High energy leptonic originated neutrinos from astrophysical objects

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The standard perception is that the detection of high energy (TeV energies and above) neutrinos from an astrophysical object is a conclusive evidence for the presence of hadronic cosmic rays at the source. In the present work we demonstrate that TeV neutrinos can also be originated from energetic electrons via electromagnetic interactions in different potential cosmic ray sources with flux levels comparable to that of the hadronic originated neutrinos at high energies. Our findings thus imply that at least a part of the neutrinos observed by Icecube observatory may be originated from energetic electrons. The present analysis further suggests that only a combine study of TeV gamma rays and neutrinos over a wide energy range from an astrophysical object can unambiguously identify the nature of their parents, hadrons or leptons.

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The IceCube experiment recently reported the first detection of extra-terrestrial high energy (\(~\sim 20\,\text{TeV}\) and above) cosmic neutrinos \cite{1} and thereby a new era of high energy neutrino astronomy has begun. A standard belief is that unambiguous identification of the acceleration sites of hadronic cosmic rays, which is one of the long-standing questions in high-energy astrophysics, can be made with the high energy neutrino astronomy \cite{2}. This is because the high energy neutrinos are produced when energetic hadrons from cosmic ray sources interact with ambient matter/radiation via meson decay. High energy gamma rays are also produced together. Being electrically neutral, both gamma rays and neutrinos detected on the Earth point back towards their sources and thus can be used to locate and study the cosmic ray sources. However, very high energy gamma rays also can be originated from energetic leptons via inverse Compton process and therefore, observation of high energy gamma rays does not warrant the presence of relativistic atomic nuclei in the source. High energy neutrinos, on the other hand, are supposed to be dominantly created only in hadronic processes and therefore, they unambiguously carry the signature of cosmic ray hadrons at the source location \cite{2}.

In this work, we would demonstrate that high energy astrophysical neutrinos also can be generated from very energetic leptons at several potential cosmic ray sources with flux level comparable to the hadronic originated neutrino flux at very high energies (quantitatively defined in the relevant part of the text below) and therefore very high energy neutrino astronomy alone cannot conclusively identify the hadronic cosmic ray sources. We shall further argue that only a combine detection of high energy gamma rays and neutrinos with appropriate flux levels and spectral pattern over a wide energy range can identify the acceleration sites of hadronic cosmic rays unambiguously.

At high energies above the muon/pion pair production threshold, interaction of electrons with ambient radiation field can lead to generation of pair of muon and an electron (to be denoted as MPP in the rest of the paper) \((e + \gamma \rightarrow e + \mu^+ + \mu^-)\) or pair of charged pions (PPP) \((e + \gamma \rightarrow e + \pi^+ + \pi^-)\) via higher order electromagnetic processes which subsequently decay into neutrinos. MPP (as well as PPP) is a third-order electromagnetic process \cite{3}. In the large (well above the threshold energy) square of centre-of-mass energy \((s)\) limit the cross section \((\sigma_{MPP}(s))\) of the MPP interaction is given by \cite{4}

\begin{equation} \label{eq1}
\sigma_{MPP}(s) \approx \frac{2\alpha^3}{m_{\mu}^2} \ln(2) \ln\left(\frac{s}{m_e^2}\right)
\end{equation}

where \(\alpha\) \((\text{siemens})\) is the electromagnetic fine structure constant, \(m_\mu\) and \(m_e\) are the rest mass of muon and electron respectively. For the PPP cross section \((\sigma_{PPP}(s))\), \(m_\mu\) has to be replaced by charged pion mass \((m_\pi)\) in the above equation.

