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High energy resolution x-ray detectors for IAXO: advantages in pre- and post-discovery phases

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The search for the existence of solar axions has been and continues to be brought forward using so-called helioscopes. In a helioscope, solar axions can travel in an evacuated volume in presence of a strong magnetic field. Along this path, axions have the possibility to convert to photons. Detecting such photons, expected to be in the keV range, will be the indication of the existence of solar axions. X-ray detectors with low background, high efficiency and high energy resolution are therefore an important component of such experiments. Metallic Magnetic Calorimeters (MMCs) are detectors operated at mK temperature which offer an energy resolution better than 10 eV full width at half maximum (FWHM) and a detection efficiency close to 100% over the energy range of interest for solar axion, including a spectral line around 14 keV generated in axion-nucleon interaction in the Sun. In addition, a very low energy threshold can be achieved, limited by the necessary window against infrared radiation. These detectors are therefore one of the technologies considered for the fourth generation helioscope IAXO. The present status of MMC optimization for IAXO will be discussed along with the importance for both the axion discovery phase and even more for the study of axion properties after discovery, thanks to the unique performance of these detectors.

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1. Introduction

The expected X-ray spectrum deriving from the conversion of solar axions could be composed by different contributions depending on how axions are produced in the Sun. Blackbody photons in the core of the Sun could convert to axions via the Primakoff effect with a rate proportional to the axion-photon coupling, $g_{a\gamma}$ to the second power. Such axion-photon coupling is present in all axion models and therefore such a component of the expected spectrum is considered to be unavoidably present. At the same time, axions could also couple to fermions. In this case, it is then possible to investigate the existence of two other components in the solar axion spectrum deriving from the coupling of axions to electrons or to nucleons, whose intensity would then be proportional to the axion-electron coupling g_{ae} to the second power and to the axion-nucleon coupling g_{aN} to the second power, respectively. Figure 1 shows the first two components of the expected axion spectrum, calculated for $g_{a\gamma} = 10^{-11}$ GeV^{-1} and $g_{ae} = 10^{-13}$ and based on calculations performed in [1].
The possibility of probing the existence of axions through the detection of axions produced in the Sun with helioscopes relies on the availability of long and wide magnets for the conversion of axions to photons, X-ray optics to focus the produced photons on a small area where detectors are located and finally high efficiency and low background X-ray detectors.
The International Axion Observatory (IAXO) is a planned fourth generation helioscope, which can reach a sensitivity on the axion to photon coupling of $g_{a\gamma} \sim 10^{-12}$ GeV^{-1} for axion and ALPS generated in the Sun [2]. As an intermediate step, the IAXO collaboration is moving forward in the construction of babyIAXO. With this helioscope not only the major components required for the construction of IAXO can be tested and optimized, but a new interesting area of the parameter space $m_a - g_{a\gamma}$ can be investigated, where m_a is the axion mass. With babyIAXO, a sensitivity to axion-photon coupling $g_{a\gamma}$ as small as 1.3×10^{-11} can be reached [3].
In a helioscope, the conversion rate of axions to photons for a given axion-photon coupling constant depends on the magnet parameters. In turn, the fraction of photons arriving to the detector system depends on the efficiency of the optics. The availability of detectors with high detection efficiency and very low background in the energy range of interest is of utmost importance for investigating lower and lower axion-photon coupling constants. Several detector technologies are presently considered to be used as focal plane detector system of the coming fourth generation helioscope IAXO. Among them, metallic magnetic calorimeters (MMCs) [4] have unique performance such as a very high energy resolution which, to a very good level, is energy independent, a demonstrated intrinsic low energy threshold at the level of a few tens of eV [5] and a quantum efficiency which can be made larger than 90% in an optimized detector design over the interesting energy range. These unique characteristics of MMCs indicate these detectors to be very promising for the discovery and study of solar axions.

