Axion-like particles (ALPs) and e-ASTROGAM

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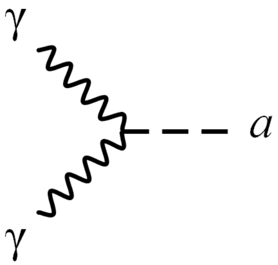
Axion-like particles (ALPs) are $s = 0$, neutral and very light pseudo-scalar particles a. They are a generic prediction of many extensions of the Standard Model, especially of those based on the M theory, which encompasses superstrings and superbranes. They are similar to the axion apart from the fact that the two-photon coupling $g_{a\gamma}$ is totally unrelated to the ALP mass m. Further, for our purposes only the two-photon coupling is important, which reads

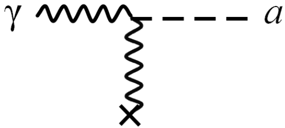
$$L_{\rm int} = g_{a\gamma}\, a\, \mathbf{B} \cdot \mathbf{E} \tag{1}$$

So, for ALPs the only new thing with respect to the Standard Model is shown by the Feynman diagram



which – at this stage – should be regarded as “God given”.

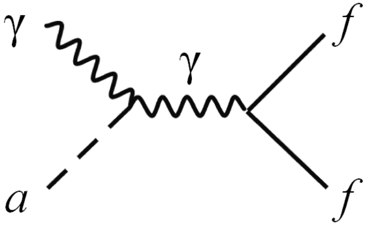
ALPs are produced in the core of MS stars (like the Sun) through the Primakoff process in the Coulomb field **E** of ionized matter



where $X = \mathbf{E}$.

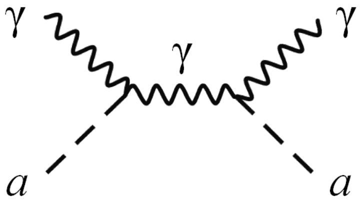
The CAST experiment at CERN was looking at the Sun and found nothing, thereby deriving the bound $g_{a\gamma} < 0.66 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$.

In spite of the coupling to two-photons, ALPs interact with nothing. To se this, denote by f a generic fermion and consider the Feynman diagram for the scattering $a\gamma \to f\bar{f}$



In the s-channel it describes the $a\gamma \to f\bar{f}$ scattering, while in the t-channel the $af \to af$ scattering. The cross-section is $\sigma \sim \alpha\, g^2_{a\gamma}$. So the previous bound yields in either case $\sigma < 10^{-50}\,\mathrm{cm}^2$.

Moreover, for $a\gamma \to a\gamma$ scattering the Feynman diagram is

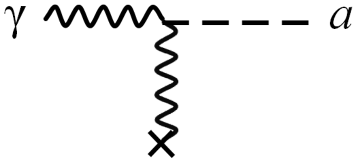


Then the cross-section is $\sigma \sim s\, g_{a\gamma}^4$, and so we find

$$\sigma < 7 \cdot 10^{-69} \left(\frac{s}{\mathrm{GeV}^2} \right) \mathrm{cm}^2 \,, \qquad (2)$$

where again the CAST bound is used.

We will henceforth consider a monochromatic photon beam and assume that an external magnetic field **B** is present. Hence in $g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$ the term **E** is the electric field of a beam photon while **B** is the external magnetic field. So $\gamma \to a$ conversions can occur



where now and in the following $X = \mathbf{B}$.

Needless to say, also the inverse process $a \to \gamma$ can equally well take place. As a consequence, as the beam propagates we can have photon-ALP oscillations

This is quite similar to what happens for massive neutrinos of different flavors apart from the need of the external field to compensate the spin mismatch.

N. B. a REAL

However here there is an additional effect.

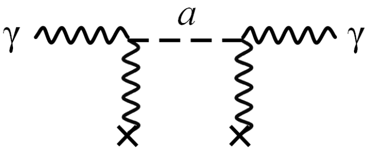
Because the $\gamma\gamma a$ vertex is $g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$, in the presence of an external magnetic field $\mathbf{B}$ we have that

- only the component $\mathbf{B}_T$ orthogonal to the photon momentum $\mathbf{k}$ matters,
- photons $\gamma_\perp$ with linear polarization orthogonal to the plane defined by $\mathbf{k}$ and $\mathbf{B}$ do NOT mix with a, and so only photons $\gamma_{||}$ with linear polarization parallel to that plane DO mix with a.

Hence the term $g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$ act as a POLARIZER.

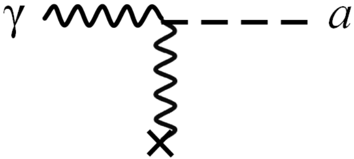
Specifically, for a beam initially LINEARLY polarized two effects occur.

- BIREFRINGENCE i. e. the linear polarization becomes ELLIPTICAL with its major axis PARALLEL to the initial polarization.