The threshold energy \((E_{th})\) for such a muon pair production reaction is

\begin{equation} \label{eq2}
E_{th} = \sqrt{s_{th}} > 2m_\mu.
\end{equation}

(in the natural unit) which translates to the following condition

\begin{equation} \label{eq3}
\epsilon_e\epsilon_\gamma > 0.02f_\gamma \text{GeV}^2
\end{equation}

where

\begin{equation} \label{eq4}
f_\gamma = (1 - \cos\theta_{e\gamma})^{-1},
\end{equation}

\(\epsilon_e\) and \(\epsilon_\gamma\) are the energy of electron and photon respectively and \(\theta_{e\gamma}\) is the angle between electron and photon direction. For PPP reaction, the right hand side of the inequality given by Eq. (2) will be \(2m_\pi\) and consequently the threshold energy is slightly higher than that of MPP.

The observation of bright day-long gamma-ray flares above 100 MeV (supposed to be synchrotron radiation
by relativistic electron-positron pairs) in the Crab Nebula by the gamma-ray space telescope AGILE [5] and the Fermi [6] suggest the presence of PeV electrons in the nebula. It is, therefore, not unlikely that electrons are accelerated to even higher energies in some more violent sources like Active Galactic Nuclei (AGNs), Gamma Ray Bursts (GRBs) etc. If \( \epsilon_e \) is of the order of PeV, \( \epsilon_e \) has to be few tens of eV to satisfy the above threshold conditions. The typical temperature of accretion disc of AGNs [7], young supernova remnants [8], young neutron stars [9,10] is of the order of 0.1 keV (corresponding to 10^8 K) while in Gamma Ray Bursts (GRBs) it is even higher [11]. Hence in all such kind of sources, the energy threshold condition given by Eq. (3) can be satisfied.

The mean free path for muon pair production

\[
l(r) = (\sigma_{MPP} n_\gamma)^{-1}
\]

where \( \sigma_{MPP} \) is the muon pair production cross section, \( n_\gamma \) is the density of photon. The \( \sigma_{MPP} \) is around 0.1 to 1 \( \mu b \) for \( s > 20m_\mu^2 \) [4].

For an astrophysical object of temperature \( T \), the radiation field density is given by

\[
n_\gamma(R) = \left( a/2.8k \right) \left( 1 + z_g \right) T^3 \sim 9 \times 10^{19} T_3^3 \gamma_{0.1 \text{ keV}} \text{ cm}^{-3}.
\]

This gives

\[
l(r) \sim 10^{12} T_3^3 \gamma_{0.1 \text{ keV}} \text{ cm}.
\]

which is well within the radial extent of different celestial sources like SNR, AGN, pulsar nebula, GRBs.

The modeling of energies and momenta of the final three particles in MPP process is very complicated and require detail Monte Carlo study. However, we can estimate the order of energies of the produced neutrinos via MPP reaction. The inelasticity of MPP reaction \( \eta_{MPP} \) at large s limit in the Lab frame is given by

\[
\eta_{MPP} \sim 0.25 \left( s/m_\mu^2 \right)^{-0.5} \text{ [4].}
\]

Hence for a source temperature of 0.1 keV, the energy of the produced muons will be of the order of a few tens of TeV. When muon decays, its energy will be, on the average, equally distribute among the three secondary leptons which include one electron neutrino and one muon neutrino. So on the average the produced neutrinos will have energies tens of TeV or so.

After establishing the viability of production of energetic neutrinos by leptonic processes, the most relevant issue at this stage is the flux of so produced leptonic neutrinos. If the flux of so produced neutrinos is too low, there will be not much relevance of leptonic originated neutrinos from astrophysical sources. The peak value of the cross-section in delta resonance is about 500 \( \mu b \) whereas the cross section for MPP reaction is around 1 \( \mu b \) for \( s >> 20m_\mu^2 \). So leptonic originated neutrino flux should be two to three order lower than those produced in p\( \gamma \) interactions. However, at higher energies the situation is dramatically different due to enhancement of effective interaction cross section of MPP process as argued below.

