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Possible observation of photon speed energy dependence

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Abstract

Current constraints on photon velocity variability are summarized and displayed in terms of an energy-dependent vacuum refraction index. It is shown that the energy–momentum balance of high energy Compton scattering is very sensitive to the outgoing photon speed. A missing energy observation in HERA Compton polarimeter data indicates that photons with 12.7 GeV energy are moving faster than light by 5.1(1.4) mm/s. An asymmetry spectrum measured by the SLC longitudinal polarimeter implies however an effect which is 42 times smaller, although the interpretation of the data is less clear here.

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Keywords: Photon speed; Compton scattering; Dispersive vacuum

1. Theoretical models

According to relativistic kinematics a photon velocity in vacuum c_γ does not depend on its energy ω, while a possible dependency is constrained by the current photon mass limit $m_\gamma < 10^{-16}$ eV [1] as $1 - c_\gamma(\omega)/c \leqslant 10^{-32}\omega^{-2}$ eV^2, where c is a massless particle vacuum speed. However, the laboratory or stellar vacuum always contains background fields (matter) and quantum interactions can slow down or speed up photon propagation. Tiny changes of the photon velocity have been predicted [2,3] for such nontrivial, polarized vacua modified by electromagnetic or gravitational fields, temperature or boundary conditions within the perturbative quantum electrodynamics which allows to derive inverse relative velocities (vacuum refraction indices $n = c/c_\gamma$) mainly for low energy $\omega \ll m$ (m is the electron mass) photons [4]. Even in the absence of background fields vacuum quantum fluctuations can influence light propagation as pointed out for the gravitational vacuum by recent developments in quantum gravity theory [5(a)–(c)]. Changes of photon speed are expected to be significant at photon energies close to the Planck mass $\approx 10^{19}$ GeV decreasing with lower energies. Hypothetical Lorentz

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symmetry deformations considered for explaining the observed ultrahigh energy cosmic rays above the GZK cutoff (and possibly neutrino oscillations) [6] may also introduce an energy-dependent photon speed [7].

2. Experimental limits

Magnitudes of these predicted effects are small and though may exceed by many orders the constraints imposed by the photon mass, all experimental tests so far show that different energy photons in vacuum move at the same velocity (light vacuum speed c) within the constraints displayed on Fig. 1 (use of vacuum refraction index $n(\omega)$ instead of photon velocity is convenient to distinguish between photon mass and vacuum properties).

The most stringent limits are coming from the detection of highest energy proton and γ cosmic particles as first noted in [8], since in a dispersive vacuum they would quickly decay by vacuum Cherenkov radiation $p \to p\gamma$ $(n > 1)$ and pair creation $\gamma \to e^+e^-$ $(n < 1)$. These processes are kinematically forbidden in case

$$
\begin{aligned}
&n - 1 < \frac{M^2}{2E^2 - 2\omega E - M^2}, \\
&1 - n < \frac{2m^2}{\omega^2}
\end{aligned}
\tag{1}
$$

for Cherenkov radiation and pair creation, respectively, with M, E the proton mass and energy. Excluded areas in Fig. 1 correspond to a highest detected proton energy of $E = 10^{20}$ eV [9] and to a cosmic photon spectrum up to $\omega_{\max} = 22$ TeV [10]. Also shown is a limit inferred from the highest observed electron energy of 2 TeV [11]. Other areas are excluded by experiments utilizing direct time of flight techniques sensitive to $|n - 1| \approx \Delta tc/D$, where Δt is a time difference between arrivals of simultaneously emitted photons with different energy and D is a distance to the source. While laboratory experiments are limited by time resolutions of typically a few picoseconds and distances of a few kilometers (an early SLAC result [12] $|n - 1| < 2 \times 10^{-7}$ is shown on Fig. 1 by a narrow white bar at 15 GeV $< \omega <$ 20 GeV) the astrophysical observations could do much better owing to huge distances to the source. In Ref. [13] one can find limits on light speed variations in wide energy ranges

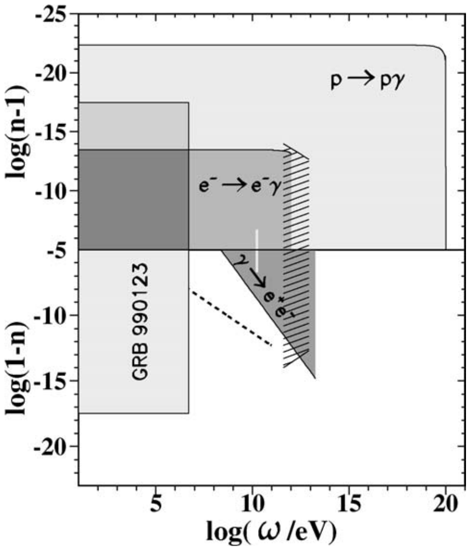

Fig. 1. Experimental constraints on the vacuum refraction index.

based on different astrophysical events; these limits suffer, however, from very uncertain distance scales. Meanwhile an observed spectacular gamma ray burst GRB990123 [14] followed by an optical counterpart detected within $\Delta t = 22$ s, with a distance $z = 1.6$, could establish a constraint $|n - 1| < 3 \times 10^{-18}$ for 2 eV $< \omega <$ 5 MeV, which is anyhow the order of constraints quoted in Ref. [13]. Photons with highest observed energies 0.35 TeV $< \omega <$ 10 TeV from a well defined active galaxy source (Markarian 421) put constraints $|n - 1| < 2.5 \times 10^{-17}\omega$ [15] (hatched area in Fig. 1).

3. Compton scattering in dispersive vacuum

Apart from the discussed threshold effects for vacuum Cherenkov and pair creation, the dispersive vacuum will modify the kinematics of other processes involving free photons according to the dispersion relation $k^2 = \omega^2(1 - n^2)$. However, the tiny refraction imposed by such vacuum becomes observable only at high energies with corresponding small angles. When the photon (four-momentum k) interacts with a particle (four-momentum P) the vacuum index will contribute to the convolution Pk as

$$
Pk \approx \frac{\mathcal{E}\omega}{2}\left(\frac{1}{\gamma^2} + \theta^2 + 2(1 - n)\right)
\tag{2}
$$