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J.Adam, K.Ya.Gromov, M.Honusek, A.Sh.Khamidov,
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J.Adam[1], K.Ya.Gromov, M.Honusek[2], A.Sh.Khamidov[3], F.Pražák[2], H.-U.Siebert[4]

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[1]*Nuclear Physics Institute, Řež near Prague, ČSSR.*
[2]*On leave from the Nuclear Physics Institute, Řež near Prague, ČSSR.*
[3]*On leave from the Institute for Nuclear Physics, Uzbek Academy of Sciences, Tashkent, USSR.*
[4]*On leave from the Technical University, Dresden, DDR.*

Адам И. и др. E6-11299

Состояния ^{165}Tm, возбуждаемые при распаде 9,8 мин ^{165}Yb

Распад ^{165}Yb ($T_{1/2}$ = 9,8 мин) изучался с помощью Ge(Li), Si(Li) и NaI(Tl) -детекторов, тороидального β-спектрометра и магнитных β-спектрографов. Использовались изобарически сепарированные источники, которые получались на установке ЯСНАПП в Дубне. Измерялись простые γ-спектры, спектры конверсионных электронов, мгновенные и задержанные γ-γ -совпадения. Предлагается схема распада ^{165}Yb, которая состоит из 40 возбужденных состояний ^{165}Tm. Были идентифицированы первые члены ротационных полос $1/2^+[411]$, $3/2^+[411]$, $5/2^+[402]$, $7/2^+[404]$, $1/2^-[541]$, $7/2^-[523]$ и $9/2^-[514]$.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Levels in ^{165}Tm Excited by the Decay of 9.8 min ^{165}Yb

The decay of ^{165}Yb ($T_{1/2}$ = 9.8 min) has been investigated with Ge(Li), Si(Li) and NaI(Tl) detectors, a toroidal β-spectrometer and magnetic β-spectrographs. The isobarically separated samples produced by the YASNAPP facility at the Dubna Institute were used. The single γ-ray spectrum, the conversion electron spectrum, prompt and delayed γ-γ coincidences have been measured. The decay scheme of ^{165}Yb involving 40 excited states in ^{165}Tm has been proposed. The first members of the rotational bands $1/2^+[411]$, $3/2^+[411]$, $5/2^+[402]$, $7/2^+[404]$, $1/2^-[541]$, $7/2^-[523]$ and $9/2^-[514]$ have been identified.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1978

1. INTRODUCTION

The excited states in ^{165}Tm populated by the decay of ^{165}Yb have been studied in refs. /1-5/. Paris /1/ has observed twenty transitions following ^{165}Yb decay and determined the decay energy and constructed the decay scheme involving 8 levels. The lifetime of the $7/2^-$ [523] state has been determined and four levels have been introduced in the decay scheme by Tamura /2/. The half-life of ^{165}Yb has been determined most precisely in ref. /6/: $T_{1/2} = 9.8 \pm 0.8$ min. The levels of ^{165}Tm were studied by several investigators via various reactions: $(p,n\gamma)$ (ref. /7/), $(p, 2n\gamma)$ (ref. /7,8,9/), $(\alpha,xn\gamma)$ (ref. /10,11/), $(^{11}B,xn\gamma)$ (ref. /4/), $(^3He,d)$ (ref. /12/) and (α,t) (ref. /12/). Most complete experimental results concerning the beta decay of ^{165}Yb have been reported in ref. /4/. The authors of this work have suggested that the γ-ray as well as conversion electron spectra and γ-γ coincidence spectra must be reinvestigated with isotopically separated sources.

Such sources of ^{165}Yb have been employed in the measurements of spectra of single γ-rays, conversion electrons, prompt and delayed γ-γ coincidences studied here. For this purpose, Ge(Li), Si(Li) and NaI(Tl) detectors, together with a toroidal β-spectrometer and magnetic β-spectrographs have been utilized. Thus, the construction of a more complete scheme of the $^{165}Yb \rightarrow {}^{165}Tm$ decay proved to be possible. Preliminary results of the present study have been reported in ref. /3,5/.

2. EXPERIMENTAL CONDITIONS AND RESULTS

2.1. Preparation of Sources

The neutron-deficient isotopes of rare-earth elements were obtained by the spallation reaction induced by high energy protons on tantalum or hafnium targets. Targets of metallic foil 0.05 mm thick and weighting approximately 0.5 g were irradiated in the external 660 MeV beam (current of 0.1 μA)) of the JINR synchrocyclotron for 15 min. The irradiated targets were transported pneumatically and loaded into the pipe-type surface ionization source /13/ of an electromagnetic isotope separator /14/. The products of the spallation reaction in the tantalum target were separated isobarically by means of the method described in ref. /15/. Sources (A=165) prepared in this way contained also ^{165}Lu activity ($T_{1/2}$ = 11.8 min). The single spectra of γ-rays were measured using hafnium targets /16/ in the later experiments. In that case the Lu activity disappeared completely and the yield ratio Yb/Tm was improved. The time interval between the end of target irradiation and the beginning of above described measurements did not exceed 5 min.

Sources for β-spectrographs were produced using a tantalum target which was exposed to the internal 2.3 μA proton beam of the accelerator. The Yb activity was chemically separated from other spallation products and was then deposited on a 50 μm platinum wire by electroplating. The measurements of the conversion electron sources started about 1 hour after the irradiation.

2.2. Gamma-Ray Singles Measurements

Gamma-ray single spectra were measured with detectors having volumes of 0.5 and 41 cm^3 and a resolution of 0.8 keV for ^{57}Co and 2.4 keV for ^{60}Co, respectively. The spectra were taken with the

4096-channel analyzers and treated by fitting a Gaussian function /17/ to the data. The low- and high-energy parts of the γ-ray spectrum of the ^{165}Yb decay are shown in Figs. 1 and 2, respectively.

