СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E6 - 4782

ЛАБОРАТОРИЯ ЯДЕРНЫХ ПРОБЛЕМ

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DECAY OF ^{167}Yb

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1. Introduction

In previous works on the level scheme of ^{167}Tm (ref./1-6/) the first four members of the $1/2^+[411]$ ground state band and the two Nilsson states $7/2^+[404]$ and $7/2^-[523]$ were identified. Both the 7/2 states were found to have a lifetime of about 1 μs. Paris/5/ proposed three additional levels at 321.7, 1218 and 1412 keV. Only few information exist for the high-energy range although the decay energy $^{167}Yb \rightarrow {}^{167}Tm$ is 1.96 MeV /6/.

We investigated the levels in the odd Z nucleus ^{167}Tm in the electron capture decay of 18 min ^{167}Yb as well as by in-beam spectroscopy/7/ in the reaction $^{165}Ho(\alpha, 2n\gamma)\,^{167}Tm$. In this paper the results of the ^{167}Yb decay will be reported. These results were obtained in a cooperation work of the spectroscopy groups in ZfK Rossendorf and JINR Dubna. The Dubna group has measured the high-energy gamma-ray spectrum and the conversion electron spectrum. The low and high-energy gamma-ray spectra as well as prompt and delayed gamma-gamma coincidences have been investigated in Rossendorf.

2. Experimental Arrangements

The ^{167}Yb activity was produced in two different ways. The Rossendorf group used the bremsstrahlung of the betatron at the Jena University for the reaction ^{168}Yb (23%) (γ, n) ^{167}Yb. Ten to fifteen irradiations, each of 20 min duration, were made for every measurement. Besides of ^{167}Yb, small amounts of the well-known activities $^{166,169}Yb$ were produced by the bremsstrahlung irradiation. In Dubna the ^{167}Yb activity was chemically separated/6/ from the Lu-fraction, the isotopes of which were produced in the 680 MeV proton induced spallation reaction on metallic tantalum in the internal beam of the Dubna synchrocyclotron. From each Lu-fraction the Yb-fraction was separated 5 times in intervals of 25 minutes (milking experiment). In order to obtain enough events, all these five gamma-ray spectra have been added.

Because of the short half-life of ^{167}Yb we measured the conversion electron spectrum in radioactive equilibrium of ^{167}Yb with the mother activity ^{167}Lu ($T_{1/2}$ = 55 min). These measurements were performed with the aid of a magnetic beta spectrograph at a resolution of 0.05%. The sources used in these experiments have been made by electrolytical deposition on a Pt-wire of 0.1 mm diameter/8/. The electrons were recorded on photo plates of type NIKFI-R-50 μ. The intensities of the lines were measured from peak heights of the photometrically determined density (corrected for radius of orbit and film response).

The gamma-ray spectra were measured with germanium detectors of 6.3, 7, and 22 cm^3. Gamma-gamma coincidence measurements were performed using either two germanium detectors of 7 and 22cm3 or one germanium detector and one NaJ scintillation counter. A time-to-amplitude converter in connection with a multi-channel analyzer enabled us to select both the prompt and delayed events, with time windows of 100 and 800 ns, respectively. The energy selection in one branch was performed with the help of an 8 channel spectrum sorter and the prompt and delayed coincidence spectra were simultaneously stored in two memories of 8 x 256 channels each.

All the gamma-ray spectra were analyzed with the computer programme GAMMA/9/.

3. Measurements and Results

The conversion electron spectrum was measured with the aid of a magnetic spectrograph in the energy range of 10 to 150 keV at a resolution of 0.05%. In order to give an idea of this instrument, we show two typical parts of this spectrum in figures 1a and 1b. Most of the short-lived conversion lines observed are given in table 1. Some other lines originating either in ^{167}Lu or ^{167}Yb decay have been found. They are listed in table 2. The transition energies were determined precisely by a direct comparison of conversion electron lines with energies of transitions well established by bent-crystal measurements.

