Women in Science – New Frontiers of Research

Is neutrino its own antiparticle?

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Neutrino is a neutral spin ½ particle, discovered through nuclear beta decay, that interacts only through the weak interaction. It is now well established that neutrinos have mass. The mass and nature of neutrinos play an important role in theories beyond the Standard Model. Whether neutrino is its own antiparticle, as proposed by Majorana, is still an open question. At present, neutrinoless double beta decay ($0\nu\beta\beta$) is perhaps the only experiment that can reveal the true nature of the neutrinos. Given its significance, there is a widespread interest in the quest for $0\nu\beta\beta$ employing different techniques. This article presents a brief overview of $0\nu\beta\beta$ experiments and highlights the indigenous effort to search for $0\nu\beta\beta$ in ^{124}Sn using a cryogenic bolometer at the India-based Neutrino Observatory.

Keywords: Antiparticle, cryogenic bolometer, double beta decay, neutrino.

Introduction

The existence of neutrinos was first proposed by Pauli[1] in 1930 to conserve fundamental quantities like momentum and energy in the nuclear beta decay process. He suggested that a massless or a very light neutral particle is produced together with the electron, which shares the transition energy, but escapes detection. The understanding of beta decay changed rapidly after the discovery of the neutron and was successfully explained by Fermi's theory of β-decay[2] with neutrino assumed to be a spin ½ particle. The first direct observation of the electron antineutrino from a nuclear reactor was made by Reines and Cowan[3], almost two decades later in 1956. Measurement of neutrino helicity followed soon thereafter[4].

In the Standard Model (SM), fundamental particles are quarks and leptons. The leptons are of three different flavours, namely (e, ν_e), (μ, ν_μ), (τ, ν_τ), each particle having its corresponding antiparticle. Lepton number, an additional quantum number assigned to leptons ($L = 1$ for particles and $L = -1$ for antiparticles), is conserved in the basic SM. Neutrinos are chargeless and interact only through the weak interaction; hence they are difficult to detect. Neutrinos are left-handed in the SM, while antineutrinos are right-handed. In 1937, Majorana[5] proposed that the neutrino can be its own antiparticle. In 1957, Wu *et al.*[6] discovered the non-conservation of parity in the β-decay, which proved that the helicity or handedness is not conserved in the weak interaction. Measurements of solar, atmospheric and reactor neutrinos have now conclusively shown that the neutrinos oscillate from one flavour (i.e. $\nu_e/\nu_\mu/\nu_\tau$) to an another[7]. Consequently, it is established that the flavour eigenstates ($\nu_e/\nu_\mu/\nu_\tau$) and mass eigenstates ($\nu_1/\nu_2/\nu_3$) of neutrinos are not identical, and neutrinos have non-zero mass. Although, the two mass-squared differences ($\Delta m^2_{\text{sol}}, \Delta m^2_{\text{atm}}$) are measured, the absolute mass of the lightest neutrino and mass ordering are not known. There are three possibilities for mass ordering of neutrinos:

Normal hierarchy:

$$m_1 < m_2 \ll m_3 \text{ with } m_2 \sim |\Delta m^2_{\text{sol}}|^{1/2} \text{ and } m_3 \sim |\Delta m^2_{\text{atm}}|^{1/2},$$

Inverted hierarchy:

$$m_3 \ll m_1 < m_2 \text{ with } m_1, m_2 \sim |\Delta m^2_{\text{atm}}|^{1/2},$$

Quasi-degenerate:

$$m_1 \approx m_2 \approx m_3 \text{ with } m_i \gg |\Delta m^2_{\text{atm}}|^{1/2}.$$

Importantly, the fundamental question regarding the nature of neutrinos: neutrino and antineutrino are distinct (referred to as Dirac fermions), or identical (referred to as Majorana fermions), is yet to be answered. The mass and nature of neutrinos (Dirac or Majorana) also play an important role in astrophysics and cosmology. In addition, CP violation in the leptonic sector is an open question in neutrino physics.

