Potential of ^{124}Sn isotope in the search for neutrinoless double beta decay

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Introduction

Globally, extensive research efforts are focused on the experimental detection of neutrinoless double beta decay ($0\nu\beta\beta$). The rationale is that the search for $0\nu\beta\beta$ represents the most sensitive experimental avenue for determining if neutrinos are Majorana particles, further providing insights into the absolute neutrino mass scale and the mechanism of mass generation [1]. Next-generation $0\nu\beta\beta$ experiments target the inverted mass hierarchy (IH) and strive to reach the normal hierarchy (NH) sensitivity domain.

The pursuit of $0\nu\beta\beta$ is a key focus in nuclear and particle physics, targeting 35 isotopes where $0\nu\beta\beta$ is allowed while single β-decay is forbidden, highlighting their experimental importance [2]. Among the isotopes used in $0\nu\beta\beta$ searches, the natural isotopic abundance of ^{124}Sn is relatively moderate, at approximately 5.79%. This is advantageous for experiments since a higher natural abundance reduces the need for isotopic enrichment, making it a potentially attractive candidate for $0\nu\beta\beta$ experiments. However, its $Q_{\beta\beta}$-value (2287.7 keV – see Fig. 1, top panel) is lower compared to some other isotopes, which can pose a challenge in terms of background discrimination. Around the $Q_{\beta\beta}$-value of ^{124}Sn, the main contributors to ambient γ-radiation are the 2.2 MeV line from ^{214}Bi and the 2.6 MeV line from ^{208}Tl. Excellent energy resolution (Δ) can significantly minimize the Compton edge contamination from such background structures within the selected region of interest (RoI), which is further beneficial for selecting a narrower RoI around the $Q_{\beta\beta}$.

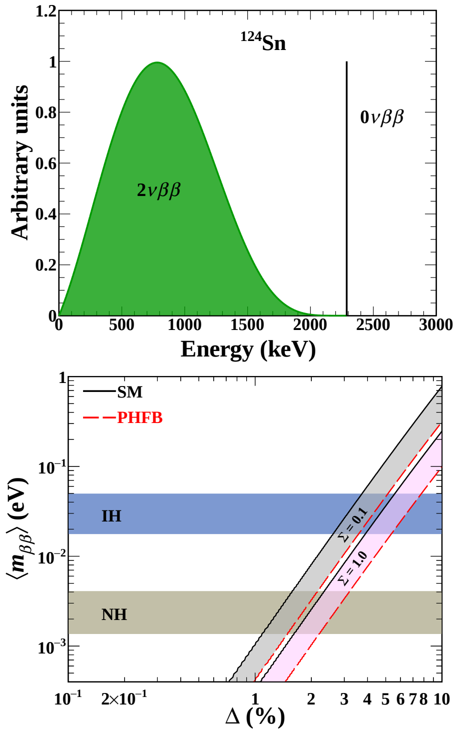

FIG. 1: (Top) The combined energy spectrum of two electrons emitted in both $2\nu\beta\beta$ and $0\nu\beta\beta$ decay modes for ^{124}Sn. (Bottom) Contamination of $2\nu\beta\beta$ events within the RoI is represented in the $\langle m_{\beta\beta}\rangle$ versus Δ space for exposure Σ=0.1 and 1.0 ty (ton-year), where the uncertainty in $|M^{0\nu}|$ causes a corresponding uncertainty in $\langle m_{\beta\beta}\rangle$.

Sensitivity projection

The INdia's TIN (TIN.TIN) is a proposed experiment aimed at searching for $0\nu\beta\beta$ decay using 90% enriched ^{124}Sn as the target iso-

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tope. Our research aims to anticipate the discovery potential of the TIN.TIN experiment, which will employ cryogenic bolometer technology [3].