The low-energy part of the ^{167}Yb gamma-ray spectrum measured with a 7 cm^3 germanium detector is shown in fig. 2. The fig.3 shows the high-energy part between 900 and 1700 keV, measured with a very strong activity, an(8 mm Pb + 1 mm Cd + 1 mm Cu) absorber and a 6.3 cm^3 germanium detector . No impurity lines are indicated. In the energy region between 200 and 900 keV we found a few more weak gamma-ray transitions ($I_\gamma \leq 0.2$ in comparison to I_γ (176.23)=100), but the statistic of the experiment was too poor for an unambiguous assignment to the ^{167}Yb decay. In a calibration measurement ^{60}Co , ^{54}Mn and ^{207}Bi added to ^{167}Yb were used to determine the energies of the unknown gamma lines. In order to place the observed transitions in the level scheme we performed gamma-gamma coincidence measurements in the low and high energy range. Besides the prompt coincidences delayed coincidence spectra were measured to investigate the gamma excitation and deexcitation of the isomeric 7/2 states. Parts of the coincidence measurements are given in figures 4a and 4b. A summary of all the observed coincidence pairs is presented in table 3. From our coincidence measurements the branching ratios I_{total}(37.05 keV)/ I_{total}(62.90)=

$= 0.09 + 0.03$, $I_{total}(25.83)/I_{total}(131.99) = 0.23 \pm 0.07$ and $I_\gamma(116.57)/I_\gamma(106.16) = 0.09 \pm 0.02$ were obtained. Table 1 shows the energies and the gamma-ray and conversion electron intensities, normalized to $I_\gamma(176.23\ \text{keV}) = 100$, using the theoretical conversion coefficient[10] α_K(M1 , 106.16 keV)=2.2. Total intensity values are given per 1000 decays.

The decay scheme of ^{167}Yb(EC)^{167}Tm basing on our experimental data is shown in fig.5 . Except the states at 187.59 and 1331.3 keV all the levels are confirmed by coincidences. The 187.59 keV level was introduced from energy fit and because of physical arguments mentioned below. Unfortunately the conversion electron lines of the transitions deexciting the 187.59 keV level are covered by other lines. Therefore it is difficult or in some cases impossible to estimate its intensity values.

4. Discussion

In the low-energy region of the scheme shown in fig.5 we found besides the known members of the $1/2^+[411]$ ground state band and the isomeric 7/2 states some rotational excitations of the configurations $7/2^+[404]$ and $7/2^-[523]$ and the 5/2 and 9/2 members of the Nilsson orbital state $1/2^-[541]$. These results of the ^{167}Yb decay are consistent with Ho(α, 2nγ) reaction data[7]. Both rotational levels of the $1/2^-[541]$ band are excited by K forbidden M1/E2 transitions from the strongly EC excited isomeric level $7/2^-[523]$. Indirect evidence for the 6.9 keV transition is obtained from the prompt and delayed coincidence spectra with the KX-rays. If the level at 285. 86 keV would not be excited via the 6.9 keV higher lying isomeric $7/2^-[523]$ state, but directly in the EC decay, the strength of the delayed coincidence peak KX- 143.5 keV (see fig. 4a) could not be explained and on the other hand the prompt coincidence peak KX – 143.5 keV had to be 4 times larger than observed. The transition probability of the K forbidden transitions 6.9 and 105.20 keV has been determined, using the theoretical conversion coefficients[10] $\alpha_{tot}(6.9\ \text{keV}) = 300$, $\alpha_K(105.20\ \text{keV}) = 2.2$ and the half-life of the $7/2^-[523]$ state of $T_{1/2} = 0.9\ \mu s$[4]. The Weisskopf retardation factors $F_W = \widetilde{T}_{1/2}(\gamma)_{exp}/T_{1/2}(\gamma)_W$ are

F_W (M1 , 6.9 keV) $\approx 6 \cdot 10^4$ 2 fold K forbidden
F_W (M1 , 105.20keV) $\approx 8 \cdot 10^5$ 2 fold K forbidden

in fairly good agreement with other K forbidden transitions in ^{167}Tm

F_W (M1 , 37.05 keV) $\approx 2 \cdot 10^4$ 2 fold K forbidden
F_W (M1 , 62.90 keV) $\approx 4 \cdot 10^4$ 2 fold K forbidden
F_W (E1 , 150.40 keV) $\approx 5 \cdot 10^8$ 2 fold K forbidden
F_W (E1 , 176.23 keV) $\approx 5 \cdot 10^6$ 2 fold K forbidden
F_W (E2 , 169.04 keV) $\approx 10^4$ Once K forbidden

Because of its large decoupling parameter $a \approx 4$ the $1/2^-[541]$ band is really splitted in two sequences 1/2, 5/2, 9/2, 13/2, 17/2, 21/2, 25/2 ... and 3/2, 7/2, 11/2, 15/2, 19/2 ...., In the (α, 2nγ) reaction the authors of the work[7] found the states 9/2, 13/2, 17/2, 21/2 and 25/2. From their energy values we calculated the parameters of the rotational formula

$$E(I,K) = E(0,K) + AI(I+1) + BI^2(I+1)^2 + (-1)^{(I+K)}((I+K)!/(I-K)!) \times$$
$$\times (A_{2K} + B_{2K} I(I+1))$$

and obtained for the $1/2^-[541]$ band in ^{167}Tm :

$A = 9.28$ keV, $A_1 = 32.49$ keV ($a = 3.5$), $B = -7.8$ eV, $B_1 = -185$ eV.

