Indian Journal of Pure & Applied Physics
Vol. 57, September 2019, pp. 634-637

Study of band structures of ^{78}Kr using triaxial projected shell model

N Behera[a], G H Bhat[b], Z Naik[a*], R Palit[c], Y Sun[d] & J A Sheikh[e]

[a]School of Physics, Sambalpur University, Burla 768 019, India
[b]Government Degree College, Kulgam 192 231, India
[c]Tata Institute of Fundamental Research, Colaba, Mumbai 400 005, India
[d]Department of Physics and Astronomy, Shanghai Jiao Tong University 200 240, Shanghai
[e]Department of Physics, University of Kashmir, Srinagar 190 006, India

Received 3 July 2019

The study of neutron-deficient Kr isotopes in the mass range A=70 - 80 is quite interesting because these isotopes show a variety of shapes and shape co-existence have been seen in this mass region. In present work, the multi-quasi particle triaxial projected shell model (TPSM) approach is employed for investigation of the yrast and γ-band of ^{78}Kr. The calculated band-energies are compared with known experimental data. The γ-band and 2γ-band are predicted up to spin I=26 h. Calculations show change in staggering phases due to configuration mixing at high spins. The calculated kinematical moment of inertia (MOI) for the yrast band is compared with the available experimental data.

Keywords: Shape co-existence, Multi-quasi particle, Triaxial projected shell model, Configuration mixing

1 Introduction

The study of nuclear shapes and deformations has been a topic of interest since the identification of nucleus. In general nuclei possess axially symmetric (prolate/oblate) shapes. However, some nuclei are triaxial and for stable triaxial shape, collective rotations of such a nucleus are possible about the entire three axis with unequal moment of inertia. Study of A~80 nuclei is of interest due to the existence of a rich variety of nuclear structure phenomena. Many neutron deficient nuclei in this mass region have large quadrupole deformation in their ground state. Again, in many nulei at proton/neutron numbers 34, 36 and 38 oblate and prolate deformations coexist within few hundred KeV. Several experimental and theoretical investigations show the existence of triaxiality for some nuclei in mass ~80 region[1-3]. In this mass region ^{76}Kr is known to have triaxiality [4, 5]. Also, ^{76}Ge was reported to have rigid triaxial deformation and its staggering behavior in the γ-band is consistent with that of the rigid triaxial model of Davydov and Filippov (DF)[6]. Hence, the nuclei in this region are ideal candidates for the study of shape-mixing and triaxiality.

The isotope ^{78}Kr has been a subject of experimental and theoretical studies for its structure and it has been studied extensively by different theoretical models[5,7-9]. The purpose of present work is to carry out a systematic study of the yrast-band and γ-band structure for ^{78}Kr nucleus using triaxial projected shell model (TPSM)[10-12].

*Corresponding author (E-mail: z.naik@suniv.ac.in)

2 Outline of the Theory

The extended TPSM qp basis consists of angular momentum projected qp vacuum (0-qp) state, two-proton (2p), two-neutron (2n) and 4-quasiparticle (2-proton plus 2-neutron) state, i.e.,

$$\{\hat{P}^I_{MK}|\phi\rangle,\ \hat{P}^I_{MK}\ \hat{a}^\dagger_{p1}\hat{a}^\dagger_{p2}|\phi\rangle,\ \hat{P}^I_{MK}\ \hat{a}^\dagger_{n1}\hat{a}^\dagger_{n2}|\phi\rangle,\ \hat{P}^I_{MK}\ \hat{a}^\dagger_{p1}\hat{a}^\dagger_{p2}\hat{a}^\dagger_{n1}\hat{a}^\dagger_{n2}|\phi\rangle\}\ldots \quad \ldots (1)$$

Where, the three-dimensional angular-momentum operator is given by:

$$\hat{P}^I_{MK} = [(2I+1)/8\Pi^2]\int d\Omega\ \ D^I_{MK}(\Omega)\ \hat{R}(\Omega) \quad \ldots (2)$$

With the Rotational operator:

$$\hat{R}(\Omega) = exp\left|-i\alpha\hat{J}_z\right|\ exp\left|-i\beta\hat{J}_y\right|\ \ exp\ \left|-i\Upsilon\hat{J}_z\right| \quad \ldots (3)$$

Where, $|\phi\rangle$ represents the triaxial qp vacuum state.

