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Solar axion search technique with correlated signals from multiple detectors

Wenqin Xu [a,b,*], Steven R. Elliott [a]

[a] Physics Division, Los Alamos National Laboratory, Los Alamos, NM, USA
[b] Department of Physics, University of South Dakota, Vermillion, SD, USA

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ABSTRACT

The coherent Bragg scattering of photons converted from solar axions inside crystals would boost the signal for axion-photon coupling enhancing experimental sensitivity for these hypothetical particles. Knowledge of the scattering angle of solar axions with respect to the crystal lattice is required to make theoretical predications of signal strength. Hence, both the lattice axis angle within a crystal and the absolute angle between the crystal and the Sun must be known. In this paper, we examine how the experimental sensitivity changes with respect to various experimental parameters. We also demonstrate that, in a multiple-crystal setup, knowledge of the relative axis orientation between multiple crystals can improve the experimental sensitivity, or equivalently, relax the precision on the absolute solar angle measurement. However, if absolute angles of all crystal axes are measured, we find that a precision of $2^\circ - 4^\circ$ will suffice for an energy resolution of $\sigma_E = 0.04E$ and a flat background. Finally, we also show that, given a minimum number of detectors, a signal model averaged over angles can substitute for precise crystal angular measurements, with some loss of sensitivity.

1. Introduction

1.1. Coherent Bragg–Primakoff conversion of solar axions

The QCD vacuum adds an extra term to the Lagrangian. The magnitude of the term is usually parameterized with an unknown constant denoted as θ. This extra term would violate parity and time reversal symmetries, but would conserve charge conjugation symmetry. As a result, it predicts a non-zero neutron electron dipole moment. Because no such dipole moment has been observed, θ must be unnaturally small. This situation is referred to as the strong CP problem.

A solution to the strong CP problem is to introduce a spontaneously broken global chiral symmetry. The associated Nambu–Goldstone boson is referred to as the axion [1–5]. Axions could be the dark matter and if they exist, the Sun would produce copious numbers of them. The science of axions is reviewed in Ref. [6].

The plasma of the solar interior can produce axions through axion-two-photon and axion-electron interactions [7–11]. The former is referred to as Primakoff axion production and its strength is given by the coupling constant, $g_{a\gamma\gamma}$. The latter results in atomic-recombination, atomic-deexcitation, Bremsstralhung, and Compton processes that produce axions with rates determined by the axion-electron coupling constant, g_{ae}. The flux produced by the Primakoff reaction dominates in hadronic axion models such as the KSVZ [12,13] where the electron-axion coupling is absent at tree level. The production of axions by the Primakoff process has been studied in Refs. [7,14,15]. The focus of this paper is the detection of axions through coherent Bragg–Primakoff conversion, and although the conclusions developed are applicable to all crystal experiments, the analysis is focused to aid upcoming experiments that will use numerous high purity Ge (HPGe) detectors. The work presented here could also be interesting to other new physics particles that can be produced in the Sun and converted back to photons in detectors, such as the hypothetical solar chameleons [16].

When solar axions reach a crystal, they can interact with the Coulomb field of nuclei and convert into photons via Primakoff conversion. This process was proposed by Buchmüller and Hoogeven [17] and Pashcos and Zioutas [18] and developed formally by Creswick et al. [19]. Given the distance between the Sun and the Earth, solar axions entering each crystal form a parallel beam. If the Bragg condition is satisfied, individual photons from axion Primakoff conversions can coherently sum to produce a strong signal, a process sometimes referred to as coherent Bragg–Primakoff conversion. The rate for this process [19,20] is

* Corresponding author.
E-mail address: Wenqin.Xu@usd.edu (W. Xu).

