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High-K band of unnatural parity in ^{49}Cr

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The nucleus ^{49}Cr has been studied using the reactions ^{28}Si(^{28}Si,$\alpha 2pn$) at 115 MeV and ^{46}Ti(α,n) at 12 MeV, respectively. A high-K band with $K^{\pi}=13/2^{+}$ has been identified, whose bandhead acts as an yrast trap for the low-lying levels with positive parity. This peculiar phenomenon is well reproduced by large-scale shell model calculations in the pf configuration space plus a proton hole in the $1d_{3/2}$ orbital. As an essential part of the work, lifetimes of some nonyrast states, as well as of a state in the $K^{\pi}=5^{+}$ band in ^{50}Mn, have been determined using the Doppler shift attenuation method. [S0556-2813(99)51010-8]

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After a long standby period, in the last few years very significant progress has been made by nuclear spectroscopy in the middle of the $1f_{7/2}$ shell, both theoretically and experimentally. Large-scale shell model (SM) calculations in the full pf shell valence space have been very successful in explaining the building up of deformation for natural parity states of low spin [1–4]. The middle of the $1f_{7/2}$ shell turns out thereby to be a unique workbench where most of the concepts related to collective properties, such as axial and triaxial deformation, band crossing, band termination, particle-rotor coupling, etc., find their microscopical explanation in terms of spherical shell model calculations. A detailed study was first made theoretically in the even-even $Z=N$ nucleus ^{48}Cr [2] and thereafter in ^{50}Cr [3]. The study then continued for odd-A nuclei such as ^{47}V, ^{49}Cr, and their mirrors [4]. The predictions of these calculations have triggered several experimental works [5–9], which have confirmed the main predictions of theory.

Recently, SM calculations for $1f_{7/2}$ nuclei have been extended to encompass unnatural parity bands, which are described as due to the presence of a hole in the $1d_{3/2}$ orbital. In this way the observed unnatural parity $K^{\pi}=3/2^{+}$ band [10,11] in ^{47}V is well described as a $1d_{3/2}$ proton hole coupled rather weakly to the ^{48}Cr ground-state (g.s.) band [12]. An essential role in this comparison is played by the analysis of the electromagnetic decay properties and, in this frame, by Doppler shift attenuation method (DSAM) lifetime measurements.

In the present paper we study the unnatural parity states in ^{49}Cr, the cross conjugate of ^{47}V. While in ^{47}V the $1d_{3/2}$ hole is coupled to the deformed, even-even, ^{48}Cr core, here we have to deal with the odd-odd, $Z=N$, ^{50}Mn core, which has two almost degenerate bands [13] based, respectively, upon the $I^{\pi}=0^{+}$ $T=1$ ground state and the $I^{\pi}=5^{+}$ $T=0$ state at 229 keV excitation energy, respectively [14]. As we shall see this gives rise to a number of unusual features. The experimental level scheme for the unnatural positive parity levels of ^{49}Cr was not well known up to now, as only a $3/2^{+}$ at 1982 keV and a $5/2^{+}$ at 2432 keV were established [15]. It can be further mentioned that in Ref. [16] a side structure of irregular properties and negative parity was reported. More recently, the same authors proposed in its place a more regular band based on a level at 3528 keV, without any parity assignment [10].

High-spin states in ^{49}Cr have been populated in the reaction ^{28}Si on ^{28}Si at 115 MeV bombarding energy. The cross section for the $\alpha 2pn$ channel leading to ^{49}Cr was measured to be $\sim$100 mb. The beam was provided by the Tandem XTU accelerator of the Legnaro National Laboratory and the target consisted of 0.8 mg/cm^2 of ^{28}Si on 15 mg/cm^2 of Au. The mean initial velocity of the recoils was 0.045 c. Coincident γ rays were collected with the γ-array GASP, which consists of 40 Compton-suppressed large volume detectors and a BGO multiplicity filter with 80 elements. Events were stored when at least two Ge detectors and two elements of the multiplicity filter fired in coincidence. A detailed spectroscopic study was performed, including level scheme, angular distribution, and DSAM lifetimes. The data obtained for the side structure are reported in Table I. The population of the lower members of the sideband is about 6% of that of the lower yrast states. Some of the present lifetime determinations disagree with previous measurements [10].

