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SEARCH FOR SOLAR AXIONS BY PRIMAKOFF EFFECT IN NAI CRYSTALS

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Abstract

A search for solar axions exploiting the Primakoff coherent converion of these particles into photons in the NaI(Tl) crystals of DAMA/NaI set-up is presented.

1 Introduction

The axion was introduced in 1977 as the Nambu–Goldstone boson of the Peccei–Quinn (PQ) symmetry proposed to explain CP conservation in QCD [1]. The theory does not provide restrictions on axion mass, therefore in the past a certain number of experiments was realised to search for these particles in a large extent, without success.

Various experimental and theoretical considerations have restricted at present the axion mass to the range 10^{-6}eV $\lesssim m_a \lesssim 10^{-2}$eV and $m_a \sim$ eV. It has also been noted that axions with a similar mass could be candidate as a possible component of the Dark Matter in the Universe.

Axions can efficiently be produced in the interior of the Sun by Primakoff conversion of the blackbody photons in the fluctuating electric field of the plasma. The outgoing axion flux has an average energy, E_a, of about 4 keV since the temperature in the Sun core is $T \sim 10^7 K$. In the hypothesis of no direct coupling between axion and leptons (*hadronic axion*) and including in the solar model helium and metal diffusion, the flux of solar axions depends on the squared root of the dimensionless coupling constant $\lambda = (g_{a\gamma\gamma} \times 10^8/\mathrm{GeV}^{-1})^4$ [2, 3], where $g_{a\gamma\gamma}$ is the coupling constant of the conversion of the axion into a photon; its value depends on the considered axion model [4, 5].

When solar axions interact with the electric field of the crystal's atoms detectable X–rays can be produced via a coherent effect, and, if the Bragg condition is fulfilled, a strong enhancement of the possible signal can be expected. Thus, a distinctive signature for solar axion can be searched for by comparing the experimental counting rate with the expected one by taking into account the position of the Sun in the sky during the data taking [6, 7, 8]. We note that positive results or bounds on $g_{a\gamma\gamma}$ obtained by this approach are independent on m_a and, therefore, overcome the limitations of some other techniques which are instead restricted to a limited mass range [9, 10].

DAMA experiment has searched for solar axions exploiting this approach [11] by means of the $\simeq$ 100 kg NaI(Tl) DAMA set-up [12] running deep underground in the Gran Sasso National Laboratory of I.N.F.N.. The Laboratory is located at $42^o 27' N$ latitude, $13^o 11' E$ longitude and 940 m level with respect to the mean Earth ellipsoid.

2 Experimental set-up

DAMA/NaI set-up – consisting in $\simeq$ 100 kg of highly radiopure NaI(Tl) – and its performances have been described in detail elsewhere [12]. Here we only remind that the data of this analysis have been collected with nine 9.70 kg NaI(Tl) crystal scintillators – $(10.2 \times 10.2 \times 25.4)$ cm^3 each one – enclosed in suitably radiopure Cu housings and coupled through two 10 cm long tetrasil-B light guides to two photomultipliers EMI9265-B53/FL work in coincidence at single photoelectron level. The detectors are enclosed in a low radioactive copper box inside a low radioactive shield made by 10 cm copper and 15 cm lead. The lead is surrounded by 1.5 mm Cd foils and about 10 cm of polyethylene. A high purity (HP) Nitrogen atmosphere is maintained inside the copper. The whole shield is enclosed in a sealed plexiglas box also maintained in HP Nitrogen atmosphere as well as the glove-box which is located on the top of the shield to allow the detectors calibration in the same running conditions without any contact with external environment. The installation is subjected to air conditioning. The typical energy resolution is $\sigma/E = 7.5\%$ at 59.5 keV.

As of interest here, the energy, the identification of the fired crystal and the absolute time occurrence are acquired for each event.

