Detecting Axion-Like Particles With Gamma Ray Telescopes

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We propose that axion-like particles (ALPs) with a two-photon vertex, consistent with all astrophysical and laboratory bounds, may lead to a detectable signature in the spectra of high-energy gamma ray sources. This occurs as a result of gamma rays being converted into ALPs in the magnetic fields of efficient astrophysical accelerators according to the “Hillas criterion”, such as jets of active galactic nuclei or hot spots of radio galaxies. The discovery of such an effect is possible by GLAST in the 1-100 GeV range and by ground based gamma ray telescopes in the TeV range.

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Introduction — The Peccei-Quinn (PQ) mechanism [1] remains perhaps the most compelling explanation of the CP problem of QCD. A new chiral $U_{PQ}(1)$ symmetry that is spontaneously broken at some large energy scale, $f_a$, would allow for the dynamical restoration of the CP symmetry in strong interactions. An inevitable consequence of this mechanism is the existence of axions, the Nambu-Goldstone bosons of $U(1)_{PQ}$ [2]. One of the most important phenomenological properties of the hypothetical axion is its two-photon vertex which allows for axion-photon conversions in the presence of external electric or magnetic fields [3] through an interaction term

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a,$$

where $a$ is the axion field, $F$ is the electromagnetic field-strength tensor, $\tilde{F}$ its dual, $\mathbf{E}$ the electric field, and $\mathbf{B}$ the magnetic field. The axion-photon coupling strength is quantified by

$$g_{a\gamma} = \xi \frac{\alpha}{2 \pi} \frac{1}{f_a},$$

where $\alpha$ is the fine-structure constant and $\xi$ is a parameter of $O(1)$ depending on the details of the electromagnetic and color anomalies of the axial current associated with the axion field. In particular, this coupling is used by the ADMX experiment to search for axion dark matter [3] and by the CAST experiment to search for solar axions [3,4]. The Peccei-Quinn axion has the important feature that its mass $m_a$ and interaction strength are inversely related to each other and are connected to the measured properties of pions. One may, however, conceive of a more general class of particles whose coupling and mass are unrelated to each other. Such states are known as axion-like particles (ALPs). ALPs may manifest themselves in the propagation of photons in magnetic fields, either in laboratory or astrophysical environments, and may have potentially interesting astrophysical and cosmological consequences [3].

In this letter, we propose another way to potentially detect ALPs, namely through their distortion of the energy spectra of high-energy gamma ray sources (we note however that a light scalar particle coupling to $F_{\mu\nu} \tilde{F}^{\mu\nu}$ in Eq. (1) would lead to similar effects). This idea is somewhat similar to that discussed in the recent Ref. [5], but with some important differences. In that paper the authors considered the ALP parameters needed to fit PVLAS data [5] (as in other recently proposed gamma ray signatures of ALPs [6]), and assumed that the conversion of photons above $\sim 10$ TeV into ALPs takes place in the turbulent component of the galactic magnetic field. Here, in contrast, we discuss the case in which the photon-ALP conversion occurs near or within the gamma ray sources. Interestingly, we find that, if the gamma sources are (or are hosted in) efficient astrophysical accelerators according to the “Hillas criterion” [7], significant conversion can occur in ALP models which are fully consistent with all laboratory and astrophysical constraints. In fact, the mechanism discussed here may offer the most practical way to detect ALPs over a significant range of masses and couplings.

Photon-ALP conversion in gamma ray sources — As a consequence of the interaction of Eq. (1), ALPs and photons oscillate into each other in the presence of an external magnetic field. For a photon of energy $E_{\gamma}$, the probability of converting into an ALP can be written [5]

$$P_{osc} = \sin^2(2\theta) \sin^2 \left[ \frac{g_{a\gamma}}{2} \frac{B}{E_{\gamma}} s \right] \frac{1 + \left( \frac{E}{E_{\gamma}} \right)^2}{2},$$

where $s$ is the size of the domain and $B$ is the magnetic field component along the polarization vector of the photon, which is assumed to be approximately constant within that domain. We have also defined an effective mixing angle $\theta$ and characteristic energy $\mathcal{E}$ via

$$\sin^2(2\theta) = \frac{1}{1 + (\mathcal{E}/E_{\gamma})^2}, \quad \mathcal{E} = \frac{m^2}{2g_{a\gamma} B},$$

where the effective ALP mass squared is $m^2 \equiv |m_a^2 - \omega_{pl}^2|$, $\omega_{pl} = \sqrt{4\pi \alpha n_e/m_e}$ is the plasma frequency, $m_e$ the electron mass, and $n_e$ the electron density. For the following considerations, it is useful to introduce the dimensionless quantities: $g_{11} = g_{a\gamma}/10^{-11} \text{ GeV}^{-1}$, $B_G = B/\text{Gauss}$, $s_{pc} \equiv s/\text{parsec}$, $m_{\mu eV} \equiv m/\mu eV$, $E_{GeV} \equiv E/\text{GeV}$. Recent results from the CAST experiment [6] provide a direct bound on the ALP-photon coupling of $g_{11} \lesssim 8.8$ for...
$m_a \lesssim 0.02 \text{ eV}$, nominally below the long-standing globular cluster limit [7]. Note that

