Recoil-Distance Lifetime Measurements in ^{46}Ti and ^{50}Cr

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The mean lifetimes of several excited states in the cross-conjugated nuclei ^{46}Ti and ^{50}Cr were measured with the recoil-distance Doppler-shift method. The levels were fed via the ^{32}S(^{16}O, $2p$) and ^{40}Ca(^{12}C, $2p$) reactions, respectively, which lead to a strong population of high-spin levels in the residual nuclei. Lifetimes of the ground-state bands up to the 6^+ states were measured in both nuclei. A decrease of the $B\downarrow(E2)$ values with increasing spin was found.

1. INTRODUCTION

$^{46}_{22}$Ti$_{24}$ and $^{50}_{24}$Cr$_{26}$ represent a pair of cross-conjugate nuclei among the even-even nuclei of the $1f_{7/2}$ shell with neither neutron or proton shell closed. In the shell-model description with pure $f_{7/2}$ configuration[1] cross-conjugate pairs should have identical spectra. Two papers[2,3] have recently been published concerning the level schemes of these two nuclei. Raman *et al.*[2] have studied γ transitions following the β decay of ^{50}Mn, and the ^{50}Cr($p,p'\gamma$) and ^{52}Cr(p, t) reactions, as well as Coulomb excitation of the first excited state with ^{35}Cl ions. Assimakopoulos *et al.*[3] have measured the lifetimes of several levels in ^{46}Ti and ^{50}Cr up to an excitation energy of 4 MeV. The states were populated by (p,p') reactions and the lifetimes were measured by the Doppler-shift attenuation method (DSAM). The results of these papers and previous measurements quoted there can be summarized as follows: Up to about 3-MeV excitation energy the levels of ^{46}Ti and ^{50}Cr, except for a low-lying 0^+ state in ^{46}Ti, follow the spin sequence calculated by the pure $(f_{7/2})^n$ configuration.[1] At higher excitation energies the experimental level density exceeds the calculated one and the occurrence of negative-parity states and 0^+ states indicate the existence of more complicated configurations. The reduced transition probabilities obtained from the lifetime measurements[3] for the transitions with known multipole character are not understood on the basis of the simple shell-model description of Ref. 1.

It is well established[4] that there exist deformations in the $1f_{7/2}$ shell. Collective effects connected with the deformation are expected especially for the nuclei with many particles outside the closed shells such as ^{46}Ti and ^{50}Cr. Häusser *et al.*[5] have found a negative static quadrupole moment for the first excited 2^+ states in ^{46}Ti and ^{48}Ti, thus implying prolate deformation of these nuclei. The results of recent lifetime measurements in ^{49}Cr with the DSAM suggest the existence of collective effects in this nucleus.[6] The DSAM, which was also used for the lifetime measurements of Ref. 3, is usually restricted to lifetimes shorter than ~1 psec. For the measurement of lifetimes in the range of from ~1–1000 psec, the recoil-distance method has been established to be the most efficient technique.

In this paper we present lifetime measurements of a number of excited states in ^{46}Ti and ^{50}Cr employing the recoil-distance Doppler-shift method (RDM). In contrast to the previous experiments, heavy-ion- (HI) induced compound-nucleus reactions were used to populate the excited states. This type of reaction was chosen for two reasons: (1) Large recoil velocities of the product nuclei were desired in order to apply the RDM down to 1 psec; (2) it was of special interest to obtain lifetimes for members of the ground-state band up to higher spin values, which should be more strongly populated in HI reactions.

2. EXPERIMENTAL TECHNIQUE

^{46}Ti and ^{50}Cr were produced by the reactions ^{32}S(^{16}O, $2p$) and ^{40}Ca(^{12}C, $2p$), respectively. Beams of ^{16}O^{V+} and ^{12}C^{IV+} ions with energies of 34.5 and 28.0 MeV, respectively, were supplied by the EN tandem accelerator of the Max-Planck-Institut für Kernphysik in Heidelberg. Beam intensities of about 10 nA on the targets (normalized to singly charged ions) were used throughout the experiments. The analyzed beam passed through a collimator and a cold trap before entering the target chamber.

In order to measure lifetimes as short as 1 psec, great care was given to the construction of a recoil-distance chamber so that the target-plunger distance could be reproducibly adjusted to within ~0.5 μm. The recoil chamber[7] was essentially a large micrometer screw having a diameter of 10 cm and a slope of 0.5 mm per turn. The large diameter and an overlap of the threads of at least 2 cm insured excellent parallelism of the target plane relative to the stopper plane. To get smooth surfaces, the target materials were evaporated onto stretched thin gold foils (1 mg/cm^2). The same stretching technique with gold foils of 2–4 mg/cm^2 in thickness, sufficient to stop the recoil ions, was used for the stopper. The beam was stopped in a second thicker gold foil (50 mg/cm^2) mounted behind the stopper foil.

