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The latest results from CAST and the IAXO project.

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The CAST experiment has been the most sensitive helioscope so far. It has extended its sensitivity to the upper bounds of axion masses allowed by cosmology, entering well into the QCD-axion band. The preliminary analysis of the data taken with sensitivity to axion masses of the range 0.64 eV to 1.17 eV show no excess of signal above background and the coupling constant is restricted to $g_{a\gamma} < 3.3 \times 10^{-10}\mathrm{GeV}^{-1}$. While CAST continues with the aim to improve its results in the vacuum phase, IAXO is the new project proposed to build a dedicated magnet for axion searches that will supersede CAST's sensitivity by one order of magnitude in $g_{a\gamma}$.

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PoS(EPS-HEP 2013)394

1. Introduction

Axions are hypothetical particles considered as the most elegant solution to the strong-CP problem. They are also a good candidate for the Dark Matter, as they could have been produced in early stages of the Universe thermally or through processes like the so-called misalignment (or re-alignment) effect [1]. In the first case they could be part of the Hot Dark Matter, with masses that cannot exceed the 1 eV limit, which has not changed with the latest Planck data [2]. In the second case, these relic axions could be the main component of the Cold Dark Matter.

The property of axions mostly exploited experimentally, and which is present in practically all models, is their coupling to photons. This property allows the axion-to-photon conversion in the presence of an electromagnetic field, also known as the Primakoff effect. In that case, axions could be produced in the core of stars like the Sun. In 1983, the helioscope concept was introduced invoking the inverse Primakoff effect [3]: solar axions coming from the Sun will be re-converted to x-ray photons as they pass through a strong transverse laboratory magnetic field. The expected signal is in the energy range of 1–10 keV. The number of excess photons expected in x-ray detectors, located outside the magnet, depends on the very weak axion-to-photon coupling, $g_{a\gamma}$. The use of focusing optics enhances significantly the signal-to-background ratio and therefore the sensitivity of the experiment. The sensitivity of a helioscope is given by the following equation [4]

$$g_{a\gamma}^4 \sim B^2 L^2 A \ \varepsilon_d b^{-1/2} \ \varepsilon_o a^{-1/2} \ \varepsilon_t^{1/2} t^{1/2} \tag{1.1}$$

which highlights the most important factors in the detection of axion-converted photons: related to the magnet, the length (L) and the strength (B) of the provided magnetic field and the axion-sensitive area A; related to the detectors, the background level (b) and their efficiencies (ε_d); the efficiency ε_o and total focusing area a of focusing optics and finally, the fraction of time the magnet tracks the Sun ε_t and the total time of data-taking of the experiment t.

The pioneering helioscope was the Rochester-Brookhaven-Florida experiment [5, 6] while SUMICO [7, 8, 9] took over soon after. CAST has been the third helioscope built so far and the most sensitive one. The IAXO project plans to improve the sensitivity of CAST in the near future.

2. The CAST experiment

The CAST experiment (CERN Axion Solar Telescope) uses a 10 m long decommissioned LHC prototype magnet which can reach a ∼9 T magnetic field as a converter of axions coming from the Sun into detectable x-rays. The magnet is twin-aperture and has four places for detectors to dock, two on each end. It is sitting on a movable platform, which allows it to follow the Sun for 1.5 h during sunrise and the same amount of time during sunset.

CAST, which has been taking data since 2003, is the most sensitive axion helioscope built up to date, thanks to its magnet and to the x-ray telescope device which can focus the photos coming from the 14.5 cm^2 aperture of the magnet onto a ∼ 9 mm^2 spot on a CCD. Three different data-taking campaigns of the experiment have been necessary in order to probe axion masses up to the ∼1 eV scale. During the first phase, the magnet bores were operating in vacuum: under this condition, the experiment was sensitive to axion masses up to m_a ∼0.02 eV [10, 11].