These parameters predict the 5/2 state 97.4 keV below the 9/2 state in good agreement with the experimental value of 98.26 keV. The 1/2 basic level is expected about 10 keV below the 5/2 state, but its excitation is too weak for observation in the decay as well as in the (α, 2nγ) reaction.

Above 1 MeV eight levels excited with $\log ft$ values between 6 and 7 have been found. Except for the level at 1331.3 keV all spin values are probably 5/2 or 7/2. From the 5 highest levels transitions deexcite to the 7/2 Nilsson states as well as to the 3/2, 5/2 and 7/2 members of the $1/2^+[411]$ band are found. The transition to the 5/2 state is in all cases weaker than the transitions to the 3/2 and 7/2 states. These transitions are very probably K forbidden. The Nilsson states $5/2^-[532]$ and $5/2^+[413]$ are expected at energies of about 1 MeV. The 5/2 and 7/2 members of these bands should be excited by ah($\Delta N = 0$) or lu EC transitions ($\log ft \approx 6-7$)[11], respectively. The state at 1216.5 keV cannot be one of these 5/2 states because of the absence of the first rotational state 70 - 80 keV higher. Furthermore the gamma branching ratio of the transitions originating in the 1216.5 keV level agrees with the theoretical value[12] for dipole transitions and the assumption of spin 7/2 for the 1216.5 keV state. Possibly this state is the octupole vibration Q(30) coupled to $7/2^+[404]$. In order to explain the low $\log ft$ value, an admixture of about 10% 7/2 [523] single particle configuration should be assumed.

We tentatively assigned the 5/2 Nilsson states mentioned above and their first rotational states to the highest levels as shown in fig.5 and table 4 although there is a discrepancy, namely the 1587.3keV transition must have the multipolarity M2. Arguments for this interpretation are the $\log ft$ values of the EC transitions, the spin values of 5/2 or 7/2 and the estimated rotational parameter $A_1(5/2^-[532])$= 10.0 keV and $A(5/2^+[413])$ = 10.5 keV. The states at 1331.3 and 1432.3 keV might be described as gamma and beta vibrational states basing on the $1/2^+[411]$ and the $7/2^-[523]$ state, respectively. This interpretation is suggested by its excitation and deexcitation mode.

A comparison of our proposed assignments with the theoretical predictions of Soloviev et al.[13] is given in table 4. Unfortunately the theoretical values are not given for the nucleus ^{167}Tm but only for ^{169}Tm. However the difference in energy values as well as in the calculated structure should be small.

Because of many unsolved problems we shall carry out further experiments. The conversion electron spectrum at higher energies will be measured to establish at least spin and parity of the states at 1216.5, 1432.3 and 1527.5 keV. The energy range 200- 900 keV will be investigated more accurately to find the states with $3/2^+$ or $5/2^+$, which can be excited by 1h transitions [11] ($\log ft \approx 8$). Levels with $K^\pi = 3/2^+$ are known in other Tm-isotopes near 600 keV[14].

It is a pleasure to thank Professor J. Schintlmeister for his support and for many helpful suggestions. We acknowledge the valuable assistance of the betatron staff of the Jena University. Our thanks are due to the radiochemical group of the JINR Dubna, especially N.A.Lebedev, for the separation of the Lu-fraction from the Tantalum target.

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Received by Publishing Department
on November 10, 1969.