2. Focal plane detectors for next generation helioscopes

The absence of signals related to the axion conversion in helioscopes experiments performed so far has been used to derive upper limits to the axion photon coupling. The most stringent of such limit has been obtained by the CAST collaboration which was able to exclude the existence of axions with coupling $g_{a\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} (95% C.L.) for masses below 10^{-2} eV [6]. The next generation experiment (baby)IAXO is designed to achieve a sensitivity to detect axions with axion to photon coupling of the order of 10^{-11} - 10^{-12} GeV^{-1} [2, 3]. If we consider $g_{a\gamma} \sim 10^{-11}$ GeV^{-1} and the design parameters of babyIAXO, we would expect to detect a photon from axion conversion every few days. The possibility to identify such photons as related to axion conversion relies on detectors with an extreme low background. Ideally, in case of zero background, no precise energy information would be needed to identify axion related events, only high efficiency in the expected energy range. Unfortunately, this ideal case is not realistic and all detectors are affected by the presence of background events due to cosmic rays and natural radioactivity. Methods to reduce the background rate have been developed for a large number of detector technologies and are mainly based on the use of extremely radio-pure materials, the use of passive and active veto and the possibility to recognize particles based on the signal shape/event topology (for example background studies for Micromegas in CAST [7]). The requirement the for focal plane detector in IAXO is a very low background, smaller than 10^{-7} counts keV^{-1} cm^{-2} s^{-1} in the energy region up to 7 keV along with a quantum efficiency larger than 70 %.

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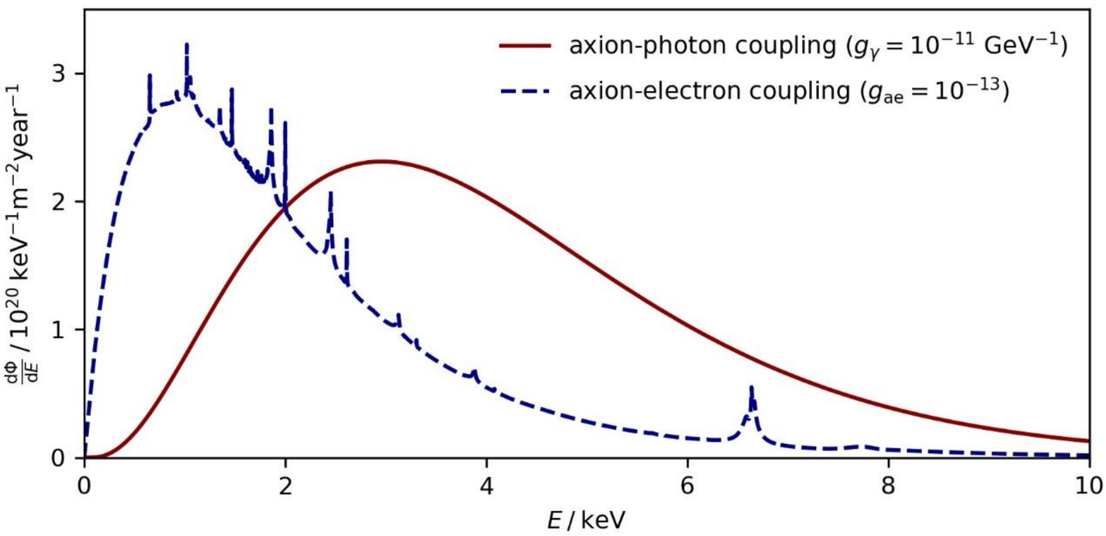

Figure 1: (Color on-line) Expected axion flux as function of energy in case of conversion in the central part of the Sun via axion-photon coupling with $g_{a\gamma} = 10^{-11}$ GeV^{-1} (red continuous line) and via axion electron coupling with $g_{ae}=10^{-13}$ (blue dashed line)

No requirements on the energy resolution are foreseen. At the same time, a good energy resolution would have an impact on background reduction because of the more precise determination of the event energy, allowing for a better interpretation of signals.

The baseline detection technology in (baby)IAXO is based on small Time Projection Chambers (TPC) with pixelated Micromegas readouts [8] which are surrounded by a passive (mostly copper and lead) and active (scintillating panels) shielding. These detectors have achieved a background rate 10^{-6} counts/keV/cm^{-2}/s in the range of interest above ground and an order of magnitude lower rate in the Canfranc underground laboratory. Along with the excellent background level one has to mention a relatively low efficiency of about 60% - 70%, which is also energy dependent, as well as a moderate energy resolution.

