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Reconciling the CAST and PVLAS Results

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The PVLAS experiment has recently claimed evidence for an axion-like particle in the milli-electron-Volt mass range with a coupling to two photons that appears to be in contradiction with the negative results of the CAST experiment searching for solar axions. The simple axion interpretation of these two experimental results is therefore untenable and it has posed a challenge for theory. We propose a possible way to reconcile these two results by postulating the existence of an ultralight pseudo-scalar particle interacting with two photons and a scalar boson and the existence of a low scale phase transition in the theory.

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I. INTRODUCTION

Two recent experiments, CAST[1] and PVLAS[2] searching for an ultralight axion-like pseudoscalar particle (denoted by a) with coupling of the form

$$\mathcal{L}_I = \frac{1}{4M_a} aF\tilde{F} \quad (1)$$

have given apparently contradictory results. The CAST[1] experiment looked for a-particles from the Sun produced in the reaction $\gamma + \gamma^* \to a$ where γ^* is the plasmon in the solar plasma and γ is a real photon. It found that in a wide mass range that includes the milli-electron-Volt (meV) mass , there was no signal for a giving an upper limit on its two photon coupling that implies $M_a \geq 10^{12}$ GeV. On the other hand in a laboratory experiment, known as PVLAS[2] a birefringence effect where the plane of polarization of a photon beam incident on a static magnetic field is rotated, was observed. A straightforward interpretation of this appears to be in terms of the production of a pseudo-scalar axion like particle with mass between 1.7-2 meV with the corresponding coupling scale in Eq. (1) $M_a \sim 2 \times 10^5$ GeV. In the context of simple axion models[3], there appears to be no way to reconcile these two results[4, 5] and several alternative mechanisms involving new particles have been suggested[6, 7, 8, 9, 10] to resolve this puzzle. This experimental observation has also stimulated a great deal of discussion on possible new properties and tests for such particles[11, 12], new ways to search for them[13] as well as their astrophysical implications[14].

It is the aim of this brief note to present a new model where the sub-GeV scale effective Lagrangian consists of two light scalars fields ϕ, σ and a light pseudoscalar a (a being the meV particle of interest) and a modified form for the a-photon (aFF) interaction. With this, we seem to be able to reconcile these two experimental results provided we assume the existence of a low temperature phase transition.

Recall that the main challenge of the axion like interpretation of the above experiments is to prevent the axion production in the Sun in $\gamma\gamma^*$ collision without affecting the same in the laboratory. Our basic idea is to avoid this problem by introducing an interaction of the form $\phi aF\tilde{F}/M^2$ rather than a direct $aF\tilde{F}$ interaction and assuming the field ϕ to have the following properties: (i) it has a non-zero vev, which is induced by a field σ such that $<\phi>\sim \kappa <\sigma>$ and $<\sigma>\sim$ keV where κ is a function of the parameters of the model which we will show later to be of order 10^5 giving $<\phi>\sim 0.1$ GeV; (ii) the field ϕ has a mass of order of 20-50 MeV. It then follows that in environments having temperature below a KeV as in the laboratory, we have the effective interaction $\frac{1}{M_a} aF\tilde{F}$ (since $<\sigma>\neq 0$ gives $<\phi>\neq 0$) with an effective coupling $\frac{1}{M_a} = \frac{<\phi>}{M^2}$ whereas in hot environments $T \gg$ KeV, as in the core of the Sun, we have $<\sigma>= 0$ giving $<\phi>= 0$. This implies that the effective interaction inside the Sun has the form $a\phi F\tilde{F}$ type only and not $aF\tilde{F}$. Since ϕ mass is far above the solar temperature, this avoids not only a production via the process $\gamma\gamma^* \to a$ but also the process $\gamma\gamma^* \to a\phi$. As we will see below, if $M^2 \sim 10^5$ GeV and $m_\phi \sim 20-50$ MeV, the model is consistent with cosmological, astrophysical as well as laboratory observations, providing a viable way to reconcile the PVLAS and CAST observations. We also advance a preliminary speculation on the possible origin of the effective interaction in terms of new physics.

II. THE SCENARIO AND AN EFFECTIVE LAGRANGIAN

Our model consists of the neutral spin zero fields, three real scalars ϕ and σ, S and one real pseudo-scalar a, which are singlets under the SM gauge group and have the effective interaction Lagrangian below GeV scale given by

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{kin} + \frac{1}{4M^2}\phi aF\tilde{F} + \lambda_1 \phi\sigma S^2 + \lambda_2 \sigma S \phi^2 \quad (2)\\ -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{2}m_a^2 a^2 + \frac{1}{2}M_S^2 S^2 - \lambda_S S^4\\ +\frac{1}{2}m_\sigma^2\sigma^2 - \lambda_\sigma\sigma^4.\end{aligned}$$