The targets were made by evaporating 80 and 120 μg/cm^2 of natural metallic Ca and PbS, respectively, onto gold foils, which were prepared in the above-mentioned way. To retard oxidation, the Ca targets were covered with an additional gold layer of 200 μg/cm^2. The target and stopper surfaces were checked with an interference microscope and found to be optically perfect.

γ rays were measured with a 25-cm^3 Ge(Li) detector placed at 0° with respect to the beam direc-

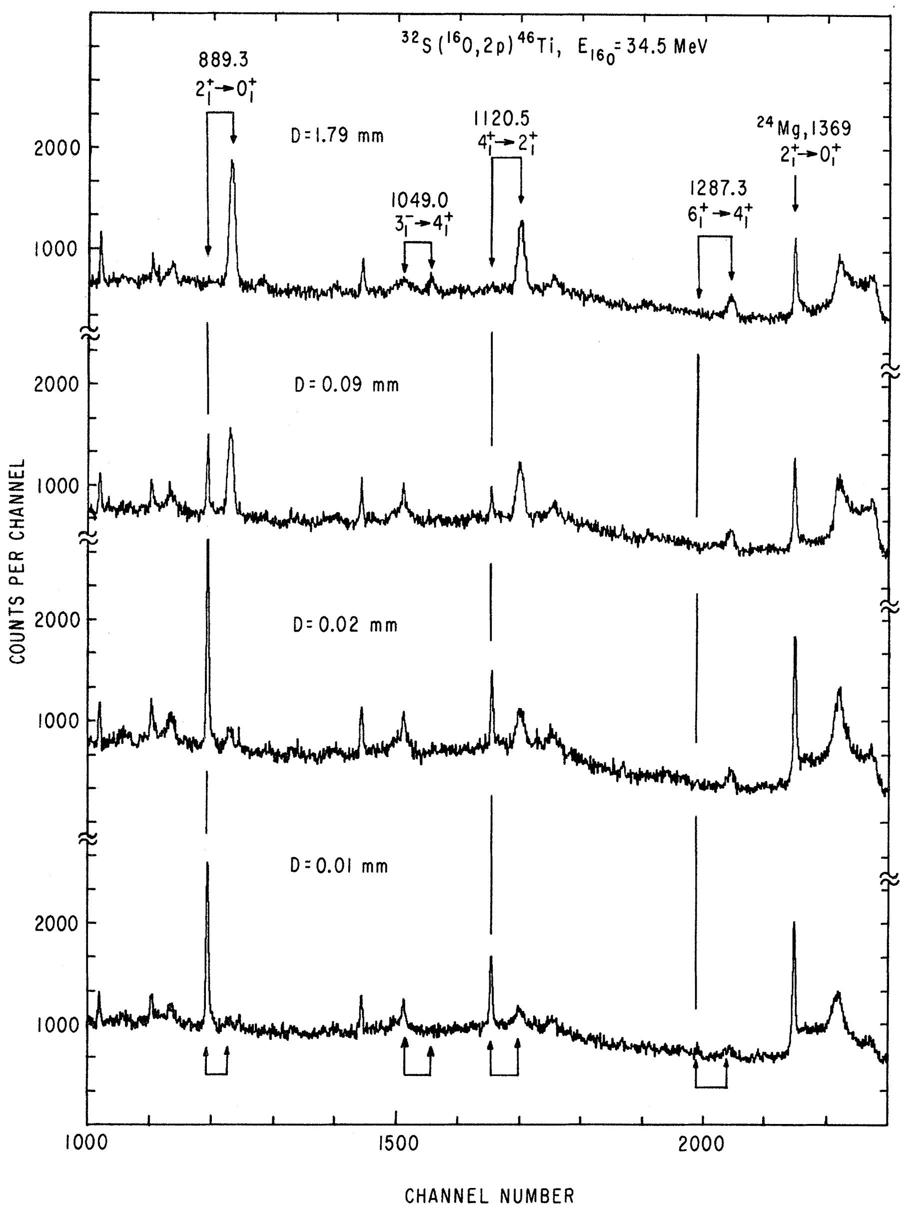

FIG. 1. Partial γ-ray spectra observed at 0° to the beam direction following the reaction ^{32}S(^{16}O,2p)^{46}Ti for different settings of the target-stopper distance D. The positions of the unshifted and shifted photopeaks are indicated.

tion at a distance of 10 cm from the target. The detector system had an intrinsic resolution of 2.5 keV for 1.33-MeV γ rays.

