Proton and neutron alignments of the K^{π}=5/2^{-} band in ^{79}Kr

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Abstract An experimental study of high-spin states in ^{79}Kr has been performed [illegible] the GASP array using the reaction ^{55}Mn(^{30}Si, αpn). Nine new states along with 10 new gamma ray transitions were found in the K^{π}=5/2^{-} band in ^{79}Kr. Three band crossings, associated with the alignments of a $\pi g_{9/2}$ pair and a $\pi g_{9/2}$ pair and also a high-j 5$h_{11/2}$ intrude orbital, were observed at rotational frequency $\hbar$=0.50, 0.65 and 0.90 MeV, respectively. A cranked shell model analysis has been made to interpret the experimental results.

Keywords $\gamma\gamma\gamma$-charged particle coincidence, Nuclear shape, Configuration, Alignments of $\nu g_{9/2}$ and $\pi g_{9/2}$ pairs, Intrude orbital

CLC numbers O571.23, O571.32+3, O571.6

1 Introduction

Because of the richness of different structure effects and the particular sensitiveness to the polarizing influences of unpaired nucleons, the medium-mass (A ≈80) nuclei in the chart of nuclides form a particularly interesting region, in which both the single particle and collective degrees of freedom interplay with each other and thus become an ideal area for testing various theoretical approaches. The microscopic reasons for the observed strong variation of collective nuclear properties in the A ≈80 mass region with particle number is the relatively lower single-particle level density by a factor of 2 compared with heavier nuclei (e.g. the A ≈160 mass region). In the heavy systems, equilibrium deformations vary smoothly from nucleus to nucleus, while in the A ≈80 mass region nuclear shape changes are much abrupt. Oblate collective, oblate non-collective, prolate collective and even superdeformed shapes have been found to coexist in the same nuclei. As an example, the yrast positive-parity band in ^{79}Kr has been observed to exhibit the shape evolution from a near-oblate shape through a prolate shape, back to a near-oblate shape[1] and finally to a superdeformed shape[2]. This kind of shape evolution has already been observed in other nuclei in this mass region, such as ^{70,72,74}Se, $^{73-76,78}$Br, $^{74-77,79}$Kr and ^{81,82,83,84}Sr, etc[3].

The header of the yrast band (9/2^{+} 149 keV) in ^{79}Kr was first observed by β^{+} decay study[4]. The first in-beam γ-ray spectroscopic study of ^{79}Kr was performed by Clemenets *et al.*[5] and the decoupled rotational band based on the 9/2^{+} states was first established.

Manuscript received date:1999-08-26

The latest results were achieved via the fusion evaporation reaction ^{65}Cu(^{18}O,p3n), the $K^{\pi}=7/2^{+}$ and $K^{\pi}=5/2^{-}$ rotational bands were extended up to states of $45/2^{+}$ 11822 keV and $31/2^{-}$ 6446 keV, respectively[1]. Here the additional results from the experimental study of high-spin states in ^{79}Kr are presented. The favored ($\alpha=+1/2$) and unfavored (α=-1/2) signature sequences in the $K^{\pi}=5/2^{-}$ band were extended up to states of $37/2^{-}$ 8992 keV and $59/2^{-}$ 20132 keV, respectively. Three band crossings, associated with the alignments of a $\nu g_9/2$ pair and a $\pi g_{9/2}$ pair, and also a high-j $\nu h_{11/2}$ intrude orbital were observed at the rotational frequencies 0.50, 0.65 and 0.90 MeV, respectively.

2 Experumental procedure

The experiment was performed at the Laboratori Nazionali di Legnaro (LNL) where the $^{30}Si^{8+}$ beam was provided by the Tandem XTU accelerator. Two stacked self-supporting foils of ^{55}Mn, each with about 400μg/cm^2 thick, were bombarded with an energy of 130 MeV and the average beam current being between 3~4 pnA. The residue ^{79}Kr was populated via the αpn channel.

