SYNOPSIS

Neutrino physics play an important role in the understanding of particle physics beyond the Standard Model, astrophysics and cosmology. The neutrino oscillation experiments have convincingly shown that neutrinos have a finite mass [1]. However, in oscillation experiments only the differences in squares of the neutrino masses ($\Delta m^2$) can be measured. Moreover, the oscillation results do not provide information about the properties of neutrinos whether it is a Dirac or a Majorana particle. Double beta decay ($\beta\beta$) is a second-order weak process and is expected to occur in many even-even nuclei where single beta decays are energetically and/or spin forbidden and strongly suppressed. Normal $\beta\beta$ decay is a two-neutrino $\beta\beta$ decay ($2\nu\beta\beta$), which conserves the lepton number and is allowed within the Standard Model and has been experimentally observed in a few isotopes [2, 3]. Neutrinoless $\beta\beta$ decay is an exotic decay, where the two Majorana neutrinos that are virtually produced can annihilate each other leaving only two electrons in the final state. This process violates lepton number conservation and is forbidden in the Standard Model of the electroweak interaction.
The $0\nu\beta\beta$ rate depends on the effective Majorana mass [4] and is given by the following expression:

\[
(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 < m_{\beta\beta} >^2
\]  

(1)

where $G_{0\nu}(Q_{\beta\beta}, Z)$ is the phase-space factor for the emission of the two electrons, $M_{0\nu}$ is the nuclear matrix element and $< m_{\beta\beta} >$ is the effective Majorana mass of the electron neutrino. Since the kinetic energy of the two electrons carry the full available decay energy, the experimental signature of $0\nu\beta\beta$ decay is a single peak at the $Q$ value of the decay. Due to the large uncertainty in the model dependent calculation of nuclear matrix element [5, 6], measurements of the $0\nu\beta\beta$ transition rate in different nuclei become extremely important. Several experiments are undergoing and many are planned to search for $0\nu\beta\beta$ decay using different detection techniques [7, 8].

For a rare process such as double beta decay ($T_{1/2} > 10^{20}$ years), the sensitivity of the measurement depends critically on the background level in the region of interest (ROI). The natural radioactivity from the decay chains of U, Th and $^{40}$K ($T_{1/2} \sim 10^9 – 10^{10}$ years), setup materials and the detector itself are the source of background. In case of $^{124}$Sn, $Q_{\beta\beta} = 2292.64 \pm 0.39$ keV [9] is close to the Compton edge of the 2.614 MeV $\gamma$-ray, originating in the decay chain of $^{232}$Th. Further, muon-induced interactions in

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the materials surrounding the detector give rise to additional background of \( \gamma \)-rays and neutrons. The flux of cosmic ray muons can be significantly reduced in an underground laboratory. Background from internal sources can be minimized by careful selection of radio pure materials [10, 11], while the background from the external sources is reduced by using suitable shielding materials. In recent experiments, ultra low levels of background \( \geq 10^{-3} \) cts/(keV kg year) have been achieved [12, 13]. The total background, both from external and internal sources, has to be taken into consideration during the interpretation of results. Generally, a background model employing Monte Carlo (MC) simulations taking into account all the contributions from the actual setup and the environment in the experimental site is used for physics analysis.

A feasibility study to search for 0\( \nu \beta \beta \) decay in \( ^{124} \text{Sn} \) using a Sn cryogenic bolometer, The INdia-based TIN detector (TIN.TIN), has been initiated at Tata Institute of Fundamental Research (TIFR) [14]. This thesis work is mainly focused on the characterization of the low background HPGe set up at TIFR for low activity counting and neutron-induced background for the TIN.TIN detector. These aspects are described briefly in the following sections.
Low Background counting setup

In low background gamma spectroscopy, high detection efficiency and complete characterization of the detector for different source geometries are required. A low background counting setup with HPGe detector has been made at TIFR for radiation background studies and qualification of materials. The HPGe detector is a coaxial p-type Ge (ORTEC GEM75-95-LB-C-HJ) with a relative efficiency of $\sim 70\%$. It is constructed with low background materials such as carbon fiber outer body and copper support structures. The detector is cooled by a 60 cm long cold finger attached to a J-shaped cryostat. This assembly allows an all-round shielding of detector capsule with low activity Pb and Cu.

Monte Carlo (MC) techniques are usually adopted to characterize the detector over a wide energy range. It has been reported in the literature [15–17] that simulated efficiencies are generally overestimated (by $\geq 10\%$) as compared to the experimental values. The discrepancy in efficiency is attributed to the inaccuracy of the supplied parameters and/or due to incomplete charge collection [16, 17]. Thus, the parameters of the detector need to be optimized by detailed measurements.