In 1935, Maria Goeppert-Mayer[8] pointed out the possibility of a double beta decay (DBD) process, i.e. transformation of a (A, Z) nucleus to its isobar (A, $Z + 2$) with the emission of two electrons and two antineutrinos

$$(A, Z) \to (A, Z+2) + 2\mathrm{e}^- + 2\bar{\nu}_e.$$

DBD is possible in a few cases, where single beta decay of a nucleus is forbidden either due to energy or spin. Figure 1 shows a schematic nuclear energy-level diagram for nuclei undergoing DBD. The Q value of the transition, $Q_{\beta\beta}$, is the difference between nuclear binding energies for decay to the ground state in the daughter nucleus. Maria Goeppert-Mayer also estimated the half-life for the DBD

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process to be ~10^{17} years. Soon after Majorana's theory, Racah[9] suggested that if the neutrino is a Majorana particle, there is a possibility of virtual annihilation of the two neutrinos in DBD leading to a neutrinoless double beta decay process ($0\nu\beta\beta$ or NDBD). The first attempt to calculate the $0\nu\beta\beta$ rates was made by Furry[10] in 1939. In 1952, Primakoff[11] calculated angular correlations and energy spectra of electrons for both DBD ($2\nu\beta\beta$) and NDBD ($0\nu\beta\beta$), providing an experimental signature for distinguishing the two processes. Both DBD and NDBD are second-order weak interactions as depicted in Figure 2, and hence are rare processes. The $2\nu\beta\beta$ process conserves lepton number (L), while the $0\nu\beta\beta$ process violates lepton number by two units ($\Delta L = 2$). After the discovery of neutrino oscillations, there is renewed interest in the study of NDBD. Presently $0\nu\beta\beta$, which can occur if neutrinos have mass and are their own antiparticles, is perhaps the only viable experiment that can tell us whether the neutrino is a Dirac or a Majorana particle. Moreover, $0\nu\beta\beta$ can provide information on the absolute effective mass of neutrinos and neutrino mass ordering (or mass hierarchy). Given its significance, there is a widespread interest in the quest for $0\nu\beta\beta$ employing different techniques. With the upcoming India-based Neutrino Observatory (INO) laboratory in the country, a multi-institutional effort to set-up a NDBD experiment has been initiated. This article presents a brief overview of $0\nu\beta\beta$ experiments, and highlights the indigenous effort to search for $0\nu\beta\beta$ in ^{124}Sn using a cryogenic bolometer.

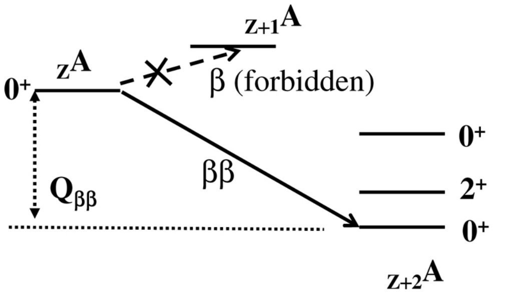

Figure 1. Schematic level diagram for double beta decay.

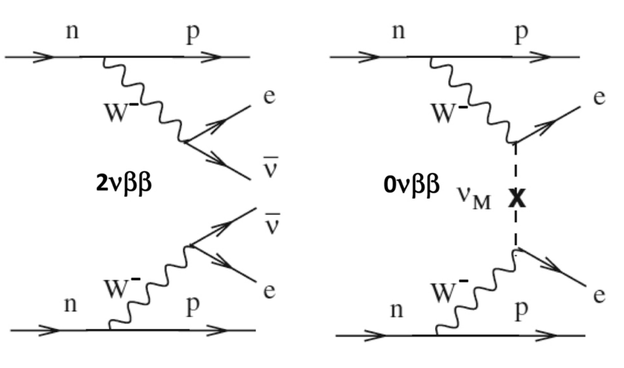

Figure 2. Feynman diagrams showing $2\nu\beta\beta$ (left panel) and $0\nu\beta\beta$ (right panel).

NDBD: experimental aspects and present status

The first geochemical observation of $\beta\beta$ decay in ^{130}Te was reported[12] in 1950. However, the direct experimental evidence for DBD came much later in 1987, when Elliot *et al.*[13] measured $2\nu\beta\beta$ in ^{82}Se. The decay rate, i.e. inverse of the lifetime, for DBD can be written as[14]

$$\frac{1}{T^{2\nu}} = G^{2\nu}(Q_{\beta\beta}, Z)|M^{2\nu}|^2,$$

where $G^{2\nu}$ is the phase space integral of four leptons emitted in the decay, and $M^{2\nu}$ is the nuclear transition matrix element (NTME) for this process. Similarly, decay rate of NDBD when mediated by virtual exchange of light Majorana neutrino can be expressed as follows

