Axions and Axion-like Particles

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Abstract
I review the theoretical motivation for the axion and present an update of the experimental status of axion searches. I finally comment on some aspects of the physics of axion-like particles.

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I. INTRODUCTION: THE STRONG CP PROBLEM

Consider the QCD Lagrangian

\[ L_{QCD} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \bar{q}(i\gamma^\mu \partial_\mu - M)q + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \ldots \]  

(1)

The last term, the so-called \( \theta \)-term, contains the dual of the gluon field

\[ \tilde{G}_{\mu\nu}^a = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} G^{a\rho\sigma} \]  

(2)

The \( \theta \)-term is Lorentz invariant and gauge invariant so that it should be present in \( L_{QCD} \), but since it is proportional to \( \vec{E} \cdot \vec{B} \) (color fields) is CP-violating.

The quark fields,

\[ q = \begin{pmatrix} u \\ d \end{pmatrix} \]  

(3)

and the quark mass matrix

\[ M = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} \]  

(4)

play an important role in the discussion of the \( \theta \)-term. Let us perform a \( U(1)_A \) rotation on a quark field, say the up quark,

\[ u \rightarrow e^{i\alpha_5} u \]  

(5)

The rotation is indeed chiral since left-handed and right-handed fields transform in a different way: \( u_L \rightarrow e^{-i\alpha} u_L, u_R \rightarrow e^{i\alpha} u_R \). Under such \( U(1)_A \) rotation, the up quark mass term is not invariant

\[ -m_u \bar{u}_Lu_R + \text{h.c.} \rightarrow -m_u e^{2i\alpha} \bar{u}_Lu_R + \text{h.c.} \]  

(6)

The conclusion is that if \( m_u \neq 0 \), \( U(1)_A \) in (5) is not a symmetry.

Naively, we could think that if \( m_u = 0 \) we would recover this axial symmetry. But this is not true. The Noether current associated to the transformation (5), \( j_5^\mu \),

\[ \delta L \sim \partial^\mu (\bar{u} \gamma_\mu \gamma_5 u) = \partial^\mu j_5^\mu \]  

(7)

is anomalous

\[ \partial^\mu j_5^\mu = \frac{\alpha_s}{4\pi} G \cdot \tilde{G} \neq 0 \]  

(8)
The $U(1)_A$ symmetry is broken by quantum effects (Adler-Bell-Jackiw anomaly). Even in a world with massless quarks, a $U(1)_A$ rotation has an effect in the $\theta$-term of the QCD Lagrangian

$$\mathcal{L}_{CP}(\theta) \equiv \frac{\alpha_s}{8\pi} G \cdot \tilde{G} \to \mathcal{L}_{CP}(\theta - 2\alpha)$$

When indeed we have at least one massless quark, we can set $\alpha = \theta/2$ and the $\theta$-term would be rotated away. But it seems that $m_u \neq 0$ in the real world so $\mathcal{L}_{CP}$ is present in the theory.

There might be still another possibility for not having $\mathcal{L}_{CP}$: since $\theta$ is a free parameter perhaps we could put $\theta = 0$ and forget about the $\theta$-term. However, one then has to face at least two problems: 1) the presence of the $\theta$-term is necessary to solve the $U(1)_A$ problem (Why $\eta'$ is not a NG boson?), and 2) there are in fact additional contributions to $\mathcal{L}_{CP}$ from the electroweak sector. Masses generated by the electroweak spontaneous symmetry breaking are complex in general,

$$\mathcal{L}_{\text{mass}} = -|m_u| e^{i\varphi} \bar{u}_L u_R + \text{h.c.} + \ldots$$

(the dots stand for the other quark mass terms). To have $\mathcal{L}$ with real masses, we can use chiral rotations of the type

$$u_L \to e^{i\varphi/2} u_L \quad u_R \to e^{-i\varphi/2} u_R$$

so that

$$\mathcal{L}_{\text{mass}} = -|m_u| \bar{u}_L u_R + \text{h.c.} + \ldots + \frac{\alpha_s}{8\pi} G \cdot \tilde{G}$$

Here, we have used (9) So, apart from the pure QCD $\theta$ parameter, that we may call $\theta_{QCD}$, there are additional contributions to the $\theta$-term, implying that physics depends on

$$\bar{\theta} = \theta_{QCD} + \text{Arg Det } M$$

The problem 2) is that even if we set $\theta_{QCD} = 0$, in general we end up with $\bar{\theta} \neq 0$.

