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NUCLEAR ORIENTATION STUDIES OF THE 51.5 MIN ^{167}Lu DECAY

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Изучение распада 51,5 мин ^{167}Lu ,
ориентированного в матрице гадолиния

Измерены анизотропии гамма-лучей при распаде 51,5 мин ^{167}Lu . Ядра ^{167}Lu ориентировались с помощью сверхтонкого взаимодействия, возникающего при внедрении ядер лютеция в гадолиниевую матрицу, охлажденную до температуры 15 мК. Для получения низкой температуры использовался рефрижератор растворения ^{3}He-^{4}He , способный быстро охлаждать короткоживущие образцы. Получены значения параметров смешивания мультипольностей для большого количества гамма-переходов. Определены спины и четности многих уровней в ^{167}Yb . Однозначно определено значение $I^{\pi} = 11/2^{-}$ для уровня 571,5 кэВ, идентифицированного как основное состояние полосы $11/2^{-}$[505], которую наблюдал Линдблад.

Проведена дискуссия ротационных полос в ^{167}Yb .

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Nuclear Orientation Studies of the 51.5 min ^{167}Lu Decay

Anisotropies of γ rays, emitted in the decay of ^{167}Lu, $T_{1/2}$ = = 51.5 min, have been measured.

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1. INTRODUCTION

The levels of ^{167}Yb populated in the 51.5 min ^{167}Lu decay have been extensively studied [1-5] and a large number of states extending up to 2.33 MeV excitation have been identified. Burke et al.[6] and Lindblad [7] investigated energy levels of ^{167}Yb in (d , t) and (α , 3n) reactions, respectively. Lindblad observed seven members of the $5/2^{-}$[523]↓ ground-state band, fifteen members of the $5/2^{+}$[642]↑ rotational band and seven members of the probable $11/2^{-}$[505]↑ band, although for the last one he could not determine the excitation energy of the band head.

However, inconsistences exist between the results of the different studies and the more important of them are connected with ambiguous spin assignments to many of the observed states. For instance, the level at 571.5 keV is proposed [4] to be the band head of the $11/2^{-}$[505] band, but Meijer et al.[3] assigned $9/2^{-}$ to the level. The levels at 213.2 and 308.5 keV proposed [1,3] to be the $5/2^{-}$ and $7/2^{-}$ members of the [512]↑ band were identified by Gromov et al.[4] as the band heads of the $3/2^{-}$[521] and $5/2^{-}$[512] bands, respectively.

The present work makes an attempt to remove some of the existing ambiguities using the experimental technique developed recently in JINR for nuclear orientation of short-lived isotopes at low temperatures [8]. A modified version of a top-loading ^{3}He- ^{4}He dilution refrigerator [9] was used.

2. EXPERIMENTAL FACILITIES

2.1. Sample Preparation

The source was prepared by a spallation reaction on tantalum using the 660 MeV proton beam of the Dubna synchrocyclotron. After chemical separation of the lutetium fraction, the ^{167}Lu isotope was selected by a mass-separator. The separator operated at an ion source voltage of 35 keV with respect to the gadolinium foil. Our recent work on ^{169}Lu and ^{172}Lu isotopes (preliminary results are given in ref. [10] has shown gadolinium to be a very convenient host for lutetium. The internal field, which the lutetium nuclei experience when the gadolinium is magnetised, is 26.0 T[11].

The gadolinium with implanted lutetium activity was melted in a vacuum of $\sim 10^{-4}$ Pa for ~30 sec onto the tantalum foil, cooled down to 950°C during 2 min, and after that to 100°C at the cut off heater. The tantalum backing was then soldered in vacuum to a copper foil using a titanium-silver solder. The sample was finally formed as a disk of 0.5 cm diameter and soldered to heat exchanger.

2.2. Top-Loading Dilution Refrigerator

The modified version of the refrigerator[9] is capable of maintaining a base temperature of 12 mK. The sample is mounted at the end of the heat exchanger which is a bundle of copper wires with a surface of 440 cm^2. These wires provide a good heat link with the liquid helium of the mixing chamber within which they are located. The source assembly is mounted at the end of a stainless-steel tube and is pre-cooled before inserting it into the mixing chamber. After the loading the temperature is about 200 mK and approximately one and half hours must elapse before the final operating temperature is reached.

Thermometry and performance of the refrigerator is monitored by a set of Speer 100 Ω resistors and the cold condition remains steady within approximately 0.5 mK. The "warm" operating condition of about 1 K is achieved within 5 min by using a heater placed in the mixing chamber.

The magnetic field of 1 T used to orientate the nuclear ensemble is provided by a pair of superconducting coils.

2.3. Data Collection and Evaluation

The γ-ray spectra were recorded along the direction of orientation by a Ge(Li) detector with a sensitive volume of 40 cm^3 and a nominal resolution of 2.5 keV at 1.33 MeV. Data were collected for periods of 1800 and 3600 seconds when the source was oriented ($\sim$15 mK) and random ($\sim$1 K), respectively. The measurements were started about three hours after the end of irradiation. The data collection system was described elsewhere[8].

The most intense peaks in the spectrum were identified using the 401.0, 1267.2 and 2013.1 keV lines and no ambiguities in energy assignment occurred.

The spectrum was in good agreement with that obtained in previous measurements[3,4]. Apart from transitions growing in due to the 17.5 min ^{167}Yb daughter decay[2] and the weak activity of ^{169}Lu extensively studied by Batsev et al.[12], no other activities have been observed.

The peak areas and their square deviations were evaluated by means of the BESM-6 computer using the system of programs SIMP[13]. The decay correction was made using the half-life of (51.5 ± 1.0) min[2,3].

Anisotropies /1 - W(0)/ were determined from the data obtained for the oriented ("cold") and random ("warm") source conditions. Two "cold" and two "warm" spectra were measured and as the anisotropies of all dominant transitions were consistent within their errors the results of the two runs were averaged.

The values of /1 - W(0)/ determined for γ-ray transitions in ^{167}Yb are presented in Table 1.

3. DATA ANALYSIS

The directional distribution of γ-radiation is described by function[14]

$$W(\theta) = \sum_{k\ \mathrm{even}} B_k(I)\, A_k U_k Q_k P_k(\cos\theta) \qquad (1)$$

in which the orientation coefficient $B_k(I)$ describes the equilibrium nuclear level populations and is thus dependent on the spin and magnetic moment of the oriented parent nucleus, on the effective magnetic field and on the temperature. The directional correlation coefficient A_k is given by

$$A_k = \frac{F_k(LLI_iI_f) + 2F_k(LL'I_iI_f) + \delta^2 F(L'L'I_iI_f)}{1+\delta^2} \qquad (2)$$

where F_k are the angular momentum coupling factors tabulated by Krane[15], $L' = L + 1$ and δ is the mixing ratio of the $L + 1$ to L multipole components in the transition. The coefficient U_k accounts for the depolarization due to all intermediate transitions which precede the γ ray of interest.

