Sensitivity of Oriented Single Crystal Germanium Bolometers to 14.4 keV solar axions emitted by the M1 nuclear transition of ^{57}Fe

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We present a calculation of the sensitivity of single crystal germanium bolometers to mono-energetic 14.4 keV axions emitted by the M1 nuclear transition of ^{57}Fe in the Sun. The narrow 14.4 keV Fe-57 line leads to very sharp temporal features in the counting rate, effectively reducing the background by several orders of magnitude. For a detector of mass 100 kg. operating for five years, we find an expected model-independent limit on the product of the axion-photon and axion-nucleon coupling $g_{a\gamma\gamma}g_{aN}^{\rm eff} < 5.5 \times 10^{-16}$ GeV^{-1} for axion masses less than 100 eV with 95% confidence level.

1 Introduction

Since axions, or more generally axion-like particles (ALPs), can couple with electromagnetic fields or directly with leptons or quarks, the Sun could be an excellent axion emitter. Solar axions could be generated by Primakoff conversion of photons, Bremsstrahlung, Compton scattering, electron atomic recombination, atomic deexcitation, and by nuclear M1 transitions.

Searches for solar axions have been carried out with magnetic helioscopes [1, 2], low temperature bolometers [3] and thin foil nuclear targets [4]. There are several existing and proposed low-background, low-temperature germanium bolometers including the Majorana demonstrator, Gerda, CDMS, SuperCDMS and LEGEND. The low-threshold and very low background possible in germanium detectors make them ideal to search for axions with a few keV energy.

In this paper we calculate the expected conversion rate of 14.4 keV solar axions produced in the M1 nuclear transition of ^{57}Fe and detected via the coherent inverse Primakoff process in Ge single crystals. We use the dramatic time dependence of this counting rate to place a bound on the product $g_{aN}^{\rm eff}g_{a\gamma\gamma}$ for a 100 kg detector operating for five years.

2 Flux of 14.4 keV Solar Axions

The stable isotope ^{57}Fe has a natural abundance of 2.2% in the solar core, and mass fraction of 2.8×10^{-5}. The first excited state of ^{57}Fe can be thermally excited in the interior of the Sun ($kT \approx 1.3$ keV) and relax to the ground state by emitting a photon with energy 14.4 keV in an M1 transition. Since the axion is a pseudoscalar, it is also possible for the nucleus to decay to the ground state by emitting a 14.4 keV axion. The branching ratio has been calculated by

Haxton and Lee [5], and based on the standard model of the Sun [6], Moriyama[7] has calculated the total flux of 14.4 keV axions from the Sun to be

$$\Phi_0 = 4.56 \times 10^{23} (g_{aN}^{\rm eff})^2 {\rm cm}^{-2}{\rm s}^{-1}$$

where $g_{aN}^{\rm eff} \equiv -1.19 g_{aN}^0 + g_{aN}^3$ is the effective axion-nucleon coupling constant [1, 3].

The production of 14.4 keV axions is confined to the solar core. Using the standard model of the Sun[6], 90% of the 14.4 keV solar axions come from a region that is about 0.10 $R_\odot$ in radius, which subtends an angle of about 8.7×10^{-4}rad (0.05 degrees) at the Earth. As we will show in the next section, this is comparable to the angular width of “Bragg rings” within which coherent Bragg conversion of axions to photons can take place, and so the Sun cannot be treated as a point source. We take the finite size of the axion-producing part of the Sun into account by defining a Gaussian brightness function

$$f(\hat{\boldsymbol{p}} - \hat{\boldsymbol{p}}_0) = \frac{1}{2\pi\Omega^2} \exp\Big(-\frac{|\hat{\boldsymbol{p}} - \hat{\boldsymbol{p}}_0|^2}{2\Omega^2}\Big)$$

which describes the angular distribution of the axion flux over the celestial sphere. Here $\hat{\boldsymbol{p}}_0$ is a unit vector that points to the center of the Sun, $\hat{\boldsymbol{p}}$ points to an arbitrary point in the sky and $\Omega = 0.87$ mrad is the angular size of the region producing axions.

The natural linewidth of the 14.4 keV transition is extremely small, 4.7×10^{-9} eV, but thermal Doppler broadening in the solar core results in a Gaussian lineshape of width $\Delta = 2.17$ eV (FWHM=5.11 eV). Taking into account both the finite size of the solar core and Doppler broadening of the line, the differential axion flux is

$$\frac{d^2\Phi}{dEd\hat{\boldsymbol{p}}} = \Phi_0 \times \frac{1}{\sqrt{2\pi\Delta^2}} \exp\Big[-\frac{(E-E_0)^2}{2\Delta^2}\Big] f(\hat{\boldsymbol{p}} - \hat{\boldsymbol{p}}_0) {\rm cm}^{-2}{\rm keV}^{-1}{\rm s}^{-1}{\rm sr}^{-1}$$