$$\frac{1}{T^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \, |\langle m_{\mathrm{ee}}\rangle|^2,$$

where $G^{0\nu}$ is the phase space integral for two electrons and $M^{0\nu}$ is the corresponding NTME. The effective Majorana mass of electron neutrino $\langle m_{\mathrm{ee}}\rangle$ is a linear combination of neutrino mass eigenstates. While the phase space integrals $G^{2\nu}$ and $G^{0\nu}$ can be calculated exactly, NTME is model-dependent. From the above equation it is evident that determination of the effective Majorana mass $\langle m_{\mathrm{ee}}\rangle$ will depend on NTME calculation, which requires an accurate knowledge of associated nuclear wave functions. Several models are employed for this purpose[15], and results show variation by a large factor (~10–50%). In order to get reliable estimate of NTME, it is important to constrain the parameters in nuclear models. With this view, experimental investigation of properties of nuclei involved in DBD is also being rigorously pursued (e.g. Gamow–Teller transitions in parent–daughter nuclei, transfer reactions, etc.)[16]. The $2\nu\beta\beta$ rate is also useful for verification of $M^{2\nu}$ calculations, which can be extended to $M^{0\nu}$ calculations for the same isotope. However, it should be mentioned that intermediate nuclear states involved in $2\nu\beta\beta$ and $0\nu\beta\beta$ processes are quite different. Hence, NDBD measurements in different nuclei are essential to overcome uncertainties in effective Majorana mass due to NTME calculations.

Experimental signature of observation of the $0\nu\beta\beta$ process is a peak at the $Q_{\beta\beta}$ value in the sum energy spectrum of the two emitted electrons. If a peak is observed, then for the measurement time $t \ll T^{0\nu}_{1/2}$, the half-life can be written as

$$T^{0\nu}_{1/2} = \ln 2 \frac{iN_{\mathrm{A}}Mt\varepsilon}{AN_{0\nu\beta\beta}},$$

where $iN_{\mathrm{A}}M/A$ is the number of $\beta\beta$ candidate atoms (i, isotopic abundance; N_{A}, Avogadro number; M, mass of detector), ε the detection efficiency and $N_{0\nu\beta\beta}$ is the number of observed $0\nu\beta\beta$ events. In the absence of a clear $0\nu\beta\beta$ signal, assuming a Gaussian approximation for the background fluctuation in the region of interest (ROI), a lower limit can be placed on $T_{1/2}^{0\nu}$

$$T_{1/2}^{0\nu} > \ln 2 \frac{i N_A \varepsilon}{A k_{CL}} \sqrt{\frac{Mt}{N_{bkg} \Delta E}},$$

where ΔE is the energy window corresponding to ROI of the $0\nu\beta\beta$ process and k_{CL} is the number of standard deviations corresponding to a given confidence level (e.g. 1.64σ for 90% CL). The N_{bkg} (keV^{-1} kg^{-1} year^{-1}) is the normalized background event rate per unit energy–mass–time, referred to as background index. From the above equation it is evident that to achieve high sensitivity in a DBD detector, it is important to have the following:

- Large source size (M), preferably with a high isotopic abundance.
- Large $Q_{\beta\beta}$, since phase space $\propto Q_{\beta\beta}^5$ for NDBD ($Q_{\beta\beta}^{11}$ for DBD). Further, $Q_{\beta\beta} > 2.6$ MeV is desirable as the energy ROI will be above the potential natural background lines.
- A low background index (N_{bkg}) – important and the most challenging aspect of a $0\nu\beta\beta$ experiment, which limits the sensitivity.
- Good energy resolution – critical due to the fact that the continuous spectrum of the $2\nu\beta\beta$ process is an inherent source of background for the $0\nu\beta\beta$ signal.
- High detection efficiency (ε) of two electrons.