Table 1: Energies and intensities of the transitions in ^{167}Tm

E_γ, keV	I_γ,rel.	I_K	I_{L_I}	$I_{L_{II}}$	$I_{L_{III}}$	I_{M_I}	$I_{M_{II}}$	$I_{M_{III}}$	I_N	exp. α_K	theory[10] α_K	theory[10] α_{tot}	$\frac{I_{tot}}{1000}$ decay	multi-pola-rity
(6.9) c)													(27)	
(10.4) c)													(920)	
25.83±0.02		-	~1	~1	~2.5								9	
37.05±0.02		-	15.7	19.7	23		4.5	4.7	2			11	70	M1+8.4%E2
62.90±0.02	16±5		50	5	2.7	10.3	2.2	0.2	2.7			12	580	M1+1.5%E2
90.83±0.06		~1												
95.22±0.06		~0.2												
98.26±0.03	≦ 0.5	<7		~0.15	(~0.11)			<0.1			1.1	3.5	1.5	(E2)
105.20±0.03	≦ 5	7.6	0.74			0.09					2.2	2.7	25	M1
106.16±0.02	102±10	224	37	3.9	1.4	6.1	0.8	0.31	0.31	2.2 a)	2.2 a)	2.7	850	M1+1.1%E2
113.32±0.02	250±15	64	8.1	1.1	1.2	1.5	0.18	0.2	0.47	0.25	0.2	0.24	690	E1
116.57±0.02	9 } 9±2	9	0.8	4	4	0.13	0.7	0.7	0.29	1	0.75	1.8	58 }	E2+<10%M1
116.6 ±0.1	(~0.2) }												~1.5 }	
131.99±0.02	14±1	6	0.6	1.9	1.8	w	0.3	0.31		0.43	0.52	1.2	67	E2
143.46±0.02	10±1	0.72								0.07	0.11	0.13	25	E1
150.40±0.03	0.2±0.1	0.02								0.1	0.09	0.11	0.5	(E1)
169.04±0.03	0.6±0.2	0.23								0.38	0.27	0.5	2	(E2)
176.23±0.03	100 a)	3.3								0.033	0.065	0.075	240	E1
177.20±0.03		0.4											~30	

Table 1 (continued)

E_γ, keV		I_γ, rel $[\times 10^{-2}]$	I_{tot}/1000 decay
920.45 ± 0.10		61 ± 5	1.35
935.5 ± 0.7	b)	6.9 ± 1.2	0.15
1024.0 ± 0.5		8.6 ± 1.5	0.19
1037.07 ± 0.10		320 ± 20	7.1
1049.9 ± 0.5	b)	22.3 ± 4	0.5
1068.8 ± 0.4	b)	7.1 ± 1.0	0.16
1110.4 ± 0.4		5.1 ± 0.8	0.11
1139.5 ± 0.2		24.5 ± 1.5	0.54
1143.4 ± 1.5	b)	1.9 ± 1.0	0.04
1198.9 ± 1.2		1.2 ± 0.7	0.03
1215.2 ± 0.5		5.9 ± 0.8	0.13
1234.65 ± 0.15		89 ± 4	2.0
1242.0 ± 0.4		8.8 ± 1.2	0.2
1288.1 ± 0.2		19.4 ± 1.5	0.43
1305.0 ± 0.2		16.4 ± 1.0	0.36
1320.7 ± 0.2		6.1 ± 0.8	0.14
1332.3 ± 0.8		3.7 ± 1.2	0.08
1337.5 ± 1.5		3.1 ± 1.5	0.07
1342.1 ± 1.5		3.3 ± 1.5	0.07
1346.3 ± 1.5		2.5 ± 1.2	0.06
1361.7 ± 0.2		9.3 ± 1.2	0.21
1369.7 ± 0.4		5.5 ± 0.8	0.12
1385.3 ± 0.3	b)	5.4 ± 0.7	0.12
1393.4 ± 0.4		4.3 ± 0.7	0.1
1401.9 ± 0.8		2.4 ± 0.7	0.05
1411.1 ± 0.8	b)	1.7 ± 0.8	0.04
1428.3 ± 0.8	b)	1.6 ± 0.9	0.04
1433.9 ± 1.0		1.8 ± 0.8	0.04
1438.5 ± 0.2		11.9 ± 1.0	0.26
1455.2 ± 0.2		12.4 ± 1.2	0.27
1464.6 ± 0.7		2.8 ± 0.8	0.06
1480.9 ± 0.7		2.0 ± 0.8	0.04
1487.0 ± 0.3	b)	6.0 ± 0.8	0.13
1498.5 ± 0.6		1.7 ± 0.7	0.04
1511.5 ± 0.4		7.7 ± 1.0	0.17
1516.7 ± 0.8		4.8 ± 1.0	0.11
1537.9 ± 1.0	b)	0.7 ± 0.4	0.02
1548.4 ± 1.0		0.7 ± 0.4	0.02
1570.4 ± 0.2		15.1 ± 1.0	0.33
1587.3 ± 0.2		14.8 ± 1.0	0.33
1619.4 ± 0.2	b)	6.8 ± 0.6	0.15
1632.2 ± 0.8		1.6 ± 0.5	0.04
1643.9 ± 0.2		7.7 ± 0.7	0.17

a) Normalization value

b) Not shown in the decay scheme

c) Indirectly observed transitions.

