Nuclear Structure Aspects of Exotic Weak Decays

P. K. Rath
Faculty of Engineering, University of Lucknow-226031, INDIA
** email: pkrath_lu@yahoo.co.in*

Introduction

Observation of neutrinoless double beta ($0\nu\beta\beta$) decay is the most pragmatic approach to establish the Majorana nature of neutrinos. Additionally, a number of issues, namely the origin of neutrino mass, absolute scale of neutrino mass, neutrino mass hierarchy, CP violation in the leptonic sector and the role of various mechanisms in different gauge theoretical models beyond the standard model of electroweak unification would also be clarified.

As the $0\nu\beta\beta$ decay is a lepton number violating process, a number of mechanisms contribute to its possible occurrence. Specifically, the exchange of light and heavy Majorana neutrinos as well as existence of right handed currents in the left-right symmetric model (LRSM), the exchange of sleptons, neutralinos, squarks and gluions in R_p-violating minimal super symmetric model, existence of heavy sterile neutrinos, Majorons, leptoquarks, compositeness and extra-dimensional scenarios have been considered [1]. Reliable gauge theoretical parameters can be extracted provided the model dependent nuclear transition matrix elements (NTMEs) are calculated as accurately as possible.

In this endeavour, different theoretical approaches, namely interacting shell-model (ISM), quasiparticle random phase approximation (QRPA), deformed QRPA, QRPA with isospin restoration, projected-Hartree-Fock-Bogoliubov (PHFB) model, interacting boson model (IBM) with isospin restoration, the generator coordinate method (GCM) and beyond mean field covariant density functional theory (BMFCDFT) have been employed [2]. Further, different alternatives are also available for the choice of model space, effective two-body residual interactions, model dependent form factors to include the finite size of nucleons (FNS), short range correlations (SRC) with Miller-Spencer parametrization, unitary operator method (UCOM), parametrization based on coupled cluster method (CCM) and the value of axial vector current coupling constant g_A. In spite of all these alternatives employed in nuclear structure calculations, the calculated NTMEs $M^{(0\nu)}$ interestingly differ by factor of 2–3. Presently, our main objective will be to deal with the estimated uncertainties in the calculated NTMEs of $0\nu\beta\beta$ decay.

Calculational Frame work

Within the PHFB approach, NTMEs have been calculated to study the three complementary modes of $\beta^-\beta^-$ decay, namely two neutrino $\beta^-\beta^-$ ($2\nu\beta^-\beta^-$) decay, neutrinoless $\beta^-\beta^-$ ($0\nu\beta^-\beta^-$) decay and Majoron models [3]. Using four different parametrizations of pairing plus multipolar type of effective two-body interaction, reliability of HFB wave functions has been ascertained by comparing a number of calculated nuclear observables, such as excitation energies E_{2^+} of yrast 2^+ states, deformation parameters β_2 and g-factors $g(2^+)$ with the available experimental data. In addition, the calculated NTMEs $M^{(2\nu)}$ of $2\nu\beta^-\beta^-$ decay have been compared with the extracted NTMEs from the experimentally observed half-lives.

Employing reliable HFB wave functions, effects due to four different parametrizations of effective two-body interactions, FNS and SRC have been studied. It has been noticed that there is no difference in the effects due to finite size of nucleons (FNS) either by employing dipole form factors or form factors taking the structure of nucleons into account. Within mechanisms involving light Majorana neutrinos, heavy Majorana neutrinos, sterile neutrinos and Majorons, uncertainties in sets of twelve NTMEs calculated with four different HFB wave functions, dipole form factor and three different parametrizations of Jastrow type of SRC, namely Miller-Spencer parametrization, Argonne NN, and CD-Bonn potentials, which are denoted by SRC1, SRC2 and SRC3, respectively, have been statistically estimated. Specifically, sets of twelve NTMEs $M^{(0\nu)}$, $M^{(0N)}$, $M^{(0\nu)}_{(m_h)}$, $M^{(\chi)}_{(m_\nu)}$, $M^{(\chi)}_{(CR)}$, and $M^{(\chi)}_{(\omega^2)}$ for the $0\nu\beta^-\beta^-$ decay of $^{94,96}Zr$, ^{100}Mo, ^{110}Pd, $^{128,130}Te$ and ^{150}Nd isotopes have been calculated.

