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Physics Potential and Prospects for the CUORICINO and CUORE Experiments

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(The CUORE COLLABORATION)

Abstract

The CUORE (*Cryogenic Underground Observatory for Rare Events*) experiment projects to construct and operate an array of 1000 cryogenic thermal detectors of

TeO_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 62 of 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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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 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 led to sensitivities capable of searching for such rare events. Dark matter detection experiments have largely benefited from the techniques developed for double 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 CUORICINO and 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 a range of energies, relies on 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 planned to have large detector mass, while keeping the other experimental parameters (background, energy thresholds and resolutions) optimized. On the other hand, the recent

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development of cryogenic particle detection [1] has led to the extended use of thermal detectors [2] 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 advantage of enlarging the choice of materials which can be used, either as DM targets or 2β 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 [3]. A major exponent of this development is the MiDBD (*Milano Double Beta*) experiment [4,5], which 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 [6] was born some years ago as a substantial extension of MiDBD. 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 MiDBD 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 44 of the above crystals (790 g in this case) and 18 smaller crystals (330 g) for a total mass of $\sim$40 kg. CUORICINO has been recently installed in the Gran Sasso Laboratory (LNGS) and is, by far, the largest cryogenic detector on the stage. The preliminary running tests are encouraging [7].

In the present work the prospects are presented for the CUORE and CUORICINO experiments with respect to their double beta decay discovery potential and their detection capability of WIMP and axions. In section 2 considerations of the expected background levels in the energy regions of interest are made taking into account all relevant sources. The theoretical motivation of neutrinoless double beta decay experiments as well as the experimental prospects of both CUORICINO and CUORE are shown in section 3. In the same way, the physics potential of the experiments is discussed for direct detection of WIMPs in section 4 and for solar axion searches in section 5.

2 Background considerations

From the radioactive background point of view, thermal detectors are very different than, say, conventional ionization detectors; the former are sensi-

tive over the whole volume, implying that surface impurities may play an important role. In principle, bolometric detectors like those used in MiDBD, CUORICINO and CUORE experiments are expected to have radioactive backgrounds larger than those of conventional germanium ionization detectors, also because the more complex technology of cryodetectors had not yet been 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 recent years, and now these devices have achieved very competitive backgrounds [8,9,10,11,5].

The MiDBD background [7] at low energy ($\sim$2 c/keV/kg/d at threshold -10 keV- and at 3500 m.w.e.) is similar to the measured event rate anticoincident with the veto in the CDMS experiment [8] ($\sim$ 2 c/keV/kg/d at 10 keV and at 20 m.w.e.) and in the EDELWEISS experiment [9]($\sim$ 1.8 c/keV/kg/d at 30 keV and 4000 m.w.e.), without a 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 and 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 MiDBD background values ($\sim$ 0.3 and 0.6 c/keV/kg/y in the old and new set-up respectively) are competitive but still higher than those of the IGEX and Heidelberg-Moscow experiments [15,16] ($\sim$ 0.05 c/keV/kg/y at 2 MeV) (which uses Pulse Shape Discrimination). The challenge of CUORE is to significantly reduce the MiDBD 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. This reduction will be accomplished by working on both the selection of low contamination materials and on the improvement of the detector geometry and the shielding efficiency. 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 all the possible background sources. A preliminary estimation is contained in Ref. [17], a more complete estimate is underway. In the following we will give a briefing of that 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, environmental γ 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 the small leakage of two neutrino double beta decay 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 MiDBD experiment, where the measured background is used as a test-bench for checking the MC estimates, has been essential in predicting the expectations for CUORICINO and CUORE. Using the MiDBD 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. Radioactive impurities in the bulk of the tellurite crystals, as well as in the dilution refrigerator and surrounding shielding were assumed. Background suppression due to the anticoincidence between crystals (which will be significant in the CUORE set up) was calculated. The code is based on the GEANT-4 [18] package; it models in detail the shields, the cryostat, the detector structure and the detector array for the MiDBD, CUORICINO and CUORE experiments. It includes the propagation of photons, electrons, α particles and heavy ions (nuclear recoils from α emission) as well as neutrons and muons. For the simulated radioactive chains (^{238}U and ^{232}Th) or radioactive isotopes (^{40}K, ^{60}Co) alpha, beta and γ /X ray emmissions are considered according to their branching ratios. The time structure of the decay chains is taken into account and the transport of nuclear recoils from alpha emissions is included.

2.1 MiDBD results

The 20 crystal MiDBD array was operated in two different configurations [5], the difference between the two was that in the latter configuration the Roman lead shield surrounding the detectors was improved by increasing its thickness, and that the crystals as well as their copper mounting structures underwent a new surface treatment. The crystals were re-polished with superpure powders while the copper was cleaned with a chemical process. The result was an improvement in the background measured in the second configuration (MiDBD-II) with respect to that measured in the previous one (MiDBD-I) either in the gamma region (below 3 MeV) and in the α region (between 3 and 10 MeV). The α peaks identified in MiDBD-I as due to a surface U and Th contamination of the crystals were reduced by a factor 2. The reduction of the α contaminations, together with the reduction of the ^{208}Tl line at 2615 keV is probably responsible of the improvement obtained in the 2448-2556 keV ($0\nu2\beta$ decay) region where the counting rate changed from b=0.59±0.06 c/keV/kg/y in MiDBD-I to b=0.33±0.11 c/keV/kg/y in MiDBD-II [5]. During MiDBD-II

run, a 10 cm thick borated polyethylene shield was mounted outside the external lead shield but no improvement in the counting rate was obtained proving that the backgroud was still dominated by other radioactive sources. With the above background value the lower limit of the neutrinoless half-life of ^{130}Te obtained is $T^{0\nu}_{1/2} \geq 2.1 \times 10^{23}$ y, or equivalently, an upper bound for the Majorana neutrino mass $\langle m_\nu \rangle \lesssim$ of 0.9 - 5.2 eV (depending on the nuclear matrix element calculation), which is the second-best published result [5]. As far as the low energy region is concerned, the background of MiDBD stands around 2.3 c/keV/kg/day between 10 and 50 keV and 0.5 c/keV/kg/day between 50 and 80 keV, region where the dark matter signal is expected [7]. With these background values, the exclusion plot of WIMPs interacting coherently with Te and O is depicted as the (dashed) contour of figure 1.

