EPJ Web of Conferences 66, 08005 (2014)
DOI: 10.1051/epjconf/20146608005

Search for neutrinoless double beta decay in ^{124}Sn

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Abstract. The mass and nature of neutrinos play an important role in theories beyond the standard model. The nuclear β decay and double beta decay can provide the information on absolute effective mass of the neutrinos, which would represent a major advance in our understanding of particle physics. At present, neutrinoless double beta decay (0νββ) is perhaps the only experiment that can tell us whether the neutrino is a Dirac or a Majorana particle. Given the significance of the 0νββ, there is a widespread interest for these rare event studies employing a variety of novel techniques. An essential criterion for detector design is the high energy resolution for a precision measurement of the sum energy of two electrons emitted in 0νββ decay. The low temperature bolometric detectors are ideally suited for this purpose. In India, efforts have been initiated to search for 0νββ in ^{124}Sn at the upcoming underground facility of India based Neutrino Observatory (INO). A custom built cryogen free dilution refrigerator has been installed at TIFR, Mumbai for the development of Sn prototype bolometer. A base temperature of 10 mK has been achieved in this setup. This paper gives a brief description of efforts towards Sn bolometer development.

1 Introduction

The mass and nature of neutrinos play an important role in theories beyond the standard model. The nuclear β decay and double beta decay (DBD) can provide the information on absolute effective mass of the neutrinos, which would represent a major advance in our understanding of particle physics. Maria Goeppert-Mayer predicted DBD process with $T_{1/2}\sim 10^{17}$ years [1] and it was suggested by G. Racah that neutrinoless double beta decay (0νββ or NDBD) can be used to probe the true nature of neutrino [2]. Presently 0νββ, which can occur if neutrinos have mass and are their own antiparticles, is perhaps the only experiment that can tell us whether the neutrino is a Dirac or a Majorana particle. Further, 0νββ can provide the information on absolute effective mass of the neutrinos. After the discovery of neutrino oscillations, there is a renewed interest in study of NDBD. Given the significance of the 0νββ, there are several ongoing and proposed experiments worldwide employing a variety of novel techniques [3, 4]. In India, a feasibility study to search for 0νββ in ^{124}Sn has been initiated [5-7]. The TIN.TIN experiment (The INdia's TIN detector) will be housed at India based Neutrino Observatory (INO), an underground facility with ~ 1000 m rock cover all around [8]. The ^{124}Sn has moderate isotopic abundance ~5.8% and a reasonably high Q value of 2.28 MeV. Since the constancy of sum energy of two electrons defines the NDBD event, good energy resolution is of

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paramount importance. Cryogenic bolometers with excellent energy resolution and high sensitivity are well suited for search of 0νββ. Tin becomes superconducting below 3.7 K; at T<100 mK its specific heat has only lattice contributions and can be made into a bolometric detector. Very small size (~ mg) Sn bolometers have been found to give good energy resolution at sub-kelvin temperature [9, 10]. This talk gives an overview of development of a prototype tin cryogenic bolometer, NTD Ge sensors for mK thermometry and radiation background studies. The proposal for a large scale experiment at INO is also presented. It should be mentioned that one of the main challenges is enrichment of ^{124}Sn.

2 Development of Tin cryogenic bolometer

Typically bolometers are operated well below 50mK. Continuous cooling at such low temperature is achieved using dilution refrigerators. A custom built cryogen free dilution refrigerator, CFDR-1200, with a high cooling power of 1.4 mW at 120 mK, has been successfully installed and tested at TIFR, Mumbai [11]. Given the long time scale of 0νββ experiment and remote location of underground laboratories, the cryogen free dilution refrigerator is preferred instead of conventional wet system that uses liquid helium supply. The lowest minimum temperature of 7 mK, measured with CMN thermometer was achieved without any external heat load on the system. With top loading probe inserted, the base temperature is measured to be 12.2±0.05mK, stable within 0.5%. Figure 1 shows a photograph of this test setup at TIFR.

Figure 1. The CFDR-1200 set up at TIFR for Sn bolometer development

The sensitivity of the 0νββ experiment is crucially dependent on the minimization of background radioactivity. Therefore, it is essential that material surrounding the detector elements should be as radio-pure as possible. However, radiation levels from the cryostat material might be higher than the tolerable sensitivity requirement and hence a bulk shielding is necessary inside the cryostat [12]. Thus, a provision for additional low activity shielding inside the cryostat is also incorporated in the design. The detectors will be surrounded by a 5cm thick low activity lead, cooled to 10 mK, to shield them from the background events arising from the cryostat as well as ambient background. The mixing chamber is capable of supporting 100 Kg weight and has a cylindrical sample space of 300 mm x 300 mm.

