Systematic shell model study of $1f_{7/2}$-shell V isotopes

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Introduction

The study of $1f_{7/2}$-shell nuclei has generated a renewed interest because these nuclei provide a unique opportunity to investigate the interplay of single particle and collective excitations. Near the middle of the $1f_{7/2}$ shell, the number of valence particles/holes is large enough to lead to collective behavior. The collectivity in the ground state therefore, increases towards the middle of the $1f_{7/2}$ shell and starts to disappear while approaching the doubly magic nucleus ^{56}Ni, as nuclei evolve towards a spherical shape.

Strong collectivity near ground state, rotation-like band structure, shape transitions towards triaxial and non-collective deformations, band terminating states, and back bending phenomena have been observed in a few nuclei near mid $1f_{7/2}$ shell [1]. In heavier well-deformed nuclei, a microscopic shell model interpretation of this rotational motion is so far found to be impractical due to the huge dimensionalities of the valence spaces. The region around A~40, is therefore important to obtain such view of rotation. For these nuclei, with ^{16}O or ^{40}Ca as an inert core, the *sd-fp* or *fp* valence space is large enough to develop collective rotation, yet small enough to be approached from the shell-model perspective. Spectroscopy of $1f_{7/2}$ nuclei thus provides a good test for the effective interactions used in shell model calculation. It also helps us to better understand the origin and evolution of the *sd-fp* shell gap, which has generated renewed interest recently.

The region around A~40 has been studied extensively using shell model. In particular, the natural parity states of the *fp* shell nuclei have been successfully explained using KB3 [2] effective interaction developed for the *fp* valence space. The unnatural parity states have been studied using *sdpf* [3] interaction developed for the *sd-fp* valence space by making suitable changes in the Hamiltonian to take into account the cross shell interactions. In most cases therefore, two different interactions are generally used to explain the natural and unnatural parity states in lower-*fp* shell nuclei. So, our primary motivation is to use a single interaction for these natural and unnatural parity states. In our previous studies, we have successfully explained the excited states of *sd*-shell nuclei using *sdpfmw* interaction [4]. We wish to extend our studies to lower-*fp* shell nuclei using this interaction. In our present work, we have chosen Vanadium isotopes for this study. The present study will be further extended to incorporate other lower-*fp* shell nuclei.

Shell Model Calculation

Large Basis Shell Model calculations have been done using the code OXBASH [5] to reproduce the states of interest in a few V isotopes. KB3 effective interaction [2] developed for the *fp* major shell above ^{40}Ca core has been used in our calculations to reproduce the natural parity states. Natural parity is defined as the parity that results from the (odd/even) number of particles in the *fp* shell, without any cross-shell excitation.

For reproducing the unnatural parity states (parity that results from cross shell excitations), cross shell excitation from the neighboring *sd* major shell becomes essential. We have therefore, performed shell model calculation using the *sdpfmw* interaction [4] developed for the *sd-fp* major shell above ^{16}O core for both natural and un-natural parity states. For calculations involving the unnatural parity states, we have only excited one nucleon from the neighboring $1d_{3/2}$ orbital into the *fp* major shell. In order to overcome dimensionality constraint, different particle restrictions in the *fp* orbitals have been used to reproduce these levels. The mass normalization factor for *sdpfmw* interaction [4], defined as the number of particles up to *sd* major shell, has been taken accordingly.

Results and Discussions

In the present work, we have considered a few V isotopes to investigate the effectiveness of the *sdpfmw* interaction [4]. Only the yrast natural and un-natural parity states of these isotopes are considered for shell model calculations. A comparison between experimental level energies of the natural parity states and those obtained using KB3 [2] and *sdpfmw* [4] interaction for ^{46}V, ^{47}V and ^{48}V has been presented in Fig.1(a), 1(b) and 1(c), respectively. It is seen from Fig.1 that, the shell model energies agree well with the experimental energies for KB3 interaction [2]. The results for *sdpfmw* interaction [4] show a good agreement between the shell model and experimental levels for low spins. But, for the high spin states, shell model energies start to deviate considerably.

