VERY HIGH ENERGY NEUTRINOS ORIGINATING FROM KAONS IN GAMMA-RAY BURSTS

K. ASANO
Division of Theoretical Astronomy, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; asano@th.nao.ac.jp

AND
S. NAGATAKI
Yukawa Institute for Theoretical Physics, Kyoto University, Oiwake-cho Kitashirakawa Sakyo-ku, Kyoto 606-8502, Japan; nagataki@yukawa.kyoto-u.ac.jp

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ABSTRACT
We simulate neutrino production in a gamma-ray burst (GRB) with the most detailed method to date. We show that the highest energy neutrinos from GRBs mainly come from kaons. Although there is little chance to detect such neutrinos, attempts of detection are very important to prove physical conditions in GRBs.

Subject headings: acceleration of particles — gamma rays: bursts — neutrinos

1. INTRODUCTION
The rapid time variabilities and the compactness problem (see, e.g., a review by Piran 1999) suggest that gamma-ray bursts (GRBs) should arise from internal shocks within relativistic flows. In the standard model, a strong magnetic field is generated, and electrons are Fermi-accelerated in shocked regions. The physical conditions in the shocked region imply (Waxman 1995) that protons may be also Fermi-accelerated to energies \( \sim 10^{20} \) eV. High-energy protons in the GRB photon field can create high-energy neutrinos via photopion production (Waxman & Bahcall 1997, 1999; Guetta et al. 2001, 2004; Dermer & Atoyan 2003; Asano & Takahara 2003; Asano 2005). Future observations of neutrinos will be important to prove the standard model of GRBs and the particle acceleration theory. The highest energy of neutrinos brings us information on physical conditions of GRBs.

Recently, Ando & Beacom (2005) have shown that the kaon contribution becomes important for neutrino production from jets in supernovae. They considered mildly relativistic jets that are much more baryon-rich than a fireball of GRBs where collisions among accelerated protons (pp) occur efficiently (Razzaque et al. 2004a), making pions and kaons that decay into neutrinos. Since high-energy charged mesons will cool down before they decay into neutrinos, the highest energy of neutrinos is determined by the equilibrium of the cooling time-scale and the decay time-scale of mesons. Considering synchrotron cooling, the highest energy of mesons that decay into neutrinos is proportional to \( m^{3/2}t_0^{-1/2} \), where \( m \) and \( t_0 \) are the mass and the lifetime of mesons at rest, respectively. So, Ando & Beacom (2005) pointed out that the heavier mass of kaons than pions leads to dominance of neutrinos from kaon decay in the highest energy region.

We note that the contribution of kaons for neutrino production may also be important even in internal shocks of GRBs. In this study, we calculate the spectrum of neutrinos from GRBs, taking account of decaying modes of charged kaons into neutrinos. Also, we consider the contribution of long-lived neutral kaons, \( K^0 \), for neutrino production, which was not taken into account in the previous work. It is noted that \( K^0 \) does not cool at all before decay into neutrinos and has some decaying modes into charged pions and neutrinos. So, it is expected that the highest energy of neutrinos comes from the decay of long-lived neutral kaons.

In this Letter, using the Monte Carlo method, we show that the highest energy neutrinos mainly come from kaons even in internal shocks of GRBs. In § 2, we explain our model and method. The numerical results are in § 3. Section 4 is devoted to discussion.

2. SIMULATION
Our method of simulation is essentially the same as in Asano (2005) but quantitatively improved. In this study, we adopt experimental results for the cross sections of \( p\gamma \rightarrow n\pi^+ \), \( p\pi^0 \), \( n\pi^-\pi^0 \), and \( p\pi^+\pi^- \) (Schadmand 2003) for \( \epsilon \leq 2 \) GeV, where \( \epsilon \) is the photon energy in the proton rest frame. We neglect the reaction \( p\gamma \rightarrow p\pi^0\pi^0 \), because the cross section is too small and the neutrino production rate is independent of this reaction. Since we do not have experimental data of multipion production for \( \epsilon \geq 1 \) GeV, we extrapolate the cross section by a constant value. However, our total photoabsorption cross section agrees well with the experimental value for \( \epsilon < 2 \) GeV (Eidelman et al. 2004). For the pion production by \( n\gamma \), we adopt the same cross sections as \( p\gamma \). Kaons are produced via \( p\gamma \rightarrow \Delta K^+ \), \( \Sigma^-K^+ \), or \( n\gamma \rightarrow \Delta K^0 \), \( \Sigma^-K^+ \), and \( \Sigma^+K^0 \). Since there are no detailed and precise data of kaon production experiments, we adopt values theoretically obtained for the cross sections of kaon production from \( p\gamma \) and \( n\gamma \) (Dreschel & Tiator 1992; Lee et al. 2001). As shown in Figure 1, the contribution of kaon production seems negligible. However, the importance of kaon production will be shown later.

