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luizno.bjp@gmail.com
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Study of Three-Quasiparticle Band in ^{83}Kr

S. Ganguly · Aparajita Dey · P. Banerjee · S. Bhattacharya · R. P. Singh · S. Muralithar · R. Kumar · R. K. Bhowmik

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Abstract Excited states of ^{83}Kr, populated in the ^{76}Ge(^{11}B, $3np\gamma$) reaction at a beam energy of 50 MeV, have been studied. The $\Delta I = 1$ band, built upon the 2,510.0 keV state, has been observed up to 5,639.4 keV with spin (27/2$^-$). Mean lifetimes have been measured up to spin 23/2$^-$ in $\Delta I = 1$ band using the Doppler shift attenuation method. The B(M1) rates derived from the measured lifetimes decrease smoothly with spin indicating that the angular momentum belonging to this band are generated by the shears mechanism.

Keywords ^{76}Ge(^{11}B · $3np\gamma$) reaction at E = 50 MeV · Excited energy levels of ^{83}Kr · Lifetimes by DSA method

S. Ganguly (✉)
Department of Physics, Chandernagore College, Chandernagore, Hooghly, 712136, India
e-mail: sgpresi78@gmail.com

A. Dey
Variable Energy Cyclotron Centre, 1/AF, Bidhannagar, Kolkata, 700064, India
e-mail: aparajita@vecc.gov.in

P. Banerjee · S. Bhattacharya
Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Kolkata, 700064, India

R. P. Singh · S. Muralithar · R. Kumar · R. K. Bhowmik
Inter University Accelerator Center, Aruna Asaf Ali Marg, New Delhi, 110067, India

1 Introduction

Very regular sequences of enhanced magnetic dipole transitions were first observed in the light Pb and Bi isotopes [1–4] and also in nuclei around mass numbers $A = 110$ and 140 [5, 6]. More recently, the regular intense M1 transitions with weak crossover E2 transitions had been observed in $^{82-84}$Rb [7, 8]. These regular sequences of M1 transitions show an energy spectrum that follows $\Delta E(I) = E(I) - E(I_b) \sim A(I - I_b)^2$, where I_b is the spin of the bandhead. This behaviour has been difficult to understand in terms of the rotational model because of the rather small deformation ($\beta_2 < 0.1$) that can be expected for these bands on the basis of the small E2/M1 branching ratios. Observed $B(\mathrm{E2})/B(\mathrm{M1})$ ratios are typically 0.025–0.05 $(eb/\mu_N)^2$. From the lifetime measurement of $\Delta I = 1$ band in these nuclei results a large value of B(M1), of several W.u. at the bandhead. With increase in spin, the B(M1) value decreases smoothly indicating the 'shears mechanism'. The large values of the ratio of the dynamic moment of inertia (J^2) to the reduced E2 transition probability, $J^2/B(\mathrm{E2})$, have also been interpreted in the literature as a fingerprint for a different origin of the inertia in these bands.

Theoretical calculations within the framework of the tilted axis cranking (TAC) model have been performed recently for the nuclei $^{79-83}$Kr [9]. In ^{79}Kr, the calculated B(M1) from the TAC calculation, with the proposed configuration $\pi g_{9/2}(fp)^1 \otimes \nu g_{9/2}$ [9], show a constant value of 0.3 μ_N^2 over a considerable frequency range. This feature has also been noticed in the $\Delta I = 1$ band in ^{79}Br. In ^{81}Kr, the calculated B(M1) rate fairly agrees with the experimental value at higher rotational frequencies. In these two nuclei (^{79,81}Kr), sizable contribution of the collective rotation in the generation of angular momentum has been inferred. The TAC calculation indicates that the $\Delta I = 1$ band in ^{83}Kr, where the neutron number is $N = 47$, and that the magnetic rotation based on oblate shapes is strongly favoured. It has also been inferred [9] that the magnetic rotation (MR) band in ^{83}Kr is probably a good example of MR band based on a shape mixing configuration as predicted by the TAC calculation.