To understand what are the main sources responsible of the MiDBD background the MC code developed to study CUORE background was used to reproduce the results obtained in the two configurations in which the MiDBD 20 crystal array was operated [19]. The radioactive impurities used as inputs were all the contaminants identified in the MiDBD background spectrum, through an analysis of the α and γ lines: ^{238}U chain in secular equilibrium, ^{238}U chain broken at the level of ^{226}Ra, ^{214}Bi or ^{210}Pb, ^{232}Th chain in secular equilibrium, ^{40}K and ^{60}Co. Either bulk contaminations (with a uniform and isotropic distribution) and surface contaminations (with an exponential density profile and various depths) were considered. The details of this analysis are reported in Ref. [19], the results obtained can be summarized as follows: the MC simulation is able to reproduce the measured background spectrum, allowing the identification and localization of the most probable sources of background. It proves that a large contribution to the counting rate in both the low energy region and the $0\nu2\beta$ region comes from the surface contaminations of the crystals and of the copper structure facing the bare crystals. In the case of the crystals, the origin of this contamination is known: it is due to the use of contaminated powders during the optical polishing of the crystals produced by the Shanghai Quinhua Material Company (SQM) in China. Indeed the re-treatment of their surfaces by means of low contamination powders reduced the contamination to one half. For this reason it was agreed that the CUORICINO crystals would undergo only a minor surface treatment in China (the one indispensable to check crystal quality) and were subsequently polished in Italy using low contamination powders. On the contrary, the origin of the copper surface contamination is still uncertain: it could either have been produced during the machining of the metal or during the surface acid treatment. As the CUORICINO copper structure was produced with the same technique of the MiDBD-II a similar contamination may have been produced. For CUORE a dedicated R&D is foreseen to reduce or cancel this kind of contamination. Finally, other important contributions come from bulk contamination of the structures outside the Roman lead shield that surrounds the detector and from outside the cryostat. Evaluating each impurity for each

simulated element, the maximum contribution to the measured background by bulk contamination of TeO_2, copper and Roman lead were obtained and have been used in CUORE simulation.

2.2 CUORICINO and CUORE instrinsic background

CUORICINO will be operated in the same set-up as that of the MiDBD experiment: the same dilution refrigerator, the same cryostat, the same external lead and borated-polyethylene shield, at the same underground location (a description of the set-up can be found in Ref. [5]). The crystals will be different but the measured upper limits of their U and Th contamination are again of the order of 10^{-13} g/g . Therefore bulk contribution to CUORICINO background should be not larger than that measured in MiDBD-II. On the other hand, for surface contamination some improvement with respect to MiDBD-II result is foreseen thanks to the different surface treatment of the crystals and to a reduced exposure of detectors to dust and Rn. A reasonable guess for CUORICINO is therefore a background of ~ 0.1 c/keV/kg/y in the $0\nu2\beta$ region, slightly better than the one measured in MiDBD-II; while in the dark matter region a background of the order of 1 - 0.1 c/keV/kg/d is anticipated.

On the contrary no extrapolation of the background achievable in CUORE is possible from the MiDBD data, nor from the CUORICINO results. This is true for several reasons: the different structure of the detector (in the case of CUORE an efficient reduction of background events will be provided by operating the detectors of the array in anticoincidence, without loosing efficiency in detecting WIMPs or $0\nu2\beta$ decay events), the different cryostat and shielding systems, and finally because a much more severe selection of the constructing materials and a much better control on their mechanical working and chemical cleaning will be applied. Also predictions based on MC simulations are not straightforward since they depend critically on the assumed inputs: contamination levels, detector design, etc. Here we present a very conservative evaluation of the background reachable with CUORE, mainly based on the state of the art of detector design and on the knowledge of radioactive contamination. The CUORE construction will require about five years and in the meantime an $R\&D$ dedicated to background reduction will be realised. This approach for intrinsic background evaluation could be rather pessimistic but it is the only one that presently guarantees a reliable but possibly conservative prediction.

In CUORE (a description of the set-up can be found in Ref. [17]) the main contribution to background due to bulk contaminations comes from the heavy structures near the detectors (the copper mounting structure of the array, the Roman-lead box and the two lead disks on the top of the array) and from the

detectors themselves (the TeO_2 crystals). In the simulation, the ^{232}Th, ^{238}U, ^{40}K, ^{210}Pb, ^{134}Cs, ^{137}Cs and ^{207}Bi impurities of TeO_2, copper and lead as well as the ^{60}Co cosmogenic contamination of copper are conservatively assumed equal to the 90% C.L. upper limits obtained for the contamination levels of those materials measured in MiDBD experiment or in low HPGe spectrometry [19,17]. The ^{60}Co cosmogenic contamination of TeO_2 is on the other hand evaluated according to the time required to produce TeO_2 powder from the ore, grow the crystals and store them underground [20]. With these contaminations, assuming a threshold of 10 keV and using the results obtained after the reduction by anti-coincidence between detectors, the background due to bulk contaminations is $\sim 4 \times 10^{-3}$ counts/(keV kg y) in the $0\nu2\beta$ decay region and $\sim 3 \times 10^{-2}$ counts/(keV kg d) in the low energy region (10-50 keV). On the other hand, surface contaminations contribute to background only when they are localized on the crystals or on the copper mounting structure directely facing them. In the simulation, U and Th surface contaminations are assumed to be: for crystals ~ 100 times lower and for copper ~ 50 times lower than the corresponding contamination in MiDBD experiment. The MiDBD crystals were contaminated during the polishing procedure due to the use of highly contaminated powders. Polishing powders with a radioactive content 1000 times lower are however commercially available and have already been used for CUORICINO, an improvement of the surface contamination of a factor 100 is therefore fully justified. A similar situation holds for copper. In the MiDBD experiment the copper surfaces were treated with an etching procedure studied to reduce impurities on surfaces before the sputtering process. This procedure resulted in an improvement of the surface quality of copper, however it is not optimized from the point of view of background. The use -for the surface treatment- of low contamination liquids in a low background environment, and special care in the mechanical working and handling will allow an improvement between one and two orders of magnitude in the surface contamination of copper. With such a contamination the surface contribution is estimated to be 2.8×10^{-3} counts/(keV kg y) in the $0\nu2\beta$ region and 1.2×10^{-3} counts/(keV kg d) in the dark matter region.

Finally, the unavoidable background produced by the $2\nu2\beta$ decay region is lower than 10^{-4} counts/(keV kg y) in the $0\nu2\beta$ region and $\sim 10^{-4}$ counts/(keV kg d) in the dark matter region (assuming 3.8×10^{20} y for the ^{130}Te $2\beta2\nu$ half-life [5]).

2.3 Cosmogenic activation

Concerning the cosmogenic activation produced by cosmic rays when the crystals are above ground (during fabrication and shipping of the crystals from the factory to the underground laboratory) we used a code based on computed

cross sections to estimate the amount and type of radionuclides produced by cosmic rays on TeO_2 [20]. The comparison between our prediction and the MiDBD-I and II run data is discussed in ref. [19]. The radionuclei produced by the activation of tellurium are mostly tellurium isotopes (A=121,123,125,127) as well as ^{124}Sb, ^{125}Sb, ^{60}Co and tritium, these last three being of more concern because of their long half-life (^{125}Sb: beta decay of 2.7 years, end-point energy of 767 keV, ^{60}Co: beta decay of 5.27 years end-point energy 2823 keV and ^{3}H: beta decay of 12.3 years, end-point energy of 18 keV). In MiDBD-I no clear evidence of cosmogenic activation was present (the crystals were stored underground for several months), while in MiDBD-II the γ lines of the tellurium isotopes were clearly seen, with an intensity that is in good agreement with our prediction (based on the period they were reexposed because of the repolishing process).

