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Assignment of the Spin and Parity to the Excited States of the ^{85,86}Rb Nuclei

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ABSTRACT

Background: The isotopes of Rb (Z=37) are one proton away from semi–magic (Z=38) proton number and deficits the characteristic of a spherical nucleus. In the ^{85,86}Rb nuclei, the γ-ray spectroscopy are already performed and given an indication of Magnetic Rotation (MR) which usually observed in nearly spherical nuclei. The angular correlation measurements were used to find the spin and parity of the states.

Purpose: To confirm the spin and parity of the states in both the nuclei using Directional Correlation of Oriented (DCO) states ratio and polarization asymmetry (Δ) measurements.

Methods: The excited states of the ^{85,86}Rb nuclei were populated via the ^{76}Ge(^{13}C,p3n/p2n) reaction at a beam energy of 45 MeV. The γ-rays emitted from the excited states were detected using Indian National Gamma Array (INGA) spectrometer at the Tata Institute of Fundamental Research (TIFR), Mumbai India.

Results: The values of the DCO states ratio and polarization asymmetry (Δ) were obtained and utilized to confirm the spin-parity of the states in the ^{85,86}Rb nuclei. The polarization asymmetry (Δ) values were obtained for the first time using Compton-suppressed clover detectors.

Conclusions: In ^{85}Rb, the spin and parity of 3491.1–, 4135.4–, 4757.2– and 5419.3 keV levels are confirmed and for the 5312.2–, 5611.8 and 6335.9 keV states, only the spin is established. The mul-tipolarity assignment of the 224.3–, 331.5–, 732.8–, 778.1–, 865.4–, 973.5–, 1002.4–, 1427.5–, 1453.7–, 1598.2–, 1814.1– and 1881.5 keV γ-ray transitions allowed to confirm the spin and parity of most of the levels above the 6^- isomer in ^{86}Rb.

1. Introduction

In the last fifty years, the spectroscopic studies of the odd-A Rb and the odd-A Br nuclei have proved the different modes of excitation plausible. For these nuclei, the configuration space for both proton and neutron is $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$ and $1g_{9/2}$ orbitals. The proton in the $1g_{9/2}$ orbital causes the large deformation in the ^{78}Kr core of the lighter isotopes of ^{77,79}Rb [1,2] and ^{73,75}Br [3,4], whereas it does not affect the core of ^{77}Br isotope [5]. The states of odd-odd Rb nuclei are subdued by the two-particle configurations that resulted from the coupling of the $1g_{9/2}$ orbital. As, the Rb isotope is one proton away from ^{88}Sr inert core, it is expected to show the non-collective excitation. However, a non-aggregate three-particle excitation of negative parity was found in ^{77,79,81}Br [6-8]and in ^{79,81,83}Rb [9-11]. Some of the interesting high spin phenomena are already reported in the doubly odd-nuclei such as chirality in ^{82}Br [12] and magnetic rotation in ^{84}Rb [13]. Also, the fast M1 transitions have been seen in ^{85,86}Rb [14,15].

Previously, the low-lying states of ^{85}Rb were studied via ^{84}Kr(p,γ) reaction along with Coulomb excitation using α-particle [16] and for ^{86}Rb using (n,γ) reaction [17]. The high spin states of ^{85,86}Rb were also studied using the ^{82}Se(^{7}Li,3*n*/4*n*) reactions [14,15]. In last two decades, Compton-suppressed clover detectors were used as Compton polarimeter for polarization asymmetry measurements [18-20]. In this paper, we are presenting the level schemes

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of ^{85,86}Rb in which spin and parity are assigned based on the R_{DCO} and linear polarization asymmetry (Δ) values. In the subsequent sections, experimental details and results will be presented along with the discussion.