It is envisaged that the prototype stage of TIN.TIN detector will consist of an array of small Sn crystals (natural/enriched of 3 x 3 x 3 cm^3) arranged in tower geometry with corresponding readout sensors. Figure 2 shows the variation in detector element size as a function of base temperature for $\Delta T \sim 100\ \mu K$ corresponding to 2 MeV energy deposition. Size of detector element has been optimized for a measurable temperature rise and reduced granularity to minimize number of readout channels. Latter is also important as increased number of sensors correspond to larger surrounding material (connecting wires etc.) which can contribute to the background.

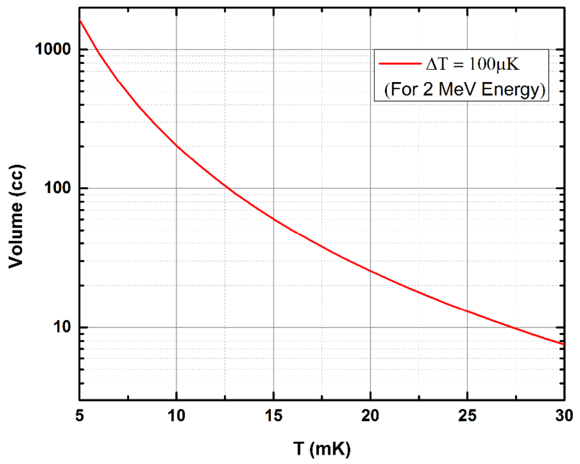

Figure 2. Detector element size as a function of base temperature for desired ΔT

It is also possible to use hit multiplicity (M) to discriminate between electron (M=1) and gamma rays ($M \geq 1$). Figure 3 shows simulation results for different element sizes for M=2 hits as a function of gamma ray energy inclusive of full or partial energy deposition. At 2.5 MeV, gamma background can be rejected by 40-60%, depending on the element size. It should be mentioned that two electron events from surface, expected to be a small fraction, may also yield M=2.

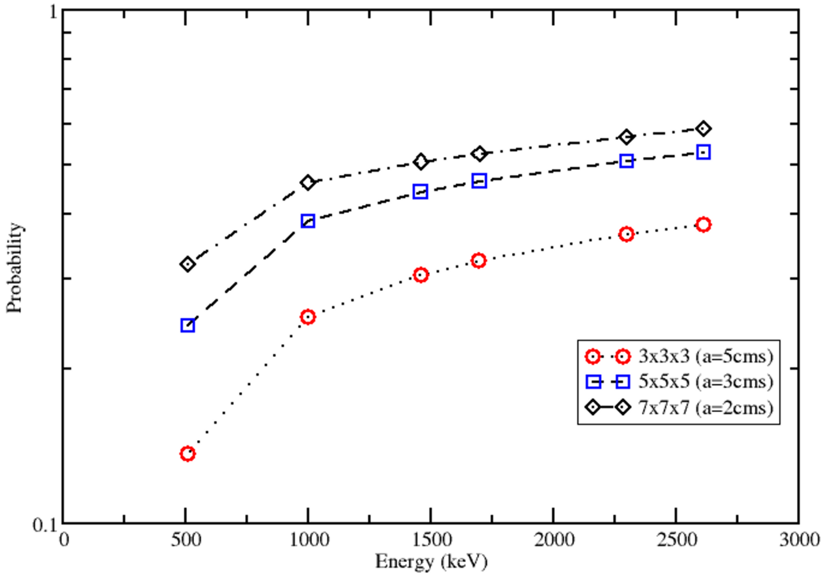

Figure 3. Probability for M=2 events as a function of energy for different element sizes.

2.1 Measurement of Heat Capacity of tin at ultra-low temperature

Although tin micro-calorimeters [9] have shown excellent energy resolution, large size tin bolometers have not yet been made. It has been reported that the relaxation time constant in superconducting material is longer than expected, which degrades the energy resolution. This can either be due to the long lifetimes of quasi-particles in superconductors or due to anomalous heat capacity at low temperature due to some impurities. It is also quite well known that a small amount of impurity can give rise to high specific heat at these low temperatures. Hence it is important to investigate the heat capacity of these samples at low temperature to check if anomalous specific heat affects the energy resolution.

