Experimental search of neutrino-less double beta decay in $^{130}$Te

Oliviero Cremonesi
INFN – Sezione di Milano Bicocca, Milano I-20126, Italy
E-mail: oliviero.cremonesi@mib.infn.it

Abstract. $^{130}$Te is one of the best candidates for the experimental search of neutrinoless double-beta decay. Thanks to its exceptionally large natural isotopic abundance $^{130}$Te represents the only isotope for which the use of isotopic enrichment is practically not indispensable. Furthermore pure tellurium metal can be procured in large amounts and radio-pure crystals of tellurium compounds are commercially available. Different experimental techniques have been envisaged and a number of tellurium based experiments have been proposed and are starting taking data or are in advanced phase of construction.

The status of current experiments is reviewed, outlining the factors characterizing their sensitivity and their role in the international competition. Future prospects and requirements are discussed.

1. Introduction

Experiments searching for neutrinoless double beta decay (NDBD) are attracting a lot of interest since they offer a unique opportunity to determine the Dirac/Majorana nature of neutrinos [1]. Indeed a direct observation of the decay would unambiguously demonstrate that neutrinos are massive Majorana particles providing at the same time a measurement of their absolute mass scale.

Based on the trend of the nuclear masses, only a limited number of nuclei are viable candidates for NDBD searches. Among them, only a few isotopes have the right features to guarantee the best sensitivities. Indeed, a simple argument shows that the experimental sensitivity can be parametrized as

$$T_{\text{exp}}^{0\nu} \propto \frac{\eta \cdot \epsilon}{A} \sqrt{\frac{M \cdot T}{\Delta \cdot B}}$$

where $\epsilon$ is the the detection efficiency, $\eta$ the isotopic abundance, $A$ the molecular mass, $M$ the detector mass, $T$ the observation time, $\Delta$ the energy resolution, and $B$ the background index (rate per unit energy and mass of the detector). Furthermore, ultimate goal of all the experiments is the measurement of the effective neutrino mass $\langle m_{ee} \rangle = \sum_k U_{ek}^2 m_k$ which is related to the observed NDBD lifetime by the relation $T_{\nu}^{0\nu} = G^{(0\nu)} |M^{(0\nu)}|^2 \left( \frac{\langle m_{ee} \rangle}{m_e} \right)^2 \equiv F^{(0\nu)} |\langle m_{ee} \rangle|^2$, where $G^{(0\nu)}$ is the phase space term and $M^{(0\nu)}$ is the nuclear matrix element (NME) of the transition, both of which can only be calculated. Although the nuclear factor of merit $F^{(0\nu)}$ shows only a weak dependence on the nuclear species [2], the strong dependence of the experimental sensitivity on the choice of the candidate nucleus is evident from eq. (1). Large masses, high efficiencies, and extremely low background levels are the big challenges common to all the experiments.
$^{130}\text{Te}$ is presently investigated with different experimental techniques. Some of them have already reached the maturity for a competitive experiment while others are still at the R&D level. Merits and limitations of the different approaches are reviewed together with a summary of the status of the art results.

2. Tellurium

An exceptionally large natural abundance (34.2%) makes $^{130}\text{Te}$ the only practical case for which the expensive and critical isotopic enrichment can be avoided. When coupled to a relatively high transition energy (2527.5 keV), in the middle of the gap between the Compton edge and the full energy peak of $^{208}\text{Tl}$ at 2615 keV, and to the possibility to get large samples of high radio-purity, the experimental interest for this isotope is evident. In the past, $^{130}\text{Te}$ has been the subject of a number of experimental searches with geochemical techniques. Since then, the need to pursue a direct measurement in order to get higher detection efficiencies has favored other isotopes (e.g. germanium and xenon) for which the homogeneous approach (where the detector acts at the same time as source of the decay) was possible. The development of the low temperature detectors and of the large mass scintillators has eliminated the restrictions on the choice of the detector materials and revived the interest on $^{130}\text{Te}$. In the meanwhile also the progress of the tellurium based semiconductors has broken down some of the initial limitations (e.g. crystal dimensions) and presently a number of experiments on NDBD of $^{130}\text{Te}$ has been devised in the homogeneous approach. Apart from the already competitive results of CUORE and the forthcoming start of SNO+, the promising results from a number of R&D projects increase the interest on tellurium for future NDBD searches.

3. Bolometers

The use of single particle bolometers for rare event searches has been introduced in the 80’s [3], mainly because of their excellent intrinsic energy resolution and the practical absence of any limitation on the choice of the detector materials.

