Investigation of low spin states in ^{48}Cr with the MINIBALL γ-ray spectrometer

K. Jessen,[1] A. Dewald,[1] J. Eberth,[1] G. Gersch,[1] J. Jolie,[1] N. Pietralla,[1] T. Steinhardt,[1] N. Warr,[1] D. Weißhaar,[1] V. Werner,[1] P. von Brentano,[1] and S. M. Lenzi[2]
[1]*Institut für Kernphysik, Universität zu Köln, Zülpicher Straße 77, D–50937 Köln, Germany*
[2]*Dipartimentio di Fisica, University of Padova, Via F. Marzolo 8, I–35131 Padova, Italy*
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Low spin states in the self-conjugate even-even nucleus ^{48}Cr were investigated using the MINIBALL γ-ray spectrometer. At the FN TANDEM accelerator in Cologne the ^{46}Ti(^{3}He,n) reaction was used for the measurement of $\gamma\gamma$ coincidences for an excitation function from 7 to 12 MeV beam energy. Seventeen excited states were observed, nine for the first time by means of γ-ray spectroscopy, and new spin assignments were made. No excited states apart from the ground band were observed below 3.4 MeV. First comparisons with different model calculations are given.

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Much experimental and theoretical work has recently been devoted to the investigation of self-conjugate nuclei, which exhibit unique and interesting properties. For example, they are the only nuclei in which isospin zero states ($T=0$), nearly degenerate isospin doublets, and large isovector $M1$ transitions can be found. In particular, the $N=Z$ nucleus ^{48}Cr, placed amidst the doubly magic nuclei ^{40}Ca and ^{56}Ni, has been the subject of recent studies [1–7]. The ground state rotational band of ^{48}Cr has been successfully described both by the shell model [5] and the collective model [6]. The latter approach shows ^{48}Cr as a prolate rotor. On the other hand, the shell model reproduces the states of the yrast structure impressively well and predicts many additional states above the pairing gap of about 3 MeV. So far these additional states had not been observed experimentally. The question of their existence puts the shell model to a crucial test. A recent ^{40}Ca$+\alpha+\alpha$ cluster model approach [7] also describes level energies and $B(E2)$ values of the ground band very well and also predicts many so far unobserved states.

Early particle-spectroscopic works on the energy levels of ^{48}Cr following the (p,t) reaction had shown that about nine excited states are to be found at level energies between 3.4 and 6.1 MeV [8–10]. Recent measurements used heavy ion induced reactions to examine both yrast and nonyrast structures of ^{48}Cr [1–3]. The nonyrast states were assumed to belong to a $K^\pi=(4^-)$ band, but the spin and parity assignments had only been tentative [3]. The aim of the present work was to extend the known level scheme and remove the spin ambiguity for the sideband. Therefore, we performed a complete γ spectroscopy experiment using the new MINIBALL spectrometer [11].

The population of nonyrast states in ^{48}Cr was carried out following the ^{46}Ti(^{3}He,n) reaction at the FN TANDEM accelerator of the University of Cologne. The MINIBALL spectrometer was used to measure $\gamma\gamma$ coincidence events. It was designed as an extremely efficient array for the detection of low multiplicity γ events. Its high full-energy peak efficiency and effective granularity are needed for the Doppler correction of γ rays emitted by fast recoiling nuclei. MINIBALL was equipped with 18 sixfold segmented encapsulated Ge detectors, clustered in six triple-cluster cryostats with three detectors each. For this experiment we used only the total energy signal, which is read out from the inner core contact. Neither the segment information of the detectors nor a pulse-shape analysis was needed, as no Doppler broadening of the γ transitions was observed in the spectra. All of the detectors were positioned as close as possible to the reaction chamber, i.e., at a distance of about 10 cm to the target. A detailed description of the detectors and the spectrometer frame can be found in Ref. [11].

The target consisted of a self-supporting foil of 0.94 mg/cm^2 ^{46}Ti, which was bombarded at 7, 8, 10, and 12 MeV beam energy for a total of about 56 h measuring time. The sorting of the recorded $\gamma\gamma$ coincidences resulted in four matrices of $4k\times4k$ resolution, containing 1.9, 2.8, 4.5, and 2.9×10^8 $\gamma\gamma$ coincidence events, respectively. The gated spectra in Fig. 1 illustrate the data quality for each of the different beam energies.

