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Required Exposure and Background Levels in the Searches of Neutrinoless Double−β Decay

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Although neutrinos have mass, their absolute mass scale and the true nature (Majorana or Dirac) are still unknown. Neutrino and particle physics communities strongly prioritize the detection of neutrinoless double−β decay. Neutrinoless double−β decay is a second-order electroweak process (a hypothetical ultra-rare nuclear decay forbidden in the Standard Model), in which a nucleus decays through the emission of two electrons: ${}^{N}_{Z}A_{\beta\beta} \rightarrow {}^{N-2}_{Z+2}A + 2e^{-}$, consequently violating the lepton number ($\Delta L = 2$). It is the most sensitive experimental probe to address the quest whether neutrinos are Majorana or Dirac particles. The observation of neutrinoless double−β decay would not only establish the Majorana nature of neutrinos but also provide direct information on neutrino masses and probe the neutrino mass hierarchy. The present work would explore the required sensitivity for the upcoming projected neutrinoless double−β decay experiments to probe the inverted mass hierarchy as well as non-degenerate normal mass hierarchy. We studied the required exposures of neutrinoless double−β decay projects as a function of the expected background (following "Discovery Potential at 3σ with 50% probability" statistical scheme) before the experiments are performed. This work would address the crucial role of background suppression in the future neutrinoless double−β decay experiments with sensitivity goals of approaching and covering non-degenerate normal mass hierarchy.

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1. Introduction

At present, neutrinoless double−β decay ($0\nu\beta\beta$) is the only experimental way to discover the Majorana nature of neutrinos [1]. The observation of $0\nu\beta\beta$ would clearly resolve the issue of lepton number conservation, thus, representing a portal to physics beyond the standard model and have fundamental implications for neutrino physics and cosmology [2]. Furthermore, the detection and study of $0\nu\beta\beta$ provide the absolute neutrino mass scale, type of neutrino mass hierarchy (normal, inverted, quasi-degenerate), and CP violation in the lepton sector (measurement of the Majorana CP-violating phases) [3].

Although the $0\nu\beta\beta$ experiments address an important set of questions, the interpretation of the results will depend on the theoretical calculations of the nuclear matrix elements (NMEs). Different approximations for complicated nuclear structure leads to an uncertainty of factor of 2-3 in the calculated NMEs. Apart from NMEs, another source of crucial uncertainty is the values of axial vector coupling constant g_A (see Fig. 1(a)), which may differ between a free nucleon and complex nuclei ($0.6 \leq g_A \leq 1.269$) [4].

2. Physics connections & our methodology

In the standard mass mechanism scenario, when the $0\nu\beta\beta$ process materializes by the exchange of light Majorana neutrinos between two nucleons inside the nucleus, the half-life of this process between 0^+ states for mother and granddaughter nuclei can be given by [4]

$$\left[\tau^{0\nu}_{\frac{1}{2}}(0^+_i \to 0^+_f)\right]^{-1} = G^{0\nu}\, g_A^4\, |M_{0\nu}|^2 \left[\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}\right]. \tag{1}$$

Here m_e is the electron mass, $|M^{0\nu}|$ is the NME, and $G^{0\nu}$ represents the phase space factor. The decay rate is proportional to the square of the $\langle m_{\beta\beta}\rangle \left(= \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|\right)$, which depends on neutrino masses (m_i for eigenstate ν_i) and mixings (U_{ei} for the component of ν_i in ν_e).

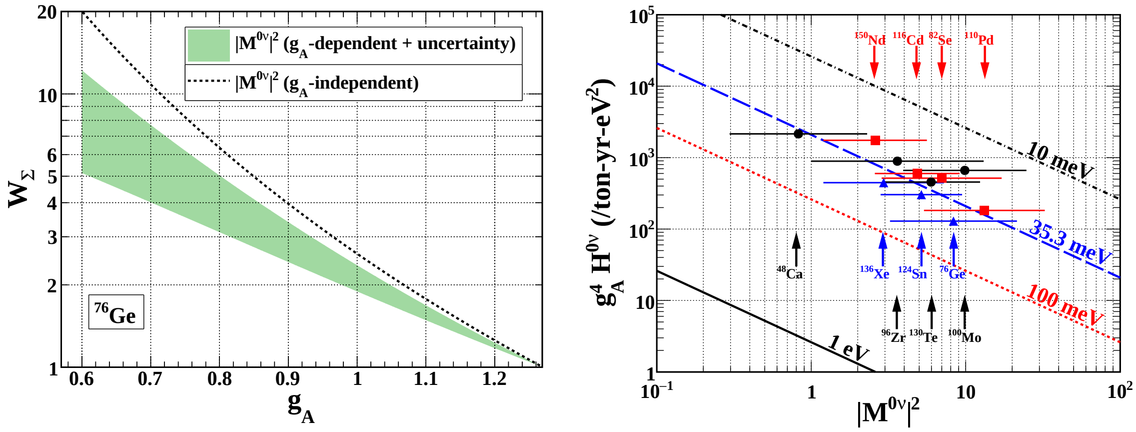
The measurable half−life from an experiment which observes $N^{0\nu}_{\rm obs}$ counts of $0\nu\beta\beta$ in time $t_{\rm DAQ}$ in a "Region of Interest" (RoI) at an efficiency of $\varepsilon_{\rm RoI}$ can be expressed as

