Axion Dark Matter at the Time of Big Bang Nucleosynthesis

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We discuss a new constraint on the parameter space of axion dark matter that was first presented in [1]. The axion increases the neutron-proton mass difference at neutron freeze-out. The precise measurements of ^{4}He produced during Big Bang Nucleosynthesis (BBN) sets meaningful bounds on its parameter space.

1 Introduction

In 1977 Peccei and Quinn proposed what would become the classic solution to the strong CP problem [2, 3]. Later it was noted by Weinberg and Wilczek that it implied the existence of a light degree of freedom, the axion [4, 5]. If a $U(1)$ symmetry, anomalous under QCD, is spontaneously broken at an high scale f_a, the QCD θ parameter

$$\mathcal{L}_{QCD} \supset -\frac{\theta}{32\pi^2} G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\,, \tag{1}$$

can dynamically be set to zero through the minimization of the axion (the $U(1)$ pseudo-Goldstone boson) potential.

The axion is a motivated dark matter candidate [6]. In this work we focus on relic axions produced through the so-called misalignment mechanism [7, 8, 9, 10]. In order to solve the strong CP problem, the leading contribution to the axion potential must come from the QCD chiral anomaly. This contribution is generated during the QCD phase transition and earlier in the history of the universe we can consider the axion potential to be zero. As it turns on, the initial condition for the axion field does not need to coincide with the minimum of the potential. So after the QCD phase transition the axion can be described as an oscillating classical field

$$a(t) = a_0 \cos(m_a t) = \frac{\sqrt{2\rho_{DM}}}{m_a}\cos(m_a t)\,, \tag{2}$$

with an amplitude proportional to the initial misalignment. In the last equality we fix the initial condition by requiring that the axion makes up all of the observed dark matter energy density ρ_{DM}. In the simple setting described above, the axion mass m_a is not a free parameter, but is given by the QCD relation $f_a\, m_a = f_\pi m_\pi \sqrt{m_u m_d}/(m_u + m_d)$ [4, 5], in terms of the decay constant f_a. However axion-like particles for which this equality is violated are common in a variety of models [11, 12]. For brevity in the following we designate with "axion" both the QCD axion and these generalizations.

As stated above the axion coupling to gluons is the one responsible for the solution of the strong CP problem. Current constraints on this coupling leave open many orders of magnitude to m_a and f_a. The axion interactions with the electromagnetic field are more strongly constrained [6], but the coupling is much more model dependent and given an f_a can span over orders of magnitude. Therefore we find interesting to explore in more detail axion-gluon interactions. This is particularly important in view of the recent proposal of new experiments aimed at detecting these interactions [15, 16]. In the next section we show how the measurement of the primordial ^{4}He abundance greatly limits the parameter space available to the axion, largely overlapping with the projected sensitivity of the proposed experiments. We conclude by giving a fine-tuning argument that disfavors an even larger fraction of this parameter space.

2 The three graces of Big Bang Nucleosynthesis

Big Bang Nucleosynthesis is an ideal setting for constraining axion dark matter for three simple physical reasons. First, the effects of the axion field are amplified by the redshirting of the axion field $a \sim \sqrt{\rho_{DM}} \sim (1+z)^{3/2}$, $z_{\rm BBN} \approx 10^{10}$. Second we have precise measurements of quantities generated at that time. For instance, the fractional error on ^{4}He abundance, Y_p, is $\delta Y_p/Y_p \approx 10\%$ at 3σ [6]. Last and most important, Y_p is exponentially sensitive to the axion interaction with gluons. This was first shown in [1] following a known result on the constant QCD θ parameter [17]. Here we briefly review the steps that led to this conclusion.

The most general Lagrangian connecting the axion with Standard Model fields charged under $SU(3)_c$ can be written as

$$\mathcal{L} = -\frac{a}{f_a}\frac{G^a_{\mu\nu}\tilde{G}^{a\mu\nu}}{32\pi^2} - \frac{\partial_\mu a}{f_a}\sum_\psi c_\psi \bar{\psi}\bar{\sigma}^\mu\psi \,, \tag{3}$$

where we have ignored possible flavor violation in the c_ψ's that is irrelevant for what follows. We have indicated with ψ all possible quark fields taken as left-handed Weyl spinors. Using the methods of Chiral Perturbation Theory it is easy to show that these interactions, below the QCD confinement scale, generate

$$\begin{aligned} \mathcal{L}_{\rm QCDCh} \supset & \quad -\tfrac{1}{2}\tfrac{f_\pi^2 m_\pi^2 m_u m_d}{(m_u+m_d)^2}\left(\tfrac{a}{f_a}\right)^2 & (4)\\ - & \quad \bar{N}\pi\cdot\sigma\left(i\gamma^5 g_{\pi NN} - 2\,\bar{g}_{\pi NN}\tfrac{a}{f_a}\right)N & (5)\\ + & \quad \tfrac{f_\pi\,\bar{g}_{\pi NN}}{2}\tfrac{m_d-m_u}{m_d+m_u}\left(\tfrac{a}{f_a}\right)^2\bar{N}\sigma^3 N\,. & (6)\end{aligned}$$

