THEORETICAL EXPECTATIONS AND EXPERIMENTAL PROSPECTS FOR SOLAR AXIONS SEARCHES WITH CRYSTAL DETECTORS

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Abstract

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.

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, the axion is remarkably also one of the best candidates to provide at least a fraction of the Dark Matter needed in Cosmology in order to explain both gravitational measurements and models of structure formation.

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, \( m_a \simeq 0.62 \) eV \((10^7 \text{ GeV}/f_a)\). No hint is provided by theory about where the \( f_a \) scale should be. A combination of astrophysical and nuclear physics constraints, and the requirement that the axion relic abundance does not overclose the Universe, restricts the allowed range of viable axion masses into a relatively narrow window:

\[
10^{-6} \text{eV} \lesssim m_a \lesssim 10^{-3} \text{eV}
\]

\[
3 \text{eV} \lesssim m_a \lesssim 20 \text{eV}.
\]

The physical process used in axion search experiments is the Primakov effect. It makes use of the coupling between the axion field \( \psi_a \) and the
electromagnetic tensor:
\[
\mathcal{L} = g_{a\gamma\gamma} \psi_a \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta} = g_{a\gamma\gamma} \psi_a \vec{B} \cdot \vec{E} \tag{2}
\]
and allows for the conversion of the axion into a photon.

Solid state detectors provide a simple mechanism for axion detection. Axions can pass in the proximity of the atomic nuclei of the crystal where the intense electric field can trigger their conversion into photons. In the process the energy of the outgoing photon is equal to that of the incoming axion.

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. The resulting flux has an outgoing average axion energy \( E_a \) of about 4 keV (corresponding to the temperature in the core of the Sun, \( T \sim 10^7 K \)) that 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. A correlation of the expected count–rate with the position of the Sun in the sky is a distinctive signature of the axion which can be used, at the least, to improve the signal/background ratio.

The process described above is independent on \( m_a \) and so are the achievable bounds for the axion–photon coupling \( g_{a\gamma\gamma} \). This fact is particularly appealing, since other experimental techniques are limited to a more restricted mass range: “haloscopes” that use electromagnetic cavities to look for the resonant conversion into microwaves of non relativistic cosmological dark halo axions, do not extend their search beyond \( m_a \approx 50 \mu eV \), while the dipole magnets used in “helioscope” experiments are not sensitive to solar axions heavier than \( m_a \approx 0.03 eV \).

A pilot experiment carried out by the SOLAX Collaboration has already searched for axion Primakov conversion in a germanium crystal of 1 kg obtaining the limit \( g_{a\gamma\gamma} \lesssim 2.7 \times 10^{-9} \text{ GeV}^{-1} \). This is the (mass independent but solar model dependent) most stringent laboratory bound for the axion–photon coupling obtained so far, although less restrictive than the globular cluster bound \( g_{a\gamma\gamma} \lesssim 0.6 \times 10^{-10} \text{ GeV}^{-1} \). Notice however that the experimental accuracy of solar observations is orders of magnitude better than for any other star.

Nevertheless the solar model itself already requires \( g_{a\gamma\gamma} \lesssim 10^{-9} \text{ GeV}^{-1} \), whereas the above Ge crystal bound has not yet reached such sensitivity. The \( 10^{-9} \text{ GeV}^{-1} \) limit sets a minimal goal for the sensitivity of future experiments, prompting the need for a systematic discussion of present efforts and future prospects for axion searches with crystals. In the following we give the result of such an analysis, focusing on Germanium, TeO\(_2\) and NaI detectors.
2 Primakov conversion in crystals

We will make use of the calculation of the flux of solar axions of Ref. 9 with the modifications introduced in Ref. 3 to include helium and metal diffusion in the solar model. A useful parametrization of the flux is the following:

\[
d\Phi/dE_a = \sqrt{\lambda} \Phi_0 (E_a/E_0)^3 (E_a/E_0)^{-1}
\]

where \(\lambda=(g_{a\gamma\gamma} \times 10^8/\text{GeV}^{-1})^4\) is an adimensional coupling introduced for later convenience, \(\Phi_0=5.95 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}\) and \(E_0=1.103 \text{ keV}\).

In the general case of a multi–target crystal, we calculate the expected axion–to–photon conversion count rate in a solid–state detector, integrated in the (electron–equivalent) energy window \(E_1<E_a<E_2\), which is given by:

\[
R(E_1, E_2) = (2\pi)^3 2\hbar c V \sum_{G} d\Phi/dE_a \frac{1}{|G|^2} \frac{g_{a\gamma\gamma}^2}{16\pi^2} \sum_j F_{a,j}^0(\vec{G}) S_j(\vec{G}) |^2 \sin^2(2\theta) \frac{1}{2} \left[ \text{erf} \left( \frac{E_a - E_1}{\sqrt{2}\sigma} \right) - \text{erf} \left( \frac{E_a - E_2}{\sqrt{2}\sigma} \right) \right]
\]

where we have used the cross–section of the conversion process calculated in Ref. 10. The first sum is over the vectors \(\vec{G}\) of the reciprocal lattice, defined by the property \(\exp i\vec{G}_i \cdot \vec{x}_i \equiv 1\), where \(\vec{x}_i\) indicate the positions in space of the target nuclei. \(V\) is the volume of the detector, \(v_a\) that of the elementary cell, \(2\theta\) the scattering angle, \(\sigma\) the resolution of the detector, FWHM=2.35 \(\sigma\), while:

\[
S_j(\vec{G}) = \sum_i e^{i\vec{G}_i \cdot \vec{x}_i}
\]

is the structure function of the crystal and

\[
F_{a,j}^0(\vec{q}) = \frac{Z_j e k^2}{r_j^2 + q^2}.
\]

\(k\equiv|\vec{k}| \approx E_a\) is the axion momentum. The crystal is described by a Bragg lattice with a basis whose sites are occupied by atoms of different types. The \(\vec{a}_i^j\) indicate the \(i\)'th basis vector occupied by the \(j\)'th target–nucleus type, \(Z_j\) is the atomic number of the \(j\)–th target nucleus while \(r_j \approx 1 \text{ \AA}\) is the screening length of the corresponding atomic electric field parametrized with a Yukawa–type potential.

