Sensitivity of TES Microcalorimeter Arrays for Solar-Axion Line Emission

PE-30

Kazuhisa Mitsuda & Keisei Maehisa (ISAS, JAXA)

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Abstract: Axion is a hypothetical elementary particle proposed to solve the strong CP problem in QCD. It is suggested that the sun is a strong axion emitter through Primakoff effect, and that the emission has an energy spectrum with a shape of a blackbody spectrum with kT ~ 1.3 keV, reflecting the photon temperature at the center of the sun. Moriyama (1995) first suggested that monochromatic lines will be also emitted by M1 transition of nuclei. He also suggested that such axion lines could be detected by using a proper conversion material at the Earth. Several experiments have been done so far, however, the upper limit is still high compared to estimations basing on axion models. In this paper, we will investigate methods to detect solar-axion line emission using TES microcalorimeter arrays and estimate the sensitivities. We consider that by using TES array of a size discussed for future X-ray astronomy mission, such as Athena X-IFU, we can reach a meaningful sensitivity.

1. Constraints on hadronic (KSVZ) axions

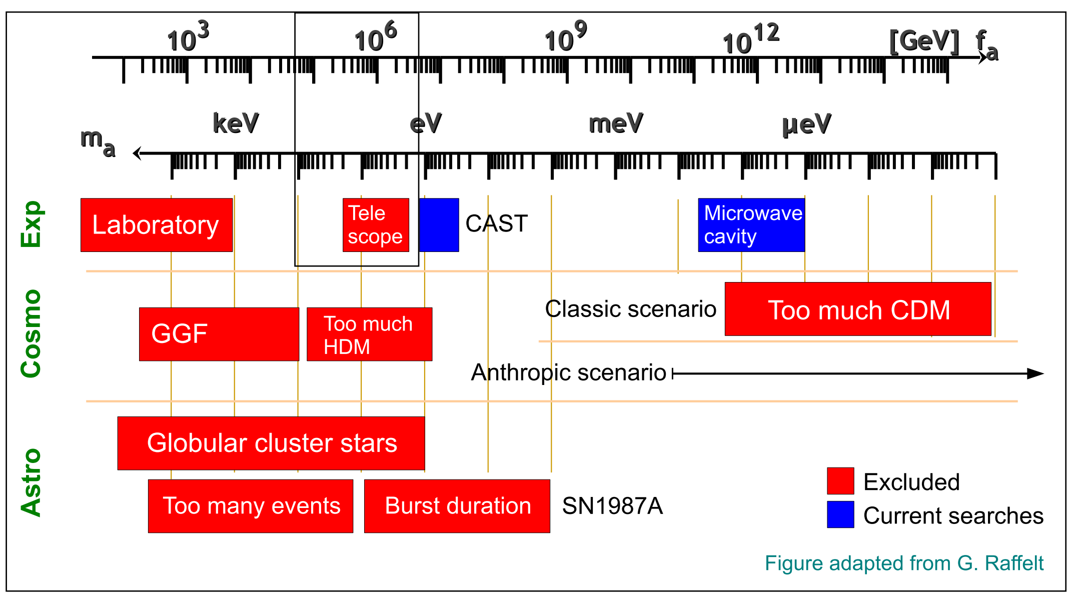
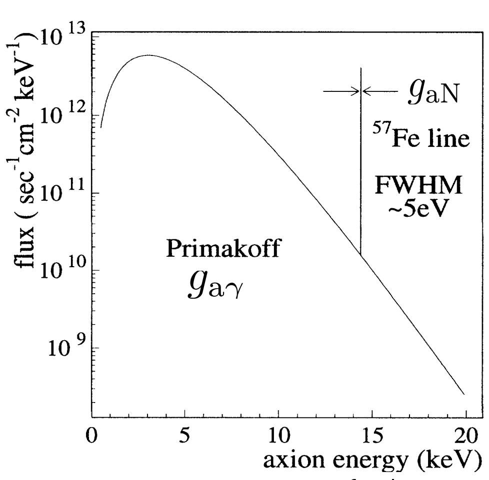


Fig 1. hadronic axion constraints. From Wong & Aachen (2011) [1].

In this paper we consider the parameter space with the the Peccei-Quinn (PQ) symmetry breaking scale fa ~ 106 GeV, corresponding to the mass ma ~ 6 eV. This mass range is totally excluded from cosmological and astronomical constraints, but is not just with experiments. We consider that it is worth searching axions in this mass range.