The experimental values of /1 - W(0)/ were compared with equation (1). Terms with $k > 2$ in this equation were ignored, but the results were not affected greatly since the estimated

Table 1

The anisotropies of the γ-ray transitions in ^{167}Yb

E_γ [keV]	1 - W(0) [%]	E_γ [keV]	1 - W(0) [%]
222.8	24.4 ± 7.6	569.9	22.2 ± 4.8
229.8	2.5 ± 5.4	591.2	19.7 ± 5.7
232.1	20.8 ± 15.1	594.3	-27.8 ± 22.3
235.9	-22.3 ± 8.7	599.0	-2.2 ± 6.9
239.2$^{a)}$	15.0 ± 3.1	609.4	-6.1 ± 9.4
243.1	5.0 ± 6.2	642.1	20.1 ± 11.8
248.6	20.8 ± 6.7	709.7	8.3 ± 17.1
258.5	5.9 ± 4.2	715.9$^{c)}$	10.2 ± 15.7
261.8	-1.8 ± 4.6	730.3	9.1 ± 8.9
278 $^{b)}$	15.2 ± 3.6	763.2$^{c)}$	-13.2 ± 9.7
298.6	30.9 ± 15.0	779.7$^{c)}$	31.8 ± 18.6
308.5	13.9 ± 21.3	788.4	5.9 ± 18.7
317.6	-11.9 ± 4.2	808.6	7.2 ± 12.5
352.0	8.1 ± 19.0	815.2$^{c)}$	20.3 ± 12.1
361.5	18.8 ± 18.5	830.7$^{c)}$	30.2 ± 11.6
377.1	28.9 ± 11.5	920.0$^{c)}$	31.3 ± 20.1
392.6	8.8 ± 7.2	988.4	20.5 ± 14.0
397.0	2.7 ± 6.2	1085.2$^{c)}$	15.8 ± 20.8
401.0	-10.5 ± 4.8	1126.6	7.3 ± 10.6
406.7	13.8 ± 8.1	1161.4$^{c)}$	16.3 ± 12.5
410.9	-16.1 ± 12.8	1164.2	-32.5 ± 23.0
417.7$^{c)}$	-18.7 ± 11.2	1188.5	-2.2 ± 9.9
427.3	-24.7 ± 21.1	1227.2	13.7 ± 4.4
445.4	23.3 ± 6.9	1255.4	2.8 ± 10.5
470.6	20.4 ± 13.2	1267.2	14.9 ± 3.1
539.5	-24.5 ± 22.0	1275.4	14.9 ± 4.3
549.0	18.2 ± 10.3	1305.5	11.2 ± 4.2

Table 1 (continued)

E_γ [keV]	1 - W(0) [%]	E_γ [keV]	1 - W(0) [%]
1376.0	19.3 ± 4.9	1759.6	30.4 ± 13.5
1394.0	20.1 ± 5.7	1833.4	8.1 ± 8.2
1397.6	-12.1 ± 7.4	1868.3$^{c)}$	25.6 ± 6.2
1403.7	-8.1 ± 9.6	1873.2	23.2 ± 10.4
1426.8	6.9 ± 5.8	1895.4	16.0 ± 5.4
1444.9	-18.2 ± 24.6	1900.0	-12.7 ± 14.8
1506.8	1.5 ± 4.4	1917.8	1.1 ± 10.9
1510.4	17.6 ± 6.6	1926.8	2.3 ± 19.1
1521.4	31.9 ± 10.8	1933.7	25.8 ± 13.1
1534.6	7.3 ± 10.6	1941.4	-5.5 ± 10.4
1542.0	4.3 ± 10.4	1951.4	-13.5 ± 29.0
1548.4	5.9 ± 11.0	1961.4	0.6 ± 5.6
1554.5	17.2 ± 15.4	1964.8	-39.4 ± 14.1
1629.7	-37.5 ± 22.2	1974.0	14.4 ± 3.2
1633.6	-7.9 ± 7.9	1979.6	19.7 ± 3.8
1644.5	7.6 ± 5.4	1983.4	-24.8 ± 17.8
1665.6	-4.1 ± 9.0	1989.5$^{c)}$	11.8 ± 5.4
1696.1	12.1 ± 8.9	2000.7$^{c)}$	-14.6 ± 15.0
1701.8	19.4 ± 11.4	2013.1	8.5 ± 3.9
1730.7$^{c)}$	31.9 ± 19.1	2204.4	-34.4 ± 18.5
1735.3	31.8 ± 15.0	2247.5	7.8 ± 9.4
1740.3	36.0 ± 20.4	2271.9	25.2 ± 3.9

a) Contains a (11.1 ± 5.6)% contribution due to a 239.0 keV $7/2^- \rightarrow 7/2^-$ transition between the 317.5 and 78.7 keV levels.

b) A triplet of the 278.2 M1, 278.5 M1 and 278.9 keV E1 transitions /3/.

c) The γ ray is not placed in the decay scheme.

maximum value of B_4 coefficient which corresponds to our experimental value of B_2 (see below) is 0.025 (ref./15/) and the A_4, U_4 and Q_4 coefficients for all the transitions analysed in present work are much less than unity.

In the evaluation of the U_2 coefficients, it was assumed that all the β transitions to the positive parity levels are the allowed Gamow-Teller and all $\Delta\pi$, yes β transitions are $\Delta j_\beta = 1$.

4. RESULTS

The analysis of the results is based on the ^{167}Lu decay scheme of Meijer et al./3/. The results published in /1,4,5/ are also used. It may be noted that there are no multipole mixing ratio data except for those derived from the internal conversion coefficients /1,4/. These were compared with the multipole mixing ratios determined in the present work.

Since many of the spin assignments were made by comparing the measured correlation coefficients with those predicted for pure dipole or quadrupole transitions between two states of given spin, the appropriate theoretical values are listed in Table 2.

Table 2

The A_2 coefficients for pure dipole or quadrupole transitions

$I_i \rightarrow I_f$	A_2	$I_i \rightarrow I_f$	A_2
5/2 → 5/2	-0.4276	9/2 → 5/2	-0.4325
5/2 → 7/2	0.1336	9/2 → 7/2	0.3028
5/2 → 9/2	-0.1909	9/2 → 9/2	-0.4404
7/2 → 5/2	0.3273	9/2 → 11/2	0.1651
7/2 → 7/2	-0.4364	11/2 → 7/2	-0.4109
7/2 → 9/2	0.1528	11/2 → 9/2	0.2876
7/2 → 11/2	-0.2182	11/2 → 11/2	-0.4425

The ^{167}Lu decay scheme including our results is given in Figs.1a and 1b.

