalism given in [1, 2].
and the corresponding galactic and the extragalactic neutrino fluxes are calculated using the relations Eq. 4,5 [1]. The total flux is now thereof the sum of the fluxes for hadronic channel and the leptonic channel in which the decay lifetime $\tau$ is an unknown parameter. We now make a one parameter $\chi^2$ analysis (using Eq. (6) for all the set of points given in Table 1 and obtained the best fit value of the decay lifetime for the dark matter mass $m_\chi = 5.2 \times 10^7$ GeV fixed at the best fit value of $m_\chi$ (Figure 2) when both the hadronic and the leptonic channels are considered. We obtain the best fit value $\tau$ to be $8.57 \times 10^{27}$ sec. This is further illustrated in Figure 4 where we plot the variation of $\chi^2$ (one parameter $\tau$) with the fitted parameter $\tau$. 

Figure 2: $m_\chi - \tau$ (two parameter) $\chi^2$ fit corresponding to the 1$\sigma$, 2$\sigma$, and 3$\sigma$ level of confidence. See text for details.

Figure 3: The neutrino flux with best fit values of $m_\chi$ and $\tau$. Only hadronic channel is considered for dark matter decay.
Thus we see we have a marginal modification of the decay lifetime when the leptonic channel effects are included in our analysis. We also show in Figure 5 the variation flux with neutrino energies (in the PeV region) for the fitted value of $\tau$ as obtained from Figure 4. This can be noted in Figure 5 that a kink appears at the tale of the fitted plot. This kink is due to the shape of the neutrino spectrum obtained from the leptonic channel which showes a sharp rise at higher energy region.

Figure 4: Variation of $\chi^2$ with the fitted parameter $\tau$. See text for details.

Figure 5: The neutrino flux with best fit values of $\tau$ when both hadronic and leptonc channel are considered for dark matter decay.
4 Summary and Conclusions

In this work, we have explored the possibility that the UHE neutrino detected by IceCube in and around PeV energy region could have originated from the decay of super heavy dark matter. Such super heavy dark matter could be created at the early Universe during spontaneous symmetry breaking at the GUT scale and they decay to leptons at the electroweak scale involving the processes of QCD cascade and electroweak cascade. The numerical evolution of such process are generally done by Monte Carlo methods or by evolving the DGLAP equations treated numerically. In a recent work M. Kachelriess et al. \cite{2} made a MC analysis for such heavy dark matter decay to leptons such as $\nu\bar{\nu}$ pair and $e^+e^-$ pair as well as the photons where the recently updated limits of diffuse gamma ray flux has also been incorporated. In our present work, we compute the neutrino spectrum from the heavy dark matter decay as prescribed in reference and obtained the galactic and extragalactic neutrino fluxes from such decays. We then constrain the two unknown parameters namely the heavy dark matter mass ($m_\chi$) and its decay lifetime ($\tau$) by making a $\chi^2$ fit of the calculated neutrino flux with those given from the observed events at IceCube by the IceCube collaboration. For this purpose we have chosen the region given by the IceCube collaboration corresponding to the upgoing muon neutrinos with energies in and around PeV region. The IceCube collaboration analysis designated this region by a pink band of 1$\sigma$ width in their published data and plots. We have made a $\chi^2$ fit adopting a data set from this region that includes the observed points as well as other points chosen from within this pink band. We first consider the hadronic channel for $\nu\bar{\nu}$ production from the heavy dark matter decay and our $\chi^2$ fit yield the best fit value for the parameters $m_\chi, \tau$ as $m_\chi = 5.2 \times 10^7$ GeV, $\tau = 7.05 \times 10^{28}$ sec. We also furnish 1$\sigma$, 2$\sigma$ and 3$\sigma$ C.L. contours in the parameter space $m_\chi, \tau$. With this best fit value of $m_\chi$ we then add the contribution of the leptonic channel for this value of $m_\chi$ and then constrain the decay life time $\tau$ by performing the one parameter $\chi^2$ analysis. From our studies it appears that in order to explain the nature of the neutrino flux for the upgoing muon events in and around PeV region by considering the decay of heavy dark matter to neutrinos, the dark matter mass should be of the order of $m_\chi \sim 5 \times 10^7$ GeV GeV undergoing the rare decays with life time $\tau \sim 7.05 \times 10^{28}$ sec. Constraining the $m_\chi - \tau$ parameter space by calculating the spectrum from both the hadronic and the leptonic channel and the analysis for the higher energy range that extends upto $10^8$ GeV are in progress. It appears that in order to explain the nature of the flux towards the $10^8$ GeV regime, the leptonic channel could be very important.
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**References**