The GASP array was used to detect gamma rays depopulating a number of different channels. The array includes 40 escape-suppressed large coaxial Ge detectors[6] in conjunction with the ball of 40 ΔE-E silicon telescopes[7]. Events, in which 3 or more escape-suppressed Ge detectors were registered in prompt time coincidence with 4 or more BGO elements, or with at least one ΔE-E silicon telescope, were accepted. With this trigger condition approximately 1.4×10^{9} Compton suppressed events with at least three gamma rays were recorded onto magnetic tape in event-by-event mode. Data were sorted into $\gamma\gamma\gamma$ cubes by setting the gates on detected charged particles. Since ^{79}Kr was produced in the αpn channel, the αp^{-}, α- and p-gated $\gamma\gamma\gamma$ cubes were used for the analysises in this work. Doppler shift correction were made from the recoil direction, which could be deduced by an event-by-event determination of the momenta of the detected charged particles. With this method the overall γ-ray energy resolution (FWHM) was improved from 11.4 keV around 1.3 keV to 8.0 keV for the πp channel. In order to determine energies and intensities of the γ-ray transitions, the energy and efficiency of the GASP spectrometer were calibrated using ^{88}Y, ^{56,60}Co and ^{152}Eu standard γ-ray sources.

To assign spins and parities to the energy levels, the directional correction of gamma rays de-exciting oriented states (DCO ratios) were extracted. The procedure for extracting the values of the DCO ratios, $R_{\rm DCO}$, can be seen in details in Ref.[2]. From the angular position of the Ge detectors in GASP array, the DCO ratios are expected to have values close to 1.0 for stretched quadrupole transitions and close to 0.5 for stretched dipole transitions.

3 Results and interpretation

3.1 Level scheme of the $K^{\pi}=5/2^{-}$ band in ^{79}Kr

The level scheme of the yrast negative-parity band in ^{79}Kr established from the established from the present work is shown in Fig.1. The order in which the transitions are placed is based primarily on their intensities and coincidence relationships. Spin assignments are based on the DCO ratio measurements. When no DCO is available, the corresponding spin assignment is tentatively made in parenthesis. The yrast negative-parity band is built on the $5/2^{-}$ state at an energy of 146.7 keV. It was previously observed up to the $29/2^{-}$ state at 5993 keV and tentatively up to the $31/2^{-}$ state at 6448 keV[1]. In the present study, we confirm the results of Ref.[1] and extend the α=-1/2 sequence up to the state of $59/2^{-}$) 20132 keV, along with 7 new transition. The favored α=+1/2 sequence was known up to the state of ($29/2^{-}$) 5993 keV and confirmed in the present work. Moreover, two additional new levels at 7422 and 8992 keV, respectively, have been found from our coincident datawith tentative ($33/2^{-}$) and ($37/2^{-}$) assignments. Fig.2 shows a background-subtracted coincidence spectrum with multi-gates on all possible combinations of the 722, 885, 1005 and 1282 keV γ-ray transitions in the α=-1/2 sequence. Two transitions of 2290 and 2668 keV, which cannot be seen on the top of the α=-1/2 sequence in the double-gated spectrum shown in Fig.2, are now clearly seen in the two dimensional $\gamma\gamma$-matrices. Note that the transition at 1026 keV was not used because of its doublet. The energy of levels and the energy, intensity, and DCO ratio of the γ-ray transitions in the $K^{\pi}=5/2^{-}$ band of ^{79}Kr produced in the ^{55}Mn(^{30}Si^{8+}, αpn) reaction at 130 MeV are given in Table 1. The γ-ray intensities were determined from the projection of the αp-gated $\gamma\gamma\gamma$ cube, except for the doublets and triplets, which were extracted from the coincidence data.

