

## Unconventional applications of the Ge detector and the axion

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**Abstract:** A brief discussion of the early history of unconventional uses of Ge detectors is given, followed by a more detailed discussion focusing on their uses for axion searches. The main purpose of this discussion is to explore the possibility of pushing the envelope of sensitivity of solar axion searches with future large Ge detector arrays applied to searches employing coherent Bragg-Primakoff conversion, as well as the axio-electric effect.

### 1. Introduction

The first unconventional application of Ge detectors of interest to particle physicists was the early search for neutrino-less double-beta decay ( $0\nu\beta\beta$ -decay) by Fiorini et al. [1]. This led to a long series of experiments [2], finally resulting in searches with detector arrays involving kg quantities of germanium enriched to ~86% in  $^{76}\text{Ge}$  [3,4].

The Ge detector was also employed in the first terrestrial search for Cold Dark Matter in the galactic halo, or Weakly Interacting Massive Particles (WIMPS) [5]. This experiment was inspired by A.K. Drukier and L. Stodolsky [6]. Although very rudimentary, it placed constraints on the mass and coupling of WIMPS to nuclei that eliminated heavy Dirac neutrinos with masses from ~10 GeV to almost 1 TeV as the dominant component of the Cold Dark Matter. There were several follow-up experiments using the same technique [7,8,9]. Later, the Ge technology was expanded to include collecting both phonon and photon signals to distinguish between ionization, caused by photons, and recoil signals that would be caused by neutrons or by WIMPS [10]. This technique led to the CDMS [11] and EDELWEIS [12] experiments. At this time, there are two large Ge detector arrays in various stages of development and construction, GERDA [13] and MAJORANA [14]. These arrays are primarily designed to search for  $0\nu\beta\beta$ -decay; however, under certain circumstances they could be very effective for searches for CDM and solar axions. It is their application to axion searches that is of main interest here.

### 2. Axions

The axion, the Goldstone boson associated with the spontaneous symmetry breaking of the Peccei-Quinn Symmetry [15,16], could be generated in the core of the sun via Primakoff interactions with nuclear electromagnetic fields. The axions could similarly be reconverted to photons in magnetic fields perpendicular to their velocities and detected with photon detectors at the end of a magnetic helioscope, or by exchanging a virtual photon with nuclei in a detector. The magnetic helioscope, CAST, briefly discussed later, has placed the most stringent constraints on the coupling of solar axions to the electromagnetic field. Both the coupling to nuclear electric fields and helioscope magnetic fields are driven by the Primakoff diagram via the Hamiltonian,

$$\mathcal{L}_{a\gamma\gamma} = a\vec{B} \cdot \vec{E} / M \quad (1)$$

In (1),  $\vec{B}$  and  $\vec{E}$  are magnetic and electric fields, respectively,  $a$  is the axion field, and  $M \equiv 2\pi f_a / \alpha$ , where  $f_a$  is the scale of the spontaneous symmetry breaking. For a value of  $f_a \approx 10^7 \text{ GeV}$  ( $M \approx 10^{10} \text{ GeV}$ ), and  $m_a \ll 1 \text{ keV}$ , for example, one expects a solar axion flux from the Primakoff process of  $\Phi_a \approx 2.1 \times 10^{11} / \text{cm}^2 \cdot \text{s} \cdot \text{keV}$  with a maximum in the spectrum at about  $4 \text{ keV}$  [17].

