Feasbility Study of Neutrinoless Double Beta Decay in ^{124}Sn

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The mass and nature of neutrinos play an important role in theories beyond the standard model. The nuclear beta decay and double beta decay can provide the information on absolute effective mass of the neutrinos. 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 are many planned and proposed experiments worldwide. The present talk gives an overview and the current status of the subject. With the upcoming INO laboratory in India, a multi-institutional effort to carry out an underground 0νββ experiment has been initiated.

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 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 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 are nearly 30 planned and proposed experiments worldwide [1]. While the half-life of 2νββ decay has been already measured for about ten nuclei (out of 35 possible candidates) [2] the only positive evidence for the 0νββ decay so far has been reported by the Heidelberg-Moscow experiment for ^{76}Ge [3]. However, this result is based on very low statistics and further experiments are needed. It should be noted that the first results from CUORICINO report no evidence for 0νββ in ^{130}Te and only lower limit has been placed [4].

The existing and planned proposals to search for 0νββ show a rich diversity of approaches with many novel techniques involving different areas of research. These experiments can be divided in two groups - active source, where the source itself serves as a detector and passive source, where the source and the detector are different. As these events are expected to be rare, both source and detector have to be large in size. Therefore active source experiments with candidates having large isotopic abundance are preferred. The half-life of 2νββ (0νββ) decay, is a product of accurately known phase space factor and the appropriate nuclear transition matrix element $M_{2\nu}$ ($M_{0\nu}$). One of the main considerations for a 0νββ candidate is the high Q value, since the decay rate is proportional Q^5 and the interference from natural radioactive background is less at higher energies.

The presently running 0νββ experiments have typical source sizes less than 100 Kg, while many of the proposed experiments, either new or upgrades of the presently running counterparts, are expected to have much better sensitivity primarily due to larger source sizes (~ ton). Since the constancy of sum energy of two electrons defines the event, good energy resolution is of paramount importance. Of various existing and proposed experiments, the CUORE experiment (^{130}Te) [5], the only low temperature bolometric detector so far, and the Ge experiment [6] have the desired energy resolution (~0.5% and 0.2%, respectively).

Indian effort towards NDBD

After reviewing various existing as well as proposed experiments worldwide and keeping in mind the necessity of high energy resolution, ^{124}Sn (Q = 2.28 MeV, 5.8% abundance) was identified as a candidate for a feasibility study of cryogenic bolometer of NDBD at INO. It is important to note that ^{124}Sn being a spherical, closed shell nucleus, its structure is well studied and better understood. Hence the $M_{0\nu}$, another crucial factor for extracting the neutrino mass from measured decay rate, is expected to be calculated with better accuracy. Therefore, the Indian community decided to focus on the Feasibility Study of Neutrinoless Double Beta Decay in ^{124}Sn, as one of the projects at INO [7,8].

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. Very small size (~ mg) Sn bolometers have been found to give good energy resolution at sub-kelvin temperature [9].

We have initiated the feasibility study of neutrinoless double beta decay ($0\nu\beta\beta$) in ^{124}Sn. This is multidisciplinary in nature and involves several scientific as well as engineering challenges. Presently, we have refurbished an old ^{3}He-^{4}He dilution refrigerator, rated for a cooling power of 20 μW at 100mK with a minimum achievable temperature of 50mK. We have modified interconnecting line with suitable isolation valves to make the ^{3}He circuit failsafe and render proper isolation for top loading sample insert. The temperature sensors in the old setup at various stations were meant only for diagnostic purposes and hence not suitable for accurate temperature measurements. We have modified the dilution refrigerator thermometry to read accurate temperature using 4-probe measurement. The electronic equipments needed for milli-Kelvin thermometry, namely, high resistance measurement set up at different cooling stages of the refrigerator, have been installed for this purpose. A Labview based interface has been developed for remote measurements. We have achieved a base temperature of around 50 mK at the mixing chamber of the Dilution unit. The temperature so achieved was fairly stable over a long period of time. An exercise to estimate the cooling power at different temperature was carried out by supplying heat to the mixing chamber (see Figure 1).