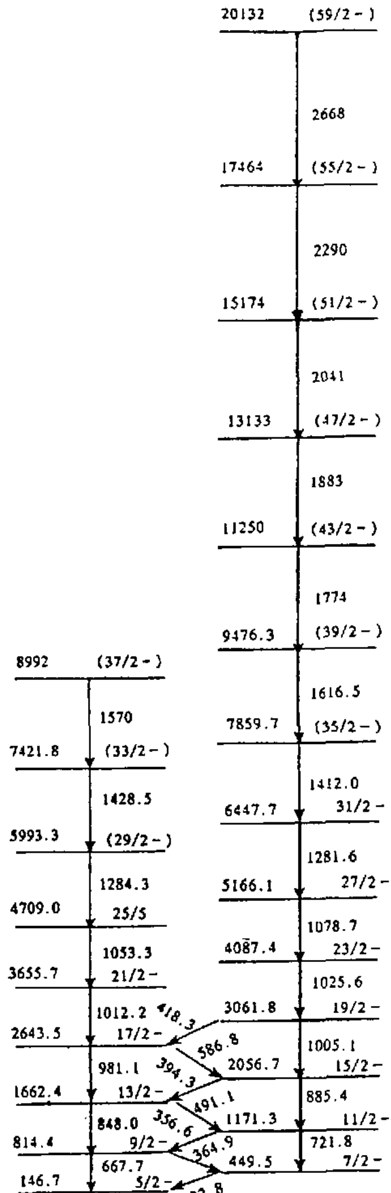

Fig.1 Level scheme of the $K^{\pi}=5/2^{-}$ band of ^{79}Kr obtained in the present work

Table 1 Energy of levels (E_{lev}), and Energy (E_γ), initial (I_i^π) and final (I_f^π) states, intensity (I_γ), and DCO ratio (R_{DCO}) of the γ-ray transitions within the $K^\pi = \frac{5^-}{2}$ band of ^{79}Kr.

E_{lev}/keV	E_γ/keV	$I_i^\pi \to I_f^\pi$	$I_\gamma^{(a)}$	R_{DCO}
146.7$^{(b)}$	146.7$^{(b)}$	$5/2^- \to 1/2^-$		
449.5	302.8(4)	$7/2^- \to 5/2^-$	40(8)	0.75(10)
814.4	667.7(5)	$9/2^- \to 5/2^-$	52(6)	0.98(12)
814.4	364.9(4)	$9/2^- \to 7/2^-$	28(6)	0.65(10)
1171.3	356.6(5)	$11/2^- \to 9/2^-$	6(2)	0.56(8)
1171.3	7218(6)	$11/2^- \to 7/2^-$	66(2)	0.95(10)
1662.4	848.0(5)	$13/2^- \to 9/2^-$	41(8)	1.12(12)
1662.4	491.1(5)	$13/2^- \to 11/2^-$	10(4)	0.58(8)
2056.7	394.3(5)	$15/2^- \to 13/2^-$	5(2)	0.60(8)
2056.7	885.4(6)	$15/2^- \to 11/2^-$	60(10)	1.01(10)
2643.5	586.8(6)	$17/2^- \to 11/2^-$	4(2)	0.45(10)
2643.5	981.1(6)	$17/2^- \to 13/2^-$	25(5)	0.90(10)
3061.8	418.3(6)	$19/2^- \to 17/2^-$	2(1)	
3061.8	1005.18(8)	$19/2^- \to 15/2^-$	48(8)	0.95(10)
3655.7	1012.2(6)	$21/2^- \to 15/2^-$	16(3)	1.20(15)
4087.4	1025.6(8)	$23/2^- \to 15/2^-$	30(6)	1.20(10)
4709.0	1053.3(8)	$25/2^- \to 15/2^-$	8(3)	1.05(10)
5166.1	1078.7(8)	$27/2^- \to 15/2^-$	19(4)	1.10(10)
5993.3	1284.3(8)	$(29/2^-) \to 15/2^-$	4(1)	
6447.7	128.6(8)	$31/2^- \to 27/2^-$	12(3)	0.90(10)
7421.8	1428.5(8)	$(33/2^-) \to 15/2^-$	2(1)	
7859.7	1412.0(8)	$(35/2^-) \to 31/2^-$	10(3)	
8992	1570(2)	$(37/2^-) \to 33/2^-$	1	
9476.2	1616.5(8)	$(39/2^-) \to 35/2^-$	8(2)	
11250	1774(1)	$43/2^-) \to 39/2^-$	7(2)	
13133	1883(2)	$(47/2^-) \to 43/2^-$	5(2)	
15174	2041(2)	$(51/2^-) \to 47/2^-$	4(1)	
17464	2290(2)	$(55/2^-) \to 51/2^-$	2(1)	
20132	2668(2)	$(59/2^-) \to 55/2^-$	1	

