The Role of a Heavy Neutrino in the Gamma-Ray Burst

GRB221009A

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Abstract

Recently, several telescopes, including Swift-BAT, GBM, and LHAASO, have observed the ever highest-energy and long-duration gamma-rays from a gamma-ray burst named as GRB221009A (located at a red-shift of $z = 0.151$) on October 9, 2022. Conventional understanding tells us that very high-energy photons produced at such a far distance suffer severe attenuation before reaching the Earth. We propose the existence of a sub-MeV to $O(10)$ MeV heavy neutrino with a transitional magnetic dipole moment, via which the heavy neutrino is produced at the GRB. It then travels a long distance to our galaxy and decays into a neutrino and a photon, which is observed. In such a way, the original high-energy photon produced at the GRB can survive long-distance attenuation.
Recently, the highest energy and long-duration gamma rays were detected on Oct. 9, 2022, first by the Swift Burst Alert Telescope (BAT) [1] and the Fermi Gamma-ray Burst Monitor (GBM) [2]. Subsequently, observations of the very highest gamma rays were recorded from the same source by the FERMI-LAT [3, 4], LHAASO [5], and the Carpet-2 [6]. Such a gamma-ray burst (GRB) was measured at a red-shift of $z = 0.151$ [7, 8], which corresponds to about 720 Mpc ($\approx 2 \times 10^{25}$ m). The energy of the very high energy (VHE) photons is determined to be at least 10 TeV and perhaps as high as 250 TeV.

The detection of very high-energy photons at such a far distance cannot be explained by conventional physics. The current understanding of such VHE photons is due to the explosion of a supermassive star and the creation of a black hole. In such a violent environment, it is not difficult to imagine very high-energy collisions taking place and thus creating a lot of hadrons such as pions, kaons, etc. The energetic neutral pions then decay into photons and charged pions into muons and neutrinos. However, since the GRB is at a very far distance from us, the VHE photons will lose most of the energies along their path to us by pair creation, Compton scattering, and other mechanisms. Thus, the detection of such VHE photons by satellite experiments or experiments on the Earth is beyond our understanding.

An explanation of photon-axion-photon conversion was put forward to explain the anomaly [9–13]. The VHE photons so-produced are converted into axions by the interaction $f_a a F_{\mu \nu} \tilde{F}^{\mu \nu}$. The axions then travel a long distance to near our galaxy without interacting with the intergalactic space and are converted back to photons in presence of a magnetic field of our galaxy. In this way, the original energy of the VHE photons is preserved. Other possible interpretations include Lorentz inverse violation [14–16], modification of ultrahigh-energy cosmic ray spectrum [17, 18].

The idea of photon-axion-photon conversion is based on the fact that axions rarely interact along the path of propagation. Another well-known particle that shares this property is the neutrino. How does a VHE photon related to a neutrino? We propose the existence of a heavy neutrino (denoted by $N$) of a mass around $O(10^{-2}) - O(10)$ MeV, which has a transitional magnetic dipole moment with an active neutrino. In the violent environment around the GRB, it is not difficult to imagine that there are numerous high-energy hadronic collisions, which produce a large number of pions, kaons, etc. Thus, we suggest that the neutral pion can decay into a photon, an active neutrino, and a heavy neutrino, and also
the charged pion into a muon, a photon, and a heavy neutrino

\[ \pi^0 \rightarrow \gamma \gamma^* \rightarrow \gamma \nu N, \quad \pi^\pm \rightarrow \mu^\pm \nu^* \rightarrow \mu^\pm \gamma N, \quad (1) \]

in which the flavor of the active neutrino is not important. The branching ratio of this decay is small, but it is not critical in our interpretation, because we do not know exactly the number of collisions that can happen there. The more important is that the lifetime of the heavy neutrino is long enough such that it can survive the path coming towards our galaxy. We give more detail in the following. The key ingredient of this interpretation is that once the heavy neutrino \( N \) is produced near or at the GRB, it acquires an energy as high as tens or hundreds of TeV. It then travels a cosmological distance without decay or attenuation, followed by its decay \( N \rightarrow \nu \gamma \) when it comes close to our galaxy. In this way, we can observe VHE photons of energies \( O(10) - O(100) \) TeV.