The energy distribution of Eq.(3) implies that the transferred momentum \(q \equiv |\vec{q}| = 2k \sin \theta\) corresponds to a wavelength of a few \(\text{Å}\), which is of the order of the distances between atoms in a typical crystal.
Figure 1: Expected axion signals for Primakov conversion in various crystals as a function of time for $\lambda = 1$. In the calculation the representative day of 1 April 1998 and the coordinates of the LNGS laboratory have been assumed. 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.

lattice. This is the reason why a Bragg–reflection pattern arises in the calculation and in Eq. (4) the integral over the transferred momentum has been replaced by a sum over the vectors of the reciprocal lattice, i.e. over the peaks that are produced when the Primakov conversion verifies the Bragg condition $\vec{q} = \vec{G}$ and the crystal interacts in a coherent way. The Bragg condition implies that in Eq. (4) $E_a = \hbar c |\vec{G}|^2 / 2 $ $\hat{u} \cdot \vec{G}$ where the unitary vector $\hat{u}$ points toward the Sun. This term induces a time dependence in the expected signal as the detector moves daily around the Sun.
3 Time correlation and background rejection

In the expected signal the dependence on $\lambda$ can be factorized: $R \equiv \lambda \bar{R}$. An example of the function $\bar{R}$ for several materials is shown in Fig. 1 as a function of time during one day for the crystallographic inputs in the calculation, see for instance Refs. 11, 12.

The signal is peaked around the maximum of the flux of Eq. (3) and presents a strong sub–diary dependence on time, due to the motion of the Sun in the sky. The time duration of the peaks decreases with growing energies, from tens of minutes in the lowest part of the axion energy window, down to a minimum of about one minute in the higher one, and is related to the energy resolution of the detector.

In order to extract the signal from the background for each energy interval $E_k < E < E_k + \Delta E$ we introduce, following Ref. 6, the quantity:

$$
\chi = \sum_{i=1}^{n} \left[ R(t_i) - \left< R \right> \right] \cdot n_i \equiv \sum_{i=1}^{n} W_i \cdot n_i \tag{7}
$$

where the $n_i$ indicate the number of measured events in the time bin $t_i, t_i + \Delta t$ and the sum is over the total period $T$ of data taking. The brackets indicate time average.

By definition the quantity $\chi$ is expected to be compatible with zero in absence of a signal, while it weights positively the events recorded in coincidence with the expected peaks.

The time distribution of $n_i$ is supposed to be Poissonian:

$$
\langle n_i \rangle = \left[ \lambda \bar{R}(t_i) + b \right] \Delta t. \tag{8}
$$

Assuming that the background $b$ dominates over the signal the expected average and variance of $\chi$ are given by:

$$
\langle \chi \rangle = \lambda \cdot A \tag{9}
$$

$$
\sigma^2(\chi) \simeq b/A \tag{10}
$$

with $A \equiv \sum_i W_i^2 \Delta t$. Each energy bin $E_k, E_k + \Delta E$ with background $b_k$ provides an independent estimate $\lambda_k = \chi_k/A_k$ so that one can get the most probable combined value of $\lambda$:

$$
\lambda = \sum_k \chi_k/\sum_k A_k \tag{11}
$$

$$
\sigma(\lambda) = \left( \sum_k A_k/b_k \right)^{-1/2}. \tag{11}
$$

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. If $\lambda$ is compatible to zero, then at the 95\% C.L. $\lambda \lesssim 2 \times 1.64 \times \sigma(\lambda)$. It is easy to verify that the ensuing limit on the axion-photon coupling $g_{a\gamma\gamma}^{\text{im}}$ scales with the background and exposure in the following way:

$$g_{a\gamma\gamma} \lesssim g_{a\gamma\gamma}^{\text{im}} \simeq K \left( \frac{b \text{ (cpd/kg/keV)}}{\text{M (kg)}} \times \frac{\text{kg}}{\text{years}} \times \frac{\text{keV}}{T} \right)^{\frac{1}{8}} \times 10^{-9} \text{ GeV}^{-1} \quad (12)$$

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.

The application of the statistical analysis described above results in a background rejection of about two orders of magnitude. In Table 1 the result of the experiment of Ref. 6 is compared to the limits attainable with running, being installed, and planned crystal detector experiments.

4 Discussion and conclusions

As shown in the expression of the $g_{a\gamma\gamma}$ bound of Eq.(12), the improvement in background and accumulation of statistics is washed out by the $1/8$ power dependence of $g_{a\gamma\gamma}$ on such parameters. It is evident, then, from Table 1 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 self–consistent range of \( g_{a\gamma\gamma} \), compatible with the solar limit of Ref.\(^8\), appears to be within reach, provided that large improvements of background as well as substantial increase of statistics be guaranteed. Collecting a statistics of the order of a few tons \( \times \) year could be not so difficult to achieve by adding properly the results of various experiments. In such a case the exploration of a particular axion window, not accessible to detectors of other types, could be only a question of time, as a bonus from current and future dark matter searches.

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