CUORE-IHE
The Cryogenic Underground Observatory for Rare Events – Inverted Hierarchy Explorer

CUORE-IHE Interest Group[1]

[1] *The current composition of the CUORE-IHE Interest Group is listed in Section XII.*
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I. EXECUTIVE SUMMARY

The observation of Neutrinoless Double-Beta decays ($0\nu\beta\beta$, DBD) would unambiguously establish the violation of lepton number conservation, and indicate that neutrinos are Majorana particles, i.e. they are their own anti-particles. The rate of the process is sensitive to the effective Majorana neutrino mass. Determining whether neutrinos are Majorana or Dirac particles and measuring their masses are among the highest priorities in neutrino physics, as was pointed out in the 2004 APS Multi-Divisional Neutrino Study as well as the 2007 NSAC Long Range Plan. The answer will also have important implications for astrophysics and cosmology. Addressing this question has become an even higher priority since the recent apparent discovery of the long-sought Higgs boson. A Majorana neutrino mass is not generated by the Higgs mechanism and Majorana particles are not accommodated in the Standard Model. Thus, discovery of the Majorana nature of neutrinos would provide a clear indication of new physics beyond the Standard Model.

CUORE, the Cryogenic Underground Observatory for Rare Events, promises to be one of the most sensitive $0\nu\beta\beta$ experiments this decade. Using a bolometric array of 988 750-g crystals of natural TeO_2, it will begin to explore the neutrino mass values in the so-called inverted mass hierarchy. CUORE is an established project within the US (DOE and NSF) and Italian (INFN) funding agencies. The detector is currently under construction at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy, and is expected to start operations in 2015.

With the expected background of 0.01 counts/(keV kg year) and the energy resolution of 5 keV FWHM in the $0\nu\beta\beta$ region of interest, CUORE is projected to reach a sensitivity of $T_{1/2} > 10^{26}$ years (at 90% C.L.) after five years of operation, which would correspond to a limit on the effective Majorana mass of the electron neutrino of $\langle m_{\beta\beta}\rangle < 52 - 120\,\text{meV}$, depending on the estimate of the nuclear matrix element.

If $0\nu\beta\beta$ decay avoids detection at this level of sensitivity, the next logical milestone in the quest for unraveling the nature of neutrinos is an experiment with the sensitivity of $\mathcal{O}(10\,\text{meV})$ to the effective neutrino mass. Such an experiment would be able to either discover the Majorana nature of neutrinos or completely rule it out, should the neutrino masses be arranged in the inverted hierarchy. Given the expected constraints on the sum of the neutrino masses from cosmological observables and the future direct measurements of the neutrino mass hierarchy in the accelerator- and reactor-based oscillation experiments, a DBD measurement of such sensitivity starting around 2020 would be both timely and scientifically relevant. Should the hierarchy prove to be inverted, a DBD measurement with sensitivity of $\mathcal{O}(10\,\text{meV})$ would unambiguously prove the Majorana or Dirac nature of neutrinos. If the hierarchy is normal, an experiment with 10 meV sensitivity would be an important demonstration milestone towards the ultimate, definitive measurement. It would also be sensitive to non-standard sources of lepton number violation.

Reaching 10 meV effective mass sensitivity requires an experiment with nearly zero background, energy resolution of a few keV, and about a ton of active mass of an appropriate isotope. This can be achieved with a bolometric experiment like CUORE, with cost-effective upgrades. The required improvements would include: (a) isotopic enrichment of the element of choice; (b) active rejection of alpha and surface backgrounds in detector materials; (c) further reduction (compared to CUORE) in the gamma backgrounds by careful material and isotope selection and active veto of multi-site events; (d) improvements in energy resolution; and (e) further reduction in cosmogenically generated radioactive backgrounds by active muon veto and/or by operating at a deeper underground location.

Successful cryogenic operations of CUORE, as well as the CUORE experience in ultra-clean assembly of bolometers and a cryostat system, are critical for demonstrating the viability of a future experiment. While our main focus is CUORE, groups in both the US and Europe are engaged in an active R&D program along all the directions outlined above. With the current support from the US and European funding agencies, we are investigating the cost and purity of bolometric crystals highly enriched in ^{130}Te as well as other potential isotopes (^{82}Se, ^{100}Mo, and ^{116}Cd), studying background rejection with scintillation, Cherenkov radiation, ionization, and pulse-shape discrimination, testing novel materials and sensor technologies. Experience with the CUORE assembly will allow us to further refine and optimize the process of putting together a 1-ton scale detector. Once CUORE is operational, we expect the vigor of these R&D activities to ramp up, with the goal of preparing a full proposal for an upgraded bolometric experiment with $\mathcal{O}(10\,\text{meV})$ Majorana mass sensitivity on the timescale of 2016.

II. INTRODUCTION

The purpose of this document, drafted by the CUORE-IHE Steering Committee[1], is to define a possible follow-up to the present CUORE [1] experiment, expected to run for about 5 years after the start of data taking, foreseen in 2015. It is natural that the next experiment will be based on the experience, expertise, and lessons learned in CUORE; thus we refer to this future project in the following as CUORE-IHE, [2] alluding to its projected ability to fully explore the inverted hierarchy (IH) region of the neutrino mass pattern [2]. We will first discuss the scientific objective of CUORE-IHE; we will then describe a set of current R&D activities – performed in a more or less close connection to the present CUORE program – which aim to develop technologies capable of achieving the desired science goal; we will finally indicate a time schedule for CUORE-IHE definition, anticipating that the general goal is to select the CUORE-IHE technology by the end of 2016, so that a Conceptual Design Report (CDR) could be produced at that time.

The motivation for a such an analysis is that the CUORE program is in an advanced state with very positive indications in all the activity areas. CUORE-0, the first CUORE tower, shows excellent performance in terms of background and detector resolution [3]; all CUORE towers have been fully built; the CUORE cryostat is under commissioning [1]. We think therefore that the time has come to plan a future use, beyond CUORE, of the existing CUORE facilities with improved detectors aiming at an even higher sensitivity to neutrinoless double beta decay ($0\nu\beta\beta$). In fact, an upgrade of the present technology or a development of a new one requires sufficient head start in order to be ready in time by the end of the present CUORE program.

III. CUORE

CUORE will be one of the most sensitive $0\nu\beta\beta$ experiments of this decade. Using a bolometric array of 988 750 g crystals of natural TeO_2, it will begin to explore the neutrino mass values in the inverted mass hierarchy. CUORE is an established project within the INFN, DOE, and NSF.