The concept of these detectors is quite simple: when cooled down at very low temperatures (of the order of 10 mK), the heat capacity of a dielectric and diamagnetic crystal can be so low that even very small energy depositions (of the order of 10–1000 keV) can give rise to a measurable temperature increase. The structure of the detector is also very simple: a single crystal (absorber) in thermal contact with a heat sink (a cryostat) and a proper temperature sensor. The energy resolution of these devices is only limited by the statistical fluctuations of the phonons maintaining the thermal equilibrium with the heat sink ($\Delta = \sqrt{k_B C T^2}$). It does not depend on the deposited energy and can reach extremely low values. Actual detectors are still far from reaching this condition, and are still limited by a number “extrinsic” noise sources arising from instabilities the cryogenic system, electronics noise from the signal read-out chain, electromagnetic interferences and mechanical vibrations. Eventually, these contributions result in energy resolutions which for O(1 kg) bolometers can be as low as few keV in the MeV energy range. A value comparable to germanium diodes and still exceptionally better than many ionization or scintillation based detectors.

Tellurium dioxide ($\text{TeO}_2$) has been soon recognized as an ideal material for a bolometric experiment on NDBD given its good thermal performance and the existence of a well established industry for the production of large mass radio-pure crystals. After a number of initial experiments on single $\text{TeO}_2$ crystals of increasing mass, and the first small arrays of detectors developed in the 90’s by the Milano group [4], the tonne-sized experiment CUORE (Cryogenic Underground Observatory for Rare Events) was eventually proposed in 1998 [5]. Since then, two large scale prototypes (Cuoricino and CUORE-0) have been constructed and operated to demonstrate the feasibility of CUORE.
3.1. CUORE

CUORE is hosted in the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, in central Italy. The CUORE detector consists of 988 cubic TeO$_2$ crystals with natural $^{130}$Te isotopic abundance, 5 cm side and a 750 g average mass, operated as bolometers at very low temperature around 10 mK [6].

The 988 TeO$_2$ bolometers are arranged into 19 towers, each consisting of 13 floors of 4 detectors. The towers are arranged in a close-packed array and thermally connected to the mixing chamber of a $^3\text{He}/^4\text{He}$ dilution refrigerator (Leiden Cryogenics DRS-CF3000 continuous-cycle). The cooling of the system at intermediate temperatures ($\sim$40 K and $\sim$4 K) is based on five pulse tube cryocoolers (Cryomech PT415-RM) with a Joule-Thomson expansion valve. The dimensions, experimental volume ($\sim$1 m$^3$), mass ($\sim$17 t), and cooling power (3 μW at 10 mK) make this the largest and most powerful cryogen-free dilution cryostat in operation [7]. To minimize transmission of vibrations from the cryostat to the bolometers, the detector towers are independently supported by a Y-shaped beam that is vibrationally isolated from the cryostat support structure [8]. The cryostat and detector supporting systems, as well as the front-end electronics are located together in a Faraday Room [9] at the second floor of the CUORE underground building.

The commissioning of the cryogenic system was completed in 2015, followed by the installation of the detector in the summer 2016. The CUORE detector commissioning phase eventually started at the beginning of 2017. The initial two months were dedicated to the system optimization and setting of the optimal working points. In April 2017, although the optimization phase was not yet complete, CUORE was eventually ready for a preliminary science run (Dataset 1). A strategy based on alternated science and technical runs (aiming at optimizing the detector performance) was chosen for the first year of CUORE data taking. A second science run was therefore started on August 2017 (Dataset 2) after a summer optimization campaign.

The data from the first two datasets were released on October 2017 [10]. Main goal of these initial physics runs was to provide preliminary information on the parameters that most strongly affect the NDBD sensitivity: the energy resolution and the background index (BI) in the NDBD region of interest (ROI). Physics data were preceded and followed by calibration periods during which 12 Kevlar strings populated with low-intensity $^{232}$Th sources were temporarily deployed (from room temperature across the cryogenic volume) inside the detector region in order to guarantee an approximately uniform $\gamma$-ray illumination of the detectors [11].

A total of 984 over 988 detectors are functioning, but a smaller subset of channels was selected for analysis based on the overall quality of the event reconstruction.

A number of improvements to detector performance were obtained during the 2017 summer and fall optimization campaigns, mainly based on the synchronization of the pulse-tube cryocoolers and the grounding scheme of the readout electronics and the working point selection.

