# Background Studies for the pn-CCD Detector of CAST

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**Abstract.** The CERN Axion Solar Telescope (CAST) experiment searches for axions from the Sun converted into photons with energies up to around 10 keV via the inverse Primakoff effect in the high magnetic field of a superconducting Large Hadron Collider (LHC) prototype magnet. A backside illuminated pn-CCD detector in conjunction with an X-ray mirror optics is one of the three detectors used in CAST to register the expected photon signal. Since this signal is very rare a detailed study of the detector background has been undertaken with the aim to understand and further reduce the background level of the detector. The analysis is based on measured data taken during the data taking period of 2003 and 2004 of CAST and on Monte Carlo simulations of background with different origin. A background study performed for this detector show that the level of background $(8.00\pm0.07)\times10^{-5}$ counts $cm^{-2}$ $s^{-1}$ $keV^{-1}$ between 1 and 7 keV is dominated by the external gamma background due to natural activities at the experimental site, while radioactive impurities in the detector itself and cosmic neutrons contribute with a smaller fraction.

**Keywords:** solar axion, pn-CCD detector, Monte Carlo simulation, radioactive background.

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## INTRODUCTION

Axions are a direct consequence of the Peccei-Quinn mechanism [1] proposed to solve the so-called strong CP problem (CP violation in strong interactions does not seem to exist in nature, although the QCD Lagrangian contains CP-violating terms). These particles could couple to two photons, which allow the production of axions inside the hot plasma of stars via the Primakoff effect. The expected flux of axions from the Sun has a mean energy of ~4.2 keV and virtually vanishes above 10 keV. In the presence of a transverse magnetic field, solar axions could be converted back to observable photons via the inverse Primakoff effect, allowing axion detection on Earth [2].

The CERN Axion Solar Telescope (CAST) is intended to search for solar axions based on this principle [3]. It uses a decommissioned 9.2 m long LHC superconducting magnet providing a 9 T magnetic field, since the probability to convert an axion into a photon depends on both the intensity of the magnetic field and the length of the magnet. Each bore of the twin aperture magnet has a cross-sectional area of 14.5 $cm^2$. The magnet is installed on a platform that permits horizontal movement from azimuthal angle 46º to 133º and a vertical movement of ±8º. It permits follow the Sun three hours per day, 1.5 hours each during sunset and sunrise. The rest of the day is dedicated to background measurements.

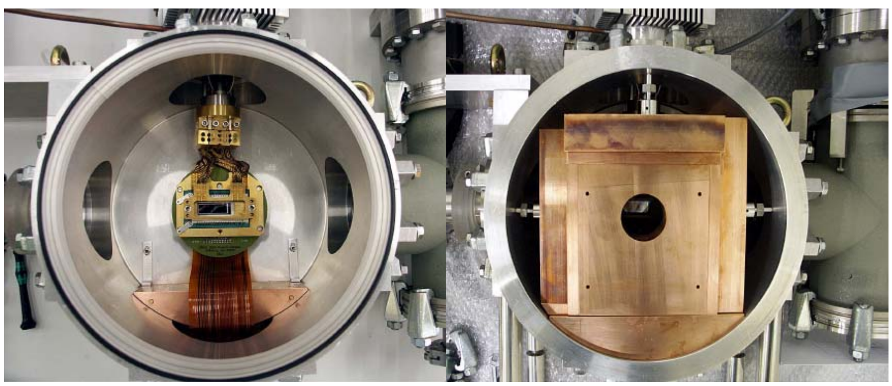
Three X-ray detectors are installed at each end of the magnet bores to search for an excess of X-rays coming from axion conversions inside the magnet during alignment with the Sun. The detectors are a Time Projection Chamber (TPC), a Micromesh Gaseous Structure (MICROMEGAS), and a Charge Coupled Device (CCD) in combination with an X-ray mirror telescope. The CCD and MICROMEGAS detectors observe sunrise axions, while the TPC detector looks for sunset axions.

During 2003 and 2004 the experiment operated with vacuum inside the magnet pipes (CAST Phase I). Due to coherence effects this setup allows us to explore an axion mass range up to 0.02 eV. No signal above background was observed in 2003 data, implying an upper limit to the axion-photon coupling of $g_{a\gamma\gamma} \leq 1.16 \times 10^{-10}$ $GeV^{-1}$ [4]. In order to extend the CAST sensitivity to higher axion masses, the CAST experimental setup has been transformed to be able to fill the axion conversion volume with a buffer gas. Allowing us to probe the axion mass range up to 0.8 eV (CAST Phase II). CAST started taking data in this configuration in November 2005.