At the same time, R&D on different detector technologies [2] like GridPix [9], MMC [4, 10], Neutron Transmutation Doped sensors (NTD), Transition Edge Sensors (TES) and Silicon Drift Detectors (SDD) are brought forward by different groups. These detector technologies are interesting due to their excellent energy resolution, low energy threshold, detection efficiency and the possibility to use ultra-pure materials.

Low temperature detectors based on highly doped semiconductors (NTD-Ge), superconducting temperature sensors (TES) or paramagnetic materials (MMC) have already demonstrated energy resolution in the few eV range [4, 11, 12]. Once these or other high energy resolution detectors would achieve the necessary background rate below 10^{-7} counts keV^{-1} cm^{-2} s^{-1}, new perspectives will open for the physics reach of helioscopes.

3. First prototype of an MMC detector system for IAXO

MMCs are composed by a particle absorber, optimized for the particles and energies to be detected, which is well thermally coupled to a paramagnetic temperature sensor located on top of a superconducting pick-up coil. A persistent current flowing in the closed superconducting circuit is used to generate a static magnetic field needed to polarize the spins in the sensor [13]. When a particle interacts in the absorber, the detector temperature increases proportionally to the deposited energy and to the inverse of the total heat capacity of the detector. This change of temperature, in turn, leads to a change of magnetization which can then be detected as a change of magnetic flux in the superconducting pick-up coil. The superconducting coil is then connected to the input coil of a dc-SQUID used to obtain a voltage signal proportional to the deposited energy. The readout consists of a 2-stage SQUID system with flux-locked loop on the front-end SQUID [14].

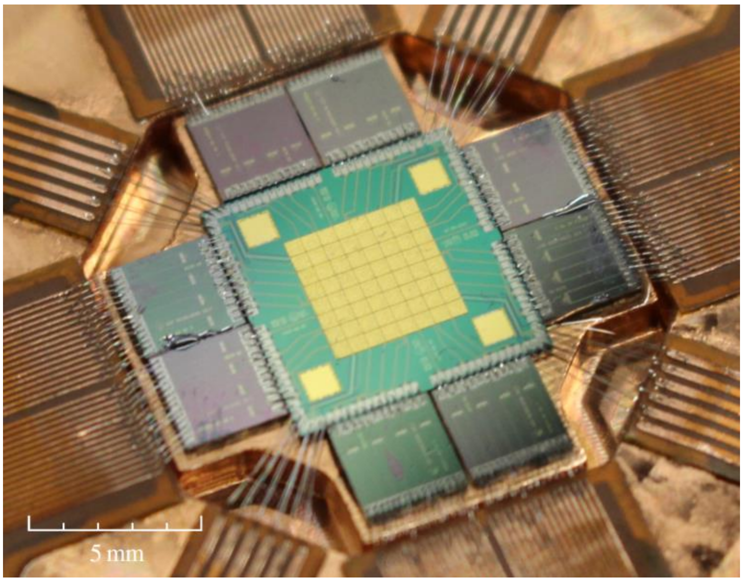

Figure 2: Left: First detector system tested for the IAXO experiment. The maXs-30 8 mm × 8 mm chip is surrounded by 8 3.5 mm × 3.5 mm chips each hosting 4 front-end SQUIDs. Right: Detector set-up mounted at the mixing chamber plate of a dilution refrigerator. A superconducting niobium shield is used to shield the detector platform from time-varying electro-magnetic signals. Ribbon cables are then used to connect the detector module to the amplifier module which is mounted on the opposite site of the mixing chamber plate, protected by a cryoperm box. Picture adapted from [10].

The MMC array used for the first detector system we have developed for (baby)IAXO is a maXs-30 and consists of 64 pixels (32 double meander channels) disposed in a 8 × 8 configuration covering a surface of 4 mm × 4 mm with a geometrical filling factor of 94% [10, 15]. Each absorber has an area of 500 µm × 500 µm and a thickness of 20 µm which ensures a quantum efficiency larger than 99% up to 10 keV. The active area of the maXs-30 is similar to the focal area of the considered (baby)IAXO optics of about 0.2 cm^2.