2. Experimental Details

Excited states of ^{85,86}Rb nuclei were populated via the ^{76}Ge(^{13}C,p3n/p2n) reaction with a beam energy of 45 MeV at Pelletron accelerator facility at Tata Institute of Fundamental Research (TIFR), Mumbai. The target consisted of a 850 μg/cm^2 foil of Ge backed with 7.6 mg/cm^2 of ^{181}Ta. The de-exciting γ-rays were detected using INGA spectrometer [20] i.e. the fifteen Compton-suppressed HPGe clover detectors, arranged in six circular rings at 157°(3), 140°(2), 115°(2), 90°(4), 65°(2) and 40°(2) angles with respect to the beam direction(the number in the parentheses is the number of detectors at the respective angle). Around 2.7x10^9 events of two- and higher-fold were recorded by a fast digital data acquisition system based on PIXIE−16 modules of XIA LLC [21]. The data were sorted using the in-house program to generate two dimensional E_γ — E_γ matrices and three dimensional E_γ — E_γ — E_γ cube, which were later analysed using RAD WARE package [22].

An asymmetric matrix was also created having events of the clovers placed at 157° along one axis and at 90° along another axis to find the order of multipolarity of the de-exciting γ-rays using DCO ratio values. DAMM[23] software was used to generate the gated spectra from the asymmetric matrix which were further analysed using the RADWARE software. The expression used to find the DCO ratio is

$$R_{DCO} = \frac{Intensity\left(\gamma_1\, at\, 157°,\, gated\, on\, \gamma_2\, at\, 90°\right)}{Intensity\left(\gamma_1\, at\, 90°,\, gated\, on\, \gamma_2\, at\, 157°\right)} \quad (1)$$

The order of multipolarity for a particular γ-ray transition was obtained from the DCO ratio by putting a gate on a stretched γ-ray transition of known order of multipolarity (Quadrupole (Q) or Dipole (D)) in the asymmetric matrix. When a gate put on a stretched dipole (D) transition, the expected R_{DCO} value is 1.0 for a stretched dipole (D) transition and 1.92 for a stretched quadrupole (Q) transition, whereas if a gate is set on a stretched quadrupole (Q) transition, then the expected R_{DCO} value is 0.52 for a dipole (D) transition and 1.0 for a stretched quadrupole (Q) transition.

The electric or magnetic nature of the γ-ray transitions was assigned from the polarization asymmetry (Δ) value obtained from the linear polarization measurements [24,25] for the clovers placed at 90° angles. The polarization asymmetry (Δ) value was obtained from the given expression

$$\Delta = \frac{\left(a\left(E_\gamma\right)N_\perp - N_\parallel\right)}{\left(a\left(E_\gamma\right)N_\perp - N_\parallel\right)} \quad (2)$$

where, a(E_γ) is the geometrical correction factor for the set-up and was determined using unpolarized γ-rays emitted from the standard ^{133}Ba and ^{152}Eu sources. The geometrical correction factor is expressed as

$$a\left(E_\gamma\right) = \frac{N_\parallel}{N_\perp} \quad (3)$$

where, $N_\parallel\left(N_\perp\right)$ denotes the number of the scattered events detected in 90° clover detectors lying in parallel(perpendicular) direction with respect to the plane containing beam axis and the direction of emitted γ-rays. The a(E_γ) for the present experiment was calculated using 0.997(7)+2.336(9)×10^{-5} × E_γ, where E_γ is the energy of γ-ray transition.

3. Results & Discussion

3.1. The Spin and Parity in ^{85}Rb

The level scheme relevant to the present discussion is shown in Fig. 1. Most of the γ-ray transitions have been observed in the coincidence of 779.3− and 1183.3 keV gates as shown in Fig. 2. The spin and parity were assigned based on the DCO ratio and polarization asymmetry (Δ) values given in Table 1 and also shown in Fig. 3.

