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On the composition of ultra-high energy cosmic rays in top-down scenarios

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Photons are predicted to be the primary constituent in "top-down" scenarios of ultra-high energy cosmic rays (UHECRs) where the fragmentation of a high-energy jet produces the UHE component of the cosmic rays. There is a tension between this expectation and preliminary observational results that seem to favor a hadronic primary. In this paper we describe how a slight violation of Lorentz invariance, proposed for other purposes, would result in photon decay and would suggest that neutrons are the primary particles of UHE cosmic rays in top-down scenarios.

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I. INTRODUCTION

UHECRs are an enduring mystery. Without the introduction of new particles or interactions, evading the Greisen–Zatsepin–Kuz'min (GZK) cutoff [1, 2] requires unidentified nearby sources. Even without the GZK cutoff, the "bottom-up" approach faces the challenge of finding in nature an accelerator capable of energies in excess of 10^{20}eV.

"Top-down" scenarios assume that the UHECRs result from the fragmentation of a ultra-high energy hadronic jet produced by cosmic strings [3] or by the decay of a supermassive particle [4]. In the supermassive particle (wimpzilla) scenario, the UHECRs are of galactic origin, resulting from the decay of relic supermassive ($M \gtrsim 10^{13}$GeV) particles. Wimpzillas can be produced copiously in the early universe [5], thus solving the energy problem. Since they would cluster in the dark matter halo of our galaxy [6, 7], they also solve the distance problem. Detailed analysis of these decays, however, show that at high energy top-down scenarios produce more photons than protons [8, 9, 10] in the UHECR spectrum seen at Earth.

Results from the Fly's Eye [11], Haverah Park [12], and AGASA [13] cosmic ray experiments all indicate that at energies above around 10^{19} to 10^{20}eV, protons are more abundant than photons in UHECRs. The top-down prediction of photon preponderance in UHECRs is the one major problem in an otherwise simple explanation.

The idea of violating Lorentz invariance (see Ref. [14] for a broad overview) has recently been studied in the context of UHECRs for proton decay [15], atmospheric shower development [16], and modifications to the cutoffs of proton and photon spectra due to cosmic background fields [17, 18, 19, 20]. As shown in Ref. [21], Lorentz invariance violation can also lead to vacuum photon decay. We exploit this fact to get rid of the extra photons.

In this paper we propose a model that, using minimal assumptions of Lorentz invariance violation and no new energy scales, will suppress the presence of photons in UHECRs through photon decay. In addition, it predicts that the dominant component of UHECR hadrons will be neutrons rather than protons. Further, for the specific case of wimpzilla models [6, 7], there would be an anisotropy in the arrival direction of UHECRs.

II. BREAKING THE LAW

There are two approaches to breaking Lorentz invariance commonly used in the literature. The first [15, 17, 18, 21, 22] is generically to modify the dispersion relations for a particle of mass m and 3-momentum $p = |\mathbf{p}|$. Here M is some large mass scale (typically taken to be around the Planck mass). We follow Ref. [22] and set $M = 10^{19}$ GeV.

There are many ways one might write modified dispersion relations. In order to use the fewest number of free parameters, we extend the method used in Ref. [18] and write the dispersion relation as

$$\begin{aligned} E^2 &= p^2c^2 + m^2c^4 + p^2c^2 f\left(p/Mc\right) \\ &\quad + m^2c^4 g\left(p/Mc\right) + mpc^3 h\left(p/Mc\right). \end{aligned} \tag{1}$$

Here, $f(x), g(x)$, and $h(x)$ are dimensionless universal functions having the property $f(0) = g(0) = h(0) = 0$, so that as $p/M \to 0$ the normal dispersion relations are recovered. Expanding these functions in Taylor series about $x = 0$ and keeping terms of $O(p^2)$ and smaller gives

$$\begin{aligned} E^2 &= m^2c^4 + mpc^3\left(\frac{1}{2}g'(0)\frac{m}{M}\right) \\ &\quad + p^2c^2\left(1 + \frac{1}{2}h'(0)\frac{m}{M} + \frac{1}{6}g''(0)\frac{m^2}{M^2}\right). \end{aligned} \tag{2}$$

The linear $g'(0)$ term would dominate over the regular quadratic one at low p, so we set it to zero. Note that to this (lowest) order, $f(x)$ has no effect.[1] Examining the

[1] Issues of photon dispersion in the vacuum, as discussed in Refs. [17, 23], will not be addressed here.

cases of massless (photon) and massive (electron) particles:

$$E_e^2 = m^2c^4 + p_e^2c^2\left(1+\frac{1}{2}h'(0)\frac{m}{M}+\frac{1}{6}g''(0)\frac{m^2}{M^2}\right) \quad (3)$$

$$E_\gamma^2 = p_\gamma^2c^2. \quad (4)$$

We can now define

$$c_e^2 = c^2\left(1+\frac{1}{2}h'(0)\frac{m}{M}+\frac{1}{6}g''(0)\frac{m^2}{M^2}\right) \quad (5)$$

$$m_e^2 = m^2\left(1+\frac{1}{2}h'(0)\frac{m}{M}+\frac{1}{6}g''(0)\frac{m^2}{M^2}\right)^{-2} \quad (6)$$

to then write the dispersion relation in the familiar form

$$E_e^2 = m_e^2c_e^4 + p_e^2c_e^2. \quad (7)$$

So, to lowest order, we have made slight changes to the electron "speed of light" and mass.

The second method, which we will not utilize here, is instead to write down a particle Lagrangian [24] which includes Lorentz and CPT violating terms. A mapping of the Lagrangian terms to a dispersion relation is nontrivial (see [20] for a simple case); however, to first order the changes to the photon and electron propagators induce shifts to c_γ and c_e [25].