3. ANALYSIS AND RESULTS

Figures 1 and 2 show the interesting part of the γ spectra for the reactions ^{32}S(^{16}O, $2p$)^{46}Ti and ^{40}Ca(^{12}C, $2p$)^{50}Cr, obtained at different target-plunger separation distances. A small fixed contribution to the stopped peaks in the ^{50}Cr transitions is due to the activity of ^{50}Mn($T_{1/2}=1.7$ min) produced via the competing reaction ^{40}Ca(^{12}C, pn)-^{50}Mn. Other reaction channels are very weak as can be expected from the work of Nomura, Morinaga, and Povh.[8] Strong lines which could not be assigned to ^{46}Ti and ^{50}Cr are due to reactions on target contaminations of ^{12}C and ^{16}O. The observed average Doppler shifts of γ rays from the decay in flight were 1.2% for ^{50}Cr and 2% for ^{46}Ti.

The ratio of the unshifted photopeak intensity I_u emitted by the nuclei at rest in the plunger, to the total photopeak intensity, is given by the expression

$$I_u/(I_u+I_s)=\exp(-D/v\tau), \tag{1}$$

where I_s is the photopeak intensity due to γ rays emitted from nuclei decaying in flight, v is the mean velocity component of the recoiling nuclei along the 0° axis, and D is the target-to-plunger separation distance.

For the case when the state in question is fed by a number n of preceding transitions with lifetimes τ_i, the expression becomes

$$I_u/(I_u+I_s)=a_0\exp(-D/v\tau)+\sum_{i=1}^{n} a_i\exp(-D/v\tau_i) \tag{2}$$

with the normalization $a_0+\sum a_i=1$.

The intensities I_u and I_s were obtained by fitting

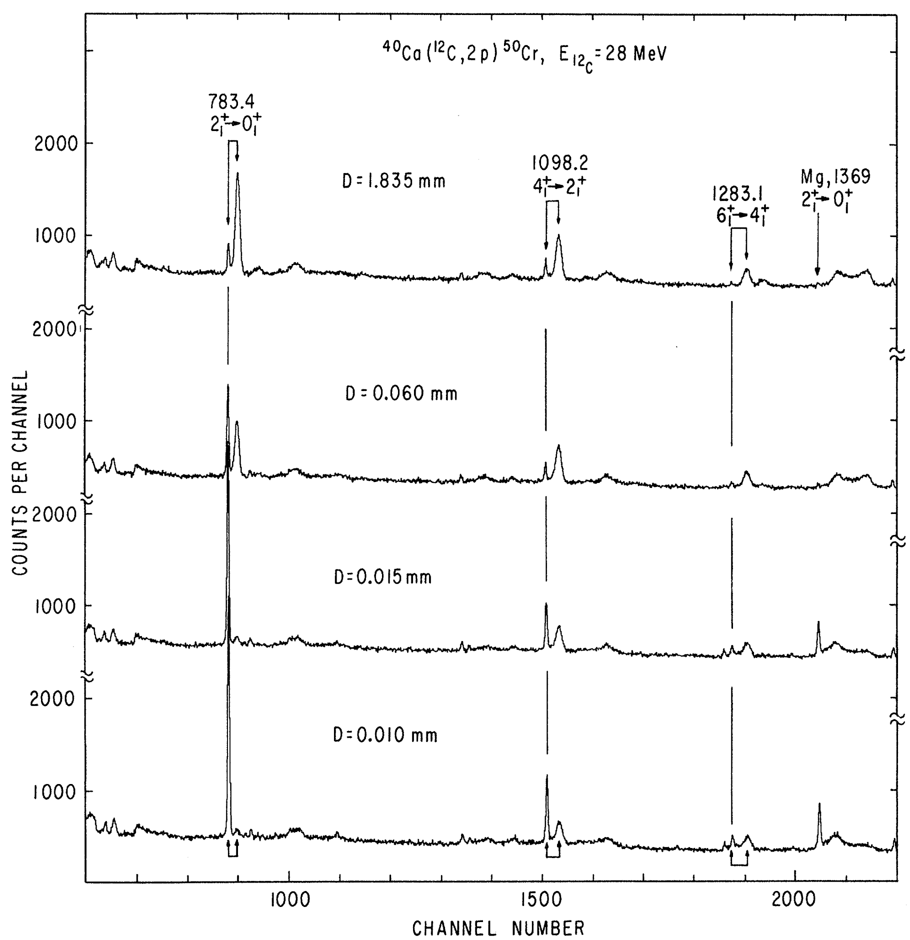

FIG. 2. Partial γ-ray spectra observed at 0° to the beam direction following the reaction ^{40}Ca(^{12}C,$2p$)^{50}Cr for different settings of the target-stopper distance D. The positions of the unshifted and shifted photopeaks are indicated.