where we have introduced the nucleon field $N = (p\ n)^T$ and the pions π. Clearly there are many more terms in the QCD Chiral Lagrangian that contain also the axion, but the three above are sufficient for our purposes. The first is the axion mass term mentioned in the introduction, the second generates an oscillating nucleon electric dipole moment (EDM) at one loop [18] that the experiments in [15, 16] intend to detect. The third and last term generates a neutron-proton mass difference

$$\begin{gathered} m_n - m_p = Q_0 + \delta Q\,, \\ \delta Q \approx \tfrac{f_\pi\,\bar{g}_{\pi NN}}{2}\left(\tfrac{m_d-m_u}{m_d+m_u}\right)\left(\tfrac{a}{f_a}\right)^2 \approx (0.37\ {\rm MeV})\left(\tfrac{a}{f_a}\right)^2\,, \end{gathered} \tag{7}$$

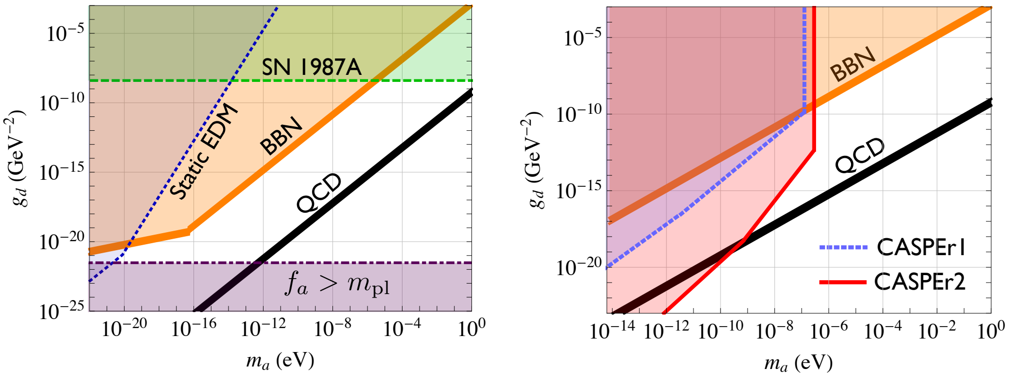

Figure 1: Taken from [1]. Left panel: In orange we show the BBN excluded region in the (g_d, m_a) plane. The blue shaded region is excluded by static EDM searches. The green region from excess SN 1987A cooling. Both were estimated conservatively in [16, 19]. We shade in purple the area where $f_a > m_{\rm pl}$. Right panel: The projected sensitivity of the oscillating EDM search of [15, 16]. CASPEr1 and CASPEr2 are the two generations of the experiment. The black line in both panels represents the QCD axion, $f_a\, m_a \approx \Lambda^2_{\rm QCD}$.

where we have taken $\bar{g}_{\pi NN} \approx 0.023$ as measured from baryon decays [17, 18]. It is this effect that feeds into the measured ^{4}He abundance though the neutron to proton ratio at freeze-out, $(n/p)_{\text{freeze-out}} \approx e^{-Q_{\rm F}/T_{\rm F}}$. Here Q_F is the value of $Q_0 + \delta Q$ at $T_F \approx 0.8$ MeV. The neutron to proton ratio stays approximately constant until the time of nucleosynthesis, when almost all neutrons bind into ^{4}He nuclei: $Y_p \approx 2(n/p)_{\rm Nuc}/(1+(n/p)_{\rm Nuc})$.

Imposing conservatively $\delta Y_p/Y_p < 10\%$, we find the constraint $f_a\, m_a \gtrsim 10^{-9}$ GeV^2. A full numerical calculation gives $f_a\, m_a \gtrsim 1.3 \times 10^{-9}$ [1]. In the left panel of Figure 1 we compare this bound with known constraints from static EDM measurements [13, 14, 16] and the excess cooling of SN 1987A [19, 16] and in the right panel with the sensitivity of the experiments proposed in [15, 16]. Note that this comparison is meaningful because the c_ψ in the UV Lagrangian do not appear at leading order in f_π/f_a in (5) and (6). So the nucleon EDM and proton-neutron mass difference are dominated by the $G\tilde{G}$ coupling of the axion and thus proportional to each other. The y-axis is given by a rescaling of the axion decay constant $g_d \approx \left(2.4 \times 10^{-16}\ \text{e cm}\right)/f_a$. We can clearly see that the bound adds on known results and strongly overlaps with the sensitivity of future experiments. For more details we refer to [1].

3 Conclusion and fine-tuning

We have shown that the measurement of the ^{4}He abundance from BBN sets a strong constraint on the axion dark matter parameter space. This bound overlaps with most of the sensitivity of projected experiments for the measurement of an oscillating nucleon EDM [15, 16].