The transitional magnetic dipole moment of the heavy neutrino (HN) is parameterized as

\[ \mathcal{L} = \frac{1}{2} \mu_\nu \nabla \sigma^{\mu \nu} N F_{\mu \nu} + \text{h.c.}, \quad (2) \]

where \( F_{\mu \nu} \) is the field strength of the photon field and \( \mu_\nu \) is the magnetic dipole moment of the active-to-heavy-neutrino transition. This interaction is responsible for both the production and decay of the HN. Production of \( N \) can proceed in meson decays, such as \( \pi^\pm \rightarrow \mu^\pm \nu^* \rightarrow \mu^\pm (\gamma N) \) and \( \pi^0 \rightarrow \gamma \gamma^* \rightarrow \gamma \nu N \), or Primakoff upscattering \( \nu \gamma^* \rightarrow N \) [19].

Since there are large uncertainties in the hadronic environment and energy profile of particles at the GRB, we do not have precise knowledge about the number of high-energy pions that can be produced there. Nevertheless, we know the total amount of energy given off in a typical supernova explosion is about \( 10^{44} \) J \( \approx 6.2 \times 10^{62} \) eV [7] and 99% of this energy is carried away by neutrinos. We perform a naive estimate that only 0.1% of the total energy is going into high-energy hadronic collisions and only 10% of this collision energy goes to pions. The number of high-energy pions \( (\sim 100 \) TeV) that can be produced is as many as \( (10^{58} \text{ GeV})/(10^{14} \text{ GeV}) \sim O(10^{44}) \). Even though the required magnetic dipole moment \( \mu_\nu \) is smaller than \( 10^{-10} \text{ GeV}^{-1} \) (shown later in Fig. [1]) due to the SN1987A constraint [19], the number of \( N \) produced should be large enough to account for the observation.

On the other hand, the decay of \( N \rightarrow \nu \gamma \) is more important in our discussion. We

\footnote{The energy of the GRB221009A was estimated to be about \( 2 \times 10^{54} \) erg \( \approx 1.2 \times 10^{66} \) eV [7].}
calculate the decay width of $N$ based on the Lagrangian in Eq. (2). In the rest frame of $N$,
\[
\Gamma(N \rightarrow \gamma\nu) = \frac{|\mu\nu|^2}{8\pi} M_N^3 ,
\] (3)
where we have ignored the mass of the active neutrino, which is tiny compared to $M_N$. The decay length is then given by
\[
L_{\text{decay}} = \beta\gamma c\tau ,
\] (4)
where $\beta \simeq 1$, $\gamma \simeq E_N/M_N$ and $\tau = 1/\Gamma$. Substituting into the above equation we obtain
\[
L_{\text{decay}} = 8\pi c E_N \frac{1}{M_N^4} \left(\frac{1}{|\mu\nu|^2}\right) .
\] (5)
To obtain a representative value of $L_{\text{decay}}$ we take $E_N = 100$ TeV, $M_N = 10^{-1}$ MeV, and $\mu\nu = 10^{-9}$ GeV$^{-1}$, we obtain
\[
L_{\text{decay}} \simeq (5 \times 10^{24} \text{ m}) \left(\frac{E_N}{100 \text{ TeV}}\right) \left(\frac{10^{-1} \text{ MeV}}{M_N}\right)^4 \left(\frac{10^{-9} \text{ GeV}^{-1}}{\mu\nu}\right)^2 .
\] (6)
With this choice of $E_N$, $M_N$ and $\mu\nu$, the decay length of $N$ falls in the right ballpark of the distance required to reach from the GRB to our galaxy. Other choices of $M_N$ and $\mu\nu$ can be obtained by the scaling in Eq. (6).

We show a contour plot of decay length $L_{\text{decay}} = 10^{24}, 10^{25}, 10^{26}$ m for the heavy neutrino with $E_N = 100$ TeV as a function of $M_N$ and $\mu\nu$ in Fig. [1]. There exist a number of constraints on the transitional magnetic moment of a heavy neutrino for mass between $10^{-2}$ and 100 MeV [20]. Among the constraints, the relevant one to our study is from supernova SN1987A [19]. From the figure, when the magnetic dipole moment is below $\sim 10^{-10}$ GeV$^{-1}$ the decay length is in the correct ballpark of the required distance for $M_N \simeq 0.3 - 10$ MeV.

To conclude VHE photons produced at the GRB221009A, if traveled directly to us, would suffer severe attenuation. We have proposed the existence of a sub-MeV to $O(10)$ MeV heavy neutrino with a transitional magnetic dipole moment, via which the heavy neutrino is produced in the neutral and/or charged pion decays. It then travels a long distance to our galaxy and decays into a neutrino and a photon, which is observed. In such a way, the original high-energy photons produced at the GRB can survive long-distance attenuation.

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FIG. 1. Contours of constant decay length $L_{\text{decay}} = 10^{24}, 10^{25}, 10^{26}$ m as a function of $(M_N, \mu_\nu)$. The constraint from the supernova SN1987A is extracted from Ref. [19].

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