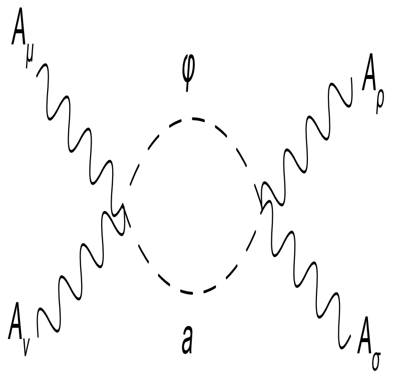

FIG. 1: Diagram for photon-photon scattering

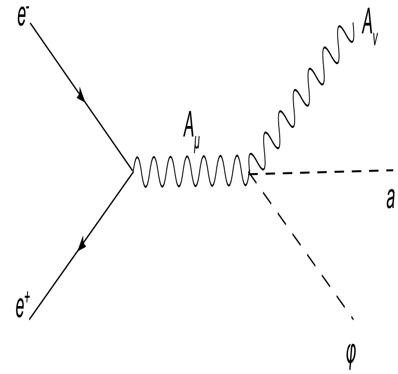

FIG. 2: The annihilation process $e^+e^- \to \gamma + a + \phi$

We have displayed only those terms in the Lagrangian which are relevant to our discussion and omitted others. We assume all parameters to be positive and couplings to be of order one and take as a working example, the masses $M \sim 10^{2.5}$ GeV, $m_\phi \sim 30$ MeV, $M_S \sim 10^3$ GeV, $m_a \sim$ meV and $m_\sigma \sim$ keV. At zero temperature, this Lagrangian has the property that $< S > \equiv v_S \sim M_S \sim 10^3$ GeV and $< \sigma > \equiv v_\sigma \sim$ keV. We see from the Lagrangian that when $< \sigma > \neq 0$ it induces a vev of ϕ of order

$$< \phi > \equiv v_\phi \sim \frac{\lambda_1 v_\sigma v_S^2}{m_\phi^2 + \lambda_2 v_\sigma v_S}, \tag{3}$$

We assume that $\lambda_1 \sim \frac{v_\phi}{v_S} \sim 10^{-3}$ and $\lambda_2 \sim 1$. We find that for $m_\phi^2 \sim \lambda_2 v_\sigma v_S \sim (0.03 GeV)^2$, $v_\phi \sim 0.5$ GeV. When the system is in an environment where $T \gg < \sigma >$, we have phase transition which gives $< \sigma >= 0$ and hence $< \phi >= 0$.

In this framework, we can easily see how to reconcile the PVLAS and CAST results. In the laboratory, $T \sim 0$ and we have $v_\phi \sim 0.5$ GeV giving $\frac{1}{4M_a} aF\tilde{F}$ coupling with $M_a \sim 2 \times 10^5$ GeV which explains the PVLAS result. When temperature of an environment $T \gg$ KeV as in the core of the Sun, there is phase transition in the σ field and we get $< \sigma > \equiv v_\sigma = 0$. This in turn implies that $< \phi > \equiv v_\phi = 0$. Thus in the Sun, $v_\phi = 0$ (since $v_\sigma = 0$) and as a result there is no direct axion-two-photon interaction. There is of course $\phi a FF$ interaction; but since $m_\phi \sim 30$ MeV or so, $FFa\phi$ interaction can produce the $a\phi$ final state only from the "tail" of the thermodynamic distribution of the photons. The cross section is then proportional to $\frac{T^2}{M^4} e^{-\frac{m_\phi}{T_\odot}} \leq 10^{-10^3}$ GeV^{-2} which is negligible and obviously well below the present CAST bound for the a production rate. This provides a reconciliation between the CAST and PVLAS results.

III. OTHER IMPLICATIONS

Before considering the phenomenological implications of this effective Lagrangian model, let us make sure that the theory after symmetry breaking is consistent i.e. all scalar fields have positive m^2. To check this, let us write down the scalar field mass matrix for the ϕ, σ, S system in the basis (ϕ, σ, S) after shifting the fields by their vevs.

$$\mathcal{M}^2 = \begin{pmatrix} m_\phi^2 & \lambda_1 v_s^2 + \lambda_2 v_s v_\phi & \lambda_1 v_\sigma v_s + \lambda_2 v_\sigma v_\phi \\ \lambda_1 v_s^2 + \lambda_2 v_s v_\phi & m_\sigma'^2 & \lambda_1 v_S v_\phi + \lambda_2 v_\phi^2 \\ \lambda_1 v_\sigma v_s + \lambda_2 v_\sigma v_\phi & \lambda_1 v_S v_\phi + \lambda_2 v_\phi^2 & M_S'^2 \end{pmatrix} \tag{4}$$

We assume that there is a fine tuning between the two entries in the $\phi - \sigma$ element of the mass matrix in such a way that the eigenvalues of this mass matrix are positive. For this to happen, we must assume that $\frac{\lambda_1}{\lambda_2} \sim \frac{v_\phi}{v_s} \sim 10^{-3}$. This is the same assumption for the parameters that we used earlier.