It is worth to notice that the whole parameter space above the QCD line in Figure 1, albeit not excluded, is strongly disfavored by fine-tuning arguments. In that region $m_a \ll m_a^{\rm QCD}$, so we are implicitly adding a Lagrangian term $\Delta\mathcal{L}(a) \propto \delta m^2 (a + \delta\theta)^2$, to cancel the QCD contribution to the axion mass. The tuning required by the mass cancellation can be estimated as: $\Delta_{mass} \sim f_a^2\, m_a^2 / f_\pi^2 m_\pi^2 \sim 10^{-14}\left(f_a\, m_a/10^{-9}\ \mathrm{GeV}^2\right)^2$. At the same time $\delta\theta$ must also be tuned to avoid reintroducing the strong CP problem. It is not possible to avoid these tunings by introducing multiple axions [1]. However the experiments in [15, 16] have a concrete chance of being built. Furthermore tuning arguments in other sectors of the Standard Model Lagrangian have started to appear less reliable since LEP and the trend seems to be confirmed by the LHC. So we find useful to give solid observational bounds such as the one discussed in this note.

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References

[1] K. Blum, R. T. D'Agnolo, M. Lisanti and B. R. Safdi, "Constraining Axion Dark Matter with Big Bang Nucleosynthesis," arXiv:1401.6460 [hep-ph].

[2] R. D. Peccei and H. R. Quinn, "Constraints Imposed by CP Conservation in the Presence of Instantons," Phys. Rev. D **16** (1977) 1791.

[3] R. D. Peccei and H. R. Quinn, "CP Conservation in the Presence of Instantons," Phys. Rev. Lett. **38** (1977) 1440.

[4] S. Weinberg, "A New Light Boson?," Phys. Rev. Lett. **40** (1978) 223.

[5] F. Wilczek, "Problem of Strong p and t Invariance in the Presence of Instantons," Phys. Rev. Lett. **40** (1978) 279.

[6] K. A. Olive *et al.* [Particle Data Group Collaboration], "Review of Particle Physics," Chin. Phys. C **38** (2014) 090001.

[7] L. F. Abbott and P. Sikivie, "A Cosmological Bound on the Invisible Axion," Phys. Lett. B **120** (1983) 133.

[8] J. Preskill, M. B. Wise and F. Wilczek, "Cosmology of the Invisible Axion," Phys. Lett. B **120** (1983) 127.

[9] M. Dine and W. Fischler, "The Not So Harmless Axion," Phys. Lett. B **120** (1983) 137.

[10] M. S. Turner, "Cosmic and Local Mass Density of Invisible Axions," Phys. Rev. D **33** (1986) 889.

[11] J. Jaeckel and A. Ringwald, "The Low-Energy Frontier of Particle Physics," Ann. Rev. Nucl. Part. Sci. **60** (2010) 405 [arXiv:1002.0329 [hep-ph]].

[12] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, "String Axiverse," Phys. Rev. D **81** (2010) 123530 [arXiv:0905.4720 [hep-th]].

[13] C. A. Baker, D. D. Doyle, P. Geltenbort, K. Green, M. G. D. van der Grinten, P. G. Harris, P. Iaydjiev and S. N. Ivanov *et al.*, "An Improved experimental limit on the electric dipole moment of the neutron," Phys. Rev. Lett. **97** (2006) 131801 [hep-ex/0602020].

[14] P. G. Harris, C. A. Baker, K. Green, P. Iaydjiev, S. Ivanov, D. J. R. May, J. M. Pendlebury and D. Shiers *et al.*, "New experimental limit on the electric dipole moment of the neutron," Phys. Rev. Lett. **82** (1999) 904.

[15] D. Budker, P. W. Graham, M. Ledbetter, S. Rajendran and A. Sushkov, "Cosmic Axion Spin Precession Experiment (CASPEr)," Phys. Rev. X **4** (2014) 021030 [arXiv:1306.6089 [hep-ph]].

[16] P. W. Graham and S. Rajendran, "New Observables for Direct Detection of Axion Dark Matter," Phys. Rev. D **88** (2013) 035023 [arXiv:1306.6088 [hep-ph]].

[17] L. Ubaldi, "Effects of theta on the deuteron binding energy and the triple-alpha process," Phys. Rev. D **81** (2010) 025011 [arXiv:0811.1599 [hep-ph]].

[18] R. J. Crewther, P. Di Vecchia, G. Veneziano and E. Witten, "Chiral Estimate of the Electric Dipole Moment of the Neutron in Quantum Chromodynamics," Phys. Lett. B **88** (1979) 123 [Erratum-ibid. B **91** (1980) 487].

[19] G. G. Raffelt, "Astrophysical axion bounds," Lect. Notes Phys. **741** (2008) 51 [hep-ph/0611350].