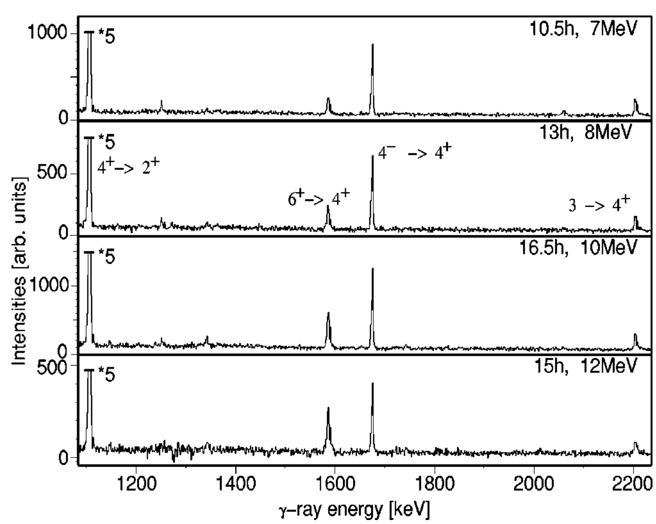

FIG. 1. Background subtracted coincidence spectra gated by the $2^+\rightarrow0^+$ transition. The intensity of the $6^+\rightarrow4^+$ decay increases with the beam energy, contrary to the constancy of the $4^-\rightarrow4^+$ transition. Measuring time and beam energy are given in the upper right corner of each spectrum.

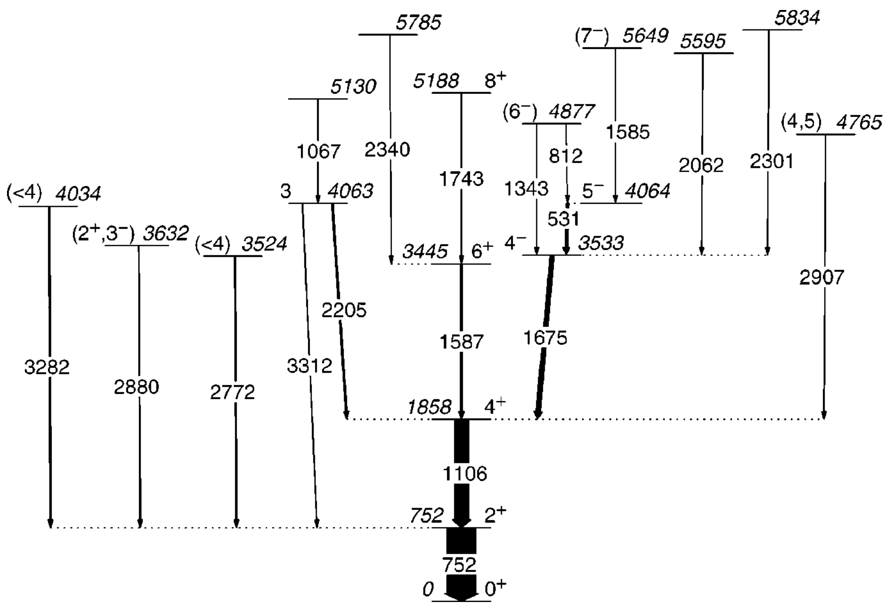

FIG. 2. Level scheme of ^{48}Cr from this work. The tentative spin value(s) of the 3632-keV level is taken from Ref. [12] and in accordance with our result.

From the $\gamma\gamma$ coincidences the level scheme of ^{48}Cr, shown in Fig. 2, was constructed. With respect to earlier γ spectroscopic works [1–3] we observed nine new levels and ten new γ transitions, exhibiting structures aside from the ground state band and the known nonyrast band. Three levels had already been observed by particle spectroscopy [9], namely, the levels at 3524 and 3632 keV and the doublet at 4063 and 4064 keV, which had not been recognized as such. Our coincidence relations gave clear placements for both levels of the doublet. No excited states except the 2_1^+ and 4_1^+ were observed below 3.4 MeV. This is a fairly notable result, since the performed γ-ray spectroscopy following the $(^3\mathrm{He}, n)$ reaction can be regarded as complete in the spin range of $3\hbar$ and $4\hbar$ up to about 4 MeV excitation energy.

In order to determine spin values, the excitation function for each level was analyzed. We compared the intensities of transitions depopulating the levels of interest as functions of the beam energy. Those intensities were determined by gating from below and normalized to the corresponding intensities at 7 MeV beam energy. For instance, gates on the 1106-keV transition $(4_1^+ \rightarrow 2_1^+)$ at different beam energies served for the determination of the intensities of the 1675-keV transition. In a second step the results were normalized to the intensities of the decay from the 4_1^+ to the 2_1^+ state (gated on the $2_1^+ \rightarrow 0^+$). The known spin values of the 1858- and 3445-keV levels, $4\hbar$ and $6\hbar$, respectively, served as references for the comparison of different intensity curves. The results for the states at 3533, 4063, and 4064 keV are depicted in Fig. 3. Our analysis is sensitive to different spins in the range from $3\hbar$ to $6\hbar$. The results are summarized in Table I.