Of course, pp collisions may also create mesons. Since the number of target photons is much larger than the proton number density in our case, we neglect the effects of pp collisions.

The inelasticity is approximated by a conventional method as \( K = [1 - (m_\gamma^2 - m^2)/s]/2 \), where \( s \) is the invariance of the square of the total four-momentum of the \( p\gamma \) (\( n\gamma \)) system, and \( m_\gamma \) is the proton mass. For the double-pion production, we approximate the inelasticity by replacing \( m_\gamma \) with \( 2m_\pi \).

Our parameter set is similar to that in Dermer & Atoyan (2003): the total photon energy in a burst \( E_{\text{tot}} \), the number of light-curve pulses (or spikes) \( N \), the Lorentz factor of the shells \( \Gamma \), and shell-collision distances from the central engine \( R \). The number \( N \) corresponds to the number of shells that emit gamma rays. The photon energy deposited into each shell is therefore \( E_{\text{sh}} = E_{\text{tot}}/N \). In the standard model, shells can collide and emit gamma rays at distances \( R \) larger than \( 3 \times 10^{14}(\Gamma/100)^{3/2}(\delta t/1 \text{ ms}) \) cm from the central sources, where \( \delta t \) is the time between shell ejection events. For simplification, \( R \) and \( \Gamma \) are common for all \( N \) shells in this simulation. The photon number spectrum in the energy range \( \epsilon + d\epsilon \) in the shell rest frame is set at \( n(\epsilon) \propto \epsilon^{-1} \) for \( 1 \text{ eV} < \epsilon < \)
1 keV and $\epsilon^{-2.2}$ for 1 keV < $\epsilon$ < 10 MeV. The break energy 1 keV corresponds to 100(T/100) keV in the observer frame. For $\epsilon$ < 1 eV, the synchrotron self-absorption may be crucial (Granot et al. 2000), while the pair absorption may be crucial for $\epsilon$ > 10 MeV (e.g., see Asano & Takahara 2003; Pe’er & Waxman 2004). Although the upper bound of the photon energy depends on the model parameter because of pair production, we fix the value as 10 MeV (~1 GeV in the observer frame). Since higher energy protons mainly interact with lower energy photons, the production rate of very high energy neutrinos is not sensitive to this upper bound.

The shell width in the comoving frame is assumed to be $R/\Gamma$, as conventionally assumed, although there is the possibility of thinner shells (Asano & Iwamoto 2002). We express the energy density of the magnetic field as $f_B$ times the photon energy density. In this Letter, we adopt $f_B = 0.1$.

We inject protons with a number spectrum proportional to $\epsilon^{-2}$ above 10 GeV in the shell rest frame. The maximum proton energy is determined by the condition that the Larmor radius is smaller than both the size scale of the emitting region and the energy-loss length. We estimate the energy-loss length using synchrotron, inverse Compton, and photomeson cooling processes. The total energy of the accelerated protons in a shell is assumed to be the same as $E_{sh}$. Our method pursues energy-loss processes of each baryon via synchrotron, inverse Compton, and photomeson cooling processes during the dynamical timescale $R/c \Gamma$ in the shell rest frame.

3. RESULTS

We have simulated for a wide range of parameters as $E_{tot} = 10^{53} - 10^{54}$ ergs, $N = 10 - 1000$, $\Gamma = 100 - 1000$, and $R = 10^{12} - 10^{15}$ cm. Of course, larger $E_{sh}$ and smaller $R$ are favorable for neutrino production, and as Dermer & Atoyan (2003) showed, very luminous bursts are required to detect neutrinos on the Earth. Therefore, we show only one representative example in this Letter. The parameter values are $E_{tot} = 10^{54}$ ergs, $N = 1000$ ($E_{sh} = 10^{51}$ ergs), $\Gamma = 100$, and $R = 10^{15}$ cm. The corresponding variability timescale $t_{vari} \approx R/c \Gamma^2 \sim 30$ ms, which is not so far from the typical observed timescale $\sim 0.1/(1+z)$ s.

Since the allowed region of the GRB parameters is wide, there may be both optically thin and thick sources to Thomson scattering (Mészáros & Rees 2000). Our example would imply that $R$ is close to the photosphere. When it is assumed that the energy density of protons is the same as the photon energy density and the average proton energy is mildly relativistic ($\leq 5 m_e c^2$), the proton number density in the comoving frame is obtained as $\propto E_{sh}/20 R^2 m_p c^2$. This means that the optical depth for the Thomson scattering is $\sim 1$ for our parameter set. Photons scatterings do not sufficiently affect the gamma-ray spectrum for this marginal optical depth.