CUORE is in the final phase of construction at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy, and is expected to start operations in 2015. The construction of all 19 detector towers is now complete. The cryogenic system has been completely assembled and the commissioning is steadily progressing.

With an expected background of 10 counts/(keV ton year) and an energy resolution of 5 keV FWHM in the $0\nu\beta\beta$ region of interest, CUORE is projected to reach a 1σ sensitivity of $T_{1/2} > 1.6 \times 10^{26}$ y after five years of operation [4], which corresponds to a range of the effective Majorana neutrino masses of $\langle m_{\beta\beta}\rangle < 41 - 95$ meV, depending on the estimate of the nuclear matrix element (90% C.L. sensitivities of $T_{1/2} > 10^{26}$ years and $\langle m_{\beta\beta}\rangle < 52 - 120\,\mathrm{meV}$, respectively).

The CUORE concept of a bolometric $0\nu\beta\beta$ detector has already been successfully demonstrated through the operation of two medium size prototypes: Cuoricino and CUORE-0. The latter in particular has been built strictly following the same protocols used for the construction of the CUORE detector. CUORE-0 has demonstrated the viability of the key performance parameters: the energy resolution of the detectors, and the background level in the region dominated by the surface contamination in ^{238}U and ^{232}Th. However, two of the most challenging aspects still need to be demonstrated through the successful operation of CUORE: long-term operation in stable conditions of a ton-sized bolometric detector and validation of the background model.

The CUORE cryostat and dilution refrigerator represent a breakthrough in the currently available technology and their successful operation will be a significant milestone for the development of the bolometric experiments. Scientific success of CUORE is a required condition for future developments. Based on careful material assay and a set of dedicated measurements, the CUORE background budget is in the range of the design value of 10 counts/(keV ton year). The background model, based on Cuoricino ad CUORE-0, still suffers from large uncertainties. In particular, the precise evaluation of the relative weight of the alpha and beta/gamma contributions in the ^{130}Te ROI and above is one of the crucial information that the operation of a large scale detector like CUORE will be able to provide. In this respect, CUORE can be considered itself a very important R&D effort for the future development of a bolometric $0\nu\beta\beta$ experiment.

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[2] This name is provisional.

IV. SCIENTIFIC OBJECTIVE

CUORE-IHE is a proposed bolometric $0\nu\beta\beta$ experiment which aims at a sensitivity to the effective Majorana neutrino mass of the order of 10 meV, covering entirely the so-called inverted hierarchy region of the neutrino mass pattern. CUORE-IHE will be designed in such a way that, if the neutrino is a Majorana particle and if the mass hierarchy is inverted, then CUORE-IHE will observe $0\nu\beta\beta$ with a sufficiently high confidence (significance of at least 3σ). This level of sensitivity corresponds to the $0\nu\beta\beta$ lifetime of $10^{27} - 10^{28}$ years, depending on the isotope. This primary objective poses a set of technical challenges: the sensitive detector mass must be in the range of several hundred kg to a ton of the isotope, and the background must be close to zero at the ton $\times$ year exposure scale.

This objective can be achieved by making use of the current CUORE infrastructure as much as possible. The CUORE dilution refrigerator and the cryostat at LNGS represent a significant state-of-the-art investment, and are an asset to any future bolometric effort. Other elements of the present facility (clean room, shielding, electronics, DAQ, data analysis tools, assembly line etc.) may also be used whenever possible after the necessary upgrades, or developed *ex novo* if required, depending on the specific bolometric technology selected for CUORE-IHE and the indications from further studies of the environmental radioactivity and the muon-induced background.

V. STRATEGIES TO REDUCE THE BACKGROUND IN THE REGION OF INTEREST

In order to achieve the aforementioned scientific goals, a significant improvement of the current CUORE background figure is mandatory. As remarked in Section III, the CUORE background index b will amount to $\sim$ 10 counts/(keV ton y), and the energy resolution ΔE_{FWHM} is expected to be $\sim$ 5 keV. These values are well supported by CUORE-0 performance. The total background in the region of interest, given by $b \times \Delta E_{FWHM}$, must be reduced by two orders of magnitude with respect to the current achievement to attain a value lower than 1 counts/(y ton), demanded by the lifetime sensitivity target of $10^{27} - 10^{28}$ years. Marginal improvements in the energy resolution are possible, which is expected to be at best 1 keV FWHM for large crystals. Therefore, most of the efforts must be concentrated on reducing b down to the $\lesssim 10^{-1}$ counts/(keV ton y) range.

The expected dominant component of the background in CUORE is due to energy-degraded alpha particles emitted from the surfaces of the materials surrounding the detector or of the detector itself [5]. Given an enormous effort already devoted to surface treatment, it is not obvious that the required reductions in the background level could be achieved by improving radio-purity of the detector materials (although this is an important R&D goal). On the other hand, active background suppression promises the required levels, either with TeO_2 as sensitive material, or with other isotopes. These ideas and the related activities performed so far are described in Section VI.

However, improvement in the detector technology may not be sufficient. Background coming from residual environmental radioactivity and that induced by sporadic muon interactions in the current CUORE configuration could produce backgrounds comparable to the $\sim 10^{-1}$ counts/(keV ton y) goal. Discussions and mitigation strategies for these backgrounds are reported in Sections VIII and IX respectively.

VI. DETECTOR TECHNOLOGY R&D

Several R&D activities aiming at improving the sensitivity of $0\nu\beta\beta$ bolometric experiments through new detector technologies are ongoing in Europe and in the US (see Fig. 1). While these activities are performed using resources separate from the CUORE project, the current interest group believes that CUORE-IHE is the proper framework for a possible final implementation of the experiment based on technologies developed in this preliminary phase.

The efforts can be divided first in two main categories: those which focus on TeO_2 bolometers (and therefore the isotope ^{130}Te) and those which study alternative compounds, moving to other isotopes. Keeping TeO_2 would of course be a big technological advantage in terms of crystal growth / processing and radiopurity (all these issues have been already successfully addressed in CUORE) and of isotope enrichment as well (^{130}Te has a large natural isotopic abundance – 34 % – and the enrichment cost is at least a factor 4 less than for the other isotopes under discussions, i.e. ^{82}Se, ^{100}Mo, and ^{116}Cd). The alternative techniques, on the other hand, have already demonstrated how the background goals of CUORE-IHE can be achieved, at least on paper. For example, an experiment based on ^{82}Se, ^{100}Mo, or ^{116}Cd would also benefit from the significantly reduced gamma background, as the signal is expected at the energy larger than the end-point of the most of the natural gamma radioactivity.