The spin of the yrast sequence i.e. 779.3−, 1183.3− and 1014.4 keV was already known in the previous measurements [14]. In the present measurements, the *E*2 character is confirmed for 779.3−, 1183.3−, and 1014.4 keV γ-ray transitions and hence confirmed the parity of yrast sequence. The *E*2 character for 1014.4 keV γ-ray transition leads to confirm the 21/2$^+$ for 3491.1 keV level. Also, the *E*1 character for 349.8 keV γ-ray and the *M*1 character for 228.0 keV γ-ray verify the previous assignment of the 19/2$^-$ and 21/2$^-$ for the 2826.7− and 3054.5 keV levels. Further, the 644.3 keV γ-ray transition is established as having *E*1 character which helped in assigning a 23/2$^-$ for 4135.4 keV level. Also, the *E*2 character of 1283.9 keV γ-ray transition and *M*1 + *E*2 nature for 621.9− and 662.2 keV γ-ray transitions obtained the 25/2$^-$ and 27/2$^-$ for 4757.2− and 5419.3 keV levels, respectively. The 5312.2 state is assigned as 25/2$^{(-)}$ based on the 1176.8− and 1820.7 keV multipolarity. The 192.5 keV *D* + *Q* and 724.1 keV *M*1 γ-ray transitions provided the spin of 29/2$^{(-)}$ and 31/2$^{(-)}$ for the 5611.8− and 6335.9 keV levels. In brief, the polarization asymmetry (Δ) and DCO ratio values of the present study established the spin and parity of 3491.1−, 4135.4−, 4757.2− and 5419.3 keV levels, and the spin of 5312.2−, 5611.8− and 6335.9 keV states.

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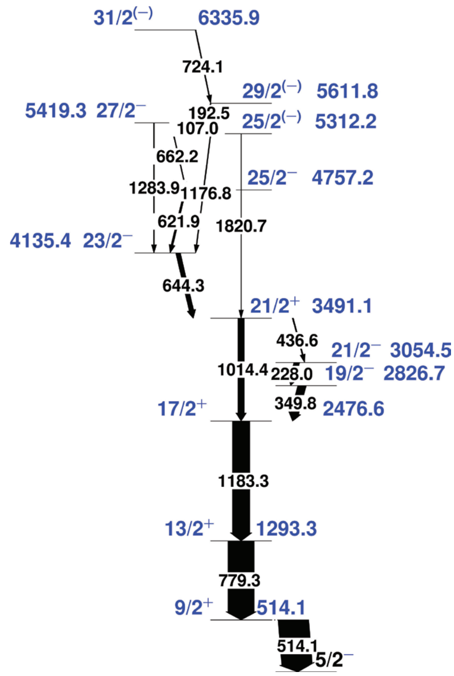

Figure 1: (Color online) The part of level scheme of ^{85}Rb relevant to the present work for spin and parity assignment.

Table 1: Table for level energy(E_i), initial $\left(J_i^\pi\right)$ and final $\left(J_i^\pi\right)$ spin-parity of the levels, measured E_γ, relative γ-ray intensity(I_γ), R_{DCO}, polarization asymmetry (Δ) value, and assigned multipolarity for γ-ray transitions in ^{85}Rb.