The $\Delta I = 1$ band in ^{83}Kr had been studied and reported in the literature [10, 11]. The lifetime results reported in [11] are smaller than those reported in [10] by about a factor of two. Therefore, a remeasurement of these level lifetimes (built on the 13/2 negative parity state lying at 2.510 MeV excitation energy) has been attempted in the present work, in view of the discrepancies of the previous results as well as to verify the previous TAC prediction.

2 Experimental Details

Excited states of ^{83}Kr were populated in the ^{76}Ge(^{11}B, $3np\gamma$) reaction at a beam energy of 50 MeV at the 15UD Pelletron Accelerator at the Inter University Accelerator Centre (IUAC), New Delhi. The target consisted of isotopically enriched (99%) ^{76}Ge with a thickness of 4 mg/cm^2 evaporated on a 9.5 mg/cm^2 gold foil. About 300 million two and higher fold $\gamma - \gamma$ coincidence data were collected using the Gamma Detector Array (GDA) [12] at IUAC. This array comprised of 12 Compton suppressed high-purity Germanium (HPGe) detectors and a 14-element BGO (Bismuth Germanium oxide) multiplicity filter, at least one of which was required to fire along with at least two HPGe detectors in order to validate a coincidence event.

Gated energy spectra with a dispersion of 0.5 keV per channel were generated from a 4,096 × 4,096 matrix, obtained from sorting the raw data of all 12 HPGe detectors. These spectra were used for the assignment of the γ-rays in the level scheme. The directional correlation of γ-rays deexciting oriented states (DCO ratios) was obtained from other matrices described in [12].

The DCO ratio (R_{DCO}) is defined as

$$R_{\mathrm{DCO}} = \frac{I_\gamma \ \text{at} \ 144^\circ \ \text{gated by} \ \gamma_G \ \text{at} \ 98^\circ}{I_\gamma \ \text{at} \ 98^\circ \ \text{gated by} \ \gamma_G \ \text{at} \ 144^\circ},$$

where I_γ is the intensity of the γ-ray of interest in coincidence with γ_G. The R_{DCO} values were compared with the theoretical DCO ratios for assignment of spin I and the γ-ray multipole mixing ratios δ using the computer code ANGCOR [13]. A width of $\sigma = 0.3I$ (I being the level spin) was used for presumed Gaussian distribution of the magnetic substate population. Gate was set on a strong $\Delta I = 2$ transition (here 1,122.1 keV transition connecting 13/2$^+$ and 9/2$^+$ state [10]).

Level lifetimes (τ) were estimated from the Doppler shift attenuation (DSA) data using the computer code LINESHAPE [14]. The details of the slowing down history of the recoils (moving with a initial recoil velocity $\beta = 0.0125$) in the target and backing were simulated using a Monte Carlo technique, which involved 10,000 histories with a time step of 0.005 ps, and the results sorted according to detector geometry. The shell-corrected stopping powers of Northcliffe–Schiling [15] were used. Effects of feedings from the observed states (discrete feeding) and the continuum (side-feeding) were taken into account in this analysis. The delays due to these feedings and the effects of the large target thickness were also accounted for in the simulation of the lineshapes. The lineshape fitting process was started with the highest observed transition with adequate statistical accuracy. This corresponds to the 651.0 keV transition depopulating the 4,868.4 keV state in the $\Delta I = 1$ band in ^{83}Kr (see Fig. 1). Considering that the feeding time has large uncertainties, only an effective lifetime (stated as the upper limit) was determined. This was then used as an input parameter for the estimation of the lifetimes of the lower-lying states in the band. Side feeding times (τ_{sf}) were taken from similar band in ^{83}Rb populated in the same reaction [16]. The errors in the lifetime results reflect the statistical uncertainties in the data and the 50% uncertainties in the side-feeding times but does not include the systematic errors up to 15%, inherent in the electronic stopping powers.