The TeO_2-based R&D activities aim at developing methods to identify and reject alpha particles or surface events. One possible way to reject alpha particles is to detect the small amount of Cherenkov light emitted by the two electrons in the $0\nu\beta\beta$ process, as alphas of the same energy are well below the Cherenkov threshold. The essential component of the R&D in this direction is to develop high-resolution light detectors capable of clearly identifying Cherenkov

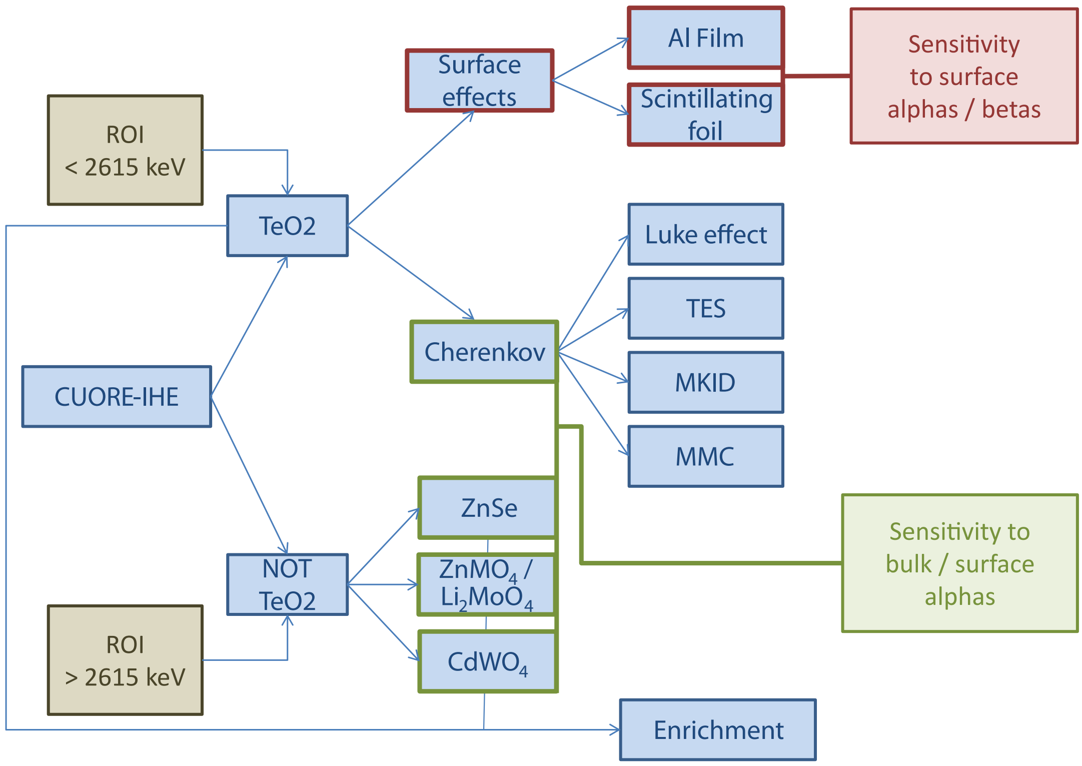

FIG. 1: Flowchart of the R&D detector activities for CUORE-IHE

emission and therefore separating alphas and betas on an event-by-event basis. Such light detectors require excellent resolution at the level of a few visible/UV photons. Several technologies are under study for the light detectors. Another approach aims at detecting surface events *tout court*, using either films deposited on the detector surface which can modify the signal shape of surface events, or surrounding the detector by a scintillating foil and detecting the consequent scintillation light emitted by a surface energy deposition (ABSURD project).

The efforts on the alternative isotopes for CUORE-IHE are all based on scintillating bolometers. These devices use isotopes with a signal expected at around 3 MeV, and therefore above the last important gamma line of natural gamma background. The residual alpha background would be once again suppressed by exploiting the different light yield between alpha and beta particles, as in the aforementioned Cherenkov approach, but with a at least an order of magnitude more light produced by scintillation. Isotopes under study are ^{82}Se (embedded in ZnSe crystals – LUCIFER project), ^{100}Mo (embedded in $ZnMoO_4$ and possibly in Li_2MoO_4 crystals – LUMINEU and LUCIFER projects), and ^{116}Cd (embedded in $CdWO_4$ crystals).

A. TeO_2 Bolometers

1. *Cherenkov Light Detection and Light Detector Technologies*

The threshold for Cherenkov emission in TeO_2 is around 50 keV for electrons, and around 400 MeV for alphas [6]. The amount of light emitted by electrons above 350 nm, the transparency threshold at room temperature, is computed to be 140 eV/MeV [6]. The real value could be higher, since at low temperatures the TeO_2 is expected to become transparent at lower wavelengths. Experimental tests confirm that light is not detected from alphas while, at the $0\nu\beta\beta$ energy, around 100 eV of light are detected from beta/gamma particles [7]. Because of the high index of refraction of TeO_2 ($n = 2.4$), most of the light remains trapped in the crystal, and the extraction of a higher light signal is difficult. To reduce the alpha counts below the level of the beta/gamma background predicted in CUORE, the signal to noise ratio in the light detector must be greater than 5 [7]. This implies that, with a signal as small as 100 eV, the noise must be below 20 eV RMS, a value that is difficult to reach. The light detectors used so far consisted in germanium disks operated as bolometers, featuring an average noise of 100 eV RMS. These detectors were developed by the LUCIFER group to detect the high amount of scintillation light from ZnSe and $ZnMoO_4$ crystals, but are clearly unsatisfactory to read the tiny Cherenkov signal. It has been recently shown that this goal can be accomplished [8] – with clear alpha / beta discrimination on an event-by-event basis – by using the so-called Neganov-Luke amplification with high sensitivity Transition Edge Sensors (both discussed below) for the light detector technology.

A large-area cryogenic light detector technology capable of reaching the required noise level already exists, and is based on Transition Edge Sensors (TES). The CRESST Dark Matter experiment uses silicon-on-sapphire light absorbers read by a tungsten TES coupled to an aluminum absorber. This configuration could be imported into CUORE, but scaling of the technology to a thousand detectors requires extra R&D. The most important issue is the reproducibility of the technology (e.g. uniformity of transition temperature T_c across many channels) at temperatures of order 10 mK and the cost and effort required for a construction of a large quantity of high-quality detectors. Additional aspects, such as multiplexing of the detector signals to reduce the wiring complexity and the heat load, would need to be developed, although solutions exists in the astrophysics community. Alternative technologies are being investigated: germanium bolometers implementing the Neganov-Luke enhancement, different TES implementations, Microwave Kinetic Inductance Detectors (MKID) sensors, and Magnetic Metallic Calorimeters (MMC) sensors.