4.1. The Evaluation of Orientation Coefficient $B_2(I)$

The spin of ^{167}Lu has been measured by Eckström et al./16/ as 7/2, while the positive parity has been established in/1-4/. The ground state of ^{167}Yb was assigned $5/2^-$ (refs. /1-4,6,7/).

Gromov et al./4/ proposed the $5/2^+$ or $7/2^+$ assignments for the level at 1267.2 keV in ^{167}Yb . The 1267.2 keV ground state transition has been measured as E1, and the observed positive anisotropy indicates a negative A_2 coefficient. Inspection of Table 2 shows that the only possible spin assignment for the 1267.2 keV level is therefore $5/2^+$. The ICC data restricts the amount of M2 admixture possible in this transition to about 1% and thus pure dipole multipolarity has been assumed. The value of $B_2(I)$ was then calculated as $B_2(I) = 0.411\ (84)$ and this result was used to analyse all other γ-ray transitions measured.

4.2. Interpretation of Results

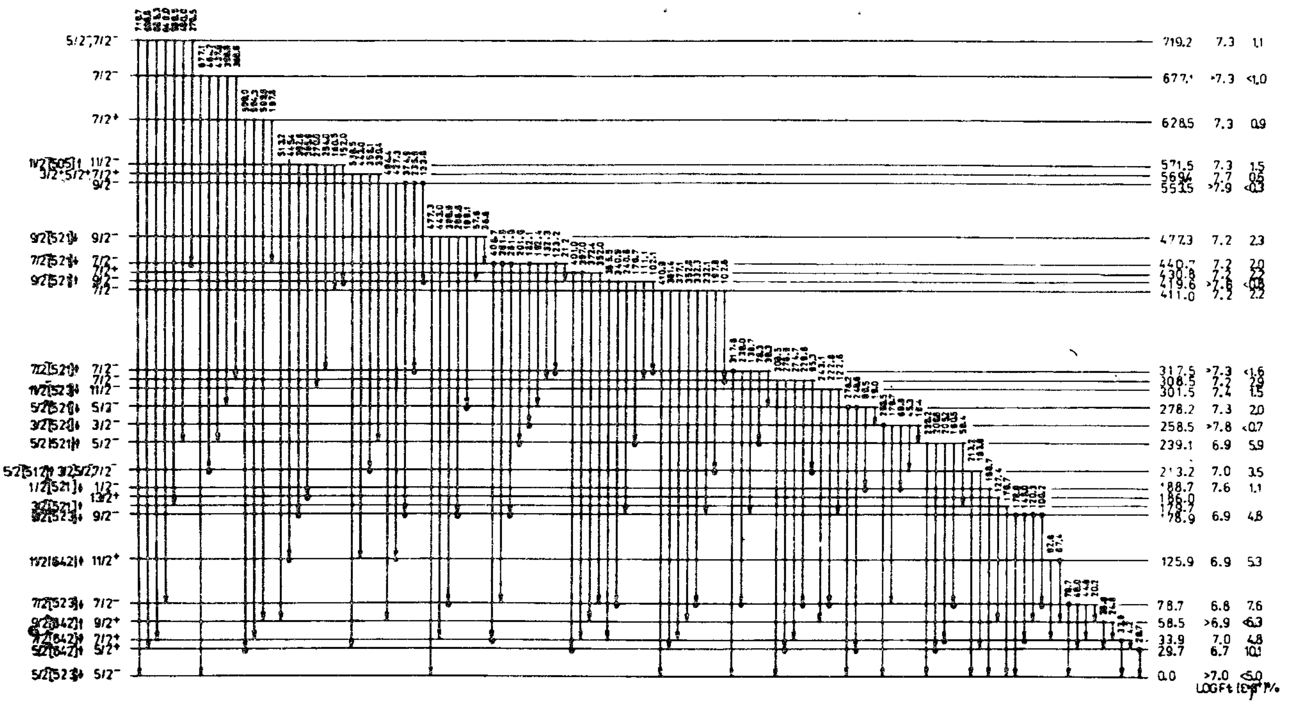
In the following discussion we have chosen to begin the analysis at the high energy levels as their U_2 coefficients influence the analysis of lower - lying transitions.

The decay modes of the level determined earlier /3,4/ and in particular the feeding to the ground state and lowest few excited states have been used to restrict the range of possible spin assignments. Our analysis is thus dependent on the previous work. Also we assumed initially that the spin-parity assignments of these levels were correct and subsequently showed that this was true.

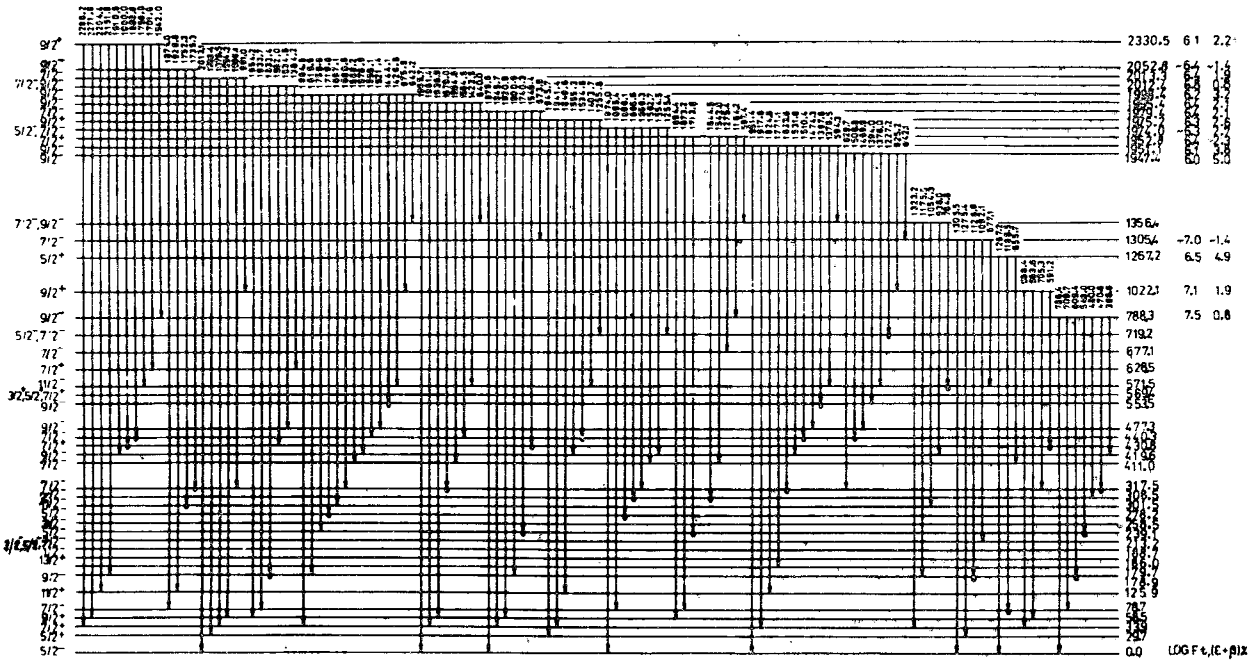
The γ-ray transitions placed twice in the level scheme have been analysed in both positions. All results obtained are presented in Table 3.