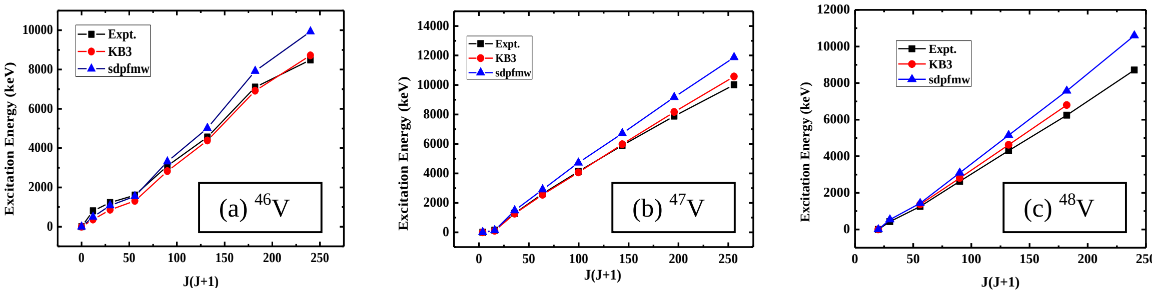

Fig. 1 Comparison between experimental and shell model results of (a) ^{46}V, (b) ^{47}V and (c) ^{48}V.

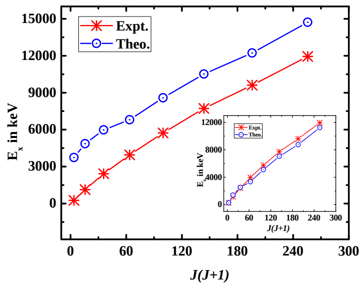

Fig.2 Comparison between experimental and shell model unnatural (positive) parity states of ^{47}V. The same comparison after normalization is shown in the inset.

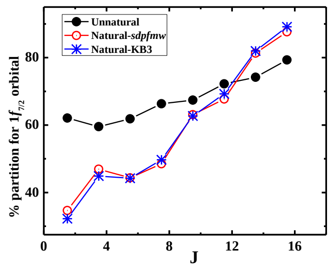

Fig.3 % partition of maximum filled $1f_{7/2}$ orbital for different natural and unnatural parity states in ^{47}V.

The same comparison for unnatural parity states has been made for ^{47}V in Fig.2. It is seen from the plot that although the rotation-like band is well reproduced by *sdpfmw* interaction [4], the level energies are significantly and consistently higher compared to the experimental ones. It has also been found from our calculations that, if we normalize the lowest unnatural parity state with the experimental state, then the level energies at higher spin are under predicted, as shown in the inset of Fig.2. Similar results have also been found in $^{48-49}$V. We have also investigated the wave functions of these states generated from *sdpfmw* [4] and KB3 [2] interaction. In Fig.3, we have plotted the % partition of maximum filled $1f_{7/2}$ orbital as a function of the total angular momentum for both natural and unnatural parity states in ^{47}V. It is seen that the % occupation of $1f_{7/2}$ orbital increases at higher spins. Thus, we have to optimize the shell gap between the *sd* and *fp* major shell as well as the energy gap between the *fp* orbitals to improve the results. The electro-magnetic properties of the decay out transitions from these levels will also be studied.

Conclusion

KB3 and *sdpfmw* interactions have been used to reproduce the states of interest in $^{46-48}$V. The results for natural parity states using KB3 interaction is in good agreement with the experimental results. The rotation-like band structures have been well reproduced using both the interactions. However, the results for high spin natural and all unnatural parity states using *sdpfmw* interaction are predicted consistently higher than the experimental values, which point towards the need to readjust the *sd-fp* shell gap and SPEs of each of the *fp* orbital.

Acknowledgements

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