CUPID
CUPID (Cryogenic Underground Observatory for Rare Events)
Upgrade with Particle IDentification

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CUPID is a proposed future tonne-scale bolometric neutrinoless double beta decay ($0\nu\beta\beta$) experiment to probe the Majorana nature of neutrinos and discover Lepton Number Violation in the so-called inverted hierarchy region of the neutrino mass. CUPID will be built on experience, expertise and lessons learned in CUORE, and will exploit the current CUORE infrastructure as much as possible. In order to achieve its ambitious science goals, CUPID aims to increase the source mass and dramatically reduce the backgrounds in the region of interest. This requires isotopic en-
I. INTRODUCTION

The observation of neutrinoless double-beta decay ($0^{\nu}\beta\beta$) would unambiguously establish the Lepton Number violation, 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. The answer will have important implications for astrophysics, cosmology, as well as particle physics. 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 [1], 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 neutrino mass values in the so-called inverted mass hierarchy. CUORE is an established project within the Italian (INFN) and US (DOE and NSF) 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 within a year.

The purpose of this document, drafted by the CUPID Steering Committee[8], is to define a possible follow-up to the present CUORE [1] experiment, after CUORE completes its scientific mission in about 5 years of data taking. The next experiment will be based on experience, expertise, and lessons learned in CUORE; thus we refer to this future project in the following as CUORE Upgrade with Particle ID (CUPID) [2]. We will first discuss the scientific objective of CUPID; we will then list the important near-term R&D activities which aim to develop technologies capable of achieving the desired science goal; we will finally indicate a time schedule for CUPID definition, anticipating that the general goal is to select the CUPID technology in the next few years, so that a Conceptual Design Report (CDR) can be produced.

Continued progress towards CUORE operations motivates planning of a next-generation double beta decay experiment with bolometric detectors. CUORE-0, the first CUORE tower which has been operating in the Cuoricino cryostat for nearly two years, shows excellent performance in terms of background and detector resolution [2]; all CUORE towers have been fully built; the CUORE cryostat has reached its design base temperature [1] and is under final stages of commissioning [1]. 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 $0^{\nu}\beta\beta$. 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.

II. 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 neutrino mass values in the inverted mass hierarchy. CUORE is in the final phase of construction at LNGS and is expected to start operations within a year. Construction of all 19 detector towers is now complete. The cryogenic system has been completely assembled and commissioning is steadily progressing.
With an expected background of 10 counts/(keV ton year) and an energy resolution of 5 keV FWHM in the 0νββ region of interest (ROI), CUORE is projected to reach a 90% C.L. sensitivity of $T_{1/2} > 1 \times 10^{26}$ y after five years of operation, which corresponds to a range of the effective Majorana neutrino masses of $\langle m_{\beta\beta} \rangle < 51 - 133$ meV, depending on the estimate of the nuclear matrix element.

The CUORE concept of a bolometric 0νββ 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 surface contamination from $^{238}$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 development of bolometric experiments. Scientific success of CUORE is a required condition for future developments. Based on careful material assays 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 and CUORE-0, has limitations due to the relatively large gamma background from the Cuoricino cryostat and limited exposure. In particular, precise evaluation of the relative contributions of the alpha and beta/gamma components in the $^{130}$Te ROI is only possible with a large-scale detector like CUORE. In this respect, CUORE itself can be considered a very important R&D effort for the development of a next-generation bolometric 0νββ experiment.

### III. SCIENTIFIC OBJECTIVE

CUPID is a proposed bolometric 0νββ experiment which aims at a sensitivity to the effective Majorana neutrino mass on the order of 10 meV, covering entirely the so-called inverted hierarchy region of the neutrino mass pattern. CUPID will be designed in such a way that, if the neutrino is a Majorana particle with an effective mass in or above the inverted hierarchy region ($\sim 15 - 50$ meV), then CUPID will observe 0νββ with a sufficiently high confidence (significance of at least 3σ). This level of sensitivity corresponds to a 0νββ 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 × year exposure scale in the ROI of a few keV around 0νββ transition energy.

The scientific goals outlined above can be achieved with a bolometric experiment like CUORE at LNGS, 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.

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. Groups in both Europe and the US 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, $^{160}$Mo, and $^{118}$Cd), studying background rejection with scintillation, Cherenkov radiation, ionization, and pulse-shape discrimination, and 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 $\mathcal{O}(10$ meV) Majorana mass sensitivity. The goals of the CUPID program, depending on the ultimate isotope of choice, are listed in Table I.

A detailed description of the ongoing R&D efforts is given in a separate document. Below, we present the roadmap for converging on an experimental proposal in the next few years.

### IV. KEY GOALS FOR THE CUPID TECHNOLOGY

In the following, we discuss the very general guidelines that will drive the CUPID detector technology and the choice of isotope. The CUPID collaboration will set up a formal process in order to make technical choices involving
The primary goal of CUPID is sensitivity of $10^{-15}$ meV to the effective neutrino mass. This requires a detector with an active isotope mass of order 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 CUPID 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, sensitivity to cosmogenic backgrounds, energy resolution, and others will be taken into account.