The most important observational consequence of $\mathcal{L}_{CP}$ is that it originates a neutron electric dipole moment,

$$d_n \sim \frac{e}{m_n} |\bar{\theta}| \frac{m_u m_d}{m_u + m_d} \frac{1}{\Lambda_{QCD}}$$
Experimentally we have a tight bound for this observable,

\[ d_n < 0.63 \times 10^{-25} \text{ e cm} \] (15)

so that we have the stringent bound

\[ \theta < 10^{-9} \] (16)

This is the so-called strong CP-problem: Why is \( \theta \) so small? We would have expected \( \theta_{QCD} \) and \( \text{Arg Det } M \) not far from \( O(1) \), and we have no reason to expect such fine-tuned cancellation between the two terms \( \theta_{QCD} \) and \( \text{Arg Det } M \), since they have totally unrelated origins.

II. THE AXION AND ITS PROPERTIES

The Peccei-Quinn (PQ) solution \([1]\) to the strong CP problem introduces a new global chiral symmetry \( U(1)_{PQ} \) and uses the freedom to rotate \( \theta \) away. The spontaneous symmetry breaking of \( U(1)_{PQ} \) at energy \( \sim f_a \) generates a NG boson: the axion, \( a \sim f_a \theta \) \([2]\). We should keep in mind however that the PQ solution to the strong CP-problem is not the unique solution (see \([3]\) for a review).

The axion, as all NG bosons, couples derivatively to matter

\[ \mathcal{L}_{a\Psi\Psi} = \sum_i c_i \frac{1}{2f_a} (\bar{\Psi}_i \gamma^\mu \gamma_5 \Psi_i)(\partial_\mu a) \] (17)

Here \( i = e, p, n \), etc, are the matter fields and \( c_i = O(1) \) are model dependent parameters. The axion is special since it has to reproduce the anomaly and there is a non-derivative term that couples the axion to two gluons,

\[ \mathcal{L}_{agg} = \frac{1}{f_a} \frac{\alpha_s}{8\pi} G \cdot \tilde{G} \cdot a \] (18)

At low \( (\Lambda_{QCD}) \) energies, the \( gga \) term generates the potential \( V(\theta) \) that makes \( \theta \to 0 \) and also generates the axion mass

\[ m_a = \frac{f_\pi m_\pi}{m_u + m_d} \sqrt{m_u m_d} = 0.6 \text{ eV} \frac{10^7 \text{ GeV}}{f_a} \] (19)

Due to these last properties the axion is not exactly a NG boson (which is exactly massless and has only derivative couplings). Notice that the axion mass is very small if the scale \( f_a \) is very large.
The axion has also a coupling to two photons:

\[ \mathcal{L}_{a\gamma\gamma} = c_\gamma \frac{\alpha}{\pi f_a} F \cdot \tilde{F} a = -g_{a\gamma\gamma} \tilde{E} \tilde{B} a \]  

(20)

Such a coupling is important from the point of view of a possible detection.

Let us stress that all \( c_i \) are mildly model dependent except for the electron \( c_e \) parameter. Indeed, there are models with \( c_e = 0 \), i.e., the axion is not coupled to \( e \) at tree level (KSVZ type or “hadronic axion”) \([4]\). However, most models have \( c_e \neq 0 \), for example in GUT-embedded models like the DFSZ type \([5]\).

Let us check, as a way of example, that the \( a\gamma\gamma \) coupling is not wildly model dependent. For the DFSZ-type axion we have \( c_\gamma = 0.36 \) and for the KSVZ-type we have \( c_\gamma = -0.97 \).

