Multipolar correlations and deformation effects on nuclear transition matrix elements of positron double-β decay

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Introduction

The nuclear ββ decay is a rare second order semi-leptonic transition between two even Z-even N isobars ${}^{A}_{Z}X$ and ${}^{A}_{Z\pm2}Y$ involving strangeness conserving charged weak currents. It is expected that the nuclear ββ decay can proceed through sixteen experimentally distinguishable modes, namely double-electron emission ($\beta^-\beta^-$), double-positron emission ($\beta^+\beta^+$), electron-positron conversion ($\varepsilon\beta^+$) and double-electron capture (εε) with the emission of two neutrinos, no neutrinos, single Majoron and double Majorons. The $\beta^+\beta^+$, $\varepsilon\beta^+$ and εε processes are energetically competing and we shall refer to them as $e^+\beta\beta$ modes. The two neutrino double beta $(\beta\beta)_{2\nu}$ decay conserves the lepton number L exactly and is an allowed process within the standard model of electroweak unification (SM). In the $(\beta\beta)_{0\nu}$ decay, the lepton number is violated by two units and it is possible in models beyond the SM. The present experimental efforts are directed towards its observation, which would immediately imply that neutrinos are massive Majorana particles.

Presently, the $(\beta^-\beta^-)_{2\nu}$ decay has been already observed experimentally in ten nuclei, out of 35 possible candidates and the validity of nuclear models employed to study the ββ decay can be tested by comparing the theoretically calculated (NTMEs) $M_{2\nu}$ with those extracted from the observed half-lives. However, $(e^+\beta\beta)_{2\nu}$ modes have not been observed so far and experimental limits on half-lives have been given for 24 out of 34 possible isotopes. The observation of $e^+\beta\beta$ decay modes will further constrain the nuclear models.

The projected Hartree-Fock Bogoliubov (PHFB) model, in conjunction with the pairing plus quadrupole-quadrupole (*PQQ*) interaction, has been successfully applied to study the $(\beta\beta)_{2\nu}$ as well as $(\beta\beta)_{0\nu}$ decay [1-6]. In the PHFB model, the existence of an inverse correlation between the quadrupolar deformation and the size of NTMEs $M_{2\nu}$ has been confirmed [1-3]. In addition, it has been also observed that the NTMEs are usually large in the absence of quadrupolar correlations. With the inclusion of the quadrupolar correlations, the NTMEs are almost constant for small admixture of the *QQ* interaction and suppressed substantially in realistic situation. The effect of hexadecapolar correlations on the NTMEs of $(\beta^-\beta^-)_{2\nu}$ as well as $(\beta^-\beta^-)_{0\nu}$ modes has been studied in our earlier work [5] where we have shown that effect of including the hexadecapole interaction channel is minor both on the deformation parameters β_2 and on NTMEs. In the present work, we study the effect of hexadecapole interaction on the NTMEs for $e^+\beta\beta$ modes of ^{96}Ru, ^{102}Pd, ^{106,108}Cd, ^{124,126}Xe, ^{130,132}Ba and ^{156}Dy isotopes for the $0^+\to0^+$ transition.

Theoretical framework

In the case of ^{96,102}Ru, ^{96}Mo, ^{102,106,108}Pd and ^{106,108}Cd nuclei, we treat the doubly even ^{76}Sr (N=Z=38) nucleus as an inert core with the valence space spanned by $1p_{1/2}$, $2s_{1/2}$, $1d_{3/2}$, $1d_{5/2}$, $0g_{7/2}$, $0g_{9/2}$ and $0h_{11/2}$ orbits for protons and neutrons. For ^{124,126,130,132}Xe, ^{124,126}Te, ^{130,132}Ba, ^{156}Dy and ^{150}Gd nuclei, the doubly even ^{100}Sn (N=Z=50) nucleus is treated as an inert core with the valence space spanned by $2s_{1/2}$, $1d_{3/2}$, $1d_{5/2}$, $1f_{7/2}$, $0g_{7/2}$, $0h_{9/2}$ and $0h_{11/2}$ orbits for protons and neutrons.

The effective two-body interaction used in the present work is pairing plus quadrupole-quadrupole plus hexadecapole-hexadecapole (*PQQHH*) type and the Hamiltonian is given as

$$H = H_{s.p.} + V(P) + \varsigma_{qq}[V(QQ) + V(HH)]$$

where $H_{s.p.}$, $V(P)$, $V(QQ)$ and $V(HH)$ denote the single particle Hamiltonian, pairing, quadrupole-quadrupole and hexadecapole-hexadecapole part of the effective two-body interaction. The ς_{qq} is an arbitrary parameter and is introduced to study the role of deformation by varying the strength of *QQHH* interaction.

Results and discussions

The parameters of *PQQHH* interaction Hamiltonian are fixed so as to obtain the spectra of considered nuclei in optimum agreement with the experimental results. The theoretical spectra is taken to be the optimum one if the excitation energy of the 2^+ state E_2^+ is reproduced as closely as possible to the experimental value. Subsequently, we employ the same wavefunction to examine the role of hexadecapole interaction on the NTMEs of $(e^+\beta\beta)_{2\nu}$ decay modes of ^{96}Ru, ^{102}Pd, ^{106,108}Cd, ^{124,126}Xe, ^{130,132}Ba and ^{156}Dy isotopes for the $0^+\to 0^+$ transition and the results are presented in table 1.

Table 1: Calculated NTMEs $M_{2\nu}$ for the $0^+\to 0^+$ transition of $(e^+\beta\beta)_{2\nu}$ decay modes.

Nuclei	$M_{2\nu}$ (*PQQ*)	$M_{2\nu}$ (*PQQHH*)
^{96}Ru	0.0537	0.0479
^{102}Pd	0.0524	0.0354
^{106}Cd	0.0819	0.0573
^{108}Cd	0.0952	0.0703
^{124}Xe	0.0525	0.0411
^{126}Xe	0.0487	0.0379
^{130}Ba	0.0415	0.0281
^{132}Ba	0.0522	0.0329
^{156}Dy	0.0138	0.0098

From table 1, one can notice that in the case of $(e^+\beta\beta)_{2\nu}$ decay modes, the NTMEs calculated with *PQQHH* interaction get reduced by 11–37% approximately in comparison with those calculated with *PQQ* interaction. The minimum and maximum changes occur for ^{96}Ru and ^{132}Ba isotopes respectively. It will be more interesting to investigate the effect of hexadecapolar correlations on the NTMEs of $(e^+\beta\beta)_{0\nu}$ modes of ^{96}Ru, ^{102}Pd, ^{106}Cd, ^{124}Xe, ^{130}Ba and ^{156}Dy isotopes. The work is in progress and the detailed results will be presented in the symposium.

Conclusions

To summarize, we employ the PHFB model using *PQQHH* type of effective two-body interaction to construct the yrast band wave functions of parent and daughter nuclei undergoing $e^+\beta\beta$ decay. The overall agreement between the calculated and observed yrast spectra as well as electromagnetic properties of the nuclei suggests that the PHFB wave functions generated by fixing the parameters of *PQQHH* interaction to reproduce the E_2^+ are quite reliable. Subsequently, we employ the same wave functions to study the $e^+\beta\beta$ decay of considered nuclei. It is observed that the effect of including the hexadecapole interaction is substantial on the NTMEs of $(e^+\beta\beta)_{2\nu}$ modes.

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