Interplay between single particle and collective excitation in $^{49}$V

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Abstract. High spin states of $^{49}$V populated through $^{48}$Ti($^3$He, 2np)$^{49}$V reaction with 48 MeV $^3$He beam, have been studied using the Indian National Gamma Array (INGA) facility. The relative intensities, $R_{DCO}$ and polarization measurements have been carried out for a few transitions in $^{49}$V. The level lifetimes have been extracted for a few negative parity yrast levels using Doppler shift attenuation method. Large basis shell model calculations have been performed to understand the microscopic structure of these levels.

Introduction

The study of $1f_{7/2}$ shell nuclei has generated new interests due to the recent employment of sophisticated techniques of gamma spectroscopy. The total number of valence particles/holes in $1f_{7/2}$ shell are 16 and near the middle of the $1f_{7/2}$ shell, the number of valence particles/holes ~8 which is large enough to lead to collective behaviour. The collectivity in the ground state, therefore, increases towards the middle of the $1f_{7/2}$ shell and starts to disappear rapidly when approaching the doubly magic nucleus $^{56}$Ni as nuclei evolve towards a spherical shape [1]. Strong collectivity has been observed near the ground state in $^{48}$V [2]. Rotational-like band structure have also been observed in a few nuclei around $^{48}$Cr [1]. Shape transitions towards triaxial and non-collective deformations have been observed at higher spins of these nuclei due to the alignment of valence nucleons in $1f_{7/2}$ shell [1]. Band terminating states, corresponding to fully aligned $1f_{7/2}$ configurations and back bending phenomena have also been observed in a few $1f_{7/2}$ nuclei [1,3] and explained successfully in shell model calculations [4]. $^{49}$V has 9 nucleons (3 protons + 6 neutrons) in the $1f_{7/2}$ orbital. Therefore, one may expect the interplay between collective and single particle excitations in $^{49}$V.

$^{49}$V has been substantially investigated through proton, deuteron, and alpha induced reaction [1]. However, only a few experimental data are available where heavy ion beams were used [1]. Recently, $^{48}$V, populated through heavy ion induced reaction, was studied by D. Rodrigues et al. [5]. They have extended the level scheme up to 13 MeV and assigned the spins and parities of most of the levels. They have established the negative parity yrast band up to the band terminating state $27/2^-$. But the lifetimes of these yrast levels are not known. Our primary motivation was to study the different modes of excitation of this band. Exact information on level lifetime is necessary for such study. In the present work, we have measured the lifetimes of a few levels of this band. The relative intensities, $R_{DCO}$ and polarization measurements have also been carried out for the decay out transitions to confirm their previous assignments. Large Basis Shell Model (LBSM) calculations with
different particle restrictions in the valance orbitals have been carried out to understand the microscopic origin of these levels.

In the following sections, we have discussed in detail about the experiment, data analysis techniques, experimental results and theoretical investigations using LBSM calculations.

![Graph](image1.png)

**Fig. 1:** A total projection spectrum and background subtracted coincidence spectrum obtained by putting a gate on 1022-keV transition. Transitions of interest are marked by (red) asterisks.

![Graph](image2.png)

**Fig. 2:** Expt. (a) $R_{\text{DCO}}$ and (b) $\Delta_{\text{IPDCO}}$ values of the decay out transitions from the yrast negative parity band as a function of gamma energy.

**EXPERIMENTAL DETAILS AND DATA ANALYSIS**

High spin states of $^{49}$V were populated through $^{48}$Ti($^4$He, 2np)$^{49}$V fusion evaporation reaction at $E_{\text{lab}}$=48 MeV. The $^4$He beam was provided by the K-130 Cyclotron at Variable Energy Cyclotron Centre (VECC) Kolkata. The experiment was carried out on a self-supported natural Ti target (12.4 mg/cm$^2$). The target thickness was chosen in such a way that ~ 95% of the recoils were stopped in the target. A multi-detector array (INGA setup), comprising of 6 Compton suppressed clovers and 2 Leps were used to detect the gamma rays. These six clovers were mounted at three different angles, viz., 125°(2), 90°(3), and 40°(1), with respect to the beam axis. The two Leps were mounted at 90° and 40°.