The experiments aim to measure the simultaneous emissions of two electrons from the same vertex inside the source, and the constancy of the sum energy of the two emitted electrons. The experiments can be broadly divided into two groups, namely active or homogeneous experiments – where the detector material itself is made of NDBD source isotope, and passive or inhomogeneous experiments – where the source and detector are separate. The active detectors are mainly calorimetric detectors (HPGe, CdZnTe, TeO_2), which measure only the energy deposited by the electrons. They have good resolution, high detection efficiency and compactness, but the background reduction capabilities are relatively poor. However, in some cases, the possibility of electron track reconstruction and particle identification result in significant background improvement. In the case of passive detectors, the DBD isotope in the form of thin foils or loaded scintillator is surrounded by tracking detectors to reconstruct the full topology of DBD events. These detectors are usually limited by large size, modest energy resolution, low efficiency and self-absorption of the electron in source mass. However, the electronic discrimination of background and correlation measurements of emitted electrons is possible in tracking detectors. Further, the passive detectors enable measurements of multiple DBD candidates. Given the rare nature of DBD and NDBD processes, the measurements time extends to several years.

In order to achieve the desired experimental sensitivity, background reduction is crucial. Most of these experiments are located in an underground laboratory to reduce cosmic muon-induced background. The cosmic muons give rise to spallation neutrons and generate long-lived activities like ^{14}C ($T_{1/2} = 5700$ years), ^{7}Be ($T_{1/2} = 53.24$ days), ^{68}Ge ($T_{1/2} = 271$ days), ^{60}Co ($T_{1/2} = 1925$ days), ^{56}Co ($T_{1/2} = 78$ days). Underground storage of detector/shield material is essential to minimize cosmogenic activities. Radiopurity of source/detector and surrounding materials is of paramount importance. Natural radioactivity (α, β, γ) which arises from the primordial activities of U, Th decay chains and ^{40}K ($T_{1/2} \sim 10^{9-10}$ years) present in the rocks and surrounding materials are a major source of background. In particular, the high-energy gamma rays from various daughter products in the ^{238}U and ^{232}Th decay chain, like 2448 and 2615 keV, are a serious concern. Neutron background arises from the spontaneous fission of ^{nat}U, Th and from (α, n) reactions with light nuclei in materials as well as from muon-induced reactions. Surface contamination of the detectors can also produce background in the ROI due to degraded a particles or $\beta + \gamma$ events from U and Th chains. In fact, above 2.6 MeV the α-particles are the dominant source of the background. Typically, a detector is surrounded by active/passive layered shields for $n + \gamma$ and active muon veto. Segmentation of detector is also useful in identifying single versus multisite events. In addition, techniques like pulse-shape discrimination enable neutron/alpha/gamma identification. It is desirable to employ isotopically enriched source material to reduce size of the detector and minimize contributions from other isotopes. Typically background levels of ~10^{-2} counts keV^{-1} kg^{-1} year^{-1} or better are expected for NDBD experiments. Presently, the best background level achieved is in KamLAND-Zen[17] and is 1.5×10^{-4} counts keV^{-1} kg^{-1} year^{-1}.

A detailed discussion of both experimental and theoretical aspects of NDBD can be found in a review article by Cremonesi and Pavan[17]. There are 35 DBD candidates, of which 11 have $Q_{\beta\beta} > 2$ MeV. For only two cases, ^{48}Ca and ^{96}Zr, beta decay is allowed energetically but is strongly suppressed because of large spin difference ($0^+ \rightarrow 6^+$). Table 1 provides a brief overview of some of the major ongoing/proposed experiments with expected sensitivity. The existing and planned proposals worldwide show a rich diversity of approaches with many novel techniques involving different areas of research like low-temperature methods, nuclear and particle detection techniques, metallurgy, background reduction, and are well summarized in a review article by Cremonesi and Pavan[17]. Presently, the half-life of DBD (~10^{18} to 10^{24} years) is measured

Table 1. A brief summary of major ongoing and proposed $0\nu\beta\beta$ experiments. The best expected $\langle m_{ee}\rangle$ values are from review article of Barabash[29] for about 5–10 years of running time for full-scale detector

Experiment	Isotope	$Q_{\beta\beta}$ (MeV)	Technique	Expected $\langle m_{ee}\rangle$ (meV)
GERDA	^{76}Ge	2039.6	Semiconductor HPGe detector; good energy resolution and efficiency	15–35
MAJORANA	^{76}Ge	2039.6	Semiconductor HPGe detector; good energy resolution and efficiency	15–35
SuperNEMO	^{82}Se	2995.0	Tracking + calorimeter; good background rejection; possibility of DBD in multiple isotopes (^{150}Nd)	44–140
LUCIFER[17]	^{82}Se	2995.0	Scintillating bolometer; good energy resolution and efficiency	~76
AMoRE[30]	^{100}Mo	3034.0	Scintillating bolometer, good energy resolution and efficiency	20–60
MOON[31]	^{100}Mo	3034.0	Tracking + scintillator; background rejection	~100
COBRA	^{116}Cd	2802.0	CdZnTe Semiconductor detector; good energy resolution, particle ID	
CUORE	^{130}Te	2533.0	Cryogenic bolometer; good energy resolution and efficiency	50–130
EXO	^{136}Xe	2479.0	Liquid TPC, ionization + scintillation; high efficiency, Particle ID, daughter identification (^{136}Ba) proposed	14–33
KamLAND-Zen	^{136}Xe	2479.0	Liquid scintillator, ultra-low background	25–60

