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Shape changes at high spin in ^{78}Kr

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Abstract. High-spin states in ^{78}Kr have been studied via the ^{63}Cu(^{19}F, 2p2n)^{78}Kr reaction at a beam energy of 60 MeV using the Indian National Gamma Array (INGA). In this nucleus, lifetimes have been measured upto the $I^\pi = 22^+$ level in the yrast positive-parity band and upto the $I^\pi = 15^-$ level in the negative-parity band using the Doppler Shift Attenuation Method (DSAM). The deduced transition quadrupole moments Q_t's are found to decrease with rotational frequency for both the bands.

PACS. 21.10.Tg Lifetimes – 27.50.+e $59 \leq A \leq 89$

Structural behavior in the light Kr isotopes has been studied by different groups [1–5] in recent years. These nuclei are very interesting because they are among the first in the $A \approx 80$ region showing large quadrupole deformations, shape coexistence and triaxiality. With 36 protons and 42 neutrons, the nucleus ^{78}Kr, the lightest stable Kr isotope, lies far away from any shell closure. It has the lowest energy of 2^+ state (455 keV) and the highest value of $B(E2, 0^+ \to 2^+) = 0.63 \pm 0.04$ e^{2}b^2 [6] among the Kr isotopes and therefore has the largest quadrupole deformation ($\beta_2 = 0.35$). The deformation decreases for the heavier isotopes.

An interesting aspect has been found recently in ^{76}Kr [7]. The yrast and negative-parity bands exhibit the phenomenon of band termination. The experimental values of transition quadrupole moments Q_t for transitions in these bands show a decrease with spin, a behaviour well known in terminating bands in the mass region $A \sim 110$ [8,9]. Band-terminating effects have also been found in ^{78}Kr [5]. The lifetimes for the excited states in the yrast band in this nucleus have been measured in ref. [10]. A decreasing trend in Q_t with rotational frequency was found.

In the present paper measurement of lifetimes of levels in the yrast band and of a negative-parity band in ^{78}Kr using the Doppler Shift Attenuation Method and a clover gamma detector array are reported. Our work provides a confirmation of the behaviour of Q_t with spin as found in [10] for the yrast band. In addition, a similar trend of Q_t decreasing with spin is also found for the negative-parity band.

Excited states in the ^{78}Kr nucleus were populated utilizing the ^{63}Cu(^{19}F, 2p2n)^{78}Kr reaction at a beam energy of 60 MeV. The ^{19}F beam was provided by the 15UD Pelletron accelerator at the Inter University Accelerator Centre (IUAC), New Delhi. The ^{63}Cu target was 700 μg/cm^2 thick and isotopically enriched to 99%. The backing used was 8 mg/cm^2 of tantalum. A thin layer of indium of thickness 70 μg/cm^2 was used in between the target and the backing to stick the two materials. The γ-rays were detected using INGA, an array consisting of eight Compton-suppressed clover detectors mounted on opposite sides of

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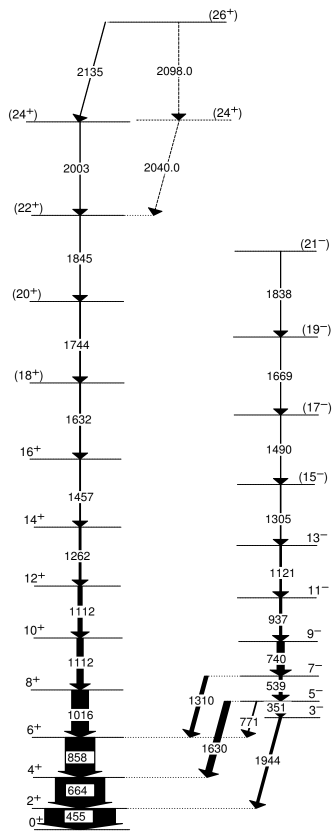

Fig. 1. Partial level scheme of ^{78}Kr [4]. Energies are given in keV.