About 10$^7$ two-fold $\gamma-\gamma$ coincidence events were recorded in list mode using a digital data acquisition system. The pulse processing and data acquisition system was that of UGC-DAE CSR, Kolkata Centre, and was based on the 250 MHz 12-bit PIXIE 16 digitizers (XIA LLC) [6]. The raw data have been sorted using the sorting program IUCPIX [6] to generate symmetric and asymmetric matrices, which have been then analysed using INGASORT [7]. Singles data were collected in list mode for relative intensity and angular distribution measurement. Energy and relative efficiency calibrations of the detectors were performed with $^{152}$Eu and $^{133}$Ba radioactive sources.

**Result and Discussion**

1. **Level Scheme**

In order to investigate the level scheme of $^{49}$V, angle-independent and -dependent (90°C vs 90°C) symmetric matrices have been used. A total projection spectrum, as well as a typical gated spectrum, are shown in Fig. 1. We have confirmed the reported negative parity yrast band in $^{49}$V based
on the coincidence relationship, relative intensities, R_{DCO}, and Δ_{IPDCO} values of the respective decay out gamma transitions. Since these transitions viz. 1241, 1479, 1946, 1153 and 956-keV show large Doppler shift, the relative intensities of these transitions were determined from the 1022-keV gated spectrum generated from the 90°-90° symmetric matrix. The spins of the excited levels in the yrast negative parity band in ^{49}V have been confirmed from R_{DCO} measurements. The DCO ratio (R_{DCO}) [8] of a γ transition is defined as the ratio of intensities of that γ ray for two different angles (θ & 90°) in coincidence with another γ ray of known multipolarity. In this analysis, the DCO ratios have been determined for θ=125°. For stretched transitions of the same multipolarity, DCO value is close to unity and for a stretched dipole (quadrupole) transition gated by a pure quadrupole (dipole), it is nearly 0.60 (1.65). For a mixed transition, it deviates from unity or 0.60 (1.65). Here, we have extracted the R_{DCO} of 1022, 1241,1946, 1153 and 956-keV transitions from 417-keV (ΔJ=1) gated spectrum. The results are shown in Fig. 2 (a). The R_{DCO} of 1479-keV transition was measured from 956-keV (ΔJ=1) gated spectrum.

In order to confirm the parities of the excited levels, polarization measurement has been carried out. We have measured the polarization asymmetry (Δ_{IPDCO}) [9] for these transitions. A positive (negative) value of Δ_{IPDCO} indicates the electric (magnetic) nature of the transition. The results are shown in Fig. 2 (b). It confirms the electric quadrupole nature of 1241, 1479, and 1946-keV transitions and the magnetic dipole nature of 1153 and 956-keV transitions.

![Experimental and simulated line-shape spectra for different angles](image)

Fig. 3: Experimental (black) and simulated (red) line-shape spectra are shown for (a) 1241-keV, (b) 1479-keV, and (c) 1946-keV transitions for different angles as mentioned in the figure.

2. Lifetime measurement

The energy spectra for γ transitions from 2263, 3742, 5688, 6841, and 7797-keV levels in ^{49}V were not fully shifted but had a large Doppler-shifted component along with a stopped component. In the present work, we have extracted the lifetimes of a few of them from line-shape analysis. The modified version of computer code LINESHAPE [10] has been used to extract the level lifetime from Doppler shifted spectra. The initial recoil momenta distributions of ^{49}V have been obtained from PACE4 [11] calculation. In the first step of the LINESHAPE program, the slowing-down histories of the 50000 ^{49}V recoiling nuclei in the natural Ti target (ρ=4.4 gm/cm^3) were simulated using the Monte Carlo technique. The velocity profiles of the recoils were generated with a time step of 0.0007 ps. The detector geometry was also taken into account. In the second step, using the stopping powers and the velocity distributions calculated in the first step, a line-shape for each decay time was obtained. In the
final step, the best fitted theoretically generated line-shapes to the experimental ones were obtained by varying the level lifetimes utilizing a \( \chi^2 \)-minimization technique. In this measurement, shell-corrected Northcliffe and Schilling stopping powers [12] were used for calculating the energy loss of ions in matter.

