

Constraints on very light axions from cavity experiments

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(Received 24 November 1997; published 22 July 1998)

In view of the ongoing galactic (or cosmic) axion detection experiments, we compare the axion-photon-photon coupling $c_{a\gamma\gamma}$'s for various invisible (or very light) axion models. [S0556-2821(98)01215-6]

PACS number(s): 14.80.Mz, 12.60.Fr, 95.35+d

The $\bar{\theta}$ parameter of the standard model is naturally understood in axion models [1]. This axion interpretation has led to the very light (or invisible) axion's role in galaxy formation [2]. If the seed of our galaxy is indeed the density perturbations due to invisible axions, cold dark matter might be these cold axions with ~ 0.3 GeV/cm³ energy density in our galaxy, which for an $f\mu$ eV axion mass corresponds to $\sim 3 \times 10^{14}/f$ axions per cm³ around us.

These ubiquitous axions can be detected using a cavity immersed in a strong magnetic field [3]. Two groups have already reported on this type of experiment [4,5]. In addition, the ¹³⁹La $M1$ transition has been studied to get a clue to these galactic axions [6]. These previous experiments have given the upper bound on the detection rate, but have not reached the level of detecting the galactic axions (or cosmic axions).

Currently, there are two ongoing experiments: the Kyoto University experiment on Rydberg atoms [7] and the Lawrence Livermore National Laboratory (LLNL) experiment [8]. In particular, the sensitivity of the LLNL experiment is at the level of distinguishing several invisible axion models. So far, the theoretical invisible axion models compared with data are not given with proper distinction. Thus it is very important at this stage to clarify the prediction of the axion-photon-photon coupling constant $c_{a\gamma\gamma}$ in various invisible (very light) axion models.

It is known that the free energy V is minimum at $\bar{\theta}=0$ in a world without weak CP violation [9]. If $\bar{\theta} \neq 0$, the QCD term

$$\frac{\bar{\theta}}{32\pi^2} F_{\mu\nu}^a \tilde{F}^{a\mu\nu} \quad (1)$$

violates P and CP symmetry, implying $|\bar{\theta}| < 10^{-9}$ from the neutron electric dipole moment bound. This can be understood if we let $\bar{\theta}$ be a dynamical variable, i.e.,

$$\bar{\theta} = \frac{a}{F_a}, \quad (2)$$

where a is a pseudoscalar field called axion and F_a is the axion decay constant. Models with $F_a \gg 250$ GeV give the so-called *invisible axions*, but in view of the possible detec-

tion of the galactic axions, it is better for them to be called *very light axions*. These axions settle $\bar{\theta}$ at ~ 0 in an evolving universe even if one starts from any initial value of $\bar{\theta}$, due to the potential of a . But introduction of weak CP violation shifts the minimum position of $\bar{\theta}$ slightly [10] to $\sim 10^{-17}$ which is far below 10^{-9} .

The invisible axions come in three broad categories, depending on how a arises: (i) pseudo-Goldstone boson [11,12], (ii) fundamental field in string theory [13], and (iii) composite axions [14]. Among these, we will concentrate on the first category, the so-called Kim-Shifman-Vainshtein-Zakharov (KSVZ) and Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) models.

The calculation of the axion-photon-photon coupling is performed in two stage, above the chiral symmetry breaking scale and below the chiral symmetry breaking scale, so that the coupling is written in the form [15]

$$c_{a\gamma\gamma} = \bar{c}_{a\gamma\gamma} - \frac{24+Z}{3(1+Z)}, \quad (3)$$

where $Z = m_u/m_d$. In any model, the chiral symmetry breaking correction is given as the second term of Eq. (3). The first term of Eq. (3) is given in terms of the Peccei-Quinn charges of fermions

$$\bar{c}_{a\gamma\gamma} = \frac{E}{C}, \quad E = \text{Tr} Q_{PQ} Q_{em}^2, \quad C \delta_{ab} = \text{Tr} \lambda_a \lambda_b Q_{PQ}, \quad (4)$$

where Q_{em} is the electric charge operator and $\text{Tr} \lambda_a \lambda_b = \frac{1}{2} \delta_{ab}$ for the triplet representation of $SU(3)_c$. The invisible axion resides mostly in the phase(s) of a complex standard model singlet field(s) σ ,

TABLE I. $c_{a\gamma\gamma}$ for several KSVZ and DFSZ models.

