Theoretical uncertainty in the sensitivity projection for neutrinoless double beta decay

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Introduction

The quest for $0\nu\beta\beta$ involves a variety of experiments that use various isotopes to address an important set of questions: absolute mass scale & the true nature (Majorana or Dirac) of neutrinos, resolve the issue of lepton number conservation, type of neutrino mass hierarchy (normal, inverted, quasi-degenerate), CP violation in the lepton sector, and many more [1].

In the standard mass mechanism scenario, the half-life of this process can be given by

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

where m_e is the electron mass, $|M^{0\nu}|$ is the Nuclear Matrix Elements, g_A is the axial vector coupling constant, and $G^{0\nu}$ represents the phase space factor. The decay rate of $0\nu\beta\beta$ is proportional to the square of the effective mass of the Majorana Neutrino $\langle m_{\beta\beta}\rangle \left(= \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|\right)$, which depends on neutrino masses (m_i for eigenstate ν_i) and mixings (U_{ei} for the component of ν_i in ν_e) [2].

Measurement of $\langle m_{\beta\beta}\rangle$ faces the theoretical uncertainty of $|M^{0\nu}|$ (nuclear structure), g_A (quenched or unquenched: $0.6 \leq g_A \leq 1.269$) and $G^{0\nu}$ (through $Q_{\beta\beta}$ and nuclear radius R). A variation in the $|M^{0\nu}|^2$ due to changes in g_A relative (f) to the unquenched value g_A=1.269 for ^{76}Ge,^{136}Xe,^{130}Te isotopes is shown in Fig. 1(Top). A finite band width results from spread in the $|M^{0\nu}|^2$ components in various models.

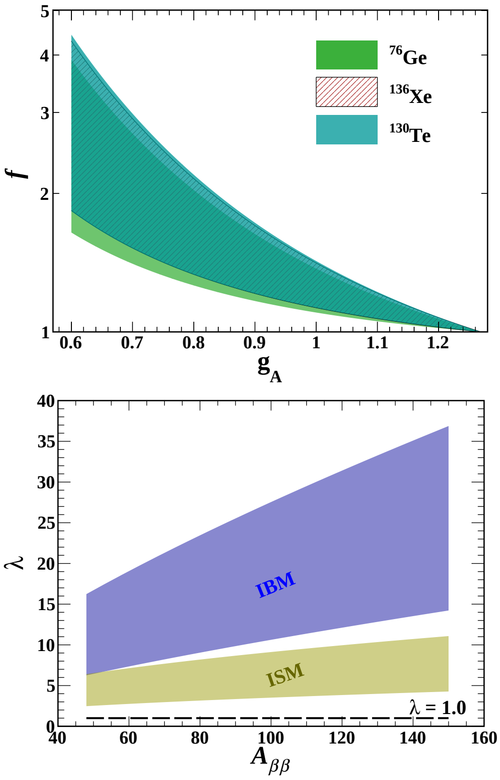

FIG. 1: (Top) Variation in the $|M^{0\nu}|^2$ due to changes in g_A relative (f) to the unquenched value g_A=1.269 for ^{76}Ge,^{136}Xe,^{130}Te isotopes. (Bottom) Variation in the effective strength of $g_A(g^{\rm eff}_{A_{\beta\beta}})$ relative (λ) to the free-nucleon & unquenched values of g_A in IBM-2 & NSM models.

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A relative variation in the effective strength of $g_A (g^{\rm eff}_{A_{\beta\beta}})$ in the IBM-2 (Interacting Boson Model) & NSM (Nuclear Shell Model) models is shown in Fig. 1(Bottom). The finite band width arises due to relative variation (λ) in $g^{\rm eff}_{A_{\beta\beta}}$ with free-nucleon and unquenched values of g_A. Due to g_A^4 being present in the rate (Eq. 1), the calculated $0\nu\beta\beta$ rates are subjected to a significant measure of uncertainty in addition to $|M^{0\nu}|$ [3].