Figure 2) left shows the first detector set-up we have developed for (baby)IAXO. In the center of the photo the 8 mm × 8 mm maXs-30 chip can be seen. Each of the 8 chips surrounding the maXs-30 chip contains 4 dc-SQUID channels, each of them connected to one of the double meander detector via aluminum bonding wires. Polymide flexible circuit boards are used for routing the signal from the detector module. The detector set-up is mounted at the mixing chamber plate of a dilution refrigerator which, during operation, is stabilized at a temperature below 20 mK. This detector set-up, featuring a tower-like geometry, was designed already considering the integration in the helioscope. In Figure 2) Right, the external niobium shield covering the copper tower can be seen. The design and properties of the detector set-up and the performance achieved by the MMC arrays are described in details in [10]. The signal from the front-end SQUIDs is then amplified by SQUID arrays, which are located in a dedicated amplifier module also mounted on the mixing chamber plate [14].

This detector system was characterized using an external ^{55}Fe source. In the calibration run, the energy calibration function and the energy resolution are determined for each pixel. Figure 3) Left shows the energy resolution achieved for all tested pixels. Three channels could not be tested, one because the front-end SQUID was damaged and the other two because of a problem with the amplifier SQUIDs. These two last channels have been repaired for a second test measurement. The average energy resolution, after removing a channel with very large readout noise, was 7.2 eV full width at half maximum (FWHM) with the best channel showing an energy resolution of 6.2 eV FWHM. Along with the energy resolution, also the energy threshold has been determined to be for all pixels around 100 eV. An energy threshold significantly below 100 eV for MMC detectors has already been demonstrated for MMCs arrays used in the ECHo experiment where a line at 50 eV was well-characterized [5].

We have performed two background measurements of the unshielded detector array. A first measurement was performed with the set-up as shown in Figure 2. The background spectrum was obtained after data

reduction using cuts defined for spectra corresponding to calibration periods which periodically occurred between two background measurements. The efficiency to extract "real" events was larger than 90%. This value was obtained as product of the efficiency of filter related to the pulse shape of about 99%, defined using the K_α line of the ^{55}Fe calibration source (as showed in Fig. 6) and the geometrical efficiency of 94% given by the maXs-30 absorber design. The background rate between 1 keV and 10 keV then can be calculated to be 3.2(1) × 10^{-4} Counts keV^{-1} cm^{-2} s^{-1} [10]. The copper K_α lines around 8.0 keV and the niobium K_α lines around 16.6 keV can be clearly identified in the spectrum. These structures can be interpreted as fluorescence lines which could originate from the interaction with materials surrounding the MMC array either of cosmic muons or, with smaller probability, of radiation emitted by naturally occurring radioactive nuclides. To reduce the effect on the background spectrum of low energy fluorescence events, we added a PTFE disc, with a thickness of 4.5 mm, between the copper collimator and the detector active area. A second experiment was performed to test the effect of the PTFE disc. No sign of the niobium K_α could be seen in the spectrum and the intensity of the copper K_α line is only marginally above the average background level. This result confirms that a large fraction of background events is due to fluorescence induced by cosmic muons and naturally occurring radionuclides. The improved background level can be determined to be 1.20(8) × 10^{-4} Counts keV^{-1} cm^{-2} s^{-1}. The demonstrated background reduction indicates that a properly designed passive shield together with an active shield to tag the passage of charged particles could strongly suppress background events and bring the background level to approach the requirement for the IAXO experiment. Dedicated Monte Carlo simulations as performed for MMC arrays for the ECHo experiment [16, 17] will help the interpretation of the background and indicate the direction for suppressing background sources.
At the same time, the flexibility in optimizing MMC arrays with different pixel geometries is also considered in the development of MMC arrays for IAXO. A first step in this direction was to design a new array with a larger detection area to cope with possible problems with the alignment of the magnet-optics-detector system or to face already estimated mechanical stress of the helioscope leading also to a minimal not stable alignment. This new detector array, called maXs-IAXO, consists of a 8 × 8 pixel array as the maXs-30, but each pixel absorber has in this design an area of about 1.25 mm × 1.25 mm. The thickness of the absorber has been reduced to 10 μm to still have a high stopping power for photons up to 15 keV, but leading to a smaller heat capacity of the detector, which is at the basis of achieving an energy resolution of about 10 eV FWHM in the energy region of interest. The total area covered by the array is 1 cm^2 with a geometrical efficiency of about 90%. Such a large detection area and the fact that the array is composed by 64 independent pixels brings as benefit the possibility to do in-situ background measurements using the pixels outside the focal area.
Both the maXs-30 array and the maXs-IAXO array are composed by 64 single pixels with identical absorbers. This major advantage is that each pixel presents the same response to equal energy deposition, which, in turn, ensures that pixels in the focal plane behave exactly as pixels measuring the in-situ background. At the same time, having a unique pixel type in an MMC array is not a fundamental requirement and arrays featuring non-identical pixels could present advantages for IAXO. One alternative design was already considered for the physics case discussed in [18] in which the possibility to have concentric disks was discussed.
Demonstrating the required background level for MMC arrays will open new interesting possibilities for the search of axions and, in particular, once axions will be detected, for the study of axion properties as well as solar properties by the interpretation of the axion spectrum [18, 19, 20, 21, 22, 23]. Thanks to the excellent energy resolution and the possibility to have a precise determination of the background in pixels surrounding the area illuminated by the optics, MMCs could play a very important role as being affected by different systematic effect compared to other detector technologies.