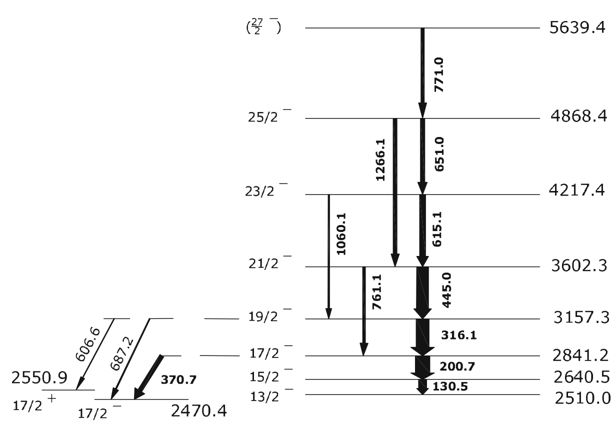

Fig. 1 Partial level scheme of ^{83}Kr. The level and transition energies are given in keV. The width of the *arrows* represent the relative intensity

Table 1 Energies, relative intensities, DCO ratios, γ-ray multipolarities and spin assignments for $\Delta I = 1$ band in ^{83}Kr

E_x (keV)	E_γ (keV)	I_{rel}	R_{DCO}	Gate (keV)	γ-ray multipolarity/ $\delta(E2/M1)$	$J_i^\pi \rightarrow J_f^\pi$
2,841.2	200.7	100 ± 6	0.49 ± 0.06	1,122.1	0.035 ± 0.01	$17/2^- \rightarrow 15/2^-$
	370.7	18.1 ± 3.3			E2	$17/2^- \rightarrow 17/2^-$
3,157.3	316.1	96.0 ± 5.3	0.93 ± 0.07	200.6	0.008 ± 0.03	$19/2^- \rightarrow 17/2^-$
	606.6	2 ± 1			(M1/E2)	$19/2^- \rightarrow 17/2^-$
	687.2	8.3 ± 2.43			(E1)	$19/2^- \rightarrow 17/2^+$
3,602.3	445.0	74.6 ± 5.2	0.94 ± 0.07	316.1	-0.042 ± 0.02	$21/2^- \rightarrow 19/2^-$
	761.1	13.7 ± 3.63			E2	$21/2^- \rightarrow 17/2^-$
4,217.4	615.1	42.9 ± 7.5	1.19 ± 0.14	316.1	-0.21 ± 0.19	$23/2^- \rightarrow 21/2^-$
	1,060.1	11.6 ± 4.4			E2	$23/2^- \rightarrow 19/2^-$
4,868.4	651.0	23.2 ± 5.1	1.22 ± 0.55	316.1	(M1/E2)	$25/2^- \rightarrow 23/2^-$
	1,266.1	35.8 ± 7.1			E2	$23/2^- \rightarrow 19/2^-$
5,639.4	771.0	13.8 ± 3.7		316.1	(M1/E2)	$(27/2^-) \rightarrow 25/2^-$

3 Experimental Results

The $\Delta I = 1$ band built on the $13/2^-$, 2,510.0 keV state has been observed up to an excitation energy of 5,639.4 keV and a tentative spin of $(27/2^-)$ in the present work (Fig. 1). The experimental results for γ-ray energies and intensities, DCO ratios and spin assignments are presented in Table 1 and the level lifetimes and transition probabilities are summarised in Table 2. The present DCO measurement indicates that the 200.7, 316.1 and 445.0 keV γ-ray are all predominantly M1 in nature with small E2 admixture (<1%). The mixing ratio for 200.7 keV γ-ray transition was determined from the R_{DCO} value obtained by gating 1,122.1 keV transition depopulating the 1,122.1 keV state (see level scheme of ^{83}Kr in [10]). Spectra gated by 200.7 keV transition was then used to obtain the mixing ratios of the 316.1, 445.0 and 615.1 keV transitions. No evidence was found for the presence of 1,026.7 and 1,423 keV transitions (see level scheme in [10]) in the present work.