The experimental procedure will be only briefly recalled, since it has been already described for similar experimental conditions [8]. Energy and intensity calibrations were performed with sources of ^{152}Eu and ^{56}Co, as well as with internal narrow lines. By gating on Doppler unbroadened and nearly unbroadened feeding lines, γ lines with a resolution of 2–3 keV could be generally obtained, so that we can quote 0.4 keV as the maximum error in energy calibration. The obtained level energies, shown in Fig. 1(a), agree essentially with those reported in Ref. [10], but one more level has been added, as well as several new connecting transitions. Angular distribution data are represented in Table I by the AD ratios: $(W(35°)+W(145°))/2W(90°)$, obtained from γ-gated spectra. As we showed in Ref. [17], they provide

TABLE I. Results for the sidestructure in ^{49}Cr. (Errors in the experimental γ-energy are less than 0.4 keV.)

Transition	E_γ expt. keV	E_γ SM keV	B expt. %	AD	τ expt. ps	τ prev. ps	$B(E2)$ expt. e^2 fm^4	$B(E2)$ th. e^2 fm^4	$B(M1)$ expt. μ_N^2	$B(M1)$ th. μ_N^2	$B(E1)$ expt. W.u.
$13/2_2^- \rightarrow 11/2^-$	1965.4	1865	78.3(30)	0.83(5)	0.38(7) [a]	>4 [c]		1.2	0.010(2)	0.005	
$13/2_2^- \rightarrow 13/2^-$	1027.6	844	16.1(20)	1.35(13)				0.9	0.025(5)	0.016	
$13/2_2^- \rightarrow 15/2^-$	337.2	245	4.0(5)					20.9	0.12(3)	0.057	
$13/2_2^- \rightarrow 9/2^-$	2444.0	2280	1.6(5)				0.04(1)	0.04			
											(10^{-5})
$13/2^+ \rightarrow 11/2^-$	2330.0		60(3)	0.79(7)	>10	>4 [a]					<0.3
$13/2^+ \rightarrow 15/2^-$	701.9		18(2)	0.90(7)							<4
$13/2^+ \rightarrow 13/2_2^-$	364.4		22(2)	1.28(9)							<35
$15/2^+ \rightarrow 13/2^-$	1966.8		4(2)								0.2(1)
$15/2^+ \rightarrow 15/2^-$	1276.7		11(2)	1.15(15)							2.0(6)
$15/2^+ \rightarrow 13/2_2^-$	939.3		6(2)								4(1)
$15/2^+ \rightarrow 13/2^+$	575.2	635	79(4)	0.60(6)	1.8(4)	>4 [c]	220(100)	192	0.12(3)	0.073	
$17/2^+ \rightarrow 13/2^+$	1410.8	1391	28(3)	1.30(11)	1.1(2)	>4 [c]	37(9)	33			
$17/2^+ \rightarrow 15/2^+$	835.5	755	72(3)	0.45(5)			140(80)	209	0.058(15)	0.002	
$19/2^+ \rightarrow 15/2^+$	1874.4	1972	65(5)	1.25(14)	0.40(10)	<0.44 [c]	58(14)	65			
$19/2^+ \rightarrow 17/2^+$	1039.4	1216	35(5)					171	0.030(10) [b]	0.02	
$(21/2^+) \rightarrow 17/2^+$	1966.6	1780	80(6)		0.26(6)		80(20)	125			
$(21/2^+) \rightarrow 19/2^+$	927.2	564	20(6)					157	0.040(15) [a]	0.007	
$5/2^+ \rightarrow 3/2^+$	450.0	557	43(9) [b]		0.80(25) [a]	0.9^{+8}_{-3} [d]	210^{+200}_{-100}	285	0.30(10)	0.078	