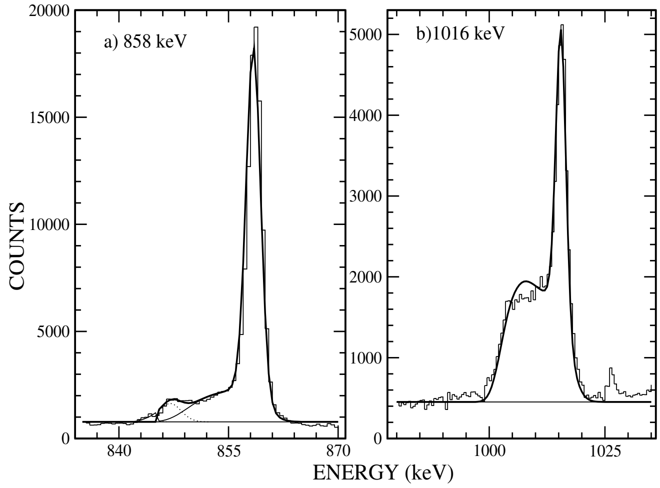

Fig. 2. Experimental and theoretical lineshapes for a) 858 keV and b) 1016 keV transitions in the yrast positive-parity band in ^{78}Kr at $\theta = 141°$. The contaminant peaks are shown by dotted lines. Gate on the 455 keV transition.

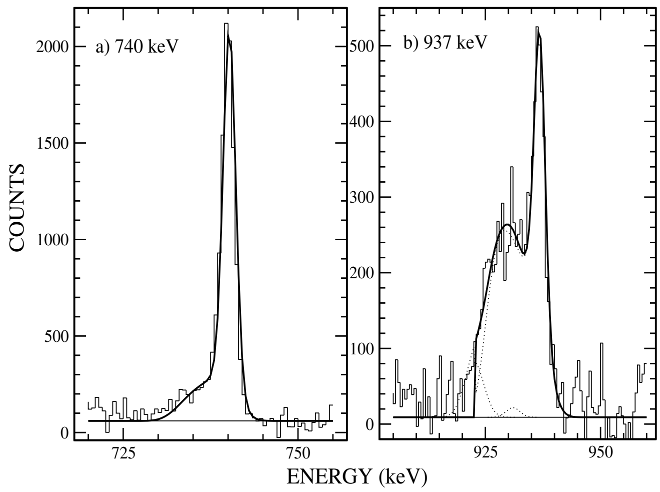

Fig. 3. Experimental and theoretical lineshapes for a) 740 keV and b) 937 keV transitions in the negative-parity band in ^{78}Kr at $\theta = 141°$. The contaminant peaks are shown by dotted lines. Gate on the 539 keV + 1310 keV transitions.

the target chamber making angles of 81° and 141° with respect to the beam direction and tilted at 18° with respect to the horizontal plane. A total of 8.5×10^8 γ-γ events were collected in list mode. The coincidence events were sorted into a 4 K × 4 K square matrix with dispersion of 0.5 keV/channel using the programme INGASORT [11]. For lifetime measurements the matrix made was all detectors *versus* the detectors at backward angle.

The partial level scheme of ^{78}Kr as reported in [4], is shown in fig. 1. In the present work, the lineshapes were analyzed above the $I^\pi = 4^+$ level of the positive-parity yrast band and above the $I^\pi = 7^-$ level of negative-parity band by setting gates on the lowest transitions in the bands. The lifetime of the $I^\pi = 15^-$ level of the negative-parity band is reported for the first time. The lifetimes of these levels were estimated by using the LINESHAPE analysis code developed by J.C. Wells [12]. This code was used to generate the velocity profile of the recoiling nuclei into the backing material using Monte Carlo technique with a time step of 0.01 ps for 5000 histories of energy losses at different depths. Electron stopping powers of Northcliffe and Shilling [13] corrected for shell effects were used for calculating the energy loss. The lifetime measurements were performed starting with the topmost transition which was assumed to have 100% side-feed. The side-feeding intensities [4] for the yrast and the negative-parity bands are mentioned in table 1. A 20% variations in the side-feeding intensities was considered in the analysis. The other parameters were allowed to vary until the χ^2 reached a minimum value. The uncertainties in the lifetimes were derived from the behaviour of the χ^2 fit in the vicinity of the minimum. The experimental lineshapes along with simulated fits for γ-rays deexciting the 6^+, 8^+ levels in the positive-parity yrast band and 9^-, 11^- levels in the negative-parity band in ^{78}Kr are shown in figs. 2 and 3. The experimental values of lifetimes τ and the transition quadrupole moments Q_t obtained in the present work are listed in table 1.

For the yrast band, an average Q_t for the lowest four transitions gives $\beta_2 = 0.35$ which is in excellent agreement with that obtained from the $B(E2, 0^+ \to 2^+)$ value [6].

Figure 4 shows the variation of Q_t with the rotational frequency, $\hbar\omega$, for the yrast band. The present measure-

Table 1. Experimental values of lifetimes, transition quadrupole moments and side-feeding intensities (relative) for excited states in the positive-parity yrast band and in the negative-parity band of ^{78}Kr.