Table 2. Best present lower limits on $T_{1/2}^{0\nu}$ (at 90% CL) and $\langle m_{ee}\rangle$

Experiment	Isotope	$T_{1/2}^{0\nu}$ (years)	$\langle m_{ee}\rangle$ (eV)
NEMO-3 (ref. 32)	^{48}Ca	$>2 \times 10^{22}$	
GREDA-I (ref. 20)	^{76}Ge	$>2.1 \times 10^{25}$	0.25–0.62
NEMO-3 (ref. 33)	^{100}Mo	$>1.1 \times 10^{24}$	0.34–0.87
CUOROCINO (ref. 34)	^{130}Te	$>2.8 \times 10^{24}$	0.31–0.76
EXO-200 (ref. 35)	^{136}Xe	$>1.6 \times 10^{25}$	0.14–0.38
KamLAND-Zen (ref. 36)	^{136}Xe	$>1.07 \times 10^{26}$	0.061–0.165

in 12 nuclei[18]. In ^{100}Mo and ^{150}Nd, DBD to excited states has also been observed. No clear signature of NDBD is seen so far. Table 2 provides the best present lower limits on $T_{1/2}^{0\nu}$ and $\langle m_{ee}\rangle$. A claim for positive evidence of the $0\nu\beta\beta$ process in ^{76}Ge has been made[19]. However, this result was based on very low statistics and was controversial. The recent results from GERDA-I (ref. 20) clearly disfavour the earlier claim. It should be mentioned that other modes of DBD like $2\nu\beta^+\beta^+$, $2\nu\beta^+$EC, 2νECEC are also possible and are being pursued.

TIN.TIN

A feasibility study to search for $0\nu\beta\beta$ in ^{124}Sn based on cryogenic particle detector has been initiated in India[21]. The **IN**dia-based **TIN** detector (*TIN.TIN*) will be set up in the upcoming INO, an underground facility with ~1000 m rock cover all around[22]. The ^{124}Sn has moderate isotopic abundance ~5.8% and a reasonably high Q value of 2.29 MeV. Moreover, from nuclear physics perspective, $Z = 50$ proton shell is closed. In a calorimetric particle detector (bolometer), energy of the incident radiation is converted into phonons leading to a measurable temperature rise. In case of pure insulators and superconductors, specific heat falls-off rapidly at $T \ll 1$ K and these are good candidates for cryogenic bolometric detectors operating typically below 50 mK. The cryogenic bolometers with excellent energy resolution and high sensitivity, are well suited for rare event studies like NDBD or dark matter search. Tin becomes superconducting below 3.7 K and hence its specific heat has only phononic contributions below 100 mK. Very small size (~mg) Sn bolometers have been found to give good energy resolution at sub-Kelvin temperature[23]. *TIN.TIN* is multidisciplinary in nature and the ultra-low event rate involves many challenges like the enrichment of ^{124}Sn, background reduction and readout electronics for low-temperature measurements with good resolution.

A custom-built, cryogen-free dilution refrigerator, CFDR-1200, with a high cooling power of 1.4 mW at 120 mK, has been installed at TIFR, Mumbai[24]. The mixing chamber stage of CFDR-1200 has been designed with a large sample volume for accommodating ~100 kg mass (detector + low activity lead shield). A four-wire readout for 75 sensors and provision to mount electronics at ~50 K stage are also incorporated. A cryo-free refrigerator is preferred due to long measurement times and operations at remote underground location. The minimum base temperature of <10 mK has been measured using a calibrated cerium magnesium nitrate (CMN) thermometer. The CFDR-1200 is surrounded by a Faraday cage (made of galvanized iron mesh and copper foil) to minimize electromagnetic interference (EMI) noise. The proposed prototype of *TIN.TIN* would consist of natural/enriched tin detector elements (~3 × 3 × 3 cm^3 each) arranged in a tower geometry with corresponding readout sensors. The size of the detector element has been optimized for a measurable temperature rise and reduced granularity to minimize the number of readout channels.