It has to be stressed that the detection of Cherenkov light is complementary to the use of scintillating foils (ABSURD project) or Al surface films to tag external betas or alphas. While with the former one can tag beta events and reject alphas and "dark" events generated by lattice relaxations of the TeO_2 or by its supports, with the latter one can identify beta and alpha background generated outside the bolometer but not dark events. Low-noise light detectors can also be used to read the scintillation light from ZnSe bolometers. They could allow discriminating nuclear recoils from beta/gamma interactions in the 10 keV region, enabling the search for Dark Matter interactions in a way similar to that of the CRESST experiment [9]. On the other hand, molybdate crystals are not compatible with the dark matter searches as they emit too low scintillation light, while no test has been done on $CdWO_4$ crystals yet.

a. Luke effect – Light detectors with thresholds of few eV can be developed by exploiting the so-called Neganov-Luke effect. In this approach, the light detector is an auxiliary bolometer consisting of a high purity Ge or Si wafer in which the ionization charges produced by the impinging Cherenkov photons are transported by an electric field. The work done by the field on the charges is detected as additional heat by a temperature sensor attached to the Ge/Si wafer.

Classical Ge/Si bolometric detectors with NTD read-out have already shown to be able to reach a threshold of the order of 50-100 eV for the total light energy. In parallel, amplification factors of one order of magnitude have been reached exploiting the Luke-Neganov effect, with constant noise. The combination of these two results should allow achieving a few eV thresholds, in the regime of a few or even single optical - UV photon counting. The quantum efficiency can also be very high with a proper coating of the light absorber, larger than 60% [10].

In order to apply the electric field, different electrode design will be compared. For Si detectors the contact pattern will be studied and realized by the Fondazione Bruno Kessler in collaboration with INFN Bicocca, which will take care of low temperature test of the devices. For Ge detectors a structure of annular concentric Al contacts is foreseen, following the scheme adopted by the EDELWEISS collaboration for the charge read-out of their hybrid dark-matter bolometers. This configuration is well tested, also in terms of deposition procedure, and will be realized at CSNSM-Orsay in France, where the EDELWEISS detectors are usually produced. Prototype Neganov-Luke effect detectors based on this approach have been developed with encouraging results. Excellent preliminary results – providing alpha/beta separation on an event-by-event basis – have been achieved also with Si absorber and TES readout technology [8].

b. Transition Edge Sensor (TESs) – Transition Edge Sensors are thin-film superconducting devices that operate at the critical temperature T_c of the superconductor. In that transition region, TES devices have a large positive temperature coefficient α, which provides a sensitive measurement of temperature. TES sensors are normally wired with a small shunt resistor in parallel, and operate in a voltage bias mode, which provides negative electro-thermal feedback and maintains the device in the transition region. Changes in the TES current are detected by a sensitive Superconducting Quantum Interference Device (or SQUID array) amplifier, located at a 600 mK or 4 K plate of the cryostat.

TES sensors have typically very low impedance, in the range of a few mΩ to an Ω. Therefore, they are inherently fast devices, with the bandwidth of MHz or more. SQUID arrays can also provide bandwidth in the MHz range. The large bandwidth compared to the NTDs offers several advantages: pulse shape sensitivity is significantly improved, and the time resolution better than 1 ms can be achieved, reducing pileup due to $2\nu\beta\beta$ and background events. In addition, large bandwidth of the SQUID amplifiers allows relatively straightforward time multiplexing of multiple sensors in a single readout channel. Such solutions exist in the astrophysics community.

Very low current noise of the SQUID amplifiers and the high temperature coefficient of the TES sensors makes them very suitable for high-resolution bolometric applications. Calculations show potential for a TES-SQUID based light detectors with eV-scale resolutions, although at this time 20-40 eV RMS resolution has been achieved by CRESST. However, there is currently no known superconductor with a critical temperature $T_c \sim 10$ mK. On the other hand, a thin-film bilayer of superconductor and normal conductor (e.g. Ir-Au, Ir-Pt, Mo-Au, etc) can be produced with a T_c that depends on the stoichiometry or the ratio of thicknesses of the two films. UC Berkeley and LBNL groups in collaboration with the Materials Sciences group at Argonne National Laboratory are developing low-T_c thin films. Initial results are already encouraging, producing a sample with T_c=21 mK and excellent temperature sensitivity. The next step is developing high-resolution sensors based on these bilayers.

Another TES version under consideration as a sensor for the light detectors uses NbSi, which is a superconductor for an appropriate stoichiometric ratio with an intrinsic high resistivity in the normal state. The superconducting films will be fabricated at CSNSM, by ultra-high vacuum electron-beam co-evaporation of niobium and silicon on germanium substrates, according to a well established technology [11]. The films will have a meander structure obtained by reactive ion etching in order to further increase their normal state impedance up to the range 1-5 MΩ. This high value allows the use of conventional electronics based on Si JFETs as for NTDs when they are operated within the transition. This solution does not provide all the advantages related to the low-impedance bilayer TESs (speed and ease of multiplexing), but it is possible to get a temperature sensitivity up to 10 times higher that that achieved by NTDs keeping the same front-end electronics, and so with a minimal impact on the CUORE readout structure. NbSi TESs with transitions around 20mK have already been fabricated and tested.

c. Microwave Kinetic Inductance Detectors (MKIDs) – MKIDs base their working principle on the property of kinetic inductance in superconducting materials. The kinetic component of the impedance depends on the density of Cooper pairs, which can be modified by an energy release able to break them. If the inductive element is part of a resonant circuit with a high quality factor, the density variation of Cooper pairs generates changes in the transfer function of the circuit. The signal is obtained by exciting the circuit at the resonant frequency, and measuring the phase and amplitude variations induced by energy releases.

The main advantage of the KID technology resides in the ability to arrange parallel readout (multiplexing) and in the room temperature electronics, overcoming technical issues related to the operation of TES. Many MKID sensors can be independently coupled to the same excitation line by making them resonate at slightly different frequencies. This feature allows using a small number of wires in the cryostat, simplifying the installation. The potential of MKIDs has been already demonstrated in astrophysical applications, where they successfully replaced the TES sensors.

