Prospects for solar axions searches with crystals via Bragg scattering

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A calculation of the expected signal due to Primakov coherent conversion of solar axions into photons via Bragg scattering in several solid–state detectors is presented and compared with present and future experimental sensitivities. The axion window \( m_a \gtrsim 0.03 \) eV (not accessible at present by other techniques) could be explored in the foreseeable future with crystal detectors to constrain the axion–photon coupling constant \( g_{a\gamma\gamma} \) below the latest bounds coming from helioseismology. On the contrary a positive signal in the sensitivity region of such devices would imply revisiting other more stringent astrophysical limits derived for the same range of the axion mass. The application of this technique to the COSME germanium detector which is taking data at the Canfranc Underground Laboratory leads to a 95% C.L. limit \( g_{a\gamma\gamma} \lesssim 2.8 \times 10^{-9} \) GeV\(^{-1}\).

1. Introduction

Introduced twenty years ago as the Nambu–Goldstone boson of the Peccei–Quinn symmetry to explain in an elegant way CP conservation in QCD [1], the axion is remarkably also one of the best candidates to provide at least a fraction of the Non Barionic Dark Matter of the Universe. Axion phenomenology is determined by its mass \( m_a \) which in turn is fixed by the scale \( f_a \) of the Peccei–Quinn symmetry breaking [1, 6]. No hint is provided by theory about where the \( f_a \) scale should be. A combination of astrophysical, cosmological and nuclear physics constraints restricts the allowed range of viable axion masses into a relatively narrow window [2]: \( 10^{-6} \)eV \( \lesssim m_a \lesssim 10^{-2} \)eV and 3 eV \( \lesssim m_a \lesssim 20 \)eV.

The physical process used in axion search experiments is the Primakov effect. It makes use of the coupling \( g_{a\gamma\gamma} \) between the axion field and the electromagnetic tensor and allows for the conversion of the axion into a photon. This coupling appears automatically in every axion model, and like all the other axion couplings, it is proportional to \( m_a \) [2, 3, 4]. \( g_{a\gamma\gamma} \simeq 0.19 C_{a\gamma\gamma} (m_a/\text{eV}) 10^{-9} \) GeV\(^{-1}\), where the constant \( C_{a\gamma\gamma} \) depends on the axion model considered. Two popular models [3] are the GUT–DFSZ axion (\( C_{a\gamma\gamma} = 0.75 \pm 0.08 \)) and the KSVZ axion (\( C_{a\gamma\gamma} = -1.92 \pm 0.08 \)). However, the possibility to build viable axion models with different values of \( C_{a\gamma\gamma} \) and the theoretical uncertainties involved [6] imply that a very small or even vanishing \( g_{a\gamma\gamma} \) cannot be in principle excluded.

2. Primakov conversion in crystals

Axions can be efficiently produced in the interior of the Sun by Primakov conversion of the blackbody photons in the fluctuating electric field of the plasma. Solid state detectors provide a simple mechanism for detecting these axions. Axions can pass in the proximity of the atomic nuclei of the crystal where the intense electric field can trigger their conversion into photons. Due to the fact that the solar axion flux has an outgoing average energy of about 4 keV (corresponding to the temperature in the core of the Sun, \( T \sim 10^7 K \)) they can produce detectable x–rays in a crystal detector. Depending on the direction of the incoming axion flux with respect to the planes of the crystal lattice, a coherent effect can be produced when the Bragg condition is fulfilled, leading so to a strong enhancement of the signal.

Making use of the calculation of the flux of solar axions of Ref. [8], as well as the cross–section of the process and appropriate cristallographic
Figure 1. Expected axion signals for Primakov conversion in various crystals as a function of time for $g_{a\gamma\gamma} = 10^{-8}$ GeV$^{-1}$. From top–left to bottom–right: a) Ge, 2 keV $\leq E_{ee} \leq 2.5$ keV; b) Ge, 4 keV $\leq E_{ee} \leq 4.5$ keV; c) TeO$_2$, 5 keV $\leq E_{ee} \leq 7$ keV; d) TeO$_2$, 7 keV $\leq E_{ee} \leq 9$ keV; e) NaI, 2 keV $\leq E_{ee} \leq 4$ keV; f) NaI, 4 keV $\leq E_{ee} \leq 6$ keV.

information, we calculate the expected axion-to-photon conversion count rate in a solid-state detector (See ref. [3] for further details). Some examples of this count rate for several materials and energy windows are shown in figure 1 as a function of time for $g_{a\gamma\gamma} = 10^{-8}$ GeV$^{-1}$. From top–left to bottom–right: a) Ge, 2 keV $\leq E_{ee} \leq 2.5$ keV; b) Ge, 4 keV $\leq E_{ee} \leq 4.5$ keV; c) TeO$_2$, 5 keV $\leq E_{ee} \leq 7$ keV; d) TeO$_2$, 7 keV $\leq E_{ee} \leq 9$ keV; e) NaI, 2 keV $\leq E_{ee} \leq 4$ keV; f) NaI, 4 keV $\leq E_{ee} \leq 6$ keV.