KSVZ		DFSZ	
e_R	$c_{a\gamma\gamma}$	x (unif)	$c_{a\gamma\gamma}$
$e_R = 0$	-1.92	any (d^c, e)	0.75
$e_3 = -1/3$	-1.25	1 (u^c, e)	-2.17
$e_3 = 2/3$	0.75	1.5 (u^c, e)	-2.56
$e_3 = 1$	4.08	60 (u^c, e)	-3.17
$e_8 = 1$	0.75	1 (non)	-0.25
(m, m)	-0.25	1.5 (non)	-0.64
(1,2)	-0.59	60 (non)	-1.25

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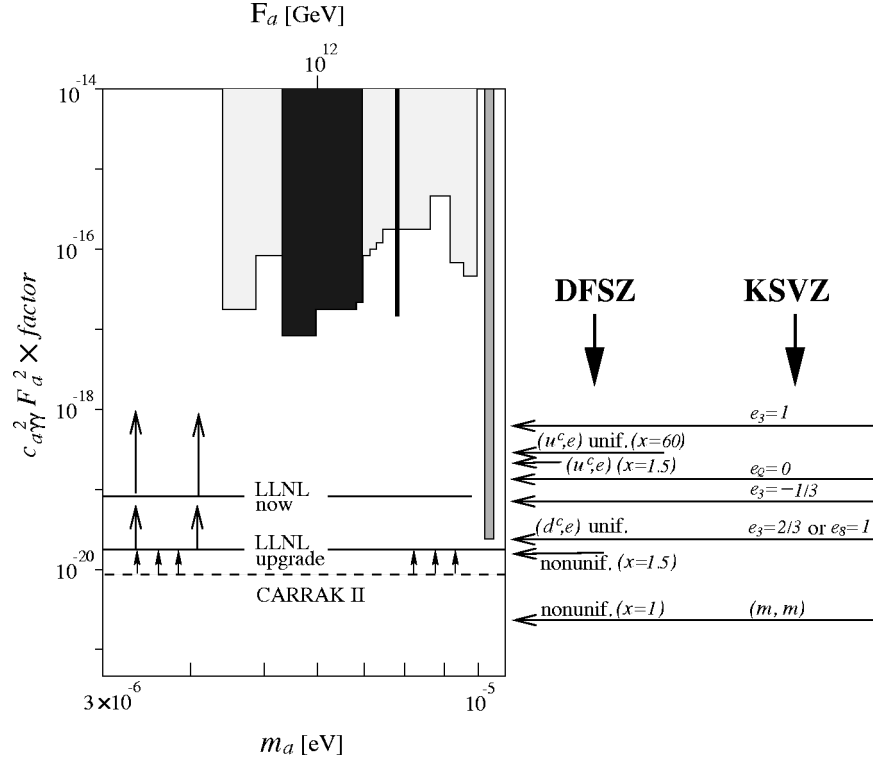


FIG. 1. Comparison of several $c_{a\gamma\gamma}$'s with high- q cavity experiments. The grey region is excluded from Rochester-Brookhaven-Fermilab experiment and the black region is excluded from the University of Florida experiment. The present and future sensitivities of LLNL experiments are also shown. The long column around $m_a \sim 1.0067 \times 10^{-5}$ eV is the one excluded from the CARRAK I experiment [24]. The sensitivity of CARRAK II is also shown.

$$\sigma = \frac{v + \rho}{\sqrt{2}} e^{ia/F_a}, \quad (5)$$

where v is the vacuum expectation value (VEV) of σ . How σ couples to quark fields distinguishes different invisible axion models. The KSVZ axion couples as

$$\mathcal{L} = f \bar{Q}_L Q_R \sigma + \text{H.c.}, \quad (6)$$

where Q is a heavy quark, while the DFSZ axion couples as

$$\mathcal{L} = \lambda \sigma H_1 H_2 + \sum_{ij} (f_d^{ij} \bar{q}_L^i d_R^j H_1 + f_u^{ij} \bar{q}_L^i u_R^j H_2) + \text{H.c.}, \quad (7)$$

where H_1 and H_2 are the two Higgs doublets of the standard model. These models have $U(1)_{\text{PQ}}$ symmetry. The corresponding PQ current for the KSVZ axion is

$$J_\mu^{\text{KSVZ}} = v \partial_\mu a - \frac{1}{2} \bar{Q} \gamma_\mu \gamma_5 Q \quad (8)$$

while the current for the DFSZ axion is

$$J_\mu^{\text{DFSZ}} \simeq v \partial_\mu a + \frac{x^{-1}}{x + x^{-1}} \sum_i \bar{u}^i \gamma_\mu \gamma_5 u^i + \frac{x}{x + x^{-1}} \times \sum_i \bar{d}^i \gamma_\mu \gamma_5 d^i + (\text{leptonic terms}), \quad (9)$$

where $x = \langle H_2^0 \rangle / \langle H_1^0 \rangle = \tan \beta$. In the DFSZ model, we neglected the small contribution from two Higgs doublets. The Q_{PQ} is calculated from these currents. We simplified the models by introducing only one σ . In the original KSVZ model, we introduced only one heavy quark for simplicity. In the DFSZ model, there is leptonic contribution in general. If VEV of H_1 (H_2) gives masses to charged leptons, the coefficient of the leptonic current is the same as that of $Q_{em} = -1/3$ ($2/3$) quark. On the other hand, if a third Higgs doublet is used to give masses to charged leptons, the leptonic terms vanish.

