Axion physics: status, prospects and challenges

Paolo Di Vecchia

Niels Bohr Institute, Copenhagen and Nordita, Stockholm

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The QCD axion

- To the usual QCD action one can add a θ term

$$L = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\Psi} M \Psi - \theta \int d^4x \; Q(x)$$

where Q is the topological charge density:

$$Q(x) = \frac{1}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu} \;\; ; \;\; \tilde{F}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} F^{a\rho\sigma}$$

- The θ term, together with a phase in the quark mass matrix, break CP and produce a non-zero electric dipole moment for the neutron:

$$D_n \sim \bar{\theta} \cdot 3.6 \cdot 10^{-16} cm \;\; ; \;\; \bar{\theta} = \theta + Arg \det M$$

- The experimental limit is $(e = 1)$

$$D_n < 6 \cdot 10^{-26} cm \Longrightarrow \bar{\theta} < 10^{-9} - 10^{-10}$$

- $\bar{\theta}$ is very small and consistent with zero.
- Can we make it to be zero in a natural way?

- Introduce, in the matter sector of QCD, some new degree of freedom with an extra $U(1)_{PQ}$ symmetry that is broken by an anomaly exactly as the $U(1)_A$ of QCD [Peccei and Quinn].
- This implies the existence of a new particle, called the axion, that has the effective Lagrangian:

$$L_{axion} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{a}{F_a} Q(x) + \frac{g_{a\gamma\gamma}}{4} F_{(em)} \cdot \tilde{F}_{(em)} + L_{int}(\frac{\partial_\mu a}{F_a}, \Psi)$$

  L_{int} describes the interaction with other SM fields.
- The first two terms are universal, while the others are not and

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi F_a}\left(\frac{E}{N} - \frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d}\right) \quad ; \quad \frac{m_u}{m_d} \sim 0.5$$

- The axion gets a non-zero vev that cancels the dependence on θ.
- It mixes with the neutral ps mesons and gets a non-zero mass:

$$m_a^2 = \frac{2}{F_a^2}\chi_{QCD} \quad ; \quad \chi_{QCD} = \langle Q(0) \int d^4x \; Q(x) \rangle$$

Axion-like particles (*ALP*) from string theory

- The 10-dim consistent string theories contain higher anti-symm. gauge potentials ($B_{\mu\nu}, C_{\mu\nu\rho}\dots$) that generalize the em pot. A_μ.
- Phenomenologically viable models require to compactify the 6 extra dimensions: $M_{10} = M_4 \times V_6$.
- For each choice of compactification we get a 4-dim Lagrangian containing, in general, several 4d $B_{\mu\nu}$ potentials.
- In $D = 4$ they correspond to pseudo-scalars fields A through

$$\epsilon_{\mu\nu\rho\sigma}\partial^\nu B^{\rho\sigma} \sim \partial_\mu A$$

with Lagrangian (as the QCD axion)

$$L = \frac{1}{2}\partial_\mu A \partial^\mu A + \frac{A}{F_A} Q(x) + \dots \; ; \; F_A \sim \frac{\alpha_G M_P}{2\pi\sqrt{2}} \sim 10^{16} GeV \; ; \; \alpha_G = \frac{1}{25}$$

- The tendency is to get large values for F_A (weakly coupled).
- Unlike their scalar partners they can have a small (sub eV) mass.
- Can we put limits on their mass and couplings?
- Is one of them the QCD axion? Can we observe them in exp. ?

Effective Lagrangian for mesons and axion (if needed)

- Denoting with $\alpha_{PQ}$the coefficient of the $U(1)_{PQ}$ anomaly and with F_α the scale of its spontaneous breaking, we can extend our previous Lagrangian [Sannino and DV, 2014] as follows:

$$L = \frac{1}{2} Tr(\partial_\mu U \partial_\mu U^\dagger) + \frac{1}{2}\partial_\mu N \partial_\mu N^\dagger + \frac{F_\pi}{2\sqrt{2}} Tr\left(\mu^2 (U + U^\dagger)\right) +$$

$$-\theta Q + \frac{Q^2}{a F_\pi^2} + \frac{i}{2} Q(x) \left(Tr(\log U - \log U^\dagger) + \alpha_{PQ}(\log N - \log N^\dagger) \right)$$

where

$$U(x) = \frac{F_\pi}{\sqrt{2}} e^{i\sqrt{2}\Phi(x)/F_\pi} \; ; \; N(x) = \frac{F_\alpha}{\sqrt{2}} e^{i\sqrt{2}\alpha(x)/F_\alpha} \; ; \; \mu_{ij}^2 = \mu_i^2 \delta_{ij}$$