For the case of axial-symmetry the qp vacuum state has only K=0, whereas in case of triaxial deformation the vacuum state is a rich superposition of different K-states. The allowed values of the K-quantum number for a given intrinsic state are obtained through the following symmetry consideration. For the symmetry operator,

$\hat{S}$ = exp $|-i\Pi\hat{J}_z|$, we have

$$\hat{P}^I_{MK}|\phi\rangle = \hat{P}^I_{MK}\hat{S}^+\hat{S}\,|\phi\rangle = exp\;|i\Pi(K-k)|\,\hat{P}^I_{MK}|\phi\rangle \quad \dots (4)$$

Where, $\hat{S}$=exp $|-i\Pi k|\phi>|$ and k characterizes the intrinsic states. For the self-conjugate vacuum or 0-qp state, k = 0 and, therefore, it follows from the above equation that only K = even values are permitted for this state. For 2-qp states, the possible values for K-quantum number are both even and odd depending on the structure of the qp state. For the 2-qp state formed from the combination of the normal and the time-reversed states, k = 0 and, therefore, only K = even values are permitted. For the combination of the two normal states, κ = 1 and only K = odd states are permitted. The triaxial deformed vacuum state is composed of K = 0, 2, 4 configurations. The projected bands from these K = 0, 2 and 4 intrinsic states are the dominant components of the ground, γ- and 2γ – bands, respectively.

The triaxially deformed qp states are generated by the Nilsson Hamiltonian:

$$\hat{H}_N = \hat{H}_0 - \frac{2}{3}\hbar\omega\,\{\varepsilon\,\hat{Q}_0 + \varepsilon'(\hat{Q}_{+2} + \hat{Q}_{-2})/\sqrt{2}\} \quad \dots (5)$$

Here, $\hat{H}_0$ is the spherical single-particle Hamiltonian. The parameters ε and ε' describe axial quadrupole and triaxial deformations, respectively. ε and ε' are related to the conventional triaxiality parameter $\gamma = tan^{-1}(\varepsilon'/\varepsilon)$. The pairing plus quadrupole - quadrupole Hamiltonian is used:

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi\sum_\mu \hat{Q}^\dagger_\mu\hat{Q}_\mu - G_M\hat{P}^\dagger\hat{P} - G_Q\sum_\mu \hat{P}^\dagger_\mu\hat{P}_\mu \quad \dots (6)$$

The monopole pairing strength G_M is of the standard form $G_M = [G_1 - G_2(N-Z)/A]A^{-1}$ for neutrons and $G_M = G_1/A$ for protons.

In the present calculation, we have taken G_1=20.25 and G_2=16.20. This choice of G_M is appropriate for the single particle space employed in the model, where three major shells are used for each type of nucleons (N=2, 3, 4 for both neutrons and protons) which are same as those used in literature[13,14] for the same mass region. The quadrupole pairing strength G_Q is proportional to G_M and the proportionality constant is fixed as 0.16 which is same as used in earlier projected shell model (PSM) calculation[15] for the same nucleus ^{78}Kr.

3 Results and Discussion

In the first step of TPSM calculations, the deformed basis space is constructed by solving the triaxially deformed Nilsson potential[16]. In the present work we have employed ε=0.335 and ε'=0.126 in the Nilsson potential to generate the deformed basis for ^{78}Kr. The value of ε and ε' has been chosen so that the behaviour of the yrast band and excitation energy of γ-band is properly described. In the second step, the good angular momentum states are obtained from the deformed basis by employing the three dimensional angular momentum projection techniques.

The projected bands obtained from 0-, 2-, 4-qp states are displayed in Fig. 1. It is observed from Fig. 1 that the projected band from two quasiproton state having K=1 cross the ground band at I=10 and becomes yrast up to I=14. The 4-qp structure having K=0 cross the ground band at I=14 and above I=15, becomes yrast for all the spin values upto I=26.

In the final step, the projected basis is used to diagonalize the shell model Hamiltonian. The lowest three bands obtained after diagonalization for each angular momentum are shown in Fig. 2 along with the available experimental data. Our calculation gives slightly higher excitation energies from spin I=10 to 18. However, theoretical results for the yrast band are overall in good agreement with known data up to spin I=26. For the γ band experimental data are available up to spin I=10 and are well reproduced by TPSM calculations and the theoretically γ band is extended up to spin I=26. The theoretical 2γ band is also predicted up to spin I=26 at an excitation energy of 2.4844 MeV, which may be populated in future experiments.

