Search for Monoenergetic Solar Axions with CAST

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We present the results of the CERN Axion Solar Telescope (CAST) search for monoenergetic axions or axion-like particles that could be emitted from the Sun by ^{57}Fe (14.4 keV) and ^{7}Li (0.478 MeV) nuclear de-excitations and D$(p, \gamma)^3$He (5.5 MeV) reaction. The non-observation of the signal above background allowed us to set model-independent limits on the coupling constants of pseudoscalar particles that couple to a nucleon and to two photons.

1 Introduction

Axions are neutral pseudoscalar particles that emerge as an inevitable consequence of the Peccei-Quinn solution [1] to the strong CP problem and are viable dark matter candidates. Despite the exhaustive search that has been going on for more than 30 years, there is still no positive signal for the axion or axion-like particles (ALPs). It is expected that pseudoscalars like axions should be abundantly produced in stars by nuclear and thermal processes. Hence, as the closest star, the Sun would be a strong axion emitter suitable for axion searches. As these particles couple to two photons, they could be produced in the solar core via Primakoff conversion of thermal photons in the Coulomb fields of the solar plasma. Such axions would have a continuous energy spectrum with a peak at 3 keV, mean energy of 4.2 keV, and dying off above $\sim$10 keV. Due to the axion-nucleon coupling, there are additional components of solar axions emitted in nuclear de-excitations and reactions. The energy of these monoenergetic axions corresponds to the energy of the particular process. With axions being pseudoscalar particles, axion emission from nuclear processes is expected to occur predominantly via M1 nuclear transitions. Several such processes have been proposed as sources of monoenergetic solar axions [2, 3]. Here we focus on the search for solar axions and more general ALPs which may be emitted from de-excitation of ^{57}Fe (14.4 keV) and ^{7}Li (0.478 MeV) nuclei, and from D$(p, \gamma)^3$He (5.5 MeV) reaction.

2 CAST experiment

The CERN Axion Solar Telescope (CAST) is the most recent implementation of the axion helioscope technique [4]. When its 9.26 m long LHC dipole prototype magnet is pointed towards the Sun, solar axions could coherently convert to photons of the same energy via the inverse Primakoff process, while traversing the 9 T magnetic field produced in the two parallel bores inside the magnet. To detect these photons, several low-background X-ray detectors are installed on both ends of the magnet. The CAST experiment is primarily designed to search for axions or ALPs that could be produced in the Sun by the Primakoff conversion of thermal photons and it set the most restrictive experimental limits on the axion-photon coupling constant for masses $m_{\rm a} < 0.4$ eV. Details about these results and experimental set-up can be found in [5, 6, 7].

3 Search for 14.4 keV solar axions

It is estimated that the most dominant component of monoenergetic solar axions is given by the 14.4 keV axions which may be emitted in the M1 nuclear transition between the first and the ground state of thermally excited ^{57}Fe nuclei [3]. This stable iron isotope can be a suitable emitter of solar axions due to its exceptional abundance among heavy elements in the Sun (2.8×10^{-5}) and the fact that its first excited nuclear state ($E^* = 14.4$ keV) is low enough to be relatively easily thermally excited in the hot interior of the Sun ($kT \sim 1.3$ keV). The excited ^{57}Fe nucleus relaxes to its ground state mainly through the emission of the 14.4 keV photon or an internal conversion electron. Since this de-excitation occurs dominantly via an M1 transition, an axion could also be emitted. Following the calculations in [8], the expected total flux of ^{57}Fe solar axions at the Earth is

$$\Phi_{\rm a}^{14.4\,{\rm keV}} = 4.56 \times 10^{23}\,(g_{\rm aN}^{\rm eff})^2 \quad {\rm cm}^{-2}\,{\rm s}^{-1}\,,$$

where $g_{\rm aN}^{\rm eff} \equiv (-1.19g_0 + g_3)$ is the effective axion-nucleon coupling constant for this particular process, while g_0 and g_3 are the isoscalar and isovector axion-nucleon coupling constants and they are model dependent parameters.