The CALDER (Cryogenic wide-Area Light Detectors with Excellent Resolution) R&D [12], supported by a European grant, aims at demonstrating the potential of KID-based light detectors for CUORE-IHE. The first prototypes, based on aluminum sensors deposited on silicon substrates, are being tested as well as the readout. The first results are encouraging: both the detectors and the multiplexed readout work. The CALDER group is now working on the choice of the superconducting materials and on the detector design to reach the noise goal.

d. Magnetic Metallic Calorimeters (MMCs) – MMC sensors are based on the strong temperature dependence of the magnetization in paramagnetic Au:Er sensors. A large variation of the magnetic moment can be read out with high sensitivity using meander-shaped thin-film pickup coils and SQUID magnetometers. This effect, already exploited with outstanding results in X-ray spectroscopy by the Kirchhoff Institute for Physics (KIP) group in the Heidelberg University, can be used to develop exceptionally sensitive thermometers for the light detectors. The LUMINEU program, with which the Heidelberg group collaborates, envisages the fabrication of devices based on this principle. The KIP group will develop new Au:Er sensors with specific meander geometry for optimized meander inductance and sensor heat capacity for LUMINEU [13]. An innovative deposition of the meander directly on the Ge crystal will be developed to ensure the very fast readout of the entire wafer with only one sensor. Signal shape, amplitude and noise calculations, usually very reliable in MMCs, foresee an energy resolution between 3 eV and 10 eV (FWHM) and the signal rise-time below 50 μs. Tests with actual devices are foreseen by the end of 2014.

2. Al Thin Film as Signal Shape Modifiers

Due to their basic working principle, bolometers do not have a dead layer (they are fully sensitive up to the surface) and often present a single response to any type of fast energy deposition, irrespective of its nature and location (e.g. in the CUORE TeO_2 case). While this property is responsible for excellent energy resolution and detection efficiency with little position dependence, it can be unfortunate when surface events are the most dominant background, since surface is as sensitive as the bulk. This disadvantage can be overcome by adding passive elements to the bolometer surface in a reproducible way and with radio-clean procedures. Surface sensitivity can be achieved by depositing Al films (of $\mathcal{O}(10\ \mu\mathrm{m})$ thickness) on the main bolometric TeO_2 absorber.

The rationale of this approach is the following. Athermal phonons generated by a particle that releases its energy within a few mm from the surface (i.e. an alpha or beta particle) will break Cooper pairs in the superconducting film and produce quasiparticles, which have in general a long lifetime (of the order of milliseconds) in high purity aluminum. Their subsequent recombination will produce athermal phonons again, that will add a delayed component to the phonon signal read out by the sensor on the main bolometric absorber. We expect remarkable difference in signal formation for bulk events. In this case, the athermal phonon population reaching the Al film is more degraded in energy and less efficient in producing quasiparticles. Clear evidence of this mechanism has already been achieved [14]. Consequently one expects different signal shapes for surface and bulk events, and in particular a longer rise-time for a surface event.

The proof of principle of this approach was already demonstrated with TeO_2 in CSNSM-Orsay [15], but using fast phonon sensors based on NbSi films, with rise times of the order of 1 ms. Not only the rise-time was longer for surface events, but the pulse shape was modified for several milliseconds after the maximum. Unfortunately, the current NbSi sensor technology does not provide an adequate energy resolution, and is therefore unsuitable for $0\nu\beta\beta$. The future R&D work, to be performed at CSNSM-Orsay and CEA/SPP-Saclay, will consist of achieving surface-to-bulk signal separation by pulse shape discrimination with NTD sensors, i.e. with heat pulse rise-time of the order of tens of milliseconds. This may be possible as the excellent signal-to-noise ratio characterizing the typical CUORE readout has the potential to highlight even tiny pulse-shape differences.

Alternatively, low-impedance bilayer TES sensors may be more suitable for pulse shape discrimination, due to their inherent fast response time and excellent noise characteristics. Once such sensors are developed, we will study their applications in pulse shape discrimination. This work is proceeding at Berkeley.

Once pulse shape discrimination is demonstrated above ground in a small prototype, a procedure will be set up to deposit Al films on all six sides of a typical $5 \times 5 \times 5$ cm TeO_2 crystals, with the aim to proceed to underground tests on real size detectors. We remark that this technology is the only one among those proposed in this document that does not involve light detectors and their additional readout.

3. *Surface Event Detection Mediated by a Scintillating Foil*

As discussed in Sec. V, the main expected limitation to the CUORE sensitivity arises from surface alpha contaminations [5]. To tag these background events two strategies are possible: (i) tag alpha particles or (ii) identify surface events. Following the (ii) strategy, the goal of the ABSuRD project (A Background SUrface Rejection Detector) is to tag surface alphas by means of an external plastic scintillator. The idea is to encapsulate a purely thermal bolometer (such as TeO_2) with a scintillating foil and to add a bolometric light detector to measure the light. When degraded alpha particles interact in the scintillating foil, the emitted light is collected by the light detector. A surface alpha particle releasing part of its energy in the crystal and part in the scintillating foil can be rejected by analyzing the coincidence signal of heat (in the absorber) and light (in the light detector) [16]. The crucial aspect of this technique is the capability of detecting the light emitted by the scintillating foil. A moderately low energy threshold of ~ 1 keV is needed for the bolometric light detector. As an example, an alpha particle of 5.3 MeV (generated by the decay of ^{210}Po) releasing 2.5 MeV in the scintillator (i.e. generating a 2.8 MeV background event in the TeO_2 bolometer) produces about 1.5 - 2 keV of photons. Another advantage of this technique is that beta radiation escaping the detector can be tagged as well due to the high scintillation of electrons, in spite of the small deposited energy. The ABSuRD project is focused on developing and characterizing plastic scintillators with large light yield and good low temperature properties to minimize the impact of the light detector energy threshold. A first bolometric prototype, realized with commercial scintillators, showed encouraging results in the capability of tagging surface alphas from an implanted ^{147}Sm source [17].

B. Alternatives to TeO_2 Bolometers

The most promising $0\nu\beta\beta$ isotopes alternative to ^{130}Te are ^{82}Se, ^{100}Mo, and ^{116}Cd. They are all characterized by a $0\nu\beta\beta$ transition energy higher than 2.6 MeV, in a region free from gamma background. The residual and presumably dominant alpha background will be rejected by embedding the isotopes under study in scintillating bolometers. The different light-to-heat ratio for alpha and gamma/beta interactions for the same thermal energy is a powerful tool to identify and eliminate alpha events.

1. *Study of ^{82}Se Embedded in ZnSe Crystals*

ZnSe crystals represent a very interesting candidate for the search for the $0\nu\beta\beta$ of ^{82}Se by virtue of its high content of Se (56%) and high Q-value ($Q_{\beta\beta} = 2997$ keV), as well as its good bolometric and scintillating properties. Several $Zn^{nat}Se$ bolometers were studied in the framework of the LUCIFER project (ERC Advanced Grant n. 247115). In particular a 430 g $Zn^{nat}Se$ crystal was characterized in terms of the energy resolution, internal contaminations, and particle identification capabilities [9].

