An application of space technology to the terrestrial search for axions: the X-ray mirror telescope at CAST

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Abstract

An X-ray mirror telescope consisting of a Wolter I type mirror assembly as used in X-ray astronomy and a new type X-ray CCD has been added to the CERN Axion Solar Telescope experiment. It will strongly improve the sensitivity in the search for axions, a so far elusive particle. The axion is predicted in order to explain the observed CP conservation in strong interaction which is not expected within the generally accepted “standard model”. Construction and performance of the X-ray telescope are described. An improvement by two orders of magnitude in the signal over background S/B event ratio is estimated.

1. Introduction

The sensitivity of the superconducting CERN Axion Solar Telescope (CAST) \cite{1,2} for the discovery of the theoretically predicted axion is strongly improved by the addition of a X-ray mirror telescope with a X-ray CCD as focal plane detector.

Axions \cite{3} have been introduced into elementary particle theory in order to explain the basic inconsistency in the “standard model” of CP conservation in strong interaction with CP violation in weak interaction. Most notably this is seen in the electric dipole moment of the neutron for which the standard model predicts a value much higher than the small experimental upper limit. As the hypothetical axion couples to photons, it is expected to be produced in the core of the sun and can be converted back to photons in a strong transverse magnetic field. The conversion probability thereby is proportional to the square of the product of magnetic field strength and length. The CAST experiment uses for this purpose a 10 m long 9 T superconducting (LHC prototype) dipole magnet tracking the position of the sun.

Essential limitations of the experiment are the low event rate expected and the error in background subtraction.
The X-ray mirror telescope added to one of the four magnet openings focuses the X-rays from axion conversions inside the full magnet aperture of 42 mm diameter to an image of the sun core of 3 mm diameter. Thus the background is not only reduced by the ratio of the respective areas of magnet aperture and image size. It is, in addition, possible to observe signal and background simultaneously, an important fact since the background, originating mainly from cosmic radiation and ambient radioactivity is expected to vary with time and orientation of the telescope.

In the following the experimental setup and its performance are described.

2. Axion production and detection

The hypothetical axion is expected to couple to the photon with a strength described by the coupling constant $g_{a\gamma\gamma}$. The production by photon–photon interaction in the extremely hot core of the sun is proportional to the square of $g_{a\gamma\gamma}$ and theory predicts energy spectrum and radial distribution within the sun [4] as shown in Fig. 1.

The same process in inverted form, the interaction of the axion with the (virtual) photon of the transverse magnetic field, converts the axion to an observable photon conserving energy and direction in the process.

The CAST experiment [1,2] uses a 9 T LHC prototype dipole magnet of 10 m length with two parallel beam pipes. The 20 ton magnet is mounted on a movable platform to be able to track the sun in the morning and evening hours. Fig. 2 sketches the experimental setup. Three of the four magnet openings are equipped with gaseous X-ray detectors, the fourth with the X-ray mirror telescope to be described in the following section.

3. The X-ray mirror telescope

The X-ray mirror telescope produces an “axion image” of the sun by focusing the photons from axion conversion in the magnetic field onto a X-ray CCD positioned in the focal plane of a Wolter I type mirror telescope. Both of these devices are prototypes developed for X-ray astronomy: the 1.6 m focal length Wolter telescope for ABRIXAS [5] and the pnCCD for the very successfully operating European XMM-Newton X-ray observatory [6].

The principle of the Wolter telescope is sketched in Fig. 3. X-ray photons are reflected twice by a combination of hyperbolic and parabolic mirrors. Reflection is achieved at very shallow angle only on mirrors with a surface roughness of a few atomic layers. Therefore an assembly of many (27) nested thin mirror shells is used in the telescope.

The pnCCD has been developed and built at the MPI Semiconductor Laboratory in Munich [7]. Its function principle shown in Fig. 4 differs strongly from that of standard CCDs. It will not be explained in detail at this place but we point out that it has important advantages, in particular when used for X-ray detection: the whole silicon volume serves as radiation detector and a thin
(20 nm) uniform radiation entrance window is located on the backside. Thus, quantum efficiency close to unity is achieved over the full energy range of interest (300 eV–10 keV) as demonstrated in Fig. 5.

The $1 \times 3 \text{ cm}^2$ 280 $\mu\text{m}$ thick pnCCD (Fig. 6) is operated at $-130^\circ\text{C}$ inside a vacuum vessel directly connected to the mirror telescope and to the magnet beam pipe without any window absorbing low energy photons.

Fig. 7 shows the X-ray telescope as mounted on the CAST magnet on the left. The mirror telescope is inside the wide part of the conical housing, the vacuum chamber with the CCD on the right end.

The excellent spectral properties of the device are demonstrated in Fig. 8 where the CCD has been illuminated with a $^{55}\text{Fe}$ source, providing a clear separation between the Mn$\text{K}_\alpha$ and Mn$\text{K}_\beta$ lines at 5.895 and 6.492 keV.

The background observed in the experiment (Fig. 9) is rather low (approx. $10^{-4}$ counts/cm$^2$ s keV) and flat in energy. The only significant structure seen is the Cu$\text{K}_\alpha$ line at 8.041 keV due to the copper shielding and cooling mask enclosing the CCD. Here one sees the benefit of the excellent energy resolution of the CCD: discrete lines can
simply be cut out of the continuous spectrum expected for axions. The background is expected to be reduced further with additional shielding to be installed.

4. Improvement of physics potential

In rare event searches, as is the case with axions, the limitation is not only given by event rate but by the ability to detect a signal above an indistinguishable background. By focusing the (converted) axions on a 7 mm$^2$ image, a factor 200 down from the magnet opening, the number of background events is reduced correspondingly while the transmission through the optical system is still above 50%. Thus the signal to background event ratio S/B is improved by two orders of magnitude. Expressed in terms of the coupling constant the improvement grows only with the eighth root of this ratio (=1.8) as axion production as well as conversion each are proportional to $g_a^2$ and the statistical error on the background varies with the square root of the number of events.

In Fig. 10 the expected upper limits of CAST for axion production as function of the axion mass are
compared to theoretical predictions and to previous experimental results.

It is worth mentioning that the use of the telescope will reduce systematic errors in background subtraction as the background is taken also in parallel to sun tracking when comparing the 3cm² detector area with the 7mm² image of the sun core. This eliminates uncertainties due to time variation of background rates and their dependence on the orientation of the telescope.

5. Summary

An X-ray telescope built of a prototype mirror telescope for an astronomical X-ray observatory (ABRIXAS) and a new type of X-ray CCD developed for the European XMM-Newton X-ray observatory has been added to the CAST axion solar telescope. The device is operating properly and will bring significant improvement to the experiment, which is just starting to take data.

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References