### III. LIMITS TO AXION PARAMETERS

One finds constraints on the axion properties using laboratory experiments and astrophysical and cosmological observations. A nice feature of the axion model is that \( f_a \) and \( m_a \) are related \([19]\), so that there is only one parameter in the model. Notice that from \((19)\) we see that the lighter the axion is, the less interacts.

There are several high energy laboratory experiments relevant for our discussion, like meson decays

\[ J/\Psi \rightarrow \gamma a \]  
\[ \Upsilon \rightarrow \gamma a \]  
\[ K^+ \rightarrow \pi^+ a \]  
\[ \pi^+ \rightarrow e^+ \nu_e a, \quad a \rightarrow e^+ e^- \]

(21) \hspace{1cm} (22) \hspace{1cm} (23) \hspace{1cm} (24)

beam dump experiments,

\[ p(e^-)N \rightarrow aX \quad a \rightarrow \gamma\gamma, e^+ e^- \]  

(25)

and nuclear deexcitation processes,

\[ N^* \rightarrow Na \quad a \rightarrow \gamma\gamma, e^+ e^- \]  

(26)

(whenever we consider \( a \rightarrow e^+ e^- \) we obviously suppose \( m_a > 2m_e \)).

The conclusion, when taking into account all these processes, is that

\[ f_a > 10^4 \text{ GeV} \]  

(27)

5
or, equivalently,

\[ m_a < 1 \text{ keV} \quad (28) \]

This excludes that \( f_a \) could be on the order of the Fermi scale, which was the original suggestion of Peccei and Quinn [1].

Astrophysical limits push very much the terrestrial limits. The idea is that a “too” efficient energy drain due to axion emission would be inconsistent with observation. The most stringent limits come from horizontal branch stars in globular clusters. The main production is from the Primakoff process \( \gamma \gamma^* \rightarrow a \) where \( \gamma^* \) corresponds to the electromagnetic field induced by protons and electrons in the star plasma. The coupling is restricted to \( 6 \times 10^{-10} \text{ GeV} \Rightarrow f_a > 10^7 \text{ GeV} \) \( (29) \)

In terms of axion mass, the interval

\[ 0.4 \text{ eV} < m_a < 200 \text{ keV} \quad (30) \]

is ruled out (for \( m_a > 200 \text{ keV} \) the axion is too heavy to be produced).

When \( c_e \sim 1 \) (for example, for the DSVZ axion), the main production is from the Compton-like process \( \gamma e \rightarrow ae \). The stellar energy loss argument leads then to a limit on the axion-electron coupling

\[ g_{aee} \equiv c_e \frac{m_a}{f_a} < 2.5 \times 10^{-13} \quad (31) \]

which enlarges the forbidden region:

\[ 0.01 \text{ eV} < m_a < 200 \text{ keV} \quad (32) \]

The most restrictive astrophysical limits come from the analysis of neutrinos from SN 1987A. In the supernova core, the main production is axion bremsstrahlung in nucleon-nucleon processes, \( NN \rightarrow NN_a \).

The observed duration of the \( \nu \) signal at Earth detectors constrains the coupling of the axion to nucleons. The range

\[ 3 \times 10^{-10} < g_{ann} \equiv c_n \frac{m_n}{f_a} < 3 \times 10^{-7} \quad (33) \]

is excluded [4]. The upper limit in [33] corresponds to axion trapping in the SN. The lower limit in [33] is equivalent to \( f_a > 6 \times 10^8 \text{ GeV} \). In terms of the axion mass, the excluded
range corresponding to (33) is
\[
0.01 \text{eV} < m_a < 10 \text{eV}
\] (34)

Other constraints from astrophysics include the ones coming from seismic solar models \[8\], that reach the level
\[
g_{a\gamma\gamma} < 4 \times 10^{-10} \text{GeV}^{-1}
\] (35)

Also, white dwarfs and asymptotic giant branch stars offer a sound astroparticle laboratories where one can get bounds on the coupling of axions to electrons (see ref.\[9\] and the the talk of Isern in these Proceedings).