each of the respective photopeak lines with a superposition of symmetric Gaussians plus a quadratic parabola for the background. In Figs. 3 and 4 the fraction of the unshifted intensity $I_u/(I_u+I_s)$ is plotted logarithmically versus D for several transitions in ^{46}Ti and ^{50}Cr. Absolute zero target-to-plunger distance was established by extrapolation of $I_u/(I_u+I_s)$ to unity for the shorter-lived transitions. The solid lines represent the best fits with Eq. (2) on the basis of the following procedure:

(1) The highest observed transitions were fitted with only one lifetime plus a constant part ($\tau_1=\infty$). The constant term was especially important in the case of ^{50}Cr, since the β decay of ^{50}Mn produced in the ^{40}Ca(^{12}C,pn) reaction populates several excited states in ^{50}Cr and thus contributes to the stopped peaks of the corresponding γ transitions.

(2) The lifetimes obtained in step one were used in the analysis of the lower-lying states fed through the corresponding transitions. The lifetimes extracted in this way are listed in Table I.

Several corrections have to be taken into account in order to get a reasonable estimate of the errors. The energy dependence of the Ge(Li)-detector efficiency results in a decrease of the shifted intensity. On the other hand the larger effective solid angle for the γ rays emitted in flight gives an opposite effect. Fortunately, both effects cancel to within 1%. An even smaller correction is due to the kinematical spread of energies and different detection angles of the γ rays because of the finite counter size. A larger uncertainty is introduced through the deorientation effect[9,10] of the nuclear spin alignment caused by the hyperfine field interactions with the magnetic moment of an excited nuclear state. The hyper-

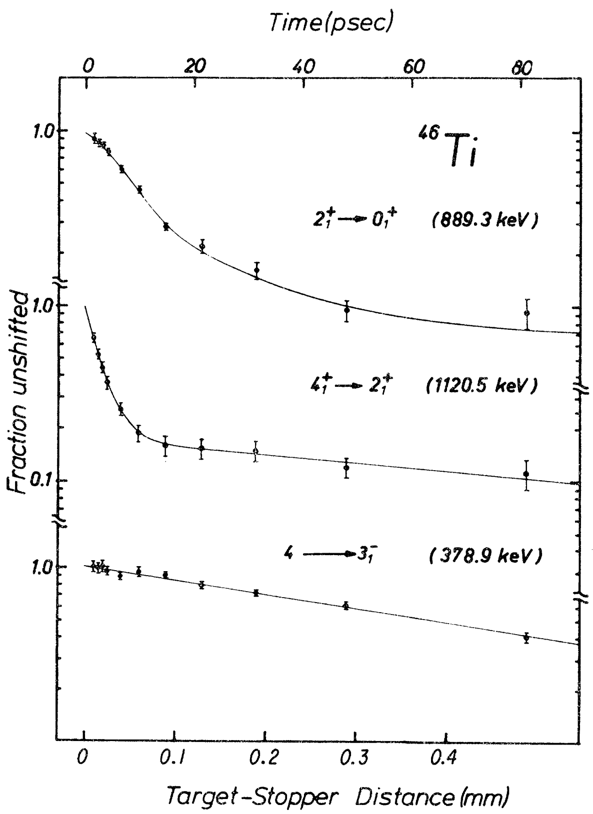

FIG. 3. The ratio of the unshifted-to-total photopeak intensity for several transitions in ^{46}Ti are plotted versus the target-stopper distance. The corresponding flight time is indicated. The solid lines are the result of the fitting procedure for the extraction of lifetimes described in the text. The indicated errors are due to statistics.

