Shell Model Study of Allowed and Forbidden Beta Decays

Anil Kumar*
Department of Physics, Indian Institute of Technology Roorkee, Roorkee 247667, India

Introduction

The nuclear β decay can be considered as a mutual interaction between the hadronic and leptonic currents mediated by a massive $W^{\pm}$ vector bosons. These currents can be expressed as mixtures of the vector and axial-vector contributions. The values of the weak vector and axial-vector coupling constants $g_{\rm A}$ and $g_{\rm V}$ enter the theory of β-decay when the hadronic current is renormalized at the nucleon level. The conserved vector-current (CVC) hypothesis and partial conserved axial-vector-current (PCAC) hypothesis yield a bare-nucleon value of $g_{\rm A} = 1.27$ and $g_{\rm V} = 1.00$, respectively. But the value of $g_{\rm A}$ is affected inside nuclear matter by nuclear many-body, delta-nucleon, and mesonic correlations. The quenched or enhanced value of $g_{\rm A}$ plays an important role when data on astrophysical processes, single beta decays, and double beta decays are to be reproduced by nuclear many-body calculations. In the single β decays, the decay rate depends on the second power of $g_{\rm A}$, while to the fourth power for $\beta\beta$ decays. The problem of the electron spectral shapes for the forbidden β-decay is connected to the uncertainty of the effective value of $g_{\rm A}$.

The aim of the present thesis is to study for the computation of the partial half-life and electron spectral shapes for the case of forbidden nonunique β^- decay transitions for the different regions of the nuclear chart [1]. Further, to access the more accurate results of the β decay from the theoretical side, we have included the next-to-leading-order corrections in the shape factor for the forbidden nonunique β decay. Also we have analyzed the spectrum-shape method (SSM) to extract the information of the effective value of the axial-vector coupling constant $g_{\rm A}$. Further, we have enhanced the SSM by constraining the small vector nuclear matrix element by tuning this matrix element to reproduce known experimental partial half-life. More details about these four novel works are summarized below.

Overview of present thesis work

We have reported a systematic study of the logft values, shape factors and electron spectra for the second-forbidden nonunique β^- decays of ^{24}Na(4^+) $\rightarrow^{24}$Mg(2^+) and ^{36}Cl(2^+) $\rightarrow^{36}$Ar(0^+) transitions in the framework of the nuclear shell-model [2]. We have performed the shell-model calculations in the sd model space, using more recent microscopic effective interactions such as Daejeon16, chiral N3LO, and JISP16. These interactions are derived from the no-core shell-model wave functions using Okubo-Lee-Suzuki transformation. For comparison, we have also shown the results obtained from the phenomenological USDB interaction. To test the predictive power of these interactions first we have computed low-lying energy spectra of parent and daughter nuclei involved in these transitions. The computed results for energy spectra, nuclear matrix elements, logft values, shape factors, electron spectra and decomposition of the integrated shape factor are reported and compared with the available experimental data.

Apart from, we present a theoretical study of the electron spectral shapes for the second-forbidden nonunique β^--decay transitions ^{59}Fe($3/2^-$) $\rightarrow$ ^{59}Co($7/2^-$) and ^{60}Fe(0^+) $\rightarrow$ ^{60}Co(2^+) in the framework of the nuclear shell model [3]. We have computed the involved wave functions by carrying out a complete $0\hbar\omega$ calculation in the full fp model space using the KB3G and GXPF1A effective interactions. When compared with the available

*Electronic address: akumar5@ph.iitr.ac.in

data, these interactions predict the low-energy spectra and electromagnetic properties of the involved nuclei quite successfully. This success paves the way for the computations of the β-decay properties, and their comparison with the available data. We have computed the electron spectral shapes of the mentioned decay transitions as functions of the value of the weak axial coupling $g_{\rm A}$. By comparing these computed shapes with the measured spectral shapes allows them to extract the effective value of $g_{\rm A}$ for these decay transitions. This procedure, coined the spectrum-shape method (SSM) in several earlier studies, complements the method of determining the value of $g_{\rm A}$ by reproducing the (partial) half-lives of decay transitions. Here we have enhanced the original SSM by constraining the value of the relativistic vector matrix element, ${}^{V}\mathcal{M}^{(0)}_{KK-11}$, using the conserved vector-current hypothesis (CVC) as a starting point. Our finding would be a strong incentive to measure the spectral shapes in the future. Also in *sdpf*-valence space, we have performed the nuclear shell-model study of the allowed and first-forbidden β^- decay of ^{46,47}K into the ^{46,47}Ca [4] and found the resonable agreement between theoretical results and experimental data.

In the Pb region, we have performed large-scale shell-model calculations for the first-forbidden β^- decay of ^{207}Hg into the one-proton-hole nucleus ^{207}Tl [5] corresponding to the recently available experimental data from ISOLDE-CERN. We have used the one-particle one-hole ($1p$-$1h$) truncation for both protons and neutrons simultaneously across the doubly-shell closure at ^{208}Pb in the final states of ^{207}Tl. In our calculations, we have also considered the effect of masonic enhancement $\epsilon_{\rm mec} = 2.01 \pm 0.05$ in the rank-0 for the axial-charge matrix element γ_5. Here, we have calculated the $\log ft$ values from the ground-state of ^{207}Hg to the several excited states of ^{207}Tl and obtained a good agreement between the calculations and the experimental data. In the experimental data spin and parity for some states are not yet confirmed, thus based on the shell-model results for the $\log ft$ values we have given the prediction for these states. This is the first theoretical calculation for the $\log ft$ values for these transitions.

For the sd-shell nuclei, we evaluate the allowed β^-- decay properties of nuclei with $Z = 8-15$ systematically under the framework of the nuclear shell-model with the use of the valence space Hamiltonians derived from modern *ab intio* methods, such as in-medium similarity renormalization group and coupled-cluster theory [6]. For comparison we also show results obtained with fitted interaction derived from the chiral effective field theory and phenomenological USDB interaction. Theoretical results of $B(GT)$, $\log ft$ values and half-lives, are discussed and compared with the available experimental data.

Acknowledgments

I would like to thank my Ph.D. supervisor, Prof. Praveen C. Srivastava for his comments, suggestions and guidance during my thesis work. I acknowledge MHRD Govt. of India for providing financial support during Ph.D. thesis work. Also, I would like to thank Prof. J. Suhonen and Prof. T. Suzuki for several useful discussions during this work.

References

[1] A. Kumar, Ph.D. thesis, Indian Institute of Technology Roorkee, Roorkee, India (unpublished) 2021.
[2] A. Kumar, P. C. Srivastava, J. Kostensalo, and J. Suhonen, Phys. Rev. C **101**, 064304 (2020).
[3] A. Kumar, P. C. Srivastava, and J. Suhonen, Eur. Phys. J. A **57**, 225 (2021).
[4] P. Choudhary, A. Kumar, P. C. Srivastava, and T. Suzuki, Phys. Rev. C **103**, 064325 (2021).
[5] A.Kumar and P. C. Srivastava, Nuclear Physics A **1014**, 122255 (2021).
[6] A. Kumar, P. C. Srivastava, and T. Suzuki, Prog. Theo. Exp. Phys. **2020**, 033D01 (2020).