[a]Determined in the ^{46}Ti(α,n) reaction.
[b]$E2$ contribution is neglected in this estimate (see text).
[c]Reference [10].
[d]Reference [15].

information equivalent to standard AD ratios from single spectra. Ratios of about 0.8 and 1.3 are predicted for stretched pure dipole and quadrupole transitions, respectively, while for a $\Delta I = 0$ pure dipole transition, the same ratio as for a stretched quadrupole is expected. The lifetimes have been determined by means of the program LINESHAPE [18], modified in order to allow data to be analyzed also with the narrow gate on transitions below (NGTB) procedure,

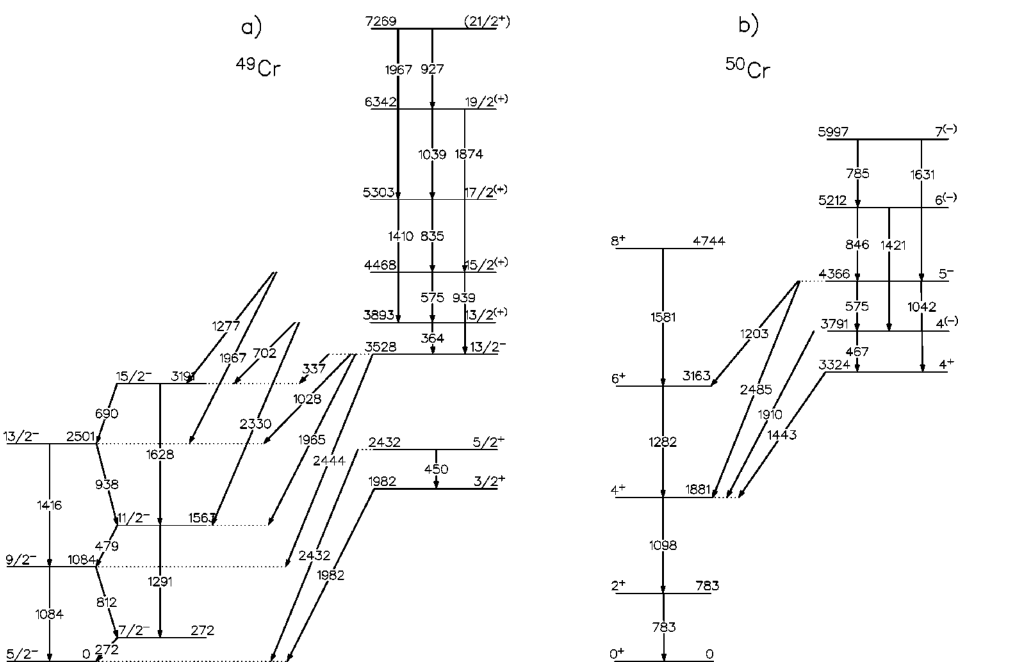

FIG. 1. (a) Part of the level scheme of ^{49}Cr relevant for the present work, showing the side-structure and its decay towards the yrast band. (b) The same for ^{50}Cr.