Our search for ^{57}Fe solar axions was based on the data acquired during the Phase I of the CAST experiment with the conventional TPC detector mounted on one end of the magnet covering both bores. The axion signal, i.e., an excess of 14.4 keV X-rays when the magnet was pointing to the Sun was not found. Hence we set model-independent limits on the product of the axion-photon and axion-nucleon coupling constants as a function of the axion mass (shown in Fig. 1 on the left side). In the mass range $m_{\rm a} \lesssim 0.03$ eV, where the axion-to-photon conversion process is coherent and has maximum probability, the limit is mass-independent and its value is $g_{{\rm a}\gamma}\, g_{\rm aN}^{\rm eff} < 1.36 \times 10^{-16}$ GeV^{-1} (95% CL). For higher axion masses, the coherence of the process is lost, which suppresses the conversion probability and, as a consequence, the sensitivity of the experiment to 14.4 keV axions diminishes rapidly with the increase of the axion mass above $\sim$0.03 eV, thus providing weaker, mass-dependent limit. From the above limit we also set the constraint on $g_{{\rm a}\gamma}$ as a function of $g_{\rm aN}^{\rm eff}$ for axion masses $m_{\rm a} \lesssim 0.03$ eV. This limit, labeled as "CAST-Fe", is shown on the right side in Fig. 1. It is constrained with the vertical boundary at $g_{\rm aN}^{\rm eff} = 3.6 \times 10^{-6}$, denoted as "Lum-Fe", due to the requirement based on the solar neutrino flux measurements that the axion emission from ^{57}Fe nuclei in the Sun should not exceed 10% of the solar photon luminosity. Due to the finite energy resolution of the TPC detector, our method to search for ^{57}Fe solar axions is significantly sensitive in the region of $g_{{\rm a}\gamma}$– $g_{\rm aN}^{\rm eff}$ parameter space below the line denoted as "Det", where the ^{57}Fe solar axion flux exceeds the tail of the Primakoff solar axion flux in the energy range of the expected ^{57}Fe axion signal. In the region above the "Det" line (light grey), the Primakoff axion contribution dominates and thus suppresses the sensitivity to the ^{57}Fe axions. This resulted in the upper limit of $g_{{\rm a}\gamma} < 3.5 \times 10^{-10}$ GeV^{-1} (95% CL) which is displayed as a red horizontal line in Fig. 1 (right side).

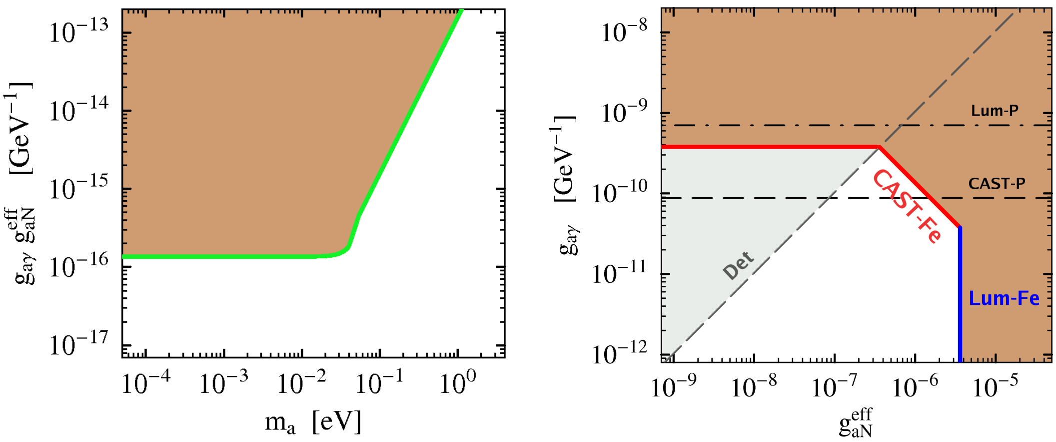

Figure 1: Left: The 95% CL upper limit on the product $g_{a\gamma}\, g_{aN}^{eff}$ as a function of the axion mass m_a, imposed by the CAST's search for ^{57}Fe solar axions. Right: The upper limit on $g_{a\gamma}$ versus g_{aN}^{eff}, based on the relations $g_{a\gamma}\, g_{aN}^{eff} < 1.36 \times 10^{-16}$ GeV^{-1} and $g_{a\gamma} < 3.5 \times 10^{-10}$ GeV^{-1} for $m_a \lesssim 0.03$ eV, is shown as the red line CAST-Fe. The dark brown area is excluded. Lines denoted as Lum-Fe and Det are described in the text. Upper limits from the Primakoff solar axion luminosity (Lum-P) and CAST's search for the Primakoff solar axions (CAST-P) [6], that rely solely on $g_{a\gamma}$, are also displayed for comparisons.