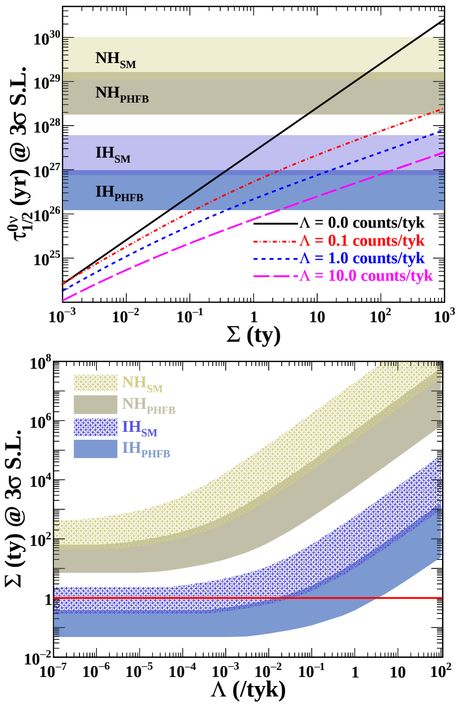

FIG. 2: (Top) The required sensitivity at a 3σ significance level (SL) in $\tau^{0\nu}_{1/2}$ versus Σ at Δ_0 is determined for Λ=(0,0.1,1.0,10)/tyk [/ty-keV]. The IH and NH bands are shown for both PHFB and SM models. (Bottom) Sensitivity requirements for both fully covering and just entering the hierarchy at 3σSL in the Σ versus Λ space at Δ_0.

The $0\nu\beta\beta$ search is intrinsically affected by the $2\nu\beta\beta$ background. Finite detector resolution (Δ [FWHM] in %) introduces irreducible $2\nu\beta\beta$ events, contaminating the RoI, as shown in the bottom panel of Fig. 1. The sensitivity of effective mass of Majorana neutrino $\langle m_{\beta\beta}\rangle$ derived from the conversion of half-life $\tau^{0\nu}_{1/2}$ is influenced by theoretical uncertainties in the nuclear matrix element $|M^{0\nu}|$. This results in a band structure for $\langle m_{\beta\beta}\rangle$ sensitivity due to the $2\nu\beta\beta$ background alone (in addition to the IH and NH bands), with maximal uncertainty observed between the shell model (SM) and Projected Hartree-Fock-Bogoliubov (PHFB) model. The maximum uncertainty range of $|M^{0\nu}|$ for Σ = 1.0 ty shows that the region free from $2\nu\beta\beta$ contamination begins at Δ = 1.6% for the SM and Δ = 2.2% for the PHFB model in the NH case. In the IH case, this uncontaminated region starts at Δ = 3.9% for SM and Δ = 5.3% for PHFB.

The dependence of $\tau^{0\nu}_{1/2}$ at 3σSL on Σ for projected Δ_0 ($\equiv$0.5%) with varying background rates (Λ) is presented in top panel of Fig. 2. It is found that to enter the $\mathrm{IH_{PHFB}}$ region with a background rate of Λ=0.1/tyk, the TIN.TIN experiment must achieve a sensitivity of Σ=0.12 ty, while a sensitivity of Σ=1.7 ty is needed to enter the $\mathrm{IH_{SM}}$ region at 3σSL.

The parameter space of Σ versus Λ at Δ_0, along with the uncertainty bands for $|M^{0\nu}|$ for both IH and NH, is used to explain the need of precise calculation of $|M^{0\nu}|$ and the potential for background improvement (see bottom panel, Fig. 2). At Λ=0.1/tyk, achieving coverage of $\mathrm{IH_{PHFB}}$ necessitates Σ=2.6 ty, while for $\mathrm{IH_{SM}}$, Σ=66 ty is required to identify the signal at 3σSL.

Summary and prospects

Investigating $0\nu\beta\beta$ decay in multiple nuclei is essential, and among the double-beta decay candidates, ^{124}Sn has received limited attention [4], though it is expected to be a focus in upcoming experiments such as TIN.TIN [3]. To achieve full coverage of the $\mathrm{IH_{PHFB}}$, the TIN.TIN experiment with Δ_0=0.5% requires a minimum exposure of Σ_{min}=0.38 ty. In contrast, a conservative approach for covering $\mathrm{IH_{SM}}$ necessitates a Σ_{min}=2.4 ty. For a comprehensive investigation into sensitivity, readers are recommended to Ref. [2].

References

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