Study of spectroscopic properties of some nuclei participating in a lepton flavor violating process in nuclear shell model

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Introduction

The search for lepton flavor violation in charged lepton decays is a highly sensitive tool to look for physics beyond the Standard Model. The question of lepton flavor non-conservation has been the subject of several review papers [1-4]. Among the possible processes, μ-decays are considered to have the largest discovery potential in most of the standard model extensions. Flavor violating decay processes of muon have been intensively studied and have been probed to high precision due to the fact that muon decay processes are simple and easy to detect and also due to the intense muon source available in experiment.

A prominent process concerning lepton flavor violation is $\mu^- - e^-$ conversion in a muonic atom. When a negative muon is stopped in some material, it is trapped by an atom, and forms a muonic atom. After it cascades down in energy levels in the muonic atom, a muon is bound in its 1s ground state. The fate of the muon is then either decay in orbit $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ or capture by a nucleus of mass number A and atomic number Z, namely

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1) \quad (1)$$

However, in the context of physics beyond the Standard Model, the exotic process of neutrinoless muon capture, such as

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z) \quad (2)$$

is also expected. This process is called $\mu^- - e^-$ conversion in a muonic atom.

The effective interaction

In the present work, we have calculated the spectroscopic properties of some nuclei namely ^{48}Ti, ^{60}Ni and ^{63}Cu and ^{72}Ge participating in lepton flavor violation to judge the validity of the wave functions. These wave functions can then be used to calculate the required NTMEs.

For *pf* shell, the GXPF1 interaction [5,6] is used that provides us with a systematic and yet quite accurate description of ^{48}Ti nucleus in the *pf* shell. This model space consists of four single particle orbits namely $f_{7/2}$, $p_{3/2}$, $f_{5/2}$ and $p_{1/2}$ with single particle energies taken as 8.6240, -5.6793, -1.3829 and -4.137 MeV respectively [7]. The ^{40}Ca nucleus is assumed to be an inert core for this model space. Also, to provide an effective interaction for nuclei in the upper part of the *pf* shell, an effective interaction JUN45 [7] is constructed in the model space consisting of four spherical orbits, namely the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ single-particle orbits. The model space is called *f5pg9* shell. The single particle energies used are -9.8280, -8.7087, -7.8388 and -6.2617 MeV for $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ orbits respectively and ^{58}Ni nucleus is assumed as inert core for this space.

Results and discussion

Using above model space and single particle energies, we have calculated the energies of 2^+, 4^+ and 6^+ states of above nuclei in the ANTOINE shell model code [8] and compared them with the available experimental data. The calculated values are shown in Table 1. we have also calculated reduced transition probabilities BE(2) for $0^+ \rightarrow 2^+$ transition and quadrupole moments Q(2^+) for 2^+ state and calculated values are given in Table 2. In Table 3, the magnetic dipole moments are presented. The detailed results, also comprising BE2 values for all above stated isotopes, will be presented in the symposium.

Table 1- The experimentally observed and theoretically calculated values of excitation energies (E_x) of ^{48}Ti,^{60}Ni, ^{63}Cu and ^{72}Ge isotopes

Nuclei	**J$^\pi$**	**E$_x$ (MeV)**	
		Calcu.	**Exp. [9,10]**
^{48}Ti	2$^+$	0.941	0.983
^{60}Ni	2$^+$	1.634	1.332
^{63}Cu	1/2$^-$	1.375	0.669
^{72}Ge	2$^+$	0.833	0.834

Table 2- Comparison of quadrupole moments (Q) of ^{48}Ti,^{60}Ni, ^{63}Cu and ^{72}Ge isotopes

Nuclei	**J$^\pi$**	**Quadrupole moment (eb)**		
		Q$_1$	**Q$_2$**	**Q$_{exp}$[10,11]**
^{48}Ti	2$^+$	-0.133	-0.207	-0.18
^{60}Ni	2$^+$	-0.076	-0.167	+0.03
^{63}Cu	3/2$^-$	-0.134	-0.188	-0.209
^{72}Ge	2$^+$	+0.164	+0.265	-0.13

Table 3- Comparison of magnetic moments (μ_N) of ^{48}Ti,^{60}Ni, ^{63}Cu and ^{72}Ge isotopes

Nuclei	**J$^\pi$**	**Magnetic moment (μ_N)**		
		μ_{fth}	**μ_{effth}**	**μ_{exp}[10,12]**
^{48}Ti	2$^+$	+0.585	+0.574	+0.90
^{60}Ni	2$^+$	-0.271	-0.189	+0.32
^{63}Cu	3/2$^-$	+3.293	+2.55	+2.223
^{72}Ge	2$^+$	+0.197	+0.216	+0.798

In Table 2, Q_1 and Q_2 correspond to two different choices of the effective charges: (e_p,e_n) = (1.5,0.5) and (1.5,1.1), respectively. It is seen that that the latter choice gives a better description for ^{48}Ti and ^{63}Cu nuclei while choice of Q_1 suits for ^{60}Ni and ^{72}Ge apart of sign. The shell-model results for Ni exhibit a poor agreement with data, primarily due to the missing $f_{7/2}$ orbit. In table 3, the magnetic moment operator used is

$$\boldsymbol{\mu} = g_s\,\boldsymbol{s} + g_l\,\boldsymbol{l}$$

where g_s and g_l are the spin and the orbital g factors, respectively. By using the free-nucleon factors g_s = 5.586, g_l = 1, for protons and g_s = −3.826, g_l = 0 for neutrons, the agreement between calculations (μ_{fth}) and experiment (μ_{exp}) appears to be reasonable. The small deviations present using free nucleon g factors disappear almost when we use effective spin g factors,

$$g(\text{eff.})_s = 0.7g(\text{free})_s\,.$$

Here, the "quenching" factor q_s = 0.7 is determined via a least squares fit to the experimental data [12]. In column 4, μ_{effth} are shown.

Conclusion

To summarize, we have calculated the spectroscopic properties of ^{48}Ti, ^{60}Ni, ^{63}Cu and ^{72}Ge isotopes isotopes in *pf* and f_5pg_9 model spaces.
Complete results will be presented in the symposium.

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Acknowledgment

One of the authors KC thanks DST-SERB, India for financial support vide file No. EMR/2016/006748.