Multi-GeV neutrinos due to $n\bar{n}$ oscillation in Gamma-Ray Burst Fireballs

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The long and short gamma-ray bursts are believed to be produced due to collapse of massive stars and merger of compact binaries respectively. All these objects are rich in neutron and the jet outflow from these objects must have a neutron component in it. By postulating the $n\bar{n}$ oscillation in the gamma-ray burst fireball, we show that, 19-38 GeV neutrinos and anti-neutrinos can be produced due to annihilation of anti-neutrons with the background neutrons. These neutrinos and anti-neutrinos will be produced before the 5-10 GeV neutrinos due to dynamical decoupling of neutrons from the rest of the fireball. Observation of these neutrinos will shed more light on the nature of the GRB progenitors and also be a unique signature of physics beyond the standard model. A possible way of detecting these neutrinos in future is also discussed.

I. INTRODUCTION

Gamma Ray Bursts (GRBs) are flashes of non-thermal bursts of low energy ($\sim 100$ KeV-1 MeV) photons and release about $10^{51}$-$10^{53}$ erg in a few seconds making them the most luminous object in the universe. They are known to occur at cosmological distance\cite{1, 2}. They fall into two classes; short-hard bursts ($\leq 2$ s) and long-soft bursts. The short bursts comprises about 25% of the total events and the rest are long-soft bursts. It is now widely accepted that long duration bursts are produced due to the core collapse of massive stars the so called hypernovae. The origin of short-duration bursts are still a mystery, but recently there has been tremendous progress due to accurate localization of many short bursts by the Swift\cite{3, 4} and HETE-2\cite{5} satellites. The afterglow observation of GRB 050709 at a redshift of 0.1606\cite{6} by HETE-2 and the Swift observation of afterglow from GRB050709b at a redshift of 0.225\cite{7} and GRB 050724 at a redshift of 0.258\cite{7} seems to support the coalescing of compact binaries as the progenitor for the short-hard bursts although definite conclusions can not be drawn at this stage.

Irrespective of the nature of the progenitor, it is believed that, gamma-ray emission arises from the collision of different internal shocks (shells) due to relativistic outflow from the source. A class of models call fireball model seems to explain the temporal structure of the bursts and the non-thermal nature of their spectra\cite{1, 2}. Sudden release of copious amount of $\gamma$ rays into a compact region with a size $c\tau \sim 100$-1000 km\cite{2} creates an opaque $\gamma - e^\pm$ fireball due to the process $\gamma + \gamma \rightarrow e^+ + e^-$. The average optical depth of this process\cite{8} is $\tau_{\gamma\gamma} \simeq 10^{13}$. This optical depth is very large and even if there are no pairs to begin with, they will form very rapidly and will Compton scatter lower energy photons. Because of the huge optical depth, photons can not escape freely. In the fireball the $\gamma$ and $e^\pm$ pairs will thermalize with a temperature of about 3-10 MeV. The fireball expands relativistically with a Lorentz factor $\Gamma \sim 100 - 1000$ under its own pressure and cools adiabatically due to the expansion. The radiation emerges freely to the inter galactic medium (ISM), when the optical depth is $\tau_{\gamma\gamma} \simeq 1$.

In addition to $\gamma$, $e^\pm$ pairs, fireballs may also contain some baryons, both from the progenitor and the surrounding medium. These baryons can be either free or in the form of nuclei. If the fireball temperature is high enough (more than 0.7 MeV), then it will be mostly in the form of neutrons and protons. The electrons associated with the matter (baryons) can increase the opacity, hence delaying the process of emission of radiation and the baryons can be accelerated along with the fireball and convert part of the radiation energy into bulk kinetic energy. So the dynamics of the fireball crucially depends on the baryon content of it. But irrespective of it, the baryonic load has to be very small, otherwise, the expansion of the fireball will be Newtonian, which is inconsistent with the present observations.

