Physics Potential and Prospects for the CUORICINO and CUORE experiments

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Abstract

The CUORE (\textit{Cryogenic Underground Observatory for Rare Events}) experiment projects to construct and operate an array of 1000 cryogenic thermal detectors of TeO\textsubscript{2}, of a mass of 760 g each, to investigate rare events physics, in particular, double beta decay and non baryonic particle dark matter. A first step towards CUORE is CUORICINO, an array of 56 of such bolometers, currently being installed in the Gran Sasso Laboratory. In this paper we report the physics potential of both stages of the experiment regarding neutrinoless double beta decay of $^{130}$Te, WIMP searches and solar axions.

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Key words: Underground detectors; double beta decay; dark matter; WIMPs; axions.

1 Introduction: The CUORE project

Rare event Physics at the low energy frontier is playing a significant role in Particle Physics and Cosmology. Examples of such rare phenomena could be the detection of non-baryonic particle dark matter (axions or WIMPs), supposedly filling a substantial part of the galactic haloes, or the neutrinoless double beta decay. These rare signals, if detected, would be important evidences of a new physics beyond the Standard Model of Particle Physics, and would have far-reaching consequences in Cosmology. The experimental achievements accomplished during the last decade in the field of ultra-low background detectors have lead to sensitivities capable to search for such rare events. Dark matter detection experiments have largely benefited from the techniques developed for double

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beta decay searches. Both types of investigation, which have very close relation from an experimental point of view, are the two main scientific objectives of CUORE.

Due to the low probability of both types of events, the essential requirement of these experiments is to achieve an extremely low radioactive background. For that purpose the use of radiopure detector components and shieldings, the instrumentation of mechanisms of background identification, the operation in an ultra-low background environment, in summary, the use of the state-of-the-art of low background techniques is mandatory. In some of these phenomena, like the case of the interaction of a particle dark matter with ordinary matter, a very small amount of energy is deposited, and the sensitivity needed to detect events within such range of energies, relies in how low the energy threshold of detection is. In addition, to increase the chances of observing such rare events a large amount of detector mass is in general advisable, and so most of the experiments devoted to this type of searches are planning to enlarge their detector mass, while keeping the other experimental parameters (background, energy thresholds and resolutions) optimized.

On the other hand, the recent development of cryogenic particle detection has lead to the extended use of thermal detectors to take advantage of the low energy threshold and good energy resolution that are theoretically expected for the thermal signals. This detection technology has also the bonus of enlarging the choice of materials which can be used, either as DM targets or $2\beta$ decay emitters. After a long period of R&D to master the techniques used in cryogenic particle detectors, low temperature devices of various types are now applied to the detection of double beta decay or particle dark matter. A major exponent of this development is the MIBETA (Milano Double Beta) experiment, which has successfully operated a 20 TeO$_2$ crystal array of thermal detectors of a total mass of 6.8 kg, the largest cryogenic mass operated up to now. With the objective of going to larger detector masses and of improving the sensitivity achieved in the smaller arrays, the CUORE (Cryogenic Underground Observatory for Rare Events) project was born some years ago as a substantial extension of MIBETA. The objective of CUORE is to construct an array of 1000 bolometric detectors with cubic crystal absorbers of tellurite of 5 cm side and of about 760 g of mass each. The crystals will be arranged in a cubic compact structure and the experiment will be installed in the Gran Sasso Underground Laboratory. The material to be employed first is TeO$_2$, because one of the main goals of CUORE is to investigate the double beta decay of $^{130}$Te, although other absorbers could also be used to selectively study several types of rare event phenomenology. Apart from the MIBETA experiment, already completed, a wide R&D program is under way in the framework of CUORICINO, a smaller and intermediate stage of CUORE, which consists of 56 of the above crystals (total mass of 42.5 kg). CUORICINO is currently being mounted in the Gran Sasso Laboratory (LNGS) and is, by far, the largest cryogenic detector on the stage. The preliminary tests are encouraging.

In the present work the prospects of CUORE and CUORICINO experiments with respect to their double beta decay discovery potential and their detection capability of WIMP and axions are presented.
2 Background considerations

From the radioactive background point of view, thermal detectors are very different than, say, conventional ionization detectors, the former being sensitive over the whole volume, implying that surface impurities may play an important role. In principle, bolometric detectors like those of the MIBETA, CUORICINO and CUORE experiments are expected to have radioactive backgrounds larger than that of the conventional germanium ionization detectors, also because the more complex technology of cryodetectors had not been yet fully optimized from the point of view of the radiopurity of the components near the detector. On the other hand, the production of radiopure absorbers for thermal detectors is less mastered than the production of radiopure Ge crystal. However, after a considerable R&D effort a significant improvement in the radiopurity of bolometers has been accomplished during the last years, and now these devices have achieved very competitive backgrounds [7, 8, 9, 10].

As one of the main ingredients in the prospective physics potential of the CUORICINO and CUORE experiments is the level of background achievable, an evaluation of the expected background must be done, including the contribution of the possible background sources. A preliminary estimation was made in the Status Report of CUORICINO presented to the LNGS Scientific Committee [11]. A more complete estimate is underway. In the following we will give a briefing of that (unpublished) reference and will add further considerations.

There are several background sources to be considered: the environmental backgrounds of the underground site (neutrons from the rocks, ambient gamma flux...), the intrinsic radioactivities of the detectors, components and shielding (bulk and surface), the cosmic muon induced backgrounds (neutrons, muon direct interactions ...), as well as the possible cosmogenic induced activities produced when the detector and components were outside the underground laboratory. Even small, the leakage of double beta counts emitted by the absorber’s nuclei in the relevant region of analysis might be a potential source of background. The depth at which the experiment will be performed, plus the addition of an efficient cosmic veto and a suitable passive shielding (lead, polyethylene, ...) will effectively reduce the external background. So we will refer mainly to the intrinsic background, although we will make some remarks concerning the other sources. On the other hand, the experience gained in the MIBETA experiment, where the measured background is used as a test-bench for checking the MC estimates, has been essential to know which could be the expectations for CUORICINO. Using the MIBETA results and the CUORICINO tests a Monte Carlo study of the expected intrinsic background has been carried out for the CUORICINO (and CUORE) set-ups. Supposed radioactivity impurities in the bulk of the tellurite crystals, as well as in the dilution refrigerator and surrounding shielding were taken into account. Background suppression due to the anticoincidence between crystals (which will be significant in the CUORE set up) was worked out. The effect of the α surface contaminations observed in the MIBETA crystals was also evaluated and scaled up to CUORICINO. The simulation was performed with the GEANT code. Alpha, beta and gamma emissions (supposed to be uniformly distributed and isotropically emitted)
from the natural chains ($^{238}U$, $^{232}Th$) and from other isotopes ($^{40}K$, $^{60}Co$, $^{210}Pb$) were included. In the case of MIBETA, the measurements based on the $\alpha$ peaks of the background have shown that the bulk intrinsic contamination of U/Th inside the crystals are very low (less than a few $10^{-10}$ g/g) and that the main sources of background are located on the surfaces. According to the method used to clean the holder of the crystals and to lap the surfaces (and depending on the radiopurity of the powders used in the lapping), the background values, in the best of the cases, stand about roughly half-a-count per keV, kg and year in the 2500-2556 keV ($2\beta$ decay) region, more precisely, $b=0.68\pm0.06$ c/keV/kg/yr in the ”old” and $b=0.35\pm0.14$ c/keV/kg/yr in the ”new” configuration (labelled respectively after the best lapping operation and a new mounting system) [6]. A background spectrum of MIBETA corresponding to the $2\beta$ decay region is shown in Fig. 2 of Ref. [10]. The addition of a neutron shielding of 10 cm of borated polyethylene does not reduce the background, as expected if the dominant contribution comes from the surface. With the above background value the lower limit of the neutrinoless half-life of $^{130}Te$ obtained is $T_{1/2}^{0\nu} \geq 1.4 \times 10^{23}$ y, or equivalently, an upper bound for the Majorana neutrino mass of $\langle m_\nu \rangle \lesssim 2$ eV (when using the Heidelberg nuclear matrix element calculation of Ref. [29]), which is the second-best published result [10]. Similarly, as far as the low energy region is concerned, the most recent current background of MIBETA, obtained after the new lapping of the crystal detector surfaces, stands around 1 c/keV/kg/day between 10–50 keV and 0.2 c/keV/kg/day between 50–80 keV, region where the dark matter signal is expected [6]. Ref. [6] shows the MIBETA background spectrum corresponding to the low energy, dark matter region. With these background values, the exclusion plot of WIMPs interacting coherently with Te and O is depicted as the (dashed) contour of figure [1]. Both results of MIBETA, for the low (<100 keV) and the high (~2500 keV) energy regions will serve as references for the CUORICINO/CUORE projections.