4. Helioscope for the study of axion properties and solar parameters

The possibility to have as a focal plane detector system in (baby)IAXO detectors featuring not only very low background, but also excellent energy resolution, has motivated the scientific community to investigate what can be learned once solar axions would be detected in helioscopes. In Section 1, the expected solar axion spectrum has been discussed. The continuous part of the spectrum deriving from the axion-electron coupling has a maximum at about 1.5 keV while the maximum of the axion spectrum generated by axion-photon coupling is at higher energy, between 3 keV and 4 keV. The possibility to distinguish axion production mechanisms by the analysis of the solar axion spectrum has been discussed in [19]. In this paper, the importance of reducing the energy threshold from 1 keV to 0.1 keV was

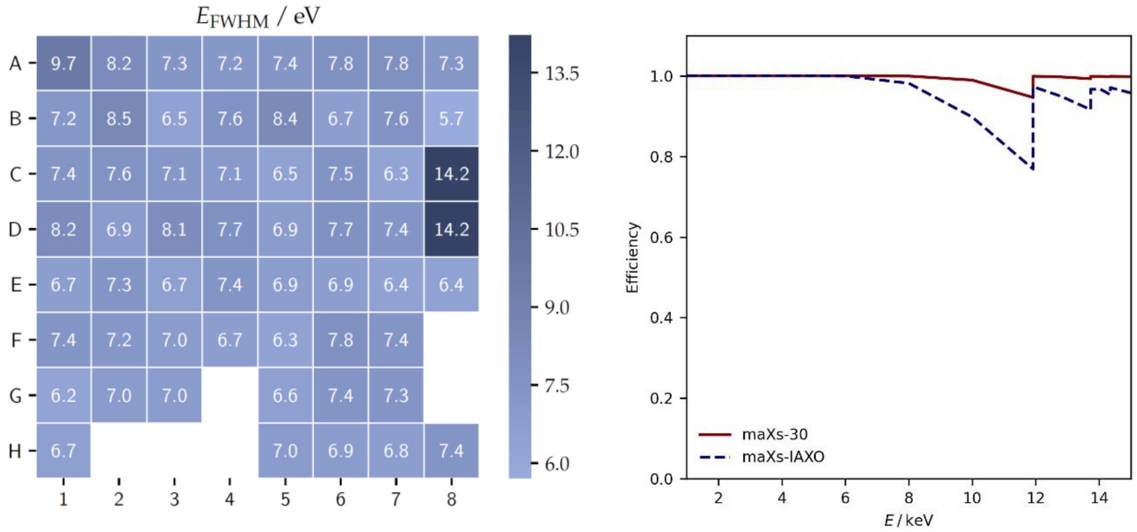

Figure 3: Left: Energy resolution given as FWHM for a Gaussian detector response determined for all the acquired channels in the characterization run [10]. Right: Stopping power for particle absorbers in maXs-30 (red continuous line) and maXs-IAXO (blue dashed line).