The energy of γ-rays accompanying the ^{165}Yb decay was determined by measuring the isobar A=165 activity together with the ^{133}Ba, ^{182}Ta, ^{110m}Ag, ^{152}Eu and ^{226}Ra calibration sources /18/. Relative efficiencies

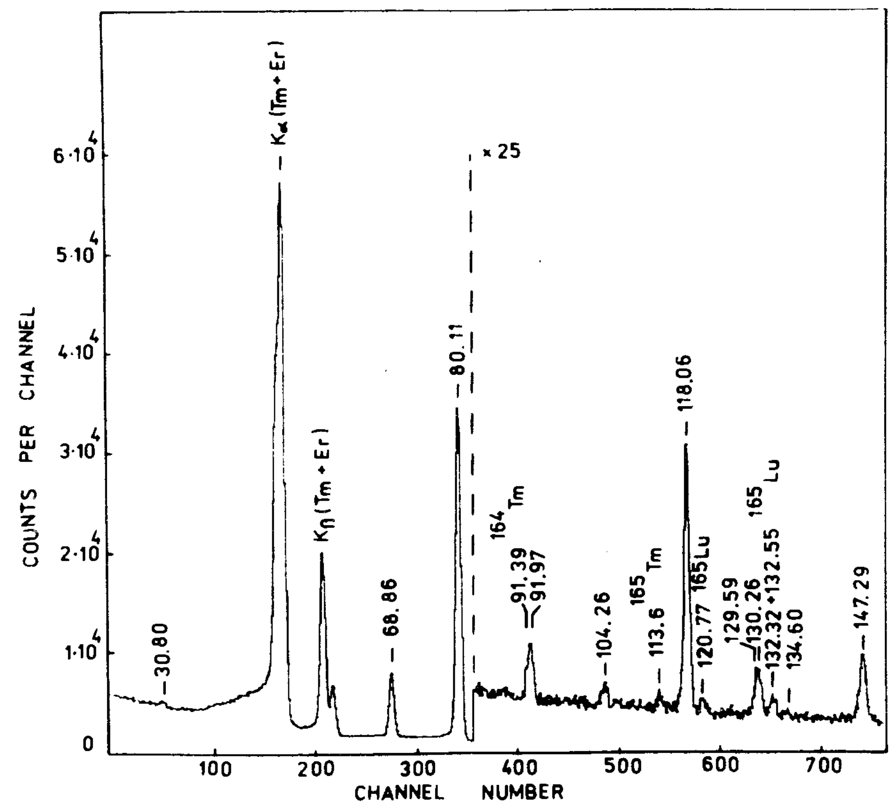


Fig. 1. Low-energy part of the ^{165}Yb γ-ray spectrum measured with the 0.5 cm^3 Ge(Li) detector.

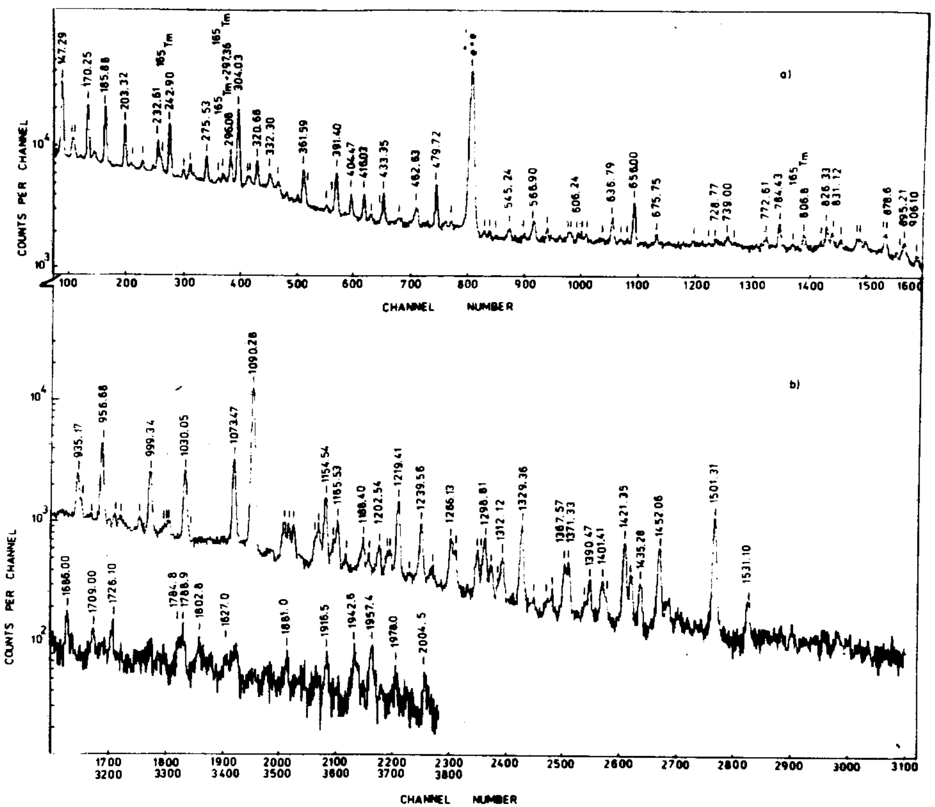


Fig. 2. High-energy part of the ^{165}Yb γ-ray spectrum measured by means of the 41 cm^3 Ge(Li) detector.

were calibrated with many standart sources and the efficiency curves were described by the six-parameter analytical function [19]. The accuracy to within 2-5% of the efficiency calibration of Ge(Li) detectors with respect to γ-ray intensities from the standart sources [18] was reached.

The ^{165}Yb activity, the ^{165}Tm (ref. [20]) activity and weak contributions from neighbouring isobars were found in γ-ray spectra. Gamma-rays accompanying the ^{165}Yb decay were identified according to their intensity reductions found in some sets of measurements of the isobar A = 165 activity. Some low intensity γ-rays seem to be an exception. Table 1 presents the data from the analysis of single γ-ray spectra in the ^{165}Yb decay. This table contains 153 γ-transitions from which as many as 48 have been observed for the first time. The energy of previously reported γ-rays has been determined in this work with an error 2-3 times smaller than in ref. [4].

2.3. Conversion Electron Measurements

Conversion electron spectra of ^{165}Yb were measured with a 3 mm thick Si(Li) detector (the working surface of 150 mm^2 and resolution of 2.2 keV for the K-electron line of the 121 keV transition) placed in the magnetic field [21] with an iron-free β-spectrometer having a toroidal magnetic field [28] (the resolution of 0.4% and the transmission of 7%) and with magnetic β-spectrographs operating at the 0.05% resolution.

The 11.60 ± 0.10 keV transition depopulating the first excited state was found by means of an iron-free β-spectrometer (see fig. 3). The results of the conversion electron measurements are summarized in Table 2. The multipolarities of the γ-ray transitions are deduced from a comparison of K-conversion coefficients and L- and M-subshell ratios with the theoretical values of conversion coefficients [22]. The multipolarity of 15 transitions was determined for the first time while the previous assignment (except the 13.7 keV one [1]) was confirmed for the other transitions (see table 2 and refs. [1, 2]).