The 2330.5 keV level. The decays of the level restrict the spin $7/2^+$ or $9/2^+$. The anisotropies of the 2204.4 and 2271.9 keV transitions are only consistent with a $9/2^+$ assignment and this is in agreement with the E1 multipolarity of the 1542.0 and 1758.8 keV transitions /4/.

The 2052.8 keV level. The level is observed to decay to the $7/2^-$, $11/2^+$ and $11/2^-$ levels and spin-parity assignments of $9/2^\pm$ or $11/2^-$ are considered possible. A $11/2^-$ assignment may be excluded on the basis of the observed anisotropy of the



<u>Fig.1a</u>. Decay scheme of ^{167}Lu (low-energy part). The γ-ray and level energies, the β-feeding intensities and the lg ft values are taken from /3/ and supplemented by the results of Gromov et al./4/. Coincidences /3,4/ are indicated by dots.



<u>Fig.1b</u>. Decay scheme of ^{167}Lu (high-energy part).

Table 3

The multipole mixing ratios of the γ-ray transitions observed in the ^{167}Lu decay.

E_{lev} [keV]	I_i^{π}	U_2	E_γ [keV]	I_f^{π}	A_2	σL	δ
1	2	3	4	5	6	7	8
2330.5	$9/2^+$	0.925	2271.9	$9/2^+$	-0.69 ± 0.16	M1 + E2	$0.2 \le \delta \le 0.5$
			2204.4	$11/2^+$	0.95 ± 0.54	M1 + E2	$0.2 \le \delta \le 11.1$
			1900.0	$7/2^+$	0.35 ± 0.41	M1 + E2	-0.25 ± 0.25 or $\lvert\delta\rvert \geq 2.1$
			1701.8	$7/2^+$	-0.54 ± 0.33	M1 + E2	$0.3 \le \delta \le 9.6$
			1542.0[a]	$9/2^-$	-0.12 ± 0.28	E1 + M2	$-0.42^{+0.36}_{-0.44}$
2052.8	$9/2^-$	0.925	1974.0[a]	$7/2^-$	-0.39 ± 0.12	M1 + E2	0.40 ± 0.08 or $4.7^{+2.4}_{-1.4}$
			1926.8	$11/2^+$	-0.06 ± 0.53	E1 + M2	$-4.4 \le \delta \le -0.1$
			1735.3	$7/2^-$	-0.88 ± 0.44	M1 + E2	$0.4 \le \delta \le 4.1$
2013.3	$7/2^-$	0.810	2013.1	$5/2^-$	-0.27 ± 0.13	M1 + E2	0.32 ± 0.09 or $9.6^{+22.5}_{-4.2}$
			1983.4	$5/2^+$	0.78 ± 0.58	E1 + M2	$-6.8 \le \delta \le 0.1$
	$7/2^{\pm}$	0.810			-0.80 ± 0.44		$-0.09 \le \delta \le 1.33$
2012.4			1933.7	$7/2^-$			
	$9/2^-$	0.925			-0.70 ± 0.38	M1 + E2	$0.4 \le \delta \le 5.9$
					-0.25 ± 0.26		$-0.31^{+0.22}_{-0.46}$ or $-24^{+1.3}_{-2.6}$
			1833.4	$9/2^-$			
					-0.22 ± 0.23	M1 + E2	$-0.30^{+0.32}_{-0.29}$ or $1.5^{+1.3}_{-0.7}$

Table 3 (continued)

1	2	3	4	5	6	7	8
					-0.23 ± 0.33		$-0.28^{+0.25}_{-0.35}$ or $-2.6^{+1.4}_{-5.2}$
			1534.8	$9/2^-$			
					-0.20 ± 0.29	M1 + E2	$-0.32^{+0.41}_{-0.40}$ or $1.6^{+2.4}_{-0.9}$
1998.4	$9/2^-$	0.925	1964.8	$7/2^+$	1.08 ± 0.43	E1 + M2	$-2.6 \le \delta \le 0.2$
			1759.6	$5/2^-$	-0.84 ± 0.40	E2 + M3	$0.0 \le \delta \le 47.0$
			1521.4	$9/2^-$	-0.88 ± 0.33	M1 + E2	$0.3 \le \delta \le 0.5$
			1444.9	$9/2^-$	0.50 ± 0.68	M1 + E2	$-0.3 \le \delta \le 1.7$
			1426.8	$11/2^-$	-0.19 ± 0.16	M1 + E2	$-0.25^{+0.12}_{-0.15}$ or $-3.0^{+1.0}_{-1.9}$
				$7/2^-$	-0.55 ± 0.34	M1 + E2	$0.3 \le \delta \le 9.8$
			642.1[a]				
				$9/2^-$	-0.55 ± 0.34	M1 + E2	$-0.3 \le \delta \le 1.6$
1995.4	$9/2^-$	0.925	1961.4	$7/2^+$	-0.02 ± 0.16	E1 + M2	0.17 ± 0.09
			1554.5[a]	$7/2^-$	-0.48 ± 0.43	M1 + E2	$0.2 \le \delta \le 85.2$
1979.4	$7/2^-$	0.810	1979.6[b]	$5/2^-$	-0.62 ± 0.16	M1 + E2	$0.61^{+0.25}_{-0.15}$ or $2.9^{+1.6}_{-1.1}$
			1740.3	$5/2^-$	-1.13 ± 0.67	M1 + E2	$0.5 \le \delta \le 4.5$
			1548.4	$7/2^+$	-0.19 ± 0.35	E1 + M2	-0.28 ± 0.44
1975.2	$9/2^+$	0.925	1941.4	$7/2^+$	0.15 ± 0.29	M1 + E2	0.08 ± 0.16 or $\lvert\delta\rvert \geq 4.0$
			1534.6	$7/2^-$	-0.20 ± 0.29	E1 + M2	$0.25 ^{+0.21}_{-0.18}$

Table 3 (continued)