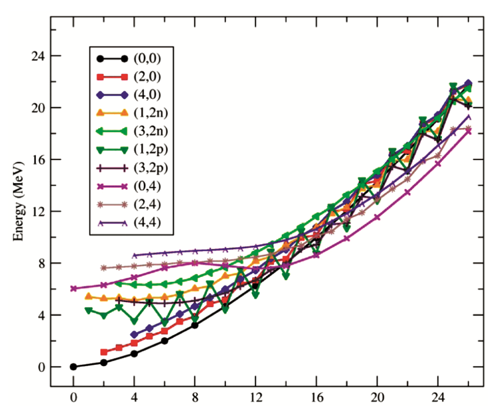

Fig. 1 – Theoretical band diagram for ^{78}Kr. The labels (K, #) characterize the states, with K denoting the K quantum number of quasi particles and '#' represents number of quasi particles of the configuration.

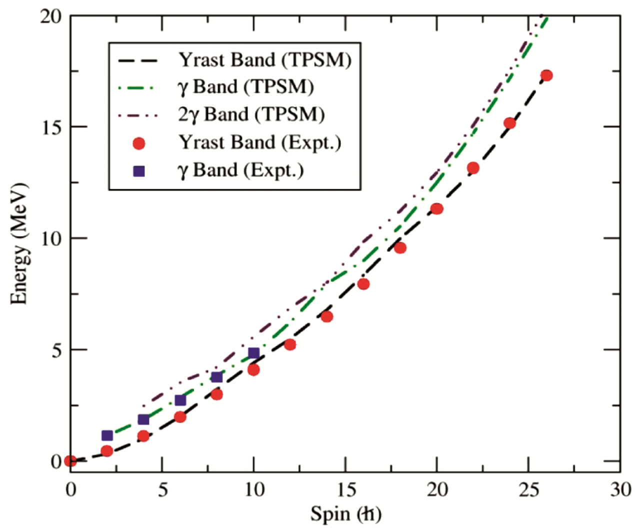

Fig. 2 – Comparison of the calculated band energies with available experimental data.

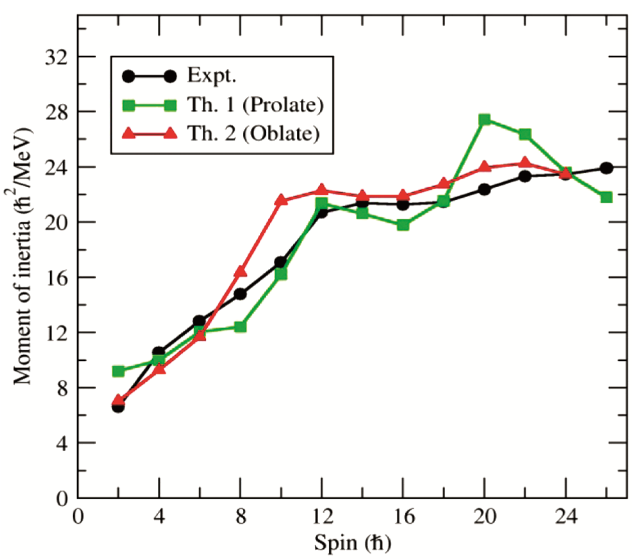

Fig. 3 – Comparison of calculated moment of inertia with available data for yrast band.

Structural changes can be properly understood from the plot of kinematical moment of inertia (MOI) defined as $\vartheta(I)=(2I-1)/E_\gamma(I)$, where $E_\gamma(I)=E(I) - E(I-2)$ is the transition energy. The calculated MOI for the yrast band is shown in Fig. 3 and compared with the available experimental data. The observed band crossing at spin I=12 is reproduced by TPSM result with prolate calculation. The prolate calculation is giving overall good result but slightly deviates from the observed MOI at high spins and a second band crossing is also seen which is not observed experimentally. This may be because of slightly higher excitation energies at high spins in our

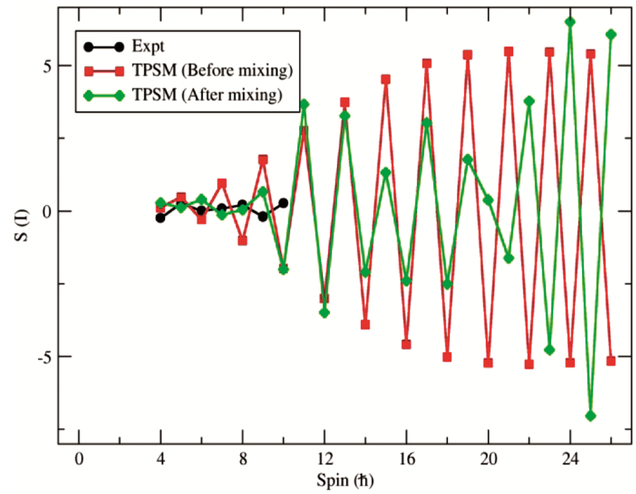

Fig. 4 – Comparison of calculated staggering parameter for the γ band before and after configuration mixing with experimental data.

calculation. To probe the shape changes, TPSM calculations are done for oblate deformation with ε=-0.29 and ε'=0.1 with γ=-19^0.