E_i^*	$J_i^\pi \rightarrow J_f^\pi$	E_γ^*	I_γ^*	R_{DCO}	Δ	Multipolarity
514.1	$9/2^+ \rightarrow 5/2^-$	514.1(1)	100	0.93(4)[a]		M2[x]
1293.3	$13/2^+ \rightarrow 9/2^+$	779.3(1)	86(4)	1.06(4)[b]	0.075(20)	E2
2476.6	$17/2^+ \rightarrow 13/2^+$	1183.3(1)	57(2)	1.00(17)[a]	0.072(16)	E2
2826.7	$19/2^- \rightarrow 17/2^+$	349.8(1)	27(2)	0.72(3)[b]	0.08(3)	E1
3054.5	$21/2^- \rightarrow 19/2^-$	228.0(1)	18(1)	0.41(4)[a]	−0.04(2)	M1+E2
3491.1	$21/2^+ \rightarrow 21/2^-$	436.6(2)	3.6(5)	1.04(16)c		Q or D (ΔI = 0)
3491.1	$21/2^+ \rightarrow 17/2^+$	1014.4(1)	21(3)	0.98(6)[b]	0.05(2)	E2
4135.4	$23/2^- \rightarrow 21/2^+$	644.3(1)	15(1)	0.46(3)[a]	0.025(27)	E1
4757.2	$25/2^- \rightarrow 23/2^-$	621.9(2)	6.1(5)	0.44(5)[a]	−0.14(8)	M1+E2
5312.2	$25/2^{(-)} \rightarrow 23/2^-$	1176.8(2)	2.7(4)	0.46(13)[b]	−0.09(16)	M1+E2
5312.2	$25/2^{(-)} \rightarrow 1/2^+$	1820.7(3)	1.1(2)	0.90(23)[c]		Q
5419.3	$27/2^- \rightarrow 25/2^{(-)}$	107.0(1)	2.7(3)	0.63(16)[a]		D+Q
5419.3	$27/2^- \rightarrow 25/2^-$	662.2(2)	2.6(3)	0.40(6)[a]	−0.06(3)	M1+E2
5419.3	$27/2^- \rightarrow 23/2^-$	1283.9(1)	2.6(3)	0.88(20)[b]	0.10(3)	E2
5611.8	$29/2^{(-)} \rightarrow 27/2^-$	192.5(1)	2.7(3)	0.60(6)[a]		D+Q
6335.9	$31/2^{(-)} \rightarrow 29/2^{(-)}$	724.1(2)	2.9(3)	0.40(7)[c]	−0.05(3)	M1+E2

[a]Gate on 779.3 keV quadrupole transition
[b]Gate on 1183.3 keV quadrupole transition
[c]Gate on 1014.4 keV quadrupole transition
[x]From adopted level
[*]Data taken from Nuclear Data Sheet A=85 for ^{82}Se(^{7}Li,4n) reaction [17]

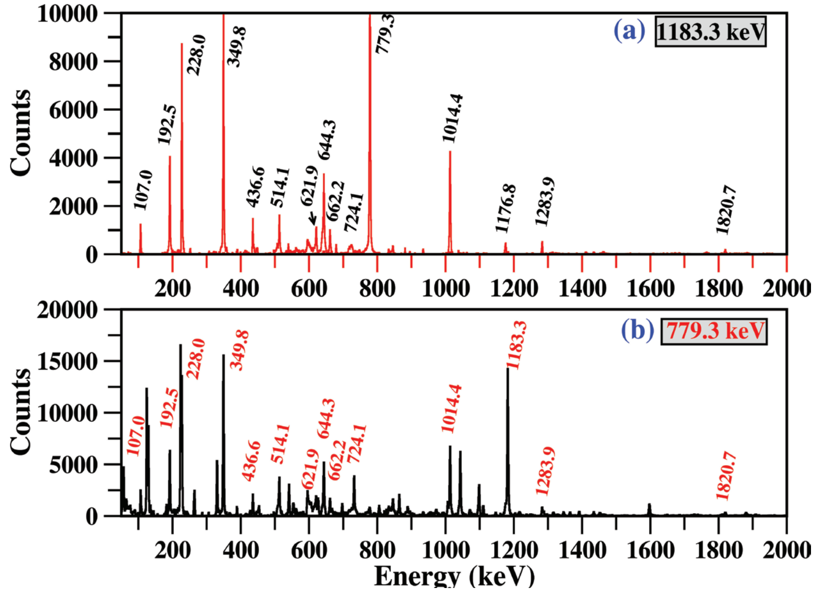

Figure 2: (Color online) Spectrum showing the γ-ray transitions belongs to ^{85}Rb in coincidence of (a) 1183.3 keV (b) 779.3 keV γ−ray transition.