1	2	3	4	5	6	7	8
			1403.7	11/2⁻	0.22 ± 0.27	E1 + M2	$-0.04^{+0.25}_{-0.11}$
			1255.4$^{a)}$	7/2⁻	-0.08 ± 0.28	E1 + M2	$0.20^{+0.18}_{-0.16}$
1974.0	5/2⁻	0.875	1974.0$^{a)}$	5/2⁻	-0.41 ± 0.12	M1 + E2	-0.02±0.13 or $1.7^{+0.6}_{-0.4}$
	7/2⁻	0.810			-0.44 ± 0.13	M1 + E2	0.45±0.12 or $4.7^{+3.4}_{-1.5}$
			1895.4	7/2⁻	-0.47 ± 0.18	M1 + E2	$-1.9 \leq \delta \leq 0.4$
					-0.50 ± 0.19	M1 + E2	$-0.2 \leq \delta \leq 1.5$
			1696.1$^{b)}$	5/2⁻	-0.35 ± 0.27	M1 + E2	$-0.07^{+0.51}_{-0.38}$ or $1.9^{+2.0}_{-1.1}$
					-0.38 ± 0.29	M1 + E2	$0.40^{+0.26}_{-0.18}$ or $5.8^{+11.9}_{-3.3}$
			1665.6	7/2⁻	0.12 ± 0.26	M1 + E2	$-0.01^{+0.26}_{-0.20}$
					0.13 ± 0.28	M1 + E2	$0.7 \pm^{0.4}_{1.2}$
			1554.5$^{a)}$	9/2⁻	-0.49 ± 0.45	E2 + M3	$-2.5 \leq \delta \leq 0.1$
					-0.53 ± 0.49	M1 + E2	$-4.2 \leq \delta \leq 0.2$

Table 3 (continued)

1	2	3	4	5	6	7	8
			1255.4$^{a)}$	7/2⁻	-0.08 ± 0.31	M1 + E2	$-0.16^{+0.23}_{-0.35}$ or $3.3^{+1.8}_{-10.7}$
					-0.09 ± 0.33	M1 + E2	$-0.39^{+0.37}_{-0.50}$ or $2.6^{+109.4}_{-1.5}$
1952.8	7/2⁺	0.810	1873.2	7/2⁻	-0.73 ± 0.35	E1 + M2	$-0.1 \leq \delta \leq 1.3$
			1644.5	7/2⁻	-0.24 ± 0.18	E1 + M2	-0.23±0.20
			1542.0$^{a)}$	7/2⁻	-0.13 ± 0.32	E1 + M2	$-0.34^{+0.37}_{-0.44}$
			1275.4	7/2⁻	-0.47 ± 0.16	E1 + M2	$-0.2 \leq \delta \leq 1.5$
			1164.2	9/2⁻	1.02 ± 0.75	E1 + M2	$-0.1 \leq \delta \leq 48.2$
1951.1	9/2⁻	0.925	1951.4	5/2⁻	0.37 ± 0.80	E2 + M3	$-0.6 \leq \delta \leq 6.6$
			1917.8	7/2⁺	-0.03 ± 0.30	E1 + M2	$-0.18^{+0.18}_{-0.16}$
			1633.6	7/2⁻	0.22 ± 0.22	M1 + E2	0.04±0.12 or $7.9^{+3.9}_{-87.2}$
			1510.4	7/2⁻	-0.48 ± 0.20	M1 + E2	$0.47^{+0.22}_{-0.14}$ or $3.6^{+1.5}_{-3.3}$
			1397.6	9/2⁻	0.33 ± 0.21	M1 + E2	$-9.8 \leq \delta \leq -0.8$ or $\delta \geq 4.6$
			594.3	7/2⁻	0.76 ± 0.62	M1 + E2	$-12.6 \leq \delta \leq 0.1$
				9/2⁻	0.76 ± 0.62	M1 + E2	$-\infty < \delta \leq -0.8$

Table 3 (continued)

1	2	3	4	5	6	7	8
1947.4	$9/2^-$	0.925	1629.7	$7/2^-$	1.03 ± 0.64	M1 + E2	$-4.6 \leq \delta \leq -0.1$
			1506.8	$7/2^-$	-0.04 ± 0.12	M1 + E2	0.18 ± 0.07 or $\lvert\delta\rvert \geqslant 12.8$
			1394.0	$9/2^-$	-0.55 ± 0.19	M1 + E2	$-0.1 \leq \delta \leq 1.1$
			1376.0	$11/2^-$	-0.53 ± 0.16	M1 + E2	$-2.0 \leq \delta \leq -0.4$
			1227.2	$5/2^-$	-0.38 ± 0.14	E2 + M3	-0.05 ± 0.13
				$7/2^-$	-0.38 ± 0.14	M1 + E2	$0.39^{+0.11}_{-0.09}$
			642.1[a)]	$7/2^-$	-0.55 ± 0.34	M1 + E2	$0.3 \leq \delta \leq 9.4$
1356.4	$7/2^-, 9/2^-$						
1305.4	$7/2^-$	0.79 ± 0.08	1305.5	$5/2^-$	-0.36 ± 0.15	M1 + E2	$0.38^{+0.12}_{-0.09}$ or $6.4^{+8.1}_{-2.5}$
			1126.6	$9/2^-$	0.23 ± 0.34	M1 + E2	0.06 ± 0.24
1267.2	$5/2^+$	0.875	1267.2[c)]	$5/2^-$		E1 + M2	
			1188.5	$7/2^-$	0.06 ± 0.28	E1 + M2	$-0.06^{+0.21}_{-0.24}$
1022.1	$9/2^+$	0.91 ± 0.08	988.4	$7/2^+$	-0.57 ± 0.41	M1 + E2	$0.3 \leq \delta \leq 12.5$
			591.2	$7/2^+$	-0.55 ± 0.19	M1 + E2	$3.0^{+2.1}_{-1.2}$
788.3	$9/2^-$	0.88 ± 0.10	788.4	$5/2^-$	-0.17 ± 0.54	E2 + M3	$-0.25^{+0.53}_{-0.75}$
			709.7	$7/2^-$	-0.24 ± 0.49	M1 + E2	$0.30^{+0.50}_{-0.27}$ or $\lvert\delta\rvert \geqslant 1.8$
			609.4	$9/2^-$	0.17 ± 0.24	M1 + E2	$-\infty < \delta \leq -0.4$ or $2.1 \leq \delta < +\infty$

Table 3 (continued)