The history of the CUORICINO crystals is rather similar to those of MiDBD, therefore their cosmogenic activation is already included in the extrapolation of CUORICINO background from MiDBD data. In the case of CUORE the control on crystal production will be more severe. The SQM that produces the crystals, oxidizing the tellurium ore and growing a 760 g crystal in about two months, will require two years to grow the 1000 CUORE detectors. Once grown, the crystals will be shipped to Italy and stored underground, therefore their total exposition to cosmic rays will be limited to about 4 months. The total induced activities remaining after 2 years underground have been estimated [20] and the consequent contribution to the detector counting rate was deduced by a MC simulation. The radionuclei that contribute to background through their β^- decay are:

- in the $0\nu2\beta$ region, the long lived ^{60}Co isotope with an activity of $\sim$0.2 μBq/kg, while a minor contribution is due to the isotopes ^{110m}Ag and ^{124}Sb whose activity is 4 times lower and fast decreasing with time;
- in the dark matter region, the long lived nuclei of ^{3}H and ^{125}Sb with an activity of $\sim$7 μBq/kg for the former and of $\sim$15 μBq/kg for the latter.

The influence of ^{60}Co in the CUORE background was already considereded in the evaluation of the contributions due to bulk contaminations of the crystals, while the contribution of ^{3}H and ^{125}Sb to the dark matter region is completely negligible ($\sim 10^{-3}$ counts/(keV kg d)) if compared to the intrinsic background.

2.4 Underground neutron, μ and γ interactions

As noted before, neither contributions from underground 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 their contribution. The depth of the LNGS (3500 m.w.e) reduces the muon flux to $\sim 2\times10^{-8}$ cm^{-2}s^{-1}, but a further effective reduction could be obtained with the use of an efficient (99.9%) active veto to detect 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. 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 either for MiDBD, for CUORICINO and for CUORE consists of a neutron screen (blocks of -borated- polyethylene of 10 cm thickness) to moderate and attenuate neutrons and a lead shell to attenuate the incoming external photons; the innermost part (10 cm thick) is made of special lead with a small content (<16 Bq/kg) of ^{210}Pb (half-life 22 years) while the outer part (10 cm thick) is made of modern lead (^{210}Pb <150Bq/kg) both with a low level of Th and U.

Neutrons may constitute a worrisome background in dark matter experiments because for appropriate neutron energies (few MeV) they can produce nuclear recoils in the detector target nuclei which would mimic WIMP interactions. Simple kinematics tells that in the case of tellurium, neutrons of 1 to 5 MeV could elastically scatter off tellurium nuclei producing recoils of energies up to 31 to 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 and 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 a few MeVs produced outside can pass the veto reaching the detector and producing "dangerous" nuclear recoils and γ 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 initiated by the muons (see Ref. [8]).

In the case of external neutrons (from the rocks, from fission processes or from (n,α) reactions, as well as neutrons originated by muons in the walls of the underground site), the environmental neutron flux has been measured in LNGS. The resulting flux is of $\sim 1\times10^{-6}$ cm^{-2}s^{-1} for the thermal component, $\sim 2\times10^{-6}$ cm^{-2}s^{-1} for the epithermal and $\sim 2\times10^{-7}$ cm^{-2}s^{-1} for energies over 2.5 MeV [21]. 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 the 10 cm thick borated polyethylene shield of CUORICINO and CUORE. The result is that the neu-

tron induced event rate on the entire energy range (from threhsold to 10 MeV) is much lower than the contribution due the bulk contamination of crystals. Other neutrons, produced by muon interactions 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 ∼100 m.w.e. the dominant sources of neutrons are nuclear fission processes and (n,α) 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 for an organic compound through the simple expression $N_n = 4.14 \times E_\mu^{0.74} \times 10^{-6}$ neutrons/(g cm^{-2}) per muon [22] which fits the value of 1.5×10^{-4} neutrons/(g cm^{-2}) of the muon-induced neutron flux measured by the LVD experiment at Gran Sasso [23].

For the LNGS muon flux (2.5×10^{-8} μ/(cm^2 s)), muons would produce in the CUORE shielding of polyethylene (10 cm) and lead (20 cm)) about ∼0.04 neutrons/(m^2 day) in the polyethylene shield and ∼25 neutrons/(m^2 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.

A preliminary evaluation of the influence of the environmental γ background in Gran Sasso [24] resulted in a negligible contribution for the $0\nu2\beta$ region and a contribution similar to that of bulk contaminations for the dark matter region.

A more complete and detailed study of the external, non intrinsic background rates for CUORE is underway.

2.5 Expected performances for CUORICINO and CUORE

Summarizing, for CUORICINO a background similar to the one measured in MiDBD-II is the most conservative prediction either in the dark matter region or in the $0\nu2\beta$ region. For CUORE on the other hand, the previous sections have shed light on how the background contamination dominating the two regions of interest is mostly the intrinsic background due to bulk and surface contaminations of the contructing materials. With the presently achieved quality of low contamination materials and considering the worst

possible condition for bulk contaminations (i.e. all the contamination equal to the present 90%/,C.L. measured upper limits) we have proved that CUORE background will be ~ 0.007 counts/(keV kg y) at the $0\nu2\beta$ transition energy and $\sim$ 0.05 counts/(keV kg d) near threshold. Even at these conservative values CUORE is, as we will prove in the following, a powerful instrument to search for double beta decay and dark matter. However, the goal of the CUORE technical $R\&D$ of the next few years will be the reduction of background to the level of 0.001 counts/(keV kg y) at the $0\nu2\beta$ transition energy and to 0.01 counts/(keV kg d) at threshold. The potential of the experiment in this background configuration will also be discussed.

Regarding the expected threshold and resolution, in the CUORICINO test experiment [4] energy thresholds of $\sim$ 5 keV have been obtained and a resolution of 1 keV at the 46 keV line of ^{210}Pb was achieved in some of the detectors. Details can be found in Ref. [7]. We will assume a conservative value of 10 keV for the energy threshold of both CUORICINO and CUORE, and energy resolutions of 1 keV at threshold. 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. An energy resolution of 5 keV will be assumed both for CUORE and for CUORICINO. Taking into account these expectations, we discuss in the following the prospects of CUORICINO and CUORE for double beta decay searches (section 3), for WIMP detection (section 4) and for solar axion exploration (section 5).

3 Double beta decay

One of the main scientific objectives of the CUORE detector is the search for the neutrinoless double-beta decay of the ^{130}Te isotope contained in the (natural) TeO_2 crystals.

