Axion Theory

Pierre Sikivie

Physics Department, University of Florida, Gainesville, FL 32611-8440, USA

The Strong CP Problem and its solution through the existence of an axion are briefly reviewed. The combined constraints from accelerator searches, stellar evolution and cosmology imply that the axion mass lies in the window $3 \cdot 10^{-3} > m_a \gtrsim 10^{-6}$ eV, with the lower bound being however much softer than the upper bound. If m_a is near the lower bound, axions are an important component of cold dark matter. I report briefly on the status of the ADMX dark matter search.

1 Introduction

The Standard Model of elementary particles present us with a puzzle. Indeed its action density includes, in general, a term [1]

$$\mathcal{L}_{\text{stand mod}} = \ldots \; + \; \frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \tag{1}$$

where $G^a_{\mu\nu}$ are the QCD field strengths, g is the QCD coupling constant and θ is a parameter. One can show that QCD physics does depend on the value of θ and that this dependence enters only through the combination $\bar{\theta} \equiv \theta - \arg\det m_q$ where m_q is the quark mass matrix. If $\bar{\theta} \neq 0$ the strong interactions violate P and CP. Such P and CP violation is incompatible with the experimental upper bound on the neutron electic dipole moment [2] unless $|\bar{\theta}| < 10^{-10}$. The Standard Model does not provide a rationale for $\bar{\theta}$ to be small. Indeed P and CP violation are introduced by letting the elements of the quark mass matrix m_q be arbitrary complex numbers [3]. In that case, $\bar{\theta}$ is of order one. The puzzle why $\bar{\theta}$ is so small in reality is usually referred to as the "strong CP problem".

The puzzle is removed if the action density is instead

$$\mathcal{L}_{\text{stand mod + axion}} = \ldots \; + \; \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{g^2}{32\pi^2} \, \frac{a(x)}{f_a} \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \tag{2}$$

where $a(x)$ is a new scalar field, and the dots represent the other terms of the standard model. f_a is a constant with dimension of energy. In the theory defined by Eq. (2), $\bar{\theta} = \frac{a(x)}{f_a} - \det\arg m_q$ depends on the expectation value of $a(x)$. This field settles to a value that minimizes the effective potential. The strong CP problem is solved because the minimum of the QCD effective potential $V(\bar{\theta})$ occurs at $\bar{\theta} = 0$ [4]. The $aG \cdot \tilde{G}$ interaction in Eq. (2) is not renormalizable. However, there is a recipe for constructing renormalizable theories whose low energy effective action density is of the form of Eq. (2): construct the theory in such a way that it has a $U(1)$ symmetry which is a global symmetry of the classical action density, is broken by the color anomaly, and is spontaneously broken. Such a symmetry is called Peccei-Quinn symmetry after its inventors [5]. Weinberg and Wilczek [6] pointed out that a theory with a $U_{\rm PQ}(1)$ symmetry has a light pseudo-scalar particle, called the axion. The axion field is $a(x)$. f_a is of order the expectation value that breaks $U_{\rm PQ}(1)$, and is called the "axion decay constant".

The axion mass is given in terms of f_a by

$$m_a \simeq 6 \text{ eV } \frac{10^6 \text{ GeV}}{f_a} . \tag{3}$$

All axion couplings are inversely proportional to f_a. The axion coupling to two photons is:

$$\mathcal{L}_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi} \frac{a(x)}{f_a} \vec{E} \cdot \vec{B} \quad , \tag{4}$$

where $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, α is the fine structure constant, and g_γ is a model-dependent coefficient of order one. $g_\gamma = 0.36$ in the DFSZ model [7] whereas $g_\gamma = -0.97$ in the KSVZ model [8]. The axion has been searched for in many places, but has not been found [9]. Axion masses larger than about 50 keV are ruled out by particle physics experiments (beam dumps and rare decays) and nuclear physics experiments. The next range of axion masses, in decreasing order, is ruled out by stellar evolution arguments. The longevity of red giants rules out 200 keV $> m_a >$ 0.5 eV [10, 11] in case the axion has negligible coupling to the electron (such an axion is usually called 'hadronic'), and 200 keV $> m_a > 10^{-2}$ eV [12] in case the axion has a large coupling to electrons. The duration of the neutrino pulse from supernova 1987a rules out 2 eV $> m_a > 3 \cdot 10^{-3}$ eV [13]. Finally, there is a lower limit, $m_a \gtrsim 10^{-6}$ eV, from cosmology which will be discussed in the next section. This leaves open an "axion window": $3 \cdot 10^{-3} > m_a \gtrsim 10^{-6}$ eV. Note however that the lower edge of this window (10^{-6} eV) is much softer than its upper edge.