Putting all the information coming from laboratory and astrophysics together we may conclude that the scale of the PQ breaking is bounded by
\[
f_a > 6 \times 10^8 \text{GeV}
\] (36)

We finally consider cosmology, that puts lower limits to \(m_a\). In the evolution of the universe, the cosmological history of the axion starts at temperatures \(T \sim f_a\), where \(U(1)_{PQ}\) is broken. All vacuum expectation values \(<a>\) are equally likely, but naturally we expect \(<a>\) of the order of the PQ scale, or in other words an initial angle: \(\bar{\theta}_1 \sim <a>/f_a \sim 1\).

The next important moment in the axion history is at \(T \sim 1 \text{GeV}\), since then QCD effects turn on and create a potential \(V(\theta)\) that forces \(\bar{\theta} \rightarrow 0\) (CP-conserving value).

One says that the \(\theta\) angle was “misaligned”: it started with \(\bar{\theta} = \bar{\theta}_1 \sim 1\) and will relax to \(\bar{\theta} \rightarrow 0\). In the relaxation, the field oscillations contribute to the cosmic energy density \[10\]
\[
\Omega h^2 \simeq 2 \times 10^{\pm 0.4} F(\bar{\theta}_1)\bar{\theta}_1^2 \left(\frac{10^{-6} \text{eV}}{m_a}\right)^{1.18}
\] (37)

\((F\) takes into account an-harmonic effects).

This is the so-called vacuum misalignment mechanism, a process where axions are born non-thermally and non-relativistically. A potentially interesting range for cosmology is
\[
\Omega h^2 \sim 1 - 0.1 \Rightarrow m_a \sim 10^{-3} - 10^{-6} \text{eV}
\] (38)
since then the axion could be part of the cold dark matter of the universe.

If we have as initial condition \(F(\bar{\theta}_1)\bar{\theta}_1^2 \sim 1\), we get a lower bound on the axion mass
\[
10^{-6} \text{eV} < m_a
\] (39)
However, for smaller values of the initial $\theta_1$, one gets a looser bound. Apart from the value of $\theta_1$, there are other cosmological uncertainties.

Another axion source is the string-produced axions. Unless inflation occurs at $T < f_a$, axion strings survive and decay into axions. For many years, there has been a debate on the importance of the string mechanism, and the question is not yet settled. While a “school” finds $\Omega_{\text{string}} \sim \Omega_{\text{misalign}}$ another “school” finds $\Omega_{\text{string}} \sim 10 \Omega_{\text{misalign}}$. We should also mention that domain walls constitute another potential axion source. For a discussion of axionic strings and walls, see ref.\cite{11}.

For $f_a < 1.2 \times 10^{12}$ GeV there is production of thermal axions in the early universe, but the relic density today is small \cite{12}

$$n_a(\text{today}) \simeq 7.5 \text{ cm}^{-3}$$

(40)

IV. LOOKING FOR THE AXION

The interaction strength of the axion scales with the inverse of $f_a$, so that the strong bound on $f_a$ \cite{36} shows that the axion is a very feeble interacting particle. The crucial observation that allows to look realistically for these particles was made by Sikivie \cite{13}. The interaction term (20) generates axion-photon mixing induced by a transverse magnetic field $B_T$ (transverse in the sense of being perpendicular to the $\vec{E}$ polarization of the photon, the reason being the scalar product $\vec{E} \vec{B}$ in (21).

The mixing makes the interaction states $|a>$ and $|\gamma>$ different from the propagation states $|a'>$ and $|\gamma'>$,

$$|a’> = \cos \varphi |a> - \sin \varphi |\gamma>$$

(41)

$$|\gamma’> = \sin \varphi |a> + \cos \varphi |\gamma>$$

(42)

The probability $P$ of the $a - \gamma$ transition is proportional to the small factor $g_{a\gamma\gamma}^2 \sim 1/f_a^2$. However, $P$ is enhanced when the $a - \gamma$ conversion in the magnetic field is coherent. A simple way to understand coherence is to describe the photon and the axion as plane waves propagating along a linear path of distance $L$. The conversion is coherent provided there is overlap of the wave functions across a length $L$, i.e.

$$|k_{\gamma’} - k_a’| L \ll 2\pi$$

(43)
The probability of the coherent conversion is then

$$P(a \rightarrow \gamma) = \frac{1}{4} g_{a\gamma\gamma} B_T^2 L^2 \quad (44)$$

Searches for axions can be roughly classified in three types: Conversion of galactic halo axions, conversion of solar axions and production and detection in laboratory experiments. We now briefly discuss each in turn.