Table 1

Energies and intensities of γ-rays in ^{165}Yb decay

E_γ	ΔE_γ(keV)	I_γ	ΔI_γ	E_γ	ΔE_γ(keV)	I_γ	ΔI_γ
30.80	0.10	11.8	2.0	(389.9)	0.5	0.35	0.20
68.86	0.05	70.2	4.0	391.40	0.08	2.31	0.30
80.11	0.02	374.0	20.0	404.47	0.10	1.08	0.07
91.97	0.05	2.64	0.30	416.03	0.13	1.26	0.10
104.26	0.07	1.21	0.15	422.26	0.25	0.29	0.03
118.06	0.05	18.40	1.00	430.8 a)	0.5	0.13	0.03
129.59	0.06	3.04	0.50	433.35	0.10	1.44	0.10
130.26	0.07	2.21	0.50	446.10	0.30	0.26	0.03
132.32	0.10	0.80	0.20	462.63	0.15	0.83	0.09
134.60	0.08	0.75	0.15	479.72	0.07	2.68	0.20
147.29	0.05	7.95	0.40	492.9 a)	0.6	0.26	0.09
156.51	0.15	1.05	0.10	522.76	0.20	0.26	0.07
158.20	0.25	0.56	0.07	527.50	0.30	0.15	0.03
170.25	0.05	4.45	0.22	533.35	0.40	0.12	0.04
185.88	0.06	4.45	0.22	545.24	0.20	0.44	0.06
203.32	0.07	2.81	0.15	557.96 a)	0.40	0.18	0.06
(208.5)	0.5	0.17	0.04	566.90	0.10	0.97	0.08
228.34 a)	0.20	0.22	0.03	578.58	0.16	0.51	0.05
232.61	0.08	1.87	0.10	597.19	0.30	0.38	0.08
235.21	0.09	0.73	0.06	599.57	0.30	0.38	0.08
255.00	0.10	0.41	0.05	606.24	0.25	0.38	0.06
260.87	0.09	0.75	0.08	(609.44)	0.30	0.20	0.06
263.89	0.20	0.16	0.04	613.52	0.20	0.36	0.05
275.53 b)	0.07	1.50	0.08	628.1	0.6	0.12	0.04
286.03	0.15	0.24	0.03	636.79	0.10	1.46	0.10
290.32	0.16	0.41	0.04	644.21 a)	0.30	0.20	0.04
304.03	0.06	8.29	0.50	650.00	0.30	0.18	0.04
312.25	0.30	0.31	0.05	656.00	0.07	2.89	0.16
314.31	0.30	0.37	0.05	675.75	0.20	0.49	0.06
320.68	0.08	1.70	0.10	708.13	0.40	0.25	0.08
332.30	0.20	1.00	0.30	722.30	0.50	0.17	0.08
339.67	0.20	0.54	0.18	728.77	0.30	0.29	0.08
361.59	0.10	2.00	0.14	739.00	0.30	0.43	0.05
363.58 a)	0.30	0.71	0.10	744.6	0.8	0.12	0.06
382.49	0.20	0.24	0.03	772.61	0.20	0.51	0.07

Table 1 (continued)

E_γ	ΔE_γ(keV)	I_γ	ΔI_γ	E_γ	ΔE_γ(keV)	I_γ	ΔI_γ
784.43	0.10	1.60	0.12	1172.7 a)	0.5	0.28	0.09
796.21	0.40	0.26	0.05	1188.40	0.13	1.05	0.10
820.87	0.40	0.29	0.14	1193.47	0.15	0.60	0.15
826.33	0.10	1.44	0.12	1202.54	0.14	0.97	0.10
831.12	0.13	0.94	0.09	1209.4	0.5	0.52	0.20
838.83	0.20	0.48	0.08	1212.3	0.5	0.63	0.20
853.05	0.20	0.68	0.07	1219.41	0.08	3.90	0.30
856.00	0.20	0.77	0.07	(1229.3)	0.8	0.18	0.10
877.0	0.6	0.77	0.40	1239.56	0.09	2.28	0.15
878.6	0.5	1.02	0.40	1249.5	1.0	0.29	0.15
892.9 a)	0.6	0.44	0.20	1266.13	0.10	1.66	0.12
895.21	0.20	1.06	0.25	1269.87	0.12	1.14	0.11
906.10	0.17	0.50	0.20	1289.65	0.12	1.22	0.10
935.17	0.08	3.21	0.20	1294.5 a)	0.5	0.59	0.20
937.96	0.25	0.71	0.08	1296.81	0.20	1.68	0.20
946.8	0.7	0.21	0.10	1302.25	0.15	0.76	0.10
956.68	0.07	8.35	0.50	1308.7	0.5	0.36	0.07
967.94	0.15	0.70	0.10	1312.12	0.11	1.08	0.08
973.10 a)	0.22	0.43	0.10	1329.36	0.08	2.82	0.20
989.97	0.30	0.61	0.14	1339.9	0.5	0.14	0.07
999.34 b)	0.07	4.85	0.25	1351.85	0.30	0.23	0.04
1009.3	0.8	0.18	0.09	1356.05	0.25	0.32	0.04
1012.40	0.40	0.47	0.15	1367.57	0.12	1.13	0.10
1015.70	0.30	0.77	0.15	1371.33	0.12	1.12	0.10
1030.05	0.07	5.20	0.30	1386.00	0.40	0.20	0.05
(1032.3)	0.8	0.29	0.15	1390.47	0.14	0.71	0.08
1073.47 b)	0.06	7.25	0.40	1401.41	0.16	0.68	0.08
1090.28 b)	0.06	34.6	2.0	1404.70	0.30	0.30	0.05
1117.74	0.10	1.55	0.15	1421.35	0.10	2.46	0.15
1122.00	0.12	1.28	0.15	1426.91	0.12	0.95	0.12
1126.34	0.12	1.25	0.15	1435.28	0.16	0.81	0.12
1145.33	0.30	0.84	0.12	1452.06	0.11	2.20	0.15
1148.56	0.10	1.49	0.15	1501.31	0.08	4.54	0.30
1154.54	0.08	3.52	0.25	1531.10	0.17	0.65	0.07
1161.78	0.18	0.74	0.09	1686.00	0.40	0.47	0.08
1165.53	0.10	1.90	0.15	1709.00	0.40	0.28	0.05

Table 1 (continued)

E_γ	ΔE_γ(keV)	I_γ	ΔI_γ	E_γ	ΔE_γ(keV)	I_γ	ΔI_γ
1726.10	0.40	0.32	0.06	1916.5	1.0	0.25	0.10
1784.8	0.5	0.29	0.07	1942.6	1.0	0.40	0.06
1788.9	0.5	0.37	0.07	1957.4	1.0	0.44	0.06
1802.8	0.8	0.20	0.05	1978.0	1.5	0.20	0.08
1827.0	1.5	0.15	0.07	2004.5	1.5	0.20	0.08
1881.0	1.0	0.15	0.06				

a) Belonging of this γ-ray to the decay of ^{165}Yb is uncertain.
b) Double transition as concluded from γ-γ coincidence measurements.

