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Axions in cosmology and laboratory

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Abstract. This contribution is a brief review on the present status of axions and axion-like particles.

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1. The strong CP problem

Quantum chromodynamics (QCD) is the successful theory of strong interactions, based on a gauge theory containing the gluon fields G^a_μ ($a = 1, \dots, 8$) and the quark fields $u, d, \dots,$ with the Lagrangian

$$\mathcal{L}_{\text{qcd}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + i\bar{u} \not{D} u + i\bar{d} \not{D} d + \cdots - m_u \bar{u}u - m_d \bar{d}d + \cdots , \tag{1}$$

where $\not{D} = \gamma^\mu D_\mu$, $D_\mu = \partial_\mu - i g_s G_\mu$.

The Lagrangian presents interesting global symmetries. For example, consider the quark piece

$$i\bar{u} \not{D} u + i\bar{d} \not{D} d - m_u \bar{u}u - m_d \bar{d}d + \cdots \ . \tag{2}$$

In the limit $m_u = m_d$ we can interchange $u \leftrightarrow d$, which corresponds to the $SU(2)_I$ of isospin. It is a fairly good approximation, which goes back to the concept of nuclear isospin by Heisenberg.

To study the symmetries of QCD further, we decompose $q = q_L + q_R$. We see that the kinetic and interaction terms preserve chirality

$$\bar{q} \not{D} q = \bar{q}_L \not{D} q_L + \bar{q}_R \not{D} q_R, \tag{3}$$

while the mass term mixes L and R,

$$m_q \bar{q}q = m_q \bar{q}_L q_R + m_q \bar{q}_R q_L. \tag{4}$$

Thus, with $m_u = m_d = 0$, we can separately mix u_L, d_L and u_R, d_R. In this limit, there is an extra symmetry, namely, $SU(2)_A$. This global axial symmetry is a spontaneously broken (SB) symmetry which leads to the pions known as Goldstone bosons (GB). In reality, m_u, m_d are small but not zero, so that pions have a small mass; they are in fact Pseudo-GB.

These global symmetries are not imposed. The symmetries we impose at the Lagrangian level on our theory of QCD are

(i) $SU(3)_c$ colour gauge theory,
(ii) Lorentz symmetry.

Once these are imposed, the consequence is that we have $SU(2)_I \times SU(2)_A$ as an approximate symmetry. In other words, we regard global symmetries as accidental symmetries.

Actually, there is a term compatible with (i) and (ii),

$$\Delta\mathcal{L} = \theta_{\text{qcd}} \, \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \tag{5}$$

with $\tilde{G}^a_{\mu\nu} = (1/2)\epsilon_{\mu\nu\rho\sigma} G^{a\rho\sigma}$. Here θ_{qcd} is a parameter of the theory, like g_s, m_q, etc.

The new term (5), called θ term, should be present in our QCD Lagrangian. However, it is CP-violating. For example, it induces a neutron dipole moment

$$d_n \sim \frac{e}{m_n} \, \theta \, \frac{m_u m_d}{m_u + m_d} \, \frac{1}{\Lambda_{\text{QCD}}}. \tag{6}$$

Actually there is another contribution to θ. In the Standard Model (SM), we have quark mixing

$$(\bar{u}\,\bar{d})\mathcal{M}\begin{pmatrix} u \\ d \end{pmatrix}. \tag{7}$$

The elements of the matrix $\mathcal{M}$ contain the complex Yukawas. The usual procedure is to diagonalize to obtain the mixing angles and the quark masses, with some of the phases absorbed in the fields. However, the global phase cannot be absorbed, and we get a term in the Lagrangian

$$(\text{Arg Det } \mathcal{M}) \, \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}. \tag{8}$$

The physical CP-violating observable is

$$\theta = \theta_{\text{qcd}} + \text{Arg Det } \mathcal{M}. \tag{9}$$

The experimental bound on neutron edm leads to

$$\theta < 10^{-9}. \tag{10}$$

The strong CP problem is the question of why two unrelated quantities cancel each other with such a precision.

Notice that $d_n \propto m_u$, and thus if m_u were massless there would not be strong CP-problem! The reason is that $m_u = 0$ implies an extra $U(1)_A$ global symmetry. Although nature seems to prefer $m_u \neq 0$, the fact of a new symmetry is at the basis of the Peccei–Quinn (PQ) solution to the strong CP problem [1]. The PQ idea is to assume a new $U(1)_A$ global symmetry. Such a symmetry is not observed at low energies, so that one needs the PQ symmetry to be SB at a high energy scale f. In the breaking, a GB – the axion – appears.