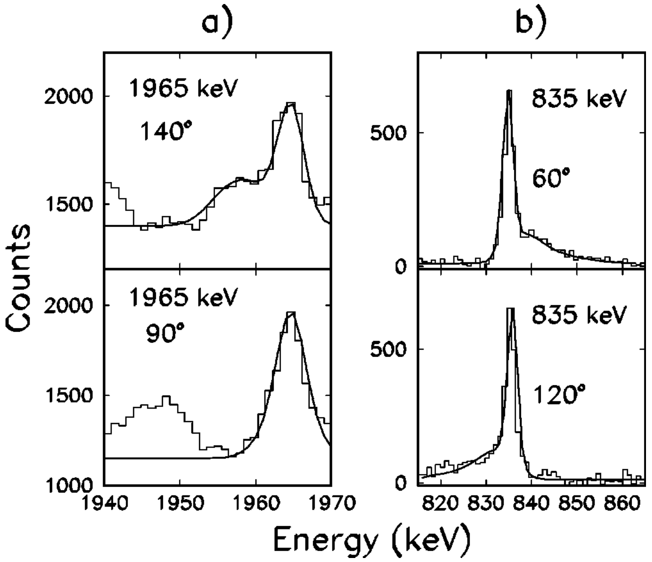

FIG. 2. (a) DSAM analysis for the 1965 keV ($13/2^-_2 \rightarrow 11/2^-$) transition in ^{49}Cr, from the reaction ^{46}Ti(α,n). (b) DSAM analysis for the 835 keV ($17/2^{(+)} \rightarrow 15/2^{(+)}$) transition in ^{49}Cr, from the reaction ^{28}Si(^{28}Si,$\alpha 2pn$).

which is free from systematic errors due to sidefeeding [19].

In order to get complementary information for some low-lying levels, not conveniently populated in the aforementioned experiment, the reaction ^{46}Ti$(\alpha,n)^{49}$Cr at a bombarding energy of 12 MeV has also been performed at the C.N. van de Graaff accelerator of Legnaro National Laboratory. The target consisted in this case of 1 mg/cm^2 ^{46}Ti on 2 mg/cm^2 Au. Two large volume Ge detectors were located at 90° and 140°. Data from this latter measurement are indicated explicitly in Table I. The obtained results below allowed a conclusion for the sidestructure in ^{49}Cr.

The level at 3528 keV decays via 337 keV, 1028 keV, 1965 keV, and 2444 keV transitions to levels $15/2^-$, $13/2^-$, $11/2^-$, and $9/2^-$, respectively. The decay out was established by putting a gate on the unbroadened 364 keV line and thus getting unbroadened coincident branchings. In this way the intensity of the 1965 keV branch could be determined precisely, even if it was coincident with the 1967 keV ($7269 \rightarrow 5303$) transition [but not with the weak 1967 keV ($4468 \rightarrow 2501$) one], because the latter is very broad and can be separated. The lifetime could not be determined from the same data set, since one had to gate on a transition below, thus getting a broadened 1965 keV line, which overlapped with the mentioned lines of close energy. Since the other branchings are too weak, the DSAM analysis of the 1965 keV line was performed in the ^{46}Ti(α,n) reaction. The best fit shown in Fig. 2(a) was obtained with a value of 0.38(7) ps. Concerning the spin-parity assignment of the level at 3528 keV, we note that, in the case of positive parity, only the $13/2^+$ assignment would be consistent with the observed AD ratios, but it can be excluded since the transition of 337 keV to the $15/2^-$ level would be an $E1$ of about 2×10^{-3} W.u., i.e., about 10 times faster than any other in this nuclear region, according to a new review of data [11]. The newly reported branching of 337 keV, which allows us to get this conclusion, has been consistently obtained from several γ-gated spectra and even from double γ-gated spectra from triples. When considering negative parity assignments, the $15/2^-$ assignment is excluded since an $E2$ character of the 1965 keV transition is not compatible with the observed AD ratio and, moreover, the 2444 keV branch would be too fast for an $M3$ transition. A $11/2^-$ assignment has to be discarded since the 337 keV $E2$ transition to the $15/2^-$ state would be too fast. We assign then $13/2^-$ to the level at 3258 keV, which thus decays to the $11/2^-$ and $13/2^-$ states mainly via magnetic-dipole transitions. It must be noted that the present assignment disagrees with Ref. [10].