E (level) (keV)	I^{π} ($\hbar$)	E_{γ} (keV)	τ (ps) Earlier works	τ (ps) Present work	Q_t (eb) Present work	I_{γ} (SF)$^{c)}$ (relative)
Yrast band						
455.0	2^+	455.0	32(2)$^{a)}$	–	–	30
1119.4	4^+	664.0	3.4(3)$^{a)}$	–	–	28
1977.7	6^+	858.3	0.82(30)$^{a)}$	1.19(28)	$2.33^{+.35}_{-.35}$	18
2993.7	8^+	1016.0	0.63(13)$^{a)}$	0.41(10)	$2.45^{+.37}_{-.37}$	15
4105.5	10^+	1111.8	0.28(11)$^{a)}$	0.22(5)	$2.59^{+.39}_{-.39}$	3
5217.3	12^+	1112.0	0.26(19)$^{a)}$	0.22(6)	$2.57^{+.39}_{-.39}$	3.3
6479.1	14^+	1262.0	0.13(6)$^{a)}$	0.17(5)	$2.12^{+.33}_{-.32}$	1.3
7935.9	16^+	1457.0	0.15(9)$^{a)}$	0.29(7)	$1.09^{+.18}_{-.17}$	0.1
9568.0	18^+	1632.0	0.22(12)$^{a)}$	0.08(3)	$1.55^{+.38}_{-.29}$	0.2
11312.0	20^+	1745.0	0.14(9)$^{a)}$	0.09(5)	$1.25^{+.76}_{-.23}$	0.4
13157.0	22^+	1844.0	0.21(17)$^{a)}$	0.08(5)	$1.15^{+.62}_{-.27}$	0.2
Negative-parity band						
4028.0	9^-	740.0	1.1(1)$^{b)}$	1.35(20)	$2.95^{+.44}_{-.44}$	8.1
4965.0	11^-	937.0	0.36(12)$^{b)}$	0.35(8)	$3.12^{+.47}_{-.47}$	0.8
6086.0	13^-	1121.0	0.32(15)$^{b)}$	0.19(4)	$2.65^{+.40}_{-.40}$	1.4
7392.0	15^-	1305.0	–	0.12(4)	$2.33^{+.35}_{-.35}$	0.4

$^{a)}$ Reference [10].
$^{b)}$ Reference [14].
$^{c)}$ Reference [4].

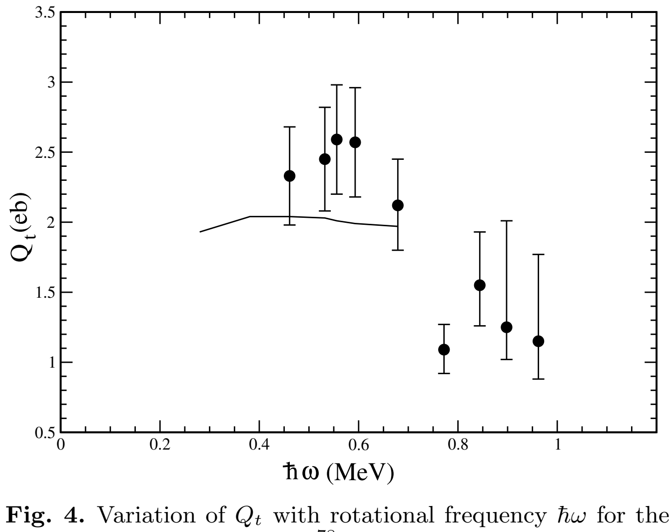

Fig. 4. Variation of Q_t with rotational frequency $\hbar\omega$ for the positive-parity yrast band in ^{78}Kr. The line shows the theoretical calculations [14].