### 3. The axio-electric effect

The first search for solar axions with Ge detectors was with the Battelle-Carolina ultra-low background Ge prototype of a  $\beta\beta$ -decay detector in the Homestake goldmine [18]. It utilized the axio-electric effect, which is simply related to the photo-electric effect as follows [19]:

$$\sigma_{ae} = \frac{\alpha_{axion}}{\alpha_{EM}} \left( \frac{\hbar\omega}{m_e c^2} \right)^2 \sigma_{photo-electric} \quad \text{and} \quad , \quad \alpha_{axion} = \frac{1}{4\pi} \left( \frac{2x'_e m_e c^2}{f_a} \right)^2 \quad (2a)$$

$$\text{where } x'_e \approx 1, \text{ and } \alpha_{axion} = \frac{8.312 \times 10^{-8} \text{ GeV}^2}{f_a^2} \quad (2b)$$

$$\sigma_{axioelectric} = \frac{8.312 \times 10^{-8} \text{ GeV}^2 (E_a / \text{keV})^2}{f_a^2} \times \sigma_{photoelectric} \quad (2c)$$

In equations (2),  $f_a$  is the Peccei-Quinn scale in GeV. This search was only a small pilot experiment, and application of this technique to a large array of low-background Ge detectors could be a very effective search for solar axions as discussed later.

### 4. Axions in M1 nuclear transitions

A completely different search technique involves the search for axions generated in competition with M1 gamma rays in nuclear transitions, and detecting them via the Primakoff conversion to photons in a Ge detector [20]. The Lagrangian describing the coupling of axions to hadrons can be written:

$$L = a \bar{\Psi} i \gamma_5 (g_0 \beta - g_3) \Psi, \quad (3)$$

where  $g_0$  and  $g_3$  are the isoscalar and isovector coupling constants respectively. The axion to photon branching ratio for M1 transitions was derived by Haxton [20,21], and is written as follows:

$$\frac{\Gamma_a}{\Gamma_\gamma} = \frac{1}{2\pi\alpha(1-\delta^2)} \left[ \frac{g_0\beta - g_3}{(\mu_0 - 1/2)\beta + \mu_3 - \eta} \right]^2, \quad (4)$$

where  $\mu_0$  is the isoscalar magnetic moment ( $\mu_0 - 1/2 \approx 0.38$ ), while  $\mu_3 \approx 4.71$ , is the isovector magnetic moment. The parameters,  $\eta$  and  $\beta$ , are nuclear structure dependent and written as follows:

$$\eta \equiv - \frac{\left\langle J_f \left\| \sum_i^A I(i) \tau(i) \right\| J_i \right\rangle}{\left\langle J_f \left\| \sum_i^A \sigma(i) \tau_3(i) \right\| J_i \right\rangle}, \quad \text{and} \quad \beta \equiv \frac{\left\langle J_f \left\| \sum_{i=1}^A \sigma(i) \right\| J_i \right\rangle}{\left\langle J_f \left\| \sum_{i=1}^A \sigma(i) \tau_3(i) \right\| J_i \right\rangle}. \quad (5)$$

The parameter  $\beta \approx +1$  for an unpaired proton, and  $\beta \approx -1$  for an unpaired neutron, while  $\eta \approx +0.80$  in the case of  $^{57}\text{Fe}$ , for example, which has an unpaired neutron, and  $\eta \approx -3.74$  for  $^{55}\text{M}$  and  $-1.20$  for  $^{23}\text{Na}$ , both of which have unpaired protons [21].

The axion-nucleon coupling constants depend on several parameters and were given by Haxton and Lee [21]. The isoscalar and isovector coupling constants are:

$$g_0 = -1.61 \times 10^{-7} \left\{ \frac{3F - D + 2S}{f_a} \right\}, \quad \text{and} \quad g_3 = -4.84 \times 10^{-7} \left\{ \frac{(D + F)(1 - z)}{f_a(1 + z)} \right\}, \quad (6)$$

where  $F$  and  $D$  are invariant matrix elements of the axial current with values:  $F \approx 0.48; D \approx 0.77$ . In (6),  $z = m_u / m_d \approx 0.56$  in the quark model, and the Peccei-Quinn mass scale,  $f_a$ , is given in units of  $10^6 \text{ GeV}$ . The quantity,  $S$ , is the flavor singlet, axial vector matrix element and plays a crucially important role in the cross section.