2 Axion cosmology

The implications of the existence of an axion for the history of the early universe may be briefly described as follows. At a temperature of order f_a, a phase transition occurs in which the $U_{\rm PQ}(1)$ symmetry becomes spontaneously broken. This is called the PQ phase transition. At these temperatures, the non-perturbative QCD effects which produce the effective potential $V(\overline{\theta})$ are negligible, the axion is massless and all values of $\langle a(x) \rangle$ are equally likely. Axion strings appear as topological defects. One must distinguish two scenarios, depending on wether inflation occurs with reheat temperature lower (case 1) or higher (case 2) than the PQ transition temperature. In case 1 the axion field gets homogenized by inflation and the axion strings are 'blown' away.

When the temperature approaches the QCD scale, the potential $V(\overline{\theta})$ turns on and the axion acquires mass. There is a critical time, defined by $m_a(t_1)t_1 = 1$, when the axion field starts to oscillate in response to the turn-on of the axion mass. The corresponding temperature $T_1 \simeq 1$ GeV. The axion field oscillations do not dissipate into other forms of energy. In case 1, their contribution to the cosmological energy density is [14, 15]

$$\Omega_a \sim 0.15 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \left(\frac{0.7}{h} \right)^2 \alpha(t_1)^2 \tag{5}$$

where $\alpha(t_1) \equiv a(t_1)/f_a$ is the initial misalignment angle. This contribution is called of 'vacuum realignment'. Note that the vacuum realignment contribution may be accidentally suppressed in case 1 because the homogenized axion field may happen to lie close to zero.

In case 2 the axion strings radiate axions [16, 17] from the time of the PQ transition till t_1 when the axion mass turns on. At t_1 each string becomes the boundary of N domain walls. If $N = 1$, the network of walls bounded by strings is unstable [18, 19] and decays away. If $N > 1$ there is a domain wall problem [20] because axion domain walls end up dominating the energy density, resulting in a universe very different from the one observed today. There is a way to avoid this problem by introducing an interaction which slightly lowers one of the N vacua with respect to the others, but there is very little room in parameter space for this to happen. More likely, the axion domain wall problem is solved by having $N = 1$ or by having inflation after the PQ phase transition (case 1).

In case 2 there are three contributions to the axion cosmological energy density. One contribution is from axions that were radiated by axion strings before t_1. A second contribution is from axions that were produced in the decay of walls bounded by strings after t_1 [21]. A third contribution is from vacuum realignment [14]. The contribution from axion string decay was the object of controversy for a number of years [22, 23, 24], but this controversy seems to have died away. Assuming it is resolved along the lines discussed in refs. [17, 24], the axion cosmological energy density is in case 2 [15]

$$\Omega_a \sim 0.7 \left(\frac{f_a}{10^{12}\ \text{GeV}}\right)^{7/6} \left(\frac{0.7}{h}\right)^2 \quad . \tag{6}$$

It should be emphasized that there is considerable uncertainty in the estimates of Eqs. (5) and (6) because cosmology allows variations on the history of the universe before the time of nucleosynthesis.

3 Dark matter axion detection

An electromagnetic cavity permeated by a strong static magnetic field may be used to detect galactic halo axions [25]. The relevant coupling is given in Eq. (4). Galactic halo axions have velocities β of order 10^{-3} and hence their energies $E_a = m_a + \frac{1}{2}m_a\beta^2$ have a spread of order 10^{-6} above the axion mass. When the frequency $\omega = 2\pi f$ of a cavity mode equals m_a, galactic halo axions convert resonantly into quanta of excitation (photons) of that cavity mode.

Axion dark matter searches were carried out at Brookhaven National Laboratory [26], the University of Florida [27], Kyoto University [28], and by the ADMX collaboration [29] at Lawrence Livermore National Laboratory. The ADMX experiment has recently been upgraded to replace the HEMT (high electron mobility transistors) receivers used so far with SQUID microwave amplifiers. HEMT receivers have noise temperature $T_n \sim 3\ K$ [30] whereas $T_n \sim 0.05\ K$ was achieved with SQUIDs [31]. In a second phase of the upgrade, the experiment will be equipped with a dilution refrigerator to take full advantage of the lowered electronic noise temperature. When both phases of the upgrade are completed, the ADMX detector will have sufficient sensitivity to detect DFSZ axions at even a fraction of the local halo density.

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