The crystal exhibited a FWHM energy resolution of 16.3 keV at 2615 keV and a light yield of 6.5 keV/MeV and 27 keV/MeV for beta/gamma and alpha particles respectively. The possibility to identify alpha events from beta/gamma interactions by pulse shape discrimination due to the the difference in the decay constant of the scintillation pulses was demonstrated. An alpha discrimination power >99.99% was achieved combining the pulse shape and light yield discrimination.

A contamination of $\sim$17 μBq/kg in ^{232}Th and of $\sim$25μBq/kg in ^{238}U in secular equilibrium was measured in a dedicated 524-hour underground run. These contaminations, obtained without particular care in material selection, are compatible with a background level of a 1 count/(keV ton y) in the region of interest. LUCIFER aims at running a pilot experiment with the $10 - 15$ kg ^{82}Se detector and the background level of 10 count/(keV kg y) in order to demonstrate the maturity of the technology [18].

The procurement of a considerable amount of ultra-pure ^{82}Se by a European company (URENCO) represented a major achievement by itself. The enrichment is done by SeF_6 centrifugation followed by the chemical conversion to elemental selenium. In order to prevent radioactive contamination of the samples, a dedicated centrifuge line and an ad-hoc conversion rig were set up. 8 kilograms of Se, enriched to 95%, in ^{82}Se, have already been delivered, and the rest of the material will be delivered in Fall 2014. The overall chemical purity turns out to be better than 99.8% on trace metal base; in particular, the concentrations of ^{238}U and ^{232}Th fall below 10^{-10}g/g and the critical impurities (Fe,Cr) have concentrations below the accepted limits for good scintillation performances. The main effort is currently focused on the refinement of the crystal growth procedure in terms of optimization of the optical and thermal quality and limitation of the irrecoverable loss of ^{82}Se [19].

The LUCIFER light detector [18] is a disk-shaped pure Ge bolometer (O= 44 mm, thickness = 180 μm) with a SiO_2 dark coating [20] on the side facing the main scintillating crystal. The light detector is read out with an NTD thermistor. FWHM energy resolution of 220 eV and rise time of few ms were typically observed [21]. These performances are suitable for particle discrimination in ZnSe bolometer given the light yield and the time profile of the scintillating pulse. The LUCIFER prototype will be installed in the dilution cryostat presently hosting CUORE-0 at the end of its operation. Data taking is foreseen in Fall 2015.

2. Study of ^{100}Mo Embedded in $ZnMoO_4$ or Li_2MoO_4 Crystals

^{100}Mo is one of the most promising $0\nu\beta\beta$ isotopes because of its high transition energy (3034 keV), outside the bulk of the natural gamma radioactivity, and its considerable natural isotopic abundance (9.7%). The best sensitivity to $0\nu\beta\beta$ of ^{100}Mo was reached by the NEMO-3 experiment that obtained a half-life limit of 1.0×10^{24} y at 90% C.L. with $\sim$7 kg of enriched ^{100}Mo and 4.5 y livetime. The NEMO-3 detection efficiency (14%) and energy resolution (10%) can be improved up to 80-90% and to $\sim$0.1% respectively by using bolometers containing Mo. If Mo is embedded in a scintillating crystal it is possible to develop hybrid devices with a double heat+light readout aiming at a full suppression of the alpha background. As discussed above, the most natural and effective device to detect scintillation photons is a dedicated bolometer.

There are several inorganic scintillators containing molybdenum. One of the most convenient choices consists of $ZnMoO_4$ crystals. Recent developments show that this material is very promising for high sensitivity $0\nu\beta\beta$ experiment [18, 22–24]. Energy resolutions better than 10 keV FWHM have been routinely obtained with crystals up to 330 g mass close to the $0\nu\beta\beta$ signal position, in the framework of the LUCIFER, LUMINEU, and ISOTTA projects. Light yields of the order of 1 keV/MeV, moderate but sufficient, were demonstrated. Underground tests of these large mass crystals, both in the Gran Sasso and in the Modane laboratories, have shown that ^{228}Th – the most critical contaminant due to emission of high energy beta particles – has a specific activity less than 10 μBq/kg [24]. This figure is compatible with a background index in the range of a few 10^{-1} counts/(keV ton y) [2, 22]. Alpha discrimination power of much better than 99.9% has been demonstrated, promising a background of the order of or better than 10^{-1} counts/(keV ton y). Differences in pulse shapes between alpha- and gamma-induced heat signals have been observed, suggesting an even better rejection of alpha events using pulse shape discrimination alone [24]. This aspect deserves to be studied further, as it can potentially lead to eliminating the need for a light sensor, which would simplify the detector structure.

An additional potential background source in ^{100}Mo-based bolometers is due to random pileup of the standard two-neutrino double beta decay ($2\nu\beta\beta$) events [22, 25]. This process has recently been observed in a bolometric experiment [26]. The relatively high rate ($T_{1/2} = 7.11 \times 10^{18}$ y) of $2\nu\beta\beta$ events makes the pileup problem particularly acute for ^{100}Mo. Time resolution of significantly better than 1 ms is required to reduce this background to a negligible level [2]. Pileup events can also be rejected using pulse-shape discrimination [25].

Very recently, two ^{100}Mo enriched crystals have been grown and successfully operated as scintillating bolometers, with negligible irrecoverable losses of the initial material [27]. No deterioration of the bolometric and scintillation performance of the enriched crystals was observed with respect to the natural ones. The only possible showstopper could be the remarkable difficulty encountered in growing large-mass regular-shape crystals. However, recent crystallization tests at the Nikolaev Institute of Inorganic Chemistry (Novosibirsk, Russia) exhibit significant improvements [28, 29], culminating in the production of high-quality cylindrical samples (h=4 cm and O=5 cm).

A natural next step for ^{100}Mo developments will involve a medium-scale pilot experiment, to be performed on a two-year time scale at LNGS or in the Modane underground laboratory. Such detector could consist of tens of $\sim$400 g $ZnMoO_4$ enriched crystals using approximately 10 kg of the isotope, belonging to ITEP (Russia) and already made available for this search. This demonstrator, with a remarkable sensitivity by itself, will constitute a general feasibility test for the use of this technology at the ton-scale level. A Memorandum of Understanding among IN2P3 (France), INFN (Italy), and ITEP (Russia) has been signed with respect to this technology demonstrator, guaranteeing in particular the use of the existing enriched ^{100}Mo for this development.