3.1 Theoretical motivation

The importance of nuclear double-beta decay as an invaluable tool to explore particle physics beyond the Standard Model has been repeatedly emphasized and widely reported [25]. 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 [26]), from experiments with solar neutrinos (from Homestake, Gran Sasso and Kamioka [27]) and from reactor experiments (from KamLAND [28]) which suggest that neutrinos have indeed masses and oscillate among the three species. The results of the

solar ν experiment from SNO with both CC (Charged Current) and NC (Neutral Current) interactions [29], also combined with SuperK have definitively provided a strong evidence that neutrinos change of flavour and, consequently, the existence of non-zero mass neutrinos. The recent results of KamLAND [28] exclude all oscillation solutions but the Large Mixing Angle solution to the solar neutrino problem using reactor antineutrino sources. 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 [30]) 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. Majorana massive neutrinos are common predictions in most theoretical models, and the value of a few tens of millielectronVolts predicted for its effective mass, if reached experimentally -as expected- will test its Majorana nature. Double-beta decay experiments with even better sensitivities (of the order of a few meV) will be essential to fix the absolute neutrino mass scale and possibly to provide information on CP violation [30,31]. 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 assumed to be different particles, but no experimental proof has been provided so far. Nuclear double-beta decay addresses both questions: whether the neutrinos are self-conjugated and whether they have Majorana mass. In fact, the lepton number violating neutrinoless double beta decay $(A, Z) \rightarrow (A, Z+2) + 2e^-$ $(2\beta 0\nu)$ is the most direct way to determine if neutrinos are Majorana particles. Another form of neutrinoless decay, $(A, Z) \rightarrow (A, Z+2) + 2e^- + \chi$ may reveal also the existence of the Majoron (χ), the Goldstone boson emerging from the spontaneous symmetry breaking of the $B-L$ symmetry which is of most relevance in the generation of Majorana neutrino mass and has far-reaching implications in Astrophysics and Cosmology. Moreover, the observation of a $2\beta 0\nu$ decay would imply a lower bound for the neutrino mass, i. e. at least one neutrino eigenstate has a non-zero mass.

It is quite straightforward to demonstrate how the determination of the effective Majorana mass of the electron neutrino constrains the lightest neutrino mass eigenvalue. This was done recently by Barger, Glashow, Marfatia and Whistnant [32]. However it is very convenient to use the approximation that $sin\,\theta_2 \simeq 0 \equiv s_2$ and $cos\,\theta_2 \simeq 1$. With the further assumption $\delta m^2_\odot \ll \delta m^2_{AT}$ in

the normal hierarchy case we obtain:

$$| < m_\nu > | \; \leq \; m_1 \; \leq \; \frac{| < m_\nu > |}{cos(2\theta_3)} \tag{1}$$

where $cos(2\theta_3) \simeq 0.5$. Similarly in the case of inverted hierarchy:

$$\sqrt{| < m_\nu > |^2 - \delta m^2_{AT}} \; \leq \; m_1 \; \leq \; \frac{\sqrt{| < m_\nu > |^2 - \delta m^2_{AT} cos(2\theta_3)}}{cos(2\theta_3)} \tag{2}$$

A related quantity, $\Sigma \equiv m_1 + m_2 + m_3$ has great importance in cosmology. It is related to the quantity Ω_ν, the fraction of the critical density, ρ_0 (that would close the universe) that is in the form of neutrinos, where:

$$\Sigma = (93.8\, eV)\; \Omega_\nu \; h^2 \tag{3}$$

and h is the dimensionless Hubble constant. It was shown in reference [32] that Σ obeys the following inequality with respect to $| < m_\nu > |$:

$$\begin{aligned} &2\,| < m_\nu > | + \sqrt{| < m_\nu > |^2 \pm \delta m^2_{AT}} \leq \Sigma \\ &\leq \frac{2\,| < m_\nu > | + \sqrt{| < m_\nu > |^2 \pm \delta m^2_{AT}\, cos(2\theta_3)}}{cos(2\theta_3)} \end{aligned} \tag{4}$$

where the $+$ and $-$ signes refer to normal and inverted hierarchies respectively, and $cos(2\theta_3) \equiv 0.5$. If this relation is written as two equalities, and each side is solved for $| < m_\nu > |$ in terms of Σ, quadratic equations result with the constant terms $(\Sigma^2 \mp \delta m^2_{AT})$. Values of Σ^2 of cosmological interest are much larger than $\delta m^2_{AT} \leq 0.005$ eV (99.73% C.L.). Accordingly the above inequality reduces to the trivial form:

$$| < m_\nu > | \; \leq \; \Sigma/3 \; \leq \; 2| < m_\nu > | \tag{5}$$

This clearly demonstrates the direct connection between neutrinoless double beta decay and neutrino dark matter. Cosmic microwave background and galaxy cluster surveys have set the bound $\Sigma \leq 1.8\, eV$ [33]. It is expected that the MAP satellite will produce data that will result in a sensitivity $\Sigma \simeq 0.5\, eV$.

One possible interesting scenario results in the case the MAP satellite, if for example it observes a clear singal well above their limiting sensitivity, and CUORE (as well as other next generation experiments) have a negative results at sensitivities of Σ far below that of the satellite data. This would be a clear indication that the phenomenon causing the density fluctuations implied by

the CMB data was not caused by Majorana neutrino dark matter. In addition a positive measurement of the mass m_{ν_e} by KATRIN ^3He beta end-point spectrum measurement would have to yield $m_{\nu_e} \geq 0.35\,eV$. The CUORE experiment will have a far greater sensitivity, and if it found a negative result, the mistery of Dirac or Majorana character of neutrinos will be solved.

These and other issues, make the search for the neutrinoless double beta decay an invaluable tool for the exploration of non-standard model physics, probing energy scales well above those reachable with accelerators. That is the motivation of why there are dozens of experiments underway looking for the double beta decay of various nuclei [25] like ^{76}Ge (IGEX [15], Heidelberg-Moscow [16]), ^{100}Mo and others (NEMO [34], ELEGANTS [35]) and ^{130}Te (MiDBD, CUORICINO) and a few big experimental projects, like CUORE, Majorana [36] (^{76}Ge), MOON [37] (^{100}Mo) and EXO [38] ($136Xe$).

3.2 Experimental prospects

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}Ca in CaF_2, ^{130}Te in TeO_2, and ^{116}Cd in $CdWO_4$. As far as the Tellurium Oxide is concerned, the ^{130}Te isotope is a good candidate for double beta decay searches: its isotopic content in natural Tellurium is 33.87%, and its 2β Q-value ($Q_{2\beta} = 2528 \pm 1.3$ 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}Tl, which leaves a clean window to look for the signal. Finally, it has a fairly good neutrinoless nuclear factor-of-merit $F_N^{0\nu} = G_{0\nu}\,|M^{0\nu}|^2$, where $G_{0\nu}$ is an integrated kinematical factor qualifying the goodness of the $Q_{2\beta}$ value (large phase space) and $M^{0\nu}$ is the neutrinoless double-beta decay nuclear matrix elements characterizing the likeliness of the transition.