The data collected in the first two datasets amount to a total TeO$_2$ exposure of 86.3 kg·yr, characterized by an effective energy resolution of $(7.7\pm 0.5)$ keV FWHM and a background in the region of interest of $(0.014 \pm 0.002)$ counts/(keV·kg·yr). No evidence for NDBD of $^{130}$Te was obtained from the analysis of the collected data, corresponding to a lower limit on the decay half-life of $T > 1.3 \cdot 10^{25}$ yr (90% C.L.) including systematic uncertainties. Combining this result with those of Cuoricino and CUORE-0, a limit of $T > 1.5 \cdot 10^{25}$ yr (90% C.L.) is obtained, which is the most stringent limit to date. In terms of the effective Majorana neutrino mass, this corresponds to an upper limit of $\langle m_{ee} \rangle < (140–400)$ meV, where the range reflects the uncertainty on the nuclear matrix element estimates employed [10].

CUORE is the first tonne-scale cryogenic detector array in operation, more than an order of magnitude larger than its predecessors. The successful commissioning and operation of this large-mass, low-background, cryogenic bolometer array represents a major advancement in the application of this technique to NDBD searches and demonstrates the feasibility of future large-
mass bolometer arrays for rare-event searches.

3.2. CUPID

Common features of any next generation experiment are isotopic enrichment and active background rejection. Since the dominant background component in bolometric detectors is due to degraded alphas from surface radioactive contaminations [12], the discrimination of this component can imply a sensitive reduction of the background index.

This is the main goal of the CUPID (CUORE Upgrade with Particle Identification) program [13]. Indeed, as realized already in the 90’s, hybrid bolometric detectors based on the simultaneous detection of scintillation or Cerenkov light can accomplish this goal. A number of small R&D projects mainly aiming at the development of very sensitive (bolometric) light detectors have been proposed in recent years in the framework of CUPID [14] and the first kg-scale demonstrator, CUPID-0 based on isotopically enriched scintillating ZnSe bolometers, has been recently put in operation at LNGS [15]. Demonstrators for other promising scintillating crystals (e.g. LiMoO$_4$) are under preparation [16]. Since no viable tellurium compound has scintillating properties, the observation of the Cerenkov signal has been suggested in order to implement hybrid bolometric detectors. Here the challenge is the observation of the faint Cerenkov signal, which requires very sensitive light detectors with very low energy thresholds. In these framework, KID’s [17] and thermistors with Neganov-Luke effect [18, 19, 20] are the most developed light detectors with very promising results which show that the concept is proven and actual detectors are already at hand. A TeO$_2$ array demonstrator with Cerenkov light observation is anticipated in 2018.

4. Scintillators: SNO+

The dispersion of a NDBD candidate nucleus in a high purity scintillator has been proposed since the end of 90’s [21] as an effective way of exploiting the high purity environments of large scale neutrino detectors after the completion of the neutrino program of measurements. It has been recently implemented with success for $^{136}$Xe in the framework of the KamLAND infrastructure.

The transformation the SNO infrastructure in a large liquid scintillator-based experiment is the basic idea of SNO+ [22]. Initially devised for $^{150}$Nd, it has been later converted in a $^{130}$Te based NDBD experiment. The 12 m diameter acrylic vessel of SNO will be filled with about 780 tonnes of ultra-pure liquid scintillator (LABPPO) which will be loaded with 0.5% natural tellurium, corresponding to nearly 1300 kg of $^{130}$Te. The expected effective Majorana neutrino mass sensitivity is in the region of 55-133 meV, just above the inverted mass hierarchy lower bound. The possibility of deploying up to ten times more natural tellurium is under investigation. The physics program of SNO+ is however more rich and includes the study of reactor antineutrino oscillations, low energy solar neutrinos, and geoneutrinos, to be sensitive to supernova neutrinos, and to search for exotic physics.

SNO+ is located in Sudbury, Ontario, Canada. 2 km (6000 m.w.e) below ground where the total muon flux is less than $10^{-9}$ cm$^{-2}$s$^{-1}$. Besides using the same acrylic vessel (AV), SNO+ is also observed by the same 9300, 8 inch Hamamatsu R1408 photomultiplier tubes of SNO. The detector is housed in a cavity filled with ultra pure water.