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expressed as,

$$\frac{dR}{dE_\gamma}(t, E_\gamma) = \int\int \frac{d\sigma}{d\Omega}\frac{d\Phi}{dE_a}\delta(E_a - E_\gamma) \times \delta(\vec{k_\gamma} - \vec{k_a} - \vec{G})dE_a d\Omega, \quad (1)$$

where E_a is the axion energy and E_γ is the energy of the axion converted photon. If the axion mass is much smaller than the axion energy, the outgoing photon carries the same energy as the incoming axion, resulting in the delta function $\delta(E_a - E_\gamma)$. $\vec{k_a}$ and $\vec{k_\gamma}$ are the axion and photon momenta respectively. $\vec{q} \equiv \vec{k_\gamma} - \vec{k_a}$ is the momentum transfer, which depends on both the lattice axis angle and the position of the Sun, resulting in a signal strength dependence on time (t). $\vec{G}$ is the reciprocal lattice vector $\vec{G} \equiv (h, k, l)\frac{2\pi}{a_0}$, where $a_0 = 0.566$ nm is the dimension of the unit cell and (h, k, l) are the Miller indices for the crystal axis. $\delta(\vec{k_\gamma} - \vec{k_a} - \vec{G})$ arises from the Bragg condition, $\vec{q} = \vec{G}$. The differential cross section for Primakoff conversion [19] is written as,

$$\frac{d\sigma}{d\Omega} = \frac{g^2_{a\gamma\gamma}}{16\pi^2}F_a^2(2\theta)sin^2 2\theta \ , \quad (2)$$

where 2θ is the scattering angle, and thus $q = 2ksin(\theta)$. $F_a(2\theta)$ is the form factor of the screened Coulomb field of the nucleus. The theoretical solar axion flux resulting from Primakoff production [19,21] can be written approximately as,

$$\frac{d\Phi}{dE_a} = \sqrt{\lambda}\frac{\Phi_0}{E_0}\frac{(E_a/E_0)^3}{e^{E_a/E_0} - 1} \ , \quad (3)$$

where $\lambda \equiv (g_{a\gamma\gamma} \times 10^8\,\text{GeV})^4$, $E_0 \equiv 1.103$ keV and $\Phi_0 \equiv 5.95 \times 10^{14}$ cm^{-2}s^{-1}. A more recent parameterization of the axion flux exists [22,23] and it can be different from Eq. (3) for up to a few percent with almost identical shape. Following the derivation in Refs. [19,20], the total signal rate of axion-converted photons in a Ge crystal with a volume of V can be expressed,

$$\frac{dR}{dE_\gamma} = (2\pi)^3 2c\hbar\frac{V}{(v_c)^2}\sum_G \frac{d\Phi}{dE_\gamma}\frac{|S(\vec{G})|^2}{|\vec{G}|^2} \times \frac{Z^2\alpha(c\hbar)^2 g^2_{a\gamma\gamma}}{16\pi}\frac{q^2(4k^2 - q^2)}{(r_0^{-2} + q^2)^2} \times \delta\left(E_\gamma - \frac{c\hbar|\vec{G}|^2}{2\hat{\vec{k}}\cdot\vec{G}}\right) \quad (4)$$

where $\hat{\vec{k}} \equiv \frac{\vec{k}}{|\vec{k}|}$ represents the direction of the solar axion flux. $r_0 = 53$ pm is the screening length in Ge crystals [24], and v_c is the volume of the unit cell. $S(\vec{G})$ is the crystal structure function, defined by Eq. (7) in Ref. [19]. A more explicit form for $|S(\vec{G})|^2$ can be found in Ref. [25]. Ref. [19] has a list of crystal planes relevant for this process with detailed discussions. The remaining delta function results from the Bragg condition expressed in terms of energy. The signal rate depends on the fourth power of $g_{a\gamma\gamma}$, and therefore it is proportional to λ.

Following Eq. (5) in Ref. [20], to account for finite energy resolution, the experimentally measured photon signal rate can be derived from a convolution,

$$\dot{R}(t, E_{exp}) \equiv \frac{dR(t, E_{exp})}{dE_{exp}} = \int \frac{1}{\sigma_E\sqrt{2\pi}}e^{\frac{-(E_{exp}-E_\gamma)^2}{2\sigma_E^2}}\frac{dR}{dE_\gamma}dE_\gamma \ , \quad (5)$$

where E_{exp} is the measured photon energy and σ_E is the 1σ detector energy resolution. This integral removes the delta function in Eq. (4).