The level at 3893 keV decays via unbroadened 702, 2330, and 364 keV lines to $15/2^-$, $11/2^-$ and $13/2^-_2$ levels, respectively. Its lifetime is longer than 10 ps (including an unpublished result of ours obtained in a plunger measurement) and shorter than 5 ns (from electronic coincidences). Considering first a negative parity assignment, we have to exclude a $15/2^-$ one since it is not compatible with the AD ratio of the 2330 keV transition to the $11/2^-$ state. The remaining negative parity assignment would be $13/2^-_3$, but in that case the two close $13/2^-_2$ and $13/2^-_3$ states should likely be mixed. One would then expect that any of the branches from the $13/2^-_3$ state do have similar transition strengths as those from the $13/2^-_2$ one, while they are in every case more than 10 times smaller. In the case of positive parity the forward-peaked 364 keV $E1$ transition allows the experimental assignment $I=13/2$, which is fully consistent with measured AD ratios, including the nonstretched $13/2^{(+)} \rightarrow 15/2^-$ transition. The assignment $I^\pi=13/2^{(+)}$ is thus made at this point.

The small AD ratios of the 575 keV ($15/2^{(+)} \rightarrow 13/2^{(+)}$) and the 835 keV ($17/2^{(+)} \rightarrow 15/2^{(+)}$) transitions point to $E2/M1$ mixing ratios $\delta=-0.20(5)$ and $-0.34(10)$, respectively. (The second solution of δ would lead to too-large $E2$ strengths.) Owing to the quadrupole character of the 1874 keV transition, $I^\pi=19/2^{(+)}$ is assigned to the 6342 keV level. The assignment $21/2^+$ is given in parentheses to the next level at 7269 keV, even if it is very probable on the basis of the level scheme. As an example of the DSAM fits along the sideband, the case of the 835 keV ($17/2^{(+)} \rightarrow 15/2^{(+)}$) transition is shown in Fig. 2(b). The $M1$ strengths of the transitions $(21/2^+) \rightarrow 19/2^{(+)}$ and $19/2^{(+)} \rightarrow 17/2^{(+)}$ in Table I are not corrected for an $E2$ contribution. Corrected values, assuming $E2$ rotational model estimates, will remain within quoted errors.

The experimental positive parity sidestructure, shown in Fig. 1(a), includes levels $3/2^+$ and $5/2^+$ observed by us only in the ^{46}Ti(α,n) reaction. It is readily explained in the Nilsson framework by the coupling of a $1d_{3/2}$ hole, described by the orbital $[202]3/2^+$, to the low-lying $K^\pi=0^+$, $T=1$ and $K^\pi=5^+$, $T=0$ bands in ^{50}Mn, based on the ground state or on the 5^+ level at 229 keV [13]. By coupling a $1d_{3/2}$ hole to the $K^\pi=0^+$, $T=1$ band, one obtains a $K^\pi=3/2^+$ band, to which the states $3/2^+$ and $5/2^+$ belong. Owing to isospin coupling rules, this band is made of proton-hole excitations (two thirds) and neutron-hole excitations (one third). At low energy one may also reasonably expect a $K^\pi=13/2^+$ band due to the coupling of the $1d_{3/2}$ proton hole with the $K^\pi=5^+$, $T=0$ band in ^{50}Mn, which we identify with the newly observed band. Note that the bandhead of the $K^\pi=13/2^+$ band lies almost 2 MeV higher than that of the $K^\pi=3/2^+$ one. This gives a measurement of the difference between the average isovector and isoscalar interactions in the $1d_{3/2}$ and $1f_{7/2}$ orbits.