2. Solar axions: continuum and line emission

At the central region of the sun, axions are considered to be generated with the Primakoff effect from photons and magnetic fields. Reflecting the photon energy spectrum, the axion should have a continuum spectrum of a shape of blackbody emission with a temperature of 1.3 keV. Moriyama 1995 [2] was the first who pointed out monochromatic line emission from an M1 nuclear transition. this paper we consider the parameter space with the the Peccei-Quinn (PQ) symmetry breaking scale $f_a \sim 10^6$ GeV, corresponding to the mass $m_a \sim 6$ eV. This mass range is totally excluded from cosmological and astronomical constraints, but is not just with experiments. We consider that it is worth searching axions in this mass range.



Tab. 1. Monochromatic solar-axion lines

Isotope	Energy	Reference
^{57}Fe	14.4 keV	Moriyama 1995 [2], [3-5]
^{7}Li	0.745 keV	Kremar+ 2001 [6]
^{83}Kr	9.7 keV	Jakovcic+ 2004 [7]
^{169}Tm	8.4 keV	Derbin+ 2009 [8]

Fig 2. Energy spectrum of solar axion with M1 transition line at 14.4 keV. From Moriyama 1995 [2].

3. Search for axions from ^{57}Fe

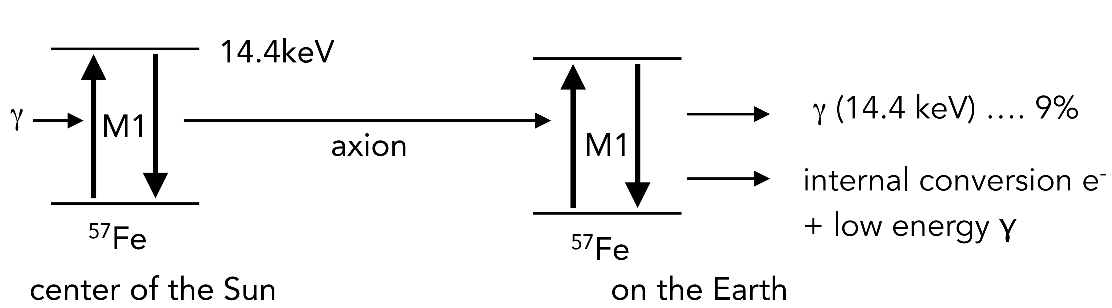


Fig 3. Emission and detection of M1 transition line at 14.4 keV.

Axions from M1 transitions can be detect on the earth using the same isotope as a converter. Among the nuclei in Table 1, ^{57}Fe is most easy to handle. All the experiments so far [3-5] try to detect 14.4 keV gamma-ray associated with the de-excitation. However, the branching ratio of 14.4 keV gamma-ray is only 9%. The background counts and the low branching ratio limits the sensitivity.

With a macrocalorimeter at a cryogenic temperature, we can increase detection efficiency by an order of magnitude by detecting all energies released in the isotope, and make the background low by the high energy resolution.

Tab. 2 ^{57}Fe branching ratio. From Krakowsky & Miller (1971)

Radiative and radiationless transitions associated with de-excitation of ^{57}Fe*.

Kind of radiation	Energy (keV)	Probability of occurrence
Resonant gamma ray	$E_{RS} = 14.4$	$1/(1+\alpha) = 0.09$
M shell conversion electron	$E_{RS}-B_M = 14.3$	$\alpha_M/(1+\alpha) = 0.01$
L shell conversion electron	$E_{RS}-B_L = 13.6$	$\alpha_L/(1+\alpha) = 0.09$
K shell conversion electron	$E_{RS}-B_K = 7.3$	$\alpha_K/(1+\alpha) = 0.81$
Kα X-ray	$B_K-B_L = 6.3$	$[\alpha_K/(1+\alpha)]\,(FY)_K = 0.24$
L shell Auger electron	$B_K-2B_L = 5.4$	$[\alpha_K/(1+\alpha)]\,[1-(FY)_K] = 0.57$
Other X-rays and electrons	Less than $B_L = 0.85$	$\approx \alpha/(1+\alpha) = 0.91$