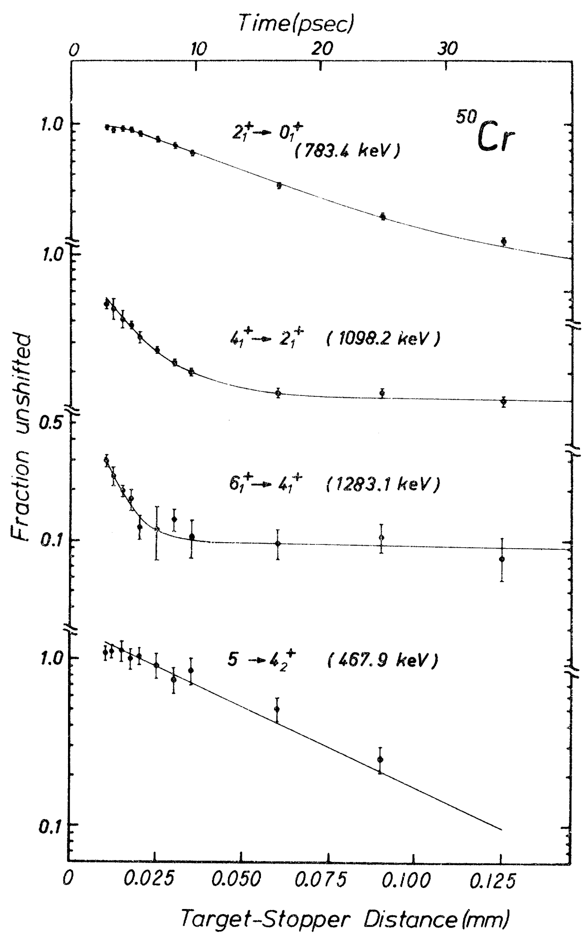

FIG. 4. The ratio of the unshifted-to-total photopeak intensity for several transitions in ^{50}Cr are plotted versus the target-stopper distance. The corresponding flight time is indicated. The solid lines are the result of the fitting procedure for the extraction of lifetimes described in the text. The indicated errors are due to statistics.

fine field is produced by the unpaired electrons in the highly ionized atoms recoiling into vacuum. This effect could be estimated with the data of Häusser *et al.*,[5] who gives values for the crucial expression $\omega^2\tau$ in Ti isotopes. With the formalism of Quebert *et al.*[11] the maximum effect on the lifetime of the first 2^+ state was calculated with the assumption of complete alignment of the first 4^+ state and pure cascade feeding. The change in the lifetime was found to be less than 5%.

The uncertainties in the above corrections combined with the statistical errors results in an error of ±10% in the most favorable cases. The large errors for the 6^+ states are due mainly to the uncertainty in the feeding time of these states, since nothing detailed is known about the time scale of the compound deexcitation process. As an approximation, an upper limit of this time was obtained from the measured lifetime of the fastest observed transition, the 1443.1-keV transition in ^{50}Cr. It must be understood, however, that strictly speaking, the lifetimes of all levels which are not known to be populated largely by discrete transitions of measurably shorter lifetime must be considered only as upper limits. The lifetimes in Table I that are subject to this limitation are marked with a superscript b.

4. DISCUSSION

A. Spin and Parity Assignments

Figure 5 shows the experimental level schemes of ^{46}Ti and ^{50}Cr up to the highest excitation energy observed in this experiment together with the calculated level scheme of the $(1f_{7/2})^n$ model.[1] The levels populated in the present experiments are drawn with heavy lines and the observed transitions are indicated. Thin lines represent levels, which were not populated in this experiment, but were seen in the $(p,p'\gamma)$ reactions.[2,3] Spin and parity assignments were taken from Ref. 2 for ^{50}Cr and Ref. 3 for ^{46}Ti with the exception of the levels at 3297.1 and 3437.7 keV in ^{46}Ti and 3164.7 and 3792.6 keV in ^{50}Cr, the assignments for which are discussed below.

The 6_1^+ State at 3164.7 keV in ^{50}Cr

This state is the upper member of a narrow doublet proposed by Twin and Willmott[12] who determined that $J^\pi = 2^+$ for the lower state at 3161.1 keV. The 3164.7-keV level is populated through the decay of the $J^\pi = 5^+$ isomer[2] in ^{50}Mn and decays entirely to the 4_1^+ state, suggesting a spin $J \geq 4$. $\gamma\gamma$ angular-correlation measurements[13] following the decay of the isomer limited the spin to 4 or 6.

TABLE I. Electromagnetic transitions and lifetimes in ^{46}Ti and ^{50}Cr.

