Sensitivity projection for future double beta decay experiments

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Tremendous efforts are required to scale the summit of observing neutrinoless double beta decay ($0\nu\beta\beta$). In the present work we studied the required exposures of $0\nu\beta\beta-$projects versus the expected background before the experiments are performed.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) $[(A_{\beta\beta}, Z) \rightarrow (A_{\beta\beta}, Z+2) + 2e^-]$ is the most sensitive experimental probe to address the quest that whether neutrinos are Majorana or Dirac particles [1]. Observation of $0\nu\beta\beta$ would implies that the neutrinos are their own anti-particles (Majorana Nature) and violation of lepton number by two units. The current work quantitatively explores the interplay between exposure (Σ = detector mass×live−time) and background levels in $0\nu\beta\beta$ experiments to meet certain mass of Majorana neutrino $\langle m_{\beta\beta}\rangle$ as target sensitivities.

2. Formulations

The half-life of $0\nu\beta\beta$ isotopes can be expressed as

$$\left[T^{0\nu}_{\frac{1}{2}}\right]^{-1} = G^{0\nu}\, g_A^4\, |M^{0\nu}|^2 \left[\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}\right] \quad (1)$$

where $G^{0\nu}$ is the known phase space factor, m_e is the mass of electron, g_A is the axial vector coupling constant, $|M^{0\nu}|$ is the nuclear physics matrix element and $\langle m_{\beta\beta}\rangle$ is the effective Majorana neutrino mass

$$\langle m_{\beta\beta}\rangle = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta}\right| \quad (2)$$

which depends on the neutrino masses (m_i for eigenstate ν_i), Majorana phases

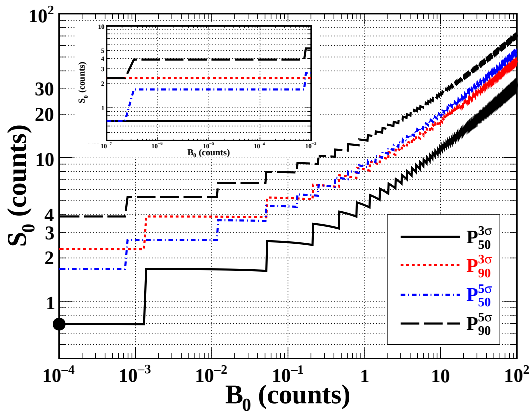

FIG. 1: Variation of Signal counts S_0 versus Background counts B_0 in discovery potential of $\geq 3\sigma;5\sigma$ with $\geq$ 50%;90% probabilities.

(α, β) and PMNS mixing matrix (U). Measurement of the mass-squared splitting, allows Inverted (IH) ($m_3 < m_1 < m_2$) and Normal Hierarchy (NH) ($m_1 < m_2 < m_3$) configurations for the mass eigenstates. The theme of current analysis is to quantify the required Σ and background to reach the following target sensitivities: $\langle m_{\beta\beta}\rangle^{IH}_{-};\langle m_{\beta\beta}\rangle^{IH}_{+};\langle m_{\beta\beta}\rangle^{IH}_{95\%} \equiv (1.4;5.1;2.0) \times 10^{-2}$eV and $\langle m_{\beta\beta}\rangle^{NH}_{-};\langle m_{\beta\beta}\rangle^{NH}_{+};\langle m_{\beta\beta}\rangle^{NH}_{95\%} \equiv (0.78;4.3;3.0)\times 10^{-3}$eV.

The measurable half−life from an experiment which observes $N^{0\nu}$ counts of $0\nu\beta\beta$ in time t_{DAQ} in a "Region of Interest" (RoI) at

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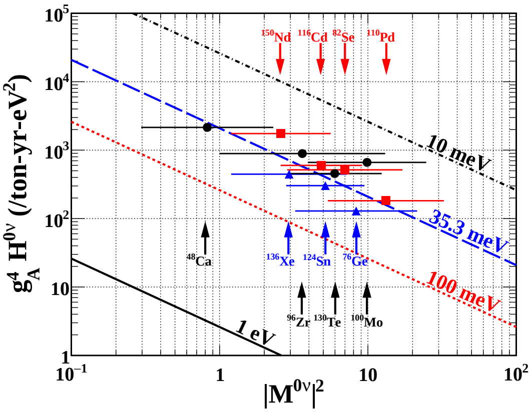

FIG. 2: Variation of "specific phase space" $(g_A^4).H^{0\nu}$ versus $|M^{0\nu}|^2$ for various $A_{\beta\beta}$.