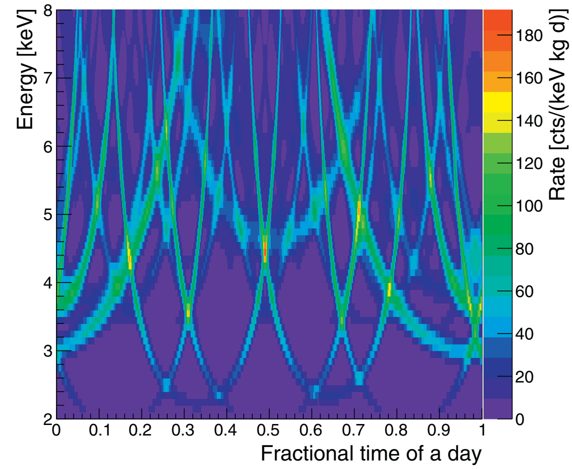

Fig. 1. Model predicted axion-induced photon signal rate with respect to photon energy and time of a day for $g_{a\gamma\gamma} = 10^{-8}$ GeV^{-1} ($\lambda = 1$) in a HPGe detector located at Lead, SD with energy resolution $\sigma_E = 0.04E$.

To facilitate calculations, Eq. (10) in Ref. [19] expressed Eq. (4) in a compact form using dimensionless kinematic variables.[1] The compact form with energy resolution incorporated becomes,

$$\dot{R}(t, E_{exp}) = \frac{M_D\dot{N}_0}{\sigma_E\sqrt{2\pi}}\lambda\sum_g\left[|S(\vec{g})|^2 \times \frac{(4\epsilon_g^2 - g^2)}{(g^2 + \gamma^2)^2} \times \frac{\epsilon_g^3}{e^{\beta\epsilon_g} - 1}e^{-\frac{(\epsilon-\epsilon_g)^2}{2\epsilon_\sigma^2}}\right] . \quad (6)$$

To obtain this compact form, the momenta and energies were made dimensionless with the conversion factor $C_{dim} \equiv \frac{a_0}{c\hbar 2\pi} = 0.457$ keV^{-1}. Explicitly, $\gamma \equiv C_{dim}/r_0$, $\epsilon \equiv E_{exp}C_{dim}$, and $\epsilon_\sigma \equiv \sigma_E C_{dim}$. $\epsilon_g \equiv \frac{|\vec{G}|^2}{2\hat{\vec{k}}\cdot\vec{G}}C_{dim}$ is the dimensionless energy that satisfies the Bragg condition, at which the solar axion flux is evaluated. In natural units ($c = \hbar = 1$), ϵ_g is written as $\epsilon_g = \frac{|\vec{g}|^2}{2\hat{\vec{k}}\cdot\vec{g}}$, where $\vec{g} \equiv \vec{G}C_{dim} = \vec{G}\frac{a_0}{2\pi} = (h, k, l)$ is the dimensionless version of $\vec{G}$. The specific constants for Ge are $\beta \equiv (E_0 C_{dim})^{-1} = 1.983$, and $\dot{N}_0 = 9.504/(\text{kg d})$. M_D is detector mass in kg and energy resolution σ_E retains its unit of energy, so that the total event rate units are explicit.

In an experiment utilizing Bragg scattering, the lattice axis angle is known to some precision and the Sun's location can be obtained based on the time of a day. Eqs. (4) and (6) are often used with detected energy and time of day as experimental variables, with axis angle an implicit parameter. Examples of the signal strength as a function of energy and time are shown in Figs. 1 and 2.

1.2. Experimental techniques

There have been several attempts to detect axions through coherent Bragg–Primakoff conversion. The SOLAX experiment [26] was a pioneer in searching for solar axions using the coherent Bragg–Primakoff conversion. The SOLAX team developed the initial detector-signature phenomenology upon which the Bragg scattering analysis is based. Like SOLAX, the COSME experiment [27] used a Ge detector in their search. The CDMS [28] and EDELWEISS [29] experiments also used Ge detectors but they were configured as bolometers. The CDMS result is notable due

[1] To avoid confusion, we note that Eq. (10) in Ref. [19] has some typographical errors. The constant $\dot{N}_0$ in that equation (or $\dot{N}$ in the text) is incorrectly given as 0.61/kg d. The denominator in $\frac{4\epsilon^2-g^2}{(g^2+\gamma^2)^2}$ should be squared, as stated here. Finally, the definition of γ should be $a_0/(2\pi r_0)$.