In table 1 we quote the values of $F_N^{0\nu}$ in the case of ^{130}Te calculated in various nuclear models [25], together with those of other emitters used in source/detector calorimeters. It can be seen that no matter the nuclear model is used to compute the neutrinoless double-beta decay matrix elements, the merits of ^{130}Te are a factor 5–10 more favorable than those of ^{76}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 $F_D^{0\nu}$, or detection sensitivity, introduced earlier by Fiorini, provides an approximate estimate of the neutrinoless half-life limit

achievable with a given detector. For source/detector devices, it reads:

$$F_D^{0\nu} = 4.17 \times 10^{26} \times \frac{a}{A}\sqrt{\frac{Mt}{b\Gamma}} \times \epsilon \quad \text{years} \tag{6}$$

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 2β neutrinoless decay region, t the running time in years, Γ the FWHM energy resolution in keV and ϵ the detector efficiency (which is 0.86 in the case of the cubic 5x5x5 cm^3 crystals). In the case of a TeO_2 crystal detector, $F_D^{0\nu} \sim 7.59 \times 10^{23}\sqrt{\frac{Mt}{b\Gamma}}$, with M the crystal mass in kg and b the background in counts per keV and year per kg of detector mass.

A simple projection for CUORICINO sensitivity can be obtained assuming 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. In that case, one would have $F_D \sim 1.07 \times 10^{24}\sqrt{Mt}$ years, with M (kg) the mass of the TeO_2 crystal array. For the mass of CUORICINO (M=40.7 kg), one will have a sensitivity of $F_D \sim 6.86 \times 10^{24}\sqrt{t}$ years. Using a typical average value of $F_N = 4 \times 10^{-13}$ y^{-1}, as obtained in QRPA [39,40,41,42,43], CUORICINO will have a mass sensitivity of $\langle m_\nu \rangle < 0.3$ eV in one year, in the least favourable case. Notice that the bound on the effective mass of the electron neutrino, $\langle m_\nu \rangle$, is given by $\langle m_\nu \rangle \leq m_e/\sqrt{F_D^{0\nu} F_N^{0\nu}}$. Using for comparison the value of $F_N = 5.33 \times 10^{-13}$ y^{-1} of Ref. [39] which is usually employed in the $\langle m_\nu \rangle$ bound ($\sim$0.33 eV) derived from the Ge experiments, with these assumptions CUORICINO would provide $\langle m_\nu \rangle$ <0.24 eV.

To go further, one needs to increase the mass of TeO_2 and to reach even a lower background. In our very conservative projection for the CUORE array (760 kg of TeO_2) a background of b=0.01 c/keV/kg/y can be easly achieved, assuming as in the case of CUORICINO a resolution Γ(2.5 MeV)=5 keV, one would get $T_{1/2}^{0\nu} \geq 9.4 \times 10^{25}\sqrt{t}$ years, which in one year of statistics would provide $\langle m_\nu \rangle$ bounds ranging from 0.07 eV [39], 0.08 eV [41], 0.15 eV [43] or 0.04 eV [44] just to mention results using a few nuclear matrix element estimates. However, the R&D to be carried out in CUORE, if succesful, would provide a value of $b \sim 0.001$ c/keV/kg/y i.e., a detection sensitivity of $F_D \sim 2.96 \times 10^{26}\sqrt{t}$ years, or $\langle m_\nu \rangle$ bounds ranging from $\sim 0.05\ t^{-1/4}$ eV (in [39,40,41,42,43,45]) to $\sim 0.03\ t^{-1/4}$ eV (in [44,46]). TeO_2 crystals made with ^{1}30Te enriched material have been already tested during the MiDBD experiment, making an enriched CUORE a feasible option. Assuming a 95% enrichment in ^{1}30Te and a background level of b=0.001 c/keV/kg/y, the sensitivity becomes $F_D \sim 8.32 \times 10^{26}\sqrt{t}$ years. For an exposure of 5 years, the corresponding $\langle m_\nu \rangle$ bounds range from 9 meV to 56 meV depending on the nuclear matrix element calculations.

4 WIMP detection

Recent cosmological observations [49] 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 [50], constitute a particular class of WIMPs.

Under the hypothesis that WIMPS are the main component of the dark matter, these particles should fill the galactic haloes and explain the flat rotation curves which are 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 [51,52,53] (derived using MSSM as the basic frame implemented with different unification hypothesis) encompass a range of values several orders of magnitude (the so-called scatter plots) providing rates ranging from 1 c/kg/day down to 10^{-5} 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 curve (at a given confidence level), as dark matter component of the halo, of those WIMPs with masses (m) and cross sections on nucleons (σ) 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 [54] 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 annual 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 [55,56,57] and since 1997 one group has reported a positive signal [12] which has been appearing throughout 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 [52] and in particular several of them [8,9,14,58] are excluding, to a larger or lesser degree, the region of mass and cross-section where the reported WIMP is supposed to exist. New data from one of them [9] have excluded totally the DAMA region. We will discuss in the following the capabilities of CUORICINO and CUORE to exclude or detect 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 mass 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. [59]), with the proviso that systematic uncertainties are under control. Data on the stability of CUORICINO will be crucial to assess such hypotheses.

To calculate the theoretical WIMP rate, standard hypothesis and astrophysical parameters 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 [60] 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 [61]. 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 interaction, as is expected, for instance, for one of the most popular dark matter candidates, the neutralino:

$$\sigma_{N\chi} = \sigma_{n\chi} A^2 \frac{\mu^2_{W,N}}{\mu^2_{W,n}} \tag{7}$$

where A is the target (oxygen and tellurium) mass number, $\mu^2_{W,N}$, is the WIMP-nucleus reduced mass, and $\mu^2_{W,n}$ the WIMP-nucleon reduced mass. The Helm parameterization [62] is used for the scalar nucleon form factor. The (m, σ) exclusion plot is then derived by requiring the theoretically predicted signal for each m and σ 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

interaction 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 MiDBD latest results (see [7]). The value 0.1 c/keV/kg/day is a one-order-of-magnitude extrapolation from that currently achieved in MiDBD (see discussion on Section 2) and is close to the one obtained above 50 keV. In the case of CUORE, background values of 0.05 and 0.01 c/keV/kg/day will be assumed. Notice, moreover, that values of a few 0.01 c/keV/kg/day 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 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 10 keV have been assumed as well as an exposure of 2 years of CUORICINO (81 kg·year). The projected exclusion contours are compared with the one currently obtained from MiDBD (dashed line). In figure 2, the exclusions for the two quoted values of the background of CUORE, 0.05 and 0.01 c/keV/kg/day, are similarly presented for an exposure of 1 year (760 kg·year).

