Experimental Study of Magnetic Rotation in $^{83}$Kr

S. Ganguly$^1*$, Aparajita Dey$^2**$, P. Banerjee$^2$, S. Bhattacharya$^2$, R.P. Singh$^3$, S. Muralithar$^3$, R. Kumar$^3$ and R.K. Bhowmik$^3$

$^1$Dept. of Physics, Chandernagore College, Chandernagore, Hooghly, India
$^2$Nuclear and Atomic Physics Division, Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata-64, India
$^3$Inter University Accelerator Center, New Delhi-110067, India
E-mail: $^*$ sgpresi78@gmail.com, $^{**}$ aparajita.dey@saha.ac.in

Abstract

In the present work 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 has been observed up to 5639.4 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 (DSAM). The B(M1) rates derived from the present lifetimes decrease smoothly with increase in spin indicating that the angular momentum belonging to this band are generated by shears mechanism.

Keywords: NUCLEAR REACTION $^{76}$Ge($^{11}$B,3np$^\gamma$), E = 50 MeV, $^{83}$Kr; Measured $\gamma$-ray energies and intensities, $\gamma\gamma$-coincidences, DCO ratios, Doppler shifts

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Introduction

Very regular sequences of enhanced magnetic dipole transitions were observed first time 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 behavior 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(E2)/B(M1) ratios are typically 0.025 to 0.05 (eb/$\mu_N$)$^2$. 
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, $J^2/B(E2)$, 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 $\pi g_{9/2}(fp)^1 \otimes v g_{9/2}$ [9], show a constant value of 0.3 $\mu_N^2$ over a considerable frequency range. This feature has also 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 indicate that the $\Delta I = 1$ band in $^{83}$Kr, where the neutron number $N = 47$, 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 Ref. [11] are smaller than those reported in Ref. [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) have been attempted in the present work in view of the discrepancies of the previous results as well as to verify the previous TAC prediction. 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 twelve Compton suppressed HPGe detectors and a fourteen element BGO 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 4096 x4096 matrix, obtained from sorting the raw data of all twelve HPGe detectors. These spectra were used for the assignment of the $\gamma$-rays in the level scheme. The directional correlation of $\gamma$-rays de exciting oriented states (DCO ratios) was obtained from other matrices described in Ref. [12].

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

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

where $I_\gamma$ is the intensity of the $\gamma$-ray of interest in coincidence with $\gamma_G$. The $R_{DCO}$ values were compared with the theoretical DCO ratios for assignment of spin and the $\gamma$-ray multipole mixing ratios $\delta$ using the computer code ANGCOR [13]. A width of $\sigma$
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$= 0.3I$ (I being the level spin) was used for presumed Gaussian distribution of the magnetic substate population. Gate was set on strong $\Delta I = 2$ transition (Here 1122.1 keV transition connecting $13/2^+$ and $9/2^+$ state [10]). Level lifetimes ($\tau$) 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 an initial recoil velocity $\beta = 0.0125$) in the target and backing were simulated using a Monte Carlo technique, which involved 10000 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 4868.4 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 ($\tau_{sf}$) 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.

The $\Delta I = 1$ band built on the $13/2^-$, 2510.0 keV state has been observed up to an excitation energy of 5639.4 keV and a tentative spin of $(27/2^-)$ in the present work (Fig. 1). The experimental results for $\gamma$-ray energies and intensities, DCO ratios and spin assignments are presented in Table I and the level lifetimes, transition probabilities, are summarised in Table II. The present DCO measurement indicates that the 200.7, 316.1 and 445.0 keV $\gamma$-ray are all predominantly M1 in nature with small E2 admixture ($< 1\%$). The mixing ratio for 200.7 keV $\gamma$-ray transition was determined from the RDCO value obtained by gating 1122.1 keV transition depopulating the 1122.1 keV state (see level scheme of $^{83}$Kr in Ref. [10]). Spectra gated by 200.7 keV transition was then used to obtain the mixing ratios of the 316.1 keV, 445.0 keV and 615.1 keV transitions. No evidence was found for the presence of 1026.7 keV and 1423 keV transitions [see level scheme in Ref. [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 M. Kudjarov et al. [11]. The results were differ by a factor of two. Mean lifetimes $2.5 \pm 0.5$ ps, $1.6 \pm 0.1$ ps, $1.0\pm 0.2$ ps, and $0.60 \pm 0.13$ has been determined for the 2841.2, 3157.3, 3602.3, and 4217.4 keV states, respectively, in the present work. An upper limit of lifetime 1.0 ps has been estimated for the 4868.4 keV state. The present lifetime results have been compared with the previous estimations [10, 11] in Table II. The DSA spectra for the 200.7 keV 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 keV and 172.1 keV transitions was utilized to obtain the DSA spectra for 200.7 keV and 316.1 keV transitions. The 200.7 keV gate has been added along with 130.5 keV and 172.1 keV transition (not shown in the present level scheme) used to obtained the DSA spectrum for 445.0 keV transition. The B(M1) rates using the present lifetime and the branching ratio indicate a large B(M1) value of $2.38^{+0.60}_{-0.40} \mu_N^2$ for the $17/2^- \rightarrow 15/2^-$ transition and decreases to $0.31^{+0.08}_{-0.06} \mu_N^2$ for $23/2^- \rightarrow 21/2^-$ transition. The B(E2) transition rate found out to be $24^{+6}_{-4}$ W.u. for 3602.3 keV state and decreases to $10.5^{+3}_{-2}$ W.u. for the 4217.4 keV state.