In order to measure the temperature rise of the detector (~100 μK) with high precision, sensors with low specific heat, fast rise time and high temperature sensitivity are needed. For the *TIN.TIN* bolometer, neutron transmutation doped (NTD) Ge sensor is chosen as the thermal sensor. NTD Ge sensors are produced by irradiating Ge wafers with thermal neutrons in a nuclear reactor. The neutron transmutation results in uniform, controlled doping, and is preferred due to mass production and reproducibility. Indigenous development of NTD Ge sensor by irradiating Ge wafers in the Dhruva reactor facility at the Bhabha Atomic Research Centre, Mumbai has been initiated. The exposure to high neutron dose also results in the production of radioactive contaminants in NTD Ge sensors due to surface impurities and other sources, even if the starting material is of high purity. Such trace radioactivity in sensors can produce significant background for rare event studies like DBD. Detailed spectroscopic studies to identify and minimize radioactive impurities in irradiated Ge wafers have been carried out. It was found that chemical etching of ~50 μm thick surface layer removed most of the long-lived impurities[25]. A cool-down period of about 2 years is estimated to reduce activities below 1 mBq/gm. Further, annealing at 600°C for ~2 h is required to recover the fast neutron-induced damage during irradiation. The carrier concentration was experimentally determined from Hall effect measurement at 77 K, and was found to be consistent with that estimated from the reactor power data. The fabricated sensors have been characterized in the temperature range 100–350 mK. The temperature dependence of sensor resistance is found to be consistent with the variable-range hopping mechanism[26]. It is found that neutron fluence of $\sim 5 \times 10^{18}/\text{cm}^2$ is optimal for making sensors with desirable R and $\mathrm{d}R/\mathrm{d}T$.

Figure 3 shows the initial test pulses in Sn bolometer (~3 gm) with NTD Ge sensor using an alpha particle source. The observed pulses are characterized by a sharp rise time (~50 ms) and very slow decay time (~2 s). In addition to alpha particles, pulses from cosmic muons are also observed. Further tests are in progress.

As mentioned earlier, understanding the background is crucial for NDBD studies. The TiLES (TIFR Low Background Experimental Setup)[27] with a special low background HPGe detector has been set up at sea level in TIFR for radiation background studies. This low background HPGe detector is completely characterized with Monte Carlo studies using GEANT4 simulations. The detector model has been optimized for measurements over a wide energy range and for different source geometries. The HPGe detector is surrounded by a low-activity copper (5 cm) + lead (10 cm) shield with cosmic veto and nitrogen flushing. Figure 4 shows a photograph of the set-up together with the ambient background spectrum in TiLES, with and without shield. The best background levels possible at sea level have been achieved in TiLES, and sensitivity of ~2 mBq/gm for ^{40}K and ~1 mBq/gm for

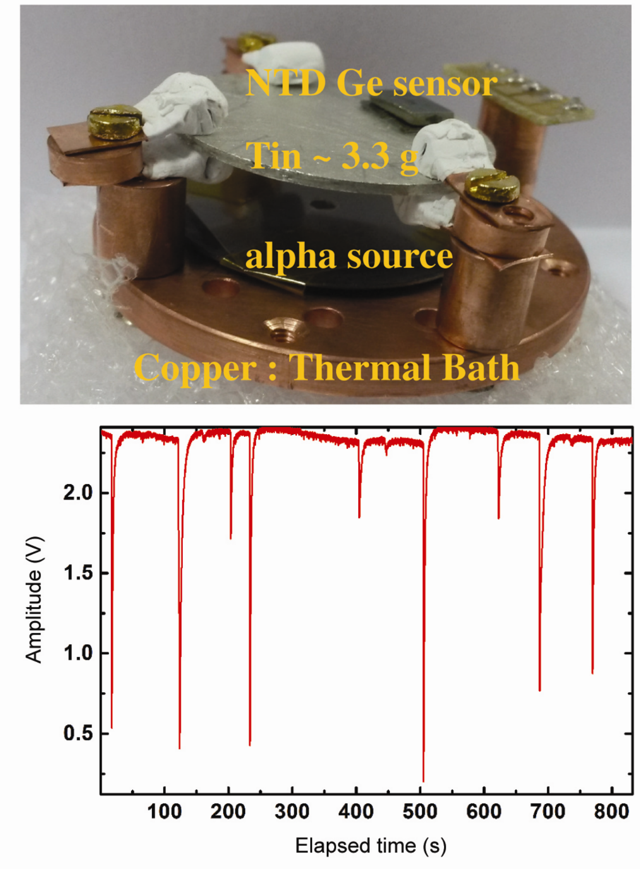

Figure 3. Photograph of bolometer test set-up (top panel), and energy pulses (bottom panel).