An alternative compound to $ZnMoO_4$ is Li_2MoO_4, which is encouraging in spite of a low light yield (of the order of 0.5 keV/MeV,about half of what observed in ZnMoO4), as preliminary tests [30] in the framework of ISOTTA have shown. The advantages of this compound are the following: first, it contains 55% of Mo in weight, to be compared with 42% of the Zn-based compound; in addition, all the preliminary indications show that the synthesis of large mass crystals is much easier than for $ZnMoO_4$. In the next months an intense activity on this compound will clarify if it may validly replace $ZnMoO_4$.

3. *Study of ^{116}Cd Embedded in $CdWO_4$ Crystals*

As ^{100}Mo and ^{82}Se, ^{116}Cd belongs to the so-called "$0\nu\beta\beta$ golden isotopes", i.e. elements whose $0\nu\beta\beta$ transition energy exceeds the 2615 keV γ-line of ^{208}Tl. Enriched $^{116}CdWO_4$ scintillating bolometers could be ideal candidates for a $0\nu\beta\beta$ searches for several reasons:

- it is a well-established *industrial* crystal scintillator. Recently, a high-yield growth technology for $^{116}CdWO_4$ crystals was developed, with single crystal masses up to several kg and with yield of production up to 90% [31]
- the light yield (LY) is comparable to the best known undoped scintillators
- the radiopurity of this compound is "naturally" high [32]

Due to these favorable features this enriched crystal compound was already used to perform a DBD experiment [32] using standard photomultipliers as light sensors. Several tests [33, 34] were also performed on scintillating $CdWO_4$ bolometers, demonstrating the high energy resolution, the low level of contaminations, and the excellent particle discrimination abilities of such detectors. Moreover, thanks to the extremely high LY, these crystals can be potential candidates for dark matter searches. In fact, the LY as well as the intrinsic radiopurity of this compound are better than $CaWO_4$ crystals used in the CRESST experiment.

The only drawback of this compound is the presence, in the natural Cd, of the ^{113}Cd isotope (12% i.a.) that undergoes β-decay with a Q-value of 319 keV and $T^{1/2} = 9.3 \times 10^{15}$ y (roughly 0.5 Hz for 1 kg of $CdWO_4$). This results in an unavoidable pile-up background spectrum at the $Q_{\beta\beta}$ value due to the convolution with the 2ν-DBD. On the other hand, the low-energy ^{113}Cd β-decay prevents – definitively – the use of this compound for Dark Matter search.

In the future bolometric $0\nu\beta\beta$ experiment, in which isotopic enrichment is mandatory, this drawback will be automatically overcome. It is obvious that the level of enrichment as well as the price of the material is fundamental aspect in view of a future ^{116}Cd $0\nu\beta\beta$ / dark matter experiment. Within the ISOTTA project, 145 g of 99.85 % enriched metallic ^{116}Cd were recently (2014) purchased. The measured level of ^{113}Cd in the sample is $\leq$0.02 %, adequate for both $0\nu\beta\beta$ and dark matter searches. The current enrichment cost of 200 Euro/g is high, although it can possibly be reduced for mass-scale production.

VII. ENRICHMENT AND CRYSTAL PRODUCTION

CUORE-IHE will require isotopic enrichment for any isotope under consideration. All of the isotopes discussed here – ^{130}Te, ^{100}Mo, ^{82}Se and ^{116}Cd – can be enriched by centrifugation. This implies that they are all viable for a next-generation experiment in terms of cost and production rate. However, technical reasons determine differences in the enrichment cost which may impact the final choice. Very approximately, the enrichment cost of ^{100}Mo and ^{82}Se is in the range \$50-100/g. A factor of 2 more is expected for ^{116}Cd. The current enrichment cost of ^{130}Te is \$17/g.

Specific studies of the enrichment have already been done in the CUORE-IHE framework for three isotopes: ^{82}Se within LUCIFER, ^{116}Cd within ISOTTA, and ^{130}Te within CUORE by the University of South Carolina (USC). USC has procured about 10 kg of Te metal, enriched to 93% in ^{130}Te. The first batch of CUORE-sized enriched 750 g crystals has recently been delivered to Gran Sasso for bolometric tests. The initial performance is compatible with that of the unenriched CUORE crystals. Further R&D aiming at improving the efficiency of the crystal growth process and reuse of the enriched material is currently ongoing.

In addition, crystal production capabilities of several manufacturers need to be investigated for a ton-scale experiment. While the TeO_2 production line at the Shanghai Instutute of Ceramics of Chinese Academy of Science (SICCAS) has performed extremely well for CUORE, large-scale production of other crystals has never been attempted. Since recent geopolitical developments may make relying on manufacturers in Ukraine and Russia problematic, investigating alternative vendors, in the US, Europe, or Asia would be a wise effort. The UCLA group in the US plans to investigate establishing a ZnSe process at SICCAS, while other possible vendors are being considered.

VIII. REDUCTION OF THE ENVIRONMENTAL RADIOACTIVITY

The active background rejection techniques, on which detector developments are focused, aim at reducing to negligible levels the effect of surface contaminations of detector materials. As mentioned, this background source is identified as the dominant contributor to Cuoricino and CUORE-0 counting rates and as the more likely limiting factor for CUORE sensitivity. However, the reduction of surface contamination effects can't by itself ensure the achievement of a background index two orders of magnitude lower than CUORE. Indeed, sources different from surface contaminations can contribute to the ROI counting rate at levels below the 10 counts/(keV ton year) foreseen for CUORE. Among these, the most dangerous are certainly the radioactive (bulk) contaminations of the detector elements: crystals, copper, lead, the "small parts" as glue, heaters, bonding wires or flat cables and pads etc. As it is clearly evident the CUORE background budget [2, 35], with the exception of the surface contaminations, no positive indication of the presence of contaminants in the different detector elements have been obtained. However, in most cases, the available upper limits on material contamination translate to potentially dangerous counting rates for the CUORE-IHE goal. For this reason, an improvement of the presently attained sensitivities is mandatory.

Two techniques will be explored in the CUORE-IHE program:

- Pre-concentration of radio-contaminants through chemical treatment of materials. When coupled to NAA, ICMPS, or HPGe screening this will allow increasing the sensitivities achieved with these techniques. As an example, in the case of copper either NAA and HPGe spectroscopy achieve a similar sensitivity of about 1 μBq/kg on ^{232}Th. In both cases the sensitivity is ultimately limited by the mass of the copper sample that can't be increased *ad libitum* (increasing the mass of a sample measured with HPGe is often not effective due to the self-absorption of the gamma lines inside the sample). A pre-concentration of the contaminant is equivalent to an increase in the mass of the sample resulting therefore in a sensitivity increase. The technique is often used in ICPMS measurements but can also be successfully applied either in NAA or in HPGe measurements. It requires however a dedicated study for each material, where the achievement of the required concentration as well as the control of systematics has to be proven.