$^{(a)}$Intensities determined from αp-gated matrices. The γ-ray transition of 827.1 keV ($13/2^+ \to 9/2^+$) in the yrast band (K^π=$9/2^+$) in ^{79}Kr is used for normalization (100). Weak lines with one intensity unit only have an uncertainty of about 60%. $^{(b)}$Taken from Ref.[1].

3.2 Band crossings

Experimental alignments and routhians for the K^π=$5/2^-$ band are presented in Fig.3 as a function of the rotational frequency. No sharper alignments have been found in the band. The alignment patterns in both sequences are similar. The experimental observation of the signature ordering for the two signature partners is consistent with that of the calculation for the neutron [303]$5/2^-$ band, i.e. the α=-1/2 routhian lies below with α=+1/2 routhian.

The kinematic, $J^{(1)}$, and dynamic, $J^{(2)}$, moments of inertia for the both signature sequences of the K^π=$5/2^-$ band are presented in Fig.4. It can been seen that the $J^{(1)}$ for both sequences rise below $\hbar\omega$=0.50 MeV. Two peaks in $J^{(2)}$ versus plot for the α=+1/2 sequence and three peaks for the α=-1/2 sequence usually indicate band crossings with large interaction strength or some other structural changes (e.g., in deformation or in pairing field) taking place within a rotational band in ^{79}Kr. The nature can be well understood in the frame of the cranking shell calculations which will be presented in the next section.

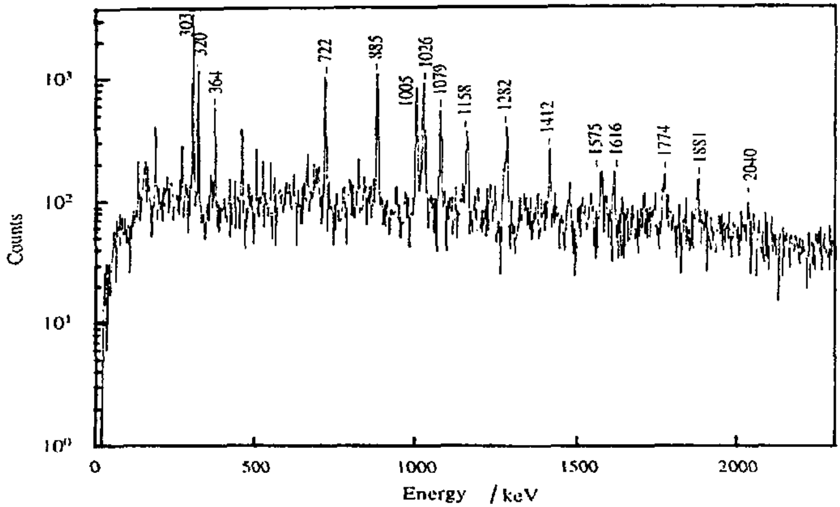

Fig.2 Sum of double-gated spectra produced in the reaction ^{55}Mn(^{30}Si^{8+}, αpn) at 130 MeV. Multi-gates were used by gating on all possible combinations of γ-ray transitions of 722, 885, 1005 and 1282 keV in the $K^{\pi}=5/2^{-}$ band. Note that the transition at 1026 keV was not used because of its doublet. The number of counts is plotted using a log-scale to enhance the small peaks at the top of the band