To reproduce and understand the contribution to the MIBETA background, a MC calculation has been made for MIBETA (and then extended to the CUORICINO and CUORE geometries) including the main components and geometry of the experimental set-up (array of crystals, holder, cryostat, shielding, . . . ). The radioactive impurities used as inputs were all the contaminants identified in the MIBETA background spectrum, through the alpha or gamma lines. They are $^{238}U$ in secular equilibrium, $^{214}Bi$, $^{210}Pb$, $^{232}Th$ in secular equilibrium, $^{40}K$ and $^{60}Co$. The amount in which each impurity is present is obtained as the upper limit for which the MC simulation matches best the measured background. A previous hint about the amount of such radioimpurities was obtained by measuring in low background HPGe detectors (at Gran Sasso and Canfranc underground Laboratories) the materials and components typically used in the experimental set-up.

The main results -which should be taken as the expectations for the CUORICINO background- are the following: in the very low energy region (from 10 to 100 keV), the background is dominated by $^{210}Pb$ surface contamination located either on the crystal surface or on the surface of the copper mounting box. This contamination has been identified through the 46 keV peak and the 5.3 and 5.4 MeV alpha lines. The continuum between 100 and 1500 keV seems to be determined by a $^{40}K$ surface contamination of the
crystals/copper mounting box. The continuum counting rate in the energy region 1500-
4000 keV could be explained by a crystal surface contamination of $^{238}\text{U}$, $^{226}\text{Ra}$, $^{232}\text{Th}$
and $^{210}\text{Pb}$. This surface contamination seems to be the dominant contribution to the
background in the $2\beta$ decay region, and only a minor contribution should be attributed
to the $^{232}\text{Th}$ bulk contamination.

The U/Th and $^{210}\text{Pb}$ surface contaminations of the old MIBETA crystals (which have
been of big concern in the R&D of CUORICINO) have been significantly reduced (but
not eliminated) by means of a new lapping procedure of the crystals. These surface
contaminations were estimated by the MC simulation of the MIBETA set-up and properly
checked with the experimental data. They produced an overall rate of about $\sim0.1-0.2$
c/keV/kg/y in the 2.5 MeV region and 0.2-0.3 c/keV/kg/d in the 10-100 keV energy
region, dominating in both cases over the bulk intrinsic background. The new cleaning
procedure carried out in the $3 \times 3 \times 6$ cm$^3$ crystals of MIBETA has reduced these values
by more than one order of magnitude.

In fact, in the CUORICINO MC simulation the following inputs have been assumed:
the bulk contamination is the upper limit deduced for such radioimpurities in the cor-
responding component of MIBETA. As far as the surface radioimpurities, they are as
follows: the $^{40}\text{K}$ is assumed to be the same as in MIBETA. The U/Th surface contamina-
tion has been scaled from that of MIBETA, but taking into account that they are factors
1.5 and 2 smaller per unit surface than in MIBETA (as deduced from CUORICINO crys-
tals tests). As far as the $^{210}\text{Pb}$ surface contamination in the crystals and/or the copper,
similar values that those derived from MIBETA have been assumed. Notice however that
a reduction of one order of magnitude (or more) in this background is expected to be
obtained and that very likely possibility will be taken into account to derive the physics
prospects of the experiment.

With the above proviso, the MC simulated contribution to the CUORICINO intrinsic
background (bulk and surface) are $b_{2\beta}(\text{bulk})\sim2\times10^{-2}$ c/keV/kg/y and $b_{2\beta}(\text{surface})\sim10^{-1}$
c/keV/kg/y (from U/Th in the crystals and from $^{210}\text{Pb}$ in the crystals and copper)
in the 2.5 MeV region and $b_{DM}(\text{bulk})\sim3\times10^{-2}$ c/keV/kg/d and $b_{DM}(\text{surface})\sim5\times10^{-2}$
c/keV/kg/d (from U/Th in crystals) and $2\times10^{-1}$ c/keV/kg/d (from $^{210}\text{Pb}$ in crystals and copper)
in the 10-100 keV region.

Taking into account that the surface contaminations could be reduced a factor 10, one
can expect that the global intrinsic background of CUORICINO could be in the most
simple and conservative estimate of $\sim$ a few $10^{-2}$ c/keV/kg/y around 2.5 MeV and a few
$10^{-2}$ c/keV/kg/d in the DM low energy region.

Concerning the cosmogenic activation of the crystals produced by cosmic rays when
they were above ground (during fabrication and transportation of the crystals from the
factory to the underground laboratory) we have carried out a Monte Carlo estimation
by using the code COSMOPACK. According with the history of the MIBETA (and
CUORICINO) detectors, we have assumed 2 months of exposure to cosmic rays and
then 1 year of cooling down of the induced activities. The radionuclei produced by the

1We thank Y. Ramachers for providing us the code used by the CRESST Collaboration
activation of tellurium are mostly tellurium isotopes (A=121,123,125,127) as well as $^{124}$Sb, $^{125}$Sb and tritium, these last two being of more concern because of their half-life (beta decays of 2.7 years, end-point energy of 767 keV and 12.3 year, end-point energy of 18 keV, respectively). The induced $^{124}$Sb has also a beta decay (half-life of 60 days, end-point energy of 2905 keV) and a few gamma lines. The total induced activities remaining after one year underground have been estimated to be 6.5 c/kg/d ($^{125}$Sb), 1.8 c/kg/d ($^{124}$Sb) and 0.1 c/kg/d ($^3$H). In the case of tritium, for instance, the contribution to the event rate (from threshold (5 keV) onwards) is $5 \times 10^{-3}$ c/keV/kg/d. Their incidence in the background count rate are still below the intrinsic radioactivities (bulk and surface) of the crystals but they might set a bound for the achievable background of the experiment, unless the cooling down period be extended. No special incidence of the cosmogenic activation has been seen in the recent MIBETA spectra. However, some lines of the above mentioned isotopes have been observed when the crystals were temporarily taken out of LNGS for lapping the surfaces and operated again.

Notice that, in any case, the cosmogenic activation is already included in the experimental data of the MIBETA background and so, it has been taken into account in the extrapolation made in going from MIBETA to CUORICINO (both types of crystals follow, roughly, the same history of fabrication in China, transportation and storage underground).

On the other hand, the leakage of $2\beta$ counts in the low energy region ($< 100$ keV), due to the double beta decay of $^{130}$Te is totally negligible ($< 10^{-4}$ c/kev/kg/d, assuming for the $^{130}$Te a $2\beta$ $2\nu$ half-life of $\sim 10^{21}$ y, an average of the two current measured results of $7.3 \times 10^{20}$ y and $1.2 \times 10^{21}$ y [10]).

As noticed before, neither cosmic muons nor neutrons have been taken into account, in detail, in the estimation of the background. However, the following simplified arguments will serve to have an approximate idea of which could be their contribution.