### 5. Moriyama's $^{57}\text{Fe}$ Solar Axion Search Proposal

In 1995, Shigetaka Moriyama [22] used the calculations of Haxton and Lee [21] to design a technique to search for the  $14.4 \text{ keV}$  axion line from the  $14.4 \text{ keV}$   $M1$  transition from the first excited  $7/2^+$  nuclear level to the  $9/2^+$  ground state in the  $^{57}\text{Fe}$  in the sun. This level is excited by the bath of thermal photons in the solar core. While this transition lies in the high-energy tail of the predicted axion spectrum [23], there is enough  $^{57}\text{Fe}$  in the sun to produce a substantial flux of axions. Haxton and Lee calculated the solar abundance of this isotope to be  $3.26 \times 10^{-5}$  of the solar mass. They calculated:  $\beta = -1.19$ , and  $\eta = 0.80$ . Even though  $^{57}\text{Fe}$  has an unpaired neutron, and  $g_0\beta$  and  $g_3$  have opposite signs, the relatively small excitation energy,  $14.4 \text{ keV}$ , yields a favorable Boltzman factor,  $e^{-14.4 \text{ keV}/kT}$ , which also compensates for the slow transition rate ( $\tau = 140 \text{ ns}; \Gamma_\gamma = 4.7 \times 10^{-9} \text{ eV}$ ). The temperature of the core of the sun would Doppler broaden the  $14.4 \text{ keV}$  axion line to a  $FWHM \cong 5 \text{ eV}$ . From this, one concludes that the portion of line in the axion flux, effective in the resonant excitation of cold  $^{57}\text{Fe}$  in a detector on earth, would only be  $\Phi_{\text{eff}} \cong 10^{-9} \Phi_{14.4 \text{ keV}}$ .

Moriyama calculated the axion flux based on [21], but with a slight modification in the solar model given by Turck-Chie`ze et al. [24]. The resulting expression is:

$$\frac{d\Phi_a}{dE_a} = 2.0 \times 10^{13} \text{ cm}^{-1} \text{ s}^{-1} \text{ keV}^{-1} \left( \frac{10^6 \text{ GeV}}{f_a} \right)^2 C^2 \quad (7)$$

where,

$$C = -1.19 \left( \frac{3F - D + 2S}{3} \right) + (D + F) \left( \frac{1 - z}{1 + z} \right). \quad (8)$$

We choose the value  $S=0.35$  [25] for the following sample calculation. Accordingly  $C^2=0.0365$ . In reference [22], the nuclear recoil and red-shift energies were evaluated as  $1.9 \times 10^{-3} eV$  and  $1.5 \times 10^{-1} eV$  respectively, and were neglected.

Assembling these pieces, the expected detection rate in a detector of  $^{57}Fe$  is written:

$$R_{\text{det}} = \frac{d\Phi_a}{dE_a} \pi \sigma_{0\gamma} \frac{\Gamma_a}{\Gamma_\gamma} \Gamma_{\text{tot}}, \quad (9)$$

where  $\sigma_{0\gamma} = 2.6 \times 10^{-18} \text{ cm}^2$ , is the resonant  $\gamma$ -ray excitation cross section for this process [26], and  $\Gamma_{\text{tot}} = 4.7 \times 10^{-12} \text{ keV}$  is the level width obtained from a measurement of the mean life of the  $14.4 \text{ keV}$  level. The quantity  $\Gamma_a/\Gamma_\gamma$  is the axion to gamma branching ratio of the  $14.4 \text{ keV}$  axion line computed using equation (4). In the following analysis we will use the top of the open hadronic-axion window given by Raffelt [27], for which the Peccei-Quinn scale is  $f_a \leq 6 \times 10^5 \text{ GeV}$ . Substituting these values into equation (9), the differential flux is:  $d\Phi_a/dE_a = 2.0 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ , and the rate can be expressed as:

$$R_{\text{det}} = (7.67 \times 10^{-17} \text{ s}^{-1}) \frac{\Gamma_a}{\Gamma_\gamma} \quad (10)$$