Data acquired during the 2003 and 2004 data taking periods have been analyzed and a series of Monte Carlo simulations have been performed using mainly the GEANT4 package [5] to achieve this goal. In particular, the response of this detector to different kinds of particles like photons and neutrons has been studied and even a quantitative estimate of the contribution of different sources of background, like external gamma and intrinsic radio-impurities in the detector materials, to the overall background of the CCD detector has been attempted.

## THE CCD DETECTOR AND THE X-RAY TELESCOPE

The X-ray telescope of CAST consists of a Wolter~I type X-ray mirror optics [6] focusing a potential axion signal on a small area on a CCD detector which is located in the focal plane of the optics.



(a) (b)

**FIGURE 1.** (a): The pn-CCD detector with its vacuum housing. The pn-CCD chip is the central black part surrounded by a gold plated cooling mask inside of the aluminum vessel. (b): The same picture with the internal passive copper lead shield being installed. The circular hole in the shield provides the aperture towards the X-ray optics.

The CCD is a depleted back side illuminated pn-CCD with a depletion depth of 280 μm and a pixel size of 150 x 150 $\mu m^2$, optimized for the 0.2-10 keV energy range. The very thin $SiO_2$ radiation window of this detector with a thickness of only 30 nm, results in a quantum efficiency of ~1 between 1 and 10 keV. Further enhancement of the sensitivity could be achieved by adding a passive shield consisting of a combination of internal (inside the vacuum vessel) and external lead and copper components. As raw material for the shield components we have chosen low activity oxygen free copper and low activity lead, almost free of $^{210}Pb$.

## BACKGROUND SOURCES

The most important contribution is expected to be originated by external gamma rays, produced mainly by primordial radio-nuclides like $^{40}K$ and the radioactive natural chains from $^{238}U$, $^{235}U$ and $^{232}Th$ in laboratory soil, building materials and experimental set-up as well as by $^{222}Rn$ in air.

Gamma rays of cosmic origin make a negligible contribution. Activity levels of the walls of the experimental hall were measured using a Ge spectrometer and radon levels have been also monitored there during long periods.

Intrinsic radioactive impurities (either primordial or cosmogenically induced) in the components materials making part or surrounding the CCD detector can also make a relevant contribution in experiments looking for rare event signals because of their alpha, beta and gamma emissions.

Since the CCD detector has an internal shielding made of lead and copper within the vacuum chamber where it operates, impurities from the external components can in principle be disregarded since they should be greatly suppressed. Therefore, only impurities in the materials composing the detector itself may be relevant and have been taken into account in this study. Activities from the CCD components were determined at the Canfranc Underground Laboratory using an ultra-low background germanium spectrometer.

Cosmic rays on the Earth's surface are dominated by muons and neutrons. While muon interactions (as those of other charged particles) can be rejected with ≈100% efficiency thanks to their long ionizing tracks and the deposited energy, signals from neutrons can contribute to the detector background.

## BACKGROUND SIMULATIONS

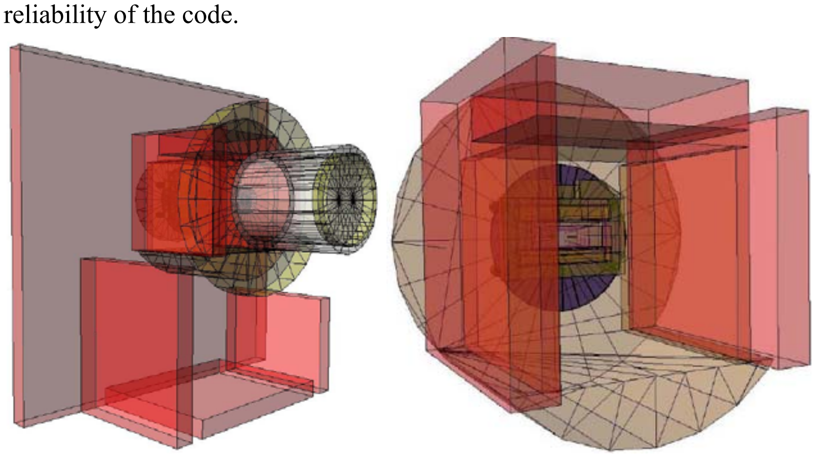
In order to estimate the contribution of external background and natural radioactivity to the overall background, a simulation tool for the CCD detector has been developed using the GEANT4 package and the library G4NDL 3.7 for neutrons.