ments show a drop in the transition quadrupole moments at high spins ($> 16\hbar$) which is in good agreement with the earlier result [10]. For this band, at low rotational frequencies, the experimental Q_t's are compared with theoretical Q_t's calculated by us using the Hartree-Fock-Bogoliubov model as prescribed in [15]. In the calculation the doubly closed shell nucleus ^{56}Ni is treated as an inert core. The single-particle energies taken (in MeV) are $\epsilon(2p_{3/2}) = 0.00$, $\epsilon(1f_{5/2}) = 0.78$, $\epsilon(2p_{1/2}) = 1.08$ and $\epsilon(1g_{9/2}) = 3.25$. The relevant effective two-body interaction that we have employed is modified from the renormalized G-matrix due to [16] and we term it as Kuo00. Kuo00 has been modified by making the $\langle (f_{5/2})^2 JT|V|(f_{5/2})^2 JT\rangle$ interaction matrix elements attractive by 100 keV and the $\langle (p_{3/2})^2 JT|V|(p_{3/2})^2 JT\rangle$ interaction matrix elements repulsive by the same amount (we term this modification as Kuo10). The theoretical values are shown by a line in fig. 4. They show a reasonable agreement with the experimental results. It appears that the decrease of Q_t at high rotational frequencies is related to the phenomenon of band termination in the yrast band. In ^{76}Kr [7], this problem has been dealt with in detail for the yrast, negative-parity band with the two-quasiproton configuration $\pi[431]3/2^+ \otimes \pi[312]3/2^-$ and other negative-parity bands. In Valiente-Dobon *et al.*'s work, the energies of these high-spin collective configurations relative to an $I(I+1)$ reference plotted *versus* spin are compared with the configuration-dependent Cranked Nilsson-Strutinsky (CNS) calculations (see fig. 10 of ref. [7]). Further, a characteristic decrease in the experimental Q_t's for both the positive- and the negative-parity bands, as well known for terminating bands in other mass

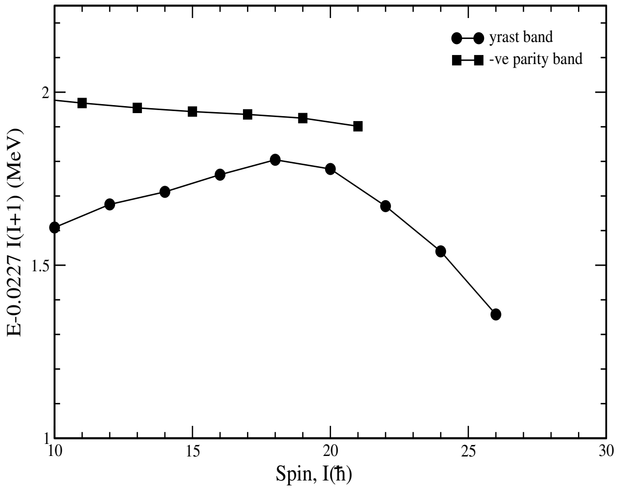

Fig. 5. Energies of high-spin collective configurations in ^{78}Kr relative to an $I(I+1)$ reference plotted *versus* spin from experimental data for both yrast band and negative-parity bands.

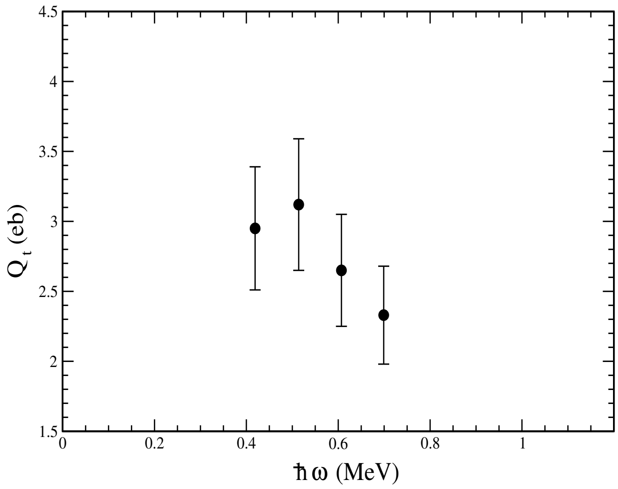

Fig. 6. Variation of Q_t with rotational frequency $\hbar\omega$ for the negative-parity band in ^{78}Kr.

regions, has been found in [7]. This clearly brings out band termination in these bands. Similar experimental energy comparison with CNS calculations for the yrast band in ^{78}Kr have been done in [4]. Figure 5 shows the variation of experimental energies, after subtraction of the energies of a rigid rotor, with spin for yrast and negative-parity bands in ^{78}Kr. The decreasing behaviour of the energy for spins $> 20\hbar$ for the positive-parity yrast band is indicative of band termination.

A decrease in Q_t with rotational frequency has also been observed for the yrast band in ^{80}Kr [17]. The experimental values of transition quadrupole moments as obtained in the present work for the two quasiparticle $\pi[431]3/2^+ \otimes \pi[312]3/2^-$ negative-parity band in ^{78}Kr are plotted *versus* the rotational frequency in fig. 6. This also shows the decreasing trend. It will, therefore, be fair to conclude that this loss of collectivity observed for the yrast and the negative-parity bands in ^{78}Kr in the present work, is related to the band termination effects.

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