4. A model TES microcalorimeter design

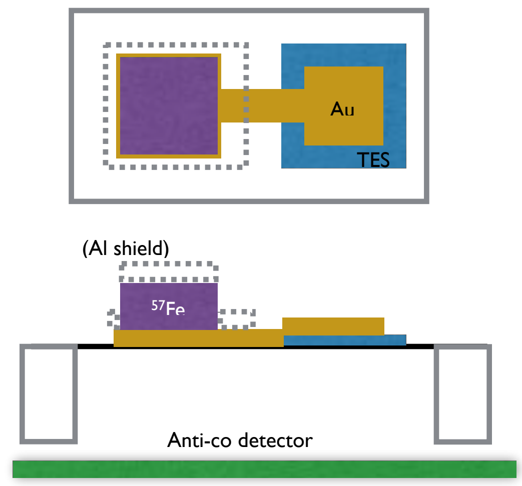


Fig. 3. Model TES microcalorimeter

Tab. 2. Material properties assumes

		Au	Fe
density	g/cc	19.32	7.874
specific heat @100mK	J/(gK)	3.72E-07	9.11E-06
thickness	μm	1	5
one side length	um	150	150
heat capacity	J/K	1.62E-13	8.07E-12
mass	g	4.35E-07	8.86E-07

intrinsic resolution <10eV if C < 8 pJ/K @ 100mK

We constructed a model TES microcaloriemter design with a < 10 eV energy resolution as a requirement. The material properties are taken from literatures.

5. Thermal simulation of detector response

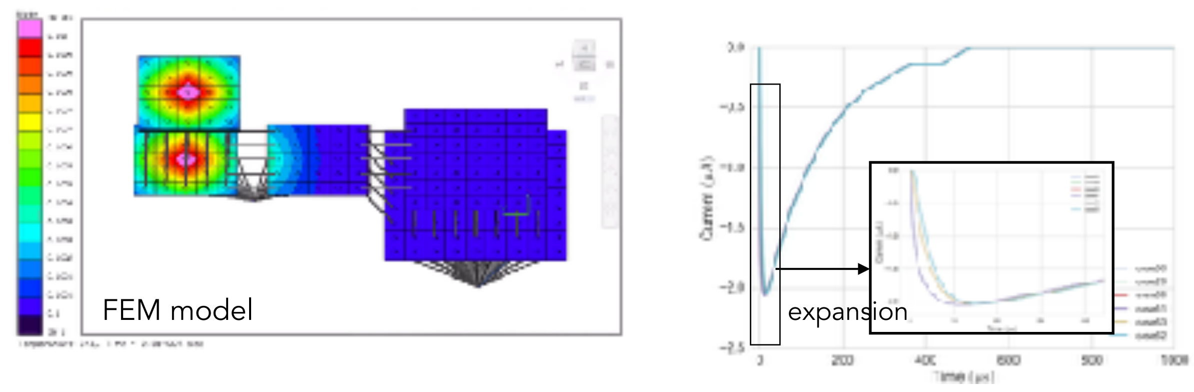


Fig. 4. FEM model of the model TES microcalorimeter (left) and the pulse shapes when an axion is converted at different positions of the ^{57}Fe converter (right).

We employed thermal model simulation using FEM (Finite Element Method). The simulation shows the pulse-height dependence of conversion position across the ^{57}Fe convertor can be made small with the parameters we used in the simulation.

6. Background rate

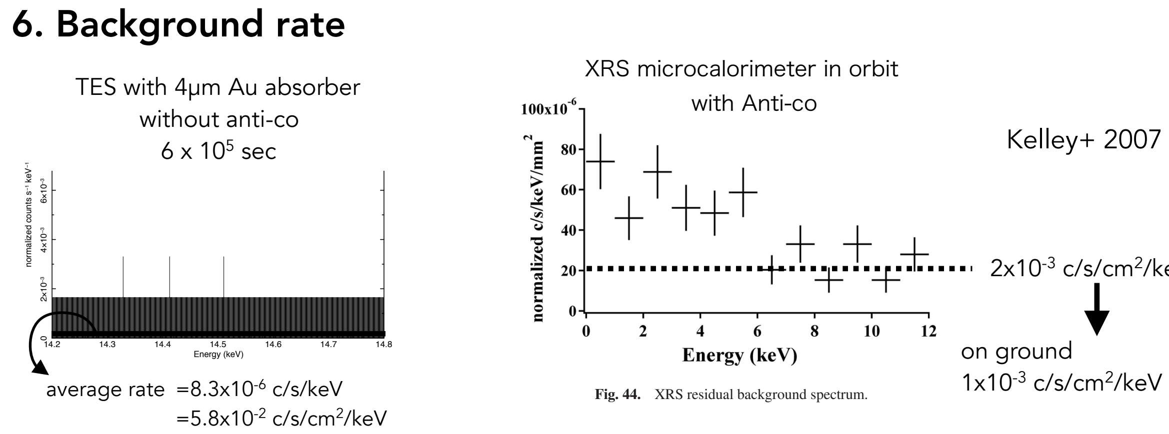


Fig. 5. Background estimations from two experiments. The one without anti-coincidence detector shows about 30 times higher rate compared with the one with.