In the $A = 80$ region, the important high-spin components of the Magnetic Rotation bands are the $\pi g_{9/2}$ proton particles coupled to $\nu g_{9/2}$ neutron holes. In $^{83}$Kr, the 3 quasiparticle configuration suggested by Kemnitz et al. [10] for the $\Delta I = 1$ band built on 2510.0 keV state is $\nu g_{9/2} \otimes (\pi g_{9/2} + f_{5/2}, p_{3/2} \text{ or } p_{1/2})$. 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 $118 h^2 \text{MeV}^{-1} (\text{eb})^{-2}$ at 3602.3 keV state (21/2-). These features strongly favour that the $\Delta I = 1$ band in $^{83}$Kr arises due to the magnetic rotation. The quadrupole deformation $\beta_2$ was found out to be 0.15 for the 3602.3 keV state and decreases to 0.10 for 4217.4 keV state.

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 ($\beta_2, \gamma$) space with respect to the hexadecapole deformation $\beta_4$ and displayed in Fig. 5 for the two rotational frequencies ($\hbar\omega$) 0.21 and 0.61 MeV. These plots indicates an onset of deformation (from $\beta_2 = 0.15$ at $\hbar\omega = 0.21$ MeV to 0.06 at rotational frequency of 0.61 MeV [see Fig. 5]) as well as change in shape from a triaxial shape ($\gamma \sim 10^\circ$) at $\hbar\omega = 0.21$ MeV to a near prolate shape ($\gamma \sim -2^\circ$) 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 S. S. 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.
### Table I: Energies, relative intensities, DCO ratios, γ-ray multipolarities and spin assignments for ΔΙ = 1 band in $^{83}\text{Kr}$.