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 superb 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 fraction of the (already tiny) expected signal. The various changes of the set-up, crystals and shielding of the MiDBD experiment have not provided a definitive estimation of the long-term stability parameters of MiDBD. 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. When 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 [63] and [64], but a more extensive and rigorous approach is followed in ref. [59] 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. [59] on purely statistical grounds. Following the guidelines of that reference, it can be precisely quantified by means of the δ parameter, defined from the likelihood function or, equivalently, from the χ^2 function of the cosine projections of the data (for further details see ref. [59]):

$$\delta^2 = y(\sigma = 0) - y_{min} \simeq \chi^2(\sigma = 0) - \chi^2_{min}. \tag{8}$$

This parameter measures the statistical significance of the modulation signal detected in an experimental set of data. However, for a given (m, σ) and a given experiment the expected value $\langle\delta^2\rangle$ can be estimated using the expression derived in ref. [59]:

$$\langle\delta^2\rangle = \frac{1}{2}\sum_k \frac{S_{m,k}(\sigma, m_W)^2 \Delta E_k}{b_k + S_{0,k}} MT\alpha + 2. \tag{9}$$

where $S_{m,k}$ and $S_{0,k}$ are the modulated and non-modulated parts of the WIMP signal in the kth energy bin of ΔE_k width, b_k is the background in that energy bin and $MT\alpha$ the effective exposure, being α 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 curves are shown obtained for a threshold of 10 keV, two years of exposure with CUORICINO (81 kg year) and two assumed flat backgrounds of 1 and 0.1 c/keV/kg/day. One can see that CUORICINO could already explore most of the DAMA region looking for a positive annual modulation signal. In figure 4 similar curves are presented, assuming flat backgrounds of 0.05 and 0.01 c/keV/kg/day, two years of exposure of CUORE (1500 kg year) and a threshold of 10 keV (solid lines). The possibility of a lower thresholds of 5 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 10 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 is sufficient.

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 [65]. 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 $10^{-2(3)}$ eV $< m_a \leq 10^{-6}$ 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 [66,67] 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 [68]. A photon-axion (γ-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 $\sim 10^{-16}$ eV and coupling to photons $g_{a\gamma\gamma} \sim 2.5 \times 10^{-12}$ 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 any generic pseudoscalar (or scalar) particle coupled to photons [69]. 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 [70,67]. 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 ($m_a \gtrsim 0.1$ 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 [71] and COSME-II [72] with the ensuing limits for axion-photon coupling $g_{a\gamma\gamma} \lesssim 2.7\times10^{-9}$ GeV^{-1} and $g_{a\gamma\gamma} \lesssim 2.8\times10^{-9}$ GeV^{-1} respectively. Also the DAMA collaboration has analyzed 53437 kg-day of data of their NaI set up [73], in a search for solar axions, following the techniques developed in ref. [74], 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 [71,72] and agrees with the result predicted in ref. [74]. These "crystal helioscopes" constraints are stronger than that of the Tokyo axion helioscope [75] for $m_a \gtrsim 0.26$ eV and do not rely on astrophysical considerations (i.e. on Red Giants or HB stars dynamics [76]). 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 $g_{a\gamma\gamma} \gtrsim 10^{-9}$ GeV^{-1} [77]. 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 keV $\lesssim E \lesssim$ 10 keV and is peaked at $E \simeq 4$ keV.

A detailed analysis has been performed [74] for a TeO_2 crystal (which has a tetragonal structure [78]) assuming different values for the experimental parameters. As it is shown in Ref. [74], the bound on axion-photon coupling which a given experiment can achieve can be estimated through the expression:

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

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 $k = 2.9$ assuming an energy resolution of 1 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 noticing 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 (see Table 2). CUORE could go even further (see Figure 5 and Table 2). Notice that in both cases an energy threshold of $E_{thr} \sim 5$ keV (and resolution of $\sim$1 keV) has been assumed. That value will be confirmed only after knowing the performances and preliminary runs of CUORICINO. As was described at length in Ref. [74], the crucial parameters for estimating the perspectives on solar axion detectors with crystals rely on the energy threshold and resolution (appearing in k), and the level of background achieved (although the influence of this parameter is damped by a factor 1/8). In particular, a threshold of 5-8 keV would loose most of the axion signal. Other crystal detectors with, say, Ge or NaI (GENIUS, MAJORANA, GEDEON, DAMA, LIBRA, ANAIS, ...) could surpass CUORE as axion detectors because the energy thresholds of these projects are supposed to be significantly lower. Also the background is expected to be better. Nevertheless, it should be stressed that the bounds on $g_{a\gamma\gamma}$ obtained with this technique in the various proposed crystal detector arrays stagnate at a few $\times 10^{-10}$ GeV^{-1}, not too far from the goal expected for CUORE, as has been demonstrated in [74]. There are no realistic chances to challenge the limit inferred from HB stars counting in globular clusters [76] 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 [75] and that of CERN (CAST experiment [79] currently being mounted). In particular, the best current experimental bound of $g_{a\gamma\gamma}$ published 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. A recent, preliminary run of CAST, with only $\sim$5 hours of "axion light" has improved already the Tokyo limit.

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 40 kg of the same crystals, 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 MiDBD 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 [39]
1.12×10^{-13}	4.84×10^{-13}	1.87×10^{-13}	QRPA [40]
1.87×10^{-14}	3.96×10^{-13}	7.9×10^{-14}	QRPA [41]
1.54×10^{-13}	1.63×10^{-12}		Weak Coupling SM [44]
1.13×10^{-13}	1.1×10^{-12}		Generalized Seniority [46]
1.21×10^{-13}	5.0×10^{-13}	1.73×10^{-13}	QRPA [42]
7.33×10^{-14}	3.0×10^{-13}	1.45×10^{-13}	QRPA without pn pairing [43]
1.42×10^{-14}	1.24×10^{-13}	9.3×10^{-14}	QRPA with pn pairing [43]
5.8×10^{-13}	3.18×10^{-12}		[47]
1.5×10^{-14}	4.52×10^{-14}	2.16×10^{-14}	Large basis SM [48]
9.5×10^{-14}	3.6×10^{-13}	6.06×10^{-14}	Operator expansion method [45]

Table 1
$2\beta0\nu$ nuclear merits $F_N^{0\nu}$ (y^{-1}) of emitters used in some source=detector calorimeters, according to various nuclear models.

Mass (kg)	**Resolution** (keV)	**Threshold** (keV)	**Background** (c/kg/keV/day)	$g_{a\gamma\gamma}^{\rm lim}$ **(2 years)** (**GeV**$^{-1}$)
40.7	1	5	0.1	1.3×10^{-9}
40.7	1	5	1	1.7×10^{-9}
750	1	5	0.01	6.5×10^{-10}
750	1	5	0.05	8.0×10^{-10}