per  $^{57}Fe$  atom in the detector fiducial volume. Substituting into equation (4), we see  $\Gamma_a/\Gamma_\gamma = 4.2 \times 10^{-14}$ , and the detection rate per atom in the detector becomes  $R_{\text{det}} = 3.2 \times 10^{-30} \text{ s}^{-1}$ . If the iron is isotopically enriched to 85% in  $^{57}Fe$ , there would be  $8.98 \times 10^{24}$   $^{57}Fe$  atoms per  $kg$ . The detection rate then becomes:  $3.2 \times 10^{-30} / (\text{sec} \cdot ^{57}Fe) \times (8.98 \times 10^{24} ^{57}Fe / kg) = 2.9 \times 10^{-5} \text{ sec}^{-1} \text{ kg}^{-1} \approx 2.5 \text{ d}^{-1} \text{ kg}^{-1}$ . While there are uncertainties in the various input parameters to this calculation, it is clear that there exist reasonable scenarios in which several events per day could be detected in a detector of reasonable mass.

This experiment has only been attempted with a very small  $^{57}Fe$  foil on top of a Ge detector [28]. For a detector with  $kg$  quantities of  $^{57}Fe$ , and high efficiency, the only choice would be a bolometer of a compound with a significant quantity of  $^{57}Fe$ . No such compound has yet been found. Later in this article, another way will be discussed to search for this solar-axion line using the material discussed with the multi  $kg$  detector arrays currently under development or construction.

## 6. The magnetic helioscope

In 1983, Sikivie proposed a technique to search for the invisible ‘‘axion’’ [29] that depended on the coupling of the axion to the electromagnetic field via the Primakoff vertex. At first glance, it appears that for a given magnetic induction,  $B$ ,  $P_{a\gamma}(L) \propto (BL)^2$  would continually increase as the square of the length. This is true in the special case of massless axions. For axions with mass there exists a coherence length,  $L_{\text{coh}}$ , beyond which the conversion probability vanishes.

The wave function of an axion entering the region of a magnetic field perpendicular to its velocity will be in a state, which is a coherent linear superposition of axion and photon wave functions. If the axion has a finite mass, its group velocity in the vacuum will be less than that of the speed of light, and after a distance the wave function will lose coherence, unless it would have already collapsed into a pure photon state. If the wave function is still in the superposition after traveling this maximum length of coherence,  $L_{coh}$ , the probability of conversion to a photon vanishes. This condition is met when the following relation is satisfied:  $(c - v_a)t = \lambda/2 = (1 - \beta_a)ct \Rightarrow ct \equiv L_{coh}$ . In this case we see,  $(1 - \beta_a^2) = m_a^2 c^4 / \hbar^2 \omega^2$  and since

$$\frac{1}{(1 + \beta_a)} \cong \frac{2\hbar^2 \omega^2}{m_a^2 c^4} \Rightarrow L_{coh} = \frac{\lambda}{2(1 - \beta_a)} = \frac{2\pi\hbar c}{\hbar\omega} \cdot \frac{1}{2} \cdot \frac{2\hbar^2 \omega^2}{m_a^2 c^4} \text{ and } L_{coh} \cong \frac{2\pi\hbar c E_a}{m_a^2 c^4} \quad (11)$$

From equation (11) we see that for an axion of  $m_a c^2 = 1eV$ ,  $L_{coh} = 0.5cm$  for an axion with  $4keV$  of energy. In fact we see that a 10-m magnet begins to lose coherence for axions with masses of about  $0.023eV$ .

There is a technique that makes the physical length of a given magnet the coherence length, i.e.,  $L_{coh} = L_{magnet}$ . The technique uses a filler gas in the magnet bore to provide an index of refraction for the photon such that  $v_\gamma < c$ . The more massive the axion, the higher the required gas density needed for an increase in the index of refraction that will make  $v_\gamma \approx v_a$ . There is an upper limit of this density beyond which the increase in gas density reaches the point of diminishing returns.