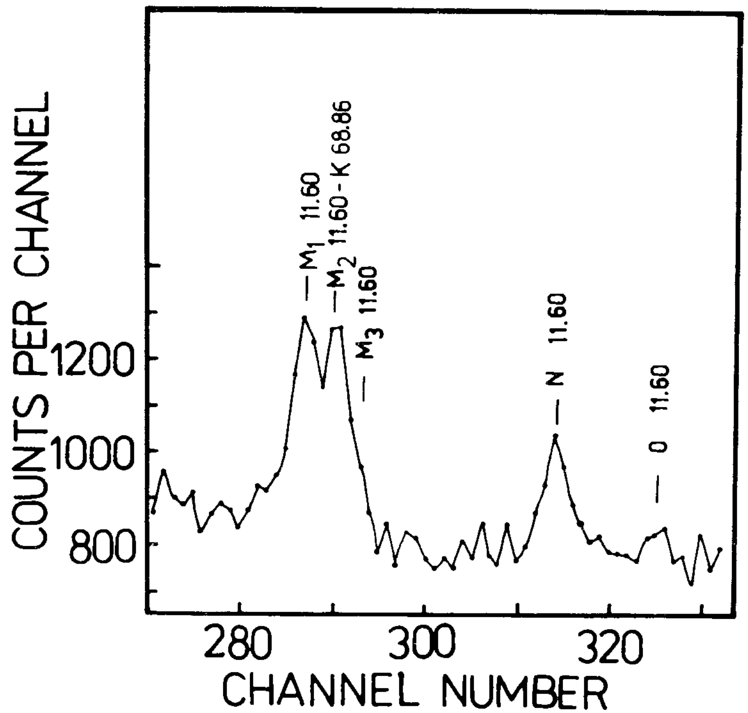


Fig. 3. A part of the conversion electron spectrum measured with a β-spectrometer having a toroidal magnetic field.

Table 2

Intensities of the conversion electrons and conclusions on the multipolarity of some transitions in ^{165}Tm

E_γ (keV)	I_K	I_{L_1} or/M_1	I_{L_2} or/M_2	I_{L_3} or/M_3	Multipolarity
11.60±0.10		~860^a)	≲ 200^a)	≲ 200^a)	M1+ ≲ 0.1%E2
30.80		<100^b)			E1
68.86	~400	≲ 70^b)	770^b)	800^b)	E2
80.11	~1600	180^b)	~40^b)		E1+ ≈ 2%M2
91.97	16				M1+E2
104.26	10				M1
118.06	45				E2, M1+E2
129.59	≲ 12				M1, E2, E1
130.26	≲ 5				E2, E1
147.29	11				E2, M1+E2
156.51	2				M1
170.25	1.5				E1 (E2)
185.88	2.5				E2
203.32	3				M1
232.61	0.5				E2
235.21	0.6				M1
275.53	< 0.2				E1
290.32	≲ 0.3				M1, E2, E1
304.03	1.6				E2, M1+E2
320.68	≲ 0.2				E1 (E2)
332.30	≲ 0.2				E2, E1

Electron intensities are normalized to gamma-ray intensities assuming that the 68.86 keV transition is pure E2 (obtained from L-subshell ratio).

a) Intensities of the conversion electrons from M-subshell.
b) Intensities of the conversion electrons from L-subshell.

2.4. Prompt and Delayed γ-γ Coincidence Measurements

The prompt γ-γ coincidence spectra were measured by means of two Ge(Li) detectors having sensitive volumes of 41 and 45 cm^3 at apparatus resolutions of 2.4 and 2.6 keV for ^{60}Co, respectively. The resolving time of the coincidence system was about 50 nsec. The two-dimensional coincidence spectrum (4096x4096 channels) was tape recorded /17/ and then treated with the HP 2116C computer /23/. The representative samples of γ-γ coincidence from gated energies of 118.06 and 147.29 keV are shown in fig. 4.

All the results from the γ-γ coincidence in the ^{165}Yb decay are summarized in table 3. The intensity errors are about 20% for strong transitions but may be as large as 50% for the weakest ones. These errors include uncertainty in the subtraction of the Compton background.

The calculated intensities of γ-γ coincidences were obtained in accordance with the ^{165}Tm level scheme (see fig. 5). The total intensity of transitions was used for the calculations of γ-γ coincidences in the case of transitions deexciting the levels: 129.62, 158.93, 181.72, 210.59, 252.44, 315.54, 362.28 and 419.79 keV. The values of theoretical conversion coefficients /22/ were used to evaluate the total intensity of transitions with the known multipolarity. For the 129.59 keV transition, the E2 multipolarity was supposed to be based on the decay scheme. The unknown mixing ratio of the 91.97 and 118.06 keV transitions increased the uncertainty of their total intensity by 10%. For other transitions we have adopted that the total intensity is equal to the γ-ray intensity.

In order to reach agreement between $I_{\gamma\gamma}^{calc}$ and $I_{\gamma\gamma}^{exp}$ for the coincidences of the 132.32 keV transition with the 1294.50 keV one the multipolarity M1 or E2 must be assumed for 132.32 keV transition.

