Proposed Bragg-Coherent Axion Search with CUORE

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2017-02/avignone_frank

We propose a technique for searching for axions with data from the CUORE detector using the Bragg-Coherent axion-photon conversion in the 988 single TeO_2 crystal bolometers of the 740 kg CUORE array. The search would be for the 14.4-keV axions from axion branch of the M1 ground-state transition from the ^{57}Fe in the solar core.

The Strong-CP problem is very familiar to all who attended this conference. The Peccei–Quinn suggested solution to the problem is also well known; however, the Goldstone boson that results from the breaking of PQ symmetry has thus far escaped detection. At this conference there were many suggested, as well as attempted, experimental efforts of detection. For completeness, we give a brief review of the formal aspects of the problem. We revisit a technique that we introduced in 1998 [1, 2], but in this case the proposed detector is the 740-kg array of 988 TeO_2 bolometers of the CUORE detector. Here, we very briefly review the theoretical motivation of the problem. To quote Roberto Peccei, "Introducing a global chiral U(1) symmetry – which has become known as a $U(1)_{PQ}$ symmetry – provides perhaps the most cogent solution to the strong CP problem. To make the SM Lagrangian $U(1)_{PQ}$ invariant, it must be augmented by axion interactions [3, 4]."

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{SM}} + \bar{\theta}\frac{g_s^2}{32\pi^2}G_b^{\mu\nu}\widetilde{G}_{b\mu\nu} - \frac{1}{2}\partial_\mu a\partial^\mu a + \mathcal{L}_{\text{int}}[\partial^\mu a/f_a, \Psi] + \zeta\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G_b^{\mu\nu}\widetilde{G}_{b\mu\nu}.$$

The last term is needed to ensure that the $U(1)_{PQ}$ has a chiral anomaly. This last term represents an effective potential for the axion field, and its minimum occurs at $\langle a\rangle = -\bar{\theta}f_a/\zeta$. One notes that the last term cancels the first (CP-offending) term, and good CP symmetry is restored. However, the broken U(1)-symmetry results in a Goldstone boson, the axion, which is the main motivation for this conference, and many of the talks presented.

The axion obeys the general property of the two-photon interaction as they are cousins to the neutral Pi-zero. Axion coupling to photons is governed by the Primakoff diagram, and the Lagrangian governing this interaction is written:

$$\mathcal{L}_{a\gamma} = \frac{1}{4}g_{a\gamma}F_{\nu\mu}\widetilde{F}^{\nu\mu}a = -g_{a\gamma}a\vec{E}\cdot\vec{B},$$

where F is the electromagnetic field strength tensor, $\widetilde{F}$ is its dual while "a" is the axion field. In both the hadronic and GUT models, the coupling constant is given by:

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{A^{\text{EM}}}{A^{\text{C}}} - \frac{2}{3}\frac{4+z}{1+z}\right) = \frac{\alpha}{2\pi f_a}\left(\frac{A^{\text{EM}}}{A^{\text{C}}} - 1.95 \pm 0.08\right),$$

where A^{EM} is the electromagnetic anomaly, and A^{C} is the color anomaly. In the DFSZ (GUT) model $A^{\mathrm{EM}}/A^{\mathrm{C}} = 8/3$, and in the KSVZ (hadronic) model, this ratio is zero in most versions, because there is no electromagnetic anomaly. Accordingly, $g_{a\gamma}^{\mathrm{KSVZ}}/g_{a\gamma}^{\mathrm{DFSZ}} = 2.72$. In both models, the value of g_{aN}^{eff} depends sensitively on nuclear parameters.