The CAST magnetic helioscope experiment is the most sensitive experiment to date [30]. It is a 9.26 m, 9.0T magnet mounted on a rotating frame that tracks the sun for about 1.5 hours at both sunrise and sunset. When searching for mass-less axions, a sensitivity of  $g_{a\gamma\gamma} \leq 10^{-10} GeV^{-1}$  was reached. When cold  $^3He$  was added, CAST rapidly lost sensitivity for an axion mass of about 1eV [31]. A recent analysis by Creswick, Nussinov and Avignone concluded [32]: “--- CAST helioscope, the most sensitive experiment to date, is near the limit of sensitivity in axion mass. Increasing the length, gas density, or tilt angle all have negative influences, and will not improve the sensitivity.” The question then is, have axion searches themselves reached their point of diminishing returns? Could Ge detectors in large arrays (GERDA, MAJORANA) play important roles? If so, how?

## 7. Bragg Coherent Primakoff Conversion in Single Crystal Detectors

The original ideas for this technique were taken from Buchmuller and Hoogeveen [33], from Pascos and Zioutas [34], and were brought to our group by Zioutas [35]. They were developed into a concise formulation by our group (see Creswick et al., [36]). Three experiments were conducted using this technique [37,38] which placed the best laboratory bounds for axion masses greater than  $\approx 0.2eV$ . The proposed large  $0\nu\beta\beta$ -decay experiments utilizing single crystals might be able to improve these bounds by another order

of magnitude. The cross section was derived by Buchmuller and Hoogeveen [33], and independently verified by a different method by Nussinov [39], and is written as:

$$\frac{\partial\sigma}{\partial\Omega} = \frac{g_{a\gamma\gamma}^2}{16\pi^2} F_a^2(2\theta)\sin^2\theta, \text{ where } F_a(2\theta) = F_a(qk) = \frac{Zek^2}{r_0^{-2} + q^2}, \quad (12)$$

where  $q = 2k \sin\theta$ ,  $r_0$  is the atomic-screening length, and  $g_{a\gamma\gamma}$  is the axion coupling constant in  $GeV^{-1}$ . Integrating over all angles:

$$\bar{\sigma}(\eta) = \frac{1}{4\pi} \int \frac{d\sigma}{d\Omega} \Omega = \frac{Z^2 \alpha \hbar^2 g_{a\gamma\gamma}^2}{8\pi c^2} \left[ \frac{2\eta^2 + 1}{4\eta^2} \ln(1 + 4\eta^2 - 1) \right]. \quad (13)$$

In (13),  $\eta = r_0 k$ , and  $Z^2 \alpha \hbar^2 g_{a\gamma\gamma}^2 / 8\pi c^2 = 1.15 \times 10^{-44} cm^2 \equiv \sigma_0$  when  $g_{a\gamma\gamma} = 10^{-8} GeV^{-1}$ .

For light axions, the Primakoff process of conversion from axion to photon will be coherent, similar to the Bragg reflection of x-rays, when the Bragg condition is met. That is to say, when the momentum transfer to the crystal is the reciprocal lattice vector,  $\vec{G} \equiv 2\pi/a_0(h, k, l)$ , where  $a_0$  is the dimension of a conventional cubic cell, and h,k,l are integers that define a given crystal plane.

The conversion rate in the detector is written in the following compact form [36]:

$$\frac{d\dot{N}}{d\Phi} = 2\hbar c \frac{V}{v_c^2} \sum_G |S(\vec{G})|^2 \frac{d\sigma}{d\Omega}(G) \frac{1}{|\vec{G}|^2} \delta \left[ E_a - \frac{\hbar c |\vec{G}|^2}{2\vec{k} \cdot \vec{G}} \right] \quad (14)$$

In equation (14),  $S(\vec{G})$  is the lattice structure function, written in equation below,  $V$  is the total volume of the crystal, and,  $v_c$  is the volume of a unit cell. The structure function is written as follows:

$$S(\vec{G}) = \left[ 1 + e^{i\pi/2(h+k+l)} \right] \left\{ 1 + e^{i\pi(h+k)} + e^{i\pi(h+l)} + e^{i\pi(k+l)} \right\}. \quad (15)$$