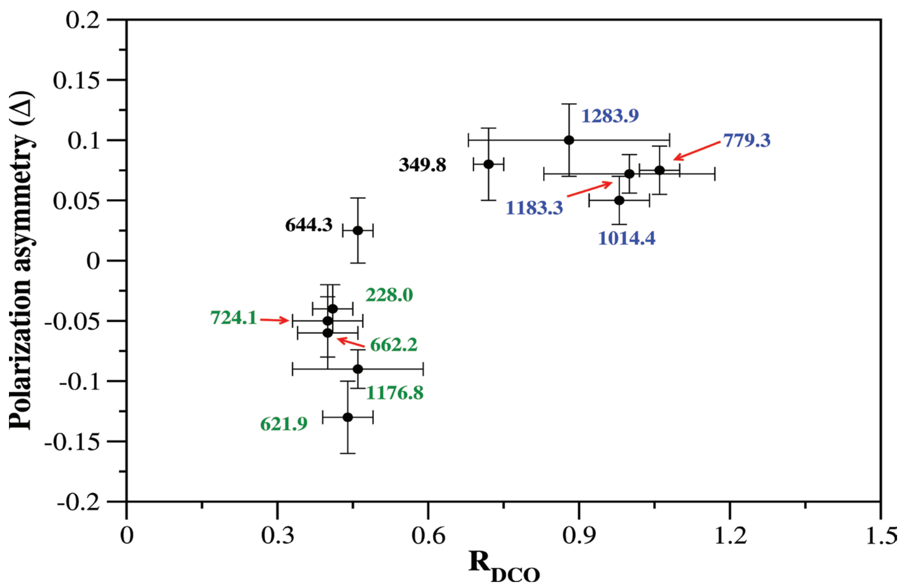

Figure 3: (Color online) The R_{DCO} vs polarization asymmetry (Δ) plot for ^{85}Rb nuclei. The color of the γ-ray represent the multipolarities (blue color for *E*2 character, red color for *M*1 character, black color for *E*1 character and green color for mixed *M*1 + *E*2 character).

3.2. The Spin and Parity in ^{86}Rb

In Fig. 4, the level scheme is shown. In the present work, the parity is obtained for the levels above 6$^-$ isomer. The new γ-ray transitions having energy 440.9− and 584.1 keV are also placed in the level scheme. The DCO ratio and polarization asymmetry (Δ) values are given in Table 2 and also shown in Fig. 5 for confirm multipolarity.

The coincidence spectrum of 224.3− and 732.8 keV γ-ray transition is shown in Fig. 6 and 7 which further confirms the placement of the γ-ray transitions as shown in Fig. 4. The *M1* + *E2* character of 224.3 keV γ-ray transition established I^π = 7$^-$ for 780.4 keV level. The I^π = 7$^+$ for 1558.5 level is confirmed as the 1002.4 γ-ray transition has *E*1 character. Also, the *E*1 (ΔI = 0) character of 778.1 keV transition based on the present measurement is supported by the already known angular distribution coefficients [15]. The assigned multipolarity (see Table 2) of 732.8−

, 865.4−, 1453.7− and 1598.2 keV γ-ray transitions justified the spin and parity of 2416.5−, 3137.5− and 3281.9 keV levels. The *M*1 character for both 331.5− and 973.5 keV γ-ray transitions confirms the parity of 3743.3− and 4716.8 keV levels, respectively. In the present measurements of both polarization asymmetry (Δ) and DCO ratio values, *E*1 character was obtained for 1427.5−, 1814.1−, and 1881.7 keV γ-ray transitions, respectively.