The method described above has been applied to the 311 days of data obtained by the COSME 0.234 kg germanium detector (which is also being used for Dark Matter detection, as is briefly commented in the Dark Matter review talk in these proceedings) in the Canfranc Underground Laboratory, with a effective threshold of 2.5 keV and a low energy background of 0.7 c/keV/kg/day. With these conditions and despite its lower statistics, we reach a limit $g_{a\gamma\gamma} \lesssim 2.8 \times 10^{-9}$ GeV$^{-1}$ very close to the one obtained by the SOLAX Collaboration [3] which is the (mass independent but solar model dependent) most stringent laboratory bound for the axion–photon coupling obtained so far.

3. Future prospects

The sensitivity of an axion experimental search can be expressed as the upper bound of $g_{a\gamma\gamma}$ which such experiment would provide from the non–appearance of the axion signal, for a given crystal, background and exposure. It is easy to verify that the ensuing limit on the axion–photon coupling $g_{a\gamma\gamma}^{\text{lim}}$ scales with the background and exposure in the following way:

$$g_{a\gamma\gamma} \leq g_{a\gamma\gamma}^{\text{lim}} \simeq K \left( \frac{b \text{ cpd/kg/keV}}{M \text{ kg} \times \text{years}} \right)^{1/8} \times 10^{-9} \text{ GeV}^{-1} \quad (1)$$

where $M$ is the total mass and $b$ is the average background. The factor $K$ depends on the parameters of the crystal, as well as on the experimental threshold and resolution.

In order to perform a systematic analysis of the axion–detection capability of crystal detectors, we have applied the technique described in the previous section to several materials. The result is summarized in Table 1, where the limit given by the experiment of Ref.[3] is compared to those attainable with COSME and other running, being installed and planned crystal detector experiments (See [4] for references).

In Table 1 a Pb detector is also included, to give an indication of the best improvement that one would expect by selecting heavy materials to take advantage of the proportionality to $Z^2$ of
Table 1
Axion search sensitivities for running (COSME,DAMA), being installed (CUORICINO, ANAIS) and planned (CUORE, GENIUS) experiments are compared to the result of SOLAX[3] (See [9] for references). A Pb detector is also included (see text). The coefficient $K$ is defined in Eq.[1].

| $m_a$ (eV) | $\lim_{a\gamma\gamma}$ (2 years) (GeV$^{-1}$) |
|------------|--------------------------------------------------|
| Ge[3] 2.5  | 1 0.7 1000 1 $10^{-4}$ 4 1 2.7 $10^{-9}$ |
| Ge 2.3 0.234 0.7 3 0.4 2.4 |
| Ge 2.5 1000 $10^{-4}$ 4 1 3 $10^{-10}$ |
| TeO$_2$ 3 42 0.1 5 2 1.3 $10^{-9}$ |
| TeO$_2$ 2.8 765 $10^{-2}$ 3 2 6.3 $10^{-10}$ |
| NaI 2.7 87 1 2 2 1.4 $10^{-9}$ |
| NaI 2.8 107 2 2 2 1.6 $10^{-9}$ |
| Pb 2.1 1000 $10^{-4}$ 4 1 2.5 $10^{-10}$ |

Figure 2. The solar axion limit attainable with crystal detectors (horizontal thick line) is compared to the present astrophysical and experimental bounds and to the DFSZ and KSVZ axion theoretical predictions.

1/8 power dependence of $g_{a\gamma\gamma}$ on such parameters. It is evident, then, that crystals have no realistic chances to challenge the globular cluster limit. A discovery of the axion by this technique would presumably imply either a systematic error in the stellar–count observations in globular clusters or a substantial change in the theoretical models that describe the late–stage evolution of low–metallicity stars. On the other hand, the sensitivity required for crystal–detectors in order to explore a range of $g_{a\gamma\gamma}$ compatible with the solar limit[3], appears to be within reach, provided that large improvements of background as well as substantial increase of statistics be guaranteed.

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