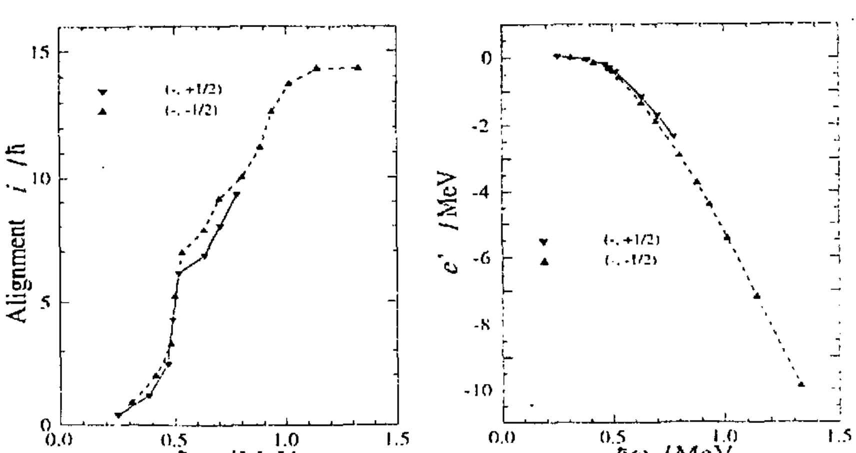

Fig.3 Experimental aligned angular momentum, I, (left) and routhians, e',(right) for the states in the $K^{\pi}=5/2^{-}$ band versus rotational frequency, $\hbar\omega$. Harris parameters $J_0 = 11\hbar^2/\mathrm{MeV}$ and $J_1 = 0\hbar^3/\mathrm{MeV}^4$ were used for the reference rotor. An effective value of K=5/2 was applied

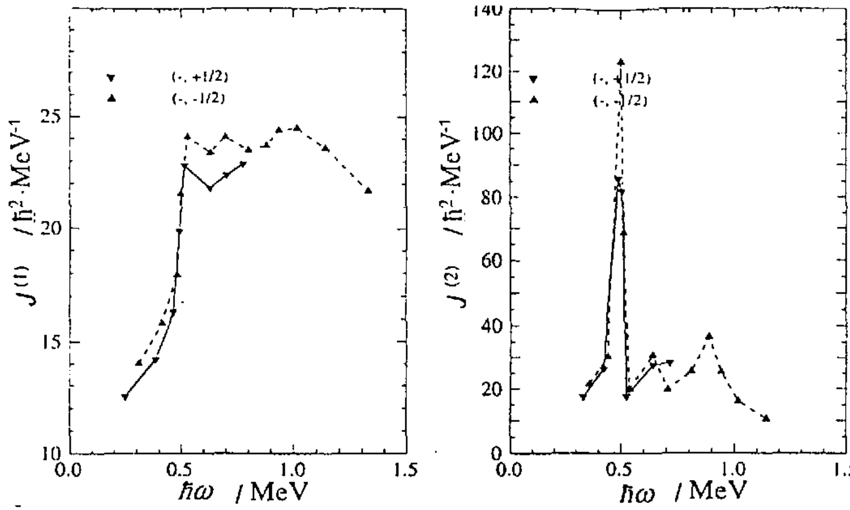

Fig.4 Kinematic, $J^{(1)}$, and dynamic, $J^{(2)}$, moments of inertia for the $K^{\pi}=5/2$ band in ^{79}Kr. A value of $K=5/2$ has been used for the two favored and unfavored sequences

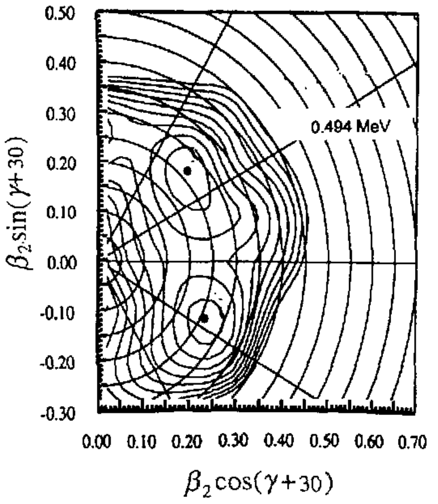

Fig.5 Total routhian surface (with pairing) at rotational frequency of 0.494 MeV in the (β_2, γ) plane for the $K^{\pi}=5/2^-$ band in ^{79}Kr. The distance between contour lines is 0.1 MeV

3.3 Deformed Woods-Saxon cranking calculations

In order to interpret the above experimental findings, a theoretical analysis has been performed using the Woods-Saxon cranking model[8]. Equilibrium shapes were calculated by minimizing the total routhian surface with respect to deformation parameters, β_2, β_4 and γ, shown in Fig.5.