In Table I, various values of $c_{a\gamma\gamma}$ are presented for the KSVZ and DFSZ models. $Z \approx 0.6$ is used. e_R means the electromagnetic charge of the heavy quark color representation R in units of the positron charge. In the KSVZ model, a model with m heavy quarks of $e_3 = 2/3$ and n heavy quarks of $e_3 = -1/3$ is represented as an (m, n) model. The (m, m) model with any value for m gives the same result. The $(1, 2)$ model is also shown. In the DFSZ model, (d^c, e) unification corresponds to the case where H_1 gives mass to the electron, (u^c, e) to the case where H_2 does, and nonunification to the

case of a third Higgs doublet. An example of the (d^c, e) unification is the familiar SU(5) unification [16], and an example of (u^c, e) unification is the flipped SU(5) [17]. The third case is denoted as nonunification. Nonunification superstring models obtained considerable attention because they have no need for a grand unified theory (GUT) symmetry breaking mechanism [18]. But these nonunification superstring models can contain (d^c, e) and (u^c, e) models, depending on how the Higgs doublets couple. Note that $c_{a\gamma\gamma}$ is very sensitive to the electromagnetic charge of the heavy quark in the KSVZ model and to the ratio of VEV's of the Higgs doublets in the DFSZ model. Therefore, one can distinguish different models.

In Fig. 1, we compare the model predictions with the existing data [4,5] and the present and future sensitivities of LLNL experiment [8]. The experimental data are presented with the axion number density given by Turner [19]. In the standard big bang cosmology, the axionic string and domain walls attached to it do not give the observed cosmological parameters if the domain wall number (N_{DW}) is not 1 [20]. In this case, the DFSZ model with $N_{\text{DW}}=6$ is not cosmologically viable. Even for $N_{\text{DW}}=1$ models, the string-wall system radiate axions in the evolving universe. The recent estimate gives a stronger bound on F_a , $F_a \leq 4 \times 10^{10}$ GeV [21] than the bound coming from cold axion density [2]. (Note, however, that Harari and Sikivie [22] give roughly the same bound as the one from cold axion density.) In the inflationary cosmology, this domain wall restriction is not applicable if the reheating temperature T_{RH} after inflation is below the axion decay constant F_a . In supergravity, if the gravitino mass is around the electroweak scale, the constraint coming from the disruption of nucleosynthesis from the decay products of regenerated gravitino restricts $T_{\text{RH}} < 10^{9-10}$ GeV [23]. In any case, we may need an inflation with a low reheating temperature. Then the energy density from cold axions is the dominant one. The vertical axis of Fig. 1 is $\propto c_{a\gamma\gamma}^2 \times F_a^2$. It is obvious from the figure that some models will soon confront serious experimental data. If the very light axion is not detected with the present sensitivity of LLNL, for example, the DFSZ model with (u^c, e) unification and the KSVZ model with $e_3=1$ and $e_Q=0$ are ruled out.

Before closing, we recapitulate the viability of the superstring axion as the solution of the strong CP problem. If invisible axion is discovered, it cannot pinpoint which model is correct as is obvious from Fig. 1. We regard this unpre-

dictability as a consequence of an *ad hoc* introduction of Peccei-Quinn (PQ) symmetry. Most probably, many heavy quarks carrying nonvanishing PQ charges would exist, and the light quarks may also carry PQ charges. If a fundamental theory exists, it should predict in that framework the invisible axion. In this regard, the discovery of the superstring model-independent axion (MIa) is of the most fundamental importance [13]. However, the MIa decay constant is several orders larger than the cosmological upper bound [25]. In string models, it is known that there is no global symmetry except the one related to a constant shift of the model-independent axion field [26], $a_{\text{MI}} \rightarrow a_{\text{MI}} + (\text{const})$. In other words, there is a nonlinearly realized Peccei-Quinn symmetry in string models. We have to lower the axion decay constant to $\sim 10^{12}$ GeV, not to violate the cosmological energy density bound. This lowering can be achieved [27] in four-dimensional string models with an anomalous U(1) gauge symmetry [28]. This is because the anomalous U(1) gauge boson eats up the MIa as its longitudinal degree of freedom [27] through the Green-Schwarz term [29], and leaves a global symmetry below this gauge boson mass scale. Then, this global symmetry can be broken at the intermediate scale $\sim 10^{12}$ GeV for example by a VEV(s) of the PQ charge carrying singlet scalar field. This leads to the very light (invisible) axion we discussed above. In general, this kind of model gives the contribution to $c_{a\gamma\gamma}$ both from the heavy quark sector and from the standard model quarks. If a *standard* superstring model is known, then one can calculate a unique value for $c_{a\gamma\gamma}$. At this moment, we do not have a standard superstring model but can only point out that superstring models with anomalous U(1) have room for the invisible axion which is on the verge of confronting data.

In conclusion, in view of the progress of axion detection experiments, one will soon be able to distinguish several toy models for the invisible axion. If detected, it would open a new road toward a fundamental theory, presumably in superstring models.

Note added: After submission, we found that the LLNL group actually excludes the left-hand side tip of the sensitivity region (LLNL now) up to $m_a = 3.31 \times 10^{-6}$ eV [30].

This work is supported in part by the Distinguished Scholar Exchange Program of the Korea Research Foundation and NSF-PHY 92-18167. One of us (J.E.K.) was also supported in part by the Hoam Foundation.

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