PoS(EPS-HEP 2013)394

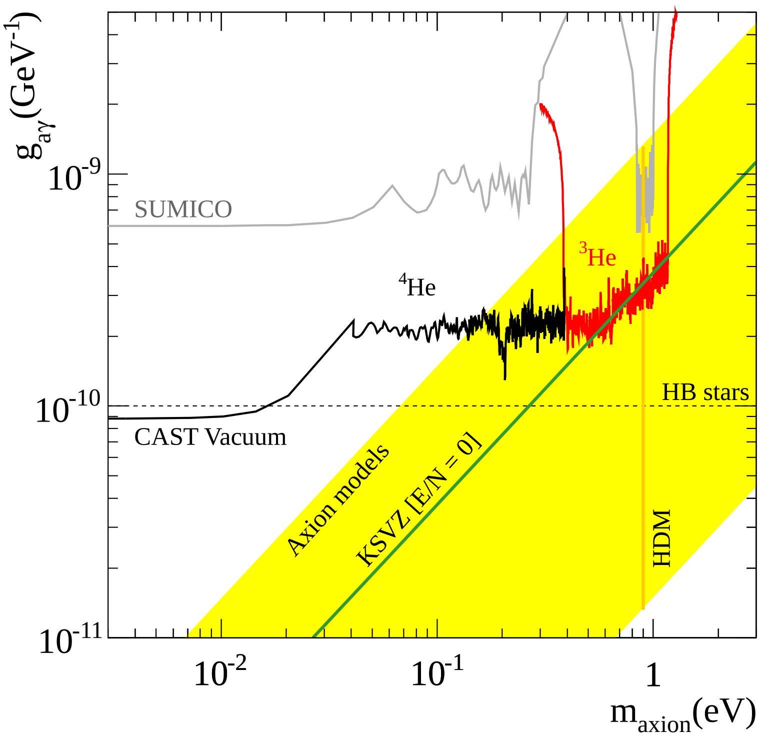

Figure 1: Expanded view of the CAST results in the vacuum,^{4}He (in black) and the ^{3}He phases with the new preliminary limit (in red). The limit from SUMICO, the hot dark matter (HDM) bound and the horizontal brunch (HB) stars are also shown. The yellow band denotes typical theoretical models, while the green solid line corresponds to $E/N = 0$ (KSVZ model).

To maintain the conversion probability of axions high for higher masses, the axion-sensitive region should be filled with a buffer gas. Increasing the gas density inside the magnet bores in steps results in a scan of the axion phase-space towards higher masses. In the second phase of the experiment, the magnet bores were being filled with ^{4}He and axion masses up to $m_a \sim 0.39$ eV were scanned during 2005 and 2006 [12]. CAST was the first helioscope to enter the QCD axion model band. Because ^{4}He condensates at higher pressures, it was substituted by ^{3}He in order to continue with the scanning of higher masses. During 2007 the gas system was adapted to using the new gas and in 2008 the data taking had reached the $m_a \sim 0.64$ eV point [13].

In 2011, the experiment concluded the data-taking period with ^{3}He in the magnet bores, which covered the mass range up to $m_a \sim 1.17$ eV. There seems to be no excess of signal over background in the data, for the three Micromgeas detectors of the experiment, which will allow CAST to put an upper limit on $g_{a\gamma}$. The preliminary result would be of $g_{a\gamma} < 3.3 \times 10^{-10}\mathrm{GeV}^{-1}$ for the mass range between 0.64 eV and 1.17 eV [14]. Figure 1 indicates the exclusion region of this result, in combination with the previous results of the experiment. After reaching this point, CAST decided to change back to ^{4}He and take data with improved detectors, increasing the sensitivity of the previous measurements. The analysis of these data is ongoing.

Apart from its baseline program, CAST has also performed searches from M1 nuclear transitions [15, 16] and low energy axions [17]. Most recently CAST published constraints on the axion-electron and axion-photon coupling constants, investigating non-hadronic axion models in which the coupling to electrons is allowed [18].

During 2013 and 2014, CAST plans to revisit the vacuum phase with more sensitivity, exploring a new part of the axion phase-space. The improvement in sensitivity is due to the low-background Micromegas detectors: with improved shielding and the use of non-radioactive materials in the construction of the chambers, the Micromegas have reached in CAST background levels of the order of 10^{-6} keV^{-1} cm^{2} s^{-1}. It is also foreseen that one of them will be equipped with a new x-ray-focusing device, which is expected to increase the signal-to-noise ratio significantly. At the same time, CAST will be looking at the low energy part, searching for other particles such as chameleons, which appear in Dark Energy models, or hidden photons[19]. The possibility to extend the searches to relic axions is also being explored.

3. The IAXO project

The International Axion Observatory is proposed as a fourth generation axion helioscope [4]. Although more physics goals can be foreseen, the primary goal will be to look for axions and ALPs coming from the Sun. The aim is to improve the signal-to-background figure of CAST by 5 orders of magnitude. In order to fulfil these prospects, IAXO will improve on all the driving forces of the sensitivity, as described in eq. 1.1, i.e. magnet, x-ray optics, low-background detectors and observation time, relying on existing technologies.

IAXO is based on the construction of a dedicated magnet, optimized for axion searches. The current design of the magnet is an 8-coil, 21 m-long superconducting toroidal, inspired by the ATLAS magnet [20]. The magnet will reach an average field of 2.5 T with a peak magnetic field of 5.4 T. The aperture of each magnet bore has a diameter of 60 cm, allowing for a an axion-sensitive area of approx. 2.26 m^{2} in total.

As already done in CAST in smaller scale, IAXO counts on the use of x-ray focusing devices, one for each bore. The size of the optics, which will focus the axions converted to photons inside the magnet bores on a spot of $\sim$0.2 cm ^{2}, put a challenge on their cost-efficient production. The fabrication process to be followed, again based on known technology, is that of segmented, slumped glass optics, the same one put in use most recently for the NuSTAR satellite mission.