$$\omega_{p1} = 0.37 \times 10^{-4} \mu \text{eV} \sqrt{n_e / \text{cm}^{-3}},$$

(5)

which means that in the interstellar medium (ISM) of the Milky Way, where $n_e \sim 0.1 \text{ cm}^{-3}$, the effective mass of the ALP will not be smaller than $m_{\mu \text{eV}} \sim 10^{-5}$, independently of how small $m_a$ is. For ultra-light ALPs ($m_a \lesssim 10^{-11} \text{ eV}$), the absence of gamma rays from SN 1987A yields a stringent limit of $g_{11} \lesssim 1$ [13] or even $g_{11} \lesssim 0.3$ [14]. But for $10^{-11} \text{ eV} \ll m_a \ll 10^{-2} \text{ eV}$, the CAST bound is the most general and stringent (bounds from ADMX, although stronger for some masses, assume that the axion is the Galactic dark matter).

General properties— From Eqs. (3) it follows that: (i) At energies below $E$, the mixing is small and a fortiori the conversion probability is small. Above this critical energy, the mixing is large, and a significant depletion probability might arise. In suitable units,

$$E_{\text{GeV}} \equiv \frac{m_{\mu \text{eV}}^2}{0.4 g_{11} B_sG}.$$

(6)

As we shall argue, when plugging in the previous formula typical astrophysical and ALP parameters, this critical energy naturally falls in the gamma ray energy range. Thus, the physics of light and weakly coupled ALPs naturally points to $\gamma$-rays as the most promising tool for discovery. (ii) A significant conversion into axions also requires that the argument of the oscillatory function in Eq. (3) is not too small, i.e.

$$g_{a\gamma} B s/2 \gtrsim 1, \text{ i.e. } 15 g_{11} B_G s_{pc} \gtrsim 1.$$

(7)

The condition in Eq. (7) depends on the product $B s$, which also determines the maximum energy $E_{\text{max}}$ to which sources can confine and thus accelerate ultra-high energy cosmic rays (UHECRs). This is known as the Hillas criterion [15], and for protons it writes

$$E_{\text{max}} \approx 9.3 \times 10^{20} \text{ eV} B_G s_{pc}.$$

(8)

This connection between cosmic ray acceleration and Eq. (7) is important. Since UHECRs with energies of a few times $10^{20} \text{ eV}$ have been observed, environments where $B_G s_{pc} \gtrsim 0.3$ must exist in nature. This implies that couplings as small as $g_{11} \simeq 0.2$ might be probed, almost two orders of magnitude below present bounds.

In the following, we shall examine in greater detail what are the signatures expected in $\gamma$-rays due to the ALP-photon conversion mechanism, what are the most promising sources to look at, and the perspectives for current instruments to probe the ALP parameter space.

Spectral signatures— The qualitative signatures of the scenario considered here are remarkably robust, although the quantitative aspects are model dependent. The reason for this is twofold: (i) concerning particle physics, we ignore the fundamental mass and coupling parameters $m_a$ and $g_{a\gamma}$; (ii) the complicated (and unknown)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{A typical power-law $\gamma$-ray spectrum (solid line) and its distortion for photon-ALP conversion with $A = 1/3$ and critical energies $E = 500 \text{ GeV}$ (dashed lines) and $E = 2.5 \text{ TeV}$ (dashed-dotted line). See text for details.}
\end{figure}
sonable exposure times. So, it would not be a surprise if such a signature had escaped detection so far, but would show up in the coming years thanks to the GLAST satellite detector and present and planned ground telescopes. In principle, if the astrophysical parameters were known, the amplitude of the depletion could be used to constrain $g_{\alpha\gamma}$, see Eqs. (3,7), while the energy at which the effect is observed could be used to infer $m$, see Eq. (6). If only upper limits were available for $B_s$, a lower limit on $g_{\alpha\gamma}$ could be obtained, at least. Another prediction is that if a hint for an ALP would show up in a source at energy $E_1$, then gamma emitters sitting in regions with similar values of $B_s$ should show a feature of similar amplitude at a characteristic energy related to $E_1$ only by the value of their field strength, see Eq. (6).