The deformation parameter of the high-*K* band, deduced from the data reported in Table I, is $\beta=0.26(3)$. In the proposed picture, the deformation associated with the high-*K* band in ^{49}Cr should be the same as that of the $K^\pi=5^+$ band in ^{50}Mn, which is not known since no lifetimes were determined in Ref. [13]. In the present work the lifetime associated with the 1503 keV ($9^+\to7^+$) transition in ^{50}Mn, populated via the αpn channel, has been determined with the NGTB procedure [19] to be 0.75(12) ps, corresponding to $B(E2)=145(22)$ e^2 fm^4. Assuming a $K^\pi=5^+$ band, a deformation parameter $\beta=0.26(2)$ is deduced for a state well below the terminating one at 15^+. The deformation of the $K^\pi=5^+$ band in ^{50}Mn, as well as that of the g.s. band [4,11] and of the high-*K* positive parity band in ^{49}Cr, consequently turns out to be intermediate between those of ^{48}Cr ($\beta=0.28$) and ^{50}Cr ($\beta=0.25$) [8].

The presence of the high-*K* positive parity band provides a natural explanation of the experimental fact that the members of the $K^\pi=3/2^+$ band are not observed in the fusion reaction experiment at GASP. These levels do not appear to be appreciably fed along the $K=3/2^+$ band, since it is nonyrast. On the other hand, they are not fed by the high-*K* band, since the bandhead decays via $E1$ to negative levels, thus acting as a yrast trap for the lower members of the $K^\pi=3/2^+$ band.

An explanation can also be given for the remarkable fact that the $13/2^+$ bandhead decays preferentially to the $13/2^-$ yrare state. The yrare $13/2^-$ state at 3528 keV in ^{49}Cr can be constructed by lifting a proton from the $[321]3/2^-$ orbital to the $[312]5/2^-$ one and coupling both unpaired protons with a $[312]5/2^-$ neutron to get the maximum value of *K*. The favored transition is thus a *K*-allowed $E1$, which connects states having both a proton excited to the $[312]5/2^-$ orbital, from the $[202]3/2^+$ and the $[321]3/2^-$ ones, respectively. On the contrary, the transitions to yrast levels are *K* forbidden. In practice, since some *K* mixing is a general feature, a hindrance is observed, which is in the present case about 10. This interpretation is confirmed by a similar behavior observed in ^{50}Cr [8], as reported in Fig. 1(b). In this case neutrons do not bring spin, so that the connected states are 4^- and 4_2^+. The *K*-allowed transition is known to be of $2.9(3)\times10^{-4}$ W.u., i.e., the maximum observed in this region. The hindrance caused by *K* forbiddenness is in this case of the order of 70.

The schematic interpretations given above have been microscopically substantiated by large-scale SM calculations, performed with the code ANTOINE [1]. Good agreement has already been reported in the full pf configuration space for the normal parity yrast states of ^{49}Cr [4], using the KB3 interaction [1]. In the present work we extend the comparison to nonyrast states of normal parity. In particular, the yrare $13/2^-$ is well reproduced also concerning the decay out, as shown in Table I. Furthermore, the possibility has been checked that the assumed yrast $13/2^+$ could be a third $13/2^-$ state, but this is predicted to lie about 1.3 MeV above the $13/2_2^-$ state. To facilitate the comparison, the calculated negative levels relevant for the discussion are included in Fig. 3. Since the accuracy of SM predictions for normal parity states in the middle of the $1f_{7/2}$ shell and, in particular in ^{49}Cr [4], is of the order of a few hundred keV, we definitely exclude the negative parity assignment.