Above the electron pair production threshold energy the dominant production process in interaction of electrons with ambient photon fields is the triplet pair production (TPP) \( e + \gamma \rightarrow e + e^- + e^- \) [12] and the inverse Compton (IC) scattering. However, in TPP reaction the loss of energy of electrons is insignificant and IC remains the main energy loss process (of electrons) till very high energies. The cross section of IC scattering decreases at large energies (in the deep Klein-Nishina regime) as \( \sim \left( \gamma/\gamma' \right) \) where \( \epsilon' \) (\( \equiv \epsilon/\gamma \)) is the photon energy in the electron rest frame. In contrast the cross section of TPP (as well as MPP/PPP) reaction remains logarithmically constant. When \( \epsilon' > 300 m_\mu^2 \), the energy loss of electrons by TPP reaction overtakes that by IC process [13]. At higher energies, particularly above around \( \epsilon' \sim 30 m_\mu^2 \) even \( \sigma_{MPP} \) will dominate over \( \sigma_{IC} \) and thereby the MPP/PPP reactions becomes one of the main energy loss process for electrons at such high energies.

The ratio of the cross sections of MPP and TPP is

\[
\sim m_\gamma^2/ m_\mu^2
\]

which implies if \( 10^5 e + \gamma \) reactions undergo triplet production, only two reactions give MPP. However, the inelasticity of TPP reaction \( \eta_{TPP} \) is very small; at large \( s \) limit \( \eta_{TPP} \sim 0.25 \left( s/m_\mu^2 \right)^{-0.5} \) (in the Lab frame) which implies that one of the produced electrons in TPP carries most of the incident electrons energy. The leading electron can again interact with the ambient photon field and the cycle will continue till the energy of electron becomes so low that the threshold energy condition given in Eq. (3) breaches. Depending on the cross section there will be a probability for MPP/PPP reaction to occur in each such interaction of leading electrons with the radiation field in the source. As a result the probability of production of muons or pions via MPP/PPP process will be enhanced largely particularly at large energies and the effective cross section for MPP/PPP process will be close to \( \sigma_{TPP} \). When the enhancement factor due to small inelasticity of TPP reaction is taken into account, at high energies the leptonic neutrino production should be comparable to those produced from p\( \gamma \) interactions.

To examine the issue of flux of leptonic originated neutrinos in a more rigorous way and also to have idea about their nature of energy spectrum we employ Monte Carlo simulation. We take three different temperatures of radiation field, 0.01, 0.1 and 1 keV. The energetic primary electrons (accelerated in the source) is considered to follow a power law energy spectrum with spectral index equal to \(-2.2\). The minimum energy of the primary electrons is taken as the threshold energy of the MPP reaction. The electrons are allowed to undergo TPP, IC, MPP and PPP reactions by interacting with the radiation field in accordance with the probability of interactions. The same treatment has been applied to the
secondary electrons till the energy of secondary electrons remains higher than the threshold energy of MPP reactions. We assume that the energy of the two produced muon daughters are equal and the energy of muons are equally distributed among the three secondary leptons which include one electron neutrino and one muon neutrino. The production energy spectrum of so produced muons are shown in Figures 1, 2 and 3 respectively for the temperatures of radiation field 0.01, 0.1 and 1 keV. The production rate is given in arbitrary units along y-axis (which can be converted into the flux once the amplitude of the primary electron energy spectrum is known). Since inelasticity of MPP reaction increases rapidly with energy, the neutrino energy spectrum falls sharply. The lower and higher energy cut-off of leptonic originated neutrinos as well as their fluxes, however, change with the temperature of radiation field as revealed from figures 1-3. For lower radiation field temperature, the lower and upper energy cut-off are higher whereas the flux is lower compare to those due to higher radiation field temperature. For comparison we also plot the energy spectrum of neutrinos produced in interaction of protons with photons in the same figures 1-3. In this case (neutrinos from $p\gamma$ interaction) we simply assume that the radiation field consists of photons with constant energy 1 keV. Since the cross section of $p\gamma$ interaction falls sharply before and after the resonance peak, the spectra of hadronic originated neutrinos as shown in figures 1-3 essentially represent upper limit of the flux. The threshold energy for delta resonance is about an order higher than that of MPP reaction. As a result, the lower cut off energy of neutrinos from $p\gamma$ interaction is higher than the leptonic originated neutrinos. The inelasticity in $p\gamma$ reaction is also higher and roughly constant over the energy range concerned. Thus there is no upper energy cut off in the hadronic originated neutrino spectrum and the shape of the spectrum roughly follow that of the primary hadrons.