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

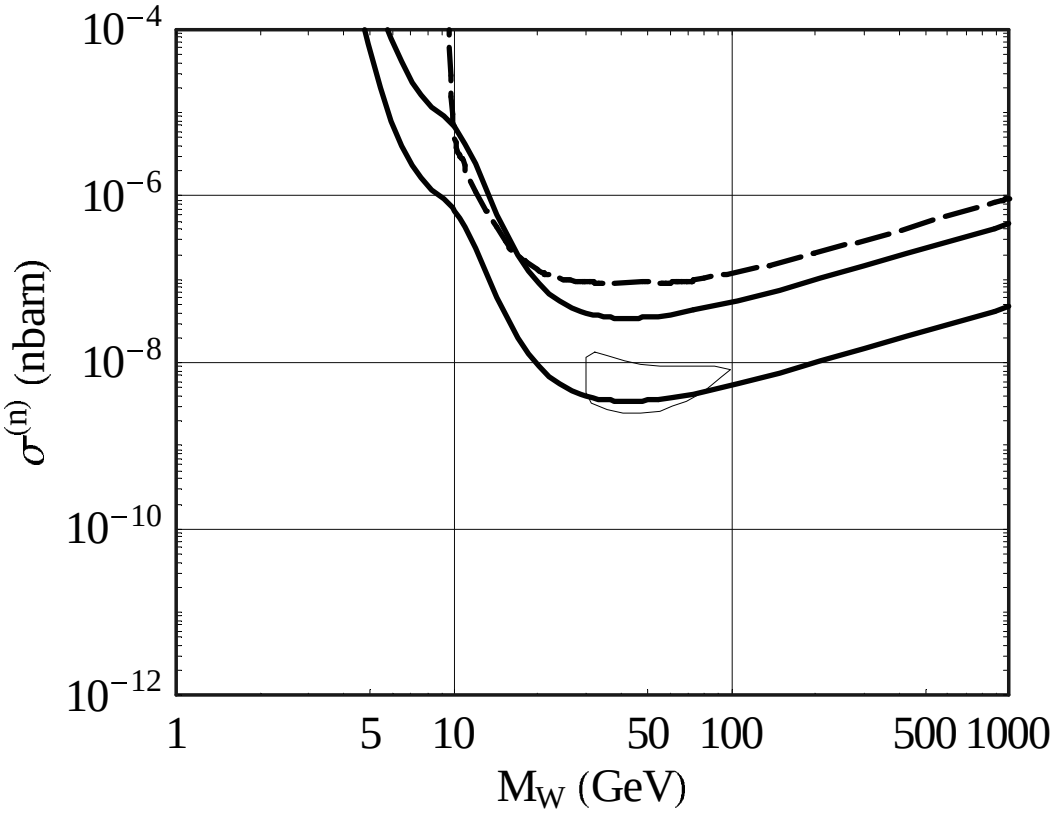

Fig. 1. Exclusion projected for 2 years of CUORICINO assuming a threshold of 10 keV, a low energy resolution of 1 keV, and low energy background levels of 1 and 0.1 c/keV/kg/day respectively. The closed curve represents the DAMA region. The dashed line corresponds to the current MiDBD result.

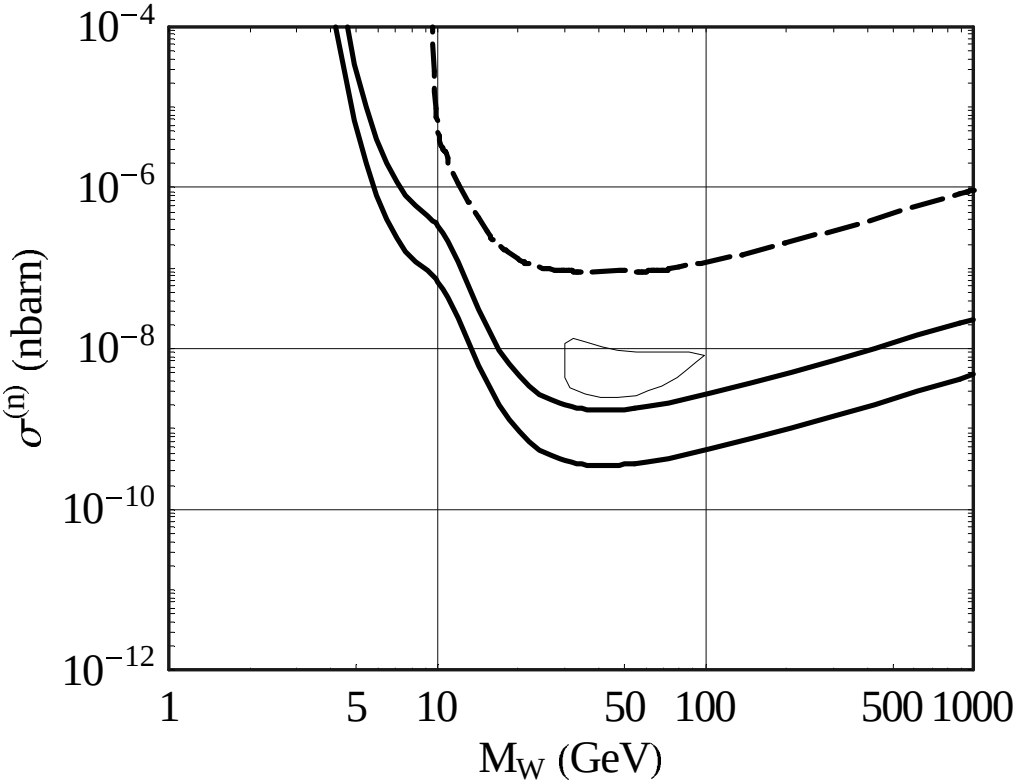

Fig. 2. Exclusion projected for 1 year of CUORE assuming a threshold of 10 keV, a low energy resolution of 1 keV, and low energy background levels of 0.05 and 0.01 c/keV/kg/day respectively. The closed curve represents the DAMA region. The dashed line corresponds to the current MiDBD result.

