The implications of gamma-ray photons from LHAASO on Lorentz symmetry

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Abstract: The Large High Altitude Air Shower Observatory (LHAASO) has reported the measurement of photons with high energy up to 1.42 PeV from twelve gamma-ray sources. We are concerned with the implications of LHAASO data on the fate of Lorenz symmetry at such high energy level, thus we consider the interaction of the gamma ray with those photons in cosmic microwave background (CMB), and compute the optical depth, the mean free path as well as the survival probability for photons from all these gamma-ray sources. Employing the threshold value predicted by the standard special relativity, it is found that the lowest survival probability for observed gamma ray photons is about 0.60, which is a fairly high value and implies that abundant photons with energy above the threshold value may reach the Earth without Lorentz symmetry violation. We conclude that it is still far to argue that the Lorentz symmetry would be violated due to the present observations from LHAASO.

1 Introduction

The recent observation by the LHAASO cooperative team has opened a new window for exploring the ultra-high-energy (UHE) cosmic rays and challenged our current understanding on the origin of such UHE gamma radiation as well as the theory of high energy physics. The LHAASO experiment has detected a large number of gamma-ray photons with energy exceeding 100 TeV from twelve gamma-ray sources in our galaxy [1]. The highest energy up to 1.42 PeV announces the coming of the new age of Galactic PeVatrons in very-high-energy astronomy. Before this the photon spectra of galactic sources with energy beyond 100 TeV have been detected by Tibet-ASγ [2, 3], HAWC [4, 5] as well as Carpet-2 [6].

In theory, the observation of UHE cosmic ray brings two fundamental problems. One is on the origin of those UHE gamma radiation [7]. It remains mysterious what kind of galactic sources could provide such extremal physical conditions to accelerate particles to such high energy level [8]. The other is on the propagation of UHE cosmic ray in the universe or galaxy, which involves in various interactions between the cosmic ray and the background such as CMB or interstellar radiation fields (ISRF). One outstanding problem is on the fate of Lorentz symmetry at such high energy level, which determines the threshold value of the possible interactions and leads to different energy cutoffs that we could observe in the Earth. It has been extensively investigated in literature on the possibility of treating the UHE cosmic ray as the probe of Lorentz symmetry violation [9–13], which, on the theoretical side, may be treated as the signal of quantum gravity effects [14–19].

The discussion on Lorentz symmetry violation based on LHAASO data has been presented in [20–24]. The constraints on the mass scale of Lorentz symmetry violation has been discussed based on the LHAASO data. In particular, the Lorentz violation due to the subluminal scenario seems to be preferred and the constraints on the mass scale becomes stronger in comparison with those appeared in literature [25–29]. One of the main reasons to consider the Lorentz symmetry violation comes from the fact that the observed energy of gamma ray photons is much higher than the threshold value of pair-production interaction. In the universe, high-energy cosmic rays interact with the background. One typical process for gamma rays is the interaction with the CMB photons, which is $\gamma\gamma \rightarrow e^+e^-$. From the threshold theorem in standard special relativity, it is straightforward to obtain the threshold energy for gamma-ray photons, which reads as $m_e^2/\epsilon_b$, with $\epsilon_b$ being the energy of background photons and $m_e$ being...
the mass of electron. Substituting the energy of CMB photons into this expression, one finds the threshold energy for gamma ray photons is about 400 TeV. Since the energy of some gamma-ray photons detected by LHAASO is much higher than this threshold value, apparently it requires people to increase the theoretical value of threshold energy by modifying the ordinary dispersion relations in special relativity, thus opens a window for the possibility of Lorentz symmetry violation, which has been investigated in Ref. [22]. On the other hand, inspired by [22], we intend to understand the LHAASO data from an alternative point of view. Although the energy of gamma-ray photons detected by LHAASO is much higher than the threshold value of the pair production, which means the gamma-ray photons must interact with background photons and thus decay during the propagation, the key point is how many photons would survive during the propagation and finally reach the Earth, which obviously depends on the number density of background photons as well as the distance between the gamma-ray sources and the Earth. This problem is addressed by considering the transparency of the universe to the gamma rays [30–32, 34]. The averaged distance that the gamma rays can propagate through the background is described by the optical depth [22].