The depth of the LNGS (3500 m.w.e) reduces the muon flux down to $\sim 2 \times 10^{-8}$ cm$^{-2}$s$^{-1}$, but a further effective reduction can be obtained with the use of an efficient (99.9%) active veto for not to miss muons traversing the detectors and to tag possible events associated with them. Consequently, the muon-induced events contributing to the background are expected to be only a small component of it. The main contribution to the expected background, as seen in MIBETA, is coming from the intrinsic radioimpurities (bulk or surface).

On the other hand, the shielding will substantially reduce the event rate due to particles external to the detector from various sources (neutrons and photons), from radioactivity in the environment (natural decay chains U/Th, $^{210}$Pb, $^{40}$K, ...), as well as muon-induced in the surroundings or in the shielding itself. The passive shielding typically consists of a neutron screen (blocks of -borated- polyethylene of 10-20 cm thickness) to attenuate and moderate neutrons and a shell in lead (of about 10-15 cm) to attenuate the incoming external photons; the innermost part is made of archaeological lead (2000 years old) with a very small content ($<4$ mBq/kg) of $^{210}$Pb (half-life 22 years) and of high radiopurity. The successive shielding barriers, active and passive, guarantee a very substantial reduction of the external background sources (we will show how this reduction
Neutrons may constitute a worrisome background in dark matter experiments because for appropriate neutron energies (few MeV) they can produce nuclear recoils ($\lesssim 100$ keV) in the detector target nuclei which would mimic WIMP interactions. Simple kinematics tells that in the case of tellurium, neutrons of 1(5) MeV could elastically scatter off tellurium nuclei producing recoils of energies up to 31 (154) keV. In general, one considers neutrons of two origins: from radioactivity in the surroundings or muon-induced. Depending on the overburden of the underground site (i.e., depending on the muon flux), muon-induced neutrons are produced, at lesser or greater rate, both inside and outside the shielding. They are moderated (according to their energies) by the polyethylene/lead shield (when produced outside) or tagged by the muon veto coincidence (when produced within the passive shielding). A certain fraction of the neutrons of, say, a few MeVs produced outside can pass the veto reaching the detector and producing ”dangerous” nuclear recoils and $\gamma$ background. However, a significant fraction of the associated events can be vetoed because of their interaction with the veto and also because of the hadronic showers trained by the muons (see Ref. [7]). We have MC-estimated -see later- how many of these neutrons can punch through the shielding.

In the case of external neutrons (from the rocks, from fission processes or from ($n,\alpha$) reactions, as well as neutrons originated by muons in the walls of the underground site), the ambient neutron flux has been measured in LNGS. The result is of $\sim 1 \times 10^{-6}$ cm$^{-2}$s$^{-1}$ for the thermal component, $\sim 2 \times 10^{-6}$ cm$^{-2}$s$^{-1}$ for the epithermal and $\sim 2 \times 10^{-7}$ cm$^{-2}$s$^{-1}$ for energies over 2.5 MeV [16]. They are fairly well moderated by the polyethylene and eventually absorbed or captured. We have carried out a Monte Carlo simulation of the propagation of neutrons through a typical (but simplified) shielding of CUORICINO. In particular, we have estimated the distance distributions for neutrons (of energies 1 and 5 MeV) to thermalize ($E<0.1$ eV) in polyethylene. The maxima of the distributions are at 5 and 7 cm respectively. For instance, 90% of neutrons of 1 MeV (5 MeV) thermalize after 12 cm (22 cm) of polyethylene. In a shielding of 40 cm of polyethylene, 99.7 % of neutrons of 5 MeV are moderated down to 0.1 eV (as well as practically all neutrons of 1 MeV). For neutrons of higher energies the fraction of them which are thermalized after, say, 40 cm of water is $\sim 92\%$ (for neutrons of 10 MeV), $\sim 83\%$ (for neutrons of 25 MeV) and $\sim 50\%$ (for neutrons of 50 MeV). Then, taking into account the energies of fission neutrons (rocks, . . . ) and the small number of cosmic muon-induced neutrons at 3500 m.w.e., a neutron shielding of $\sim 40$ cm of polyethylene (or water) would practically reduce the external neutron flux down to energies not dangerous from the point of view of the nuclear recoils they could produce.

On the other hand, the incoming flux of external neutrons becomes attenuated in the shielding material (in the polyethylene neutron moderator or in the gamma lead shielding). As said before, we have developed a MC simulation of such attenuation as well as the associated photon production originated by these neutrons (via inelastic scattering, radiative capture) in the shielding material. The MC estimate assumes a shielding box of external dimensions typical of those of CUORE (1 m $\times$ 1 m $\times$ 2 m), with walls of lead and polyethylene of various thickness, to determine the fraction of incident neutrons (of
initial energies of 1 and 5 MeV) which are able to punch through the thickness of the shielding box. Taking, for instance, a box consisting of 10 cm of polyethylene (external) and 10 cm of lead (internal), it turns out that about 2%, 4% and 10 % of external neutrons having respectively energies of 0.1, 1 and 5 MeV, are able to punch through that shielding. The number of neutron-induced photons, which arrive inside the box (in the detector volume) has been also evaluated. Starting, for instance, with neutrons of 5 MeV entering the shielding and reaching the region of the crystals with energies of 2.6 MeV (generated by inelastic scattering with $^{208}$Pb) or with 2.2 MeV (due to thermal neutron capture in hydrogen), they produce $10^{-4}$ photons per neutron (or $8 \times 10^{-4}$ photons per neutron) respectively. In the case of neutrons of 1 MeV, these figures are, respectively, $10^{-4}$ photons per neutron and practically zero photons. These considerations referred to the typical shielding of the CUORICINO/CUORE experiment give an idea of the limited incidence of the external neutrons, as previously stated.

Other neutrons, produced by muon interaction inside the shielding materials, are very scarce and tagged as events coincident with the muon veto. As it is well-known, muon-induced neutrons are originated in a variety of processes. The reduction of muon flux in underground sites results in a substantial depletion of the associated neutrons and below $\sim 100$ m.w.e. the dominant sources of neutrons are nuclear fission processes and $(n,\alpha)$ reactions in rocks and other environmental material with sizeable content of U/Th. The energy spectrum of muon-induced neutrons is approximated by an inverse energy power law ($E^{-0.88}$ for 1-50 keV and $E^{-1}$ above 50 keV) but other neutron energy spectra have been proposed. The neutron yield per muon can be approximately evaluated through the simple expression $N_n = 4.14 \times E_\mu^{0.74} \times 10^{-6}$ neutrons/(gcm$^{-2}$) per muon [17] which fits the value of $1.5 \times 10^{-4}$ neutrons/(gcm$^{-2}$) of the muon-induced neutron flux measured by the LVD experiment at Gran Sasso [18]. Other authors have used similar expressions.

Using an average neutron yield per muon of $2.2 \times 10^{-4}$ neutrons/(gcm$^{-2}$), together with the LNGS muon flux ($2.5 \times 10^{-8}$ $\mu$/(cm$^2$s)), that would produce in the simplified CUORE shielding referred above (box of $1 \times 1 \times 2$ m$^3$, with walls of polyethylene (10 cm) and lead (10 cm)), about $\sim 0.5$ neutrons/day in the polyethylene shield and $\sim 4$ neutrons/day in the lead shell. So, independently of the mechanism set up to reject or tag the events associated to neutrons, their rather small number is expected to play a secondary role in the total background compared with other, intrinsic, sources of background. On the other hand, much in the same way, the remarks we made above about the cosmogenic induced activity when going from MIBETA to CUORICINO also apply to the neutron induced background, which is already incorporated to the MIBETA background data, and so taken into account in the extrapolation. A more complete and detailed study of the external, non intrinsic background rates is underway.

The $\gamma$-ambient background in Gran Sasso is $\sim 1$ cm$^{-2}$s$^{-1}$ [19] and it can be attenuated by a proper lead shielding.