proposed as important requirement for increasing the sensitivity to quantify the fractions of axion produced through axion-photon coupling and axion-electron coupling. As discussed in Section 3, MMCs can be optimized to provide very low energy threshold. At the same time, the presence of a thin window to prevent infrared radiation to reach the detector module is the crucial component determining the energy threshold. Presently we have considered to use as X-ray windows thin aluminated Mylar foils (40 nm Al on 500 nm Mylar). The transparency of this window starts to clearly deviate from unity already around 3 keV and it reaches a value of slightly more than 80% at 1 keV. Such a window will allow for the study of axion production model by the analysis of the high intensity part of the spectrum.
The possibility to investigate the axion nucleon coupling was discussed in [20]. The feature in the solar axion spectrum which would bring information on this coupling is a resonance at 14.4 keV. Those axions are produced in the decay of the first excited nuclear state of ^{57}Fe. In fact, axions, being pseudoscalar particles, can be emitted in magnetic nuclear transitions. This line has been considered because of the expected larger intensity with respect to other nuclear transitions and because of its energy, which is very close to the energy range where detectors for helioscopes are optimized. The sensitivity to identify this line and, with this, investigate the axion nucleon coupling resides in the availability of detectors with high detection efficiency at 14.4 keV, low background and also high energy resolution. Figure 3) Right shows the stopping power for the two MMCs arrays we have developed so far for helioscopes. The energy resolution of both detector arrays is about 10 eV FWHM. The fact that both the maXs-30 array and the maXs-IAXO array show high efficiency for energy below 8 keV and still feature a large efficiency at 14.4 keV (100% and 97% for maXs-30 and maXs IAXO respectively) indicates that MMCs arrays have the potential to investigate axion parameters over the full energy range. This is a very attractive scenario for combining different investigations with a single instrument.
Another component of the solar axion spectrum which has been discussed in literature is the axion production from plasmon conversion [1, 21]. In particular, for longitudinal plasmon, a relatively high axion rate would be expected at a very low energy around 100 eV. The possibility to have a high sensitivity in such energy region would be very interesting for axion discovery in helioscopes. Nevertheless, challenging modifications would be required to make a helioscope as IAXO sensitive to those axions. First of all, the possibility to have a threshold as low as 30-50 eV which is very difficult for detectors requiring a window. A second problem is related to the optics which are presently optimized for energy above 1 keV. MMCs have already demonstrated such low energy threshold. Such a threshold could be also reached for MMC detector systems for IAXO if the X-ray window could be avoided. Such a case would be possible only if the focusing optics could be cooled down to about 4 K, in order to strongly

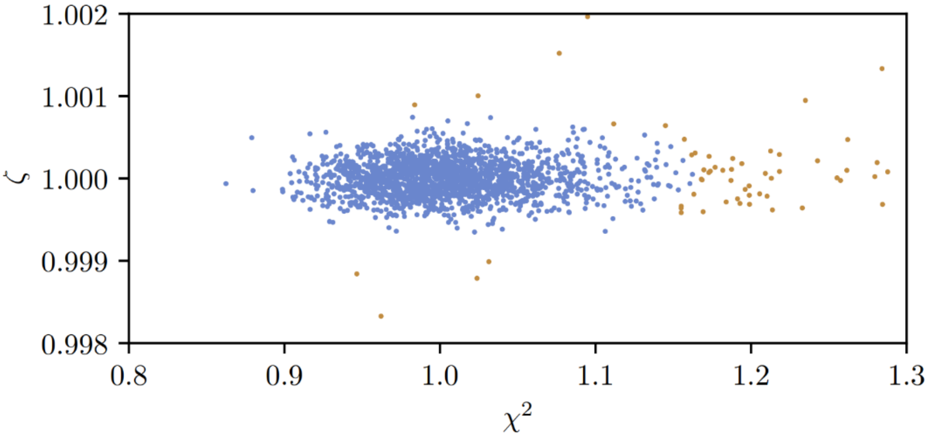

Figure 4: Ellipse Cut with χ^2 and ζ of the K_α line from the ^{55}Fe source. Similar pulses as the template pulse have $\chi^2 \approx 1$ and $\zeta \approx 1$ and are colored in blue (90% of the events in the amplitude region of the K_α line from the ^{55}Fe source). Here ζ is a special amplitude ratio based on the matched filter.