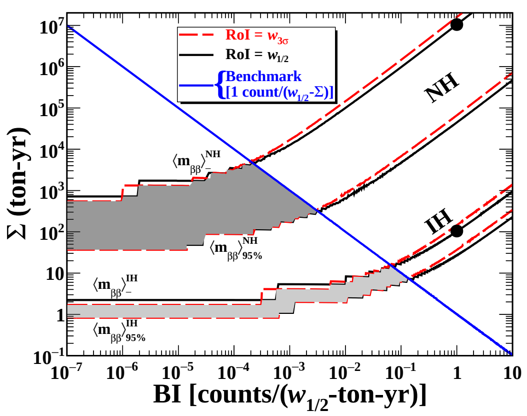

FIG. 3: Required exposure versus BI universally applicable to all $A_{\beta\beta}$ under $P_{50}^{3\sigma}$.

an efficiency of ε_{RoI} can be expressed as

$$\begin{aligned} T_{1/2}^{0\nu} &= \ln 2.N(\mathrm{A}_{\beta\beta}).t_{\mathrm{DAQ}}.\left[\frac{\varepsilon_{\mathrm{RoI}}}{N_{\mathrm{obs}}^{0\nu}}\right] \\ &\equiv \ln 2.\left[\frac{N_{\mathrm{A}}}{M(A_{\beta\beta})}\right].\Sigma.\left[\frac{\varepsilon_{\mathrm{RoI}}}{N_{\mathrm{obs}}^{0\nu}}\right] \end{aligned} \quad (3)$$

where $N(A_{\beta\beta})$ is the number of $A_{\beta\beta}$ atoms being probed. N_A is Avogadro's number, $M(A_{\beta\beta})$ is the molar mass of $A_{\beta\beta}$, and Σ is in units of ton−year at isotopic abundance = 100% and $\varepsilon_{\mathrm{expt}}$ = 100%. Eqs.(1) & (3) gives

$$|M^{0\nu}|^2[g_A^4.H^{0\nu}] = \frac{1}{\langle m_{\beta\beta}\rangle^2}\left[\frac{1}{\Sigma}.\frac{N_{\mathrm{obs}}^{0\nu}}{\varepsilon_{\mathrm{RoI}}}\right] \quad \text{where}$$
$$H^{0\nu} \equiv \ln 2.\left(\frac{N_{\mathrm{A}}}{M(A_{\beta\beta}).m_e^2}\right).G^{0\nu} \quad (4)$$

where $H^{0\nu}$ is called "specific phase space". In the case where $0\nu\beta\beta$ is driven by the neutrino mass mechanism, there exists an inverse correlation between $H^{0\nu}$ and $|M^{0\nu}|^2$, the consequence of which is that the decay rates per unit mass for different $A_{\beta\beta}$ are similar at a given $\langle m_{\beta\beta}\rangle$ and constant g_A. That is, there is no favored $0\nu\beta\beta$−isotope from the nuclear physics point of view (Fig. 2).

We studied the required exposures of $0\nu\beta\beta$−projects versus the expected background before the experiments are performed. Present work [1] have expressed the sensitivity goals of experiments as: "Discovery Potential at 3σ with 50% probability ($P_{50}^{3\sigma}$)" (Fig. 1).

3. Results and Discussion

Considering the scheme of $P_{50}^{3\sigma}$ and following the inverse correlation between $H^{0\nu}$ and $|M^{0\nu}|^2$, an interplay between Background Index (BI=B_0(RoI)/Σ) and Σ is shown in Fig. 3 for the RoI=FWFM ($w_{3\sigma}$) as well as RoI=FWHM ($w_{1/2}$). Here blue line represents the benchmark background index corresponding to 1 count/($w_{1/2}$.Σ). The shaded regions correspond to the preferred hardware specification space for future $0\nu\beta\beta$ experiments−where the exposure should be sufficient to cover at least $\langle m_{\beta\beta}\rangle_{95\%}^{\mathrm{IH(NH)}}$. In particular, the minimum exposures to cover $\langle m_{\beta\beta}\rangle_{-}^{\mathrm{IH(NH)}}$ under zero-background conditions are 1.7(550) ton-yr.

The contamination levels to $0\nu\beta\beta$ at the $Q_{\beta\beta}$-associated RoI depend on the Standard Model-allowed $2\nu\beta\beta$ half-life and the detector resolution. The required FWHM energy resolutions (Δ) to cover $\langle m_{\beta\beta}\rangle_{-}^{\mathrm{IH(NH)}}$ under background-free conditions are Δ ≤ (0.3-0.9)% and Δ ≤ (0.1-0.4)%, respectively.

References

[1] M.K. Singh, H.T. Wong *et. al.*, Phys. Rev. **D 101**, 013006 (2020).