Table 2. Energies and Intensities of conversion electron lines, which have a half-Life of $T_{1/2} \leq$ 1h and belong either to the decay of ^{167}Lu or ^{167}Yb.

E_e, keV	I_e, rel. a)	E_e, keV	I_e, rel. a)
28.II	3.8	I06.I0	0.2
28.78	I.7	II7.5I	I.I
29.62	I.8	II8.44	0.2
32.72	I.I	II9.02	0.2
35.84	I.I	I49.02	
38.97	7.8	I60.67	
39.50	11	I70.7I	
39.93	3.4	I73.82	
40.76	7.8	I77.49	
40.93	15	I94.77	
4I.90	6	2I2.79	
58.98	0.4	2I7.45	
59.83	0.7	237.26	
62.86	0.4	300.9I	
70.87	0.3	33I.27	
72.53	2.2	448.77	
83.07	0.7		
83.64	0.5		
9I.58	0.6		

a) I_e is given in the same units as in table 1.

Table 3: Prompt and delayed gamma-gamma coincidences observed in the ^{167}Yb decay

I) Prompt coincidences

$E_{\gamma 1}$, keV	$E_{\gamma 2}$, keV
80 – 100 (90.8 keV)	(935), (1024), 1050.
100 – 130 (106.2, 132 keV)	920.5, (1393), 1438, 1455, 1487, 1511. a)
130 – 160 (143.5 keV)	no clear coincidences above 132 keV.
116.6	920.5
143.5	106.2, 116.6, 132.
176.2	106.2, 116.6.

II) Delayed coincidences

$E_{\gamma 1}$, keV (deexcitation)	$E_{\gamma 2}$, keV (excitation)
~100 (106.2, 113.3, 132, 143.5)	920.5, (935), (1024), 1037, (1050), 1139, 1235, 1288, 1305, 1362. a)
106.2, 132	1037.
~180 (176.2)	1235, (no 1037)
62.9, 106.2, 113.3, 116.6, 132, 143.5, 176.2.	Kx-ray
62.9, 106.2, 116.6, 132.	113.3

a) No coincidences with the relatively strong lines at 1570.4, 1587.3, 1619.4 and 1643.9 keV.

Table 4: Comparison of the proposed ^{167}Tm levels with the prediction of the microscopic theory

K^{π}	experiment	theory a)		
	E, keV	E, keV	structure (main component)	
$1/2^+$	0	0	$1/2^+$ [411]	96 %
$7/2^+$	179.5	270	$7/2^+$ [404]	92 %
$7/2^-$	292.8	360	$7/2^-$ [523]	98 %
$3/2^+$		580	$3/2^+$ [411]	83 %
$9/2^-$	-	650	$9/2^-$ [514]	98 %
$5/2^+$		850	$5/2^+$ [402]	87 %
$5/2^+$		900	$1/2^+$ [411] + Q(22)	60 %
$3/2^+$		950	$7/2^+$ [404] + Q(22)	64 %
$1/2^-$	~175	1000	$1/2^-$ [541]	80 %
$3/2^-$		1050	$7/2^-$ [523] + Q_{22}	100 %
$3/2^+$	1331.3	1100	$1/2^+$ [411] + Q_{22}	85 %
$7/2^+$	(1629.7)	1200	$3/2^+$ [411] + Q_{22}	90 %
$5/2^+$	1580.9	1250	$5/2^+$ [413]	62 %
$5/2^-$	1527.5	1300	$5/2^-$ [532]	87 %
$7/2^-$	1432.3		$7/2^-$ [523] + Q(20) b)	

a) These values are given for ^{169}Tm (ref. 13)

b) The core excitation 0^+ in ^{166}Er is situated at 1460 keV [14]. Not given in ref. 13.