2. Axions

QCD effects induce a small mass for the axion, and therefore the axion is in fact a Pseudo-GB. The axion mass m and breaking scale f are related as

$$m = \frac{f_\pi m_\pi}{f} \frac{\sqrt{m_u m_d}}{m_u + m_d} = 0.6\,\text{eV}\,\frac{10^7\ \text{GeV}}{f}. \tag{11}$$

The couplings to matter are

$$\mathcal{L}_{a\Psi\Psi} = \sum_i c_i \frac{1}{2f} (\bar{\Psi}_i \gamma^\mu \gamma_5 \Psi_i)(\partial_\mu a) \quad (i = p, n, e, \text{etc.}). \tag{12}$$

There is also a coupling to two photons,

$$\mathcal{L}_{a\gamma\gamma} = c_\gamma \frac{\alpha}{\pi f} F \cdot \tilde{F} a = -g_{a\gamma\gamma} \vec{E}\vec{B} a. \tag{13}$$

The PQ breaking scale f is a high scale so that the axion mass is small and the axion couplings are weak.

The coupling to photons leads to the phenomenon of axion–photon mixing in a magnetic field. The interaction states are different from the propagation states:

$$\begin{aligned} |a'\rangle &= \cos\varphi\,|a\rangle - \sin\varphi\,|\gamma\rangle, \\ |\gamma'\rangle &= \sin\varphi\,|a\rangle + \cos\varphi\,|\gamma\rangle. \end{aligned} \tag{14}$$

As a consequence, in the propagation of a photon beam (energy E) travelling a distance L, there is a probability of photon to axion conversion:

$$P(\gamma \to a) = \frac{1}{4} g_{a\gamma\gamma}^2 B_T^2 L^2. \tag{15}$$

This formula holds provided there is coherence, $Lm^2/E < 1$.

3. Constraints on axions

A lower bound on the PQ-scale is obtained using particle physics processes, like $K^+ \to \pi^+ a$, and one obtains $f > 10^4$ GeV. However, astrophysical limits lead to much strict limits [2]. The strongest constraints come from SN1987a, specifically from the bremstrahlung process $NN \to NNa$ which would alter observed neutrino burst, and from the $ee \to eea$ bremstrahlung in white dwarfs which would alter the period decrease $\dot{P}$. These astrophysical arguments imply a limit $f > 10^9$ GeV.

Axions are dark matter candidates [3]. Let us summarize how they are created. Consider the early Universe at high temperatures $\Lambda_{\text{qcd}} \ll T < f$ but with a broken PQ symmetry. In this period of the early Universe, we have a vacuum with $\theta_i \neq 0$. In the expansion, the Universe cools down. When $T \sim \Lambda_{\text{qcd}}$ is reached, the vacuum evolves towards the CP-conserving value $\theta = 0$. Field oscillations produce a nonrelativistic axion fluid, a mechanism known as vacuum misalignment. An axion cosmic density is produced, with density [3]

$$\Omega_a h^2 \simeq 2 \times 10^{\pm 0.4}\, \theta_i^2 \left(\frac{10^{-6}\,\text{eV}}{m_a} \right)^{1.18}. \tag{16}$$

We obtain $\Omega_a h^2 \simeq 0.1$ when $m_a \simeq O(10\ \mu\text{eV})$. At any rate, the limit $\Omega_a < \Omega_{dm}$ leads to an upper bound on f. The reason we get an upper bound rather than a lower bound is that the less coupled is the axion the more production we have.

4. Axion searches

Searches are on to find dark galactic axions. The source is the axion DM flux, to be converted to photons of energy $h\nu = m_a(1 + \beta^2/2)$. There is a small dispersion because galactic axions are virialized with $\beta = 10^{-3}c$. For preferred values $m_a = O(1\text{–}10\ \mu\text{eV})$ the conversion is into μ-wave photons (1 GHz = 4 μeV). The most stringent results are from ADMX, a third generation experiment [4].

The second type of search is on to detect solar axions. The source is the interior of the Sun, so that the conversion is into X-ray photons. The method is valid for axion masses where conversion would be coherent. CAST [5] has not observed any positive signal and they put a limit $g_{a\gamma\gamma} < 2.2 \times 10^{-10}$ GeV^{-1} (95% CL) valid for $m < 0.4$ eV. They also have runs using buffer gas to reach $m < 1.2$ eV (coherence depends on the difference $m^2 - \omega^2_{\text{plasmon}}$).

The third way to search for axions is in optical experiments, where axions are produced and detected in the laboratory. Until now, there has not been any positive signal, and the best limits come from the light-shining-through-a-wall (LSW) experiment ALPS [6].

It is worth noting that the search for solar axions and the searches in optical experiments are sensitive to any light particle which couple to photons. We call such generic particles an axion-like particles (ALP). In this phenomenological approach we consider the coupling to two photons and the mass of the ALP as two unrelated quantities. Until now, optical experiments reach limits which are worse than the limits based on astrophysical arguments. However, one should take into account that there are models where production of ALPs can be suppressed at high energies [7]. It is then highly desirable to continue the search for axions and ALPs in laboratory experiments.

I would like to conclude saying that there is a hot discussion about possible signals of ALPs in astronomical observations, like white dwarfs observables, cosmological gamma-ray propagation, etc. It remains to be seen if these claims can be verified when more data are available. For some of the papers discussing different aspects of this issue, see ref. [8].

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