The transformation of the SNO detector from a heavy water based detector to a liquid scintillator detector required a substantial amount of work and is now almost complete. As the LABPPO is less dense than water, a hold down rope system is needed during operation. The system was installed in 2012 and has been tested at various levels throughout commissioning. A new processing plant had been constructed to achieve the purity of the scintillator needed to ensure the low backgrounds required ($< 10^{-17}$ g/g). The plant is currently being commissioned with 40 tonnes of LABPP.
Telluric Acid (TeA) is stored underground since 2015. A full scale purification plant is now in construction underground. It will produce the final LAB+PPO+Te-ButaneDiol cocktail which will guarantee the expected initial 0.5% Te concentration. The nitrogen cover gas already existing on SNO and aiming to protect the detector from high levels of Radon gas in the mine air, has been upgraded and commissioned in 2014. As the light output of liquid scintillator is larger, the SNO+ electronics have also been upgraded. New XL3 readout cards as well as new MTC/A+ trigger cards will handle the increase in PMT hits. Also, the data acquisition system (DAQ) has undergone a complete renovation, with a complete decoupling of the data flow from detector controls. The original in situ LED/Laser optical calibration system has been completely redesigned in order to monitor the scintillator quality. It is expected to come online for scintillator phase. A substantial effort has been devoted to the update of the deployed calibration sources. Also this system is expected to be ready for the SNO+ scintillator phase.

SNO+ is currently filled with water. The detector electronics were switched on in early 2017 and are working properly. Both in situ and deployed source calibration is on going. When detector calibration will be complete, SNO+ will collect data to search for nucleon decay as well as characterising the state of the detector. In 6 months of running, SNO+ will set world leading limits on invisible nucleon decay.

Scintillator fill will follow. The Scintillator phase will build upon the work done in the previous phase and assess the background levels present in the detector. Reactor and Geo anti-neutrino studies will be undertaken in this phase, as well as low energy solar neutrino observations. With the background studies complete, $^{130}$Te loading is expected to begin in late 2018 [23].

5. Semiconductors: COBRA

Tellurium based semiconductors have well known features, with a number of applications in radiation detection [24]. With respect to germanium diodes, CdTe and CdZnTe devices suffer from a rather poor collection efficiency of holes which strongly limits the dimensions of the available detectors. With a proper readout electronics, large arrays of (very) small CdZnTe pixels can be a valid alternative with tracking capabilities which can help in strongly reducing the background contributions.

COBRA [25] is the only NDBD experiment based on CdZnTe detectors, and is planning to use a large amount of them, operated at room temperature, to search for NDBD. CdZnTe contains 9 NDBD candidate isotopes, including electron capture and positron decay modes. Two of them are tellurium isotopes ($^{130}$Te and $^{128}$Te), although the isotope with the highest Q-value (2813.50 keV) is $^{116}$Cd, which represents therefore the main target of the search. Indeed, the sensitivities for the other NDBD candidate isotopes are lower, given the lower Q-value and the unavoidable background coming from the $^{116}$Cd two neutrino double beta decays.

After a number of performance studies on small scale detectors, a demonstrator setup is operated at LNGS to investigate the experimental challenges of operating CdZnTe detectors in low background mode and to identify potential background components. The experiment consists of an array of 16 monolithic, calorimetric detectors of coplanar grid design (CPG detectors) of $1 \times 1 \times 1$ cm$^3$, arranged in four layers of $4 \times 4$ detectors. This setup has already demonstrated the high potential of pulse-shape analyses to reduce the background. Further improvements are expected by the use of the pulse-shapes and the coincidence analysis between multiple CPGs.

Furthermore, larger detectors ($2 \times 2 \times 1.5$) cm$^3$ are commercially available with a better surface-to-volume ratio. The final goal is to operate 11,000 of such detectors. With an enrichment of 90% in $^{116}$Cd, an energy resolution of better than 1.5% (FWHM) and a background rate of less than $0.5 \times 10^{-3}$ counts keV$^{-1}$ kg$^{-1}$ y$^{-1}$, COBRA should be able to reach a sensitivity of less than 50 meV on $\langle m_{ee} \rangle$. 
6. Conclusions

$^{130}$Te is still one of the most interesting NDBD isotopes. It currently shares with $^{76}$Ge and $^{130}$Xe the most sensitive experimental NDBD searches.

Two next generation tellurium based experiments have been constructed: the bolometric CUORE has started operation at LNGS early in 2017 while the SNO+ scintillator is expected to start the NDBD program late in 2018. Both of them aim at sounding the inverted hierarchy region of neutrino masses.

Promising results from a number of R&D’s show that significant improvements of the experimental sensitivities are possible making tellurium an excellent candidate for next generation experiments.

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