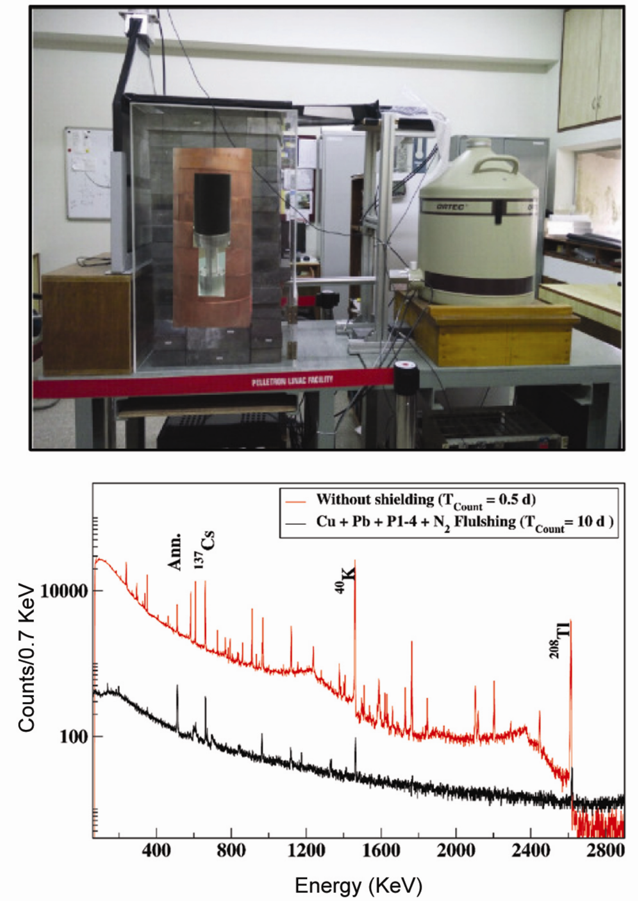

Figure 4. Photograph of TiLES (top panel), and ambient background spectrum (bottom panel).

^{232}Th has been obtained for impurity measurements. TiLES is used for pre-qualification/selection of radiopure materials for the cryogenic bolometer set-up. The rock sample from INO site was found to have considerably high level of ^{40}K (1050(16) mBq/gm). The Sb impurity in NTD Ge at ~100 ppt level has been measured[25]. Further, DBD of ^{94}Zr to 2_1^+ excited state of ^{94}Mo at 871.1 keV has been studied in TiLES and significantly improved half-life limit, $T_{1/2} > 2 \times 10^{20}$ years at 68% CL has been reported[28] with 232 gm-year exposure.

It should be mentioned that there is strong effort in India for NTME calculations relevant to $\beta\beta$ and $\beta^+\beta^+$ DBD. The NTME calculations for NDBD in ^{124}Sn are in progress by our collaborators. Also, the NDBD experiment has synergy with the proposed dark matter experiment at INO-DINO.

Summary

The NDBD search is entering a new era of large-scale interdisciplinary experimentation. The next-generation NDBD experiments are expected to reach sensitivity of 10 meV, which will allow us to probe the degenerate or inverted mass hierarchy. However, for normal hierarchy ($\langle m_\nu \rangle < 10$ meV), a new approach will be required. With the upcoming underground laboratory at INO, a feasibility study for cryogenic *TIN* bolometer to search for NDBD in ^{124}Sn ($Q = 2.29$ MeV) has been initiated. Since *TIN* becomes superconducting below 3.7 K, its specific heat becomes very small at $T < 100$ mK and enables the use of Sn as a bolometric detector. The R&D on prototype development of ^{nat}Sn is in progress. A large-scale detector ~100 kg, up-scalable to 1 tonne, is envisaged at the underground laboratory at INO.

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