The efficiency measurement in a close geometry with multi gamma line sources is difficult due to the coincident summing effect. Single line gamma sources such as $^{241}\text{Am}$, $^{57}\text{Co}$, $^{65}\text{Zn}$ etc., are used to scan the Ge crystal in
directions parallel and perpendicular to its cylindrical axis. Measurements are also done with sources over an energy range of $E_\gamma = 100$-1500 keV as a function of distance to estimate its active volume. Complete details of the surrounding absorbing materials such as top and side Ge dead layers, Al window, Cu cup support structures, outer carbon fiber body have been included in the MC model. The detector parameters have been optimized corresponding to a minimum relative deviation (< 5%) between the simulated and measured values of absolute photopeak efficiencies of different $\gamma$-rays. The optimized detector model works very well for different source geometries and also reproduces the overall experimental spectral shape [18].

The detector is shielded from ambient background $\gamma$-rays with a 10 cm thick low activity Pb ($^{210}$Pb < 0.3 Bq/kg) and low activity 5 cm OFHC Cu shield on all sides. The maximum sample size that can be mounted at $d \sim 1$ cm is $9 \text{ cm} \times 9 \text{ cm} \times 5 \text{ cm}$. The background, at sea level, is dominated by the muon-induced interactions originating in the high Z shield materials. The addition of muon veto system to the setup resulted in a gamma background reduction of $\sim 50\%$ in the region of 0.2-3.0 MeV.

A digital system with a commercial FPGA based 100 MHz digitizer (CAEN-N6724) is used for data acquisition. The setup has been extensively used to test radio-impurities in various samples like the Electrolytic Tough
Pitch (ETP) Copper from the Sn bolometer cryostat, natSn and 124Sn samples of different purity, NTD (Neutron Transmutation Doped) Ge sensors etc. The sensitivity of the setup is \( \sim 1 \text{ mBq/g} \) for 232Th and \( \sim 2 \text{ mBq/g} \) for 40K. Using this setup, radio-impurities in the rock sample from INO site (Bodi West Hills (BWH)) have been estimated. The BWH rock samples was found to have considerable high content of 40K, i.e., 1050(16) mBq/g.

**Effect of neutron-induced background in the TIN.TIN detector**

Of the different sources of background, namely, \( \alpha, \beta, \gamma \) and neutrons, background arising from neutrons is most difficult to suppress and hence crucial to understand. In an underground location, neutrons are produced in the spontaneous fission of natU (mainly 238U) and Th present in the rocks and surrounding materials. Neutrons are also produced from (\( \alpha, n \)) reactions on the light nuclei present in the rocks [19]. Neutrons can lead to gamma background due to radiative neutron capture or through inelastic scattering processes.

Hence, it is crucial to evaluate the neutron-induced gamma background in the region of interest (ROI) for 0νββ decay 124Sn. This will also help in the selection/rejection of materials to be used in and around the cryogenic bolometer [20]. As the expected energy resolution of the Sn bolometer is 0.2–0.5\% (full width at half maximum) at \( Q_{\beta \beta} \), the ROI for background estimation is taken as 2292.6 \( \pm 25 \) keV (i.e., \( Q_{\beta \beta} \pm 5\sigma \)). The materials xxx
studied by the neutron activation technique are: ETP $^{\text{nat}}$Cu used inside the
cryostat; Torlon (4203), Torlon (4301) and Teflon – cryogenic materials
for detector holders; $^{\text{nat}}$Pb, $^{\text{nat}}$Sn and 97.2% enriched $^{124}$Sn. The neutron
activation was performed using proton beam on Be and Li production targets
in the neutron irradiation setup at the Pelletron Linac Facility, Mumbai [21].
Proton beams of energy $E_p = 10, 12$ and $20$ MeV on a Be target (5 mm
thick) were used to obtain neutrons of a broad energy range with reaction
$^9$Be($p,n)^9$B ($Q = -1.850$ MeV) [22]. In addition, nearly mono-energetic
neutrons were produced using a $^{\text{nat}}$Li target with the $^7$Li($p,n)^7$Be ($Q = -$
$1.644$ MeV) reaction at $E_p = 12$ MeV. The irradiated targets were counted
offline for the detection of characteristic $\gamma$-rays of reaction products. All the
observed gamma rays and the corresponding channels of production were
identified.