N.B. *a* VIRTUAL

- DICHROISM i. e. selective photon CONVERSION, which causes the ellipse's major axis to be MISALIGNED with respect to the initial polarization.



N. B. *a* REAL

We suppose that our monochromatic γ/a beam of energy $E < (10 - 100)\,\mathrm{GeV}$ – not to be confused with the electric field – propagates along the y direction from a far-away astronomical source reaching us.

In the approximation $E \gg m$ the beam propagation equation becomes a Schrödinger-like equation in y, hence the beam is FORMALLY described as a 3-LEVEL NON-RELATIVISTIC QUANTUM SYSTEM.

Consider now the simplest possible case where **B** is homogeneous. Taking the z-axis along **B**, we have

$$P_{\gamma \to a}(E; 0, y) = \left(\frac{g_{a\gamma}\, B}{\Delta_{\rm osc}} \right)^2 \sin^2 \left(\frac{\Delta_{\rm osc}\, y}{2} \right) \ , \qquad (3)$$

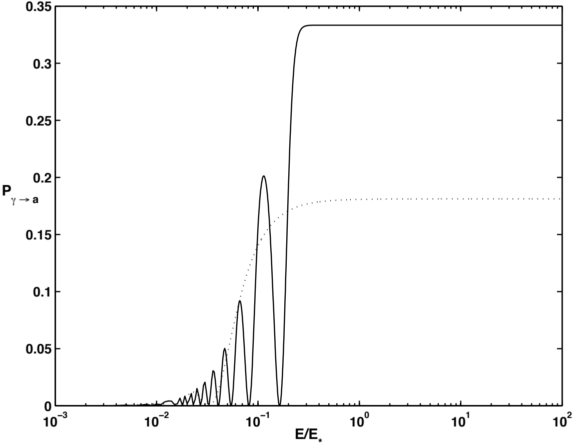
with

$$\Delta_{\rm osc} \equiv \left[\left(\frac{m^2 - \omega_{\rm pl}^2}{2E} \right)^2 + \left(g_{a\gamma} \, B \right)^2 \right]^{1/2} \quad , \tag{4}$$

where $\omega_{\rm pl}$ is the plasma frequency of the medium. As far as the extragalactic magnetic field $\mathbf{B}_{\rm ext}$ is concerned, we assume – as usual – that it has a domain-like structure, strongly motivated by galactic outflows: the domain size is dictated by the $\mathbf{B}_{\rm ext}$ coherence length, the strength is the same in all domains but the direction changes randomly from a domain to another. Specifically, it has been shown that typically $B_{\rm ext} \simeq (0.1 - 1) \, {\rm nG}$ over $L_{\rm dom} \simeq (1 - 10) \, {\rm Mpc}$. Defining next

$$E_* \equiv \frac{|m^2 - \omega_{\rm pl}^2|}{2 g_{a\gamma} \, B} \ . \tag{5}$$

It turns out that the behaviour of the $\gamma \to a$ conversion probability over a single domain as a function of E is



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where we have taken $g_{a\gamma} = 0.33 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$, $B_T = 0.5\,\mathrm{nG}$ and $N = 200$ magnetic domains.

Coming back to e-ASTROGAM – on top of the above oscillation behavior – we also have a slight dimming of the signal: because of energy conservation, the production of ALP implies a reduced photon flux. Actually, it can be shown that for $N \gg 1$ magnetic domains, the two photon polarization states an the single ALP state undergo equipartition, so that the signal becomes dimmer by a factor of 0.66. In conclusion, the two features showing up in the energy spectrum due to an ALP are an oscillatory behavior and a dimming of 0.66.

Yet, this is not the end of the story, because e-ASTROGAM can perform also polarimetric measurements, and we have seen that an initially linearly polarized beam becomes elliptically polarized with the ellipse's major axis misaligned: this fact provides additional information to discriminate an ALP from other possible effects. Very remarkably, we actually do *not need* to know the initial polarization by employing a simple trick. Because when one does not measure the polarization one has to sum over the two final photon polarizations – while when one does measure it no sum is performed – the signal has to be *twice as large* when the polarization is not measure as compared with the case in which the polarization is measured.

What is the ALP mass range of that can be probed by e-ASTROGAM? Previous considerations imply that the answer is given by $E \sim E_*$. Neglecting $\omega_{\rm pl}$ and Eq. (5), such a condition becomes

$$0.3\,\mathrm{MeV} < \frac{m^2}{2 g_{a\gamma}\, B} < 3\,\mathrm{GeV}\ . \tag{6}$$

Taking e.g. $g_{a\gamma} = 0.33 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$ and $B = 0.5\,\mathrm{nG}$ the answer is

$$0.78 \cdot 10^{-12}\,\mathrm{eV} < m < 0.78 \cdot 10^{-10}\,\mathrm{eV}\ . \tag{7}$$

Note that this result is independent of N.