The sensitivity of the bolometer depends on its heat capacity, weak heat link that brings about the relaxation and thermalisation time within the detector as well as the sensor equilibration time. Low temperature measurements are very difficult because all parameters (resistances, specific heat, thermal conductivity) change by several orders of magnitude in temperature range of interest (20 – 200 mK). Many aspects like sensor mounting, design of thermal links need several trials to optimize.

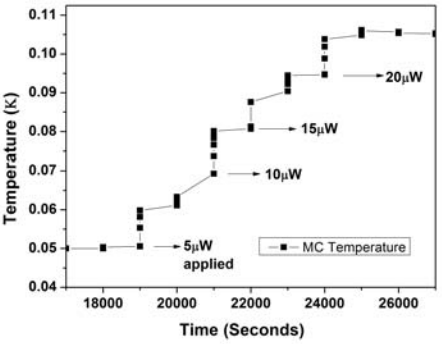

Figure 1: Measurement of cooling power as a function of base temperature.

Further, since the measurements are carried out at low power (low current/low voltage), they are very sensitive to noise pickup. Major challenge in these measurements is to reduce the RF and EMI noise, and a considerable effort has been devoted to improve noise conditions of the readout system. The vibration isolation is also of paramount importance and novel techniques need to be implemented. Another important factor that needs to be taken into consideration is the effect of thermal equilibrium on different geometries of detector modules.

Development of NTD Ge sensors for low temperature measurement has also been initiated. We plan to irradiate commercially available device grade Germanium wafers (2 inch dia, 400 micron thick with resistivity ~ 30 Ω-cm) with thermal neutrons (~10^{17}-10^{19} /cm^2) in a reactor at BARC.

Initially, we propose to make a prototype bolometric detector of natural Sn of mass 0.5-1 Kg. This will also serve as a test bench for qualifying mK thermometry. The present limit in literature for $T_{1/2}$ for ^{124}Sn is 6 x 10^{18} years [10].

In this experiment, the expected events are rare since the half-life for the decay is $\geq 10^{25}$ years. The sensitivity of detector is critically dependent on the reduction of background. It is therefore essential to have an understanding of various issues related to the background prior to the designing a setup. The cosmogenic background is significantly reduced in underground laboratories, but the decay of radioactive trace impurities present in the detector and in surrounding material also contributes to the background. It is essential to discriminate these background gamma-ray events from electron events of interest. Unlike electrons, photons would typically interact with more than one detector element. Hence, by using the multiplicity information from a segmented array the e-γ discrimination can be achieved, in a limited manner. We have therefore carried out the simulations using GEANT4 to study the background resulting from gamma ray interactions for different crystal configurations The simulation results indicate that the 3x3x3 cm^3 crystals with a minimum inter-detector spacing would be preferable for the prototype module, to operate in the temperature range of 10−15 mK [11].

We have set up a low background counting laboratory at TIFR with 70% HPGe detector specially housed in low background cryostat (ORTEC make) for characterization of materials and background studies.

Since natural abundance of ^{124}Sn is only ~ 5.8%, it is essential to have isotopically enriched radiopure Sn for the large size detector detector. The R&D towards ^{124}Sn enrichment using laser based techniques will be undertaken by TIFR-BARC collaborators [12].

Proposed NDBD laboratory@INO:

Based on preliminary NTME calculation of Rath [13] of F_n~2.754x10^{-14} yr^{-1} for ^{124}Sn and assuming 0.5% energy resolution with a background of ~ 0.2 cts/kev/yr, similar to Cuoricino, we estimate that a large detector of ~1 ton will be needed to be housed at INO underground laboratory to achieve a sensitivity of $m_ν$~ 200 meV in 1 year observation time. Suppression of cosmogenic and ambient background at underground laboratory, using both active and passive shielding will have to be taken into consideration. It is also proposed to have underground laboratory for preparation of bolometer crystals (high purity material processing, crystal growth, polishing, cutting storage etc. and mounting). This is essential to minimize the contamination due to n-induced reactions in the detector.

Acknowledgement

This is a multi-institutional project with TIFR, BARC, IIT (Ropar), IIT (Kharagpur), Univ. of Lucknow, PRL, participating presently.

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