The background values quoted for MIBETA were obtained nevertheless with a more simplified shielding (no active veto, no neutron shielding except in the last running, where 10 cm of polyethylene was added). In spite of this fact, the MIBETA background [6] at low energy ($\sim 1$ c/keV/kg/d at threshold -10 keV- and at 3500 m.w.e.) is similar than
the measured event rate anticoincident with the veto in the CDMS experiment [7] (\(\sim 2\) c/keV/kg/d at 10 keV and at 20 m.w.e.) and in the EDELWEISS experiment [8] (\(\sim 1.8\) c/keV/kg/d at 30 keV and 4000 m.w.e.), without veto, (in both cases, obviously, prior to charge-heat discrimination) and is roughly equal to that of DAMA [12] and ANAIS [13] (\(\sim 1.5\) c/keV/kg/d, at 2 keV and 3500 m.w.e. and at 4 keV and 2450 m.w.e. respectively) but still one order of magnitude worse than that of IGEX [14] (\(\sim 0.2-0.05\) c/keV/kg/d at 4 keV and 10 keV respectively, and at 2450 m.w.e.). In the double beta decay region (\(\sim 2.5\) MeV) the MIBETA background values (\(\sim 0.3-0.6\) c/keV/kg/y in, respectively, the old and new set-up) are competitive but still higher than those of the IGEX experiment [15] (0.05 c/keV/kg/y at 2 MeV) (which uses Pulse Shape Discrimination).

The challenge of CUORICINO (and later on, of CUORE) is to reduce significantly the MIBETA background values (both in the low and high energy regions) by, say, two orders of magnitude without using background discrimination mechanisms like the simultaneous measurement of charge (or light) and heat. We argue that it can be achieved in two steps.

Starting from the current background values of MIBETA (\(\sim 1\) c/keV/kg/d from 10-50 keV, \(\sim 0.2\) c/keV/kg/d between 50-80 keV and \(\sim 0.3\) c/keV/kg/y around 2.5 MeV) and taking into account the preceding discussion about the incidence of the various components of the background, we expect that these background values can be reduced by one to two orders of magnitude, going down to values smaller than 0.1-0.05 c/keV/kg/day in the low energy region and to about 0.01 c/keV/kg/y (or lower) in the double beta region, as suggested by the MC simulation and the nature and location of the background radioactivities. That extrapolation is very conservative if one takes into account the exhaustive radiopurity selection of the detector materials and components which is being done for CUORICINO, the new lapping procedure of the crystal surface, the closer packing of the crystals, the suppression of significant amount of holding material, the powerful anticoincidence rejection provided by the segmented geometry of the crystal array and the use of a much better shielding than that employed in MIBETA. Nevertheless, as a first step in the background achievements, we will assume in the following prospective analysis of the CUORICINO capabilities, even more conservative background values (including intrinsic and external), more precisely of 1 c/keV/kg/day and of 0.1 c/keV/kg/day in the low energy region (at threshold, \(\sim 5\) keV) and values of 0.1 c/keV/kg/y and of 0.01 c/keV/kg/y in the 2–2.5 MeV region. The forthcoming results of the CUORICINO experiment will tell us how much this reduction can be further pursued. Even at these conservative values, CUORICINO is, as we will proof in the following, a powerful instrument to look for 2\(^\beta\) decays and WIMPs. In the case of CUORE the background values that will be assumed (also approximatively) are 0.1 and 0.01 c/keV/kg/day in the low energy region and 0.1 and 0.01 c/keV/kg/y around 2.5 MeV, which should be considered, also, two successive steps of the experiment.

Regarding the expected threshold and resolution, in the CUORICINO tests [4] energy thresholds of \(\sim 5\) keV have been obtained and a resolution of 1 keV at the 46 keV line of \(^{210}\)Pb achieved, in some of the detectors. Ref. [6] illustrates this point. In the case of CUORE thresholds of 5 keV and energy resolutions of 1 keV at low energies will be assumed. As far as the energy resolutions obtained in the double beta decay region, values
of 3 keV at 2615 keV were achieved in some crystals but they are worse (by a factor two) in others. See Fig. 1 of Ref. [11]. Nevertheless, they are clearly better than that obtained in the previous $6 \times 3 \times 3 \text{ cm}^3$ (MIBETA) crystals (8~10 keV). Taking into account these expectations, we discuss in the following the prospects of CUORICINO and CUORE for double beta decay searches (section 2), for WIMP detection (section 3) and for solar axion exploration (section 4).

3 Double beta decay

One of the main scientific objectives of the CUORE detectors is to search for the double beta decay of the $^{130}\text{Te}$ isotope contained in the (natural) TeO$_2$ set of crystals.

The importance of the nuclear double beta decay as an invaluable tool to explore particle physics beyond the Standard Model has been repeatedly emphasized and widely reported [20]. In the Standard Model of Particle Physics neutrinos are strictly massless, although there is no theoretical reason for such a prejudice. On the experimental side, moreover, there exist strong evidences from atmospheric neutrino data (from SuperKamiokande) and from experiments with solar neutrinos from Homestake, Gran Sasso and Kamioka, since long time ago, which suggest that neutrinos have indeed masses and oscillate among the three species. The recent results of the solar $\nu$ experiment from SNO with both CC (Charged Current) and NC (Neutral Current) interactions [21], also combined with SuperK have provided, definitively, a strong evidence that neutrinos do oscillate and, consequently, the existence of non-zero mass neutrinos. However, neutrino oscillation experiments provide the squared mass difference between the neutrino species but not their absolute value and scale. The neutrinoless double beta decay would help to solve this question and to disentangle the hierarchy scheme of the neutrino flavours. Most of the models (see [22]) indicate that the Majorana neutrino mass parameter could be around (or slightly below) $\langle m_\nu \rangle \sim 0.05$ eV, value within reach of the future double beta decay experiments, like CUORE. On the other hand, galaxy formation requires a small amount of hot non-baryonic dark matter likely in form of neutrinos to match properly the observed spectral power at all scales of the universe. The question of the neutrino mass is one of the main issues in Particle Physics.

In the Standard Model, neutrinos and antineutrinos are supposed to be different particles, but no experimental proof has been provided so far. The nuclear double beta decay addresses both questions: whether the neutrinos are self-conjugated and whether they have non-zero Majorana masses. In fact, the lepton number violating neutrinoless double beta decay $(A, Z) \rightarrow (A, Z + 2) + 2e^- (2\beta0\nu)$ is the most direct way to determine if neutrinos are Majorana particles. Moreover, the observation of a $2\beta0\nu$ decay would imply a lower bound for the neutrino mass, i. e. at least one neutrino eigenstate has a non-zero mass.

Another form of neutrinoless decay, $(A, Z) \rightarrow (A, Z + 2) + 2e^- + \chi$ may reveal also the existence of the Majoron ($\chi$), the Goldstone boson emerging from the spontaneous symmetry breaking of $B - L$, of most relevance in the generation of Majorana neutrino
masses and of far-reaching implications in Astrophysics and Cosmology. These and other issues, make the search for the neutrinoless double beta decay an invaluable tool of exploration of non-standard model physics, probing mass scales well above those reached with accelerators. That is the motivation why there are underway dozens of experiments looking for the double beta decay of various nuclei \( ^{76}\text{Ge} \) (IGEX \[23\], Heidelberg-Moscow \[23\]), \(^{100}\text{Mo} \) and others (NEMO \[24\], ELEGANTS \[25\]) and \(^{130}\text{Te} \) (MIBETA, CUORICINO) and a few big experimental projects, like CUORE, Majorana \[26\] (\(^{76}\text{Ge} \)), MOON \[27\] (\(^{100}\text{Mo} \)) and EXO \[28\] (\(^{136}\text{Xe} \)).