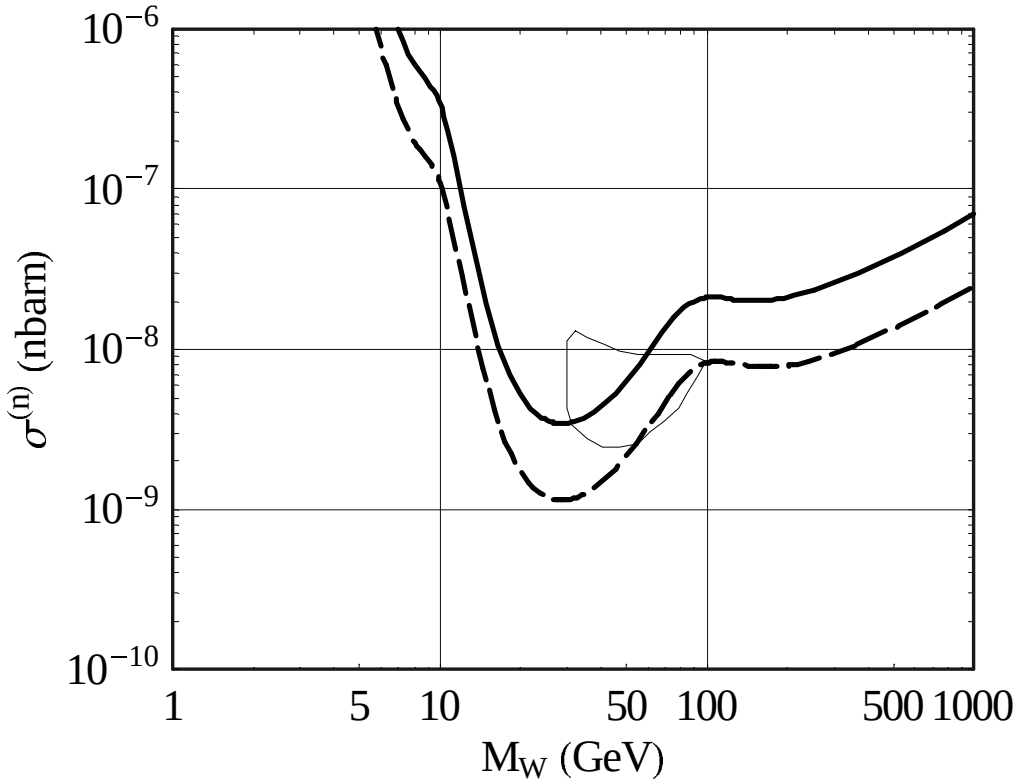

Fig. 3. Sensitivity plot in the (m, σ) plane for CUORICINO, assuming a threshold of 10 keV, flat background $b = 1$ (solid line) and 0.1 c/keV/kg/day (dashed line) and two years of exposure (81 kg year). It has been calculated for $\langle \delta^2 \rangle = 5.6$ (see the text). The closed contour represents the 3σ CL region singled out by the modulation analysis performed by the DAMA experiment [12].

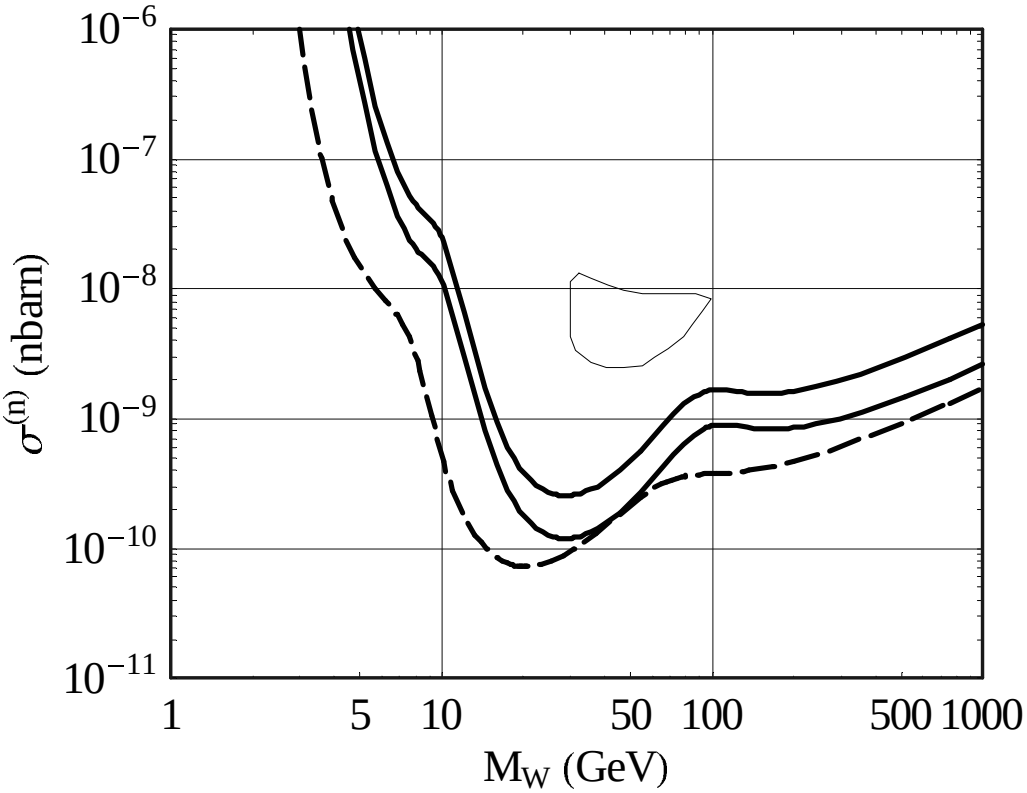

Fig. 4. The solid lines represent the sensitivity plot in the (m, σ) plane for CUORE, assuming a threshold of 10 keV, two years of exposure (1500 kg year) and flat backgrounds of 0.05 and 0.01 c/keV/kg/day. It has been calculated for $\langle \delta^2 \rangle = 5.6$ (see the text). The sensitivity curve has been also calculated for a possible threshold of 5 keV with a background of 0.01 c/keV/kg/day (dashed line). The closed contour represents the 3σ CL region singled out by the modulation analysis performed by the DAMA experiment [12].

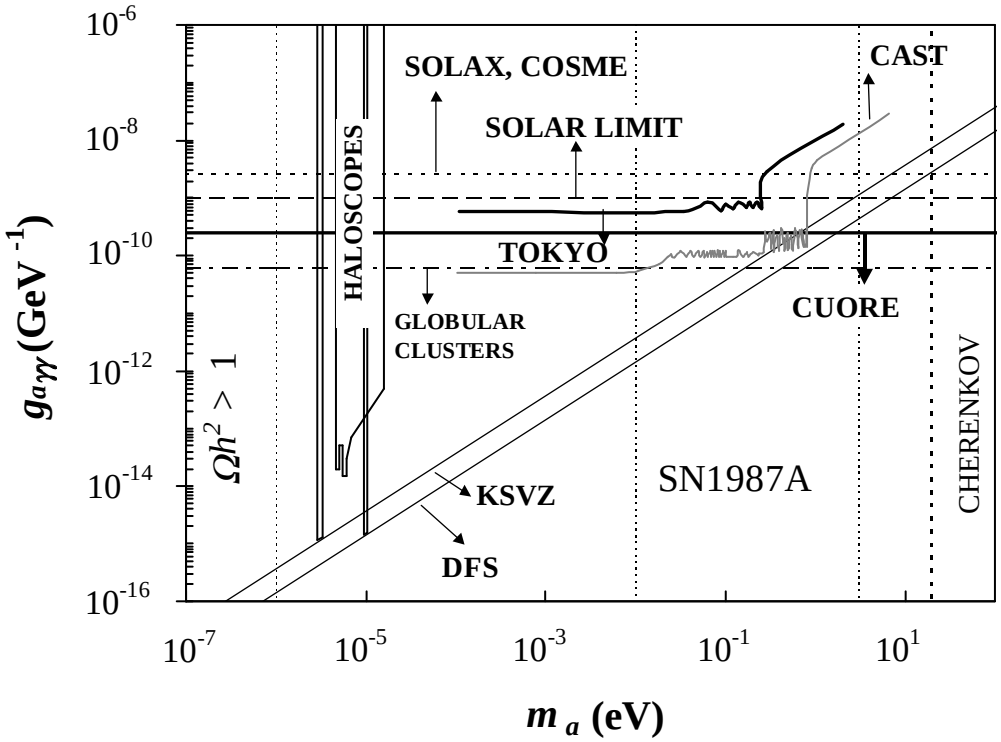

Fig. 5. Best bound attainable with CUORE (straight line labelled "CUORE") compared with others limits.