Integrating over the solar axion flux, equation (14) can be written in the following very convenient form:

Equation (14) is the predicted rate of the conversion of axions for a given axion energy given the position of the sun,  $\hat{k}$ , and the reciprocal lattice vector,  $\vec{G}$ . The detector will have a finite energy resolution and to account for this, the rate is smoothed with a Gaussian with a finite width  $\Delta E$ . The smoothed version of (14) is:

$$R(\hat{k}, E) = \hbar c \frac{V}{v_c} \sum_G |S(G)|^2 \frac{d\sigma}{d\Omega} \frac{1}{|\vec{G}|^2} \frac{d\Phi}{dE} \left[ \operatorname{erf} \left( \frac{E - E_a(\hat{k}, \vec{G})}{\sigma\sqrt{2}} \right) - \operatorname{erf} \left( \frac{E - E_a(\hat{k}, \vec{G}) - \Delta E}{\sigma\sqrt{2}} \right) \right] \quad (16)$$

where  $E_a(\hat{k}, \vec{G}) = \hbar c |\vec{G}|^2 / 2\hat{k} \cdot \vec{G}$  and  $\operatorname{erf}(x) = 2/\sqrt{\pi} \times \int e^{-t^2} dt$  is the error function.

The following theorem applies to the structure function,  $S(G)$ : “the individual indices h, k, and l, must all be either even or odd if  $S(G) \neq 0$ . If they are all even, they must all add up to a multiple of 4”. Further, it can be shown that if (h, k, l) are all even  $|S(G)|^2 = 64$ ; if they are all odd,  $|S(G)|^2 = 32$ , or  $|S(G)|^2 = \{3 + (-1)^{h+k+l}\} \times 16$ .

It is of course necessary to know when the vector,  $\vec{s}$ , from the solar core to the detector is parallel to the crystal’s inverse lattice unit vectors,  $\vec{g}$ . To this end we recall that Ge detector crystals are pulled by the Czrachsalski method along either the 100 or 011 axis. In the SOLAX experiment discussed in reference [36,37], the z-axis, which was the vertical axis, was the 100 axis. For an experiment to have real discovery potential, the angles between the other two axes and true north, for example, must also be known. The determination of the instantaneous vector,  $\vec{s}$ , between the solar core and the detector can be made using the U.S. Naval Observatory Vector Astronomy Subroutines, NOVAS [40]. Fig.1 shows an example of the detection rate on a given day, at a given location for  $g_{a\gamma\gamma} = 10^{-8} \text{ GeV}^{-1}$ , with zero background.

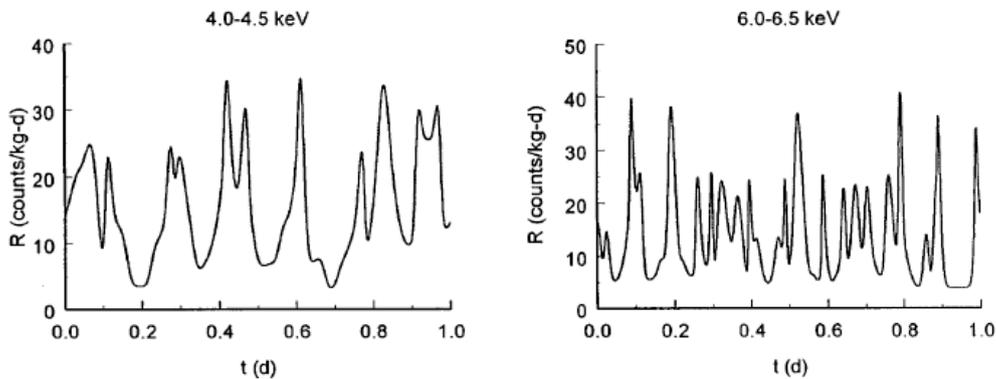


Figure 1. A sample predicted modulation of the signal in a 1-kg Ge detector computed with equation (16). The location was in southern Argentina at the SOLAX site [36,37].