4 Search for high-energy solar axions

In addition to the search for ^{57}Fe axions, CAST also performed a similar search for high-energy monoenergetic solar axions and ALPs. Two processes were considered: a) de-excitation of the first excited state of ^{7}Li nuclei produced in the Sun by the ^{7}Be electron capture, and b) radiative capture of proton on deuteron $D(p,\gamma)^3$He. The energies of axions that may be emitted instead of photons in both processes are 0.478 MeV and 5.5 MeV, respectively. Following the calculations in [9], the expected total fluxes of these solar axions at the Earth are

$$\Phi_a^{0.478\,\mathrm{MeV}} = 5.23 \times 10^8\, (g_0 + g_3)^2\ \mathrm{cm}^{-2}\, \mathrm{s}^{-1} \quad \text{and} \quad \Phi_a^{5.5\,\mathrm{MeV}} = 2.03 \times 10^{10}\, g_3^2\ \mathrm{cm}^{-2}\, \mathrm{s}^{-1}\,,$$

which is many orders of magnitude smaller than the ^{57}Fe solar axion flux. To detect photons produced by conversion of high-energy axions in the magnet bores, a special low-background γ-ray calorimeter based on CWO crystal was installed on one end of the magnet during the CAST Phase I. Since no evidence of an axion signal was observed for any of the two considered processes, an upper limit on the axion-photon coupling constant was set as a function of axion mass and axion-nucleon coupling constant. Figure 2 shows the exclusion plots of $g_{a\gamma}$ versus m_a obtained for two indicated values of the parameter $g_0 + g_3$ (for ^{7}Li axions) and g_3 (for proton-deuteron fusion axions). These values are chosen as representative of the range of couplings corresponding to the Peccei-Quinn symmetry breaking scale of $f_a = 10^6 - 10^8$ GeV. The presented contours serve as an example to show how the excluded region in the $g_{a\gamma} - m_a$ parameter space can be scaled for various choices of g_0 and g_3. In this manner, our results can also be generally applied to impose the constraints on light pseudoscalars that couple to a nucleon and to two photons.

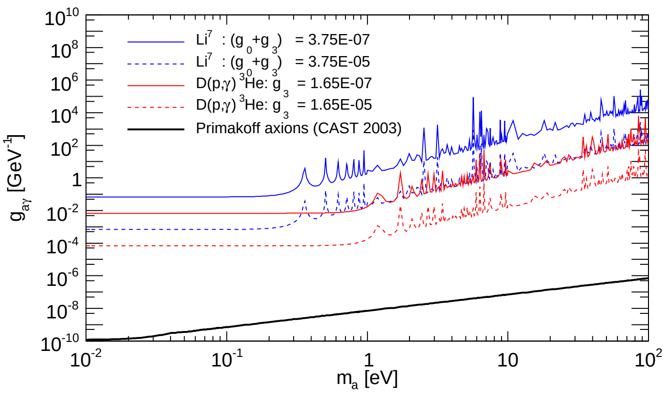

Figure 2: Exclusion plot (95% CL) in the axion-photon coupling versus axion mass plane imposed by the CAST's search for 0.478 MeV axions from ^{7}Li de-excitation (blue lines) and 5.5 MeV axions from proton-deuteron fusion (red lines). The limit obtained from each of the processes is presented for two indicated values of the axion-nucleon coupling constants g_0 and g_3. The upper limit from the CAST's search for the Primakoff solar axions (black line) is also shown for the comparison.

5 Conclusions

As extension to its main research program, i.e., the search for the Primakoff solar axions and ALPs, CAST also performed the first search for monoenergetic axions using a helioscope approach. Three nuclear processes were considered as sources of monoenergetic solar axions: de-excitation of ^{57}Fe (14.4 keV) and ^{7}Li (0.478 MeV) nuclei, and proton-deuteron fusion (5.5 MeV). The search was sensitive to axion interactions both with a nucleon (in the emission processes) and photons (in the detection process). This allowed us to explore the relation between axion-nucleon and axion-photon coupling constants for a wide range of axion masses and set the model-independent limits that can generally apply not only to axions but also to similar exotic pseudoscalar particles that couple to two photons and can be emitted in the nuclear magnetic transitions.

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