Previously, lifetimes of the $\Delta I = 1$ band in ^{83}Kr were determined by Kemnitz et al. [10] as well as Kudojarov et al. [11]. The results were differed by a factor of two. Mean lifetimes 2.5 ± 0.5, 1.6 ± 0.1, 1.0 ± 0.2 and 0.60 ± 0.13 ps have been determined for the 2,841.2, 3,157.3, 3,602.3 and 4,217.4 keV states, respectively, in the present work. An upper limit of lifetime 1.0 ps has been estimated for the 4,868.4 keV state. The present lifetime results have been compared with the previous estimations [10, 11] in Table 2. The DSA spectra for the 200.7 and 316.1 keV transitions along with the LINESHAPE fitting have been shown in Fig. 2. The data from the backward (144°) and 98° detectors were used in order to estimate the level lifetimes. The fitted DSA spectrum for 445.0 keV transition has been displayed in Fig. 3. The sum gated spectra containing 130.5 and 172.1 keV transitions were utilized to obtain the DSA spectra for 200.7 and 316.1 keV transitions. The 200.7 keV gate has been added along with 130.5 and 172.1 keV transitions (not shown in the present level scheme) used to obtained the DSA spectrum for 445.0 keV transition.

The B(M1) rates determine using the present lifetime and the branching ratio indicate a large B(M1) value of $2.38^{+0.60}_{-0.40}$ μ_N^2 for the $17/2^- \rightarrow 15/2^-$

Table 2 Present experimental results on the mean lifetime (τ), B(M1) for $\Delta I = 1$ band in ^{83}Kr

E_x (keV)	$J_i^\pi \rightarrow J_f^\pi$	τ(ps)			$B(\mathrm{M1})^a$
		Present	Previous [10]	Previous [11]	(μ_N^2)
2,841.1	$17/2^- \rightarrow 15/2^-$	2.5 ± 0.50	–	7.0 ± 2.0	$2.38^{+0.60}_{-0.40}$
3,157.3	$19/2^- \rightarrow 17/2^-$	1.6 ± 0.10	$4.0^{+2.0}_{-1.0}$	$1.7^{+0.9}_{-0.4}$	$1.12^{+0.07}_{-0.07}$
3,602.3	$21/2^- \rightarrow 19/2^-$	1.0 ± 0.20	$1.5^{+0.60}_{-0.40}$	$1.0^{+1.0}_{-0.5}$	$0.54^{+0.14}_{-0.09}$
4,217.4	$23/2^- \rightarrow 21/2^-$	0.60 ± 0.13	$0.8^{+0.5}_{-0.3}$	–	$0.31^{+0.08}_{-0.06}$
4,868.4	$25/2^- \rightarrow 23/2^-$	<1.0	0.9 ± 0.2		$>0.065^b$

[a]Calculated using present lifetime and branching ratio
[b]Assuming a mixing ratio of 0.05

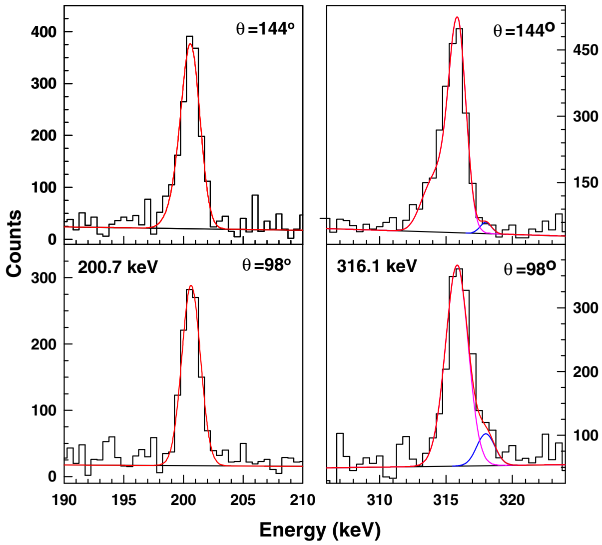

Fig. 2 Gated DSA spectra for the 200.7 keV (*left*) and 316.1 keV (*right*) transitions. The angles at which the spectra were recorded are indicated at the top right-hand corner of each panel. *Continuous lines* are theoretical fits to the experimental data using LINESHAPE. Weak contaminated peak also shown