1	2	3	4	5	6	7	8
			549.0	$5/2^-$	-0.53 ± 0.32	E2 + M3	$0.09^{+0.37}_{-0.30}$
			470.6	$7/2^-$	-0.59 ± 0.40	M1 + E2	$0.3 \leq \delta \leq 10.8$
719.2	$5/2^-, 7/2^-$						
628.5	$7/2^+$	0.81 ± 0.13	599.0	$5/2^+$	0.07 ± 0.22	M1 + E2	0.14 ± 0.12
			569.9	$9/2^+$	-0.69 ± 0.20	M1 + E2	$-1.2 \leq \delta \leq 0.7$
571.5	$11/2^-$	0.86 ± 0.11	445.4	$11/2^+$	-0.69 ± 0.26	E1 + M2	$-0.01 \leq \delta \leq 0.70$
			392.6	$9/2^-$	-0.26 ± 0.22	M1 + E2	$0.31^{+0.17}_{-0.13}$
569.4	$3/2^+$	0.655	539.5	$5/2^+$	0.94 ± 0.86	M1 + E2	$-4.16 \leq \delta \leq -0.02$
	$5/2^+$	0.875			0.71 ± 0.65	M1 + E2	$-\infty < \delta \leq -0.5$
	$7/2^+$	0.810			0.77 ± 0.70	M1 + E2	$-13.3 \leq \delta \leq 0.2$
553.5	$9/2^-$	0.90 ± 0.12	427.3	$11/2^+$	0.69 ± 0.64	E1 + M2	$-0.08 \leq \delta \leq 0.38$
			235.9	$7/2^-$	0.62 ± 0.29	M1 + E2	$-2.7^{+1.1}_{-2.5}$
477.3	$9/2^-$	0.90 ± 0.14	298.6	$9/2^-$	-0.87 ± 0.47	M1 + E2	$-0.1 \leq \delta \leq 0.9$
440.7	$7/2^-$	0.78 ± 0.08	406.7	$7/2^+$	-0.46 ± 0.28	E1 + M2	$-0.3 \leq \delta \leq 2.1$
			361.5	$7/2^-$	-0.62 ± 0.62	M1 + E2	$-0.5 \leq \delta \leq 3.6$
			261.8	$9/2^-$	0.06 ± 0.15	M1 + E2	-0.06 ± 0.10
430.8	$7/2^+$	0.75 ± 0.06	401.0	$5/2^+$	0.36 ± 0.18	M1 + E2	-0.02 ± 0.09

Table 3 (continued)

1	2	3	4	5	6	7	8
			397.0	$7/2^+$	-0.09 ± 0.21	M1 + E2	$-0.41 {+0.20 \atop -0.31}$
			352.0	$7/2^-$	-0.28 ± 0.65	E1 + M2	$-0.26 {+0.70 \atop -0.89}$
419.6	$9/2^-$	0.79 ± 0.16					
411.0	$7/2^-$	0.81 ± 0.12	410.9	$5/2^-$	0.51 ± 0.35	M1 + E2	$-3.1 {+1.4 \atop -4.9}$
			377.1	$7/2^+$	-0.92 ± 0.42	E1 + M2	$0.08 \leq \delta \leq 0.90$
			232.1	$9/2^-$	-0.66 ± 0.50	M1 + E2	$-3.0 \leq \delta \leq 0.2$
317.5	$7/2^-$	0.70 ± 0.24	317.6	$5/2^-$	0.43 ± 0.23	M1 + E2	-0.05 ± 0.13
308.5	$7/2^-$	0.73 ± 0.12	308.5	$5/2^-$	-0.46 ± 0.71	M1 + E2	$0.04 \leq \delta \leq 4.53$ or $\delta \leq -5.7$
			229.8	$7/2^-$	-0.09 ± 0.19	M1 + E2	$-0.39 {+0.20 \atop -0.24}$
301.5	$11/2^-$	0.87 ± 0.12	243.1	$9/2^+$	-0.15 ± 0.20	E1 + M2	0.20 ± 0.14
			222.8	$7/2^-$	-0.72 ± 0.27	E2 + M3	$0.30 {+0.59 \atop -0.31}$
278.2	$5/2^-$	0.76 ± 0.18	248.6	$5/2^+$	-0.70 ± 0.31	E1 + M2	$0.45 {+0.11 \atop -0.48}$
258.5	$3/2^-$	0.49 ± 0.10	258.5	$5/2^-$	-0.31 ± 0.23	M1 + E2	$-2.6 \leq \delta \leq 0.2$
239.1	$5/2^-$	0.70 ± 0.15	239.1[d]	$5/2^-$	-0.19 ± 0.14	M1 + E2	$2.9 {+1.5 \atop -0.9}$

a) The γ-ray is placed twice in the decay scheme. b) This placement is preferred on the basis of the coincidence data found in /3/ and our analysis. c) This transition was used to evaluate the $B_2(I)$ coefficient. d) See Table 1.

1735.3 keV $11/2^- \rightarrow 7/2^-$ transition which would require more than 0.2% M3 admixture. If the 2052.8 keV level is $9/2^+$, the positive anisotropy of the 1735.3 keV E1 transition indicates a negative A_2 coefficient. Inspection of Table 2 shows that the $9/2^-$ assignment is the only one possible. The range of a mixing ratio of the 1926.8 keV transition to the $11/2^+$ level is also compatible with the $9/2^-$ assignment.

The 2013.3 keV level. The possible spin-parity assignments are limited to $5/2^+$ or $7/2^-$ by the observed γ-ray decays. The negative anisotropy of the 1983.4 keV transition is only consistent with a $7/2^-$ assignment. This $7/2^-$ assignment satisfies also the observed anisotropy of the 2013.1 keV ground state transition.

The 2012.4 keV level. It is not possible to assign a unique spin value. The possible solutions for $7/2^\pm$ or $9/2^-$ are listed in Table 3.

The 1998.4 keV level. The decays of the level restrict the spin to $7/2^-$ or $9/2^-$. Positive parity proposed by Gromov et al. /4/ for this level was excluded by the 1719.8 keV transition to a $5/2^-$ level found /3/ in coincidences with the 278.2 keV γ ray. A $9/2^-$ assignment is only consistent with a negative anisotropy of the 1964.8 keV transition to the $7/2^+$ level and with the anisotropies of other transitions from this level.

The 1995.4 keV level. Again the $7/2^-$ or $9/2^-$ assignments are possible on the basis of observed decays. If the level is $7/2^-$, the $(18.1 {+3.5 \atop -6.3})$% M2 admixture is required to satisfy the anisotropy of the 1961.4 keV transition, and the $9/2^-$ assignment is preferable.

The 1979.4 keV level. The decay scheme indicates that the level should be $7/2^\pm$ or $9/2^-$. The anisotropy of the 1740.3 keV transition is not consistent with a $9/2^-$ assignment. The positive anisotropies of the 1740.3 and 1979.6 keV transitions both to the $5/2^-$ levels indicate a negative A_2 coefficient. Inspection of Table 2 shows that the only possible spin-parity assignment for the 1979.4 keV level is therefore $7/2^-$.

The 1975.2 keV level. Gromov et al. /5/ make a $9/2^+$ assignment on the basis of observed decays. The anisotropies of the transitions observed are only consistent with the $9/2^+$ assignment.