As a matter of fact, the attenuation of galactic gamma-rays due to the interaction with photons from CMB and ISRF is briefly discussed in the original paper by LHAASO team and the opacity for four gamma sources is presented in its Figure 6 [1]. In this note we are very concerned with the fate of Lorentz symmetry, thus we wonder what is the lowest value for the survival probability among the eleven gamma ray sources [30–32, 34]. Therefore, following the suggestion from [22], we intend to elaborate the investigation on gamma ray photons with the background based on LHAASO data. Specifically, we will compute the optical depth, the mean free path as well as the survival probability for photons from all gamma-ray sources in LHAASO, and then find the lowest survival probability for observed gamma ray photons. Our key result is that among the eleven gamma ray sources, the optical depth is always less than one, and the lowest survival probability is about 0.60, which is a fairly high value and implies that abundant photons with energy above the threshold value may reach the Earth without Lorentz symmetry violation. We conclude that it is still far to argue that the Lorentz symmetry would be violated due to the present observations from LHAASO.

## 2 The optical depth and the survival probability of gamma ray photons

In this section we just present the main process for computing the optical depth and the survival probability of gamma ray photons, and the detailed derivation and discussion can be found in Ref. [32]. Since the photons detected by the LHAASO are galactic and in the range of 100 TeV to 10 PeV, we only consider the interaction process with CMB photons, which is dominant in comparison with the process with ISRF photons, as shown in Ref. [32, 34]. Usually, during a propagating process, the survival probability of photons is defined as

$$P_{\gamma \rightarrow \gamma}(E_0, z_s) = e^{-\tau_{\gamma}(E_0, z_s)},$$  

(1)

where $E_0$ is the observed energy and $z_s$ is the redshift. The key quantity $\tau_{\gamma}(E_0, z_s)$ is the optical depth which characterizes the dimming of the source at $z_s$. During the propagation in the universe, $\tau_{\gamma}(E_0, z_s)$ is given by [30, 32]

$$\tau_{\gamma}(E_0, z_s) = \int_0^{z_s} d\zeta \frac{dl(z)}{dz} \int_{-1}^{1} d(\cos \varphi) \frac{1-\cos \varphi}{2} \times \int_{\epsilon_{thr}(E(z), \varphi)}^{\infty} d\epsilon(z)n_{\gamma}(\epsilon(z), z)\sigma_{\gamma\gamma}(E(z), \epsilon(z), \varphi),$$  

(2)

where $\varphi$ is the scattering angle, and $n_{\gamma}$ is the number density of background photons. $\sigma_{\gamma\gamma}$ is the cross-section of the interaction of pair production and $\epsilon_{thr}$ is the threshold energy of background photons in the interaction, while $\epsilon(z)$ and $E(z)$ are the energy of background photons and gamma ray photons at a certain redshift $z$, respectively. In standard special relativity with Lorentz symmetry, it can be derived that $\epsilon_{thr}(E, \varphi) = \frac{2m_e^2c^4}{E(1-\cos \varphi)}$. In addition, $dl(z)/dz$ is the distance travelled by a photon per unit redshift at redshift $z$, which within the standard ΛCDM cosmological model is given by

$$\frac{dl(z)}{dz} = \frac{c}{H_0 (1+z) [\Omega_\Lambda + \Omega_m (1+z)^3]^{1/2}},$$  

(3)

*Since no possible origin was found for the source “LHAASO J2108+5157” in [1], we only analyze eleven of total twelve gamma ray sources.*
where $H_0 \simeq 7 \times 10^3 \text{cm s}^{-1} \text{kpc}^{-1}$ is the Hubble-Lemaitre constant, and $\Omega_\Lambda \simeq 0.7$ is the dark energy density, and $\Omega_M \simeq 0.3$ is the matter energy density.