The cryogenic thermal detectors provide new double beta emitter nuclei to be explored in ”active” source=detector calorimeters. Some of them have been tested and others are already in running detectors, like \(^{48}\text{Ca} \) in CaF\(_2\), \(^{130}\text{Te} \) in TeO\(_2\), and \(^{116}\text{Cd} \) in CdWO\(_4\). As far as the Tellurium Oxide is concerned, the 130-Tellurium isotope is a good candidate for double beta decay searches: its isotopic content in natural Tellurium is 33.87\%, and its 2\(\beta\) Q-value \(Q_{2\beta} = 2528 \pm 1.3 \text{ keV} \) is reasonably high to escape from the main radioimpurity lines when looking for a neutrinoless signal. Moreover, this Q-value happens to be between the peak and the Compton edge of the 2615 keV line of \(^{208}\text{Tl} \), which leaves a clean window to look for the signal. Finally, it has a fairly good neutrinoless nuclear factor-of-merit \(F_0^\nu N \) in the \(^{130}\text{Te} \) case calculated in various nuclear models \[20\], together with those of other emitters used in source=detector calorimeters. It can be seen that no matter the nuclear model used to compute the neutrinoless decay matrix elements, the merits of \(^{130}\text{Te} \) are a factor 5–10 more favorable than those of \(^{76}\text{Ge} \) (the emitter where the best neutrinoless double beta decay half-life limits have been achieved so far), which translates into a factor 2 to 3 better as far as the \( \langle m_\nu \rangle \) (Majorana neutrino mass parameter) bounds are concerned.

The detector factor-of-merit \(F_0^\nu D\), or detection sensitivity, introduced long time ago by Fiorini, provides an approximate estimate of the neutrinoless half-life limit achievable with a given detector. For source=detector devices, it reads:

\[
F_0^\nu D = 4.17 \times 10^{26} \times \frac{a}{A} \sqrt{\frac{Mt}{b\Gamma}} \times \epsilon \text{ years} \tag{1}
\]

where \(A\) is the atomic mass, \(a\) is the isotopic abundance, \(M\) the detector mass in kg, \(b\) the background in c/keV/kg/y in the 2\(\beta\) neutrinoless decay region, \(t\) the running time in years, \(\Gamma\) the FWHM energy resolution in keV and \(\epsilon\) the detector efficiency (which is practically one within the fiducial volume of the detector). In the case of a TeO\(_2\) crystal detector, \(F_0^\nu D \sim 8.86 \times 10^{23} \sqrt{\frac{Mt}{b\Gamma}}\), with \(M\) the crystal mass in kg and \(b\) the background in counts per keV and year per kg of detector mass.

The simplest projection for CUORICINO uses a background of \(b=0.3\) c/keV/kg/y (at 2.5 MeV) and an energy resolution FWHM(2.5 MeV)\(\sim 8\) keV, which are the performances obtained currently in MIBETA (notice that the background in the ”old” MIBETA ver-
sion was of $\sim 0.6$ c/keV/kg/y. With that proviso, the sensitivity of 1 year exposure of CUORICINO (42.5 kg mass of crystals) will be $T_{1/2}^{0\nu} \geq 3.7 \times 10^{24}$ y. As far as the $\langle m_\nu \rangle$ limit is concerned (given as usually by $\langle m_\nu \rangle \leq m_e/\sqrt{F^D_{0\nu} F^W_{0\nu}}$), since the nuclear factor-of-merit of $^{130}$Te is larger than that of $^{76}$Ge (see Table I), the $^{130}$Te emitter provides a factor 2–3 better $\langle m_\nu \rangle$ bound than that obtained from $^{76}$Ge for the same half-life limit. In other words, one needs to reach a half-life limit of only $T_{1/2}^{0\nu} > 5 \times 10^{24}$ years to get the same $\langle m_\nu \rangle$ upper bound currently achieved in the best Germanium experiments $(1.6 - 1.9 \times 10^{25}$ years respectively [15] and [23]). In terms of $\langle m_\nu \rangle$ bound, the above simplest projection of $T_{1/2}^{0\nu} \geq 3.7 \times 10^{24}$ y means $\langle m_\nu \rangle < 0.36 - 0.21$ eV using [29] or [32], i.e., values comparable to, or better than, the best currently achieved with Ge experiments.

A second, still very conservative projection would be provided in the case of reaching a background of $b = 0.1$ c/keV/kg/y (as discussed in Section 2) and a resolution of $\Gamma = 5$ keV in the 2.5 MeV region. Such performances can be easily achieved in the very first stage of CUORICINO (notice that MIBETA has already achieved 0.3 c/keV/kg/y and that the energy resolution in the tests of the CUORICINO crystals ranges from $\Gamma = 3$ keV to $\sim 6$ keV at 2615 keV, i.e., notably better than that of smaller $3 \times 3 \times 6$ cm$^3$ of the 20 crystal array of MIBETA). In that case, one would have $F_D \sim 1.25 \times 10^{24} \sqrt{M t}$ years, with $M$ (kg) the mass of the Tellurite crystal array. For the mass of CUORICINO ($M = 42.65$ kg), one will have a sensitivity of $F_D \sim 8.15 \times 10^{24} \sqrt{t}$ years. Using a typical average value of $F_N = 4 \times 10^{-13}$ y$^{-1}$, as obtained in QRPA [29, 30, 31, 34, 35], CUORICINO will have a mass bound sensitivity of $\langle m_\nu \rangle < 0.28$ eV in one year, in the least favourable case. Using, in particular, (for comparison purposes) the value of $F_N = 5.33 \times 10^{-13}$ y$^{-1}$ of Ref. [29] which is usually employed in the $\langle m_\nu \rangle$ bound ($\sim 0.33$ eV) derived from the Ge experiments, CUORICINO would provide with these assumptions $\langle m_\nu \rangle < 0.24$ eV.

To go further, one needs to increase the mass of TeO$_2$ (CUORE 760 kg) and to reach even a lower background, which the anticoincidence capability of the CUORE array of one thousand crystals and the surface radiopurity could, likely, achieve going down to, say, $b = 0.05-0.01$ c/keV/kg/y. In the case of the full CUORE detector, formed by one thousand crystals of a total mass of 760 kg, even keeping, conservatively, $b$ and $\Gamma$ as above ($b = 0.1$ c/keV/kg/y, $\Gamma(2.5$ MeV$) = 5$ keV), one would get $T_{1/2}^{0\nu} \geq 3.4 \times 10^{25} \sqrt{t}$ years, which in one year of statistics would provide $\langle m_\nu \rangle$ bounds ranging from $0.12$ eV [29], $0.14$ eV [31], $0.26$ eV [35] or $0.07$ eV [32] just to mention a few nuclear matrix element estimates. However, the R&D to be carried out in CUORE and the operation in the anticoincidence mode is expected to provide better figure-of-merit than the values used in the previous predictions. According to such expectatives, values of $b \sim 0.01$ c/keV/kg/y and a FWHM energy resolution of $\Gamma \sim 1$ keV will be used for the last step of CUORE, i.e., a detection sensitivity of $F_D \sim 8.86 \times 10^{24} \sqrt{M t}$ years, from where one can work out the best expectatives of the whole CUORE ($M = 760$ kg of tellurite), i.e., $F_D \sim 2.5 \times 10^{26} \sqrt{t}$ years, or $\langle m_\nu \rangle$ bounds ranging from $\sim 0.05$ $t^{-1/4}$ eV (in [29, 34, 31, 34, 35, 38]) to $\sim 0.03$ $t^{-1/4}$ eV (in [32, 33]). The ultimate sensitivity of CUORE (as far as the Majorana neutrino mass bound is concerned) stagnates at $\sim 0.05$ eV with a very softened dependence with time.
4 WIMP detection

Recent cosmological observations [39] provide compelling evidence for the existence of an important component of non-baryonic cold dark matter in the Universe. Among the candidates to compose this matter, Weakly Interacting Massive Particles (WIMPs) and axions are the front runners. The lightest stable particles of supersymmetric theories, like the neutralino [40], describe a particular class of WIMPs.

