Physics Letters B 690 (2010) 25–28

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

TeV gamma rays from distant BL Lacs and photon–paraphoton kinetic mixing

R. Anantua, O.K. Baker *

Department of Physics, Yale University, PO Box 208120, New Haven, CT 06520, USA

ARTICLE INFO

Article history:
Received 12 January 2010
Received in revised form 6 April 2010
Accepted 26 April 2010
Available online 27 April 2010
Editor: S. Dodelson

Keywords:
BL Lacertae objects: general
Dark matter
Gamma rays: observations

ABSTRACT

An effect of a proposed Beyond the Standard Model particle physics process on the energy spectra of distant astrophysical objects is presented. It is suggested that TeV gamma rays from distant BL Lacs may kinetically mix with hypothetical hidden sector paraphotons. The latter can traverse vast distances of space because of only very weak interactions with intervening objects or material. These paraphotons would then reconvert back into photons that have identical characteristics as their originators, and are detected on earth. Laser based photon regeneration experiments test this model of hidden sector physics in the range of parameters that would impact the TeV gamma ray energy spectra arriving from distant BL Lacs.

1. Introduction

Theories of fundamental interactions that are beyond the Standard Model (BSM) of particle physics are thought to be necessary in order to explain much natural phenomena: Dark Matter, Dark Energy, an unnaturally small CP-violating parameter associated with the strong interaction, to name a few examples. When the SM is embedded in a larger unified theory based, for example, on superstrings or supergravity, a hidden sector of particles and interactions usually results [6,17]. The gauge bosons of this hidden or "Dark" sector would couple only very feebly to SM fields, in order to be consistent with observations. There is work by several authors proposing the existence of light, sub-electron volt mass particles that interact only feebly with SM fields [15,13,11,1,22,24,26,18,21,25]. In cases where there are U(1) factors in the gauge interactions (in realistic string compactifications) there can be very light, hidden sector U(1) gauge bosons that are kin to the visible photon; we refer to them as hidden sector paraphotons. The hidden sector photon may have sub-electron-volt mass. Then the dominant interaction between hidden sector photons and visible sector photons is via the mechanism of kinetic mixing. There has been speculation, for example, that paraphoton mixing may give rise to a hidden Cosmic Microwave Background (hCMB). This hCMB would give a distortion to the CMB [16].

The spectra of ultra high energy (UHE) gamma rays from distant astrophysical sources such as active galactic nuclei is a topic of great interest in astrophysics. Correlations between the arrival direction of UHE cosmic rays (CRs) of BL Lac objects have been observed. In some studies, the correlation exists without the need to take into account galactic magnetic fields. These CRs may experience no magnetic deflection in traversing the vast distances of space and are therefore neutral particles, challenging conventional models of CR objects. Accurately measured UHE photon spectra at approximately a TeV are of particular interest here. As pointed out in [19] the measured TeV γ ray spectra of BL Lacs could be strongly modulated by the extragalactic background light (EBL) and diffuse interstellar or intergalactic infrared (IR) radiation due to absorption and pair creation, for example. There is a lack of direct measurements of this background radiation. Consequently, attempts to fit the energy dependence of these spectra must rely of models of their opacity to TeV γ rays. At the same time, these features may also be attributed to the source itself, limiting the detailed use of these models. It is intriguing therefore to consider the possible effects of BSM fields on the spectra of UHE gamma rays from BL Lacs.

BSM effects on UHE photons have been previously considered. Interactions mediated by a pseudoscalar axion have, for example, been proposed to provide a contribution to the observed spectra of TeV gamma-ray sources [20,9,12,28,29,14]. In this case, the photon–axion conversion would take place in the turbulent magnetic fields of our galaxy. In the case considered here of the energy spectra of TeV gamma rays from distant BL Lacs, the photon–paraphoton conversion may take place even in the absence of external electric or magnetic fields, that is, in free space with or void of matter [31]. The weakly interacting paraphotons would be able to traverse great distances relatively unimpeded before reconversion back into SM photons that are detected in terrestrial experiments. TeV gamma rays that would otherwise scatter, or be

* Corresponding author.
E-mail address: oliver.baker@yale.edu (O.K. Baker).