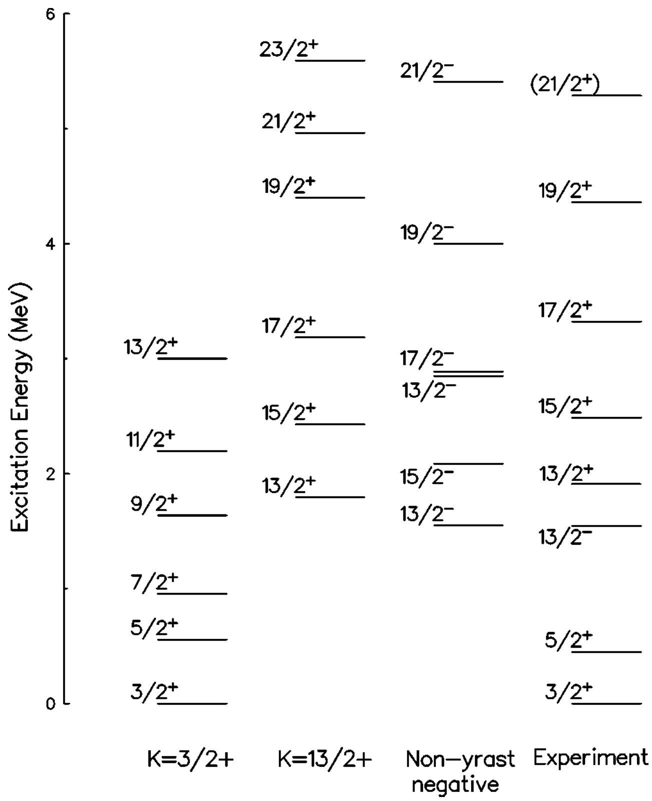

FIG. 3. Theoretical sidebands of positive and negative parity in ^{49}Cr, as compared with the experimental levels.

To calculate the positive parity states, the pf configuration space has been extended to include a hole in the $1d_{3/2}$ orbital, with a similar approach as in Ref. [12]. In this case, however, the increase in dimensions forces us to make truncations in the calculation. Hence, we allowed a maximum of three particles to jump out of the $1f_{7/2}$ orbit, which has been shown to be a quite reasonable approximation to the complete results [1]. For the cross sd-pf part we used the interaction of Ref. [20], where the difference between the isoscalar and the isovector centroids was fixed to its experimental value. The calculated and the experimental level schemes are presented in Fig. 3. The yrast trap behavior of the $13/2^+$ bandhead is apparent, as it is predicted close to the $9/2^+$ state of the $K^\pi=3/2^+$ band. But, even if the $E2$ transitions were energetically possible, the trap would still exist because of the smallish $B(E2)$ values (0.01 and 0.001 e^2 fm^4, respectively) predicted by the calculations. Those values give a hint about the degree of *K* forbiddenness of the transitions. The measured $B(E2)$ values are quite well reproduced, as shown in Table I. The deduced deformation of $\beta \simeq 0.26$ for the lowest members of the band points to a negligible mixing with the $K^{\pi}=3/2^{+}$ band, as theoretically predicted and, consequently, to a high-K character for this band. The fact that the interband $E1$ transitions towards the ground state band are not very much hindered may indicate that the g.s. band does not have a good K quantum number, as shown by the relevant signature splitting, which points to some triaxiality and thus K mixing. It has to be noted, however, that the agreement for positive parity levels is not so good as for the negative parity ones. This may be due to the necessary truncation of the model space.

We have also examined the Nilsson model hint that the yrare $13/2^{-}$ state could be the head of a $K^{\pi}=13/2^{-}$ band. As displayed in Fig. 3, a rather regular dipole sequence is predicted by SM calculations to be based on the $13/2^{-}$ yrare state. The $B(E2)$ values for interband and intraband transitions are consistent, in this case, with 10–20 % configuration mixing with the g.s. band. In the present GASP experiment yrare states were not efficiently populated, so that the latter predictions could not be checked.

In summary, a novel coupling has been found in ^{49}Cr, between the $K^{\pi}=5^{+}$, $T=0$ band in ^{50}Mn and a $1d_{3/2}$ proton-hole, giving rise to a high-K band of unnatural parity. The bandhead acts as a yrast trap for the lower positive parity levels, which belong to the $K^{\pi}=3/2^{+}$ band. An interplay of K-allowed and K-hindered transitions has also been observed. These unusual phenomena in the $1f_{7/2}$ shell are well described by large-scale SM calculations.

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