As mentioned above, for galactic sources as presented in Ref. [1], the background photons are dominated by CMB photons and the effect of the redshift $z$ on the quantities in (2) is ignored throughout the paper, since the redshift is tiny. In this context, the number density of CMB photons $n_\gamma(\epsilon, z)$ can be approximately written as

$$n_\gamma(\epsilon) = \frac{8\pi \epsilon^2}{c^3 h^3 (\epsilon / \sqrt{T} - 1)},$$

where $k$ is Boltzmann constant and $T$ is the temperature of the background. While the cross-section $\sigma_{\gamma\gamma}(E(z), \epsilon(z), \phi)$ is given by [32, 34]

$$\sigma_{\gamma\gamma}(E, \epsilon, \phi) = \frac{2\pi \alpha^2}{3m_e^2} W(\beta) \simeq 1.25 \times 10^{-25} W(\beta) \text{cm}^2,$$

with

$$W(\beta) = (1 - \beta^2) \left[ 2\beta (\beta^2 - 2) + (3 - \beta^4) \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right],$$

where $\alpha$ is the fine-structure constant, and $\beta = (1 - \epsilon_{\text{thr}} / \epsilon)^{1/2}$.

Furthermore, the distance $D$ is more appropriate than the redshift $z_s$ for galactic sources and their relationship is given by

$$D = cz_s / H_0.$$  

Thus to the leading order of $D$, Eq. (2) is replaced by the following expression

$$\tau_\gamma(E_0, D) = D \int_1^1 d(\cos \phi) \frac{1 - \cos \phi}{2} \int_{\epsilon_{\text{thr}}(E, \phi)}^\infty \, d\epsilon_\gamma(\epsilon) \sigma_{\gamma\gamma}(E, \epsilon, \phi),$$

which is the key formula used in this paper. Also, notice that for the source distance corresponding to the tiny redshift, we have $E_0 \approx E$.

Once the optical depth is computed, one can obtain the mean free path of gamma ray photons by the following relation [32],

$$\lambda_\gamma(E_0, D) = \frac{D}{\tau_\gamma(E_0, D)},$$

where $\lambda_\gamma(E_0, D)$ stands for the mean free path of photons with energy $E_0$.

### 3 Numerical Results

![Fig. 1. The relationship between the mean free path and the energy of observed photons, where the LHAASO detected gamma ray photons are marked by red dots.](image)

In this section we apply the above theoretical analysis to LHAASO data. The optical depth, mean free path and the survival probability are computed for the eleven LHAASO sources and the main results are summarized in
Furthermore, from the last column in Table 1, we notice that most of the survival probability for gamma ray photons is
\[ \tau \]
that the optical depth for all the LHAASO sources is much less than one, namely
\[ \tau \ll 1 \]
as the survival probability for the eleven LHAASO sources. First of all, from the fourth column in Table 1, we notice
indicates that the mean free path is only sensitive to the energy for galactic sources in this context.

We notice that the optical depth increases with the increase of the source distance, while the survival probability decreases. This trend is reasonable because the UHE gamma rays from the source farther from the Earth can be seen directly from Table 1. This result is qualitatively the same as depicted in Fig.6 of Ref.[1].

Even taking the statistical uncertainties into account we find the survival probability stays at a very high level, which even for the remaining one (LHAASO J1929+1745), we choose the possible location with the maximal distance.