Nucleus	Initial E(keV)	J^π	Final E(keV)	J^π	E_γ (keV)	Relative γ intensities	τ (psec)
^{46}Ti	889.3(5)	2_1^+	g.s.	0_1^+	889.3(5)	100	6.5(7)
	2009.8(7)	4_1^+	889.3	2_1^+	1120.5(5)	81(4)	2.6(3)
	3058.8(12)	3_1^-	2009.8	4_1^+	1049.0(5)	8.2(12)	$0.65 < \tau < 83$ [a]
	3297.1(15)	6_1^+	2009.8	4_1^+	1287.3(12)	25(2)	1.5(7) [b]
	3437.7(12)	(4_2^+)	3058.8	3_1^-	378.9(5)	9.2(9)	83(9) [b]
			2009.8	4_1^+	1427.9(15)	3.1(5)	
^{50}Cr	783.4(5)	2_1^+	g.s.	0_1^+	783.4(5)	100 [c]	12.1(12)
	1881.6(7)	4_1^+	783.4	2_1^+	1098.2(5)	82(4) [c]	3.2(4)
	3164.7(9)	6_1^+	1881.6	4_1^+	1283.1(5)	32(3) [c]	1.8(4) [b]
	3324.7(12)	4_2^+	1881.6	4_1^+	1443.1(5)	3.3(5) [c]	<1.0
	3792.6(10)	5	3324.7	4_2^+	467.9(5)	1.9(3)	13(2) [b]
			1881.6	4_1^+	1910.9(9)	1.5(3)	
	3826.4(10) ≥ 4		3164.7	6_1^+	661.7(5)	0.3(2) [c]	$5(^{+5}_{-2})$ [b]

[a] The lower limit is taken from Ref. 3.
[b] These lifetimes have been derived on the assumption that the unobserved feeding time of these levels is ≤1 psec.
[c] Corrected for the contribution from the β decay of the $J^\pi = 5^+$ isomer in ^{50}Mn.

Strong excitation of this level was found[13] by the reaction $^{50}V(p,n)^{50}Cr$ compared to the population of the 4_1^+ and 4_2^+ states. Since the ground-state spin of ^{50}V is $J^\pi = 6^+$ this supports the assignment $J=6$. Very recently, γ angular distributions with the reaction $^{40}Ca(^{16}O, 2p\alpha\gamma)^{50}Cr$ were measured,[14] which showed quadrupole character for the 1283.1-keV transition. Thus, $J^\pi = 6^+$ is assigned to this level.

The 6_1^+ State at 3297.1 keV in ^{46}Ti

The compilation of levels in mass-46 nuclei by Auble[15] reports a level at 3310 ± 12 keV in ^{46}Ti. This state is not excited in the $(p,p'\gamma)$ reaction.[3] On the other hand it is populated by the $^{45}Sc(^3He,d)$-^{46}Ti reaction[16,17] with $l_p = 3$, which can lead to positive-parity states from 0^+ to 7^+. The spins 0^+ to 4^+ can be ruled out by the results of the inelastic proton scattering.[3] Dubois and Maripuu,[18] by NaI(Tl) γ-γ coincidence studies following resonant proton capture in ^{45}Sc, have found a state of about this energy which decays via a 1.29 ± 0.02-MeV transition to the 4^+ state. On the basis of selective population of this state at particular resonance energies they suggest $J^\pi = 6^+$. Strong population of this level in the $^{32}S(^{16}O, 2p)^{46}Ti$ re-