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2010.04.064

subject to pair creation with the intervening matter on their path to earth would in this case have an increased contribution to the observed spectra. This proposed phenomena is considered in the present work.

2. Photon–paraphoton kinetic mixing

The kinetic mixing of photons with paraphotons allows transitions between them. This mechanism has been tested in recent experimental searches. These all use the photon regeneration technique [8] (also referred to as "Light Shining Through a Wall") where photons kinetically mix with paraphotons which then pass unimpeded through an optical barrier. These paraphotons then reconvert to SM photons downstream of the barrier and would be detected in a carefully designed experiment. The process is depicted in Fig. 1. Recently, several experimental groups have obtained new data that may illuminate and constrain the hidden sector with its potentially small couplings to SM fields in the sub-eV energy range: LIPSS [2], GammeV [10], BMV [27], OSQAR [7], and PVLAS [30].

The most general renormalizable Lagrangian describing the interaction dynamics of these two fields at low energies is [6]

$$L = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 B^{\mu}B^{\mu} \tag{1}$$

Here $F^{\mu\nu}$ is the ordinary electromagnetic gauge field strength tensor, $B^{\mu\nu}$, is the field strength tensor for the hidden sector field, and $m_{\gamma'}$ denotes the hidden sector paraphoton mass. The first two terms in (1) are the kinetic terms for the SM photon and hidden sector photon fields, respectively. The third term corresponds to a non-diagonal kinetic term, that is, kinetic mixing between the two fields. The last term of the Lagrangian indicates a possible mass for the paraphoton. The mixing parameter χ is predicted to range between 10^{-16} and 10^{-4} in some string theory based calculations [6,17]. However it is a completely arbitrary parameter and even $\chi = 0$ is possible.

The rate of regenerated photons that would be detected, r_s, is

$$r_s = r_i P_{trans}\frac{\Delta\Omega}{\Omega}\epsilon \tag{2}$$

where r_i is the incident photon rate, $\frac{\Delta\Omega}{\Omega}$ is the photon solid angle for detection, ϵ is the detection efficiency and

$$P_{trans} = 16\chi^4 \sin^2\left(\frac{\Delta k L_1}{2}\right)\sin^2\left(\frac{\Delta k L_2}{2}\right) \tag{3}$$

is the probability for photon regeneration from paraphotons that kinetically mix with incident photons in the generation region and propagate through the wall indicated in Fig. 1. Here L_1 (L_2) is the length of the generation (regeneration) region to the left (right) of the wall shown in Fig. 1 and the momentum difference between the photon and the hidden-sector paraphoton is defined as

$$\Delta k = \omega - \sqrt{\omega^2 - m_{\gamma'}^2} \approx \frac{m_{\gamma'}^2}{2\omega} \tag{4}$$

where ω is the photon energy.

This process would affect the spectra of TeV gamma rays from distant BL Lacs as follows. The stream of high energy photons would travel a distance towards the earth as SM photons, some disappearing due to pair creation or to scattering with the IBL. After a distance L_1, some of these high energy photons would have converted to hidden sector paraphotons due to kinetic mixing between the two fields. These paraphotons would travel a distance L_2 before some of them would be reconverted back into SM photons via the identical mechanism. It is these latter regenerated photons that are detected in earth-bound arrays.

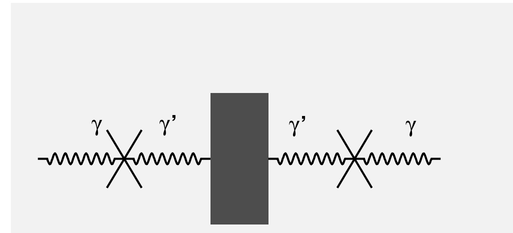


Fig. 1. Photon regeneration ("Light Shining Through a Wall"). Photons (γ) may convert into hidden-sector paraphotons (γ') via kinetic mixing. The latter proceed unimpeded through an optical barrier and reconvert back into photons as shown. The reconverted photons have the same properties as the original photons. This process can occur in free space void of magnetic or electric fields.