In the sense of ignoring the statistical uncertainties, these sources have definite distances.

| LHAASO Source | Distance (kpc) | Observed energy (PeV) | Optical depth | Mean free path (kpc) | Survival probability |
|---------------|----------------|-----------------------|---------------|----------------------|----------------------|
| LHAASO J2032+4102 | 1.40±0.08 | 1.42±0.13 | 0.18±0.02 | 7.68±0.25 | 0.83±0.01 |
| LHAASO J0534+2202 | 2.0 | 0.88±0.11 | 0.20±0.02 | 10.00±0.30 | 0.82±0.02 |
| LHAASO J1825-1326 | 3.1±0.2 | 0.42±0.16 | 0.11±0.10 | 29.07±9.85 | 0.90±0.08 |
| LHAASO J1839-0545 | 1.6 | 0.42±0.16 | 0.06±0.04 | 29.07±9.85 | 0.95±0.04 |
| LHAASO J1849-0003 | 7 | 0.35±0.07 | 0.15±0.09 | 45.71±46.23 | 0.86±0.07 |
| LHAASO J1908+0621 | 2.4 | 0.44±0.05 | 0.09±0.02 | 26.28±3.98 | 0.91±0.02 |
| LHAASO J1956+2845 | 2 | 0.42±0.03 | 0.04±0.01 | 29.07±3.99 | 0.93±0.01 |
| LHAASO J2018+3651 | 1.8±1.1 | 0.27±0.02 | 0.02±0.01 | 104.88±36.22 | 0.98±0.01 |
| LHAASO J2226+6057 | 0.8 | 0.57±0.19 | 0.05±0.02 | 16.48±20.37 | 0.95±0.03 |

Table 1. The optical depth and the survival probability of gamma ray photons detected by LHAASO.

\[ \text{In the sense of ignoring the statistical uncertainties, these sources have definite distances.} \]
above 0.8. For instance, Ref. [1] observes that the gamma rays in LHAASO J2032+4102 have energy of 1.42 PeV, and the survival probability of such high-energy photons reaching the Earth is $P_{\gamma\rightarrow\gamma}(E_0,z_s) \approx 83.3\%$. The lowest survival probability for observed gamma ray photons comes from LHAASO J1929+1745, which is about 0.60. This further shows that although the energy of gamma ray photons is 0.71 PeV and beyond the threshold value of pair production, a large number of gamma-ray photons can still reach the Earth without the violation of Lorentz symmetry.

Therefore, we intend to conclude that it is still far to argue that the Lorentz symmetry would be violated due to the present observations from LHAASO.

4 Discussion

In this note we have computed the optical depth, the mean free path as well as the survival probability for photons from all the gamma-ray sources detected by LHAASO in Ref. [1]. The cross-section of the pair production due to the interaction with CMB photons is obtained within the standard special relativity and we find the survival probability is fairly high for galactic gamma ray photons, even though the energy of those photons may exceed the threshold value of pair production. Thus there is no tension to consider the violation of Lorentz symmetry. This should be true for general galactic pevatrons, because in comparison with the cosmic scale, the distance between the galactic sources and the Earth is still too close to provide enough chances to collide with CMB photons during the propagation.

To be more specific, the current data from [1] are not sufficient to result in a subluminal correction constrained by the pair-production reaction $\gamma\gamma \rightarrow e^+e^-$. While the superluminal corrections constrained by the photon decay reaction does not conflict with our results, since the distances of possible origins shown in [1] are far enough for photons to decay [33].

Nevertheless, we may wonder what kind of observations on UHE cosmic rays would imply that one is urged to
consider the Lorentz symmetry violation. For gamma-ray photons, such kind of condition would be reached once the optical depth is much close to one or larger than one. From Fig.3 as suggested also in [21, 22], one would expect that if some of PeV photons with much higher source distance would be detected by LHAASO in future, then the tension of violating Lorentz symmetry would become strong.

Of course, it is completely possible to consider the corrections of the survival probability due to the Lorentz symmetry violation. For instance, one may modify the dispersion relations for photons and obtain the threshold energy with corrections, and finally plot the optical depth with Lorentz symmetry violation, as performed in Ref. 34.

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