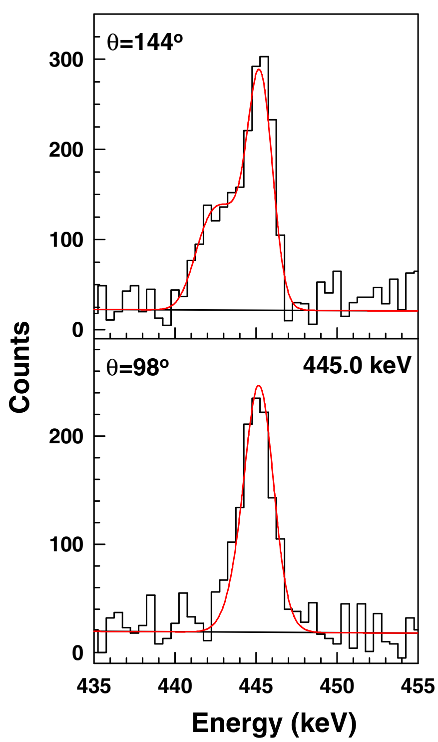

Fig. 3 Gated DSA spectrum for the 445.0 keV transition. The angles at which the spectrum was recorded indicated at the top right-hand corner of each panel. *Continuous lines* are theoretical fits to the experimental data using LINESHAPE

transition and decreases to $0.31^{+0.08}_{-0.06}$ μ_N^2 for $23/2^- \rightarrow 21/2^-$ transition. The B(E2) transition rate was found out to be 24^{+6}_{-4} W.u. for the 3,602.3 keV state and decreases to 10.5^{+3}_{-2} W.u. for the 4,217.4 keV state.

4 Discussions

In the $A = 80$ region, the important high-spin components of the magnetic rotation bands are the $\pi_{9/2}$ proton particles coupled to $\nu_{9/2}$ neutron holes. In ^{83}Kr, the three-quasiparticle configuration suggested by Kemnitz et al. [10] for the $\Delta I = 1$ band built on 2,510.0 keV state is $\nu g_{9/2} \otimes (\pi g_{9/2} + f_{5/2},\ p_{3/2}$ or $p_{1/2})$. Thus, a strongly coupled neutron hole at $g_{9/2}$ and two aligned proton particles give a constructive superposition of their magnetic moments and enhancement of the M1 radiation. The experimental B(M1) rate in ^{83}Kr decreases smoothly with increase in spin as seen from the Fig. 4. Similar decreasing trend in B(M1) rate has also been observed in ^{81}Kr [17]. Although the TAC predicts a smaller B(M1) rates in ^{83}Kr than the experimental value, the decreasing trend is correctly reproduced. Sequences of M1 transitions in ^{82,84}Rb, interpreted as shear bands show a similar behaviour. The J^2/B(E2) ratio for ^{83}Kr is also large, about 118 $\hbar^2$MeV^{-1}(eb)$^{-}$2 at 3,602.3 keV state (spin $21/2^-$). These features strongly favour that the $\Delta I = 1$ band in ^{83}Kr arises due to the magnetic rotation. The quadrupole deformation β_2 was found out to be 0.15 for the 3,602.3 keV state and decreases to 0.10 for the 4,217.4 keV state.

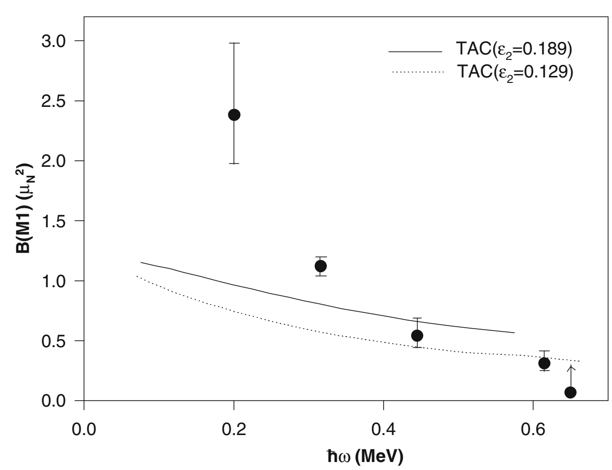

Fig. 4 The variation of B(M1) rate plotted against frequency $\hbar\omega$. The *solid lines* represent the previous TAC calculation results [9]