From our simulation, we obtain spectra of created mesons as is shown in Figure 2. One-half of neutral kaons are $K^0$, while the rest are $K^+$. Since the cross sections of kaon production are smaller than those of pion production, the number of kaons is much less than pions. However, the highest energy charged mesons will cool down before they decay into neutrinos.

Our results for other parameter sets agree with the condition of ultra–high-energy cosmic-ray production obtained by Asano (2005); $R \approx 10^{44} (E_{sh}/10^{51}$ ergs)$^{1/2}$ cm. In the case of Figure 2, also protons above $10^{20}$ eV cool down before they escape from the shell.

We follow the behavior of pions and kaons until they decay into positrons (electrons) and neutrinos using the same method as in Asano (2005). Synchrotron and inverse Compton emissions are taken into account. Charged kaons have six decay modes; $K^+ \rightarrow \mu^+ \nu_\mu$ (63%), $\pi^+ \pi^-$ (21%), $\pi^+ \pi^- \pi^0$ (6%), $\pi^+ e^+ \nu_e$ (5%), $\pi^0 \mu^+ \nu_\mu$ (3%), and $\pi^- \pi^+ \pi^0$ (2%). While $K^0$ will decay into $\pi^+ e^- \bar{\nu}_e$ (39%), $\pi^- \mu^+ \bar{\nu}_\mu$ (27%), $\pi^- \pi^0 \pi^0$ (21%), and $\pi^- \pi^- \pi^0$ (13%). In Figure 3, total neutrino spectra emitted from this example are shown. Although there are fewer kaons than pions, the highest energy neutrinos originate from kaons around $\epsilon_\nu \sim 10^{20}$ eV.

Since very high flux is required to detect neutrinos from GRBs by a 1 km$^2$ neutrino detector such as IceCube (Dermer & Atoyan 2003), we consider an optimistic case: a GRB occurs at 30 Mpc, and the detection efficiency of upward-going neutrinos with energy $\epsilon_\nu$ is assumed to be $10^{-4}(\epsilon_\nu/10^{14}$ eV)$^{1/2}$ for $\epsilon_\nu > 10^{14}$ eV, although it may be difficult to measure energies of neutrinos above $10^{17}$ eV by IceCube. Figure 4 shows the detectable number of spectra of neutrinos in this case. The vertical axis $\epsilon_\nu N(\epsilon_\nu)$ roughly corresponds to the detectable number in each energy range. In this case, the expectation value of neutrinos from kaons is 0.1–1 by a 1 km$^2$ detector. However, for very high energy...
neutrinos, it may be possible to build detectors with effective volume orders of magnitude larger than 1 km$^3$, such as the Extreme Universe Space Observatory (10$^5$ km$^2$ detector), because the Earth is thick for such neutrinos. From the step-function-like features in the spectra, we can easily distinguish origins of neutrinos.

As shown in Figures 3 and 4, $K_L^0$-decay neutrinos are dominant above 10$^{18}$ eV, although the flux is too dim to detect on the Earth. On the other hand, the contribution of $K^0$-decay in the energy band below 10$^{18}$ eV is not so prominent.

Since we have considered many decaying modes, the production ratio of high-energy muon and electron neutrinos is not 2 : 1 exactly. However, the neutrinos will be almost equally distributed between flavors as a result of vacuum neutrino oscillations (Waxman & Bahcall 1997). So, there may be a possibility that tau neutrinos are detected through double-bang events (Athar et al. 2000).

4. DISCUSSION

As we have shown in this Letter, the highest energy neutrinos may originate from kaons in GRB internal shocks. The detection of such neutrinos is very important to prove the physical conditions in internal shocks and the particle acceleration theory. In order to observe such neutrinos, a bright GRB should occur at a very close distance, or amazing progress in the technology of neutrino observation is required. When we use the observed local GRB rate, 0.4 Gpc$^{-3}$ yr$^{-1}$ (Guetta et al. 2005), the chance probability of having a source within 30 Mpc away from the Earth is about 1 event per 10$^5$ yr. However, the nearest burst ever observed is GRB 980425 at 40 Mpc, which was less luminous than usual bursts. Although a GRB at 30 Mpc seems to be optimistic, we should prepare for an event beyond expectation, such as the giant flare from SGR 1806–20 (Hurley et al. 2005).