A dedicated setup is made for measuring extremely small heat capacity (~100 μJ/K) of superconductors at low temperature and is mounted on the top loading probe insert which goes to the base temperature of the CFDR-1200. This setup consists of a Tin platform (0.8138g, 99.999% pure polycrystal) supported by insulated NbTi wires inside a copper box. A NiCr chip resistor (100 Ω) is used to supply the heat pulse and a commercial Dale ruthenium oxide chip resistor (1 kΩ at room temperature) sensor is used for temperature measurement (100-400 mK). Both the chip resistors are stuck to the tin platform using araldite and are also connected using bare NbTi wires. Current to the heater is supplied by a Keithley 220 programmable current source, while AVS47B A.C, resistance bridge is used to measure the change in the resistance. Heat capacity of three different masses of 5N purity Tin (1.7543 g, 2.8448 g and 1.7382 g) is measured using the above setup. To extract the specific heat, the difference of heat capacities for two different samples is normalised by the mass difference of the two samples. This ensured that the heat capacity of the addenda and any other systematic error is properly eliminated. The heat capacity of tin samples has been measured in the temperature range of 120 to 400 mK using relaxation calorimetric technique The specific heat obtained is shown in the Figure 4 and is consistent with the reported value in the literature within 5% [13, 14]. The Debye temperature obtained for Tin is 197 K while that reported in literature is 200 K. Further, it can be seen from the figure that within measurement errors no difference is found between the heat capacity of a polycrystal and a single crystal sample. The same technique is being used to extend measurements to T<100 mK as well as to other superconducting bolometer candidates.

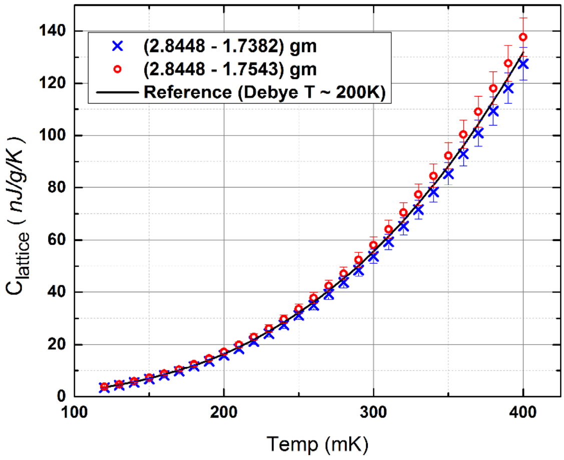

Figure 4. Measured specific heat for polycrystal and singe crystal tin. Data using Debye temperature from Ref. [14] is also shown for comparison.

3 Development of NTD sensors

In a cryogenic bolometer, energy deposited by incoming radiation is detected through the resultant temperature increase. Thus, it is essential to have low temperature sensors with very good resolution and sensitivity. Moreover, as this involves pulse detection, the sensor should have fast rise time. Neutron Transmutation Doped (NTD) Ge/Si sensors are well suited for mK measurements and are widely used [15]. The NTD sensors have low specific heat and hence fast rise time, high dR/dT-which can be adjusted by doping levels and are found to show good reproducibility. The NTD Ge sensors are produced by irradiating with the thermal neutrons in a reactor, which yields a uniform doping. Semiconductor grade Ge crystals (<111> cleavage plane, 0.4 mm thick) of size 10mm x 10mm are irradiated with a reactor neutron exposure corresponding to thermal dose of 0.9-1.65 x 10^{19} at Dhruva reactor, BARC (India). After an initial cool-down period of 45 days, samples are counted in low background counting facility at TIFR. In addition to the gamma rays of interest, ^{109}Ag and ^{181}Ta impurities are also present at ppb level. The VI characteristics of one of the irradiated samples has been measured in the range 30-300 K and is shown in the Figure 5, clearly illustrating the Ohmic contacts.

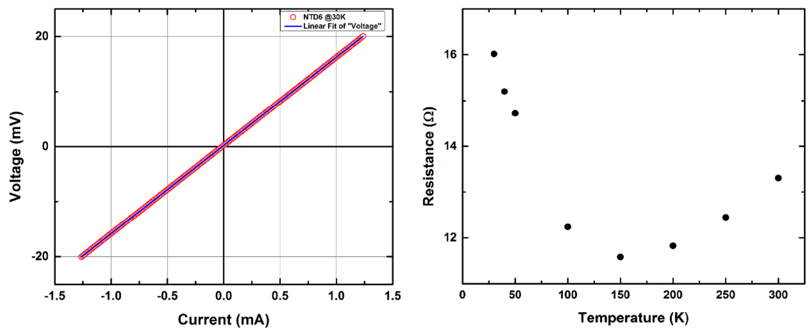

Figure 5. VI characteristics of one of the irradiated samples at 30 K (left panel) and R vs T (30-300 K)