A. Detection of halo axions

In the presence of a galactic halo density, we expect the conversion of axions into $\mu$-wave photons ($1 \text{ GHz} = 4 \mu\text{eV}$)

$$h\nu = E \simeq m_a(1 + \beta^2/2) \quad \beta \sim 10^{-3} \quad (45)$$
in a cavity with a strong magnetic field (haloscope) [13]. When the (tunable) frequency of a cavity mode equals the axion mass, there is a resonant conversion into radiation. Axions are supposed to be virialized in the halo with $\beta \sim 10^{-3}$, so that there should be a very small dispersion.

Earlier experiments [14] put some limits, and presently there is already a second-generation experiment running, the US large scale experiment [15], sensitive in the range

$$2.9 < m_a < 3.3 \mu\text{eV} \quad (46)$$

This experiment has already excluded the possibility that KSVZ axions constitute the whole of the galactic dark matter density,

$$\rho = 7.5 \times 10^{-25} \text{ g cm}^{-3} \quad (47)$$

In the near future, they expect to reach $1 < m_a < 10 \mu\text{eV} \ [13].$

A promising experiment in development is CARRACK [16], in Kyoto. They will use a Rydberg atoms’ technique to detect $\mu$-wave photons.

B. Detection of axions from the Sun

A nice idea is to convert axions from the Sun into photons by means of a strong magnetic field (helioscope) [13]. This search is independent of the galactic dark matter hypothesis. The produced photons have energies $E \sim \text{ few keV (X-rays)}$. 
In Tokyo there is an experiment currently running, that has detected no signal, giving the limit 

\[ g_{a\gamma\gamma} < 6 \times 10^{-10} \text{ GeV}^{-1} \]  

(48)

which is only valid for \( m_a < 0.03 \text{ eV} \), to preserve coherence.

A word of caution is needed to interpret this mass \( m_a \). In this experiment, as well as in the experiments we describe below it is convenient to consider \( g_{a\gamma\gamma} \) as giving the coupling of a pseudo-scalar particle having a mass \( m_a \), i.e., mass and coupling not related through the relation (19). This allows to set limits with two free parameters, \( g_{a\gamma\gamma} \) and \( m_a \). Of course, they are related for the axion model, through the relations (19) and (20).

The Tokyo experiment has been improved recently by using gas to generate a plasmon mass \( \omega_{pl} \) and thus enhancing a possible signal for higher particle masses, since then \( k' - k_a \simeq (m_a^2 - \omega_{pl}^2)/2E \) (see (43)). They get 

\[ g_{a\gamma\gamma} < 6 \times 10^{-10} \text{ GeV}^{-1} \]  

(49)

now valid for \( 0.05 < m_a < 0.26 \text{ eV} \).

In the future, a strong improvement along this line of work will be the CAST experiment at CERN (19) (see the talk of Irastorza in these Proceedings). The experiment is ready to take data. After two years of running, if they have found nothing, they expect to reach the exclusion limit

\[ g_{a\gamma\gamma} < 6 \times 10^{-11} \text{ GeV}^{-1} \]  

(50)

An alternative way to convert axions from the Sun into photons is to use a crystal (20). The needed external electromagnetic field is supplied by the atomic Coulomb field. There is a coherent \( a \rightarrow \gamma \) conversion in a crystal when the angle of incidence satisfies the Bragg condition. The exclusion limits is

\[ g_{a\gamma\gamma} < 2.7 \times 10^{-9} \text{ GeV}^{-1} \]  

(51)

valid for \( m_a < 1 \text{ keV} \).