As discussed above, core collapse of massive stars and merger of binary compact objects (neutron star-neutron star, neutron star-black hole) as possible progenitors of the long and short GRBs respectively. In both the cases neutrons are the main ejected materials from the central engine. So it seems obvious that, the outflow from the central engine, which later on give rise to GRBs, has neutron as a principal component. The presence of neutron component in GRBs was first proposed by Derishev et al.,\cite{9} and later on it was showed that the presence of neutron component in the GRBs are practically inevitable and its presence drastically changes the dynamics of the fireball. The possible role of neutron in observed emission has been discussed by many authors\cite{9, 10, 11, 12, 13}. The dynamical decoupling of neutron from the rest of the relativistic shell will give rise to inelastic n-p scattering and lead to emission of observable multi-GeV neutrinos\cite{12, 13}.

It is believed that, baryon number is not a good symmetry of nature, due to the fact that, our universe is matter dominant and this requires baryon number violating interactions. Thus the breaking of exact-baryon number conservation in unified theories of the fundamental gauge interactions\cite{14} has lead to searches for proton decay and $n\bar{n}$ oscillation, but so far with no success\cite{15}. The $n\bar{n}$ oscillation occurs due to $\Delta B = 2$ transition. The present experimental limit for unbound neutrons is

\[ n \bar{n} \rightarrow n \bar{n} \, \Delta B = 2 \]
The neutron oscillation in free space and its effect on cosmic rays has been discussed in Ref. [17]. As a phenomenological implication of $n\bar{n}$ oscillation, it has been suggested that, the excess of sub-GeV anti-protons over protons in the galactic cosmic rays is due to the $n\bar{n}$ oscillation in supernova explosions, which are site for large oscillation put a lower limit on the primordial magnetic field applied to the neutron rich environment of the nucleosynthesis era[19]. Here we propose that, if $n\bar{n}$ oscillations take place within the neutron rich GRB fireball, $19-38$ GeV neutrinos will be produced prior to the production of 5-10 GeV neutrinos due to dynamical neutron decoupling from the rest of the fireball as predicted by Bahcall and Mészáros[12]. By using earth as the detector and assuming the magnetic field in the jet outflow from the central engine to be $\sim 10^{-6} G$, about 4 events can be recorded per year. The future international project Extreme Universe Space Observatory (EUSO) may be able to detect these neutrinos[20].

II. $n\bar{n}$ OSCILLATION AND PHYSICS OF GRBS

In the rest frame, a neutron has a mean life time of $\tau_\beta = 888.6 \pm 3.5$ s. In the comoving frame, when the neutron has a Lorentz factor $\Gamma_n$, the mean decay radius is $r_\beta = \Gamma_n\tau_\beta$. So due to beta decay, at a distance $r$ from the source, the neutron number is given by

$$N_n = N_{n,0}e^{-r/r_\beta},$$

where $N_{n,0}$ is original number of neutron within a radius $r \sim r_\beta \sim 10^6$ cm. In the presence of a magnetic field, the neutron energy levels are split by an amount $\Delta E = g_\nu B$ and this is responsible for the oscillation of neutron to anti-neutron, where $g = -1.91$ is the anomalous magnetic moment of neutron, $\mu = e\hbar/2m_pc = 3.152 \times 10^{-12}$ eV $G^{-1}$ and $B$ is the magnetic field in Gauss. Due to $n\bar{n}$ oscillation, the number of anti-neutron is given by[17]

$$N_{\bar{n}} \approx \frac{1}{2} N_n \left(\frac{\delta m}{\Delta E}\right)^2 = 0.6 \times 10^{-26} N_n \left(\frac{B}{G}\right)^{-2},$$

where $\delta m = \tau_{n\bar{n}}^{-1}$ and here we take $\tau_{n\bar{n}} \approx 10^9$s. The number of $\bar{n}$ is inversely proportional to the square of the magnetic field. So for large magnetic field this is very much suppressed and for small one it is enhanced.