Promising sources— To be consistent with existing bounds [9], an ALP should have a coupling $g_{11} \lesssim 9$, which implies that $B_s s_{pc} \gtrsim 10^{-2}$ must hold at the source. In Fig. 2, the Hillas diagram is shown, reporting the typical $B$ and $s$ values for UHECR candidate sources. It is clear that virtually all the objects proposed as UHECR accelerators, from gamma-ray bursts to clusters of galaxies, appear suitable for the search of ALP signatures. This is fortunate, since many observed (e.g. blazars) or expected (e.g. galaxy clusters) gamma ray sources are hosted in or near putative UHECR accelerators. However, at least the compact sources on the Hillas plot are not likely the best candidates due to their higher densities. Even a density of $10^{-6}\, g/cm^3$, very low for terrestrial standards, would imply $m \gg 1$ meV [see Eq. (6)] and thus the condition $E \gtrsim E$ cannot be satisfied in the energy range probed by gamma ray astronomy. This is a general, although qualitative, argument disfavoring too compact (and presumably dense) sources as possible sites to observe photon-ALP mixing. Very promising sources are instead AGN jets and hot spots in radio galaxies such as Cygnus A and M87. For example, typical parameters for the hot spots of Cygnus A are $B_G \approx 0.15 \times 10^{-3}$, $s_{pc} \approx 2 \times 10^{7}$ [18], and similar numbers apply to the hot spots of M87 [19], which has been detected in the TeV range. In these environments, the quantity of Eq. (7) is near unity for $g_{11} \approx 0.3$, while for propagation in our galaxy the same coupling would fail to satisfy that condition by more than one order of magnitude.

A remark is in order. If it were proved that conservative estimates for the product $B_s$ of a detected $\gamma$-ray emitter satisfy Eq. (7) for $g_{11} \lesssim 9$, then gamma observations would turn into powerful probes of ALP physics. But vice versa is not necessarily true: indeed, although some fits assuming synchrotron-self-Compton models seem to indicate that many detected gamma ray sources (see e.g. Refs. [12,20]) fall short of the requirement of Eq. (7) by one order of magnitude or more, it is important to remember that the ALP conversion feature depends on the properties of the environment crossed, not of the emitting region. In these cases, although a negative result can not be used to put significant bounds, a serendipitous discovery is by no means excluded.

Exploring the ALP parameter space— One can easily estimate the range of ALP parameters observationally accessible. As we argued earlier, from the highest energy UHECR observed the Hillas criterion suggests conservatively that sites where $B_G s_{pc} \gtrsim 0.3$ must exist in nature. Once plugged into Eq. (7) (assuming equality), this implies that at least couplings as small as $g_{11} \approx 0.2$ may produce significant depletions in gamma-ray spectra. To deduce the range of masses which can be probed, we proceed as follows: (i) we neglect too compact objects on the Hillas plot and restrict our attention to the most promising range of astrophysical source sizes previously discussed, $s_{pc} \approx 10^{-4}$ to $10^{7}$, deducing the corresponding field strength (see Fig. 2); (ii) we plug these values in Eq. (6) thus obtaining $E_{\text{GeV}} \approx 4 \times 10^{-3} \div 4 \times 10^{6} \, m_{\mu eV}$. Unless $m \lesssim 0.1\mu eV$ and the region is very compact (which is disfavored, as previously discussed), the transition energy is expected to fall in the gamma ray band, confirming again our initial, general remarks. Considering the energy range most interesting for GLAST (sub-GeV to a few tens of GeV), we deduce that ALPs in the mass range $m_{\mu eV} \sim 10^{-3} \div 10^{2}$ can be probed. For ground based gamma ray telescopes such as HESS, MAGIC and VERITAS, which are sensitive to gamma rays in the approximate range of $10^{2}$ to $10^{4}$ GeV, the photon-ALP conversion can also be significant for masses in the range of $m_{\mu eV} \sim 10^{-3} \div 10^{3}$. Globally, we estimate the approximate range of parameters which could lead to observable effects as the region schematically shown in Fig. 3 along with the range excluded by CAST and the band preferred by QCD axion models [9]. The particularly interesting region which overlaps with the QCD models band corresponds to $\sim 10$ TeV transition energies.
FIG. 3: The approximate range of ALP parameters which could lead to observable effects in gamma ray telescopes. Also shown are the parameters excluded by CAST and the band preferred for QCD axion models.

Summary — Space and ground-based gamma ray telescopes may have a chance to observe the effects of ALP-like particles (ALPs) through the mechanism of photon-ALP mixing. This mechanism leads to the depletion of gamma rays at high energies, resulting in a peculiar signature in the spectra of gamma ray sources such as the jets of active galactic nuclei, the hot spots of radio galaxies, or clusters of galaxies. If the astrophysical parameters at the sources were known sufficiently well, the mass and coupling of the ALP could be reconstructed or, in case of negative outcome, excluded. Without a detailed knowledge of the field strength and geometry around the gamma source a detection is still possible, but a negative result cannot easily be translated into interesting exclusion plots in the ALP parameter space. We believe that the mechanism discussed here should be thought of as an example of the opportunities that the new generation of gamma ray telescopes will offer for studying fundamental physics. Note that gamma ray telescopes may observe the effects of ALPs with parameters which are exceedingly difficult to explore otherwise, as shown in Fig. 3. An appearance experiment such as CAST is actually sensitive to $g_{a \gamma}^2$, and thus would require an improvement of five to six orders of magnitude in sensitivity to cover the entire range of parameters considered here. However, a detection of the kind described here could be confirmed, in part of the parameter space, by other astrophysical techniques, such as that suggested in Ref. [21].

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