Under the hypothesis of WIMPs as main component of the dark matter, these particles should fill the galactic haloes and explain the flat rotation curves which are usually observed in many galaxies. The detection of such particles could be attempted both by means of direct and indirect methods. The direct detection of WIMPs relies on the measurement of their elastic scattering off the target nuclei of a suitable detector [3]. The non relativistic and heavy (GeV – TeV) WIMPs could hit a detector nucleus producing a nuclear recoil of a few keV. Because of the small WIMP-matter interaction cross sections the rate is extremely low. In the case of SUSY WIMPs most of the cross section predictions [41, 42, 43] (derived using MSSM as the basic frame implemented with different unification hypothesis) encompass a range of values several orders of magnitude wide (the so-called scatter plots) providing rates ranging from $1 \text{ c/kg/day}$ down to $10^{-5} \text{ c/kg/day}$ according to the particular SUSY model.

It is well known that the predicted signal for the WIMP elastic scattering has an exponentially decaying energy dependence, hardly distinguishable from the background recorded in the detector. The simple comparison of the theoretical WIMP spectrum with the one experimentally obtained, provides an exclusion (at a given confidence level), as dark matter component of the halo, of those WIMPs with masses ($m$) and cross sections on nucleons ($\sigma$) which yield spectra above the measured experimental rate. To claim a positive identification of the WIMP, however, a distinctive signature is needed. The only identification signals of the WIMP explored up to now are provided by the features of the Earth’s motion with respect to the dark matter halo. In particular, the annual modulation [44] is originated by the combination of the motion of the solar system in the galactic rest frame and the rotation of the Earth around the Sun. Due to this effect, the incoming WIMP’s velocities in the detector rest frame change continuously during the year, having a maximum in summer and a minimum in winter. Therefore the total WIMP rate changes in time with an oscillating frequency which corresponds to an annual period and a maximum around the beginning of June.

The relative variation of the signal is small (a few percent) so in order to detect it one needs large detector masses to increase statistics and several periods of exposure to minimize systematics. Several experiments have already searched for this effect [45, 46, 47] and since 1997 one group has reported a positive signal [12] which has been appearing along four yearly periods. The present situation is no doubt exciting: on one hand that result has triggered an intense activity in the field; on the other, the experimental sensitivities of various types of underground detectors are entering the supersymmetric parameter space [12] and in particular three of them [6, 8, 14] are excluding, to a larger or shorter extent, the region of mass and cross-section where the reported WIMP is supposed
to exist. New data from one of them [8] have excluded totally the DAMA region. We will
discuss in the following the capabilities of CUORICINO and CUORE to exclude WIMPs
using the total time-integrated experimental rate and comparing it with the predicted
nuclear recoil rate. To look for the annual modulation signal in CUORICINO / CUORE
experiments, which in principle have enough masses to be sensitive to it, one needs to
know their stability performances. The analysis of the CUORE / CUORICINO potential
for annual modulation searches will be performed -following statistical consideration- (see
Ref. [53]), with the proviso that systematic uncertainties are under control. Data on the
stability of MIBETA and on the first running of CUORICINO will be crucial to asses
such hypothesis.

To calculate the theoretical WIMP rate, standard hypothesis and astrophysical pa-
rameters are assumed, i.e., that the WIMPs form an isotropic, isothermal, non-rotating
halo (the isothermal sphere model) of density $\rho = 0.3$ GeV/cm$^3$, which has a maxwellian
velocity distribution with $v_{rms} = 270$ km/s (with an upper cut corresponding to an escape
velocity of 650 km/s), and a relative Earth-halo velocity of $v_r = 230$ km/s). Other, more
elaborated halo models, which have been considered recently [48] would lead to different
results. The same applies when other astrophysical parameters are employed or when
uncertainties in the halo WIMPs velocity distribution are included [48]. The theoretical
predicted rate is expressed in terms of the mass and cross-section of the WIMP-matter
interaction. The cross sections are normalized per nucleon assuming a dominant scalar in-
teraction, as is expected, for instance, for one of the most popular dark matter candidates,
the neutralino:

$$\sigma_{N\chi} = \sigma_{n\chi} A^2 \frac{\mu_{W,N}^2}{\mu_{W,n}^2}$$

where $A$ is the target (oxygern and tellurium) mass number, $\mu_{W,N}^2$ is the WIMP-nucleus
reduced mass, and $\mu_{W,n}^2$ the WIMP-nucleon reduced mass. The Helm parameterization
[50] is used for the scalar nucleon form factor. The $(m, \sigma)$ exclusion plot is then derived
by requiring the theoretically predicted signal for each $m$ and $\sigma$ in each energy bin to be
less than or equal to the (90% C.L.) upper limit of the (Poisson) recorded counts. The
bin width is assumed to be equal to the detector resolution.

In figure 1 the exclusion plots for coherent spin-independent WIMP-matter interac-
tion are shown for two possible values of the background of CUORICINO, 1 and 0.1
c/keV/kg/day. The first value is of the order of the background already achieved from
threshold onwards (10-50 keV) in the MIBETA latest results (see [3]). The value 0.1
c/keV/kg/day is a one-order-of-magnitude extrapolation from that currently achieved in
MIBETA (see discussion on Section 1) and is close to the one obtained above 50 keV.
The main challenge of this hypothesis is to get $b=0.1$ c/keV/kg/day below 10 keV. Notice
that these values are more conservative than that derived from the MC simulation, and
could be taken as moderate extrapolations of the background of MIBETA and of the
CUORICINO test crystals. In the case of CUORE, background values of 0.1 and 0.01
c/keV/kg/day will be assumed. Notice, moreover, that values of a few 0.01 have been
obtained above 10 keV in the raw spectra of Germanium experiments (like IGEX [14]).
without using mechanisms of background rejection, and so it does not seem impossible to achieve such equivalent ($\leq 0.04 \text{ c/keV/kg/day}$) small values in crystal thermal detectors of Tellurium (only phonons, and no discrimination mechanism). To draw the two exclusion contours of Fig. 1, a low energy resolution of 1 keV and an energy threshold of 5 keV have been assumed as well as an exposure of 2 years of CUORICINO (84 kg-year). The projected exclusion contours are compared with the one currently obtained from MIBETA (dashed line). In figure 2, the exclusions for the two quoted values of the background of CUORE, 0.1 and 0.01 c/keV/kg/day, are similarly presented for an exposure of 1 year (760 kg-year). In both Figures 1 and 2, the region corresponding to the annual modulation positive signal reported by the DAMA collaboration is depicted as the closed "triangular" contour. One can see that the DAMA region could already be explored by the CUORICINO experiment with a background of 0.1 c/keV/kg/day. Of course CUORE will be able to explore a larger region of the $(m, \sigma)$ plane entering substantially into the scatter plots of the theoretical predictions of the various SUSY models (see [12] and references therein). The reader could make his own choice according to the credibility he might give to the above extrapolation of the background and other parameters from the current obtained performances.

As previously noted, CUORE and to some extent CUORICINO have detector masses large enough to search for the annual modulation signal. As it is well known, an essential requirement to estimate the prospects of any detector to search for annual modulation is to have a superbe control of systematic errors and to assure that the stability of the various experimental parameters, which might mimic periodic variations of the signals, are kept within a small percent of the (already tiny) expected signal. The various changes of set-up, crystals and shielding of the MIBETA experiment have not provided a definitive estimation of the long-term stability parameters of MIBETA. Possible instabilities are that of the electronic gain and the ensuing time fluctuation of the energy scale (both in energy thresholds and energy resolutions), the temperature variations, the possible fluctuation in time of the efficiency with which the triggered noise is rejected and others. They must be kept well below the small expected seasonal modulation of the WIMP signal. The fact that we are dealing with a very small signal depending on time, which typically amounts to a fraction between 1% and 7% of the average count rates, reinforces the need for a control of the stability of the experiment (well below that range) over long periods of time. In the case of assuming that all these fluctuations are controlled well below the levels needed (<1%), then one can proceed to analyze the sensitivity of CUORICINO/CUORE to the annual modulation signal on purely statistical grounds. This has been first attempted in [51] and [52], but a more extensive and rigorous approach is followed in ref. [53] where sensitivity plots for several types of detectors (and experimental parameters) are presented, and in particular, for CUORE and CUORICINO.