<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$E_γ$</th>
<th>$I_{rel}$</th>
<th>$R_{DCO}$</th>
<th>Gate</th>
<th>γ-ray Multipolarity/</th>
<th>$J_i^γ → J_f^γ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(keV)</td>
<td>(keV)</td>
<td></td>
<td>(keV)</td>
<td></td>
<td>$δ$($E2/M1$)</td>
<td></td>
</tr>
<tr>
<td>2841.2</td>
<td>200.7</td>
<td>100 ± 6</td>
<td>0.49 ± 0.06</td>
<td>1122.1</td>
<td>0.035 ± 0.01</td>
<td>17/2$^-$ → 15/2$^-$</td>
</tr>
<tr>
<td>370.7</td>
<td>18.1 ± 3.3</td>
<td>E2</td>
<td></td>
<td></td>
<td></td>
<td>17/2$^-$ → 17/2$^-$</td>
</tr>
<tr>
<td>3157.3</td>
<td>316.1</td>
<td>96.0 ± 5.3</td>
<td>0.03 ± 0.07</td>
<td>200.6</td>
<td>0.008 ± 0.03</td>
<td>19/2$^-$ → 17/2$^-$</td>
</tr>
<tr>
<td>606.6</td>
<td>2 ± 1</td>
<td></td>
<td></td>
<td>(M1/E2)</td>
<td></td>
<td>19/2$^-$ → 17/2$^-$</td>
</tr>
<tr>
<td>687.2</td>
<td>8.3 ± 2.43</td>
<td>(E1)</td>
<td></td>
<td></td>
<td></td>
<td>19/2$^-$ → 17/2$^+$</td>
</tr>
<tr>
<td>3602.3</td>
<td>445.0</td>
<td>74.6 ± 5.2</td>
<td>0.94 ± 0.07</td>
<td>316.1</td>
<td>−0.042 ± 0.02</td>
<td>21/2$^-$ → 19/2$^-$</td>
</tr>
<tr>
<td>761.1</td>
<td>13.7 ± 3.63</td>
<td>E2</td>
<td></td>
<td></td>
<td></td>
<td>21/2$^-$ → 17/2$^-$</td>
</tr>
<tr>
<td>4217.4</td>
<td>615.1</td>
<td>42.9 ± 7.5</td>
<td>1.19 ± 0.14</td>
<td>316.1</td>
<td>−0.21 ± 0.19</td>
<td>23/2$^-$ → 21/2$^-$</td>
</tr>
<tr>
<td>1060.1</td>
<td>11.6 ± 4.4</td>
<td>E2</td>
<td></td>
<td></td>
<td></td>
<td>23/2$^-$ → 19/2$^-$</td>
</tr>
<tr>
<td>4808.4</td>
<td>651.0</td>
<td>23.2 ± 5.1</td>
<td>1.22 ± 0.55</td>
<td>316.1</td>
<td>(M1/E2)</td>
<td>25/2$^-$ → 23/2$^-$</td>
</tr>
<tr>
<td>1266.1</td>
<td>35.8 ± 7.1</td>
<td>E2</td>
<td></td>
<td></td>
<td></td>
<td>23/2$^-$ → 19/2$^-$</td>
</tr>
<tr>
<td>5639.4</td>
<td>771.0</td>
<td>13.8 ± 3.7</td>
<td>316.1</td>
<td>(M1/E2)</td>
<td></td>
<td>(27/2$^-$) → 25/2$^-$</td>
</tr>
</tbody>
</table>

### Table II: Present experimental results on the mean lifetime (τ), B(M1) for ΔΙ = 1 band in $^{83}\text{Kr}$.

<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$J_i^γ → J_f^γ$</th>
<th>τ (ps)</th>
<th>B(M1)$^b$</th>
<th>$μ_N^s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(keV)</td>
<td>present</td>
<td>previous</td>
<td>[10]</td>
<td>previous</td>
</tr>
<tr>
<td>2841.1</td>
<td>17/2$^-$ → 15/2$^-$</td>
<td>2.5 ± 0.50</td>
<td>–</td>
<td>7.0 ± 2.0</td>
</tr>
<tr>
<td>3157.3</td>
<td>19/2$^-$ → 17/2$^-$</td>
<td>1.6 ± 0.10</td>
<td>4.0$^{+2.0}_{-1.5}$</td>
<td>1.7$^{+0.6}_{-0.4}$</td>
</tr>
<tr>
<td>3602.3</td>
<td>21/2$^-$ → 19/2$^-$</td>
<td>1.0 ± 0.20</td>
<td>1.5$^{+0.60}_{-0.40}$</td>
<td>1.0$^{+1.0}_{-0.5}$</td>
</tr>
<tr>
<td>4217.4</td>
<td>23/2$^-$ → 21/2$^-$</td>
<td>0.60 ± 0.13</td>
<td>0.8$^{+0.5}_{-0.3}$</td>
<td>–</td>
</tr>
<tr>
<td>4808.4</td>
<td>25/2$^-$ → 23/2$^-$</td>
<td>&lt; 1.0</td>
<td>0.9 ± 0.2</td>
<td>&gt; 0.003$^a$</td>
</tr>
</tbody>
</table>

$^a$Calculated using present lifetime and branching ratio.

$^b$Assuming a mixing ratio of 0.05.
Figure 1: Partial level scheme of Kr. The level and transition energies are given in keV. The width of the arrows represents the relative intensity.

Figure 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.
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Figure 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.

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

Figure 5: Total Routhian Surface plots for $\Delta I = 1$ band in the $\beta_2-\gamma$ plane for rotational frequencies of (a) 0.21 MeV, (b) 0.61 MeV. The interval between successive contours is 0.50 MeV.
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KC/CRS/2009/NP05/1353.

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