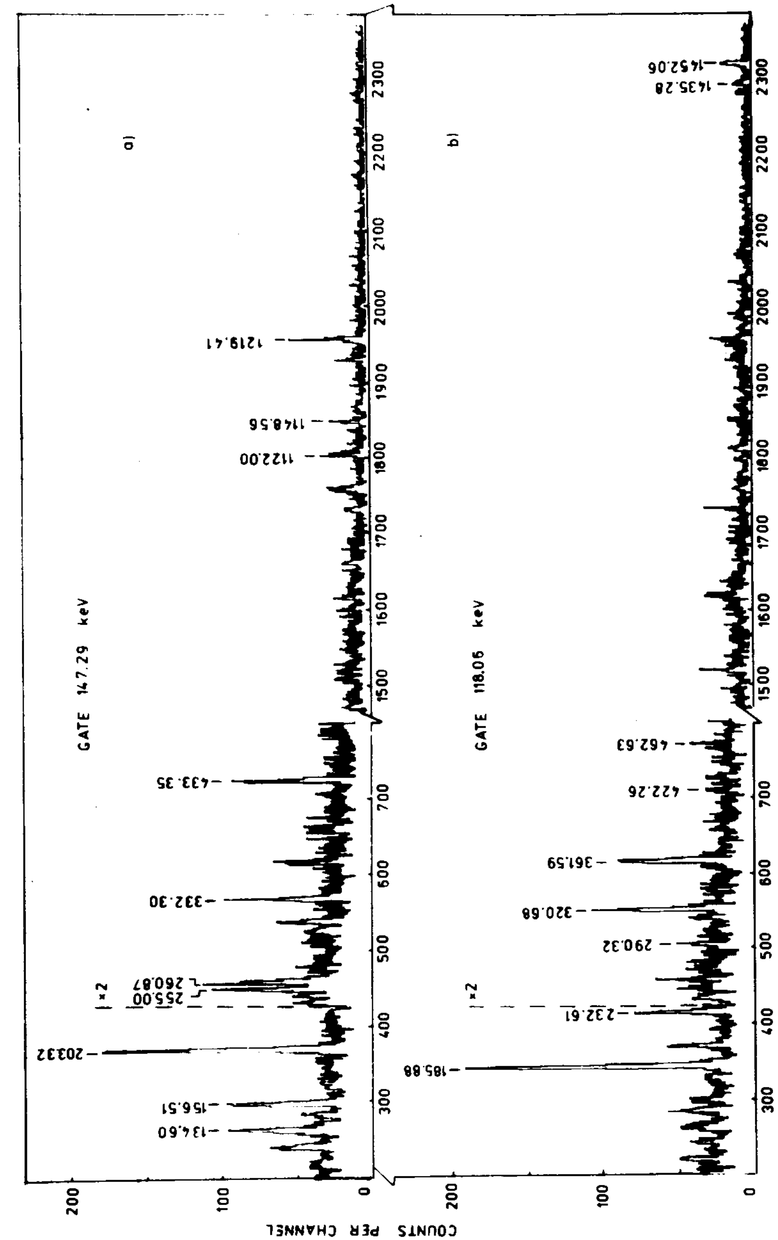


Fig. 4. The γ-ray spectra obtained in the γ-γ coincidence measurement from gated (a) 118.06 and (b) 147.29 keV γ-rays.

Table 3

Results of γ-γ coincidence measurements in the decay of ^{165}Yb

Level E(keV)	Gated lines $E_{\gamma 1}$(keV)	Coincident lines $E_{\gamma 2}$(keV)	$I_{\gamma\gamma}^{exp}$ [a]	$I_{\gamma\gamma}^{calc}$ [b]
129.62	118.06	185.88	0.78	1.39
		232.61	0.28	0.58
		290.32	0.11	0.13
		320.68	0.40	0.53
		361.59	0.40	0.62
		422.26	~0.13	0.09
		462.63	0.22	0.26
		1435.28	~0.17	0.25
		1452.06	0.45	0.68
	129.59	185.88	0.17	0.22
		1452.06	yes	0.11
158.93[c]	147.29	134.60	0.33	0.44
		156.51	0.45	0.62
		203.32	0.16	0.17
		255.00	~0.33	0.24
		260.87	0.45	0.44
		332.30	0.50	0.59
		433.35	0.78	0.85
		566.90	0.4	0.57
		1122.00	0.78	0.76
		1148.56	0.55	0.88
181.72[d]	170.25	708.13	~0.39	0.23
		739.00	~0.29	0.40
		831.12	0.87	0.87
		1126.34	1.45	1.16
		1188.40	0.97	0.97
210.59	130.26	826.33	0.55	0.63
		1371.33	0.45	0.49
252.44	91.97	545.24	0.09	0.09
		578.58	0.14	0.10
		937.96	0.16	0.14
		998.38[e]	0.23	0.20
		1073.56[e]	1.0	0.95

Table 3 (continued)

Level E(keV)	Gated lines $E_{\gamma 1}$(keV)	Coincident lines $E_{\gamma 2}$(keV)	$I_{\gamma\gamma}^{exp}$ [a]	$I_{\gamma\gamma}^{calc}$ [b]
		1117.74	0.28	0.29
		1312.12	0.16	0.20
		1329.36	0.55	0.55
315.54	156.51	104.26	~0.055	0.071
	185.88		0.22	0.30
	235.21		~0.05	0.05
	304.03		0.50	0.57
	156.51	606.24	~0.04	0.023
	156.51	935.17	0.16	0.19
	185.88		0.72	0.80
	304.03		1.55	1.51
	156.51	999.46[e]	0.33	0.24
	185.88		1.0	1.0
	235.21		yes	0.17
	304.03		2.1	1.83
	304.03	1249.50	yes	0.14
	156.51	1266.13	yes	0.10
	185.88		0.33	0.41
	304.03		0.67	0.78
	304.03	1531.10	0.46	0.30
362.28	203.32	363.58	0.22	0.32
	232.61		0.28	0.22
	203.32	1202.54	0.40	0.44
	232.61		0.33	0.30
	203.32	1219.41	1.0	1.76
	232.61		0.9	1.18
413.93	255.00	312.25	0.28	0.30
419.79	104.26	132.32	yes	0.15
	104.26	895.21	0.18	0.20
	260.87		yes	0.12
	104.26	1161.78	0.16	0.14
	104.26	1426.91	0.15	0.18
491.23	332.30	1073.54[e]	0.55	0.40
	361.59		0.83	0.80
	479.72		1.1	1.1

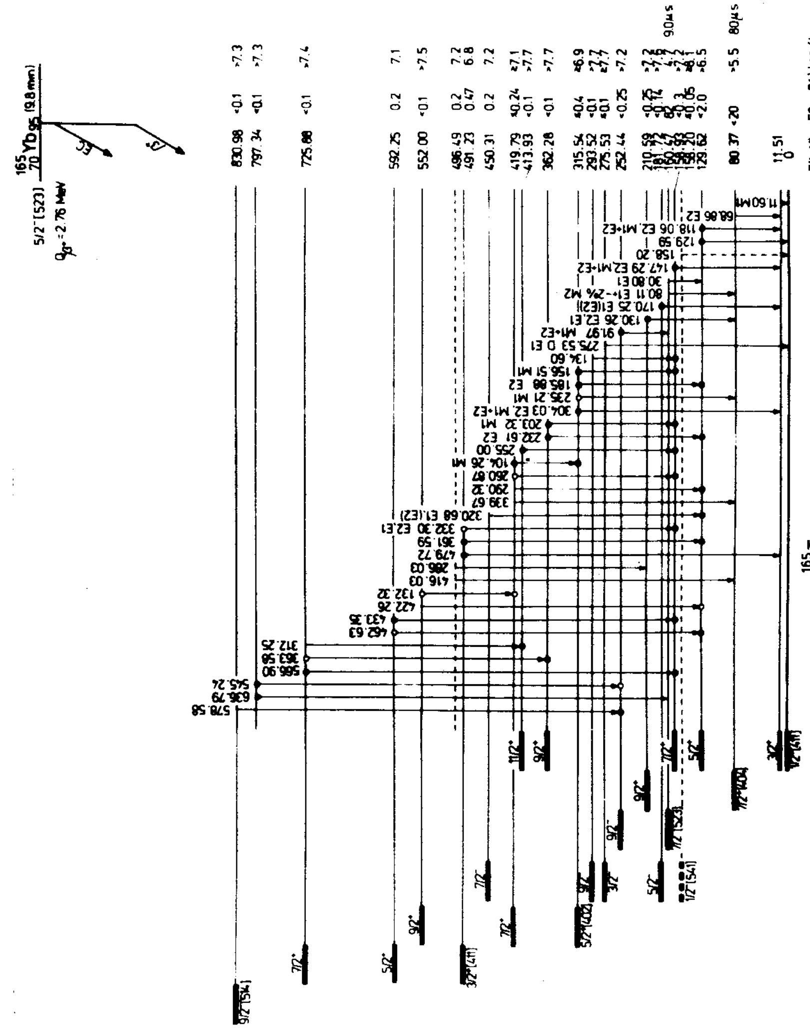
Table 3 (continued)