Usually, in line-shape analysis, the angle-dependent line-shape spectra are generated by putting a gate above the transition of interest (GTA) to remove the side feeding effect. However, generation of gated spectra using a transition above the transition of interest was not always possible due to their low population yields. In the present work, the level lifetimes of 2263, 3742, and 5688-keV levels have been extracted using spectra generated by putting gates on 1022-keV transition (GTB: gate below the transition of interest). The side feeding intensities have been estimated from the relative intensities of the feeding and decay out transitions. In the present work, we have measured the lifetimes of 3742 and 5688-keV levels from the Doppler shifted spectra of 1479 and 1946-keV transitions, respectively. These shifted spectra were generated for three different angles by putting a gate on the 1022-keV transition (Fig. 3). The mean life of 2263-keV level (938\(+548\) - 139 fs) has been reported earlier with a large uncertainty [1]. In the present work, we have re-measured the lifetime of 2263-keV level from the Doppler shifted spectra of 1241-keV transition (Fig. 3). The preliminary results of the lifetimes, the B(E2) strengths, quadrupole deformation (\( \beta_2 \)) and X (major to minor axis ratio of an ellipsoid) [13] are shown in Table-1. The quadrupole deformation (\( \beta_2 \)) and X are calculated from the intrinsic quadrupole moment (\( Q_2 \)) obtained from line-shape analysis. The results clearly show that the collectivity decreases with angular momentum. In order to make more concrete comments on the interplay between different modes of excitations with varying excitation energies and angular momenta, we need to know the lifetimes of 6841 and 7797-keV levels. The analysis is going on to find out the lifetimes of these levels. Line-shape analysis with GTA (gate above the transition of interest) spectra will be performed to reduce the uncertainty due to side feeding.

**Table-1:** Experimental level lifetimes, B(E2) strengths together with quadrupole deformation (\( \beta_2 \)) and X for the yrast negative parity band in \(^{49}\text{V} \). The unit of B(E2) is \( e^2\text{-fm}^4 \).

| \( E_x \) (keV) | \( E_f \) (keV) | \( J_i \) | \( J_f \) | \( \tau \) (fs) | \( \tau \) (fs) | \( B(E2) \) Present | \( B(E2) \) Earlier [1] | \( \beta_2 \) | X |
|-----------------|----------------|---------|---------|-------------|-------------|-------------------|-------------------|---------|-----|
| 1022            | 1022           | 11/2    | 7/2     | -           | 4906(886)   | -                 | 146(30)           | -       | -   |
| 2263            | 1241           | 15/2    | 11/2    | 1402(255)   | 938\(+548\) | 193(40)           | 289(171)          | 0.28    | 1.30|
| 3742            | 1479           | 19/2    | 15/2    | 758(139)    | -           | 71(15)           | -                 | 0.22    | 1.23|
| 5688            | 1946           | 23/2    | 19/2    | 422(74)     | -           | 66(13)           | -                 | 0.14    | 1.14|

### 3. Theoretical calculation

Large-basis shell-model calculations have been done using the code OXBASH [14] to understand the microscopic origin of the negative parity yrast band in \(^{49}\text{V} \). The valence space consists of full \( fp \) shell for both protons and neutrons above the \(^{40}\text{Ca} \) inert core. The number of valence particles (protons + neutrons) in \(^{49}\text{V} \) is 9. The KB3 effective interaction [15] developed for the \( fp \) major shell above \(^{40}\text{Ca} \) core has been used for the calculation. In Fig. 4(a), we have compared the calculated energies of the negative parity yrast levels with the experimental energies. It shows a very good agreement between the results of shell model calculation and experiment. The calculated B(E2) values also agree well with the experimental values (Fig. 4(b)). In this calculation, effective charges
$e_p = 1.5e$ and $e_n = 0.5e$ and the free values of $g$ factors have been used. A detailed analysis of the calculated wave functions are being carried out to understand the interplay of collective and single particle excitations.

#### Conclusion

The negative parity yrast band of $^{49}$V populated through $^{48}$Ti($^4$He, 2np)$^{49}$V reaction with 48 MeV $^4$He beam, have been studied using the Indian National Gamma Array (INGA) facility. The relative intensities, $R_{DCO}$ and polarization measurements have been carried out for the decay out transitions to confirm their multipolarities. A preliminary estimate of the lifetimes of 2263, 3742, and 5688-keV levels have been done. Large basis shell model calculations have been performed to understand the microscopic origin of these levels. Detailed analysis is in progress.

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