$$T^{0\nu}_{1/2} = \ln 2 \cdot N(\mathrm{A}_{\beta\beta}) \cdot t_{\rm DAQ} \cdot \left[\frac{\varepsilon_{\rm RoI}}{N^{0\nu}_{\rm obs}}\right] \equiv \ln 2 \cdot \left[\frac{N_{\rm A}}{M(A_{\beta\beta})}\right] \cdot \Sigma \cdot \left[\frac{\varepsilon_{\rm RoI}}{N^{0\nu}_{\rm obs}}\right] \tag{2}$$

where $N(A_{\beta\beta})$ is the number of $A_{\beta\beta}$ ($0\nu\beta\beta$-isotope) atoms being probed, N_A is Avogadro's number, $M(A_{\beta\beta})$ is the molar mass of $A_{\beta\beta}$, and Σ is exposure (= detector-mass×live-time in units of ton−year) at isotopic abundance (IA) = 100% and other experimental efficiencies $\varepsilon_{\rm expt}$ = 100%. Eqs.(1) & (2) gives

$$|M^{0\nu}|^2[g_A^4 \cdot H^{0\nu}] = \frac{1}{\langle m_{\beta\beta}\rangle^2}\left[\frac{1}{\Sigma} \cdot \frac{N^{0\nu}_{\rm obs}}{\varepsilon_{\rm RoI}}\right] \text{ where } H^{0\nu} \equiv \ln 2 \cdot \left(\frac{N_{\rm A}}{M(A_{\beta\beta}) \cdot m_{\rm e}^2}\right) \cdot G^{0\nu} \tag{3}$$

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 $|M^{0\nu}|^2$ [2] (Fig. 1(b)). Consequently, the decay rates per unit mass for different $A_{\beta\beta}$ are similar at a given $\langle \mathrm{m}_{\beta\beta}\rangle$ and constant g_A. Thus, there is no favored $0\nu\beta\beta$−isotope from the nuclear physics point of view. We assume that this correlation is quantitatively valid.

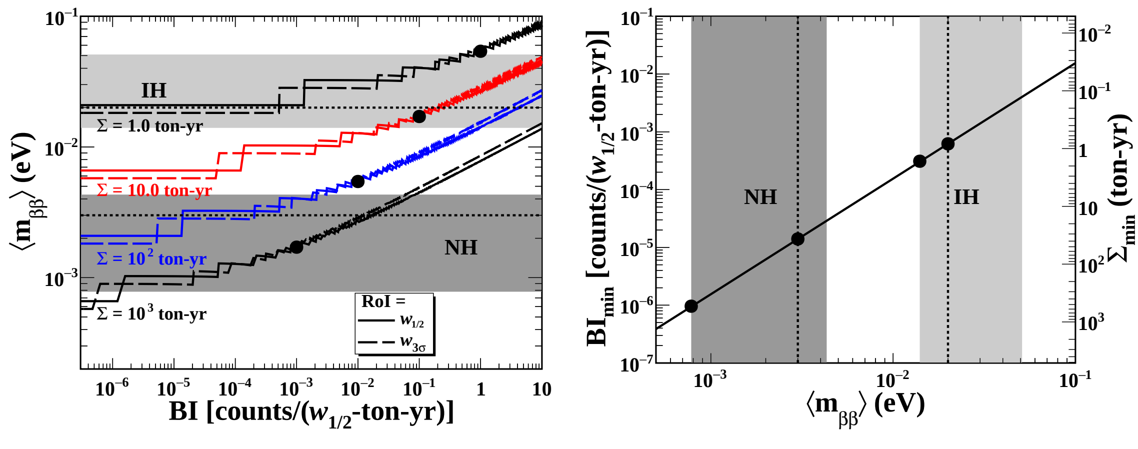


(a) (b)

Figure 1: (a) Variation in the weight factor for Σ (W_Σ) due to the g_A dependence of $T^{0\nu}_{1/2}$ in Eq. (1) relative to that of g_A=1.27 in the case of ^{76}Ge. The finite band width is the consequence of the spread in $|M^{0\nu}|^2$ predictions. (b) Variations of "specific phase space" $g_A^4 H^{0\nu}$ versus $|M^{0\nu}|^2$ for various $A_{\beta\beta}$.