Definite spin assignments were made for the states at 3533 and 4064 keV, which are attributed to the nonyrast band. The states at 3524-, 3632-, 4034-, and 4063-keV level energy are assigned to have a spin of $3\hbar$ or less, but due to the lack of known $\gamma\gamma$ excitation functions in this spin range, we are not able to give definite assignments. With the information from an additional $\gamma\gamma$ angular correlation experiment, performed with the OSIRIS-6 cube spectrometer in Cologne, a lower spin limit of $3\hbar$ was determined for the 4063-keV level. The experimental details are described in Ref. [13]. This measurement gave multipole mixing ratios for three levels and branching ratios for the decays of the 4063-keV level, see Table I.

The adopted spin information for the levels that had already been observed in Ref. [9] is in accordance with the previous results. The spin-parity assignment of $J^\pi = 3^-$ for one level at (4067 ± 5) keV from particle spectroscopy has to be questioned, since it is a doublet, that had not been resolved in triton spectra. Nevertheless, the spin assignment of $3\hbar$ for the 4063-keV state is supported by our data. A negative parity assignment would be supported by shell model calculations performed with the code ANTOINE [14] using the KB3 interaction, which show no 3^+ state decaying to the 4_1^+.

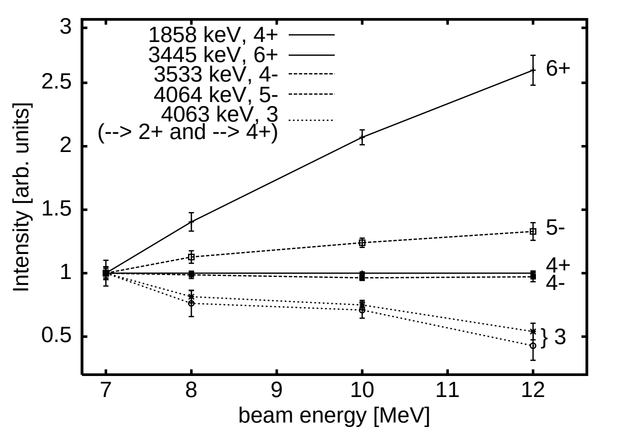

FIG. 3. Depopulating intensities of different levels (gated from below, see text) normalized to the value at 7 MeV and the $4_1^+ \rightarrow 2_1^+$ decay. The reference curves for the 4_1^+ and 6_1^+ states are drawn solid, the curves for the negative parity band are dashed, and the ones obtained from both decays of the 4063-keV level are dotted.

TABLE I. New levels, spins, and transitions in ^{48}Cr from this work. The intensities were determined by gating on the $2_1^+ \to 0_1^+$ transition at 9 MeV beam energy. The intensity of the $4_1^+ \to 2_1^+$ transition corresponds to 100%. The last columns give the information resulting from the additional measurement. See text for details.

E_x (keV)	J ($\hbar$)	E_γ (keV)	Intensity (%)	δ	Branching ratio
3524	(<4)	2772	3.9(4)		
3533	4	1675	24.4(20)	−0.01(5)	
3632	(<4)	2880	6.8(6)		
4034	(<4)	3282	8.8(7)		
4063	3	2205	7.8(6)	−0.04(5) or ⩾10	100(13)
		3312	3.0(3)		28(6)
4064	5	531	8.8(7)	0.01(5) or ⩾7	
4765	(4,5)	2907	2.4(2)		
4877	(5,6)	1343	2.0(2)		
5130		1067	1.7(2)		
5595		2062	1.2(2)		
5785		2340	0.8(1)		
5834		2301	0.9(2)		

