AXIONS AND OTHER VERY LIGHT BOSONS

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In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. They arise if there is a global continous symmetry in the theory that is spontaneously broken in the vacuum. If the symmetry is exact, it results in a massless Nambu–Goldstone (NG) boson. If there is a small explicit breaking of the symmetry, either already in the Lagrangian or due to quantum mechanical effects such as anomalies, the would-be NG boson acquires a finite mass; then it is called a pseudo-NG boson. Typical examples are axions (A^0) [1], familons [2], and Majorons [3,4], associated, respectively, with spontaneously broken Peccei-Quinn [5], family, and lepton-number symmetries. This Review provides brief descriptions of each of them and their motivations.

One common characteristics for all these particles is that their coupling to the Standard Model particles are suppressed by the energy scale of symmetry breaking, *i.e.* the decay constant f, and the interaction is described by the Lagrangian

$$\mathcal{L} = \frac{1}{f}(\partial_\mu \phi) J^\mu, \tag{1}$$

where J^μ is the Noether current of the spontaneously broken global symmetry.

An axion gives a natural solution to the strong CP-violation problem: why the effective θ-parameter in the QCD Lagrangian $\mathcal{L}_\theta = \theta_{\mathit{eff}} \frac{\alpha_s}{8\pi} F^{\mu\nu a} \widetilde{F}^a_{\mu\nu}$ is so small ($\theta_{\mathit{eff}} \lesssim 10^{-9}$) as required by the neutron electric dipole moment, even though $\theta_{\mathit{eff}} \sim O(1)$ is perfectly allowed by the QCD gauge invariance. Here, θ_{eff} is the effective θ parameter after the diagonalization of the quark masses, and $F^{\mu\nu a}$ is the gluon field strength and $\widetilde{F}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma a}$. An axion is a pseudo-NG boson of a spontaneously broken Peccei–Quinn symmetry, which is an exact symmetry at the classical level, but is broken quantum mechanically due to the triangle anomaly with the QCD gluons. As a result, the axion acquires an effective coupling to gluons

$$\mathcal{L} = \left(\theta_{\mathit{eff}} - \frac{\phi_A}{f_A}\right) \frac{\alpha_s}{8\pi}\, F^{\mu\nu a}\, \widetilde{F}^a_{\mu\nu}\ , \tag{2}$$

where ϕ_A is the axion field. It is often convenient to *define* the axion decay constant f_A with this Lagrangian [6]. The QCD non-perturbative effect induces a potential for ϕ_A whose minimum is at $\phi_A = \theta_{\mathit{eff}} f_A$ cancelling θ_{eff} and solving the strong CP problem. The mass of the axion is related to f_A by

$$m_A = 0.62 \times 10^{-3}\text{eV} \ \times (10^{10}\text{GeV}/f_A) \ . \tag{3}$$

The original axion model [1,5] assumes $f_A \sim v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and has two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings are completely fixed in terms of one parameter ($\tan\beta$): the ratio of the vacuum expectation values of two Higgs fields. This model is excluded after extensive experimental searches for such an axion [7]. Observation of a narrow-peak structure in positron spectra from heavy ion collisions [8] suggested a particle of mass 1.8 MeV that decays into e^+e^-. Variants of the original axion model, which keep $f_A \sim v$, but drop the constraints of tree-level flavor conservation, were proposed [9]. Extensive searches for this particle, A^0(1.8 MeV), ended up with another negative result [10].

The popular way to save the Peccei-Quinn idea is to introduce a new scale $f_A \gg v$. Then the A^0 coupling becomes weaker, thus one can easily avoid all the existing experimental limits; such models are called invisible axion models [11,12]. Two classes of models are discussed commonly in the literature. One introduces new heavy quarks which carry Peccei–Quinn charge while the usual quarks and leptons do not (KSVZ axion or "hadronic axion") [11]. The other does not need additional quarks but requires two Higgs doublets, and all quarks and leptons carry Peccei–Quinn charges (DFSZ axion or "GUT-axion") [12]. All models contain at least one electroweak singlet scalar boson which acquires an expectation value and breaks Peccei–Quinn symmetry. The invisible axion with a large decay constant $f_A \sim 10^{12}$ GeV was found to be a good candidate of the cold dark matter component of the Universe [13](see Dark Matter review). The energy density is stored in the coherent oscillation of axion field around its potential minimum.

The constraints on the invisible axion from astrophysics are derived from interactions of the axion with either photon, electron or nucleon. The strengths of the interactions are model-dependent (*i.e.*, not a function of f_A only), and hence one needs to specify the model in order to place lower bounds on f_A. Such constraints will be discussed in another minireview to appear in the 1998 edition of this *Review*. Serious experimental searches for an invisible axion are underway; they typically rely on axion-photon coupling and some of them assume that the axion is the dominant component of our galactic halo density. Another minireview in the 1998 edition will discuss experimental techniques.

Familons arise when there is a global family symmetry broken spontaneously. A family symmetry interchanges generations or acts on different generations differently. Such a symmetry may give explanations to the structure of quark, lepton masses and their mixings. A familon could be either a scalar or a pseudoscalar. For instance, an SU(3) family symmetry among three generations is non-anomalous and hence the familons are exactly massless. In this case, familons are scalars. If one has larger family symmetries with separate groups of left-handed and right-handed fields, one also has pseudo-scalar familons. Some of them have flavor-off-diagonal couplings such as $\partial_\mu \phi_F \bar{d}\gamma^\mu s/F_{ds}$ or $\partial_\mu \phi_F \bar{e}\gamma^\mu \mu/F_{\mu e}$, and the decay constant F can be different for individual operators. The decay constants have lower bounds constrained by flavor changing processes. For instance, $\mathrm{B}(K^+ \to \pi^+ \phi_F) < 3 \times 10^{-10}$ [14] gives $F_{ds} > 3.4 \times 10^{11}$ GeV [15]. The constraints on familons primarily coupled to third generation is quite weak [15].

If there is a global lepton number symmetry and if it breaks spontaneously, there is a Majoron. The triplet Majoron model [4] has a weak-triplet Higgs boson, and Majoron couples to Z. It is now excluded by the invisible Z decay width. The model is viable if there is an additional singlet Higgs boson and if Majoron is mainly a singlet [16]. In the singlet Majoron model [3], lepton number symmetry is broken by a weak-singlet scalar field, and there are right-handed neutrinos which acquire Majorana masses. The left-handed neutrino masses are generated by "seesaw" mechanism [17]. The scale of lepton number breaking can be much higher than the electroweak scale in this case. Astrophysical constraints require the decay constant to be $\gtrsim 10^9$ GeV [18].

There is a revived interest in a long-lived neutrino, to improve the Big-Bang Nucleosynthesis [19] or large scale structure formation theories [20]. Since a decay of neutrinos into electrons or photons is severely constrained, these scenarios require a familon (Majoron) mode $\nu_1 \to \nu_2 \phi_F$ (see, *e.g.*, [15] and references therein).

Other light bosons (scalar, pseudoscalar or vector) are constrained by "fifth force" experiments. For a compilation of constraints, see [21].

It has been widely argued that a fundmental theory will not possess global symmetries; gravity, for example, is expected to violate them. Global symmetries such as baryon number arise by accident, typically as a consequence of gauge symmetries. It has been noted [22] that the Peccei-Quinn symmetry, from this perspective, must also arise by accident and must hold to an extraordinary degree of accuracy in order to solve the strong CP problem. See, for example, Ref. 22 for a possible resolution to this problem. String theory also provides sufficiently good symmetries, especially using a large compactification radius motivated by recent developments in the M-theory [23].

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