The total routhian surfaces (TRS) with pairing for the interesting $\nu f_{5/2}$, $\nu f_{5/2}\otimes\pi g_{9/2}^2$, $\nu f_{5/2}\otimes\pi g_{9/2}^2\otimes\nu g_{9/2}^2$ and $\nu h_{11/2}$ configurations corresponding to the $K^{\pi}=5/2^-$ band, are calculated at different rotational frequencies. Six different shapes of the minima with the increasing of the rotational frequency, $\hbar\omega$, have been seen in the TRS. As an example, TRS calculation at the rotational frequency of 0.494 MeV is given in Fig.5. At low frequency ($\hbar\omega\sim 0.2$ MeV), 1qp ($\nu f_{5/2}$)-

configuration favors positive γ-values and forms a minimum at about β_2=0.29, γ=19°. With the rotational frequency increases, a first band crossing occurs at $\hbar\omega \approx$0.50 MeV and the prolate structure (β_2=0.25-0.27, β_4=-0.03, γ=14°-16°) is more pronounced, obviously due to the alignment of a $\pi g_{9/2}$ pair. A minimum at $0.26 \leq \beta_2 \leq 0.29$, $-0.016 \leq \beta_4 \leq -0.011$, $-55° \leq \gamma \leq -48°$ with $\nu f_{5/2} \otimes \nu g^2_{9/2} \otimes \pi g^2_{9/2}$ configuration is well developed to coexist with the excitation (γ=15°) at frequency above 0.5 MeV. Thus, a second band crossing (BC crossing) takes place at around $\hbar\omega \approx$0.66 MeV due to the alignment of two $g_{9/2}$ neutrons. Meanwhile, a new minimum around $0.33 \leq \beta_2 \leq 0.36$, $\gamma \approx 0°$ forms and this minimum is pronounced at $\hbar\omega \approx$0.90 MeV for the (π, α)=(-,-1/2) configuration, but it disappears for the (π, α)=(-,+1/2). Calculations of the quasi-particle routhians at deformation parameter fixed at (β_2,β_4,γ)=(0.36, 0.00, 0°) shows that a high-j neutron intrude orbital ($\nu h_{11/2}$) become occupied for the unfavored sequence when the rotational frequency above 0.9 MeV. This neutron intrude orbital most probably drives the deformation back to prolate shape.

4 Conclusion

The present investigation has resulted in the placement of some 10 new γ-ray transitions and 9 new levels in the decay scheme of the $K^{\pi}=5/2^-$ band in ^{79}Kr. The favored (α=+1/2) and unfavored (α=-1/2) sequences were extended up to states of ($37/2^-$) at the excited energy of 8992 keV and ($59/2^-$) 20132 keV, respectively. Two band crossings at rotational frequency $\hbar\omega$=0.50, 0.75 MeV, associated with the alignments of a $\pi g_{9/2}$ pair and a $\nu g_{9/2}$ pair, were observed for both signature sequences. The lowest $\pi g_{9/2}$ excitation in ^{79}Kr polarizes the core towards near-prolate shapes, while the $\nu g_{9/2}$ excitations polarize the core towards near-oblate shapes. A third structural change has been seen in the unfavored sequence above $I^{\pi}=(39/2^-)$ state. The most probably reason is due to a high-j $h_{11/2}$ neutron intrude orbital.

Acknowledgement

The authors are grateful to the operational staff of the Tandem XTU accelerator of Laboratori Nazionali de Lagnaro (LNL).

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