Aside from spin assignments for the nonyrast band, a parity assignment for this band is of special interest. In the following, the experimental information on the band is summarized and arguments in favor of negative parity are given. Since ^{48}Cr is a well deformed nucleus with $\beta \approx 0.3$ for the yrast and nonyrast bands [3], K is regarded as a good quantum number. As the band head spin was found to be $4\hbar$ and the level directly above this state, connected by the 531-keV transition, has a spin of $5\hbar$, we obtain $K=4$. The multipole mixing ratio for the 1675-keV transition to the ground state band vanishes, excluding an appreciable contribution of quadrupole radiation and strongly favoring a negative parity assignment. The nanosecond lifetime and pure dipole character of the $4^\pi \to 4_1^+$ decay contradicts the estimated probability of a twofold K-forbidden $E2$ transition at least by two orders of magnitude. On the other hand, the observations are in good agreement with the expected transition probabilities of a threefold K-forbidden $E1$, which is isospin forbidden, and a twofold K-forbidden $M2$ transition. Thus, we assign negative parity to this state and the band built upon it. In the case of a positive parity band considerable $E2$ character and an $E2$ decay to the 2_1^+ state would have been observed. Furthermore, no $5^\pi \to 4_1^+$ was observed. The upper limit for the ratio of $B(E2)$ values is $B(E2;5^\pi \to 4_1^+)/B(E2;5^\pi \to 4^\pi) < 2\times 10^{-4}$ and for the intensity ratio $I_\gamma(5^\pi \to 4_1^+)/I_\gamma(5^\pi \to 4^\pi) < 0.1$, which excludes an appreciable mixing with the ground state band, supporting the negative parity assignment to the $K=4$ band.

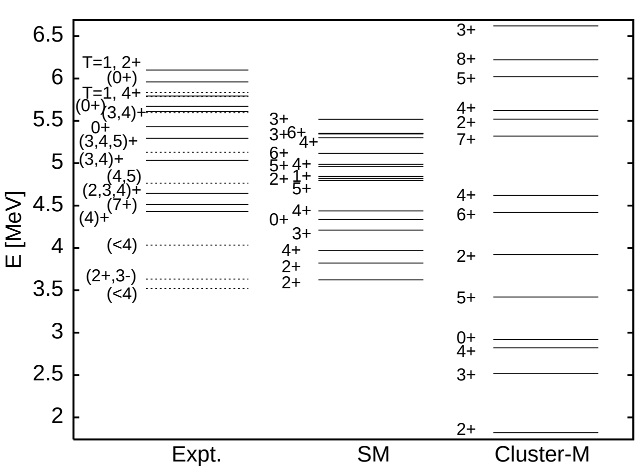

FIG. 4. Comparison of experimental level energies for positive parity states aside from the ground band with the results from our shell model calculation and from Ref. [7]. States of unknown parity are drawn with dotted lines.

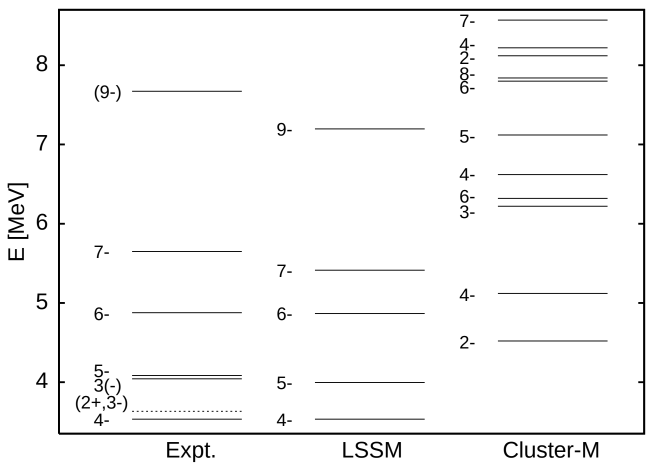

FIG. 5. Comparison of experimental level energies in the $K^\pi = 4^-$ band with the results from [3,7].

In Refs. [3,7] recent shell model and cluster model calculations have been found to be in very good agreement with the experimental level energies and reduced transition probabilities of the ^{48}Cr ground state band. For positive parity states aside from the ground band, our shell model calculations mentioned above reproduce the energy gap to the first nonyrast state and the experimental level density (see Fig. 4). A more sophisticated comparison is not possible yet, due to the fragmentary experimental information on level spins and parities. The calculations with the microscopic ^{40}Ca$+\alpha+\alpha$ cluster model by Sakuda and Ohkubo [7] predict about five positive parity states aside from the ground band below 3.4 MeV excitation energy. In the present work those states were not observed in the given energy range. In particular, the 2^+ band head of a presumed γ band must be above 3.4 MeV (instead of the calculated 2 MeV). On the other hand, the cluster model predicts the negative parity states at rather high excitation energies, e.g., the lowest 4^- state above 6 MeV, which also contradicts the experimental observations. The comparison of negative parity level energies is given in Fig. 5. In contrast to this the $K^\pi = 4^-$ band had been well described by Brandolini *et al.* In their shell model calculations the full pf shell had been extended by hole excitations in the $1d_{3/2}$ orbital [3].

As a future task the collection of more information on the level properties remains, as the comparison of experimental data with the shell model seems promising. Therefore, a further investigation of ^{48}Cr is of high interest, in particular, measurements of parities for the newly found low spin states.

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