The sensitivity of a given experimental device to the annual modulation signal (according to the detector material employed and the experimental parameters of the detectors) has been extensively studied in Ref. [53] on purely statistical grounds. Following the guidelines of that reference, it can be precisely quantified by means of the $\delta$ parameter, defined from the likelihood function or, equivalently, from the $\chi^2$ function of the cosine...
projections of the data (for further details see ref. [53]):

\[ \delta^2 = y(\sigma = 0) - y_{\text{min}} \simeq \chi^2(\sigma = 0) - \chi_{\text{min}}^2. \]  

(3)

This parameter measures the statistical significance of the modulation signal detected in an experimental set of data. However, for a given \((m, \sigma)\) and a given experiment the expected value \(\langle \delta^2 \rangle\) can be estimated using the expression derived in ref. [53]:

\[ \langle \delta^2 \rangle = \frac{1}{2} \sum_k \frac{S_{m,k}(\sigma, m_W)^2 \Delta E_k}{b_k + S_{0,k}} MT \alpha + 2. \]  

(4)

where \(S_{m,k}\) and \(S_{0,k}\) are the modulated and non-modulated parts of the WIMP signal in the \(k\)th energy bin of \(\Delta E_k\) width, \(b_k\) is the background in that energy bin and \(MT \alpha\) the effective exposure, being \(\alpha\) a coefficient accounting for the temporal distribution of the exposure time around modulation maxima and minima (\(\alpha = 1/n \sum_{i=1}^{n} \cos^2 \omega (t_i - t_0)\) for \(n\) temporal bins).

Using this equation we have estimated the region that could be within reach for CUORE and CUORICINO with the above mentioned assumptions on the background levels. We have fixed a value of 5.6 for \(\langle \delta^2 \rangle\) that corresponds to 50\% probability of obtaining a positive result at 90\% C.L.. In figure 3 it is shown the curves obtained for a threshold of 5 keV, two years of exposure with CUORICINO (84 kg year) and two assumed flat backgrounds of 1 and 0.1 c/keV/kg/day. One can see that CUORICINO could already explore pretty well the DAMA region looking for a positive annual modulation signal. In figure 4 similar curves are presented, assuming flat backgrounds of 0.1 and 0.01 c/keV/kg/day, two years of exposure of CUORE (1500 kg year) and a threshold of 5 keV (solid lines). The possibility of a lower thresholds of 2 keV with a background of 0.01 c/keV/kg/day is also shown (dashed line).

In conclusion, CUORE and CUORICINO will be able to explore and/or exclude WIMPs lying in large regions of their parameter space. The capability of CUORICINO / CUORE to investigate the DAMA region through the exclusion plot (time integrated method) relies in getting a background of 0.1 c/keV/kg/day from 5 keV onwards, independently of more elaborated time modulation methods which require an exhaustive control of the stability of the experiment. However, CUORICINO and CUORE could also attempt to look for annual modulation of WIMP signals provided that the stability of the experiment be guaranteed.

5 Solar axion detection

Axions are light pseudoscalar particles which arise in theories in which the Peccei-Quinn U(1) symmetry has been introduced to solve the strong CP problem [54]. They could have been produced in early stages of the Universe being attractive candidates for the cold dark matter (and in some particular scenarios for the hot dark matter) responsible to 1/3 of the ingredients of a flat universe. Dark matter axions can exist in the mass
window $10^{-2(3)} \text{ eV} < m_a \leq 10^{-6} \text{ eV}$, but hadronic axions could exist with masses around the eV.

Axions could also be copiously produced in the core of the stars by means of the Primakoff conversion of the plasma photons. In particular, a nearby and powerful source of stellar axions would be the Sun. The solar axion flux can be easily estimated within the standard solar model, resulting in an axion flux of an average energy of about 4 keV that can produce detectable X-rays when reconverted again in an electromagnetic field. Moreover, it has been pointed out recently that the dimming of supernovae SNIa might be due to the conversion of photons into axions in the extra-galactic magnetic field. That $\gamma$-a oscillation could make unobservable about 1/3 of the SN emitted light and so, they would appear fainter than implied by the luminosity-distance versus redshift relation, without need to invoke an accelerated expansion of the Universe. The SN result would be matched by axions of mass $\sim 10^{-16} \text{ eV}$ and coupling to photons $g_{a\gamma\gamma} \sim 2.5 \times 10^{-12} \text{ GeV}^{-1}$. So stellar axions may play an important role in Cosmology. We would like to stress that, although we focus on the axion because its special theoretical motivations, all this scenario is also valid for a generic pseudoscalar (or scalar) particle coupled to photons. Needless to say that the discovery of any type of pseudoscalar or scalar particle would be extremely interesting in Particle Physics. We will keep our discussion, however, restricted to the case of solar axions.

Crystal detectors provide a simple mechanism for solar axion detection. Axions can pass in the proximity of the atomic nuclei of the crystal where the intense electric field can trigger their conversion into photons. The detection rate is enhanced if axions from the Sun coherently convert into photons when their incident angle with a given crystalline plane fulfills the Bragg condition. This induces a correlation of the signal with the position of the Sun which can be searched for in the data and allows for background subtraction. The potentiality of Primakoff conversion in crystals relies in the fact that it can explore a range of axion masses ($m_a < \sim 0.1 \text{ keV}$) not accessible to other direct searches. Moreover it is a relatively simple technique that can be directly applied to detectors searching for WIMPs.

Primakoff conversion using a crystal lattice has already been employed in two germanium experiments: SOLAX and COSME-II with the ensuing limits for axion-photon coupling $g_{a\gamma\gamma} \lesssim 2.7 \times 10^{-9} \text{ GeV}^{-1}$ and $g_{a\gamma\gamma} \lesssim 2.8 \times 10^{-9} \text{ GeV}^{-1}$ respectively. These constraints are stronger than that of the Tokyo axion helioscope for $m_a \gtrsim 0.26 \text{ eV}$ and do not rely on astrophysical considerations (i.e. on Red Giants or HB stars dynamics). The orientation of the crystal was not known so that the data were analyzed taking the angle corresponding to the most conservative limit.

It has been noted that the model that yields the solar axion fluxes used to calculate the expected signals is not compatible with the constraints coming from helioseismology if $g_{a\gamma\gamma} \gtrsim 10^{-9} \text{ GeV}^{-1}$. This would imply a possible inconsistency for solar axion limits above that value, and sets a minimal goal for the sensitivity of future experiments.

The use of CUORE to search for solar axions via Bragg scattering should have a priori some advantages with respect to germanium detectors, because of the larger mass and the known orientation of the crystals. On the other hand, as the cross-section for Primakoff
conversion depends on the square of the atomic number, TeO$_2$ will be a priori a better candidate than Germanium. Needless to say that a low energy threshold is mandatory because the expected signal lies in the energy region $2\text{ keV} \lesssim E \lesssim 10\text{ keV}$ and is peaked at $E \approx 4\text{ keV}$.

A detailed analysis has been performed [66] for a TeO$_2$ crystal (which has a tetragonal structure [65]) assuming different values for the experimental parameters. As it is shown in Ref. [66], the bound on axion-photon coupling which a given experiment can achieve can be estimated through the expression:

$$g_{a\gamma\gamma} < g_{a\gamma\gamma}^{\text{lim}} \simeq k \left( \frac{b}{c/\text{keV}/\text{kg/day} \cdot M / T} \right)^{1/8} \times 10^{-9} \text{ GeV}^{-1}$$

where $k$ depends on the crystal structure and material, as well as on the experimental threshold and resolution. For the case of TeO$_2$ and a threshold of 5 keV, $k$ has been calculated to be $k = 3.0$ assuming an energy resolution of 2 keV. The computation of this expression for some assumed values of the experimental parameters is shown in table 2 for CUORICINO and CUORE. In all cases flat backgrounds and 2 years of exposure are assumed.