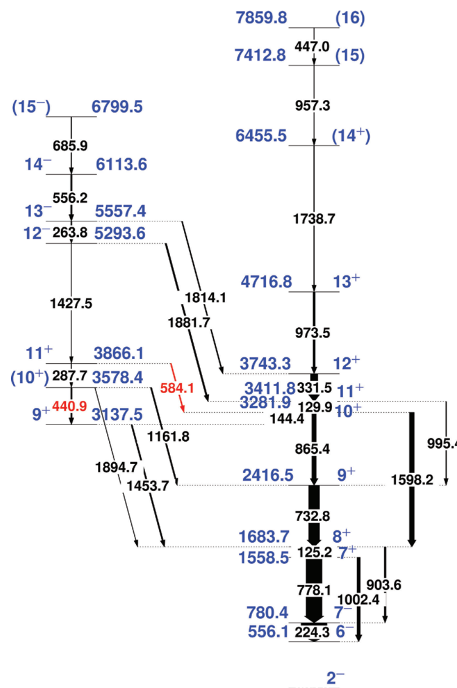

Figure 4: (Color online) The level scheme of ^{86}Rb showing the part for which spin and parity is obtained from the present work. The newly observed γ-ray transitions are shown by red color.

Table 2: Table for level energy(E_i), initial(J_i^π) and final(J_i^π) spin−parity of the levels, measured E_γ, relative γ-ray intensity(I_γ), R_{DCO}, polarization asymmetry (Δ) value, and assigned multipolarity for γ-ray transitions in ^{86}Rb.

E_i^*	J_i^π	→	J_f^π	E_γ^*	I_γ^*	R_{DCO}	Δ	Multipolarity
556.07	6⁻	→	2⁻	556.07(18)				E4[x]
780.4	7⁻	→	6⁻	224.3(1)	100(10)	0.52(4)[a]	−0.045(12)	M1+E2
1558.5	7⁺	→	7⁻	778.1(1)	63(6)	1.06(11)[c]	−0.103(14)	E1 (ΔI = 0)
1558.5	7⁺	→	6⁻	1002.4(2)	12(1)	0.82(7)[c]	0.011(32)	E1
1683.7	8⁺	→	7⁺	125.2(1)	62(6)	0.97(15)[e]		M1[x]
1683.7	8⁺	→	7⁻	903.6(3)	6.5(7)			
2416.5	9⁺	→	8⁺	732.8(1)	42(4)	0.61(4)[b]	−0.055(15)	M1+E2
3137.5	9⁺	→	8⁺	1453.7(3)	4.9(8)	0.32(5)[a]	−0.013(33)	M1+E2
3281.9	10⁺	→	9⁺	144.4(3)	2.6(3)	0.77(14)[a]		M1[x]
3281.9	10⁺	→	9⁺	865.4(2)	17(2)	0.60(7)[c]	−0.073(19)	M1+E2
3281.9	10⁺	→	8⁺	1598.2(2)	19(2)	2.17(27)[b]	0.052(29)	E2
3411.8	11⁺	→	10⁺	129.9(1)	34(3)	0.86(13)[c]		M1[x]
3411.8	11⁺	→	9⁺	995.4(3)	2.5(4)	1.18(12)[d]		D
3578.4	(10⁺)	→	9⁺	440.9(3)	5.2(3)			

E_i^*	J_i^π	→	J_f^π	E_γ^*	I_γ^*	R_{DCO}	Δ	Multipolarity
3578.4	(10^+)	→	9^+	1161.8(3)	4.9(5)	0.66(40)[a]	0.16(5)	(Q/D)
3578.4	(10^+)	→	8^+	1894.7(3)	1.2(2)			
3743.3	12^+	→	11^+	331.5(1)	28(4)	0.46(5)[c]	−0.064(15)	M1
3866.1	11^+	→	(10^+)	287.7(3)	1.4(1)	0.37(6)[a]		D/Q
3866.1	11^+	→	10^+	584.1(3)	4.1(3)			
4716.8	13^+	→	12^+	973.5(2)	8.5(2)		−0.009(29)	
5293.6	12^-	→	11^+	1427.5(3)	0.5(1)	0.94(17)[a]	0.022(45)	E1
5293.6	12^-	→	11^+	1881.7(3)	5.7(9)	0.75(20)[e]	0.045(37)	E1
5557.4	13^-	→	12^-	263.8(3)	4.0(6)	0.76(6)[a]		(M1+E2)
5557.4	13^-	→	12^+	1814.1(3)	3.6(5)	0.56(19)[a]	0.061(36)	E1
6113.6	14^-	→	13^-	556.2(3)	5.6(8)	0.54(5)[e]	−0.12(4)	M1
6455.5	(14^+)	→	13^+	1738.7(3)	2.8(4)			
6799.5	(15^-)	→	14^-	685.9(3)	2.3(3)			(M1)
7412.8	(15)	→	(14^+)	957.3(3)	1.5(2)			
7859.8	(16)	→	(15)	447.0(3)	1.4(1)			