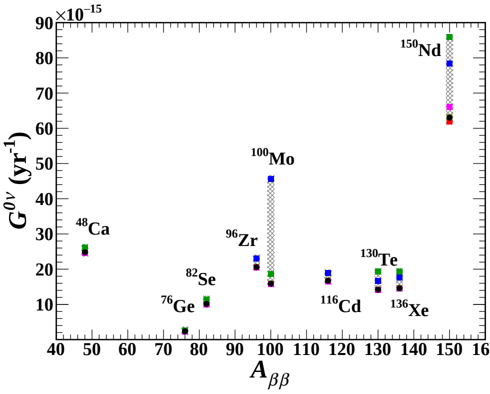

FIG. 2: The range of $G^{0\nu}$ values following earlier and recent approaches [4].

$Q_{\beta\beta}$ and R are the input parameters in the calculation of $G^{0\nu}$. Experimental error associated with the measurement of $Q_{\beta\beta}$ introduces marginal uncertainty. On the other hand, uncertainty in R dominates, resulting in $\approx 7\%$ uncertainty in $G^{0\nu}$. The range of $G^{0\nu}$ values following earlier and recent approaches is exhibited in Fig. 2. The current work follows recent computed values [4], with a maximum uncertainty of $\approx 7\%$ in the $G^{0\nu}$ values.

Results and discussion

Present work follows the criteria of $\mathrm{P}^{50}_{3\sigma}$ statistical scheme (see Ref. [5]) to evaluate the impact of maximum possible theoretical uncertainty in the required sensitivity to reach the following target sensitivities: $(\langle m_{\beta\beta}\rangle^{\rm IH}_{-}; \langle m_{\beta\beta}\rangle^{\rm IH}_{+}) \equiv (1.4;5.1)\times 10^{-2}$eV and $(\langle m_{\beta\beta}\rangle^{\rm NH}_{-}; \langle m_{\beta\beta}\rangle^{\rm NH}_{+}) \equiv (0.78;4.3)\times 10^{-3}$eV.

In the absence of a precise knowledge of $|M^{0\nu}|$, g_A, and $G^{0\nu}$, we consider the two most likely scenarios: (1) *Most optimistic* – the nature may choose to follow the largest among the current values of these parameters and observe the signature of $0\nu\beta\beta$ by simply entering the IH or NH; (2) *Most pessimistic* – these parameters may follow their smallest values in current range and need to cover IH or NH in order to see the signal of $0\nu\beta\beta$.

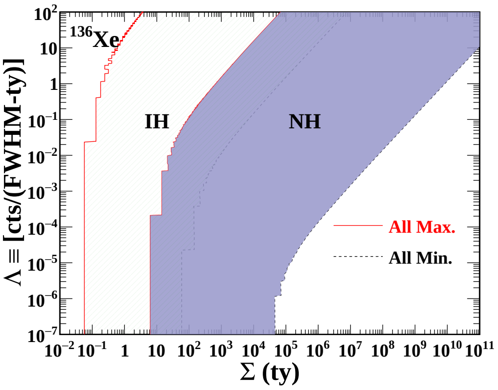

FIG. 3: Sensitive Σ vs Λ to enter and cover the hierarchies (IH/NH) under most conservative (all min.) & optimistic (all max.) scenarios at $\mathrm{P}^{50}_{3\sigma}$.

Under this maximum possible uncertainty, the required sensitive exposure (in ton-year) vs background level (in counts/FWHM-ton-year) for ^{136}Xe at $\mathrm{P}^{50}_{3\sigma}$ is shown in Fig. 3. Even at background-free level ($\Lambda = 0.0$), the required Σ in most optimistic(conservative) scenario is 0.057(59) ty to enter(cover) the IH. If nature favors NH, it requires $5.8(1.9\times 10^4)$ ty to enter(cover) the NH (relative uncertainty $\mathcal{O}10^3$ ty). Uncertainty of this magnitude in Σ will severely impact the prospects of upcoming & current $0\nu\beta\beta$-projects.

References

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