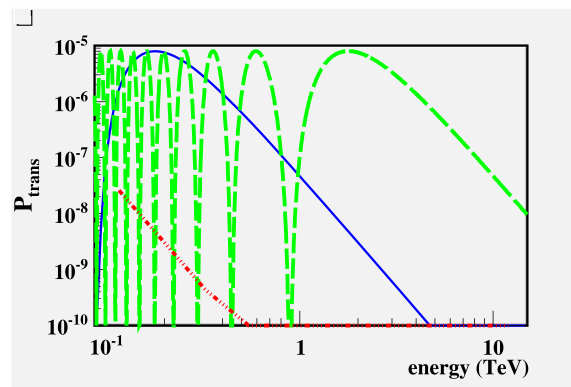
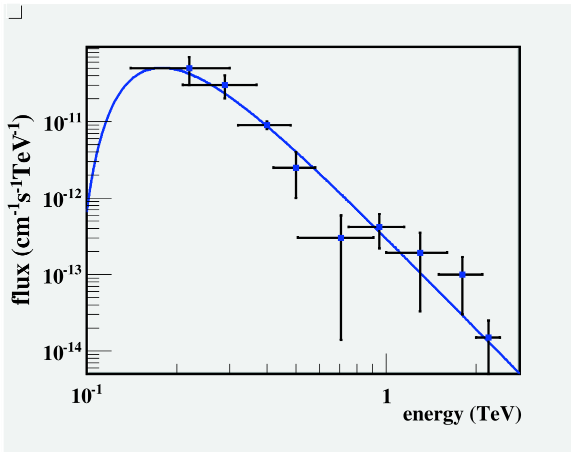


Fig. 2. The transmission probability P_{trans} from (3) as a function of the photon energy. The curves represent three different values of the combination of paraphoton mass and baselines L_1 and L_2. The full (blue in the web version) curve corresponds to the combination of paraphoton mass and baselines in the middle of the range studied here. The dashed-dot (red in the web version) curve shows the results when this combination is increased by an order of magnitude, while the long-dashed (green in the web version) curve is for this combination decreased by an order of magnitude.

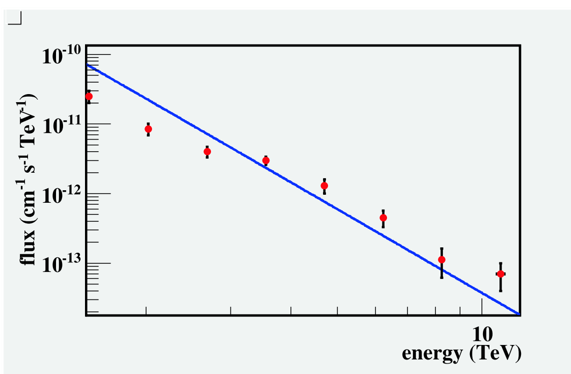
Presented in Fig. 2 is a comparison of the effect of the different baselines and paraphoton masses on P_{trans} versus the photon energy. For each curve $L_1 = L_2$. There are already limits set on the mixing parameter χ and the paraphoton mass from LSW experiments and from astrophysical studies [16]. The relevant region of parameter space suitable for this present study would be for paraphoton masses of between 10^{-5} and 10^{-2} eV and below 10^{-9} eV for values of the mixing parameter at or above 10^{-11}.

The important parameter in this study is the combination of the oscillation length L and the paraphoton mass, $m_{\gamma'}$; this is shown in Eqs. (3) and (4). The results presented here use a combination $L \cdot m_{\gamma'}$ of 0.28 in all the cases presented in Fig. 3. For example, the distance to BL Lac shown in Fig. 3a in the manuscript has a redshift of 0.071 or 284.72 megaparsecs (Mpc) from earth corresponding to L of 4.39×10^{31} eV^{-1}. The distance to the BL Lac from earth is divided into three parts; the photon travels a distance $L/3$ from the Bl Lac on its way to earth, during which there is mixing with the paraphoton; the paraphoton then travels a distance $L/3$ before a second photon–paraphoton mixing; then this latter photon travels a distance $L/3$ before being detected by one of the earth-bound arrays. So the combination $L \cdot m_{\gamma'}$ of 0.28 with L equal to $4.39/12 \times 10^{31}$ eV^{-1} yields a paraphoton mass of 2.77×10^{-10} eV. (The factor 1/12 comes from $L/3$ and from the extra factor 2×2 in Eqs. (3) and (4); the photon energy is expressed in eV.)