[a]Gate on 125.2 keV transition
[b]Gate on 224.3 keV dipole transition
[c]Gate on 1598.2 keV quadrupole transition
[d]Gate on 732.8 keV dipole transition
[e]Gate on 778.1 keV transition
[x]From adopted level
[*]Data taken from Nuclear Data Sheet A=86 for $^{82}Se(^7Li,3n)$ reaction[26]

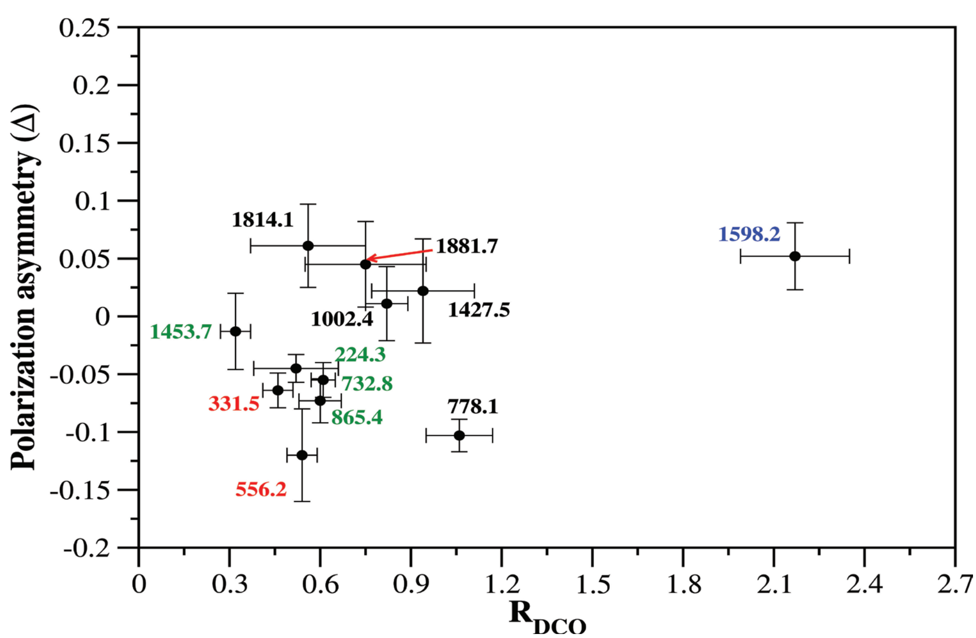

Figure 5: (Color online) The R_{DCO} vs polarization asymmetry (Δ) plot for ^{86}Rb nuclei. The color of the γ-ray represent the multipolarities(blue color for $E2$ character, red color for $M1$ character, black color for $E1$ character and green color for mixed $M1 + E2$ character).