In the fireball, a substantial fraction of the baryon kinetic energy is transferred to a non thermal population of electrons through Fermi acceleration at the shock and these accelerated electrons cool via synchrotron emission and/or inverse Compton scattering to produce the observed prompt (due to internal shocks) and afterglow (due to external shocks) emission. For the synchrotron emission, strong magnetic field is needed to fit the observed data. But it is difficult to estimate the strength of the magnetic field from the first principle. One would expect large magnetic field if the progenitors are highly magnetized, for example, magnetars with $B \sim 10^{16}$ G. Also a relatively small pre-existing magnetic field can be amplified due to turbulent dynamo mechanism, compression or shearing. Despite all these, there is no satisfactory explanation for the existence of strong magnetic field in the fireball. Also even if some magnetic flux is carried by the outflow, it will decrease due to the expansion of the fireball at a larger radius. Recently, it has been proposed that, the emission in the GRBs can also be explained through Compton-drag process and magnetic field is not necessary for the production of gamma rays [21, 22, 23]. Because of the above uncertainties, here we consider the magnetic field as a parameter.

By combining both the neutron decay and the $n\bar{n}$ oscillation, the number of anti-neutrons at a distance $r$ from the source are given by

$$N_{\bar{n}} \approx \frac{1}{2} \left(\frac{\xi}{1 + \xi}\right) \frac{E}{\eta m_p} e^{-r/r_\beta} \left(\frac{\delta m}{\Delta E}\right)^2 = 2 \times 10^{27} \left(\frac{B}{G}\right)^{-2} \left(\frac{2E}{1 + \xi}\right) \frac{E_{53}}{\eta_{100}} e^{-r/r_\beta},$$

where $\xi$ is the neutron to proton ratio at the source and for simplicity we take $\xi = 1$ and the dimensionless entropy $\eta = E/M \sim 10^5 - 10^6$, where $E$ is the initial radiation energy produced due to $e^\pm, \gamma$ and $M$ is the rest mass of the fireball due to baryon load.

The protons, neutrons and electrons are coupled to the thermal radiation in the expanding jet outflow from the central engine until the Compton scattering time scale $t'_C \sim (n'_p\sigma_T)^{-1}$ and the elastic n-p scattering time scale $t_{np} \sim (n'_p\sigma_{np})^{-1}$ are shorter than the co-moving plasma expansion time scale $t'_{exp} \approx r/T$, where $\sigma_{np} \sim 3 \times 10^{-26}$ cm$^2$ is the n-p elastic scattering cross section, $n'_p$ is the co-moving number density of protons in the fireball. In fact when all the components in the jet are coupled, they have a common bulk Lorentz factor $\Gamma \sim 300$ Ref. [12]. The neutrons and protons are coupled until the opacity $\tau_{np} > 1$, which corresponds to the $r_{np}$ radius

$$r_{np} < \frac{L\sigma_{np}}{(1 + \xi)4\pi m_p \Gamma^2 \eta} \sim 6 \times 10^{10} \frac{L_{52}}{(1 + \xi)\Gamma_{50} \eta_{100}} \text{ cm.$$

(4)

So the radius $r$ for the n-p to be coupled should be smaller than $r_{np}$, i.e. $r < r_{np}$. Also the mean beta decay radius is $r_\beta \sim 10^{16}$ cm $>> r$. So $\exp(-r/r_\beta) \sim 1$ and we can comfortably neglect the effect of beta decay in Eq. 3 when we are in the regime $r < r_{np} < r_\beta$.

In the jet frame protons and neutrons have the same Lorentz factor $\Gamma$ and the $n\bar{n}$ oscillation takes place with in the equilibrium plasma. The produced anti-neutrons can annihilate with the background neutrons to produce pions and also can have elastic scattering (but not inelastic

$\tau_{n\bar{n}} \sim 10^9$ s[16].
scattering) with the background protons. The beta-decay of anti-neutrons will be suppressed due to the longer life time of the anti-neutrons in the comoving jet plasma unless the decay takes place in the regime \( r < r_{np} < r_p \).

