Point-contact detectors in searches for bremsstrahlung production of axions from the Sun.

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The low-energy portion of the published spectrum of the COGENT experiment has been reanalyzed to search for evidence of low-energy bremsstrahlung-generated solar axions. In the case of the DFSZ model, an upper bound of $g_{ae} \leq 3.0 \times 10^{-11}$ (90% C.L.) is placed on the direct coupling of axions to electrons.

1 Introduction

The strong-CP problem has been with us for many years. The strong force described by QCD has a CP-violating term in the Lagrangian, the strength of which is fixed by a parameter θ. This parameter must be less than 10^{-10} for QCD to be consistent with the experimental bound,$|d_n| \leq 2.9 \times 10^{-26}$ e-cm for the electric dipole moment of the neutron[1]. The fact that the strong-interaction parameter, θ, must have such a small value is indeed unnatural. To address this problem, Roberto Peccei and Helen Quinn postulated a new global symmetry that is spontaneously broken at a high-energy scale[2]. This mechanism produces a term that cancels the problematic one. The properties of the Goldstone boson (the axion) resulting from this symmetry breaking were discussed in the context of the standard model in 1978 in independent articles by Weinberg[3] and by Wilczek[4].

The standard-model axion was ruled out by early experiments. However, to explain the lack of experimental observation, a model for the "invisible hadronic axion" was introduced by Kim[5], and also by Shifman, Vainstein and Zakharov[6], the KSVZ model. In this model, the axion couples directly to hadrons and photons but does not couple to electrons at the tree level. In the KSVZ model the axion and electron couple radiatively at the one-loop level.

Another model for an "*invisible axion*" was introduced by Zhitnitskii[7], and independently by Dine, Fischler and Srednicki[8], the DFSZ model. In this model the axion couples to hadrons and photons, and also to electrons at the tree level. In this paper we present a reanalysis of a previously published spectrum from the COGENT experiment[9] in order to place bounds on the coupling of DFSZ axions to electrons. We assume that the axions in question are produced by a bremsstrahlung-like process in the Sun and are detected with the axioelectric effect in the point-contact COGENT germanium detector. In this way the predicted rate depends only on the coupling of axions and electrons since both production and detection depend on the same coupling. The COGENT experiment was a search for cold dark matter with a well-shielded, ultra-low-background, point-contact germanium detector operated in an underground facility. All details can be found in reference[9] and references therein, and will not be discussed here.

2 Axion Phenomenology

The mass of the axion, m_a, (in eV) is connected to the Peccei-Quinn symmetry breaking scale, f_a, in both the DFSZ and KSVZ models by

$$m_a = \frac{f_\pi m_\pi}{f_a}\Big(\frac{z}{(1+z+w)(1+z)}\Big)^{1/2} \simeq 6.0(\mathrm{eV})\frac{10^6(\mathrm{Gev})}{f_a(\mathrm{GeV})} \quad (1)$$

where, $f_\pi = 93$MeV is the pion decay constant,$z = m_u/m_d \simeq 0.56$ is the ratio of the masses of up and down quarks, and $w = m_u/m_s \simeq 0.029$ is the ratio of up and strange quark masses.

In this analysis we choose to use the form for the axion flux produced by a bremsstrahlung-like process in the Sun derived in a recent paper by Derbin et al.[10]. This expression differs somewhat from that derived by Kekez et al.[11]. The differential flux is

$$\frac{d\Phi}{dE} = 4.14 \times 10^{35} g_{ae}^2 E_a^{0.89} e^{-0.7E_a - 1.26\sqrt{E_a}} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1} \quad (2)$$

where g_{ae} is the dimensionless coupling constant of axions to electrons, and E_a is the axion energy in keV. The cross section for the axioelectric absorption of very light, relativistic axions on electrons is also driven by g_{ae}. This expression was rederived by Pospelov, Ritz and Voloshin[12], and is a factor of two larger than the originally published expression[13, 14]. It can be conveniently expressed in terms of the photoelectric cross section,σ_{pe}, as follows:

$$\sigma_{ae} = \frac{\omega_a^2}{2\pi\alpha f_a^2}\sigma_{pe} \quad (3)$$

In the DFSZ model, the axion-electron coupling constant, g_{ae}, is related to the axion mass, m_a by[8]

$$g_{ae} = \frac{m_e}{3f_a}\cos^2\beta \quad (4)$$

where $\cos\beta$ is the ratio of Higgs expectation values[8], and it is customary to set $\cos^2\beta = 1$[10]. Combining equations (1) and (4) the relation between g_{ae} and f_a can be expressed $1/f_a = 5.87 \times 10^3 g_{ae}\mathrm{MeV}^{-1}$. Equation (3) becomes

$$\sigma_{ae} = 7.72 \times 10^{-4} g_{ae}^2 E_a^2 \sigma_{pe} \quad (5)$$

Integrating the product of the axion flux, (2), with the cross section (5) over an energy interval between 0.45 keV $\leq E_a \leq$ 1.0 keV gives the rate

$$\int_{0.45}^{1.0} \frac{d\Phi}{dE_a}\sigma_{ae} dE_a = 2.505 \times 10^{-20} \mathrm{axions/sec} \quad (6)$$