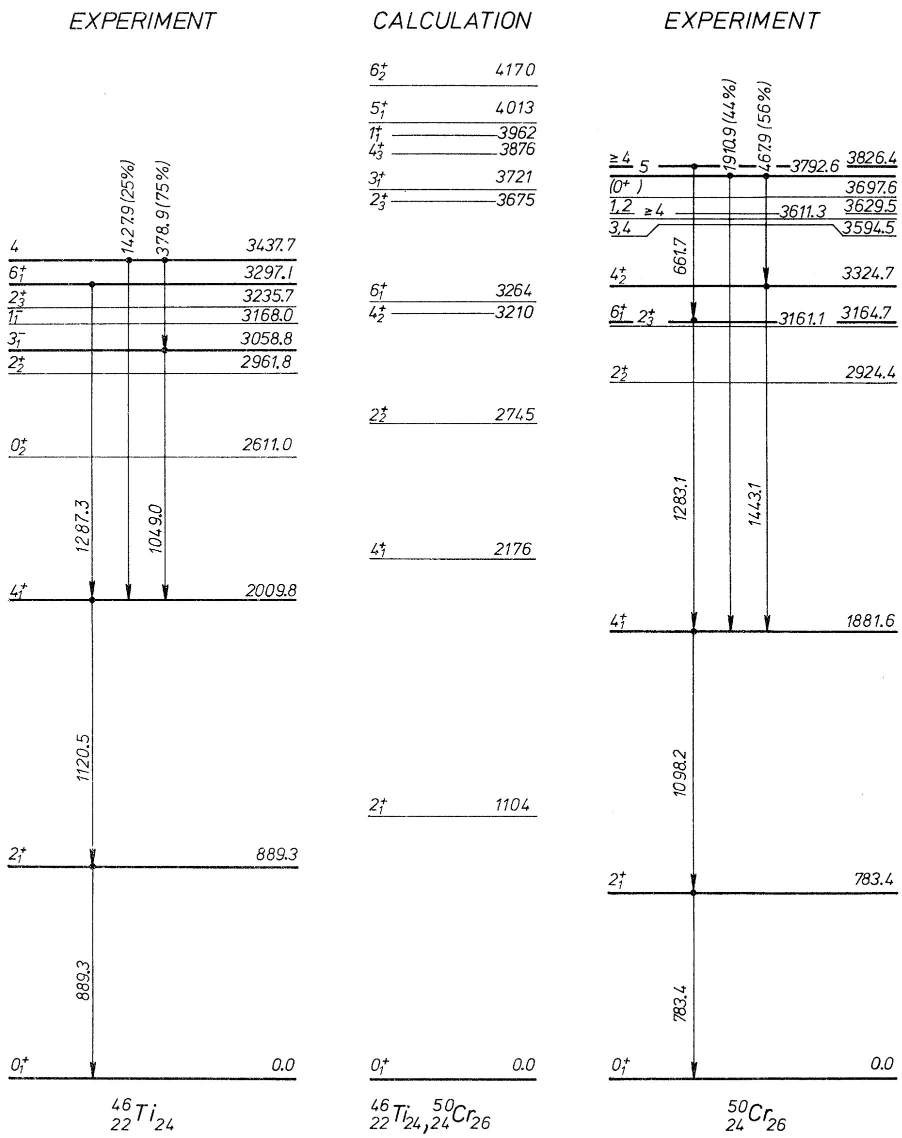

FIG. 5. Comparison of the experimental level schemes of ^{46}Ti and ^{50}Cr with the predictions of the $(1f_{7/2})^n$ model (Ref. 1). Levels marked with heavy lines were populated in the present experiment and the observed transitions are indicated. Additional levels (thin lines) are taken from Ref. 3 for the ^{46}Ti and from Ref. 2 for ^{50}Cr.

action which favors population of high-spin states would be expected. The strong transition of 1287.3 keV which is the only significant discrete transition in this energy region and which is comparable in relative strength to the $6_1^+ \to 4_1^+$ transition observed in ^{50}Cr is therefore very likely the $6_1^+ \to 4_1^+$ transition in ^{46}Ti. The assignment of $J^\pi = 6^+$ for a level at 3297.1 keV is therefore very probable though $J^\pi = 5^+$ cannot be excluded.

The J = 4 State at 3437.7 keV in ^{46}Ti

This state decays with a branch of 75% to the 3_1^- state and 25% to the 4_1^+ state. Lewis *et al.*[19] have tentatively assigned a value of $J = 5$ to this level on the basis of $(p, p'\gamma)$ angular-correlation measurements and the assumption that $J = 4$ for the 3058.8-keV state. However, an equally low χ^2 is reported[19] fitting the angular correlation with a $4 \to 3$ transition. Since Horoshko, Hinrichsen, and Scott[20] have recently determined $J^\pi = 3^-$ for the 3058.8-keV level, an assignment of $J = 4$ to the 3437.7-keV level is therefore indicated.

No unique parity assignment is available since two ^{45}Sc(^{3}He, d)^{46}Ti measurements, Barnard and Jones[16] and Broman and Pullen,[17] assign $l_p = 2$ and $l_p = 3$ transitions, respectively, to this state. Lewis *et al.*[19] have reported a multipole mixing ratio of $\delta = -1.0^{+0.42}_{-0.94}$ for the $4 \to 3_1^-$ transition and $-1.4 < \delta < +0.1$ for the $4 \to 4_1^+$ transition. Assuming an $M2/E1$ mixing for the $4 \to 3_1^-$ transition one obtains from the measured lifetime an $E1$ strength of $(6.5 \pm 4.0) \times 10^{-5}$ Weisskopf unit (W.u.) and an $M2$ strength of 200 ± 120 W.u., which is unusually high. On the other hand an $E2/M1$ mixing results in an $M1$ strength of $(2.6 \pm 1.5) \times 10^{-3}$ W.u. and an $E2$ strength of (47 ± 30) W.u. Compared to the $4 \to 3_1^-$ transition strengths the $4 \to 4_1^+$ transition strengths are hindered by an additional factor of 10^{-2} to 10^{-3}. On the basis of the reported δ for the $4 \to 3_1^-$ transition, our lifetime results therefore favor a negative-parity assignment for the 3437.7-keV level. These considerations also make it more probable that the measured 83 psec lifetime is the intrinsic lifetime of this level and is not due to an unobserved feeding transition.