Results and Discussions

As expected, closure approximation is reasonably valid in the calculation of NTMEs. Evaluated NTMEs $M^{(0\nu)}$ of considered nuclei but for ^{128}Te with PQQ1 and PQQ2 parameterizations are quite close. With the inclusion of the hexadecapolar term, NTMEs $M^{(0\nu)}$ are reduced in magnitude, depending specifically on the structure of nuclei. Due to the PQQHH1, PQQ2, and PQQHH2 parameterizations, the maximum variation in $M^{(0\nu)}$ with respect to PQQ1, lies between 20%–25% . The maximum variations in $M^{(0N)}$ due to PQQHH1, PQQ2, and PQQHH2 parametrizations with reference to PQQ1 interaction, are about 24%, 18%, and 26%, respectively. With respect to PQQ1 parametrization, NTMEs $M^{(\chi)}_{(CR)}$, and $M^{(\chi)}_{(\omega^2)}$ due to other three parametrizations change up to 25%-34%. It is also noticed that there is an inverse correlation between the deformation parameter and the NTMEs $M^{(K)}$ in general and deformation plays a crucial role in the nuclear structure aspects of $0\nu\beta^-\beta^-$decay.

Relative changes (in %) in NTMEs $M^{(0\nu)}$, $M^{(0N)}$, $M^{(0\nu)}_{(m_h)}$, $M^{(\chi)}_{(m_\nu)}$, $M^{(\chi)}_{(CR)}$, and $M^{(\chi)}_{(\omega^2)}$ due to the inclusion of FNS and FNS+SRC (FNS+SRC1, FNS+SRC2, and FNS+SRC3) have been studied. NTMEs $M^{(0\nu)}$ are reduced by about 18%–23% in the case of FNS and with the inclusion of SRC1, SRC2, and SRC3, the NTMEs are further reduced by 12%–17%, 1.0%–2.0%, and 2.4%–3.0% approximately. Due to FNS, the maximum change in the values of $M^{(\chi)}_{(CR)}$ is in between 13% and 16%. With the inclusion of SRC, the NTMEs $M^{(\chi)}_{(CR)}$ change by about 12%–15%, less than 1% and 3%–4% due to SRC1, SRC2, and SRC3, respectively. It is noteworthy that the NTMEs $M^{(\chi)}_{(\omega^2)}$ change negligibly due to FNS and SRC. With respect to the point nucleon case, the NTMEs $M^{(0N)}$ are reduced by about 40% due to FNS. Due to SRC1, the NTMEs are reduced to about one third of its original value and the other two parameterizations of the SRC, namely SRC2 and SRC3, have a sizable effect, albeit much smaller than SRC1.

Uncertainties in $M^{(0\nu)}$ and $M^{(\chi)}_{(CR)}$ are of the order of 10%–15% and 9%–15%, respectively. Estimated uncertainties $\Delta M^{(\chi)}_{(\omega^2)}$ in NTMEs $M^{(\chi)}_{(\omega^2)}$ exhibit a negligible dependence on SRC and are about 7.5%–21%. Further, uncertainties in NTMEs $M^{(0N)}$ are about 35%. Depending on the considered mass of the sterile neutrinos, uncertainties $\Delta M^{(0\nu)}_{(m_h)}$ in $M^{(0\nu)}_{(m_h)}$ are about 9%–36%.

Conclusions

Limits on the effective mass of light Majorana neutrino $\langle m_\nu \rangle$, effective mass of heavy Majorana neutrino $\langle M_N \rangle$, the ν_h–ν_e mixing matrix element U_{eh}, and effective Majoron-neutrino coupling constants g_α have been extracted from the largest observed limits on half-lives $T^{(0\nu)}_{1/2}$ of $0\nu\beta^-\beta^-$ decay. In the case of ^{130}Te nuclei, the most stringent limits on $\langle m_\nu \rangle$ and $\langle M_N \rangle$ are < 0.17 eV and > 1.12×108 GeV, respectively. Within classical Majoron models, the most stringent extracted limit on $g_\alpha < 1.89 \times 10^{-5}$ is obtained for ^{100}Mo isotope. Extracted limits on g_α of new Majoron models are large by a factor of 10^{4-5} than those of classical Majoron models. In comparison to laboratory experiments, astrophysical and cosmological observations, the extracted limits on the ν_h–ν_e mixing matrix element U_{eh} span a wider region of sterile neutrino ν_h mass m_h.

References

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