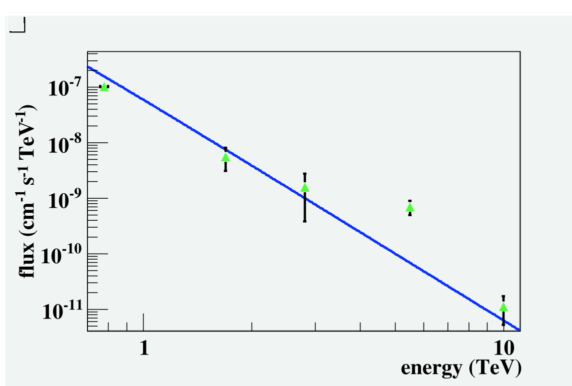
The solid (blue) curve corresponds to the combination of baselines and paraphoton mass in the middle of the range (0.28)



(a)



(b)



(c)

Fig. 3. A comparison of the transmission probability from (3) to UHE gamma rays from BL Lacs. Shown in (a) is the data from the HESS stereoscopic array at a redshift of 0.071. Part (b) compares the data from the HEGRA stereoscopic system at a redshift of 0.047. Part (c) shows the comparison of the data from the HEGRA array at a redshift of 0.129.

of this study. The dashed-dot (red) curve shows the results when this combination is increased by an order of magnitude (2.80), while the long-dashed (green) curve is for this combination decreased by an order of magnitude (0.028). There could be many oscillations between the state of photon and paraphoton in its trip from the BL Lac to earth. The simplest case of a single oscillation, photon → paraphoton → photon is considered here.

3. Results and conclusion

Making use of the BL Lacs listed in [19], a comparison is made between their energy distribution and that which would results from the transmission probability (3). This is done for the case of UHE gamma rays with energies of order a TeV or more. The absolute normalization for comparison between the two is unknown since the photon flux originating from the BL Lacs is not given. However, the shape of the energy distribution may be compared as done here.

Shown in Fig. 3a is the data from the HESS stereoscopic array [3] at a redshift of 0.071 compared with the shape of the curve from expression (2). (The curve is normalized to fit the data since it is the shape of the distribution that is emphasized here.)

Similarly Fig. 3b compares the data from the HEGRA stereoscopic system [4] at a redshift of 0.047 with the normalized curve of (2). Even though the redshift is almost 40 per cent smaller than that Fig. 3a, the shape of the curve still gives a reasonable fit to the data.

Fig. 3c shows the comparison of the data from the HEGRA array [5,23] at a redshift of 0.129, almost 90 per cent farther away than the BL Lac whose data is shown in Fig. 3a. Again, the shape of the curve (normalized to the data) agrees well with the data, within the error of the measurement.

This study suggests that there may be some motivation for including effects on TeV gamma rays from distant BL Lacs of photons that traverse large distances of space due to their conversion into hidden sector paraphotons. The latter are able to cross the interstellar and intergalactic space with only very feeble interactions with the IBL and other objects. They would then reconvert back into SM photons that have identical characteristics to the original BL Lac TeV photons. Such an effect may need to be included in studies of these objects. Experiments in the near future using the LSW technique may be able to test this hypothesis.

Acknowledgements

Funding from the Office of Naval Research Award N00014-06-1-1168 is gratefully acknowledged.