We now make add few comments on the phenomenology of this model:

(i) First point to note is that our interaction leads to light by light scattering $\gamma\gamma \to \gamma\gamma$ with a strength $A_{\gamma\gamma\to\gamma\gamma} \sim \frac{1}{M^4}$ arising from a one loop diagram involving the $\phi - a$ intermediate state in the loop (see Fig. 1). This is much smaller than the electron contribution to this process which goes like $A_{\gamma\gamma\to\gamma\gamma} \sim \frac{\alpha^2}{m_e^4}$ by a factor $\alpha^{-2}(m_e/M)^4 \sim 10^{-18}$. The contribution of this to $(g-2)$ of muon and electrons depends on the ultraviolet behavior of the theory. If we assume that above a 100 GeV, the theory is strongly damped by form factors giving effectively $M \sim 100$ GeV as the cutoff then its contribution to $g-2$ of muons and electrons is safely consistent with the present experiments.

(ii) In the presence of this interaction, there will be new contribution to e^+e^- annihilation of type $e^+e^- \to \gamma\phi a$ as displayed in figure 2. Since ϕ has a decay width of approximately $\Gamma_\phi \sim \frac{m_\phi^5}{\pi^3 M^4} \sim 10^{-14}$ GeV (or lifetime of about 10^{-10} sec.), it will decay within a detector to 2 photons plus an a particle. Thus the signal will look like $e^+e^- \to 3\gamma + 2a$. For $m_\phi < GeV$,the cross section for this process is

$$\sigma(e^+e^- \to \gamma + a + \phi) \simeq \frac{\alpha}{(4\pi)^2} \frac{E^2}{M^4} \tag{5}$$

which for $E \sim 100$ GeV is of order 10^{-2} pico barns which is smaller than the predicted standard model background process $e^+e^- \to \nu\overline{\nu} + 3\gamma$ by one order of magnitude [16].

(iii)The new interaction could also lead to the quarkonium (such as J/ψ, Υ) decay

$$\mathcal{Q} \to \gamma + a + \phi \tag{6}$$

since we have $m_\phi < m_{\mathcal{Q}}$. In our model, the branching ratio for the radiative decay of $\Upsilon(1S)$ into axion and ϕ is

$$Br(\Upsilon(1S) \to \gamma + a + \phi) \simeq 2.1.10^{-7}(\frac{100\ GeV}{M})^4 \tag{7}$$

This is about two order of magnitude below the experimental limit $Br(\Upsilon(1S) \to \gamma + \ invisible) < 3.10^{-5}$ and is safely consistent with our assumptions.

(iv) Second point to note is that this four particle interaction also does not lead to new channels for rapid energy loss from the supernova. This is because the $\gamma\gamma \to a\phi$ scattering has a strength of order 10^{-5} GeV^{-2} which is of the same order as the Fermi constant G_F. As a result, the a and the ϕ particles produced in the $\gamma\gamma$ collision will get trapped in the supernova core and will therefore contribute to the energy loss from supernova by approximately the same amount as a single neutrino species. This possibility is not ruled out by the SN1987A observations, which has considerable uncertainty as to how much total energy is emitted in neutrinos compared to the total energy generated in supernova core collapse.

(v) To see if this new interaction affects considerations of big bang nucleosynthesis, we note that above $T \sim$ GeV in the early universe, the ϕ and a were in thermal equilibrium with the rest of the primordial plasma. As the universe cools below $T \simeq m_\phi$, the ϕ particle decays since its decay rate is bigger than the Hubble expansion rate at $T \simeq m_\phi$. Thus at the BBN epoch, in addition to the standard model particles the only two new particles in equilibrium are a and σ. Together they contribute $\delta N_\nu \simeq \frac{8}{7}$. This appears to be consistent with latest BBN results[17].

(vi) Finally, we advance a preliminary speculation on the possible origin of the higher dimensional $a\phi F\tilde{F}$ interaction. Consider extending the standard model by adding a vector like pair of fermions $\psi_{L,R}$ which are leptonic and have electric charge ± 1 (or equivalently $Y = \pm 2$ and $M_\psi \geq 100$ GeV. Let there be a neutral pseudo-scalar particle A with mass $M_A \sim$ few GeV with an interaction of the form

$$\mathcal{L}_I \ = \ fA\bar{\psi}\gamma_5\psi + M_0 A a\phi \ + \ h.c \tag{8}$$

In this model the familiar triangle diagram will induce an effective $AF\tilde{F}$ interaction with approximate strength $\frac{\alpha}{4\pi M_\psi}$. The tree level exchange of A will then generate an effective Lagrangian below the GeV scale of the form we have been discussing. The parameters of the theory can be so chosen as to give $M_a \sim 10^5$ GeV (e.g $M_0 \sim$ GeV). This would provide a renormalizable version of our model. Of course one could perhaps interpret A as an axion corresponding to a different strongly interacting theory (technicolor ?). Further discussion of this model as well as its detailed implications is postponed to a future publication.

In conclusion, we have presented an effective Lagrangian below the GeV scale which seems to be able to reconcile the CAST and the PVLAS experiments in a way that is different from other existing explanations. We find the model to be compatible with all laboratory, astrophysical as well as cosmological observations. We also advance a preliminary speculation on a possible origin of this effective Lagrangian. Detailed phenomenological and astrophysical implications of this model are currently under investigation.

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