### The Code

In the first simulations for neutrons and external gamma backgrounds a simplified description of the detector was implemented just considering the Si chip, the copper cooling mask and the printed circuit board. A much more detailed geometry for the detector was defined to carry out simulations of the radioactive impurities in the detector components; shapes and sizes of Si chip (including active area), ceramics, zero-force sockets, front and rear cooling mask, and printed circuit board have been reproduced as accurately as possible, keeping all the relations between the sizes. For both, the simplified and detailed implementations of the detector, it is placed inside the aluminum housing. Copper-lead shielding as well as the tube connecting to the telescope have been considered.

Usual electromagnetic processes for photons and charged particles have been taken into account using models specially developed for low energy (valid above 250 eV), which is important to reproduce fluorescence and emission of Auger electrons. Elastic and inelastic scattering, capture and fission are considered for neutrons.For each simulation, the spectrum of the energy absorbed in the CCD detector is recorded.

An energy calibration with a $^{55}$Fe source was first simulated and compared to the corresponding experimental spectrum to check the reliability of the code.



(a) (b)

**FIGURE 2.** (a): View of all simulated components, including shield, aluminum vessel and connection to telescope. (b): View of simulated components inside the aluminum vessel, including copper and lead shields and detector.

## External Gamma Background

The response of the CCD detector has been studied by simulating photons with discrete energies from 30 up to 2000 keV. Four different geometries have been considered corresponding to the successive shieldings added to the CCD set-up: no shield, internal copper shield, internal copper shield and external lead shields and finally internal lead and copper shields and external lead shield. “Figure3” presents the ratio between the counts in the region up to 7 keV (to exclude X-rays from copper) and the total simulated events for each one of the considered initial energies of the incident photons.

Gamma rays with energies around 100 keV contribute most to the CCD background. However, the effect of this external gamma background above 50 keV does not seem to be very dependent on energy. This fact may be due to the balance of two trends: low energy photons are less penetrating but their contribution is higher while high energy photons can pass more easily through the housing and the shielding but their contribution is lower.

Using this simulated response to external gamma including the effect of the complete shielding Fig.3, an estimate of the contribution to the counting rate of the CCD detector from the external gamma background has been attempted.

The measurements of the activity of the walls with a Ge spectrometer have been used as input. A mean radon concentration of ~10 Bq $m^{-3}$ has been assumed as well. Total contribution from radon up to 7 keV turns out to be ~$10^{-6}$ counts $cm^{-2}$ $s^{-1}$ $keV^{-1}$, almost negligible compared to the measured background rate in the CCD detector. Considering an uniform distribution of these impurities in the walls and attenuation of photons through the walls the counting rate due to the activities of the experimental walls could be around 3-4x$10^{-5}$ counts $cm^{-2}$ $s^{-1}$ $keV^{-1}$.

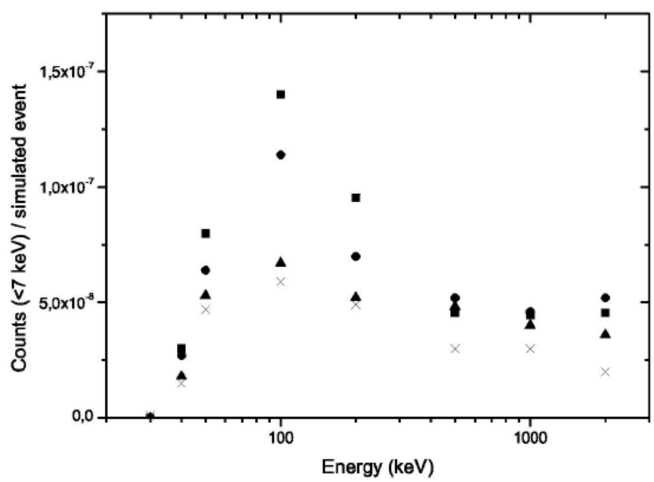



**FIGURE 3.** Simulated response of the CCD detector to the external gamma background: events in the region up to 7 keV per simulated photon as a function of the energy of the incident photons. Four shielding conditions have been considered: with no shield (squares), with the internal copper shield (circles), with the internal copper + external lead shields (triangles) and with internal copper + external lead + internal lead shields.

## Neutrons

In a similar way as for photons, an evaluation of the contribution of neutrons from different sources to the CCD counting rate has been attempted (from thermal up to 10 MeV), after studying the response of the detector to neutrons using simulations.