Level E(keV)	Gated lines $E_{\gamma 1}$(keV)	Coincident lines $E_{\gamma 2}$(keV)	$I_{\gamma\gamma}^{exp}$ a)	$I_{\gamma\gamma}^{calc}$ b)
	361.59	1090.54[e])	~ 0.25	0.26
	479.72		~ 0.37	0.35
552.00	132.32	1294.50	~ 0.16	0.43
592.25	433.35	989.97	0.50	0.40
	462.63		~ 0.33	0.22
725.88	363.58	838.83	~ 0.22	0.17
	566.90		~ 0.3	0.23
	363.58	856.00	~ 0.4	0.25
	566.90		~ 0.5	0.34
797.34	545.24	784.43	0.55	0.37
	636.79		1.66	1.23
1190.50	1030.05	275.64	~ 0.28	0.28
	937.96	391.40	yes	0.27
	1030.05		2.2	2.0
	1030.05	404.47	~ 0.42	0.33
	937.96	656.00	yes	0.34
	1030.05		2.8	2.6
1466.20	275.64[e])	728.77	~ 0.23	< 0.3
1790.40	599.57	404.47	~ 0.32	0.4

a) Intensities have been obtained from the analysis of $\gamma-\gamma$ coincidence spectra.
b) Intensities have been determined from the level scheme. The normalization of the intensity values is based on coincidences from 315.54 keV level. The intensity $I_{tot} = I_\gamma$ was taken for γ-transitions with unknown multipolarity.

c) The calculation of the $I_{\gamma\gamma}^{calc}$ was performed including the 29.31 keV transition (see table 4).
d) The calculation of the $I_{\gamma\gamma}^{calc}$ was performed including 22.78 keV and 52.10 keV transitions (see table 4).
e) The intensity corresponding to the component of the doublet (see table 4) was used for calculation of the $I_{\gamma\gamma}^{calc}$.

Fig. 5a. Low-energy part of the ^{165}Yb decay scheme.



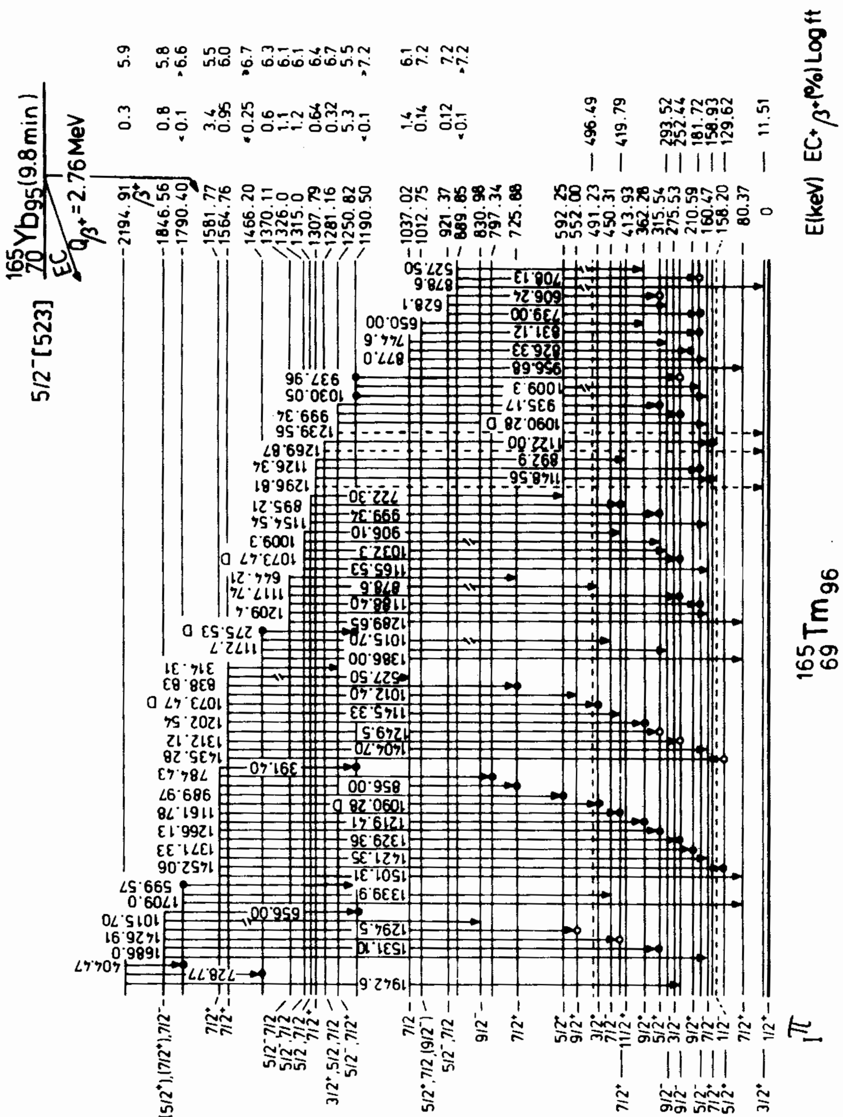


Fig. 5b. High-energy part of the ^{165}Yb decay scheme.

The disagreement in experimental and calculated coincidence rate between 118.06 keV and other transitions (see table 3) can be explained by an admixture of the transition with closed energy (120 keV) from the ^{165}Lu decay. The coincidence data indicate that the peaks at 275.53, 999.34, 1073.47 and 1090.28 keV observed in the ^{165}Yb decay are double lines (see table 4). The energies of the doublet components were determined from the decay scheme and their intensities were evaluated on the basis of the coincidence measurement results. The low energy transitions 22.78, 29.31 and 52.10 keV were introduced analysing the coincidence intensity for transitions connected with the 158.93 and 181.72 keV levels.