[1] M. Kacherlriess, O. E. kalashev and M. Yu. Kuznetsov, Phys. Rev. D. **98**, 083016 (2018).

[2] V. Berezinsky, M. Kacherlriess and S. Ostapchenko, Phys. Rev. Lett. **89**, 171802 (2002).

[3] M. G. Aartsen et al., IceCube and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS and VLA/17B-403 Collaborations, Science **361**, 6398, eaat1378 (2018).

[4] V. A. Kuzmin and I. I. Tkachev, Phys. Rep. **320**, 199 (1999).

[5] L. Covi, M. Grefe, A. Ibarra, D. Tran, JCAP **1004**, 017 (2010).

[6] A. Esmaili, S. K. Kang, P.D. Serpico, JCAP **1412**, 054 (2014).

[7] C. Rott, K. Kohri, S.C. Park, Phys. Rev. D **92**, 023529 (2015).

[8] Y. Bai, R. Lu, J. Salvado, JHEP **01**, 161 (2016).

[9] A. Esmaili, P.D. Serpico, JCAP **1311**, 054 (2013).

[10] A. Bhattacharya, M.H. Reno, I. Sarcevic, JHEP **06**, 110 (2014).

[11] A. Esmaili, A. Ibarra, O.L.G. Peres, JCAP **1211**, 034 (2012).

[12] C.S. Fong, H. Minakata, B. Panes, R.Z. Funchal, JHEP **1502**, 189 (2015).

[13] C. El Aisati, M. Gustafsson, T. Hambye, Phys. Rev. D **92**, 123515 (2015).

[14] S.M. Boucenna et al., JCAP **1512**, 055 (2015).
[15] S. Troitsky, JETP Lett. 102, 785 (2015).

[16] M. Chianese, G. Miele, S. Morisi, E. Vitagliano, Phys. Lett. B 757, 251 (2016).

[17] M. Chianese, G. Miele, S. Morisi, JCAP 1701, 007 (2017).

[18] A. Bhattacharya, A. Esmaili, S. Palomares-Ruiz, I. Sarcevic, JCAP 1707, 027 (2017).

[19] M. Chianese, G. Miele, S. Morisi, Phys. Lett. B 773, 591 (2017).

[20] M. G. Aartsen et al., IceCube Collaboration, Eur. Phys. J. C 78, 831 (2018).

[21] R. Aloisio, V. Berezinsky and M. Kachelriess, Phys. Rev. D. 69, 094023 (2004).

[22] The IceCube Collaboration, 35th International Cosmic Ray Conference - ICRC2017, PoS (ICRC2017) 981.

[23] V. Berezinsky and M. Kachelriess, Phys. Rev. D. 63, 034007 (2001).

[24] V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. 15, 438 (1972); 15, 675 (1972).

[25] G. Altarelli and G. Parisi, Nucl. Phys. B126, 298 (1977); Yu. L. Dokshitzer, Sov. Phys. JETP 46, 641 (1977).

[26] M. Ciafaloni, P. Ciafaloni and D. Comelli, Phys. Rev. Lett. 88, 102001 (2002).

[27] S. R. Kelner, F. A. Aharonian and V. V. Bugayov, Phys. Rev. D. 74, 034018 (2006) [Erratum: Phys. Rev. D. 79, 039901 (2009)].