It is worth to notice the faible dependence of the ultimate achievable axion-photon coupling bound on the experimental parameters, background and exposure MT: the 1/8 power dependence of $g_{a\gamma\gamma}$ on such parameters softens their impact in the final result. The best limit shown in table 2 is in fact only one order of magnitude better than the present limits of SOLAX and COSME-II. The $g_{a\gamma\gamma}$ bound that CUORE could provide is depicted comparatively to other limits in figure 5.

The limit which can be expected from the CUORICINO experiment is comparable to the helioseismological bound mentioned before. CUORE could go even further (see Figure 3). It should be stressed that the bounds on $g_{a\gamma\gamma}$ obtained with this technique stagnate at a few $\times 10^{-10}$ GeV$^{-1}$, not too far from the goal expected for CUORE, as has been demonstrated in [64]. No bounds below these limits can be expected by this technique from other crystal detectors like NaI, Ge or TeO$_2$, and consequently, there are no realistic chances to challenge the limit inferred from HB stars counting in globular clusters [63] and a discovery of the axion by CUORE would presumably imply either a systematic effect in the stellar-count observations in globular clusters or a substantial change in the theoretical models that describe the late-stage evolution of low-metallicity stars. To obtain lower values of $g_{a\gamma\gamma}$ one should go to the magnet helioscopes like that of Tokio [62] and that of CERN (CAST experiment [67] currently being mounted). In particular, the best current experimental bound of $g_{a\gamma\gamma}$ comes from the Tokyo helioscope: $g_{a\gamma\gamma} \leq 6 \times 10^{-10}$ GeV$^{-1}$ for $m_a \lesssim 0.03$ eV and $g_{a\gamma\gamma} \leq 6.8 - 10.9 \times 10^{-10}$ GeV$^{-1}$ for $m_a \sim 0.05 - 0.27$ eV. The sensitivity of CAST is supposed to provide a bound $g_{a\gamma\gamma} \leq 5 \times 10^{-11}$ GeV$^{-1}$ or even lower.

Recently the DAMA collaboration has analyzed 53437 kg-day of data of their NaI set up [68], in a search for solar axions, following the techniques developed in ref. [69], where a calculation of the perspectives of various crystals detectors (including NaI) for solar axion searches has been made. The DAMA result $g_{a\gamma\gamma} \lesssim 1.7 \times 10^{-9}$ GeV$^{-1}$ improves
slightly the limits obtained with other crystal detectors \cite{60,61} and agrees with the result predicted in ref. \cite{63}.

6 Conclusions

We have reported the perspectives of CUORE, a projected massive 760 kg array of 1000 TeO\(_2\) bolometers, and of its first stage CUORICINO, with 42 kg of the same crystals (currently being mounted), as far as their physics potential to detect various types of rare events is concerned. The estimated background and resolution, based on Monte Carlo studies, together with the results obtained in recent improvements in the performances of the MIBETA experiment and the information obtained from the preliminary tests of CUORICINO, have allowed us to assess the potentialities of these experiments for double beta decay searches, solar axion detection and WIMP exclusion or identification. In these three types of searches, CUORE and to some extent CUORICINO will be powerful tools to explore, with higher sensitivity, such rare phenomena.

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|        | $^{76}$Ge | $^{130}$Te | $^{136}$Xe | nuclear model                          |
|--------|-----------|-----------|-----------|----------------------------------------|
| 1.12 × 10$^{-13}$ | 5.33 × 10$^{-13}$ | 1.18 × 10$^{-13}$ | QRPA [29] |
| 1.12 × 10$^{-13}$ | 4.84 × 10$^{-13}$ | 1.87 × 10$^{-13}$ | QRPA [30] |
| 1.87 × 10$^{-14}$ | 3.96 × 10$^{-13}$ | 7.9 × 10$^{-14}$ | QRPA [31] |
| 1.54 × 10$^{-13}$ | 1.63 × 10$^{-12}$ |           | Weak Coupling SM [32] |
| 1.13 × 10$^{-13}$ | 1.1 × 10$^{-12}$ | 1.73 × 10$^{-13}$ | Generalized Seniority [33] |
| 1.21 × 10$^{-13}$ | 5.0 × 10$^{-13}$ | 1.45 × 10$^{-13}$ | QRPA without pn pairing [35] |
| 7.33 × 10$^{-14}$ | 3.0 × 10$^{-13}$ | 9.3 × 10$^{-14}$ | QRPA with pn pairing [35] |
| 1.42 × 10$^{-14}$ | 1.24 × 10$^{-13}$ | 3.18 × 10$^{-12}$ | [36] |
| 5.8 × 10$^{-13}$ | 2.16 × 10$^{-14}$ |           | Large basis SM [37] |
| 1.5 × 10$^{-14}$ | 3.6 × 10$^{-13}$ | 6.06 × 10$^{-14}$ | Operator expansion method [38] |

Table 1: $2\beta\nu$ nuclear merits $F_N^{0\nu}$ (y$^{-1}$) of emitters used in some source=detector calorimeters, according to various nuclear models.
Table 2: Expected limits on the photon-axion coupling for 2 years of exposure of CUORICINO and CUORE assuming the quoted values for the experimental parameters.

| Mass (kg) | Resolution (keV) | Threshold (keV) | Background (c/kg/keV/day) | $g_{a\gamma\gamma}^{\text{lim}}$ (2 years) (GeV$^{-1}$) |
|----------|------------------|----------------|---------------------------|-----------------------------------------------------|
| 42       | 2                | 5              | 0.1                       | 1.3$\times$10$^{-9}$                                |
| 760      | 2                | 5              | 0.01                      | 6.7$\times$10$^{-10}$                                |
Figure 1: Exclusion projected for 2 years of CUORICINO assuming a threshold of 5 keV, a low energy resolution of 1 keV, and low energy background levels of 1 and 0.1 c/keV/kg/day respectively. The closed curve represents the DAMA region. The dashed line corresponds to the current MIBETA result.
Figure 2: Exclusion projected for 1 year of CUORE assuming a threshold of 5 keV, a low energy resolution of 1 keV, and low energy background levels of 0.1 and 0.01 c/keV/kg/day respectively. The closed curve represents the DAMA region. The dashed line corresponds to the current MIBETA result.
Figure 3: Sensitivity plot in the \((m, \sigma)\) plane for CUORICINO, assuming a threshold of 5 keV, flat background \(b = 1\) (solid line) and 0.1 c/keV/kg/day (dashed line) and two years of exposure (84 kg year). It has been calculated for \(\langle \delta^2 \rangle = 5.6\) (see the text). The closed contour represents the 3\(\sigma\) CL region singled out by the modulation analysis performed by the DAMA experiment [12], and the cross indicates the minimum of the likelihood found by the same authors.
Figure 4: The solid lines represent the sensitivity plot in the $(m, \sigma)$ plane for CUORE, assuming a threshold of 5 keV, two years of exposure (1500 kg year) and flat backgrounds of 0.1 and 0.01 c/keV/kg/day. It has been calculated for $\langle \delta^2 \rangle = 5.6$ (see the text). The sensitivity curve has been also calculated for a possible threshold of 2 keV with a background of 0.01 c/keV/kg/day (dashed line). The closed contour represents the $3\sigma$ CL region singled out by the modulation analysis performed by the DAMA experiment [12], and the cross indicates the minimum of the likelihood found by the same authors.
Figure 5: Best bound attainable with CUORE (straight line labelled "CUORE") compared with others limits.