- Development of a bolometric detector for the measurement of surface/bulk contamination of small samples and foils. In a number of cases the aforementioned screening techniques can't be applied either because the available mass sample is too small (HPGe spectroscopy require large mass samples to reach high sensitivity) or because the material properties are inappropriate (NAA and ICPMS have restrictive conditions on the chemical elements that can be analyzed). For CUORE this was true in the case of "small parts" or of materials used in the form of foils (superinsulation, flat cables, etc). In these cases, the use of surface alpha spectroscopy through Si surface barrier diodes has been proven to reach competitive sensitivities in shorter times. The same kind of screening, implemented through the use of bolometric detectors, will achieve a sensitivity that is between 10 and 100 times higher thanks to the better energy resolution of these devices as well as to their higher radiopurity. Si wafers or TeO_2 slabs can be used for this purpose realizing a sandwich-like detector where samples are inserted in-between thin bolometers. If able to reach very low thresholds these detector could also provide information on the X-ray emission of the samples providing in this way a complementary information for contamination identification.

If successful, the improvement reached with the development of these two technologies will allow us to reach a sensitivity on U and Th concentrations of about one to two orders of magnitude higher than what is obtained today, which is the required goal for CUORE-IHE materials.

IX. CONTROL OF THE MUON-INDUCED RADIOACTIVITY

According to the simulations [2] based on CUORE and the measured muon flux at LNGS, the event rate induced by the cosmic ray muons or muon showers in the $0\nu\beta\beta$ region of interest is expected to be of the order of 0.5 counts/(ton y). For a 5-10 year exposure, a reduction in this rate of about a factor of 10 or more would be required for a zero-background experiment. Such reduction would require either a deeper underground site, or a dedicated anti-muon veto around the active volume of the CUORE-IHE detector. The muon-induced neutron rate is estimated to be another order of magnitude smaller; however, simulating muon-induced showers with high precision is a notoriously difficult endeavor.

The Yale group of the CUORE collaboration is developing a muon tagger around CUORE as part of the R&D towards a future CUORE-IHE experiment. The goals are to enable a data-driven study of muon-induced backgrounds in CUORE and to confirm that LNGS is deep enough for a future bolometric experiment like CUORE-IHE.

X. SELECTION CRITERIA FOR THE CUORE-IHE TECHNOLOGY AND TIME SCHEDULE

The CUORE-IHE Steering Committee will set up a formal process (based on discussions within the collaboration) in order to take a decision about the structure of CUORE-IHE, involving the isotope choice, the detector technology, and additional measures required to achieve the sensitivity goals of the new experiment. In the following, we discuss the very general guidelines for the process leading to the final selections of the CUORE-IHE detector technology and the isotope of choice.

- The primary goal of CUORE-IHE is the sensitivity of 10-15 meV to the effective neutrino mass. Achieving this goal requires a detector with the active isotope mass of approximately a ton, and a background level of $\lesssim 10^{-1}$ counts/(ton y) in the region of interest. While this background level cannot be verified directly before CUORE-IHE is in operation, the chosen technology should prove convincingly that this target can be achieved, by means of dedicated experimental tests and verifiable simulations. Key performance parameters such as internal radioactivity of the crystals and other detector materials, alpha/beta and/or surface/bulk event rejection capability, alpha backgrounds above 2.6 MeV, energy resolution, and others will be taken into account.

- One of the key features of the bolometric technology is the high energy resolution. It is important that this feature is maintained in the CUORE-IHE approach. Ideally, the CUORE-IHE energy resolution should not be worse than that achieved by CUORE. This must be proven in dedicated experimental tests with crystals of the the size to be used for CUORE-IHE.

- A ton-scale bolometric detector will imply $\mathcal{O}(1000)$ single detectors. A chosen technology must demonstrate reproducibility in terms of technical performance (energy resolution, pulse shape, noise features). The detector behavior should therefore be tested with an array of at least 8 modules and, if possible, larger, operated underground under conditions as similar as possible to those expected in the CUORE-IHE experiment in terms of base temperature, vibration level, read-out, and electronics configuration. Detector assembly reproducibility similar or better than that achieved in CUORE must be feasible.

- The cost and schedule of the enrichment process and of the crystal production must be compatible with a timely realization of the experiment. This compatibility must be proven by means of already established contacts with the companies or institutions responsible for enrichment and crystal production, which will be invited to provide preliminary but realistic cost figures and production time plans.

- A point that will be considered in assessing a technology for CUORE-IHE is the degree of compatibility with the existing CUORE infrastructure, in terms of mechanical coupling, cryogenics, readout, and DAQ features.

In the next two years, the R&D efforts will proceed along the lines outlined in this document. The decision about the detector technology (as well as the isotope choice) will be taken by the end of 2016. We foresee producing the CDR and forming the international collaboration on a similar timescale.

XI. CONCLUSIONS

Ton-scale bolometric detectors based on CUORE technology and infrastructure have the potential to convincingly discover or rule out Majorana nature of neutrinos in the so-called Inverted Neutrino Mass Hierarchy [2]. This document describes the R&D efforts towards the next-generation bolometric experiment, dubbed (tentatively) CUORE-IHE. These efforts focus on background reduction beyond that foreseen in CUORE and demonstrated by CUORE-0. These R&D activities are currently performed either within CUORE collaboration, or as independent projects for small-scale double beta decay demonstrators. In addition to systematically reviewing the ongoing efforts, this document outlines guidelines and milestones for a convergence towards a detailed design of a future $0\nu\beta\beta$ decay experiment based on the CUORE experience and – to the largest possible extent – on the CUORE infrastructure. The objective of this future experiment is to achieve at least a 3σ discovery potential for $0\nu\beta\beta$ decay if the neutrino is a Majorana particle and if the mass hierarchy is inverted. We aim for a comprehensive proposal to the international funding agencies on the timescale of 2016-2017.

XII. CUORE-IHE INTEREST GROUP

The CUORE-IHE Interest Group is an evolving collection of scientists, supporting the scientific goals of CUORE-IHE, and interested in pursuing a future bolometric search for $0\nu\beta\beta$. This group is not a formal collaboration, and does not imply commitments of any kind at this point. The group consists of both the current members of the CUORE Collaboration [1], as well as new institutions that have contributed to the R&D efforts described in this document.

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