References

[1] S.A. Abel, B.W. Schofield, Nucl. Phys. B 685 (2004) 150.
[2] A. Afanasev, et al., Phys. Lett. B 679 (2009) 317.
[3] F. Aharonian, et al., Astron. Astrophys. 436 (2005) L17.
[4] F. Aharonian, et al., Astron. Astrophys. 406 (2003) L9.
[5] F. Aharonian, et al., Astron. Astrophys. 384 (2002) L23.
[6] M. Ahlers, et al., Phys. Rev. D 77 (2008) 095001.
[7] R. Ballou, et al., Report CERN-SPSC-2007-039 SPSC-M-762, CERN, 2007; R. Pugnat, et al., Phys. Rev. D 78 (2008) 092003.
[8] K.V. Bibber, et al., Phys. Rev. Lett. 59 (1987) 759.
[9] C. Burrage, A.-C. Davis, D.J. Shaw, Phys. Rev. Lett. 102 (2009) 201101; C. Burrage, in: 5th Patras Workshop on Axions, WIMPs, and WISPs, Durham, 2009, http://axino-wimp.desy.de/e30.
[10] A. Chou, et al., Phys. Rev. Lett. 100 (2008) 080402; GammeV Collaboration, http://gammev.fnal.gov.
[11] K.R. Dienes, et al., Nucl. Phys. B 492 (1997) 104.
[12] M. Fairbairn, T. Rashba, S. Troitsky, Phys. Rev. Lett. 98 (2007) 201801; M. Fairbairn, in: 5th Patras Workshop on Axions, WIMPs, and WISPs, Durham, 2009, http://axino-wimp.desy.de/e30, arXiv:0901.4085 [astro-ph].
[13] R. Foot, X.G. He, Phys. Lett. B 267 (1991) 509.
[14] K. Hochmuth, G. Sigl, Phys. Rev. D 76 (2007) 123011.
[15] B. Holdom, Phys. Lett. B 166 (1986) 196.
[16] J. Jaeckel, J. Redondo, A. Ringwald, Phys. Rev. Lett. 101 (2008) 131801.
[17] J. Jaeckel, A. Ringwald, Phys. Lett. B 659 (2008) 509.
[18] J. Khoury, A. Weltman, Phys. Rev. Lett. 93 (2004) 171104; J. Khoury, A. Weltman, Phys. Rev. D 69 (2004) 044026.
[19] A. Konopelko, et al., astro-ph/0507479v1, 2005.
[20] A. Mirizzi, G.G. Raffelt, P.D. Serpico, Phys. Rev. D 76 (2007) 023001.

[21] D.F. Mota, D.J. Shaw, Phys. Rev. D 75 (2007) 063501;
D.F. Mota, D.J. Shaw, Phys. Rev. Lett. 97 (2006) 151102.
[22] L.B. Okun, Sov. Phys. JETP 56 (1982) 502.
[23] D. Petry, et al., Astrophys. J. 580 (2002) 104.
[24] V.V. Popov, O.V. Vasil'ev, Europhys. Lett. 15 (1991) 7.
[25] G.G. Reffelt, W.-M. Yao, et al., Particle Data Group, J. Phys. G 33 (2006) 1;
G.G. Reffelt, W.-M. Yao, et al., Lect. Notes Phys. 741 (2007) 51.
[26] A. Ringwald, J. Phys. Conf. Ser. 39 (2006) 197.
[27] C. Robilliard, et al., Phys. Rev. Lett. 99 (2007) 190403.
[28] M. Roncadelli, A. Angelis, O. Mansutti, AIP Conf. Proc. 1018 (2008) 147;
M. Roncadelli, A. Angelis, O. Mansutti, Phys. Lett. B 659 (2008) 847;
M. Roncadelli, A. Angelis, O. Mansutti, Phys. Rev. D 76 (2007) 121301.
[29] M. Simet, D. Hooper, P.D. Serpico, Phys. Rev. D 77 (2008) 063001.
[30] E. Zavattini, et al., http://axion-wimp.desy.de/index_eng.html, 2007.
[31] H.-S. Zechlin, D. Horns, J. Redondo, in: Heidelberg Int. Symposium on High Energy Gamma-Ray Astronomy, Heidelberg, 2008, arXiv:0810.5501 [astro-ph].