AXIONS AND OTHER VERY LIGHT BOSONS

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. These have been proposed to solve a variety of mostly theoretical concerns. Typical examples are pseudo-Goldstone bosons like axions (A^0) [1], familons [2], and Majorons [3,4], associated, respectively, with spontaneously broken Peccei-Quinn [5], family, and lepton-number symmetries.

In QCD, SU(3) gauge invariance does not forbid a term $\theta(g_s^2/32\pi^2)F^{\mu\nu a}\widetilde{F}^a_{\mu\nu}$ in Lagrangian. However, CP invariance is broken if $\theta \neq 0$ or π, and the parameter θ has to be small $\lesssim 10^{-9}$ in order not to generate too large elecric dilopole moment of neutron. This is called strong CP problem. Peccei-Quinn symmetry gives a natural solution to the strong CP problem. The axion mass and its coupling to stable particles are inversely proportional to the scale of Peccei-Quinn symmetry breaking, f_A. The original axion model [1,5] assumed $f_A \sim v$, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and had two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings were completely fixed in terms of one parameter, the ratio of the vacuum expectation values of the two Higgs fields. The result of extensive experimental searches for such an axion have been negative [6].

Observation of a narrow-peak structure in positron spectra from heavy ion collisions [7] 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 [8]. Extensive searches for this particle, A^0(1.8 MeV), ended up with another negative result [9].

Another way to save the Peccei-Quinn idea is to introduce a new scale $f_A \gg v$. Then the A^0 mass becomes smaller and its coupling weaker, thus one can easily avoid all the existing experimental limits; such models are called invisible axion models [10,11]. See the note on Invisible Axions later in this section.

Familons arise when there is a global horizontal symmetry (a symmetry which interchanges different generations) broken spontaneously. They could be either scalars or pseudoscalars. An SU(3) horizontal symmetry among three generations is non-anomalous and hence the familons are exactly massless. In this case, familons are scalars. If one has larger horizontal 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 $\partial_\mu \phi_F \overline{d}\gamma^\mu s/F$ or $\partial_\mu \phi_F \overline{e}\gamma^\mu \mu/F$, and the decay constant F can be different for individual operators. The decay constants have lower bounds constrained by flavor-changing processes. For instance, $\mathrm{B}(K^+ \to \pi^+\phi_F) < 1.7 \times 10^{-9}$ [12] gives $F_{K\pi} > 1.3 \times 10^{11}$ GeV [2].

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 the Majoron couples to Z. The original version is now excluded by the invisible Z decay width. The model would remain viable if there were an additional singlet Higgs boson and if the Majoron were mainly a singlet [13]. In the singlet Majoron model [3], lepton number symmetry is broken by a weak-singlet scalar field, and there are right-handed neutrinos that acquire Majorana masses. The left-handed neutrino masses are generated by a "seesaw" mechanism [14]. 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 [15].

Other light bosons (scalar, pseudoscalar or vector) are constrained by "fifth force" experiments. For a compilation of constraints, see [16].

References

1. S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978);
   F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).
2. F. Wilczek, Phys. Rev. Lett. **49**, 1549 (1982).
3. Y. Chikashige, R.N. Mohapatra, and R.D. Peccei, Phys. Lett. **98B**, 265 (1981).

4. G.B. Gelmini and M. Roncadelli, Phys. Lett. **99B**, 411 (1981).
5. R.D. Peccei and H. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); also Phys. Rev. **D16**, 1791 (1977).
6. T.W. Donnelly *et al.*, Phys. Rev. **D18**, 1607 (1978);
S. Barshay *et al.*, Phys. Rev. Lett. **46**, 1361 (1981);
A. Barroso *et al.*, Phys. Lett. **106B**, 91 (1981);
R.D. Peccei, in *Proceedings of Neutrino '81*, Honolulu, Hawaii, Vol. 1, p. 149 (1981);
L.M. Krauss and F. Wilczek, Phys. Lett. **B173**, 189 (1986).
7. J. Schweppe *et al.*, Phys. Rev. Lett. **51**, 2261 (1983);
T. Cowan *et al.*, Phys. Rev. Lett. **54**, 1761 (1985).
8. R.D. Peccei, T.T. Wu, and T. Yanagida, Phys. Lett. **B172**, 435 (1986).
9. W.A. Bardeen, R.D. Peccei, and T. Yanagida, Nucl. Phys. **B279**, 401 (1987).
10. J.E. Kim, Phys. Rev. Lett. **43**, 103 (1979);
M.A. Shifman, A.I. Vainstein, and V.I. Zakharov, Nucl. Phys. **B166**, 493 (1980).
11. A.R. Zhitnitsky, Sov. J. Nucl. Phys. **31**, 260 (1980);
M. Dine and W. Fischler, Phys. Lett. **120B**, 137 (1983).
12. M.S. Atiya *et al.*, Phys. Rev. Lett. **70**, 2521 (1993).
13. K. Choi and A. Santamaria, Phys. Lett. **B267**, 504 (1991).
14. T. Yanagida, in *Proceedings of Workshop on the Unified Theory and the Baryon Number in the Universe*, Tsukuba, Japan, 1979, edited by A. Sawada and A. Sugamoto (KEK, Tsukuba, 1979), p. 95;
M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, proceedings of the Workshop, Stony Brook, New York, 1979, edited by P. Van Nieuwenhuizen and D.Z. Freedman (North-Holland, Amsterdam, 1979), p. 315.
15. For a recent analysis of the astrophysical bound on axion-electron coupling, see G. Raffelt and A. Weiss, Phys. Rev. **D51**, 1495 (1995). A bound on Majoron decay constant can be infered from the same analysis.
16. E.G. Adelberger, B.R. Heckel, C.W. Stubbs, and W.F. Rogers, Ann. Rev. Nucl. and Part. Sci. **41**, 269 (1991).