It should be noted that during the irradiation the Ge crystal is also exposed to fast neutrons, which can create defects and can affect the performance of sensors. Defects in NTD Ge sensors due to neutron irradiation are investigated using Positron Annihilation Lifetime Spectroscopy (PALS) and channeling, which are expected to give complementary information. The defect studies are carried out in 3 sets of samples, namely, virgin sample (unirradiated), irradiated sample (without annealing) and irradiated sample after annealing at 600^0 C for 2 hours in Ar atmosphere.

In a defect free crystal, the β^+ interacts with a valance electron and annihilation leads to two 511keV γ-rays. In presence of defects the β^+ can remain trapped in the defect due to the strong repulsive force from core ions and the observed β^+ lifetime (τ) will be longer. The PALS measurement has been carried out with a ^{22}Na source sandwiched within two identical Ge samples (virgin/irradiated), mounted between two plastic scintillators in a face to face geometry. Measured τ for the virgin sample is consistent with that of the bulk Ge crystal (228 ps) [16]. For the irradiated sample, τ~293.6 ps, indicates *monovacancy* type defects. As positrons undergo saturation trapping, exact defect concentration cannot be inferred and is estimated to be ~0.1%. The τ~225.6 ps observed for the annealed sample is very similar to that of the virgin crystal, clearly implying that defects are cured after annealing.

The crystal channeling is sensitive tool for probing interstitial and strain related defects [17]. The channeling experiment with 2MeV alpha particles has been carried out using PARAS facility at IUAC [18], using Rutherford back scattering (RBS) at a scattering angle of 170^0. The beam current is kept lower than 10 nA to minimize the damage. Figure 6 shows an axial scan of virgin and irradiated Ge samples. No significant change in the channeling dip, either in the minimum yield or the width of the dip, is visible within measurement errors. Therefore, the NTD Ge samples after annealing are good for sensor fabrication and further work is in progress.

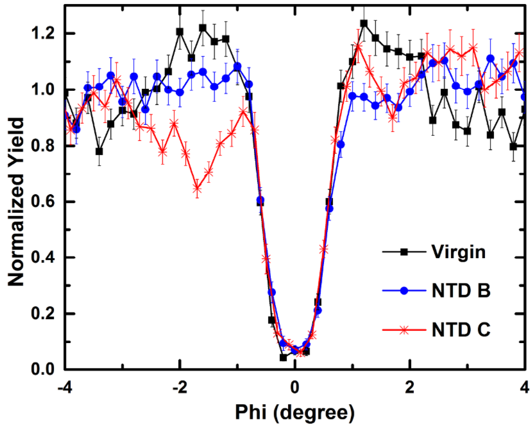

Figure 6. A comparison of angular scans (channeling dips) for virgin and irradiated Ge samples

4 Low background HPGe setup

The background understanding and minimization is critical in improving the sensitivity of the 0νββ measurement where $T_{1/2}>10^{24}$ yrs. The major sources contributing to the background are: the radioactivity from natural decay chains of U, Th ($T_{1/2}\sim10^{10}$ years), the radioactive trace impurities in the materials surrounding the detector, the primordial elements like ^{40}K, the cosmic ray muons and muon-induced reactions, neutrons and neutron-induced reactions, etc. A low background counting facility with a high efficiency, Ortec make HPGe detector with a carbon fibre window is set up at TIFR. Both the detector and cryostat are made of low background material with a very long cold finger that permits shielding of the detector from all sides. The detector is shielded from gamma rays from surroundings with low activity lead (<0.3Bq/kg). It is proposed to add high purity copper shield inside the lead shield. The background level achieved with 10 cm thick lead shield in all directions is about 4 cts/keV/day in the $Q_{\beta\beta}$ region of ^{124}Sn (2.2-2.3MeV). This setup is currently used for qualifying various materials to be used in and around the Sn cryogenic bolometer and NTD Ge sensors. Figure 7 shows a typical background spectrum with and without shield.