The 1974.0 keV level. It is not possible to assign a unique spin value. Possible solutions for the $5/2^-$ or $7/2^-$ assignments are presented in Table 3. The positive parity proposed by Gromov et al. /5/ on the basis of ICC measurements /4/ may be excluded as the A_2 coefficients have negative signs for both the 1696.1 keV transition to the $5/2^-$ level and the 1895.4 keV transition to the $7/2^-$ level.

The 1952.8 and 308.5 keV levels. The possible spin-parity assignments for these levels are limited to $5/2^+$ or $7/2^+$ and $5/2^-$ or $7/2^-$, respectively, on the basis of the decay scheme scheme /3,4/. The positive anisotropies of the 1873.2 and 1644.5 keV transitions to the 78.7, $7/2^-$ and 308.5 keV levels indicate the $7/2^+$ and $7/2^-$ assignments for the 1952.8 and 308.5 keV levels, respectively.

The 1951.1 keV level. Only $9/2^-$ assignment is possible on the basis of the level decays and this is consistent with the anisotropies of the observed γ-ray transitions.

The 1947.4 keV level. Inspection of Table 2 shows that the positive anisotropies of the 1376.0 and 1394.0 keV transitions to the $11/2^-$ and $9/2^-$ levels, respectively, are not consistent with the $9/2^+$ assignment proposed by Gromov et al./4/ on the basis of the ICC data. Meijer et al./3/ placed the 1917.8 keV γ ray as depopulating the 1947.4 keV level to the $5/2^+$ level and proposed the $7/2^-$ assignment. The $7/2^- \to 11/2^-$ transition, hewever, would require more than 3.5% M3 admixture to satisfy a large anisotropy observed for the 1376.0 keV transition and on this basis the $7/2^-$ assignment can be excluded. The possible assignments are then $9/2^-$ or $11/2^-$ and the 1917.8 keV γ ray has to be placed elsewhere. We exclude the $11/2^-$ assignment as the small anisotropy of the intense 1506.8 keV γ ray would imply more than 8.3% M3 admixture.

The 1356.4 keV level. Gromov et al./4/ introduce the level and make the $9/2^+$ or $11/2^+$ assignments. However, the negative parity assignments for the 1952.8 and 1951.1 keV levels made in present work together with the negative anisotropy of the 594.3 keV transition from the 1951.1 keV level restrict the spin-parity to $7/2^-$ or $9/2^-$.

The 1305.4 keV level. The level was introduced by Meijer et al./3/. The decays of the level restrict the spin to $5/2^-$ or $7/2^-$. The $5/2^-$ assignment may be excluded as the $5/2^- \to 9/2^-$ transition would require more than 4.4% M3 admixture to satisfy the anisotropy of the 1126.6 keV transition. The 1275.4 keV transition placed twice by Meijer et al. is then the $7/2^- \to 5/2^+$ transition, but the $(18.1^{+2.8}_{-1.4})$% M2 admixture in this case indicates that another placement is more probable.

The 1022.1 keV level. The decay scheme indicates that the level should be $7/2^+$ or $9/2^+$. Only the E2 : M1 ratio $\delta = 3.0^{+2.1}_{-1.2}$ for the 591.2 keV $9/2^+ \to 7/2^+$ transition is consistent with the $|\delta(\alpha_K)| = 2.5^{+\infty}_{-1.0}$ obtained by Gromov et al./4/.

The 788.3 keV level. Gromov et al./4/ indicate possible assignments of $7/2^-$ or $9/2^-$. The negative anisotropy of the 1164.2 keV transition from the $7/2^+$ level at 1952.8 keV is only consistent with the $9/2^-$ assignment.

The 719.2 keV level. The possible spin assignments made on the basis of published data are listed in Table 3. The anisotropies of the γ rays feeding this level are consistent with these assignments.

The 677.1 keV level. The level was introduced by Meijer et al./3/. Gromov and Khamidov /5/ indicated possible assignments of $3/2^-$, $5/2^-$ or $7/2^-$. The presence of the 1275.4 keV transition from the $7/2^+$ level at 1952.8 keV and its positive anisotropy exclude the $3/2^-$ and $5/2^-$ assignments.

The 628.5 keV level. The level was also introduced by Meijer et al./3/. Our results for the 569.9 and 599.0 keV transitions are in good agreement with the ICC data /3,4/ $|\delta(\alpha_K)| = 1.8^{+2.4}_{-0.8}$ and $|\delta(\alpha_K)| \leq 0.8$, respectively, for the $7/2^+$ assignment /5/.

The 571.5 keV level. Gromov et al./4/ make a unique $11/2^-$ assignment for this level. The observed anisotropies of the 445.4 keV and 392.6 keV γ rays are consistent with this assignment and the mixing ratios are in good agreement with the ICC results /3,4/ $|\delta(\alpha_K)| = 0.03^{+0.05}_{-0.03}$ and $|\delta(\alpha_K)| = 0.34^{+0.37}_{-0.34}$, respectively.

The 569.4 keV level. The level was introduced by Meijer et al. The $3/2^+$, $5/2^+$ or $7/2^+$ assignments are possible on the basis of all results available.

The 553.5 keV level. The feeding and decays of the level restrict the spin to $9/2^-$ or $11/2^-$. Inspection of Table 2 shows that the $11/2^-$ assignment may be excluded on the basis of the negative anisotropies of the 235.9 and 427.3 keV transitions to the $7/2^-$ and $11/2^+$ levels, respectively. The anisotropies of these transitions are only consistent with the $9/2^-$ assignment and it is supported by the results obtained for the γ rays feeding this level.

The 477.3 and 440.7 keV levels. The unique spin-parity assignments of $9/2^-$ and $7/2^-$, respectively, were made by Gromov et al./4/ on the basis of the decay scheme and the ICC data. Our results confirm these assignments.

The 430.8 keV level. The decay scheme indicates that the level schould be $5/2^+$ or $7/2^+$. A $5/2^+$ assignment may be excluded as the M2 ≥ 3% admixture is required to satisfy the 352.0 keV γ-ray anisotropy. All anisotropies to/from the 430.8 keV level are consistent with the $7/2^+$ assignment and the mixing ratios obtained for the 352.0, 397.0 and 401.0 keV γ rays are in good agreement with the ICC results [3,4] $|\delta(\alpha_K)| = 0.05^{+0.09}_{-0.05}$, $0.70^{+0.43}_{-0.38}$ and $0.10^{+0.21}_{-0.10}$, respectively.

The 411.0 and 317.5 keV levels. The $7/2^-$ assignments were made for these levels on the basis of the level scheme and the ICC data. Our results are consistent with these assignments.