The Torlon/Teflon samples produced 511 keV $\gamma$-ray activity formed via
the reaction $^{19}$F($n,2n)^{18}$F at $E_n \geq 11.5$ MeV. Both the Torlon samples showed
presence of Al which contribute to high energy gamma background of 2754
keV $\gamma$-ray from decay of $^{24}$Na. The Torlon 4301 showed Fe which pro-
duces short-lived activity $^{56}$Mn ($T_{1/2} = 14.997$ h) but the presence of such
a magnetic impurity makes it undesirable for use in Sn cryogenic bolometer
at low temperatures. The Ti present in Torlon 4203 can produce long-lived
impurities like $^{46}$Sc ($T_{1/2} = 83.79$ d). Since there is no gamma background

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at $E_\gamma > 511$ keV in Teflon, it appears to be a better material for support structures in the Sn cryogenic bolometer. Gamma-rays originating from decay of $^{203}$Pb and $^{204m}$Pb and $^{122,124}$Sb were seen in the Pb spectrum. Decay of $^{124}$Sb produces a $\gamma$-ray 2294.02 keV near to the $Q_{\beta\beta}$ of $^{124}$Sn but with a small branching fraction (0.032%). The $^{nat}$Cu showed short-lived activities with $T_{1/2}$ ranging from $\sim$ min ($^{62m}$Co and $^{66}$Cu) to $\sim$ h ($^{64}$Cu and $^{65}$Ni). Of these, $^{62m}$Co decay produces several high energy $\gamma$-rays such as 2882.3 keV. The $^{60}$Co ($T_{1/2} = 5.27$ y) was also produced from $^{63}$Cu(n, $\alpha$)$^{60}$Co reaction. Hence, it is essential to store Cu in an underground location for extended periods prior to use in the bolometer setup.

Reaction products of other Sn isotopes, namely, $^{112}$Sn, $^{115}$Sn, $^{116}$Sn, $^{117}$Sn and $^{122}$Sn were found in the Sn samples. Among the various Sn isotopes formed $^{123}$Sn has the longest half-life $T_{1/2} = 129.2$ d, while decay of $^{116m}$In produces high energy $\gamma$-ray 2112.3 keV. The contribution to the gamma background (a lower limit) within the ROI had been evaluated for an average neutron flux $\sim 10^6$ n cm$^{-2}$s$^{-1}$ integrated over neutron energy $E_n = \sim 0.1$ to $\sim 18$ MeV. It is found that $^{nat}$Sn will produce $\sim 5(2)$ times higher gamma background from the 2112.3 keV $\gamma$-ray produced in decay of $^{116m}$In. Thus, for background reduction enriched Sn is preferable as compared to $^{nat}$Sn.
**Simulation studies for neutron shield in the INO cavern**

The composition of the surrounding rocks namely, the U, Th content and the presence of low Z isotopes determine the level of neutron background in an underground laboratory. A GEANT4-based MC simulations study has been done by incorporating the Bodi West Hills (BWH) rock composition, obtained from Secondary Ion Mass Spectrometry (SIMS). The U and Th content of the rock has been obtained using Inductively Coupled Plasma Mass Spectrometry (ICPMS). The neutron energy spectrum from spontaneous fission of $^{238}\text{U}$ (60 ppb) present in the BWH rock has been generated.

A concept shield design for the neutrons and gammas is suggested as layers of Borated paraffin (BPE) and Pb, of thickness 10 cm and 5 cm respectively. A composite shielding (BPE + Pb + BPE + Pb) is found to be better to reduce the neutron-induced background. The 20 MeV neutron flux in this configuration is attenuated to 0.2%. The overall gamma background, arising from neutron interactions in the paraffin, is 1.5% to that without Pb.

In the first chapter of the thesis, neutrinoless double beta decay is introduced. A brief review of current ($0\nu\beta\beta$) experiments is presented together with the importance and role of background studies for search of $0\nu\beta\beta$ decay. The chapter also presents some of the novel techniques used for background reduction. The second chapter describes the low background
HPGe setup and the Monte Carlo-based optimization of the detector geometry. The third chapter describes the shielding arrangement of the detector. The results of the counting of various materials and their radio-impurity levels are also discussed. Neutron-induced background study of the detector and surrounding materials using activation techniques are described in the fourth chapter. The fifth chapter describes the estimation of the neutron flux in the cavern from the BWH rock activity (spontaneous fission and \((\alpha, n)\) interactions). Summary and conclusions are presented in Chapter 6. Further improvements to the setup and scope of the future work for rare decay studies with the low background setup are also presented.