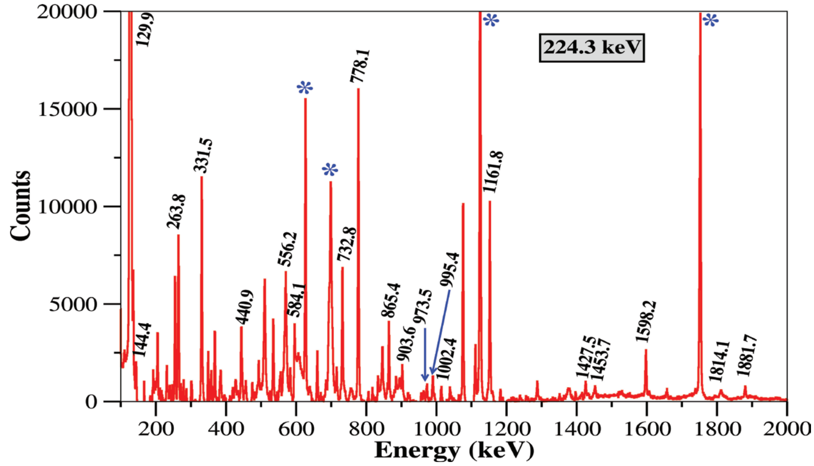

Figure 6: (Color online) Spectrum showing the γ-ray transitions in the coincidence of 224.3 keV transition. The asterisk(*) is showing the γ-ray transitions belonging to the neighbouring populated nuclei.

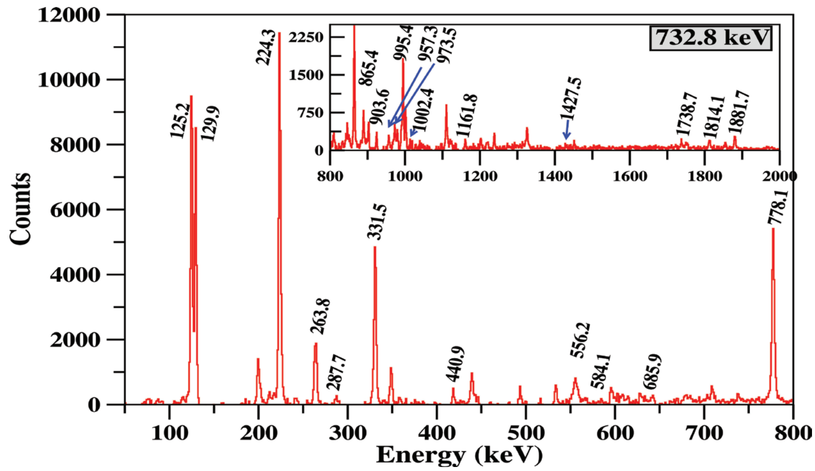

Figure 7: (Color online) Spectrum showing the γ-ray transitions in the gate of 732.8 keV transition.

Conclusion

The multipolarity is assigned for the γ-rays based on the DCO ratio and polarization asymmetry (Δ)values that established the spin and parity of most of the levels previously known in the ^{85,86}Rb nuclei. In Rb, the sequence of 779.3−, 1183.3− and 1014.4 keV γ-rays below $21/2^+$ state of the positive parity yrast band have been confirmed as *E2* characters while most of the above transitions are having mixed multipolarity character of $M1 + E2$. This change may be due to the transition in the coupling scheme from collective to spherical where angular momenta are generated by the unpaired protons and neutrons. The 644.3 keV transition is assigned as $E1$ character. The spin and parity of 3491.1−, 4135.4−, 4757.2− and 5419.3 keV levels were confirmed and for the 5312.2−, 5611.8− and 6335.9 keV states only spin is assigned. In Rb, two new transitions of energy 440.9− and 584.1 keV are placed. The spin and parity of the states with level energy 3866.1−, 5293.6−, 5557.4− and 6113.6 keV are confirmed in the present work based on the $E1$ character of 1814.1 keV, 1881.7 keV and $M1$ character of 556.2 keV transitions. In the future, we would like to expand the level scheme for both the nuclei to identify the magnetic rotation phenomena.

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Authorship Contribution

The contribution for the idea, execution and data analysis goes to S. Kumar, Naveen Kumar and Anuj. The authors S. K. Mandal, S. Saha, J. Sethi and T. Trivedi for the execution of experiment by participating. The other authors Neelam, H. Chutani and M. Goyal contributed in editing the content and finalizing the manuscript.

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Conflict of Interest

All authors declare that they have no conflicts of interest. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report.

Declaration

The work has not been published elsewhere and is not under consideration by another journal. All the authors were agreed to submit this manuscript to "Journal of Nuclear Physics, Material Sciences, Radiation and Applications".

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