The spin-parity assignments for the lower-lying levels made in previous investigations [1,3,4] are consistent with the observed γ-ray anisotropies. The appropriate results are listed in Table 3. The anisotropies of the γ rays to and from the 239.1 keV level, however, do not exclude the $7/2^-$ assignment also considered by Meijer et al. [3].

5. DISCUSSION

The ground state of ^{167}Yb is assigned $5/2^-[523]\downarrow$ (refs. [2,6,7]). The first two members at 78.7 and 178.9 keV [1,4], the $11/2^-$ member at 301.5 keV [3,4] and the tentative 442.4 keV level [4] of the $[523]\downarrow$ ground state rotational band are known from the radioactive decay. The (d, t) and (α, 3n) reaction data [6,7] and our results confirm these assignments. The nonadiabatic rotational model calculations [17] also agree with this identification.

The members of the $1/2^-[521]\downarrow$ band with spin-parities $1/2^-$, $3/2^-$, $5/2^-$, $7/2^-$ and $9/2^-$ have been proposed [1,3,4] at 188.7, 258.5, 278.2, 440.7 and 477.3 keV, respectively. Our results confirm these assignments. As pointed out in ref. [4], the level energies of the band are in good agreement with those calculated for the K = 1/2 rotational band using the simple rotational formula with the moment of inertia and decoupling parameters A = 13.5 keV and α = 0.71, respectively. Moreover, the A parameter obeys the systematics for the $1/2\,[521]\downarrow$ band in the adjacent N = 97 nuclei and the a parameter is close to a Nilsson value $a_N = 0.8$ for the deformation $\delta = 0.2 \div 0.3$. However, the intensity ratios [4] for the γ rays depopulating the members of the $[521]\downarrow$ band at 440.7 and 477.3 keV to the levels of the same band, $I_{182.1}/I_{162.4} = 43 \pm 13$ and $I_{199.1}/I_{36.8} \approx 20$, seem to be anomalously great. In ref. [17], for the $7/2^-$ state at 440.7 keV and for the $9/2^-$ state at 477.3 keV the maximum amplitude of the $7/2^-[514]\downarrow$ and $3/2\,[521]\uparrow$ components was found, while the 411.0 keV $7/2^-$ level was identified as the $7/2^-$ member of the $1/2\,[521]\downarrow$ band. The difficulties with the interpretation of these levels indicate that their structure may be complex.

The $3/2^-$, $5/2^-$, $7/2^-$ and $9/2^-$ members of the $3/2^-[521]\uparrow$ rotational band have been proposed [1] at 179.7, 239.1, 317.5 and 419.6 keV, respectively, but Gromov et al. [4] proposed the 213.2 keV level as the $3/2^-[521]\uparrow$ band head. The $5/2^-$ or $7/2^-$ assignments, however, are also possible for the 213.2 keV level on the basis of γ-ray data. The 3.5% β feeding (lgft = 7.0) to this level was obtained in ref. [3] as compared with the value < 0.7% (lgft > 7.8) for the second - forbidden β decay to the $3/2^-$ level at 258.5 keV. Thus the $3/2^-$ assignment seems to be less probable for the 213.2 keV level. The 179.7 keV level seems to be more suitable $3/2^-$ member of the $[521]\uparrow$ band. The β feeding to this level is very weak. The upper limit for the intensity of the ground - state transition is consistent with an M1 or E2 multipolarity [3]. The level energies in the $3/2^-[521]\uparrow$ band calculated using the simple rotational formula are compatible with the experimental values. The experimental values of the moment of inertia parameters for the $3/2^-[521]\uparrow$ band in ^{167}Yb are listed in Table 4 and they are in agreement with those for the ^{163,165,169}Yb [18,19]. The A parameters for the $5/2^-[523]\downarrow$ ground-state band are also presented in Table 4 for comparison. The 553.5 keV level was assigned as the $11/2^-$ member of this band [3,4], but our results are consistent with the $9/2^-$ assignment only.

The $5/2^-$ and $7/2^-$ members of the $5/2^-[512]\uparrow$ rotational band have been proposed at 213.2 and 308.5 keV in ref. [1] and at 308.5 and 411.0 keV in ref. [4], respectively. On the basis of the experimental data [1,3,4,6] and the theoretical analysis carried out in ref. [4,17] the unique interpretation of these levels cannot be made.

The present data confirm the proposed [4] assignment of the 571.5 keV $11/2^-$ level as a band head of the $11/2^-[505]\uparrow$ rotational band.

Our data are consistent with the interpretation of the levels at 29.7, 33.9, 58.5 and 125.9 keV as the $5/2^+$, $7/2^+$, $9/2^+$ and $11/2^+$ members of the $5/2^+[642]\uparrow$ rotational

Table 4

The moment of inertia parameters for the rotational bands in ^{167}Yb

K^{π} $[Nn_z\Lambda]$	$A_{1,2}$	$A_{1,3}$	$A_{1,4}$	$A_{2,3}$	$A_{2,4}$	$A_{3,4}$
$5/2^-$ [523]	11.24	11.18	11.16	11.13	11.14	11.15
$3/2^-$ [521]	11.89	11.48	11.42	11.20	11.28	11.34
$5/2^+$ [642]	0.61	1.80	3.56	2.74	4.60	6.12

band /1,3,4,6,7/ . As pointed out in ref./7/, the large deviations from the rotational spacings are observed. This is evident from Table 4 where the Λ parameters for the [642]↑ band are listed.

The unique spin-parity assignments were made for the most of the higher-lying levels in ^{167}Yb on the basis of our results. The interpretation of these levels, however, is difficult. Gromov et al./4/ identified the 788.3 keV $9/2^-$ level as the gamma-vibrational ([523]↓ + Q_{22}) state.

There are three Nilsson states, $7/2^-$[514], $7/2^-$[503] and $9/2^-$[505], which may be fed by the normal first - forbidden β transitions in the decay of ^{167}Lu , $7/2^+$[404] . The situation, however, is similar to that in ^{169}Yb/19/ : about ten $7/2^-$ and $9/2^-$ levels fed by β transitions with the lg ft values of 6.0 ÷ 7.9 compatible to those for normal first - forbidden transitions are observed in ^{167}Yb . The $7/2^-$[514], $7/2^-$[503] and $9/2^-$[505] states are probably spread over all these levels as it is assumed in ^{169}Yb .

In conclusion, it appears that the ^{167}Lu decay scheme cannot be regarded as final. The 85 γ rays with the intensity of ~8% are not placed in the decay scheme of Meijer et al./3/, while 12 of γ rays are placed twice. The anisotropies of several of unplaced γ rays have been observed and they are presented in Table 2. Moreover, some of γ rays cannot have certain placings according to the spin - parity assignments made in this work. After the additional levels will be established or if certain placings of γ rays shown be incorrect, the measured anisotropies can be re-analysed for those cases and appropriate conclusions drown concerning the new levels involved.

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