We estimated the background rate from two experiments. The first is the spectrum obtained with 6x10^5 sec (=6.9 day) run of our TES microcalorimeter. The other one was from XRS, the microcalorimeter onboard the Suzaku spacecraft. The latter had an anti-coincidence detector and significantly low rate. In the estimation in the next section we assume the value from XRS, assuming that we will use anti-co detectors.

7. Sensitivity

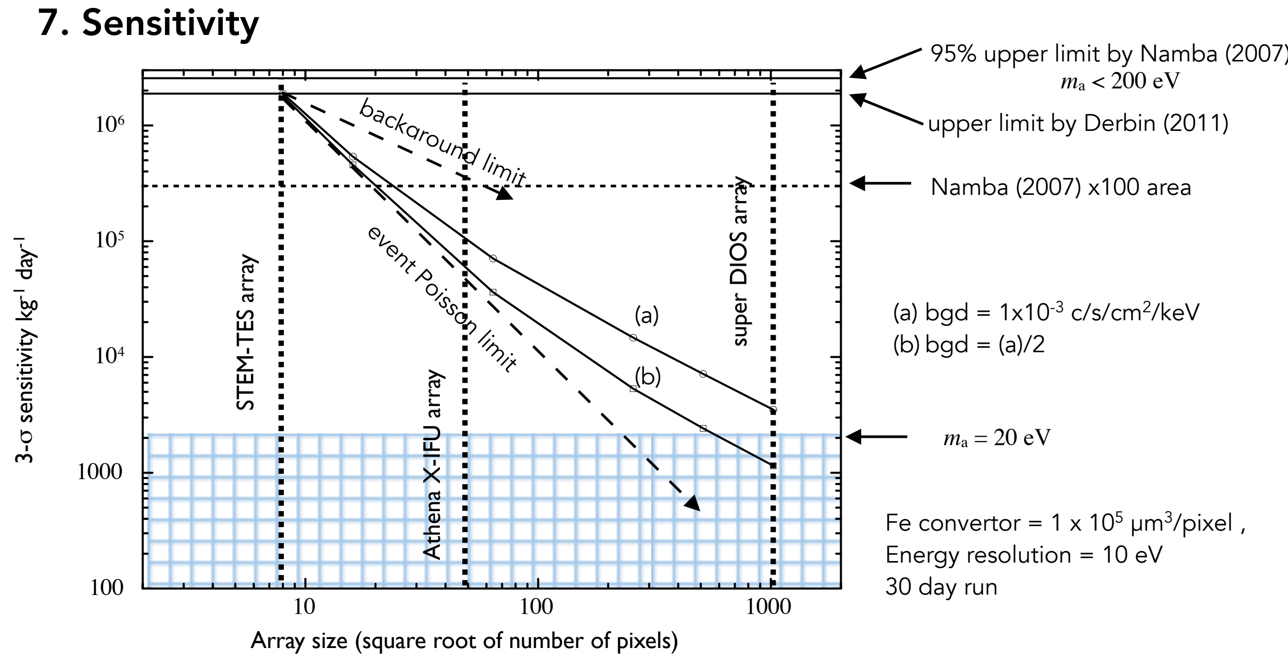


Fig. 5. Sensitivity to solar axion 14.4 keV line emission as a function of array size.

We estimated the sensitivity to the solar axion line emission as a function of the array size of the detector. With an 8x8 pixel array, we can reach the present best upper limit with a conventional Si detector. With this size of array, the background rate is negligible and the sensitivity is limited by event Poisson statistics. With increasing array size we can lower the upper limit. At some point, the background starts to limit the sensitivity. With a M pixel array we can improve the sensitivity by four orders of magnitude, which corresponds to lower mass limit improvement by an order of magnitude since sensitivity is proportional to the 4th power of m_a.

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