The main contribution of neutrons to the counting rates in the energy region of interest comes from the elastic scattering off of silicon nuclei. Simple kinematics says that for neutrons up to ~250 keV all the induced recoils deposit in the detector an energy below 10 keV; neutrons with higher energies can produce more energetic recoils. The counting rate due to the external neutron background in the region up to 10 keV has been estimated to be 6x$10^{-6}$ counts $cm^{-2}$ $s^{-1}$ $keV^{-1}$. Since this number is one order of magnitude lower than the experimental background levels of the CCD detector, it seems that environmental neutrons are not very significant at the present level of sensitivity.

At sea level, neutron production by capture of negative muons is strongly enhanced especially in high Z materials. Therefore, an estimate has been made also for the muon-induced neutrons in the lead shielding of the CCD detector. Induced neutrons come mainly from evaporation and therefore their energy spectrum is peaked around 1 MeV and reduced above 5 MeV. Using a measured total muon flux of ~$50.3 \times 10^{-3} cm^{-2} s^{-1}$, give a yield for neutrons of around ~$1 \times 10^{-3} cm^{-2} s^{-1}$ which is more than one order of magnitude lower than the flux due to environmental neutrons.

## Intrinsic radioactive impurities

The levels of radioactive impurities in the main components of the CCD detector were measured in the Canfranc Underground Laboratory in Spain using an ultra-low background germanium detector and can be found in a database of radiopurity of materials [7] inside the ILIAS program (Integrated Large Infraestructures for Atroparticle Science). Activity come mainly from the radioactive chains $^{235}U$, $^{238}U$, $^{232}Th$ and the isotope $^{40}K$ .

**TABLE 1**. Total contribution to CCD counting rate between 1 and 7 keV from natural radioactivity of the individual components in units of counts $cm^{-2} s^{-1} keV^{-1}$

| Detector Component | Differential Flux |
|---|---|
| CCD Board | $(5.83 \pm 0.41) \times 10^{-7}$ |
| CCD Chip | $< 2.2 \times 10^{-5}$ |
| Ceramics | $(1.17 \pm 0.14) \times 10^{-6}$ |
| Sockets | $(1.34 \pm 0.15) \times 10^{-6}$ |
| Front Cooling Mask | $< 3.6 \times 10^{-7}$ |
| Back Cooling Mask | $< 2.6 \times 10^{-7}$ |

Considering the upper limits of radio-impurities for all the other components, the total contribution to background would be $2.6 \times 10^{-5}$ counts $cm^{-2} s^{-1} keV^{-1}$. Compared to the measured background level in the CCD detector impurities from CCD board, ceramics, and sockets account for 4% of the observed counting rate; including all the other simulated impurities, up to ~33\% of the counting rate would be justified at most.

## Conclusions

The CCD detector of the CAST experiment looks for the very rare signal of solar axions, consisting of photons peaked at around 4 keV. Different background components entangle the expected signal. A Monte-Carlo simulation tool for this detector has been developed and used for the most relevant background sources with the aim to help in the understanding of the origin of observed events and constructing a plausible background model for the measured counting rate $(8.00 \pm 0.07) \times 10^{-5}$ counts $cm^{-2} s^{-1} keV^{-1}$ between 1 and 7 keV.

Using the simulated response of the CCD detector to the external gamma background an estimate of the contribution of this background component has been attempted, finding that measured radon levels in the air could produce on average ~1% of the registered counting rate, while however just the measured activities from $^{40}K$ and $^{232}Th$ and $^{238}U$ chains in the walls could justify more than 50% of this counting rate. The response of the CCD to neutrons of different energies has also been simulated. Based on this response and typical fluxes of neutrons at sea level, a rough estimate of the contribution to the CCD counting rate of environmental neutrons has been made. They do not seem to be a very relevant source of the CCD background, producing just a few per cent of the observed counting rate. Contribution from muon-induced neutrons in the present lead shieldings has been checked to be negligible.

Finally, the contribution to the CCD counting rate of the internal radioactive impurities of the main detector components has been simulated using the activities measured at the Canfranc Underground Laboratory with an ultra-low background germanium detector. This contribution could justify at most 33% of the measured counting rates.

Taking into account all these results, a quite complete model for the background measured by the CCD detector has been obtained. Other possible relevant sources of background, not evaluated up to now, are thought to be the radioactive impurities from the soil and from massive components of the experimental set-up.

## ACKNOWLEDGMENTS

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