The source of axions of interest here are from the 14.4-keV M1 ground-state transition in ^{57}Fe in the solar core. The axion branching ratio in nuclear decay was presented by Haxton in Avignone et al., [5], and by Haxton and Lee [6].

$$\Gamma_a/\Gamma_\gamma = (k_a/k_\gamma)^3 \frac{1}{2\pi\alpha}\frac{1}{(1+\delta^2)}\left[\frac{g_{aN}^0\beta + g_{aN}^3}{(\mu_0 - 1/2)\beta + \mu_3 - \eta}\right]^2$$

This ratio enters into the calculation of the axion flux from nuclear transitions, hence it will depend on the model where, g_{aN}^0 and g_{aN}^3, are the isoscalar and isovector coupling constants, respectively. We use the values of the relevant nuclear parameters given by Haxton and Lee [6]:

$$\mu_0 = 0.88 : \beta = -1.19 : \delta = 0.002 : \mu_3 = 4.71 : \eta = 0.80, \text{ and}$$
$$\Gamma_a/\Gamma_\gamma = (k_a/k_\gamma)^3 1.82(-1.19 g_{aN}^0 + g_{aN}^3)^2; \text{ where we define } g_{aN}^{\mathrm{eff}} \equiv (-1.19 g_{aN}^0 + g_{aN}^3).$$

Recall that the sign on -1.19 is negative when the unpaired nucleon is a neutron. In the case that the unpaired nucleon is a proton, the sign is positive. The flux can be written:

$$\Phi_a(14.4\,\mathrm{keV}) = \frac{n(^{57}\mathrm{Fe})}{4\pi d^2\tau_\gamma} 2\frac{\Gamma_a}{\Gamma_\gamma}\int_0^R e^{-E/kT(r)}\rho(r)4\pi r^2\,dr.$$

In the above equation, $n(^{57}\mathrm{Fe}) = (3 \times 10^{17})\,^{57}\mathrm{Fe/g}$ is the number of ^{57}Fe nuclei per gram of solar material, τ_γ is the mean-life of the M1 ground state transition, d is the earth sun distance, $\rho(r)$, and is the radial dependent solar mass density. The solar temperature profile was taken from the standard solar model of Bahcall and Pinsonneault [7]. Integrating, and substituting values for the all the parameters, we obtain:

$$\Phi_a^{\mathrm{KSVZ}}(^{57}\mathrm{Fe}) = 4.56 \times 10^{23}(g_{aN}^{\mathrm{eff}})^2_{\mathrm{KSVZ}}\,\mathrm{cm^{-2}s^{-1}}.$$

This is the same value determined by the CAST Collaboration [8], and depends on the particular solar thermal profile used. The effective axion-nucleon coupling is very model dependent.

Coherent Bragg conversion in single crystals

The derivation of the axion-to-photon conversion rate was given earlier [9]. The formalism follows from the vector diagram shown in Fig. 1.

The coherent cross section was given in ref. [9], and is written as follows:

$$\sigma(\vec{\rho}) = g_{a\gamma\gamma}^2 \frac{4\pi^2\alpha N_c \hbar^3 c^3}{v_c}\sum_{\vec{G}}\left|\frac{\widetilde{\rho}(\vec{G})}{G^2}\right|^2 \frac{|\vec{\rho}\times\vec{G}|^2}{G^2}\delta(E_a - E_\gamma)$$
$$\widetilde{\rho}(\vec{p}-\vec{k}) = 0, \text{ unless } \vec{p}-\vec{k} = \vec{G}.$$

Accordingly, only when the line from the solar core to the crystal satisfies this condition (a Bragg condition) will the cross section not vanish. To achieve our goal, the uncertainties in

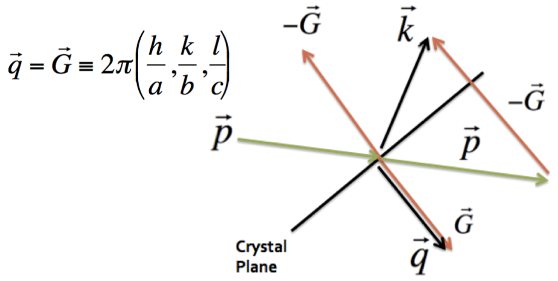

Figure 1: A vector diagram showing the initial axion momentum, $\vec{p}$, the reflected momentum, $\vec{k}$, the momentum transfer, $\vec{q}$, and the reciprocal lattice vector, $\vec{G}$.