The J = 5 State at 3792.6 keV in ^{50}Cr

The spin of this state was determined by Mo *et al.*[21] through a $(p, p'\gamma)$ angular-correlation measurement. A multipole mixing ratio of $\delta = -0.47 \pm 0.16$ was given for the transition to the 4_1^+ state and the limits $-2.45 < \delta < -0.58$ for the transition to the 4_2^+ state. Assuming an $M2/E1$ mixture for the $5 \to 4_1^+$ transition, one calculates with the measured lifetime, (neglecting the possibility of a delayed feeding transition), an $E1$ strength of $(3 \pm 1) \times 10^{-6}$ W.u. and an $M2$ strength of 0.24 ± 0.15 W.u. On the other hand, an $E2/M1$ mixture yields an $M1$ strength of $(1.6 \pm 0.3) \times 10^{-4}$ W.u. and an $E2$ strength of $(1.7 \pm 1.0) \times 10^{-2}$ W.u., which are both rather low. For the $5 \to 4_2^+$ transition one obtains an $E1$ strength of $\approx 2 \times 10^{-4}$ W.u. and an $M1$ strength of $\approx 10^{-2}$ W.u., both of which seem to be reasonable. However, from the $5 \to 4_1^+$ transition strengths a negative-parity assignment to the $J = 5$ state seems to be more probable.

B. Ground-State Bands

The present experiment has yielded lifetime measurements of the first three members of the ground-state bands in ^{46}Ti and ^{50}Cr. Table II summarizes the $B\downarrow(E2)$ values and W.u. estimates for the intraband transitions deduced from these

TABLE II. Intraband transitions of the ground-state bands in ^{46}Ti and ^{50}Cr.

Nucleus	Transition	$B\downarrow(E2)$ (e^2 fm^4)	$\lvert M\rvert^2$ (W.u.)	Normalized $B(E2)$ Exp.	Rot.	Vib.
^{46}Ti	$2_1^+ \to 0_1^+$	217(17) [a]	21.6(17)	1.0	1.0	1.0
	$4_1^+ \to 2_1^+$	177(20)	17.6(20)	0.82(10)	1.43	2.0
	$6_1^+ \to 4_1^+$	150(80) [b]	15(8) [b]	0.71(35) [b]	1.58	3.0
^{50}Cr	$2_1^+ \to 0_1^+$	229(12) [c]	20.4(10)	1.0	1.0	1.0
	$4_1^+ \to 2_1^+$	160(20)	14.3(18)	0.70(10)	1.43	2.0
	$6_1^+ \to 4_1^+$	130(30) [b]	12(3) [b]	0.59(15) [b]	1.58	3.0

[a] Weighted average of Refs. 5 and 15 and this work.

[b] The validity of the upper limits depends on the assumption that the unobserved feeding times of the 6^+ state is ≤ 1 psec.

[c] Weighted average of Ref. 2 and A. McNair, Phil. Mag. 6, 559 (1961) and F. K. McGowan, P. H. Stelson, R. L. Robinson, W. T. Milner, and J. L. C. Ford, Jr., in *Proceedings of the Conference on Nuclear Spin-Parity Assignments, Gatlinburg, Tennessee, 1965* (Academic, New York, 1966), p. 222, and this work.

lifetimes. (The validity of the lower limits of the 6^+ state lifetimes depends on the assumption that the unobserved feeding times of the 6_1^+ states in both nuclei are ≤ 1 psec.) The $2_1^+ \rightarrow 0_1^+$ transition strengths are rather high, suggesting the application of collective models to the ground-state bands. However, the comparison of the experimental $B\downarrow(E2)$ values with the pure rotational and vibrational model shows that the transition strengths do not follow either of these models. In fact, the $B\downarrow(E2)$ values decrease with increasing spin. This may indicate that the high-spin states have cleaner shell-model configurations, whereas the low-lying states have larger admixtures of more complicated configurations. This trend is supported by the energy positions of the 6_1^+ state in both ^{46}Ti and ^{50}Cr, which fit better than the 2_1^+ and 4_1^+ states to the corresponding levels calculated in the $(1f_{7/2})^n$ model.[1]

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