The delayed γ-γ coincidence measurement /17/ was performed using the Ø 4x4 cm^3 NaI(Tl) scintillation counter as a gate detector and the 41 cm^3 Ge(Li) detector for recording the delayed coincidence spectra. The resolving time of the system was 10 nsec. The time distribution curves corresponding to the 80.11 keV and to the 118.06 keV transitions confirmed the half-life of 9.0$\pm$0.5 μsec determined by T.Tamura /2/ for the 160.47 keV isomeric level. The obtained value of 20 for the ratio of coincidence intensity of the 80.11 and 118.06 keV transitions is in agreement with proposed decay scheme. The half-life of the 80.37 keV isomeric state, depopulating via the 69.3 keV transition, being $T_{1/2}$ = 80.3$\pm$3 μsec, was determined in ref./8/. We are not able to remeasure this half-life because the upper limit of our apparatus is 3 μ sec.

3. DISCUSSION

3.1. The Decay Scheme of ^{165}Yb

The decay scheme proposed in fig. 5 is based on the previously reported results from nuclear reaction studies and on the present experimental in–

Table 4

Energies and intensities of γ-rays in ^{165}Yb decay, existence of which follow from $\gamma-\gamma$ coincidencies

E_γ a)	ΔE_γ a)	I_γ a)	ΔI_γ a)	E_γ b)	ΔE_γ b)	I_γ b)	Placement in the decay scheme E_i	E_f
				22.78 d)	0.07	c)	181.72	158.93
				29.31 d)	0.05	14±5 f)	158.93	129.62
				52.10 d)	0.07	c)	181.72	129.62
275.53	0.07	1.50	0.08	275.53 e)	0.20	1.2±0.2	275.53	0
				275.70	0.20	~0.3	1466.20	1190.50
999.34	0.07	4.85	0.25	998.38	0.08	~1.0	1250.82	252.44
				999.46	0.1	~3.9	1315.00	315.54
1073.47	0.06	7.25	0.40	1073.54	0.10	~2.4	1564.76	491.23
				1073.56	0.13	~4.8	1326.00	252.44
1090.28	0.06	34.6	2.0	1090.28	0.08	33.9±2.0	1250.82	160.47
				1090.54	0.09	~0.7	1581.77	491.23

a) Data from table 1 for double transitions, they are indicated by D in fig. 5.

b) This value is calculated on the basis of the level scheme and results of $\gamma-\gamma$ coincidence.

c) $I_{tot}(22.78) + I_{tot}(52.10) \approx 4$

d) Transitions are not shown on decay scheme in fig. 5.

e) Conclusion on multipolarity E1 for this transition holds.

f) The total intensity has been determined only.

vestigations. Transitions of 91.97, 118.06, 129.59, 130.26, 147.24 and 170.25 keV were placed in the decay scheme using data from nuclear reaction /4,10-12/. This placement is confirmed by the present data on the coincidence of transitions depopulating the higher excited levels. The levels at 158.20 and 275.53 were introduced comparing our results with data from refs. /4,12/.

Other excited levels were found on the basis of the mentioned placement of transitions and using the present coincidence results, except the 496.49 keV state. The full (open) dots in fig. 5 stand for the transitions having placements strongly (weakly) supported by coincidences. Transitions not marked by dots are included in the decay scheme from energy sum relations and they were not observed in coincidence measurements. The dashed line marks the 1239.56, 1269.87 and 1296.81 keV transitions, which are placed tentatively, because their energies are by ~0.4 keV higher than the energy difference of the corresponding levels.

The energies of excited states in ^{165}Tm were calculated by the least-squares method /24/ using energies and respective errors of all the γ-transitions included in the decay scheme (see fig. 5). The double transitions (see table 4) and transitions, placement of which in decay scheme is ambiguous, were excluded from energy level calculations.

The total intensity of the 11.60, 68.86 and 80.11 keV cascade transitions is equal to 91% of the full intensity of all observed transitions. Altogether, 154 transitions were found from which 112 transitions were introduced in the decay scheme. The intensity of the observed transitions not placed in the proposed decay scheme is about 0.5%.

The level scheme of ^{165}Tm is extended by adding 10 new levels: 158.20, 469.49, 7[illegible]7.34, 830.98, 889.85, 921.37, 1466.20, 1790.40, 1846.56 and 2194.91 keV. All except seven (369.8, 609.5, 950.0, 1100.5, 1129.1, 1352.6 and 1424.8 keV) of the 37 levels proposed by Tamura et al. [4] have been confirmed.

Calculation of the log ft values has been carried out by assuming the Q-value [1] to be 2.76 MeV and neglecting the intensity of β-feeding of the first excited and ground states, respectively. The allowed unhindered character (log ft = 4.7) was established for the γ-transition to the state at 160.47 keV, which leads to the assignment $n5/2^-[523] \rightarrow p7/2^-[523]$ for this β-decay. Then, the ground state of ^{165}Yb is described by the $5/2^-[523]$ quantum characteristics.

The assignment of levels corresponding to the rotational bands above Nilsson states was based on the conclusions of ref. [10,11,12]. The multipolarities of transitions deexciting the above mentioned levels confirm the spin-parity determination. The spins and parities for other levels were proposed provided that the multipolarities of transitions M1, E1 or E2 are possible only. Further restrictions for spin and parity assignment of levels follow from the range of log ft values. The comparison of identifications for low energy levels between the present results and previous works (ref. [4, 10–12]) is given in table 5.

3.2. Levels of Rotational Bands with Positive Parity

The members of the $1/2^+[411]$ rotational band. The spin I=1/2 for the ground state of ^{165}Tm has been measured by Ekström et al. [25]. They have attributed the $1/2^+[411]$ Nilsson orbital to this state, which corresponds to the ground states in neighbouring odd thulium isotopes and a level scheme in the Woods-Saxon potential. The half-life of the 158.93 keV level, $I^\pi = 7/2^+$, has been measured to be $T_{1/2} = 322 \pm 20$ psec (ref. [7]). This value and total intensity of the 29.31 keV transition (see table 4) allowed us to calculate the intrinsic quadrupole moment $Q_0 = 5.3 \pm 0.7$ b for the ground state