the orientation angles of each of the crystals in the array must be determined. The required data are the energy, $14.4\,\mathrm{keV} \pm \delta E$, where δE reflects the energy resolution, and the time of the event, $t \pm \delta t$, where δt is determined from the uncertainty in the absolute orientations of the individual crystal bolometers. A typical plot of the detection rates, with an unrealistic coupling is shown in Fig. 2.

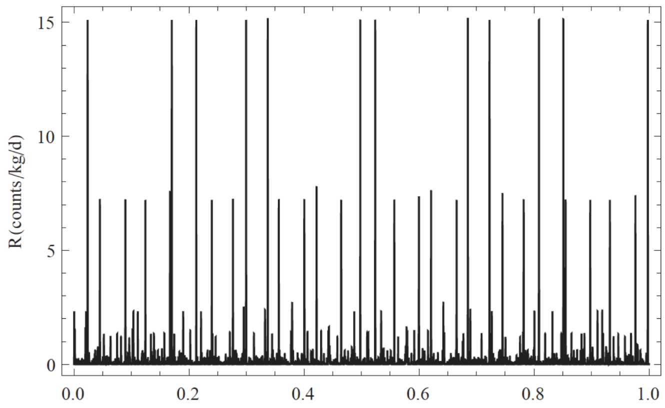

Figure 2: The theoretical pattern of predicted count rates at the predicted times when the Bragg condidtions are satisfied. The horizontal axis represents 24 hours of a particular day. These rates were calculated with a unrealisticly large value of the axion-photon coupling constant, $10^{-8}\,\mathrm{GeV}^{-1}$.

The CUORE detector

The Cryogenic Underground Observatory for Rare Events (CUORE) is a multipurpose array of 988, 750 gram TeO_2 bolometers in the LNGS in Assergi, Italy [10]. Its main mission is to search for the neutrino-less double-beta decay ($0\nu\beta\beta$-decay) of ^{130}Te; however, it also has the capability to search for Cold Dark Matter (CDM) as well as axions.

For such a large detector mass one would expect a very sensitive search; however, the sensitivity depends on the product, $(g^{\mathrm{eff}}_{aN} \times g_{a\gamma\gamma})$. Our analyses lead us to conclude that our sensi-

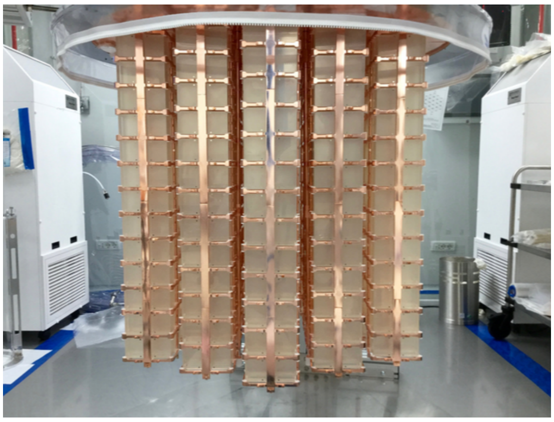

Figure 3: The CUORE array of 988 TeO_2 Bolometers in 19 towers prior to installation in the cryostat. All crystal axes are nomonaly equally oriented with small uncertainties.

tivity would be about the same as that publisted by the CAST Collaboration below 0.07 eV [8]; however, CAST looses coherence for axion masses above ~0.07 eV. CUORE does not have a coherence issue at these energies, and therefore could explore a significant portion of the $(g_{a\gamma\gamma} - m_{\mathrm{axion}})$-space not reachable by CAST. CUORE started collecting physics data in early 2017. At this point, the axion search group is in the process of determining the uncertainties in the absolute orientation of the crystals.

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