As a rough standard, we have used a simple formula of the detection efficiency, extrapolating the case for upward-going neutrinos. However, in the very high energy band downward-going neutrinos are favorable to be detected rather than upward-going neutrinos, because the Earth is thick for such neutrinos. For downward events, the detection efficiency of very high energy neutrinos would be enhanced. In addition, it may be possible to build detectors with effective volume orders of magnitude larger than 1 km$^3$, which would enhance the chances of detection of the kaon decay neutrinos.

The neutrinos produced from kaon decays may be detected as a neutrino background, so let us estimate the flux of the neutrino background roughly. It can be seen from Figure 3 that the fluence of neutrinos $e^2 N(e)$ at 10$^{17}$–10$^{18}$ eV from this example is $\sim 10^{53}$ GeV. If we adopt this value, the resulting neutrino background level at 10$^{17}$–10$^{18}$ eV is $\sim 3 \times 10^{-11}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, where we use the local GRB rate, 0.4 Gpc$^{-3}$ yr$^{-1}$, without correction due to jet collimation (Guetta et al. 2005) and the age of the universe, $\sim 10^{10}$ yr. This background level is far below the detection limit expected from 3 years of IceCube operation. Since our example is an optimistic case for neutrino emission, a more realistic background level may become lower 1 or 2 orders of magnitude than above. Dominant sources of background neutrinos in the highest energy band are not sure so far. If we can observe the background neutrinos at 10$^{17}$–10$^{18}$ eV with a highly efficient detector in the future, the characteristic flat spectrum predicted from GRB sources is distinguishable from spectra of other sources, such as GRB early afterglows or blazars (see, e.g., Schneider et al. 2002).

Razzaque et al. (2004b) showed that very high energy gamma rays from $\pi^0$-decay ($\geq 10^{17}$ eV) can escape from shells without electron-positron pair creation. However, this result largely depends on the assumption of spectra in the lower energy region. A recent observation (Blake et al. 2005) shows brighter optical emission than Razzaque et al. (2004b) assumed. On the other hand, $K_L^0$ also has some decaying modes into neutral pions. So, there is a possibility that delayed gamma rays come from the decays of $K_L^0$. We can investigate the validity of this statement by checking whether $K_L^0$ can decay after GRB photons escape from shells. Since the mean lifetime of $K_L^0$ is 5.17 $\times$ 10$^{-4}$ s in the kaon rest frame, the mean lifetime of $K_L^0$, $\Delta t_k$, of energy $E_k$ in the shell rest frame becomes $\Delta t_k = 3.3(\epsilon_k/10^{16.5})$ s. On the other hand, the typical dynamical timescale of GRBs in the shell rest frame is $3(T/100)(t_{\text{max}}/30 \text{ ms})$ s. So, we expect that gamma rays produced from kaons with energy larger than 10$^{18.5}$ (T/100) eV can escape from shells.

Of course, such gamma rays cannot travel more than $\sim$1 Mpc because of electron-positron pair creation with a radio background (Protheroe & Biermann 1996). The secondary emission via inverse Compton of cosmic microwave background photons may be observed as GeV–TeV photons. Razzaque et al. (2004b) concluded that the corresponding time delays are in the range of 10–100 s and the duration timescale may be much longer.
These timescales are much longer than the lifetime of \( K^0 \) in the observer’s frame. Therefore, unfortunately, the GeV-TeV secondary photons from kaons may not be distinguishable from other sources, such as \( \pi^0 \)-decay.

There is a possibility that failed GRBs occur near/in our galaxy. As Mészáros & Waxman (2001) pointed out, for very extended or slowly rotating stars, the jet may be unable to break through the envelope of a massive star. However, penetrating and choked jets will produce, by photomeson interactions of accelerated protons, a burst of \( \approx 5 \) TeV neutrinos while propagating in the envelope (Razzaque et al. 2004a). Such neutrinos from nearby galaxies may be detectable by a 1 km\(^2\) detector. In failed GRBs, kaons may be also produced through the photomeson interactions (Ando & Beacom 2005).

When these classes of GRBs are taken into account, the chance probability of detecting neutrinos will be enhanced considerably. In previous works, the neutrino spectrum was estimated assuming that the baryon density in the jet is sufficiently high that the \( pp \) process is the dominant process to produce neutrinos. However, the efficiency depends sensitively on the baryon density. So, there is a possibility that photomeson production becomes the dominant process to produce neutrinos in the failed GRBs. In such a case, the spectrum of neutrinos will depend sensitively on the photon spectrum. So, the detection of high-energy neutrinos from such kaons will give us a clue to help understand the physical conditions of failed GRBs, too.

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