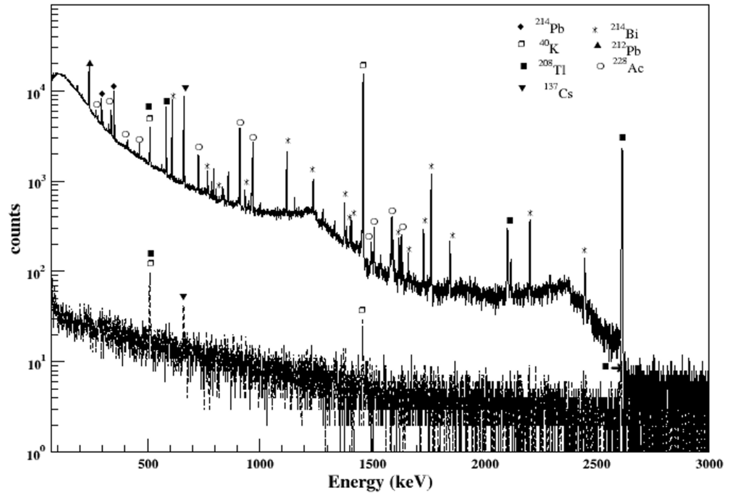

Figure 7. A typical background spectrum with (dashed line) and without shield (solid line)

In order to count low activity samples with different geometrical configurations in a close geometry, complete response model of the detector is required. The detector model is generated using Monte Carlo simulations and by optimizing detector dimensions to match detection efficiency and peak shapes over energy range of interest. We have carried out detailed measurements using several single line calibrated sources like ^{241}Am, ^{57}Co, ^{65}Zn, ^{54}Mn and ^{203}Hg, covering a wide energy range of 60 to 1000 keV. Absolute efficiency measurements have been carried out over entire detector face by moving the source in radial and lateral directions at a distance (d) of 5mm from the face of the detector. Measurements in far geometry, d = 5 to 25 cm, are also done. Efficiency at varying distances is also measured for liquid source of ^{137}Cs in a cylindrical case, for simulating extended source response. Detailed MC simulations using Geant4 [19] have been carried out and various detector parameters of the HPGe crystal like radius, length, dead layer on top and side, central hole length, hole diameter, end-cap to detector distance are optimized by making a best fit to the experimental data. The active volume of the optimized detector is ~230 cc as compared to 288cc supplied by the manufacturer and is in very good agreement with measured efficiencies [20]. As mentioned in the previous section, NTD Ge are counted in the low background setup in a close geometry, to identify and to estimate impurity concentration. It is proposed to study DBD to excited states in some nuclei like ^{94}Zr (~17% abundance, E_γ = 871 keV) using this low background setup.

One of the major sources of background NDBD is neutron-induced reactions. We have therefore initiated neutron (thermal and fast) induced background studies in ^{nat}Sn and ^{124}Sn. In addition, we propose to study neutron induced reactions in ^{nat}Cu which is the cryostat material, ^{nat}Zr and other related materials. For fast neutrons, obtained using p+^{9}Be reaction, the (n, γ) and (n, 2n) are dominant channels. This indicates the necessity of having final stage of tin processing as well as storage in the underground location, to minimize neutron exposure.

5 Summary

With the upcoming underground laboratory at INO, a feasibility study for cryogenic tin bolometer to search for NDBD in ^{124}Sn (Q = 2.28 MeV, 5.8% abundance) has been initiated. Since tin becomes superconducting below 3.7 K, at T <100 mK its specific heat has only lattice contributions. The low specific heat enables use of Sn as a bolometric detector. The R&D on prototype development of ^{nat}Sn (~ 1 Kg) is in progress. The efforts are also underway for precise measurement of $Q_{\beta\beta}$ value in ^{124}Sn. The present limit in literature for $T_{1/2}$ of DBD in ^{124}Sn is 0.8-1.2 x 10^{21} years [21]. The preliminary NTME (Nuclear Transition Matrix Element) calculations of Rath et al. [22] give F_n~8.569x10^{-13} yr^{-1} with PFHB (Projected Hartree-Fock-Bouglebov) and ~1.382 x10^{-13} yr^{-1} with SM (Shell Model). Assuming 0.5% energy resolution with a background of ~ 0.01 cts/kev/yr (similar to Cuore) [23], the sensitivity of a large detector of ~1 ton (90% enrichment) is estimated as m_ν~ 50-100 meV in one year observation time (PFHB and SM, respectively). A proposal for laboratory at INO to house a ton scale detector with suitable infrastructure has been made. One of the main challenges is enrichment of ^{124}Sn and different options are being explored.

6 Acknowledgement

The development of TIN.TIN prototype is a multi-institutional project with several institutions in India like TIFR, BARC, IIT -Ropar, Univ. of Lucknow, VECC and PRL participating presently. I am grateful to all TIN.TIN collaborators for their help & contribution and to the INO collaboration for their support.

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