reduce the power of blackbody photons reaching the active area of the MMC detector system operated at mK temperatures. Typically, solar axion searches with helioscopes are considered to be blind to the axion mass when this is below the coherence limit of about 0.01 eV, depending on the length of the magnet. On the other hand, axion masses around 0.01 eV could be distinguished helioscopes thanks to oscillations in the measured photon spectrum. This interesting case has been studied in [22]. Based on the design parameters of IAXO, a sensitivity to constrain axion masses between 3×10^{-3} eV and 10^{-1} eV at the 3σ level could be reached. The possibility to reach such a good sensitivity is based on the availability of high resolution detectors which allow for the identification of the spectral oscillations.
Detectors with high efficiency and high energy resolution are not only interesting for the possibility to investigate properties of axions, but with the analysis of the photon spectrum deriving from solar axion conversion in helioscopes also properties of the Sun can be investigated. In Figure 1 the expected axion spectrum considering the production mechanism to be based on axion-electron coupling is shown. On top of the continuous component several lines can be seen. Those lines correspond to the production of axions via axion-electron coupling in ions present in the plasma in the center of the Sun. The intensity of those line is then related to the abundance of the different elemental ions. In [23] the possibility to study the solar metallicity with solar axions has been discussed. Such approach is complementary to the study of solar metallicity with solar neutrinos, but potentially more sensitive since atomic transitions are used instead of nuclear transitions, which are more selective. For the calculation of the sensitivity of the IAXO helioscope, detectors with an energy resolution of 10 eV FWHM have been considered. This energy resolution has been already demonstrated for MMCs arrays suitable for the IAXO experiment.
The availability of pixelated detectors with relatively good energy resolution was considered in [18] to investigate the possibility to determine the temperature profile from the core of the Sun to outer radii. In this work, the most important feature of the detector system is, along with a very low background, the availability of many pixels which are necessary to identify how the number of events decreases with increasing distance from the center of the focal area (distance from the center of the Sun). In particular, it has been pointed out that a 2D array with 64 × 64 pixel would reach the limiting sensitivity. The MOCCA MMC array, developed for the detection of molecular fragments, is a 64 × 64 pixel array covering and area of about 4 cm × 4 cm [24]. The number of readout channels for such a large array is still the same as the one used for maXs-30 and maXs-IAXO. The detection area of a MOCCA-like detector can be scaled down by reducing the size of the single pixels, which, in turn, would lead to a better energy resolution. Under these assumption, a detector module for the IAXO helioscope could be designed to be suitable for both a maXs-like detector array or a MOCCA-like detector array.

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5. Conclusions

If axions exist, a large axion flux originated in the Sun would be expected. Helioscopes are optimized to search for the existence of solar axion by having a large telescope following the Sun in which axions could convert back to photons in presence of a large static magnetic field. Axions can couple to photons, electrons and nucleons with different coupling constants and all these interaction mechanisms could occur in the Sun. Therefore, we could expect the solar axion spectrum to be composed by different sub-spectra related to the different interactions. Once axions would be discovered, the possibility to investigate the solar axion spectrum would open many possibilities to study axions properties as well as Sun parameters. IAXO will be the next generation helioscope designed to surpass the sensitivity reached in CAST by 1 or even 1.5 orders of magnitude. Towards IAXO, an intermediate stage of the experiment will be constructed at DESY (Hamburg) which goes under the name babyIAXO. This helioscope will already have the possibility to investigate a new portion of the axion mass – coupling space. In (baby)IAXO, after a long magnet and an x-ray optics, low background detectors play a very important role in the identification of photons related to axion conversion. At the same time, the use of different detectors and in particular detectors featuring high energy resolution are important both in the identification and reduction of background and in the identification and reduction of possible systematic effects.
In addition, detectors featuring high energy resolution along with a low energy threshold will be of utmost importance in case of first axion detection. In fact, a relatively small number of detected photons from solar axion conversion could already reveal intrinsic properties of this elusive particle as coupling strength to photon, electron, nucleons.
MMC arrays with energy resolution better than 10 eV FWHM, an energy-averaged quantum efficiency of more than 90% and featuring a detection area up to 1 cm^2 with geometrical efficiency of about 90% are presently considered as detectors for the IAXO experiment. In addition, the 1 cm^2 detection area, being larger that the focal area of the optics, allows for in-situ background measurement. Nevertheless, the present background level is still about 3 orders of magnitude larger than the requirements. Achieving the required background level for MMC arrays will open the possibility to have a competitive detector system for the axion discovery phase and a suitable instrument for studying axion properties as well as determining solar parameters in helioscopes after discovery.

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