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

A tonne-scale bolometric detector will imply $O(1000)$ single detectors. An appealing feature of the bolometric technology is its scalability: from single-module devices, to a full-tower demonstrator prototypes, to the full CUORE-sized array. The next-generation technology should maintain this feature.

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**TABLE I: CUPID sensitivity goals**

| Parameter                                           | Projected value and/or range                  |
|-----------------------------------------------------|-----------------------------------------------|
| Readiness for construction                           | 2018 (technical limit)                        |
| Construction time                                    | 5 years                                       |
| Total fiducial mass (kg)                             | TeO$_2$ 750                                   |
|                                                    | ZnMoO$_4$ 540                                 |
|                                                    | ZnSe 670                                      |
|                                                    | CdWO$_4$ 980                                  |
| Isotope fiducial mass (kg)                           | $^{130}$Te 543                                |
|                                                    | $^{100}$Mo 212                                |
|                                                    | $^{82}$Se 335                                  |
|                                                    | $^{116}$Cd 283                                 |
| Energy resolution at endpoint (FWHM)                 | $\leq 5$ keV                                  |
| Event selection efficiency in fiducial volume        | 75-90%                                        |
| Background within FWHM of endpoint                   | $\leq 0.02$ counts/(ton-year)                 |
| 90% C.L. $0\nu\beta\beta$ lifetime limit for 10 year run (10$^{27}$ years) | $^{130}$Te 5.1                                |
|                                                    | $^{100}$Mo 2.2                                |
|                                                    | $^{82}$Se 4.2                                  |
|                                                    | $^{116}$Cd 3.0                                 |
| 90% C.L. $m_{\beta\beta}$ limit for 10 year run (90% C.L.) (meV) | $^{130}$Te 6–15                              |
|                                                    | $^{100}$Mo 6–17                               |
|                                                    | $^{82}$Se 6–19                                |
|                                                    | $^{116}$Cd 8–15                               |
| $0\nu\beta\beta$ lifetime discovery sensitivity (3$\sigma$) in 10 years | $^{130}$Te 4.9                                |
|                                                    | $^{100}$Mo 2.1                                |
|                                                    | $^{82}$Se 4.0                                 |
|                                                    | $^{116}$Cd 2.9                                |
| $m_{\beta\beta}$ discovery sensitivity (3$\sigma$) in 10 years | $^{130}$Te 6–15                              |
|                                                    | $^{100}$Mo 7–17                               |
|                                                    | $^{82}$Se 6–19                                |
|                                                    | $^{116}$Cd 8–15                               |
• 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 CUPID experiment in terms of base temperature, vibration level, read-out, and electronics configuration. Detector assembly reproducibility and radiopurity similar to 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 timescales.

• CUPID technology should be as compatible as possible with the existing CUORE infrastructure, in terms of mechanical coupling, cryogenics, readout, and DAQ features.

In the next two years, the R&D efforts \cite{7} will proceed vigorously. CUORE operations and background measurements will inform the decision about the detector technology (as well as the isotope choice). We foresee producing the CDR and forming the international collaboration on a similar timescale.

V. CONCLUSIONS

Tonne-scale bolometric detectors with background rejection capabilities beyond that of CUORE have the potential to convincingly discover the Majorana nature of neutrinos in the so-called Inverted Neutrino Mass Hierarchy \cite{2}. Following commissioning of the CUORE detector and a brief period of vigorous R&D activities aiming to demonstrate that the science goals of CUPID can be effectively achieved, we will complete the design of a future 0νββ experiment based on the CUORE experience and – to the largest possible extent – on the CUORE infrastructure. The objective of this future experiment is to discover 0νββ decay and, therefore, establish violation of Lepton Number if the neutrino is a Majorana particle with the effective mass in or above the inverted hierarchy range.

[1] D.R. Artusa et al. [CUORE Collaboration], Adv. High En. Phys. 2015, 879871 (2015).
[2] D.R. Artusa et al. [CUORE Collaboration], Eur. Phys. J. C74, 3096 (2014).
[3] C.P. Aguirre et al. [CUORE Collaboration], Eur. Phys. J. C74, 2956 (2014); K. Alfonso et al. [CUORE Collaboration], arXiv:1504.02454.
[4] INFN Press release http://www.interactions.org/cms/?pid=1034217; J. Ouellet, arXiv:1410.1560.
[5] F. Alessandria et al. [CUORE Collaboration], arXiv:1109.0494.
[6] D.R. Artusa [CUORE collaboration], “CUORE background budget”, in preparation; see also O. Cremonesi’s talk at Neutrino 2014.
[7] The CUPID Interest Group, “R&D towards CUPID (CUORE Upgrade with Particle IDentification)”, arXiv:
[8] CUPID steering committee: F.T. Avignone, F. Bellini, C. Bucci, O. Cremonesi, F. Ferroni, A. Giuliani, P. Gorla, K.M. Heeger, Yu.G. Kolomensky, M. Pallavicini, M. Pavan, S. Pirro, M. Vignati