3 Results

For a detailed discussion about the data analysis one can refer to [11]; here we only recall that expected rate for solar axion in a crystalline detector is directly proportional to the adimensional constant λ and depends on the particular features of the NaI lattice and on the position of the Sun respect to the detector. In particular, it is possible to introduce the coordinates θ_z, angle between the vector pointing to the Sun and one crystallographic axis of the NaI crystal (here the growth symmetry axis, *gsa*), and ϕ_{az}, angle between the horizontal plane of the crystal and the plane containing both the Sun and *gsa*. They are related to the versor $\hat{k}$ of the axion momentum, which identifies the Sun position in the sky, by the expression: $\hat{k} = -\hat{x}sin(\theta_z)cos(\phi_{az}) - \hat{y}sin(\theta_z)sin(\phi_{az}) - \hat{z}cos(\theta_z)$. In this analysis in order to be the most conservative on the used crystals features, only a symmetry around *gsa* has been condsidered, and the expected counting rate was calculated by averaging over the ϕ_{az} coordinate. This average reduces the sensitivity achievable here with respect to the case when three crystalline axes orientations are taken into account.

The expected counting rate in the NaI detector – averaged over ϕ_{az} – is reported in Figure 1 as a function of θ_z considering 2 keV energy bin from 0 to 8 keV. Other energy intervals up to 16 keV are shown in ref. [11].

Since the mean value of the expected counting rate in energy intervals above 10 keV is significantly lower than at low energy, in the present analysis the energy range 2 keV (software energy threshold of our experiment) to 10 keV has been considered [11]. The data analysed here refer to a statistics of 53437 $kg \cdot day$.

To investigate with high sensitivity either the possible presence of a solar axion signal or to achieve upper limit on λ (and, consequently, on $g_{a\gamma\gamma}$), we exploit the time dependence of the solar axion signal. For this purpose the distribution of the experimental data as a function of θ_z is investigated. A code using the NOVAS (*Naval Observatory Vector Astrometry Subroutines*)

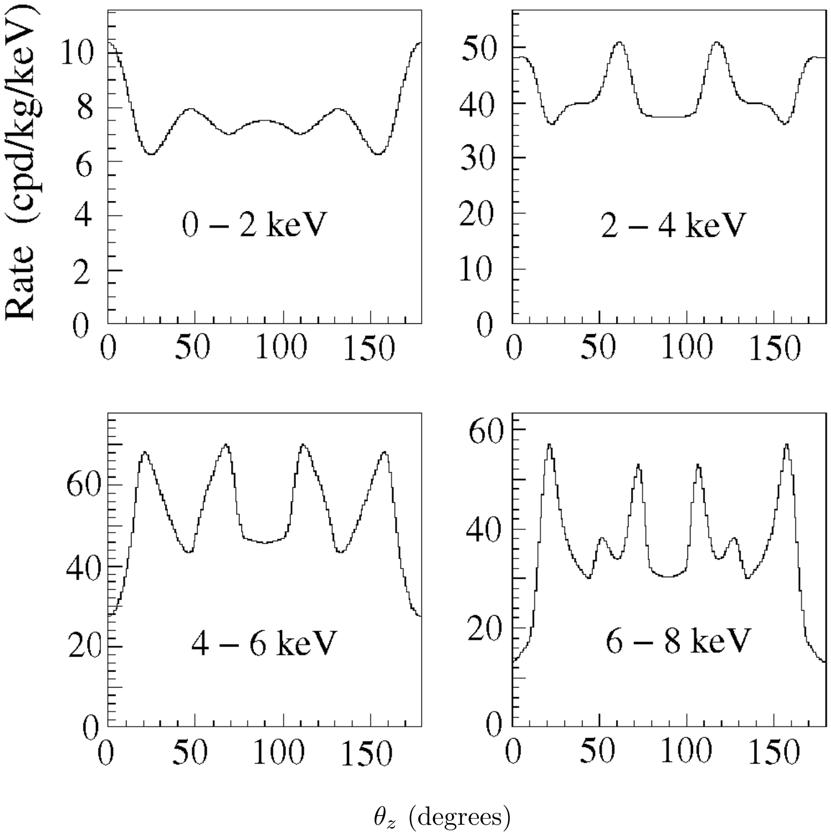

Figure 1: Expected counting rate for solar axions in NaI(Tl) evaluated for $\lambda = 1$ as a function of θ_z in the energy intervals: 0-2 keV, 2-4 keV, 4-6 keV, 6-8 keV. The rate is averaged over ϕ_{az}. Other energy intervals up to 16 keV are shown in ref. [11].