III. CALCULATION

For this paper we consider the tree-level photon decay process $\gamma \to e^+e^-$, which is kinematically forbidden for $c_e = c$. Following Ref. [25], we define the parameter $\delta_{\gamma e}$ as[2]

$$\delta_{\gamma e} = c^2 - c_e^2. \quad (8)$$

For $\delta_{\gamma e} > 0$, photon decay occurs above a photon energy threshold given by

$$E_{th} = \frac{2m_ec_e^2}{\sqrt{\delta_{\gamma e}}}c. \quad (9)$$

This decay rate of was computed in Coleman & Glashow (1997) as

$$\Gamma = \frac{1}{2}\alpha\left(\frac{\delta_{\gamma e}}{c_e^2}\right)E\left[1-(E_{th}/E)^2\right]^{3/2}. \quad (10)$$

Using astrophysical constraints [23, 26], $\delta_{\gamma e}$ can be limited to the range $10^{-16} > \delta_{\gamma e} > -10^{-17}$.

For decay product energy above about 2×10^{20}eV, photons will outnumber protons, so we set E_{th} to this value and suggestively rewrite the decay rate above threshold as:

$$\frac{\Gamma}{\hbar c} \approx (1\text{ km})^{-1}\left(\frac{E}{2\times10^{20}\text{ eV}}\right)\left(\frac{\delta_{\gamma e}}{3\times10^{-29}}\right). \quad (11)$$

This would rule out all but a terrestrial source of UHE photons. The value $\delta_{\gamma e} = 3\times10^{-29}$ is used is a lower limit; if $\delta_{\gamma e}$ would be any lower the energy threshold would become too high. This means that only $\delta_{\gamma e} \in (3\times10^{-29}, 10^{-16})$ will correct for the photon overabundance in top-down scenarios.

IV. DISCUSSION

Now we see what is required to have $\delta_{\gamma e}$ in the necessary range to allow for this photon decay. Using Eqs. (5) and (8), we can write

$$\delta_{\gamma e} = -\frac{1}{2}c^2h'(0)\frac{m}{M} - \frac{1}{6}c^2g''(0)\frac{m^2}{M^2}. \quad (12)$$

Since the functions $g(x)$ and $h(x)$ are *a priori* arbitrary, so are the values and signs of their derivatives. It is argued in Ref. [18] that too strongly varying functions would be unphysical, and that the derivatives should be of order unity.[3] Adopting this, we can ignore the $g''(0)$ term in the above equation. In this case, in order to have photon decay we need to require $h'(0)$ negative. Then $\delta_{\gamma e} \sim mc^2/2M \sim 3\times10^{-23}$ and $E_{th} = 2m_ec_e^2c\sqrt{2M/mc^2} = 2\sqrt{2m_eM}c^2 \approx 2\times10^{17}$eV. This value of $\delta_{\gamma e}$ is (logarithmically) in the middle of our allowable range.

While we only consider the case of photon to electron decay, this tree level process requires only a charged decay product Q and $c_\gamma > c_Q$; so at higher photon energies one would have $\gamma \to l\bar{l}, q\bar{q}$ for charged leptons (l) and quarks (q). Further, at one-loop level one also allows for processes such as $\gamma \to \nu_l\bar{\nu}_l$ [25] and $\gamma \to N\gamma$ (photon splitting) [27].

Unlike previous investigations [23, 25] where the "speed of light" for each particle could be chosen independently, this is not so in our case. Since Eq. 1 holds for all types of particles, it is straightforward to see other effects this level of Lorentz invariance violation would have. Using Eq. 5, we can in general write for two particles a and b

$$\delta_{ab} = c_a^2 - c_b^2 = \frac{1}{2}h'(0)c^2\frac{m_a-m_b}{M} \approx \frac{(m_b-m_a)c^2}{2M}, \quad (13)$$

[2] This is identical to $\xi - \eta$ for $n = 2$ in the notation of Ref. [23].

[3] Note that if this holds also for $f(x)$, we erred in not including the $f'(0)$ term in Eq. (2), as that dominates over the $h'(0)$ term when $p \gtrsim mc$. We will not apologize much for this, as we are looking at the "lowest order" change in phenomenology (the change in the "speeds of light") and not "next order" changes (such as vacuum photon dispersion).

where we have used $h'(0) \sim -1$. As a consequence, $\delta_{pn} \approx 10^{-22}$ for the proton-neutron system. From Ref. [25], this would imply the proton would become unstable above 5×10^{18}eV and the neutron stable above 3×10^{18}eV. Thus, as noted in [15], the primary single hadron component of UHECRs above about 10^{18}eV would be neutrons. Further, since $\delta_{\pi p} \approx 4\times10^{-20}$, this would eliminate the GZK cutoff for protons and neutrons [15, 19, 20, 25].

Although we were motivated by the $\gamma \to e^+e^-$ reaction, we can also allow $\gamma \to \pi^0\gamma$: $\delta_{\gamma\pi} \approx 7\times10^{-21}$, so that above $E_{\gamma\pi} \sim 2\times10^{18}$eV the photon is unstable to this decay [25]. Note that this is one decade higher than where the photon becomes unstable to electron decay.

However, above $E_{\gamma\pi} \sim 2\times10^{18}$eV, the pion is stable against decay into photons. Since the overabundance of photons in top-down spectra [8, 9, 10] is primarily due to pion decay, these decays would not lead to photons with energy more than 10^{18}eV in the first place. The decay $\pi^0 \to e^+e^-\gamma$ can still occur, but with a branching ratio which is two orders of magnitude smaller than $\pi^0 \to \gamma\gamma$. Clearly, in order to see fully the modifications of the top-down decay spectra, incorporations of Lorentz invariance violation must be taken into account during, not just after, the shower creation.

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