## 8. Possible searches with large Ge arrays

The SOLAX experiment used the above technique in Sierra Granda Argentina [37]. It had a 1-kg detector, 4-keV energy threshold and a background of  $3.4 \text{ keV}^{-1}\text{kg}^{-1}\text{d}^{-1}$ . It operated for 708 kg.d, and achieved a limit,  $g_{a\gamma\gamma} \leq 2.7 \times 10^{-9} \text{ GeV}^{-1}$ . The COSME experiment [38], run later, used a 0.25 kg detector with a 2.5-keV threshold, a background of  $0.7 \text{ keV}^{-1}\text{kg}^{-1}\text{d}^{-1}$ . It operated for 72.7 kg.d, and achieved an upper bound of  $g_{a\gamma\gamma} \leq 2.75 \times 10^{-9} \text{ GeV}^{-1}$ . It is tempting to attempt to scale these parameters to determine what a large array could achieve by  $g_{a\gamma\gamma}(\text{sensitivity}) \propto [b/Mt]^{1/8}$ . This would be adequate for a counting experiment, but the sensitivity of a Bragg-Primakoff, SOLAX type experiment depends very sensitively on the analysis of the time-modulation structure in the data. Just scaling the experiment to a 1-ton

Ge experiment for a 10-y exposure would result in a sensitivity of  $g_{a\gamma\gamma} \approx 6 \times 10^{-10} GeV$ . This is an oversimplification; what is needed is a completely new look at the analysis technique to minimize the effect of background. The goal should be to achieve a sensitivity of  $g_{a\gamma\gamma} \leq 10^{-10} GeV$ , to cover the axion-model space in axion mass, which cannot be done with a helioscope.

Another approach depends involves the search for the axions from the 14.4 keV M1 transition in  $^{57}Fe$  in the sun. Following the reasoning of Moriyama discussed above,  $\Phi_a(14.4keV) \approx 2.8 \times 10^{10} cm^{-2}s^{-1}$ . The photoelectric cross section from standard tables is:  $\sigma_{photo} = 8.8 \times 10^{-21} cm^2$ . Applying equations (2a,b,c),  $\sigma_{axioelectric} = 1.2 \times 10^{-42} cm^2$ , using the Peccei-Quinn scale corresponding to  $g_{a\gamma\gamma} = 10^{-10} GeV^{-1}$ . Accordingly, the detection rate would be:  $R = N\sigma_a\Phi_a \approx 2.4 \times 10^{-2} kg^{-1}d^{-1}$ , or about 525 detections in a 60 kg Ge detector array per year.

The rate of detection of solar axions produced by the Primakoff process is also interesting. In this case we use the flux suggested by Raffelt [27] and integrate the product of flux and cross section over axion energy  $E_a = \hbar\omega$ , where  $d\Phi_a(E_a)/dE_a = 6 \times 10^{10} \cdot E_a^{2.481} (e^{-E_a/1.205})$ . The result is:

$$R = \int_{E_1}^{E_2} \Phi_a(E_a)\sigma(E_a)dE_a = 0.134 kg^{-1}d^{-1} . \quad (17)$$

This is a healthy rate of ~8 per day in a 60 kg array, like the Majorana Demonstrator, or 134 per day in a 1-ton array. This rate will fall rapidly as  $g_{a\gamma\gamma}$  decreases.

## 9. Conclusions

While the search for axions has almost run into a stone wall, there is still some hope for discovery with large germanium detector arrays, for coupling constants not too much smaller that with a Peccei-Quinn scale corresponding to  $M \approx 10^{10} GeV$ . Since large arrays are being proposed by the GERDA and Majorana collaborations, it is well worth including these searches in their scientific programs. It is also still worth- while continuing the search for a compound containing  $^{57}Fe$  that would make a good bolometer, although this appears to be a long shot at this time.

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