3 Coherent Bragg-Primakoff Conversion of Axions to Photons

The cross section as a function of the energy and direction of the axion for the conversion to a photon by the inverse Primakoff effect was given earlier[8]:

$$\sigma_{a\gamma}(E, \hat{\boldsymbol{p}}) = m\hbar c \frac{4\pi^2 \alpha N_a}{\mu_c v_c} g_{a\gamma}^2 E^2 \sum_{\boldsymbol{G}} \Big| \frac{\tilde{\rho}_c(\boldsymbol{G})}{G^2} \Big|^2 |\hat{\boldsymbol{p}} \times \hat{\boldsymbol{G}}|^2 \delta\Big[E - \frac{\hbar c G}{2\hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{G}}}\Big]$$

where m is the mass of the detector, N_a Avogadro’s constant, μ_c is the molar mass of the unit cell, v_c is the volume of the conventional unit cell, α is the fine structure constant, $\boldsymbol{G}$ is a reciprocal lattice vector, $g_{a\gamma}$ is the coupling of the axion to the electromagnetic field and $\hat{\boldsymbol{p}}$ is a unit vector parallel to the incoming axion.

The Fourier transform of the charge density distribution, $\tilde{\rho}_c$ (in units of the electron charge) was calculated within density functional theory [9, 10] using WIEN2k [11]. The delta function ensures that coherent conversion can only take place when the Bragg condition

$$E_a = \frac{\hbar c G}{2\hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{G}}}$$

is satisfied. For an axion with energy E_a and a reciprocal vector $\boldsymbol{G}$ the locus of points that satisfy the Bragg condition form a circle of radius $\cos\theta = \hat{\boldsymbol{p}} \cdot \hat{\boldsymbol{G}} = \hbar c G/2E_a$. The Doppler broadening of the axion spectrum expands the Bragg circle to an annulus, or Bragg ring, of width

$$\Delta\theta = \frac{\Delta}{E_0}\cot\theta \sim 1.46 \times 10^{-4}\mathrm{rad}$$

or about 0.01 degrees. This is comparable to the angular size of the core. The angular velocity of the Sun is $7.27 \times 10^{-5}\mathrm{s}^{-1}$, so it takes the Sun just a matter of seconds to pass through one of these Bragg rings. Conversion of axions to photons can only take place during these very brief time intervals.

The time dependent counting rate is

$$\frac{\dot{N}}{m} = 4\pi^2\alpha N_a\Phi_0\frac{\hbar c E_0^2 g_{a\gamma}^2}{\mu_c v_c}\sum_{\boldsymbol{G}}\Big|\frac{\tilde{\rho}_c(\boldsymbol{G})}{G^2}\Big|^2\frac{|\hat{\boldsymbol{p}}_0 \times \hat{\boldsymbol{G}}|^2}{\sqrt{2\pi\sigma_E^2}}\exp\Big[-\frac{(E_a(\hat{\boldsymbol{p}}_0, \boldsymbol{G}) - E_0)^2}{2\sigma_E^2}\Big]\mathrm{s}^{-1}\mathrm{kg}^{-1}$$

where $\hat{\boldsymbol{p}}_0$ is a unit vector pointing to the center of the Sun, $E_0 = 14.4$ keV is the center of the axion line, and

$$\sigma_E^2 = \frac{2E_0^2\Omega^2}{\hbar c G} + \Delta^2$$

is the effective width of the Bragg ring taking into account Doppler broadening, the size of the solar core and the angle at which the Sun crosses the ring.

4 Statistical Bounds on $g_{a\gamma}g_{aN}^{eff}$

The theoretical counting rate depends both on the coupling of axions to the nucleus through the flux and the coupling of axions to the electromagnetic field in the detector. The CAST collaboration [2] has placed a bound on the product of

$$g_{a\gamma}g_{aN}^{\mathrm{eff}} < 1.36 \times 10^{-16}\mathrm{GeV}^{-1}\ 95\%\ \mathrm{CL}$$

for axion masses $m_a < .03$ eV. One of the advantages of detection by the coherent inverse Primakoff effect in crystals is that the rate is very insensitive to axion masses less than about 100 eV.

The total instantaneous counting rate can be written as

$$\dot{N}(t) = \dot{N}_a(t) + B$$

where B is the background rate (assumed constant) and $\dot{N}_a(t)$ is the axion counting rate.

We construct a random function [8] χ using the theoretical counting rate over the time of the experiment, T, and the times of individual events. By the central limit theorem the probability distribution for χ is Gaussian with mean

$$\langle\chi\rangle = \sqrt{\int_0^T dt\big(\dot{N}_a(t) - \langle\dot{N}_a\rangle\big)^2}$$

and, in the limit $B \gg |\dot{N}_a|$ the variance is

$$\Delta\chi^2 = B$$

Low-energy backgrounds as small as $0.02\text{keV}^{-1}\text{kg}^{-1}\text{d}^{-1}$ have been reported [12] for current generation germanium bolometers, and energy resolutions on the order of 200 eV are possible. If we set energy cuts at 14.4 ± 0.25keV, the background rate is approximately $0.01\text{kg}^{-1}\text{d}^{-1}$. We then find a bound on the product of the couplings

$$g_{aN}^{\text{eff}} g_{a\gamma} < 5.5 \times 10^{-16}\text{GeV}^{-1} \text{ 95\% C.L.}$$

which is is about a factor of three larger than the bound set by CAST [1], but is better than the CAST bound for axion masses greater then 0.1 eV.

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