The detectors to be used in IAXO are required to have background levels of 10^{-7}keV^{-1}cm^{-2}s^{-1} or better. For the project baseline, Micromegas detectors of the microbulk technology, optimized for the 0.5 keV to 10 keV energy range will be used. As mentioned in the previous section, this type of detectors, have already reached in CAST levels of the order of 10^{-6}keV^{-1}cm^{-2}s^{-1}. Tests underground and in the laboratory, have shown that these numbers can be improved to values well within the IAXO requirements [21].

The whole apparatus will sit on a platform which will allow it to move around and track the Sun for approximately 12 h per day. This would constitute an increase of the observation time per day for IAXO of a factor 4 with respect to CAST. This by itself, would be an important improvement comparing with all the other helioscopes up to now.

The improvement expected to achieve with IAXO, translates into a factor of 20 in sensitivity of $g_{a\gamma}$. As it can be seen in figure 2, this means that the project would be able to probe the level

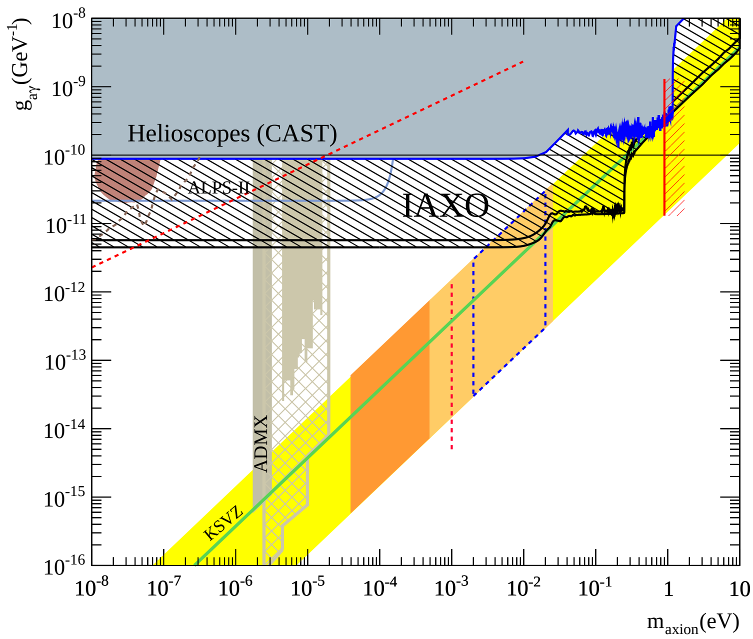

Figure 2: An extended version of the plot with the expected IAXO sensitivity compared with current bounds (solid) and future prospects (dashed) of other experiments (CAST, ADMX [22], ALPS-II [23]). The region below the red dashed line is viable ALP DM parameter space. The region at low m_a above the dashed grey line is the one invoked in the context of the transparency of the universe while the solid brown region is excluded by H.E.S.S. data [24]. For the sake of clarity the labels of the other bounds have been removed. For those,we refer to [25].

of few times 10^{-12}GeV^{-1} for a wide range of axion masses up to approx. 0.25 eV, big part of which has not been accessible so far. IAXO will cover a good part of the QCD-favoured region of the standard axion for the higher masses. A wide range of masses below the eV scale appears in different models in which the axion would compose all or part of the dark matter of the Universe. There are other cosmological scenarios in which the dark-matter related phase space is enlarged and largely covered by IAXO. At the lower end of the mass spectrum, for masses below 10^{-7} eV, within the sensitivity of IAXO, there lie ALPs invoked to explain anomalies in light propagation over astronomical distances [26].

Another clear possibility for IAXO would be to look for axions and ALPs exploring the axion-to-electron coupling. An astrophysical observation shows that axions with g_{ae} of few $\times 10^{-13}$ could solve the anomalous cooling observed in white dwarfs [27]. IAXO would be sensitive enough to measure the solar flux of axions produced with the same mechanism as in white dwarfs and test this hypothesis. As in CAST, more models proposing other particles, such as chameleons and hidden photons, would also be able to be tested by IAXO at the low energy part [19]. Direct detection of relic axions that would have produced in the early stages of the universe is another interesting possibility; the magnet is designed in such a way that new equipment (e.g. microwave cavities, antennas) could be introduced for such type of searches to take place in parallel to the baseline of the project.

The increase of the sensitivity improves greatly the potential for a discovery, which would be ground-breaking for the particle physics. A letter of Intent has been submitted to CERN [25].

4. Summary

The CAST experiment has probed a previously unexplored part of the axion and ALPs phase-space, entering well into the QCD-axion region at the upper masses end. The latest results lead to a preliminary upper limit for the coupling constant of $g_{a\gamma} > 3.3 \times 10^{-10}\text{GeV}^{-1}$ for m_a between 0.64 eV and 1.17 eV. CAST is revisiting the vacuum phase with a better sensitivity, while looking for other exotica such as hidden photons or chameleons. The International Axion Observatory is planning to improve CAST results by at least one order of magnitude in $g_{a\gamma}$, using known technologies: it will feature a dedicated magnet with 8 bores on which x-ray detectors coupled to x-ray focusing devices will be installed.

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PoS(EPS-HEP 2013)394