Experimental studies on beyond the Standard Model interactions using the HPGe detector

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Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) has complete the last missing piece in the SM of particle physics. It has an excessive impact on the success of the SM. However, there are numerous issues such as the presence of Dark Matter (DM), mass of neutrinos, etc., which challenges the validity of SM and to expect physics Beyond the Standard Model (BSM). Present thesis focuses on the experimental searches of possible DM candidates (Weakly Interacting Massive Particles (WIMPs), Bosonic Super-WIMPs [$\chi_{\rm b} \equiv$ vector $\chi_{\rm v}$ & pseudoscalar $\chi_{\rm ps}$], and millicharged particles (χ_q)) with sub-keV point contact High Purity Germanium detectors (HPGe) at the TEXONO (**T**aiwan **EX**periment **O**n **N**eutrin**O**) experiment.

Neutrinoless double-β decay ($0\nu\beta\beta$) is at present one of the most feasible method to probe the physics BSM because the total lepton number is violated by two units in this process. Projection of the required experimental sensitivity to probe the $0\nu\beta\beta$ in leading isotopes is also one of the important aspects of this thesis.

Experimental details

The TEXONO experiment is located inside the Kuo-Sheng Nuclear Power Plant at a distance of $\sim$28 m from the core-II & under 30 m.w.e overburden [1]. It is acquiring data with both n-type and p-type point contact high purity Germanium detectors. In order to minimize the ambient γ-rays & cosmic ray background the TEXONO experiment have used 50 tons of passive shielding, cosmic ray veto plastic scintillators and anti-Compton shielding [2]. Anti-Compton shielding reduces not only the Compton continuum but also the cosmic ray muons & their induced backgrounds. High detection efficiency of NaI(Tl) crystals for secondary cosmic rays and γ-rays leads to the very effective background suppression. In order to acquire the good data a versatile NI based DAQ system has been developed.

Constraints on DM candidates

Acquired data are compatible with the background model, and no significant excess of $\chi_{\rm b}$ signals are observed. In the absence of obvious signal, new constraints on couplings of electrons with LDM candidates $\chi_{\rm ps}$ and $\chi_{\rm v}$ are presented. The results of current work are stringent in the (0.20$-$0.50) keV/c^2 mass region. Analysis of the data acquired with nPCGe detector excludes the $\chi_{\rm ps}$ couplings to the electrons $g_{\chi_{\rm ps}ee} < 1.55\times10^{-11}$ and $\log_{10}[\alpha^{'}/\alpha] < -27.66$ for $\chi_{\rm v}$. Better detection threshold of pPCGe detector leads more strict upper limits on $g_{\chi_{\rm ps}ee}$ and $\log_{10}[\alpha^{'}/\alpha]$ coupling constants. A preliminary result using the data from pPCGe detector excludes the value of $g_{\chi_{\rm ps}ee} < 4.35\times10^{-12}$ and $\log_{10}[\alpha^{'}/\alpha] < -28.39$ for $\chi_{\rm v}$ in the selected (0.20$-$0.50) keV/c^2 mass region [3].

In the absence of any positive WIMPs signal, we have provided constraints on the WIMPs-nucleon interaction spin independent cross section ($\sigma_p^{\rm SI}$) using Binned Poisson statistical method at 90% C.L. Preliminary results on $\sigma_p^{\rm SI}$ coupling between low mass WIMPs and nucleon are comparable to the other potentially involved underground experiments. Enhancement in low energy back-

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ground & presence of intrinsic noise near the threshold constraints the current limit of nPCGe detector data. However, owing to comparatively better threshold, energy resolution and low background leads stringent limit with the data acquired by pPCGe detector.

Hidden sector with massless gauge boson permits to the possibilities for existence of multicomponent DM. Its ionic components can get small charge χ_q under the hidden sector gauge group. Present thesis have derived the constraints on χ_q with nPCGe detector under the scenarios of χ_q produced at (i) nuclear power reactors, (ii) as products of cosmic rays interactions, and (iii) as DM particle accelerated by supernova shock. The sub-keV sensitivity leads to improving direct laboratory limits of fractional charge δ at small m_{χ_q} and enhancing the lower reach of δ to 10^{-6} [4].

Sensitivity projection for $0\nu\beta\beta$

The long-term goal of the TEXONO-CDEX program is to built a ton-scale Germanium experiment at CJPL for the searches of DM as well as $0\nu\beta\beta$. Observation of $0\nu\beta\beta$ will have following far reaching consequences: (1) Neutrinos are of Majorana nature, (2) Provide the absolute mass of neutrinos and shed light on the mass-generation mechanism, (3) Provide insight to the leptogenesis scenarios, a further key to help in understanding the matter-antimatter-asymmetry in the Universe [5].

The optimistic region of required sensitivity in terms of the background rate (Λ) in counts/ton-year-keV (/tyk) to enter & completely cover the inverted mass hierarchy (IH) starts from $\Lambda \leq 0.1$/tyk and the pessimistic region starts from $\Lambda > 0.1$/tyk at 3σ SL and 90% CL. On the other hand, entering & completely coverage to the normal mass hierarchy (NH) claims for rigorous efforts in the background suppression. Therefore reduction in background towards $\Lambda \sim 0.0$/tyk should be the aim of future generation experiments [5].

The ambiguity of nuclear matrix elements ($|M^{0\nu}|$) leads to put severe uncertainty in the required sensitivity. Present thesis also studies the relation between the background index (BI in counts/FWHM-ty) and exposure [Σ = mass$\times$live-time in ton-year (ty)] in the absence of theoretical uncertainty of $|M^{0\nu}|$ with $\mathrm{P}_{50}^{3\sigma}$ signal identification scheme [6]. An unrealistic $\mathcal{O}(10)$ Mty enriched target mass is necessary at the current best achieved background level $\mathrm{BI}_0{\sim}1$. Reduction of BI towards the Background-free conditions to cover NH correspond to additional background suppression from the current best $\mathrm{BI}_0{\sim}1$ and benchmark [1/(FWHM-Σ)] levels by factors of (0.96×10^{-6}) and (4.4×10^{-3}), respectively. This would reduce the required Σ from 11 Mty and 4600 ty, respectively, to 550 ty. The pursuit of background towards $\mathrm{BI}{\sim}\mathcal{O}(10^{-6})$ to probe NH, while challenging, is highly investment-effective, as it is equivalent to reduction of Σ by $\mathcal{O}(10)$ Mty and $\mathcal{O}(1)$ kty relative to those required for the current best and benchmark background levels, respectively. Detailed studies of $2\nu\beta\beta$ background & other channels like residual cosmogenic radioactivity and long-lived radioactive isotopes are themes of on-going research efforts in TEXONO-CDEX Collaboration.

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