3 Data Analysis

We consider the low-energy portion of the COGENT spectrum published by Hooper et al.[9]. This spectrum was collected over 56 days with a point-contact, high-purity germanium detector with a fiducial mass of 0.33 kg. The energy range of the present analysis is from 0.45keV $\leq E_a \leq$ 1.0keV. A fit to the data including the x-ray peaks up to 3 keV is shown in Figure (3) of reference [9] and justifies the subtraction of 2 background counts from each 0.05 keV

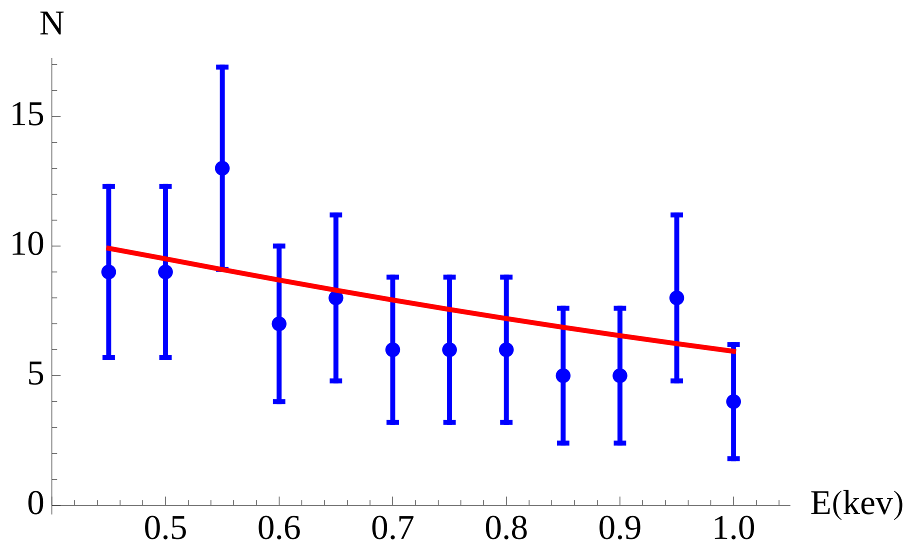

Figure 1: The experimental data with a constant 2 counts per 0.05 keV subtracted across the energy range 0.45 keV to 1.0 keV. This is justified from the fit to the data above the x-ray peaks shown in Figure 3 of ref. [9]. The red curve is a plot of the theoretical prediction for $g_{ae} = 2 \times 10^{-11}$.

bin. The portion of interest of the corrected spectrum is shown in Figure 1. The number of Ge atoms in the fiducial mass is $N = 2.74 \times 10^{24}$ and $t = 56$ days $= 4.84 \times 10^6$s which gives $Nt = 1.33 \times 10^{31}$ atom-s.

If we arbitrarily choose $g_{ae} = 10^{-10}$ and calculate the predicted axio-electric absorption rate of solar axions in the COGENT detector, we find $R = 7.95 \times 10^{28}$/atom-s.

The total number of predicted events in this scenario is 10595. There were only 85 candidate events in the experimental data, or less than 100 events with 90% C.L. If we make the conservative assumption that all the events in the energy interval $0.45\text{keV} \leq E_a \leq 1.0\text{keV}$ are caused by axions we can place an upper limit

$$g_{ae} \leq 3.0 \times 10^{-11} \; 90\% \text{ C.L.} \tag{7}$$

This is similar the limit $g_{ae} \leq 5.4 \times 10^{-11}$ 90% C.L. obtained by the XMASS Collaboration with their 835-kg xenon detector running for 6 days[16]. It should also be pointed out that the data used in the present analysis are vastly lower in background at 0.5-keV than the data of XMASS[16], or from the that of reference[11]. The present 95% C.L. bound is similar to the 95% solar bound of Gondolo and Raffelt[17].

In the present case, the experimental spectrum and the predicted bremsstrahlung-like solar-axion spectrum are very similar. Therefore, it is appropriate to assume that all the counts in the spectrum above the flat 2 counts/0.05 keV from fitting the background at higher energy could be candidate events. For this reason, in searches for the continuous solar-axion spectra, it is most important to have the lowest background possible.

For experiments of this type to have discovery potential, it would be ideal to use the model-independent annual modulation in the sun-earth distance. The solar- axion flux is proportional to $1/r^2$, which is 6.68% larger in January than in July. The analysis of the data from the MAJORANA Broad-Energy Detector at Kimallton, MALBEK, is being analyzed in this way by the MAJORANA Collaboration.[19]

Acknowledgments

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