C. Production and detection of axions in the laboratory

We finally summarize the laboratory searches. Laser light can be converted into axions when a external magnetic field is applied and this has a variety of effects. For example, once
a photon has converted into an axion, it can cross an opaque substance, and after crossing it the axion may convert back into a photon due to the magnetic field action. The net effect is that we have light shining through a wall. The non observation of this phenomenon leads to the bound

\[ g_{\gamma\gamma} < 6.7 \times 10^{-10} \text{ GeV}^{-1} \] \hspace{1cm} (52)

for \( m_a < 10^{-3} \text{ eV} \).

A very interesting idea to search for axions uses polarized laser light \([23]\). Since the polarization \( E_\parallel \) is affected by the magnetic field but not \( E_\perp \), there are two main physical consequences. The axion can be produced so that there is a selective absorption of \( E_\parallel \). This is called dichroism and produces a rotation of the polarization plane. The second effect is birefringence, since when there is virtual production of an axion, the index of refraction for \( E_\parallel \) is different than for \( E_\perp \).

The PVLAS experiment \([24]\) constructed to search for these effects is now running. They get some signal and are analyzing whether it comes from some new physics. In any case, they expect to be sensitive to

\[ g_{\gamma\gamma} \sim 10^{-7} \text{ GeV}^{-1} \] \hspace{1cm} (53)

for

\[ m_a < 10^{-3} \text{ eV} \] \hspace{1cm} (54)

Although the figure (53) is above other limits we have been quoting, we should stress that this experiment is independent of the galactic dark matter and solar production hypothesis.

The PVLAS experiment \([24]\) is also interesting for “conventional physics”, because when improving the sensitivity, they should “see” the birefringence in vacuum generated by the QED light-light box-diagram.

V. AXION-LIKE PARTICLES

Global symmetries that are spontaneously broken lead to NG bosons. An example is family symmetry, which would be related to the number and properties of families (we still don’t have an answer to Rabi’s question: Who ordered the muon?). The breaking of the symmetry would give rise to familons. Another example is lepton-number symmetry, that would produce majorons. There are more theoretical examples, so the axion is not the only
NG boson that has been proposed. In general, all these bosons couple to photons, so that they could give signatures in most of the experiments that look for axions.

It is then interesting to analyze experimental constraints with two free parameters: mass and coupling to $\gamma\gamma$. To do that, we make the hypothesis that there is a boson $\varphi$ with mass $m$ and coupling $g$

$$\mathcal{L} = \frac{1}{8} g \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta} \varphi$$  \hspace{1cm} (55)

Experimental constraints for $g$ as a function of $m$ are presented in [25].

Another reason to relax the relation (19) is that it could be no longer valid in axion model where there are contributions to axion mass from exotic sources.

There are still many open questions in the field of hypothetical NG bosons. For example, the coupling of familons to the third family is very poorly constrained [26]. Also, there may be unexpected possibilities, like for example the suggestion of Ref.[27], where they show that an axion-like $\varphi$ particle with

$$m \sim 10^{-16} \text{ eV}$$  \hspace{1cm} (56)

and

$$g \sim 2 \times 10^{-12} \text{ GeV}^{-1}$$  \hspace{1cm} (57)

would make that 20-30% of photons from distant SNe oscillate into axion-like particles in presence of an extra-galactic magnetic field $B \sim 10^{-9} \text{ G}$, contributing to the dimming of SNe. Although it is highly speculative, the consequences for the measurements of the acceleration of the universe are very exciting. As a final example, let us mention that in Ref.[28] the production of pseudoscalars in very strong electromagnetic fields has been analyzed.

VI. CONCLUSIONS

The axion was born as a consequence of the PQ elegant solution to the strong CP problem. It has quite precise properties, with just one free parameter. Laboratory, astrophysical and cosmological observations constrain the axion parameter. The upcoming experiments may find the axion, or may exclude it. Descendants of axions, that we call axion-like bosons, also offer a piece of interesting physics.
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