We consider the following annihilation processes within the comoving plasma,

\[
\begin{align*}
\bar{n} + n &\rightarrow \pi^+ + \pi^- + \pi^0, \\
\bar{n} + n &\rightarrow \pi^+ + \pi^-, \\
\bar{n} + n &\rightarrow \pi^0 + \pi^0.
\end{align*}
\]  

(5)

The \( \pi^0 \) will decay to \( 2\gamma \) and the charge pions will decay as,

\[
\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu) + \bar{\nu}_\mu(\nu_\mu).
\]  

(6)

In Eq.(5) the energy carried by each pion in the c.m. frame is \( 1.88 \text{ GeV}/k_\pi \), where \( k_\pi \) is the multiplicity of pion. The produced pions are relativistic and in the first step of Eq.(4), the charged pions will decay to \( \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \). In these decays, the average energy carried by muon is \( \sim 80\% \) of the pion energy and rest is carried by \( \nu_\mu(\bar{\nu}_\mu) \). In the second step of the decay muon will decay as shown in Eq.(6) and the average energy carried by each particle is about \( 1/3 \) of the muon energy. So on an average the energy carried by each neutrino or anti-neutrino due to muon decay is \( \epsilon_{\nu,\bar{\nu}} \sim 0.5\text{GeV}/k_\pi \) in the comoving frame. In the observer frame this will be translated to

\[
\epsilon_{\nu,\bar{\nu}} \simeq 0.5 \frac{\text{GeV}}{k_\pi} \frac{1}{(1+z)}.
\]  

(7)

By normalizing the burst at redshift \( z = 1 \), we obtain

\[
\epsilon_{\nu,\bar{\nu}} \simeq 75 \frac{\text{GeV}}{k_\pi} \frac{\Gamma_{300}}{1+z}.
\]  

(8)

For the pion multiplicity \( k_\pi = 3 \) and \( 2 \), this gives \( \epsilon_{\nu,\bar{\nu}} = 25 \text{GeV} \) and \( 37.5 \text{GeV} \) respectively. Similarly the energy of the muon neutrinos due to pion decay \( \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \) is

\[
\epsilon_{\nu_{\mu,\bar{\nu}_{\mu}}} \simeq 56 \frac{\text{GeV}}{k_\pi} \frac{\Gamma_{300}}{1+z}.
\]  

(9)

which is \( 19 \text{GeV} \) and \( 28 \text{GeV} \) respectively for \( k_\pi = 3 \) and \( 2 \). So the neutrinos and anti-neutrinos produced due to \( n\bar{n} \) annihilation are having energies in the range \( 19 \text{GeV} \) to \( 38 \text{GeV} \).

The neutral pions will decay to photons and have energies \( 0.3 \text{GeV} \) (first of Eq.(4)) and \( 0.47 \text{GeV} \) (last of Eq.(4)) respectively in the c.m. frame. In the observer frame, these will be boosted to \( 45 \text{GeV} \) and \( 71 \text{GeV} \) respectively. As we have discussed earlier, these photons are produced at a radius \( r < r_{np} \) and \( \tau_{\gamma\gamma} > 1 \), they will degrade their energy by producing \( e^\pm \) pairs and thermalize within the fireball medium. But the neutrinos and anti-neutrinos which are produced due to \( n\bar{n} \) annihilation will stream away from the fireball much before the decoupling of neutrons. So these neutrinos are different from the one that are produced due to neutron decoupling in the later stage of the fireball evolution \[12\]. The total amount of energy released due to \( n\bar{n} \) annihilation is

\[
\epsilon_{n\bar{n}} = 2m_nN_n \simeq 6 \times 10^{24} E_{53}^{-1}\left(\frac{B}{G}\right)^{-2}\frac{2\xi}{1+\xi} \text{erg},
\]  

(10)

and a major fraction of it will be emitted in the form of neutrinos and anti-neutrinos.