Table 5

Low energy states in ^{165}Tm

I^π	E_{exp}(keV) This work	Cheung et al.[42])	Gizon et al.[10])	Foin et al.[11])	Tamura et al.[4])	E_{calc}(keV)
	$1/2^+[411]$		a)	a)	a)	
$1/2^+$	0	0	0	0	0	0.39
$3/2^+$	11.51	12	11.9	11.9	11.8	14.39
$5/2^+$	129.62	130	130.2	130.2	129.9	125.51
$7/2^+$	158.93	160	159.2	159.2	159.1	161.19
$9/2^+$	362.28	370	367.0	362.5	362.4	355.60
$11/2^+$	413.93		414.2	414.2	414.1	422.38
	$3/2^+[411]$					
$3/2^+$	491.23	(491)			491.2	490.16
$5/2^+$	592.25	(688)			609.5	591.63
$7/2^+$	725.88				725.1	725.72
$9/2^+$						902.52
$11/2^+$						1100.03
	$5/2^+[402]$					
$5/2^+$	315.54	316			315.8	317.56
$7/2^+$	419.79				420.1	418.22
$9/2^+$	552.00				552.2	556.20
$11/2^+$						717.90
	$7/2^+[404]$		a)	a)	a)	
$7/2^+$	80.37	81	81.1	81.1	80.9	76.90
$9/2^+$	210.59		211.3	211.3	211.3	215.27

Table 5 (continued)

I^{π}	This work	Cheung et al.[12]	Gizon et al.[13]	Poin et al.[14]	Tamura et al.[4]	E_{calc} (keV)
	E_{exp} (keV)					
$11/2^+$			366.9	366.9	366.9	383.21
	$1/2^-[541]$		a)	a)	a)	
$1/2^-$	158.20	160				
$3/2^-$	275.53	277			275.0	
$5/2^-$	181.72	182	182.2	182.1	182.2	
$7/2^-$	450.31	451			451.1	
$9/2^-$	293.52	293	293.9	293.9	293.7	
	$7/2^-[523]$		a)	a)	a)	
$7/2^-$	160.47	160	161.4	161.4	161.2	
$9/2^-$	252.44		253.4	253.4	253.2	
	$9/2^-[514]$					
$9/2^-$	830.98					
$11/2^-$		970				

a) Levels of rotational band with higher spin were observed.

band. The rotational band was observed up to the state with $I^{\pi} = 11/2^+$ in the present investigation.

The $3/2^+[411]$ rotational band. Tamura et al.[4] have established the following assignments to the excited levels: 491.2 keV - $3/2^+$, 609.5 keV - $5/2^+$ and 725.1 keV - $7/2^+$. On the other hand, Cheung et al.[12] proposed tentatively that the 491 and the 688 keV levels are members of this band. Based upon the present results, we conclude that the given rotational band corresponds very likely to the levels at 491.23, 592.25 and 725.88 keV with spin $3/2^+$, $5/2^+$ and $7/2^+$ respectively. The 592.25 keV level depopulates by the 433.55 and 462.63 keV transitions to members with $I^{\pi} = 5/2^+$ and $7/2^+$ of the ground state band as follows from our coincidence data. The 688 keV level was not observed in the present investigation. Tamura et al.[4] introduced the 609.5 keV level as a result of the energy sum relations for the 479.6 and the 597.8 keV transitions. However, we conclude from coincidence measurement that the 479.72 keV transition is placed in another part of the decay scheme and thus the 609.5 keV level does not appear.

The $5/2^+[402]$ rotational band. The 316 keV level with $5/2^+$ spin was indicated by Cheung et al.[12]. The levels with spins and parities $5/2^+$, $7/2^+$ and $9/2^+$ at 315.54, 419.79 and at 552.00 keV, respectively, belong[4] to the $5/2^+[402]$ rotational band, as is firmly established by the present results.

The $7/2^+[404]$ rotational band. Two levels with $I^{\pi} = 7/2^+$ and $I^{\pi} = 9/2^+$ at 80.37 and 210.59 keV, respectively, have been observed and their previous assignment[4,10-12] is confirmed here.

The Coriolis coupling analysis was performed for the rotational levels with positive parities. The rotational parameter: $A = \hbar^2/2J$, decoupling factor of $K = 1/2$ band: a, band-head energy: E_B, and the value of matrix element of Coriolis interaction: $\langle K|J_-|K+1\rangle$ were allowed to vary. The results of the energy fit are given in table 5. The calculated energy was obtained using the parameters A=15.75 keV and a = -0.57. The resulting value of the decoupling factor a = -0.57 for $1/2^+$[411] rotational band is close to a typical value a ≈ -0.7 for this band /27/.

3.3. Levels of Rotational Bands with Negative Parity

The members of the $1/2^-$[541] rotational band. The levels with spin-parities $3/2^-$, $5/2^-$, $7/2^-$ and $9/2^-$ belonging to this band were observed in refs. /4,10-12/. Cheung et al. /12/ have identified the level with $I^\pi = 1/2^-$ at 160 keV and Tamura et al. /4/, using the rotational formula, determined the energy for this level to be 156 keV. The present results confirm the levels with the spin-parities $3/2^-$, $5/2^-$, $7/2^-$ and $9/2^-$ at 275.53, 181.72, 450.31 and 293.93 keV, respectively. The 158.20 keV transition is the only one among transitions corresponding to ^{165}Yb decay with energy lower than 208 keV and being not placed in the level scheme. Based on the above- mentioned facts we introduced the 158.20 keV level, deexciting by the 158.20 keV transition, tentatively.

The $7/2^-$[523] rotational band. Two levels with spin-parities $7/2^-$, $9/2^-$ at 160.47 and 252.44 keV, respectively, have been observed and their previous assignments /4,10-12/ are confirmed.

The $9/2^-$[514] state. Cheung et al. /12/ have established the $I^\pi=11/2^-$ level at 970 keV corresponding to the $9/2^-$[514] rotational band and calculated that the energy of the $9/2^-$ level is 834.4 keV. From coincidence data we have introduced the 830.98 keV level which deexcited to the $I^\pi=9/2^-$ level of the $7/2^-$[523] state. The assignment $9/2^-$[514] for the 830.98 keV was assumed.

3.4. Levels at 1250.82, 1281.16, 1307.79 and 1581.77 keV

Cheung et al. /12/ have found the states with $K^\pi=1/2^+$ at 917 and at 1338 keV. We observed levels with energies of 1250.82, 1281.16 and 1307.79 keV which may be of positive parity and depopulate by strong transitions to the $I^\pi=3/2^+$ level of the $1/2^+$[411] band. These strong transitions indicate the existence of the component $K^\pi=1/2^+$ in the 1250.82, 1281.16 and 1307.79 keV states. On the other hand, the admixture of the $\{1/2^+[411] + Q_1(22)\}$ component /26/ interferes likely in above-mentioned levels.

It is necessary to note the following contradiction connected with the deexcitation of the 1581.77 keV level. The 1090.54 keV transition depopulates this level to the state with $I^\pi=3/2^+$ as implied by the coincidence results. Then the positive parity should be attributed to the 1581.77 keV level if the multipolarity E2 is supposed for the 1090.54 keV transition. From the low value of log ft = 5.5 we conclude that the 1581.77 keV level is populated by the allowed β-transition and then the negative parity is ascribed to this level.

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