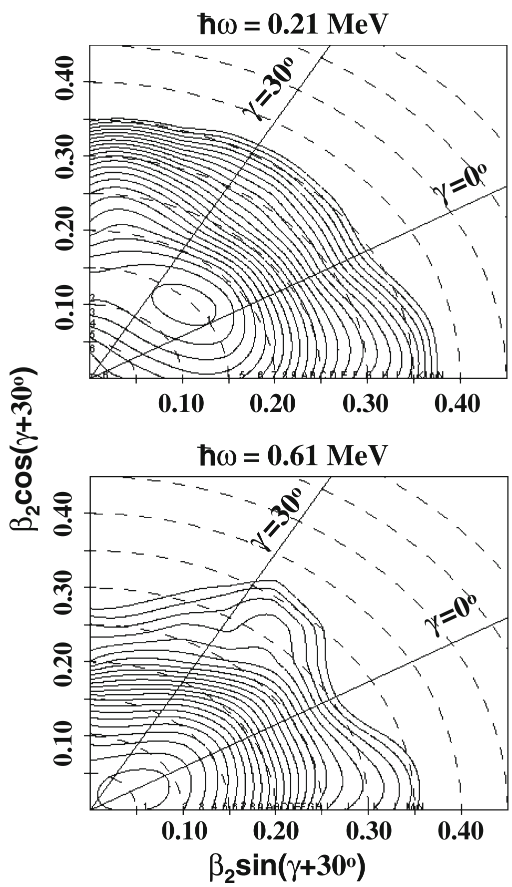

Fig. 5 Total Routhian Surface plots for $\Delta I = 1$ band in the β_2-γ plane for rotational frequencies of **a** 0.21 MeV, **b** 0.61 MeV. The interval between successive contours is 0.50 MeV

The evolution of the total Routhian surface (TRS) with rotational frequency ($\hbar\omega$) has been studied for the $\pi g_{9/2}(fp)^1 \otimes \nu g_{9/2}$ configuration for $\Delta I = 1$ band in ^{83}Kr. These calculations were performed using a deformed Woods–Saxon potential and monopole pairing [18]. The total Routhian was minimised on a lattice in the (β_2, γ) space with respect to the hexadecapole deformation β_4 and displayed in Fig. 5 for the two rotational frequencies ($\hbar\omega$) 0.21 and 0.61 MeV. These plots indicate a decrease in deformation (from $\beta_2 = 0.15$ at $\hbar\omega = 0.21$ to 0.06 MeV at rotational frequency of 0.61 MeV; see Fig. 5) as well as change in shape from a triaxial shape ($\gamma \sim 10°$) at $\hbar\omega = 0.21$ MeV to a near prolate shape ($\gamma \sim -2°$) at $\hbar\omega = 0.61$ MeV. The lifetime results as well as the present TRS calculations are in accordance with the previous TAC prediction by Malik et al. [9] where they inferred that the $\Delta I = 1$ band in ^{83}Kr is a strong candidate for magnetic rotation band based on a shape mixing configuration.

5 Summary

The excited states of ^{83}Kr have been populated in the reaction ^{76}Ge(^{11}B, $3np\gamma$) at 50 MeV beam energy. In the present work, the $\Delta I = 1$ band built upon the $13/2^-$, 2,510.0 keV state has been observed up to an excitation energy of 5,639.4 keV and a tentative spin of ($27/2^-$). Mean lifetimes have been measured for four states up to the $21/2^-$, 4,217.4 keV level, and an upper limit of the lifetime has been estimated for the $23/2^-$, 4,868.4 keV state. The B(M1) and B(E2) values derived from the present lifetime results decrease with increasing spin. It has been found that the quadrupole deformation β_2 decreases from 0.15 to 0.10 with spin. Total Routhian surface calculations with $\pi g_{9/2}(fp)^1 \otimes \nu g_{9/2}$ configuration for $\Delta I = 1$ band in ^{83}Kr predict a decrease in deformation and a change in shape from triaxial to near prolate.

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