

Search for Neutrinoless Double-Beta Decay with CUORE

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The observation of $0\nu\beta\beta$ decays (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 and 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. It will be sensitive to the neutrino mass values suggested by recent atmospheric neutrino oscillation experiments in the so-called inverted mass hierarchy. CUORE is an established project within the DOE and NSF. The detector is currently under construction at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy, and is expected to start operations in 2014.

CUORE is a cryogenic-bolometer detector consisting of 988 TeO₂ crystals, 750 g each, operated at a temperature of 10mK. ¹³⁰Te decays exclusively by double beta decay processes and represents 34% of natural tellurium. The effective mass of CUORE will be 200 kg of ¹³⁰Te without enrichment. Cryogenic-bolometer detectors are a perfect match for the present phase of $0\nu\beta\beta$ experiments and there is great potential for scaling to future larger-scale detectors should they become necessary. If $0\nu\beta\beta$ is discovered with the coming generation of experiments, then the techniques developed with CUORE can be applied to other double beta decaying isotopes. This will help resolve the uncertainties of the nuclear matrix elements, providing a precise value for the effective neutrino mass. If $0\nu\beta\beta$ is not discovered, a future experiment with an improved sensitivity based on techniques pioneered by CUORE can be developed.

Our understanding of detector performance, background levels, and techniques for reducing them are based on the analysis of the data from the prototype Cuoricino detector, which operated between 2003-2008 at LNGS with a natural TeO₂ detector mass of 40.7 kg. In five years of running with the background level of 0.153 ± 0.006 counts/(keV kg year), Cuoricino set a limit on $0\nu\beta\beta$ half-life of $T_{1/2} > 2.8 \times 10^{24}$ at 90% C.L., which results in the upper limits on the effective neutrino mass of 300-700 meV, depending on the nuclear matrix elements.

We are about to commission CUORE-0, the first production tower cleaned and assembled to CUORE specifications. Preparation of the CUORE-0 tower is part of CUORE R&D plan, designed to perfect the cleaning and assembly procedures, as well as to confirm the reduction in the surface contamination expected for CUORE. Construction of the tower has been completed at Gran Sasso; it has been installed into the cryostat in Hall A (formally used for Cuoricino), and the initial cooldown is underway. CUORE-0 has significant physics reach since the background levels in the region of interest are expected to be about a factor of 3 lower than Cuoricino. We expect CUORE-0 to overtake Cuoricino sensitivity in less than a year of running, well before CUORE is fully assembled. Overall, after two years of running CUORE-0, we expect the half-life sensitivity for $0\nu\beta\beta$ decay of 9.4×10^{24} years, which would correspond to an effective neutrino mass on the order of 200-300 meV.

CUORE is currently under construction at LNGS and plans to start operations in late 2014, reaching a sensitivity of $T_{1/2} > 1.6 \times 10^{26}$ years after five years of operation, which would correspond to a limit on the effective Majorana neutrino mass of $\langle m_{\beta\beta} \rangle = 41-95$ meV, depending on the estimate of the nuclear matrix element. CUORE's sensitivity is predicated on reducing the radioactive background in the region of interest

around the double-beta decay transition energy of 2538 keV to the level of 0.01 counts/(keV kg year), roughly a factor of 15 compared to Cuoricino. The background reduction strategies, in particular reduction in the bulk contamination of the TeO₂ crystals, reduction of the surface contamination of the crystals and surrounding copper support structures, careful screening of cryostat and detector materials, and ultra-clean assembly procedures have been developed based on Cuoricino experience, and tested at the low-background cryogenic facility in Hall C at LNGS. Quality of the crystals produced for CUORE is also continuously monitored in dedicated QA runs. The assembly procedures have been fine-tuned with CUORE-0.

In addition to the search for neutrinoless double beta decay, the CUORE detector would also be capable of making other interesting measurements, such as searches for cosmological dark matter particles, solar axions, supernova neutrinos, and other rare events. CUORE can be upgraded to be more sensitive by using enriched ¹³⁰Te should this become necessary in the future. Enrichment would increase the signal by a factor of 2-3 without affecting the background. Further, R&D on the ideas for reducing the background by at least an order of magnitude or more is being pursued in Italy and the US. Such ideas include use of additional signal detection techniques (scintillation, ionization, Cherenkov radiation), active rejection of surface background events, as well as improved pulse shape discrimination between signal and background.

Answers to NSAC charge questions:

1. What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?

Final results from Cuoricino have been published in 2010, and until the more recent measurement by EXO and KamLAND-Zen, were the world's most stringent limits on the Majorana neutrino mass. There has been significant progress on the calculation of the nuclear matrix elements for $0\nu\beta\beta$ decays, which will reduce the uncertainty on the effective Majorana mass should $0\nu\beta\beta$ decays be observed. The new measurement of $0\nu\beta\beta$ rate in ¹³⁰Te by Cuoricino, as well as measurements of two-nucleon transfer reactions, provides a further set of constraints for the theoretical calculations.

2. What compelling and unique science is to be done in the next 5 years?

CUORE-0 will operate in the next two years, improving on the results of Cuoricino by a factor of 2-3. Its sensitivity to $0\nu\beta\beta$ will be competitive with the other currently running DBD experiments. CUORE will start operations in 2014, and will be one of the leading $0\nu\beta\beta$ experiments this decade.

3. What science would you expect to pursue in the program in 2020 and beyond?

CUORE, along with other $0\nu\beta\beta$ experiments, will continue the search for lepton number violation, and may answer the long-standing question of whether neutrinos are Dirac or Majorana particles. CUORE will reach the sensitivity to the effective Majorana neutrino mass of down to 40 meV, probing the inverted hierarchy region of the neutrino masses. R&D on ¹³⁰Te enrichment and techniques for active background rejection are expected to mature to the point where the experiment with the sensitivity to explore the inverted hierarchy region in its entirety can be proposed.

4. What is the international context, and how does it affect your vision?

A number of neutrinoless double-beta decay experiments with the sensitivity approaching the inverted hierarchy are being pursued worldwide. Multiple R&D efforts towards a ton-scale experiment are also being pursued in parallel. An experiment of such scale would require broad international collaboration, and the US is poised to play leadership role in several $0\nu\beta\beta$ efforts.