Instead if we consider TeV neutrinos from $p-p$ collisions, again the flux of the leptonic originated neutrinos should be comparable to those produced from $p-p$ interactions. This is because though $\sigma_{pp}$ is about two order higher than the effective $\sigma_{MPP}$, but to interpret the observed GeV to TeV gamma ray flux via leptonic production, the product of energetic electron density and and ambient photon density has be be taken substantially higher than the product of energetic proton density and the density of ambient matter as $\sigma_{pp}$ is much higher than $\sigma_{1IC}$. The flavor ratio of the leptonic originated neutrinos at the Earth also should be $1:1:1$ as in the case of hadronic originated neutrinos due to neutrino oscillations.

In an early work non-hadronic neutrino production mainly via $\eta$-resonance formation in several astrophysical sources was discussed [15]. In that production channel for neutrinos in leptonic processes a low energy thermal photons ($\gamma'$) gain energy interacting with energetic elec-

**Fig. 1**: A comparison of energy spectrum of leptonic originated and hadronic generated neutrinos when the temperature of the radiation field of the source is 0.01 keV.

**Fig. 2**: Same as the Fig. 1 but for radiation field temperature of 0.1 keV.

neutrons via inverse Compton mechanism ($e + \gamma' \rightarrow e + \gamma$) and subsequently the upscattered photons ($\gamma$) interacting with low energy environmental photons gives rise $\eta$ resonance and the subsequent decay (with branching ratio of around 23%) of $\eta$ particle leads to charged pions ($\eta \rightarrow \pi^0 + \pi^+ + \pi^-$). The peak cross-section of $\eta$-resonance production is about 3 mb, substantially
higher than the MPP reaction. However, because of the multi step processes, inverse Compton to produce high energy gamma rays from energetic electrons and subsequent $\eta$-resonance production and decay, the neutrino flux via this channel will substantially small.

To the question of identification of the origin of detected neutrinos we propose that a combined study of the high energy neutrinos and the accompanying high energy gamma rays from an astrophysical source will be useful. In the leptonic scenario, the energetic gamma ray flux from the stated sources is supposed to be the upscattered photons via inverse Compton process. In fact the observations of TeV gamma rays from the sources like AGN, GRBs, SNRs are often explained in terms of IC scattering of the radiation field of the source by energetic electrons. As mentioned already the inverse Compton cross section decreases sharply with energy and therefore TeV gamma ray flux will decrease sharply with energy. So if the energetic electrons are responsible for the observed gamma rays and neutrinos from a source, the ratio of high energy neutrino to gamma ray flux will increase with their energy. In the case of hadronic originated gamma rays and neutrinos, by contrast, the ratio of flux of these two species will be nearly one and remains constant over a wide energy range.

In conclusion we may say that detection of neutrinos from an astrophysical source does not conclusively mean the presence of energetic hadrons in the source; high energy TeV neutrinos with comparable flux also can be originated from energetic leptons. The neutrino events detected by Icecube experiment so far, at least a part of them therefore may be leptonic in origin. The observation of appropriate fluxes of gamma rays and neutrinos together over an energy range only can give clear signature of hadronic cosmic ray sources. A joint venture between upcoming high energy gamma ray telescopes such as the Cerenkov Telescope Array (CTA) and the Precision IceCube Next Generation Upgrade (PINGU)/Icecube thus may give conclusive evidence for sites of hadronic cosmic rays.

On various estimation of astrophysical neutrinos, such as diffuse neutrino flux, the production mechanism of neutrinos is important. The interstellar radiation field and the interstellar gas are the targets for diffuse gamma-ray production by energetic hadronic cosmic rays. In view of the present findings, the role of energetic electrons in production of TeV neutrinos by interaction with galactic ultra-violet and soft x-rays background radiation also need to be judged.

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