It is clear from Fig. 3 that the trend of experimental moment of inertia for high spin states are well reproduced with these deformations.

The staggering parameter defined as $S(I)=[\{E(I) - E(I-1)\}- \{E(I-1)-E(I-2)\}] / E(2_1^+)$ is plotted for the γ band in Fig. 4 and compared with the experimental data. It is clear from the figure that the experimental staggering is well reproduced for low lying states. The staggering of ^{78}Kr follows the opposite phase as that of ^{76}Ge and it predicts γ-softness in low spin region. For high spins, the amplitude of oscillation is increasing with spin and shows a change in staggering phases which predicts rigid triaxial shape[6].

4 Conclusions

Theoretical calculations have been done for the lowest two bands of ^{78}Kr using multi-quasiparticle TPSM approach. TPSM results for the yrast and γ band-energies are in good agreement with known experimental energies. The significant change in shapes has been described from MOI plot by taking a triaxial basis. The observed band crossing is well reproduced with polate calculation. However at high spins the experimental MOI matches well with TPSM calculation for oblate deformation. Coexistence of prolate and oblate shapes in the low spin region requires further investigation in both theory and experiment.

Acknowledgement

One of the authors, Dr Z Naik would like to acknowledge DST-FIST, India and this research is supported by Biju Patnaik Research Fellowship Grant awarded to Ms Nirupama Behera under Department of Science and Technology (DST), Odisha.

References

1 Hasegawa M, Kaneko K, Mizusaki & Sun Y, *Phys Lett B*, 656 (2007) 51.
2 Heyde K & Wood J L, *Rev Mod Phys*, 83 (2011) 1467.
3 Clement E, Gorgen A, Korten W, Bouchez E, Chatillon A, Delaroche J -P, Girod M, Goutte H, Hurstel A, Coz Y Le, Obertelli A, Peru S, Theisen Ch, Wilson J N, Zielinska M, Andreoiu C, Becker F, Butler P A, Casandjian J M, Catford W N, Czosnyka T, France G de, Gerl J, Herzberg R D, Iwanicki J, Jenkins D G, Jones G D, Napiorkowski P J, Sletten G & Timis C N, *Phys Rev C*, 75 (2007) 054313.
4 Nazarewicz W, Dudek J, Bengsson R & Rangarsson I, *Nucl Phys A*, 435 (1985) 397.
5 Gross C J, Heese J, Lieb K P, Ulbig S, Nazarewicz W, Lister C J, Billowes B J & Chisti A A, *Nucl Phys A*, 501 (1989) 367.
6 Toh Y & Chiara C J, *Phys Rev C*, 87 (2013) 041304.
7 Billowes J, Cristancho F, Grawe H, Gross C J, Heese J, Mountford A W & Weiszflog M, *Phys Rev C*, 47 (1993) R917.
8 Tripathy K C & Sahu R, *Nucl Phys A*, 597 (1996) 177.
9 Jakhar U R, Yadav H L & Ansari A, *Pramana J Phys*, 65 (2005) 1041.
10 Sheikh J A & K Hara, *Phys Rev Lett*, 82 (1999) 3968.
11 Palit R, Sheikh J A, Sun Y & Jain H C, *Nucl Phys A*, 686 (2001) 141.
12 Sheikh J A, Bhat G H, Palit R, Naik Z & Sun Y, *Nucl Phys A*, 824 (2009) 58.
13 Palit R, Sheikh J A, Sun Y & Jain H C, *Nucl Phys A*, 686 (2001) 141.
14 Sun Y, *Eur Phys J A*, 20 (2004) 133.
15 Verma S, Devi R & Khosa S K, *Eur Phys J A*, 30 (2006) 531.
16 Nilsson S G, *Dan Mat Fys Medd*, 29 (1955) 16.
17 Sun H & Doring J, *Phys Rev C*, 59 (1999) 655.