### III. POSSIBLE NUMBER OF NEUTRINO EVENTS

By considering both the long and short GRBs rate within a Hubble radius of \( R_b \sim 10^3 R_{15} \), the number of events per year in a detector with \( N_t \) target protons is

\[
R_{\nu\bar{\nu}} \sim \left( \frac{N_t}{4\pi D^2} \right) R_b N_n \bar{\sigma}_{\nu\bar{\nu}},
\]  

(11)

where

\[
D = 2.64 \times 10^{28} h_{70}^{-1}(1 - 1/\sqrt{1+z}) \text{cm},
\]  

(12)

is the proper distance out to red shift \( z \) with \( h_{70} = H_0/70 \text{ km/s/Mpc} \) and \( \bar{\sigma}_{\nu\bar{\nu}} \sim 5 \times 10^{-40} \Gamma(1+z)^{-1} \text{ cm}^2 \) is the total detection cross section per neutron. If we consider the whole earth as the detector with \( N_t \sim 10^{51} \) and taking a small magnetic field \( B \sim 10^{-6} \text{ G} \) in the jet outflow (in Eq.(5)), the event rate is

\[
R_{\nu\bar{\nu}} \sim 4 h_{70}^{-2} R_{b5}^2 \frac{E_{53}}{\eta_{100}} N_{151} \Gamma_{300} \left(\frac{B}{10^{-6} \text{G}}\right)^{-2} \times \left(\frac{2\xi}{1+\xi}\right) \left(\frac{3-2\sqrt{2}}{2+z-2\sqrt{1+z}}\right) \text{ year}^{-1}. \]  

(13)

So the expected rate of multi-GeV neutrino event is about \( 4 \) per year and the increase in the initial neutron to proton ratio \( \xi \) will slightly increase the event rate \[20\]. May be in future, the EUSO will be able to detect these neutrinos by emission of fluorescence light of nitrogen due to the extensive air showers through the interaction of the multi-GeV neutrinos with the atmosphere \[20\].

### IV. CONCLUSIONS

The production of neutrinos and anti-neutrinos due to \( n\bar{n} \) annihilation is inversely proportional to the square of the magnetic field. If the magnetic field in the fireball is very weak, the number of anti-neutrons will be more as can be seen from Eq.(12). The produced anti-neutrons will annihilate with the background neutrons through the processes in Eq.(10) to produce neutrinos, anti-neutrons and photons. A large fraction of the annihilation energy will stream away in the form of neutrinos, thus reducing the energy content of the fireball.
For example if the magnetic field in the fireball is very small \((B \simeq 10^{-12} \, G)\), the amount of energy release due to \(n\bar{n}\) annihilation is \(e_{n\bar{n}} \sim 10^{49} \, \text{erg}\). Apart from the \(n\bar{n}\) annihilation, if beta decay of anti-neutrons take place within the region \(r < r_{np}\) with a very small magnetic field, the excess amount of baryon, anti-baryon annihilation will result in decreasing the baryon content of the fireball further and making it cleaner, which can probably explain the almost baryon free environment of the fireball. On the other hand, strong magnetic field will suppress the \(n\bar{n}\) oscillation and ultimately produce very less number of neutrinos and anti-neutrinos. So if the \(n\bar{n}\) oscillation exist in GRB fireballs, magnetic field can not be arbitrarily weak or strong. The produced neutrinos and anti-neutrinos are unique signature of \(n\bar{n}\) oscillation as well as the presence of magnetic field in the fireball. It is unique in the sense that, there is no other process which can produce these neutrinos in between the production point (the source at \(r = r_0\) ) and \(r = r_{np}\). Flux of these neutrinos depends on the original neutron contain as well as the magnetic field in the fireball. Due to very low flux, these neutrinos will be very difficult to detect. The future project EUSO may be able to detect these neutrinos. However, if at all detected, it will be before the 5-10 GeV neutrinos due to inelastic scattering of decoupling neutrons with the protons in the fireball. The observed time difference between the \(n\bar{n}\) neutrinos and the 5-10 GeV neutrinos is \(\Delta t \simeq r_{np}/c^2 \sim 4 \times 10^{-6} \, \text{s}\). Although this time difference is very small, the energies of the neutrinos are very different. So the neutrinos within the energy range 19-38 GeV have different physics (production mechanism) as compared to 5-10 GeV neutrinos. Observation of these multi-GeV neutrinos will not only tell more about the nature of the GRB progenitors but also shed more light on the physics beyond the standard model.

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