routines [13] has been developed to evaluate the distribution of the experimental data as a function of θ_z. Then, a standard maximum likelihood analysis has been carried out by accounting for the fired crystal, using 1 keV bins for the energy and 1^o bins for θ_z [11]. Since the orientations of the *gsa*'s of the nine crystals, used in this experiment, were not known (for detailed discussion see [11]), the calculation of λ has been repeated for every possible configuration of the nine *gsa*'s in the set-up. It can be inferred that all the obtained λ values are compatible with absence of signal. Therefore, the most conservative upper limit obtained for λ has been cautiously considered in the evaluation of the bound on $g_{a\gamma\gamma}$. The obtained conservative value for λ from the maximum likelihood analysis has been $(4.3 \pm 3.1) \times 10^{-4}$. According to the standard

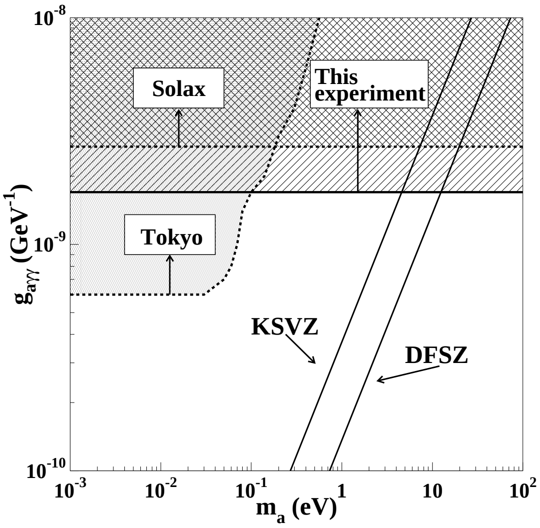

Figure 2: Exclusion plot for $g_{a\gamma\gamma}$ versus m_a. The limit achieved by the present experiment ($g_{a\gamma\gamma} \leq 1.7 \times 10^{-9} GeV^{-1}$ at 90% C.L.) is shown together with the expectations of the KSVZ and DFSZ models. The results of other – previous to our experiment – direct searches for solar axions by Solax [8] (exploiting the same technique as our experiment) and by the Tokyo helioscope [10] are also shown for comparison. For the sake of completeness, we note that recently the new result from CAST collaboration excludes $g_{a\gamma\gamma}$ down to 10^{-10} GeV^{-1} for $m_a < 10^{-2}$ eV.

procedure [14], this result gives an upper limit on the coupling of axions to photons: $\lambda \leq 8.4 \times 10^{-4}$ (90% C.L.), which corresponds to the limit: $g_{a\gamma\gamma} \leq 1.7 \times 10^{-9} GeV^{-1}$ (90% C.L.).

In fig. 2 the region in the plane $g_{a\gamma\gamma}$ versus m_a excluded at 90% C. L. by this experiment is shown.

4 Conclusions

The obtained limit on λ is about one order of magnitude more stringent than the one set by the COSME and SOLAX collaborations [7, 8], while the limit on the coupling constant $g_{a\gamma\gamma}$ has been improved by a factor 1.6 with respect to these experiments. The obtained result is at present the best direct limit on solar axions conversion in crystals and for axion masses larger than $\simeq 0.1$ eV is better also than the limit set by the helioscopes.

In conclusion, this experiment has explored the axion mass window $m_a \sim$ eV still open in the KSVZ model (where $g_{a\gamma\gamma} = 3.7 \times 10^{-10}\ GeV^{-1}\frac{m_a}{eV}$) and has allowed to exclude KSVZ axions for $m_a > 4.6$ eV at 90% C.L.

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