3. Results and discussion

Present work follows the criteria of $P^{50}_{3\sigma}$ statistical scheme [5] and Ref. [2] in adopting the geometric means of the realistic ranges for the various $|M^{0\nu}|^2$ in different isotopes at g_A=1.27. The aim of current analysis is to quantify the required Σ and background index (BI)$\left(= \frac{\text{Background counts(RoI)}}{\Sigma}\right)$ to reach the following target sensitivities: $(\langle m_{\beta\beta}\rangle^{IH}_{-};\langle m_{\beta\beta}\rangle^{IH}_{+};\ \langle m_{\beta\beta}\rangle^{IH}_{95\%}) \equiv(1.4;5.1;2.0)\times10^{-2}$eV and $(\langle m_{\beta\beta}\rangle^{NH}_{-};\langle m_{\beta\beta}\rangle^{NH}_{+};\ \langle m_{\beta\beta}\rangle^{NH}_{95\%}) \equiv(0.78;4.3;3.0)\times10^{-3}$eV.



(a) (b)

Figure 2: (a) Sensitivities of $\langle m_{\beta\beta}\rangle$ versus BI, which is universally applicable to all $A_{\beta\beta}$, following $P^{50}_{3\sigma}$ under different exposures at Σ=(1; 10; 100; 1000) ton-yr. (b) The variations of the background-free and minimal-exposure conditions (BI_{min}, Σ_{min}) at $P^{50}_{3\sigma}$-criteria with $\langle m_{\beta\beta}\rangle$.

The dependence of $\langle m_{\beta\beta}\rangle$ sensitivities to BI is depicted in Fig. 2(a). Taking RoI=FWHM($w_{1/2}$) is obviously not the optimal choice when the expected background $B_0\to0$. An alternative choice for low B_0 is RoI≡FWFM($w_{3\sigma}$) covering $\pm3\sigma$ of $Q_{\beta\beta}$, such that $\varepsilon_{RoI}\cong100\%$. The choice of RoI=$w_{3\sigma}$ at $B_0\to0$ would expectedly give better sensitivity by a factor of $\varepsilon_{RoI}(w_{1/2})$=0.76, such that the covered $T^{0\nu}_{1/2}$ is 32% longer, or the required Σ is 24% less. The target exposure is Σ=10 ton-yr for the next generation $0\nu\beta\beta$ projects to cover IH with ton-scale detector target. Following Fig. 2(a), this exposure would require BI<(0.21, 0.033) counts/($w_{1/2}$-ton-yr) to cover ($\langle m_{\beta\beta}\rangle_{95\%}$, $\langle m_{\beta\beta}\rangle^{\rm IH}_{-}$). This matches the background specifications of BI=$O(0.1)$ counts/($w_{1/2}$-ton-yr). Alternatively, the Σ=10 ton-yr target exposure of next-generation projects can probe $\langle m_{\beta\beta}\rangle$>(5.8×10^{-3}) eV, approaching $\langle m_{\beta\beta}\rangle^{\rm NH}_{+}$=(4.3×10^{-3}) eV, when the BI$_{\rm min}$<5.1×10^{-5} counts/($w_{1/2}$-ton-yr) is achieved. It should be noted that the required exposure (Σ') in realistic experiments would be larger and can be readily converted from the Σ values via ($\Sigma' \simeq \Sigma \cdot (1/{\rm IA}) \cdot (1/\varepsilon_{\rm expt}) \cdot {\rm W}_{\Sigma}({\rm g_A})$).

The background-free (BI$_{\rm min}$) – equivalently, minimal-exposure ($\Sigma_{\rm min}$) – condition is where one single observed event can establish the signal at the $\rm P^{3\sigma}_{50}$-criteria. The variations of (BI$_{\rm min}$, $\Sigma_{\rm min}$) with $\langle m_{\beta\beta}\rangle$ are depicted in Fig. 2(b). As shown by the black dots, $\Sigma_{\rm min}$=(0.83, 1.7) ton-yr at BI$_{\rm min}\leq$(6.3×10^{-4}, 3.1×10^{-4}) counts/($w_{1/2}$-ton-yr) are required to cover ($\langle m_{\beta\beta}\rangle_{95\%}$, $\langle m_{\beta\beta}\rangle_{-}$)$^{\rm IH}$. The corresponding requirements for NH are $\Sigma_{\rm min}$=(37, 550) ton-yr at BI$_{\rm min}\leq$(1.4×10^{-5}, 0.96×10^{-6}) counts/($w_{1/2}$-ton-yr). The required $\Sigma_{\rm min}$ from $\langle m_{\beta\beta}\rangle_{-}$ to $\langle m_{\beta\beta}\rangle_{95\%}$ is reduced by a fraction $f_{95\%}$=0.49(0.068) for IH(NH). The contamination levels to $0\nu\beta\beta$ at the $\rm Q_{\beta\beta}$-associated RoI depend on the Standard Model-allowed $2\nu\beta\beta$ half-life and the detector resolution. The required FWHM energy resolution (Δ) to cover $\langle {\rm m}_{\beta\beta}\rangle^{\rm IH(NH)}_{-}$ under background-free conditions are $\Delta \leq$ (0.3-0.9)% and $\Delta \leq$ (0.1-0.4)%, respectively.

Acknowledgments

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