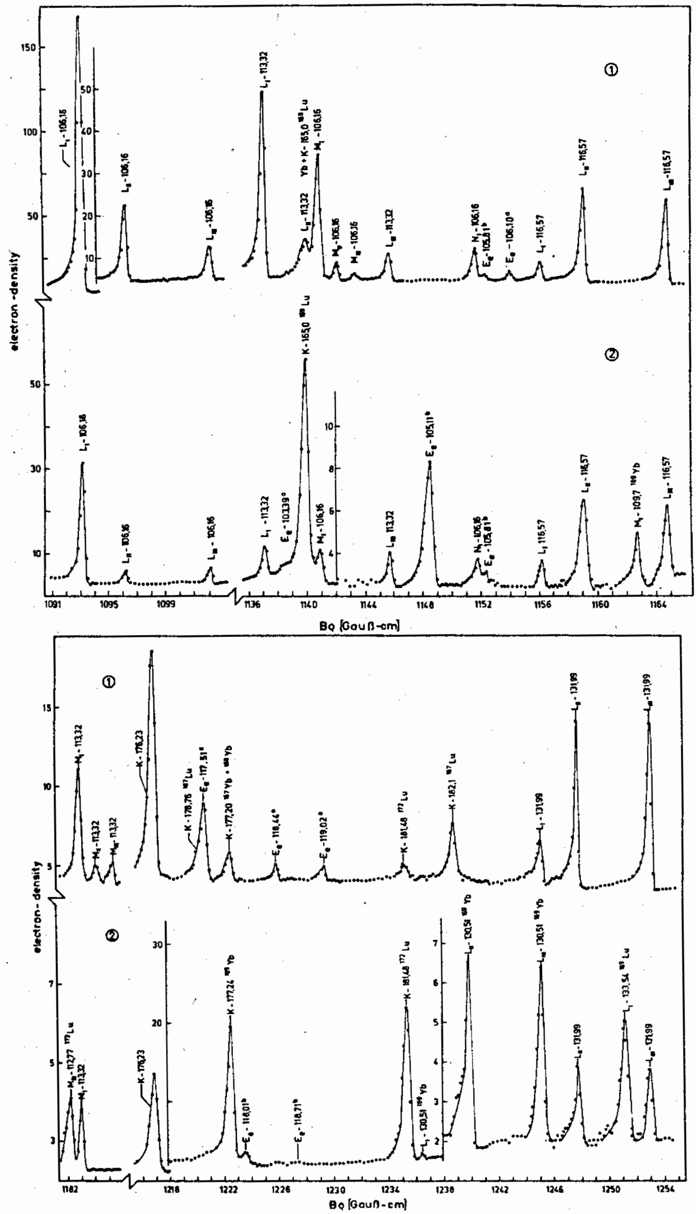

Fig. 1a, 1b. Parts of the conversion electron spectrum measured with a magnetic spectrograph. Spectrum "1" shows the short-lived components, spectrum "2" the longer-lived ones (measuring time: spectrum "1" - 3h, spectrum "2" - 25h). Lines without denotation of the isotope are belonging to ^{167}Yb decay. Denotation a) and b) means short-lived or long non-identified lines, respectively.

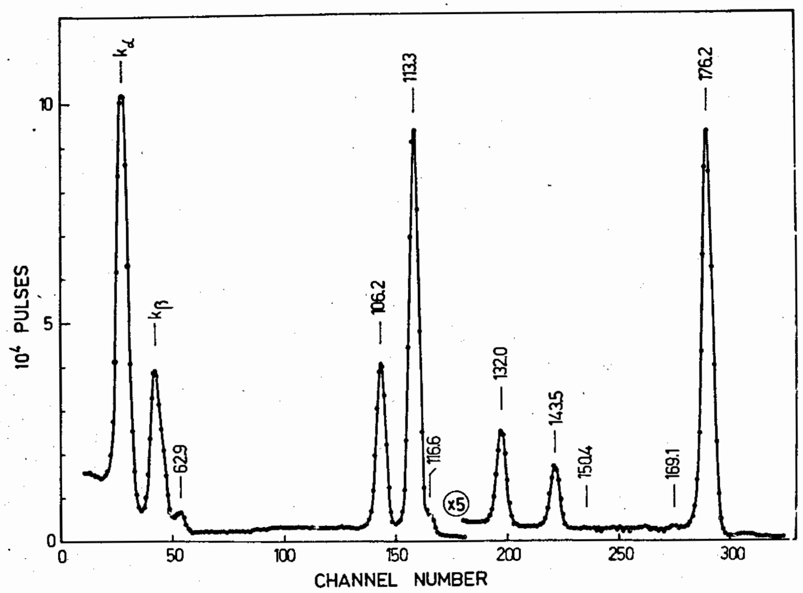

Fig. 2. Gamma-ray spectrum of ^{167}Yb (low energy part) measured with a 7 cm^3 germanium detector. Energies are given in keV.

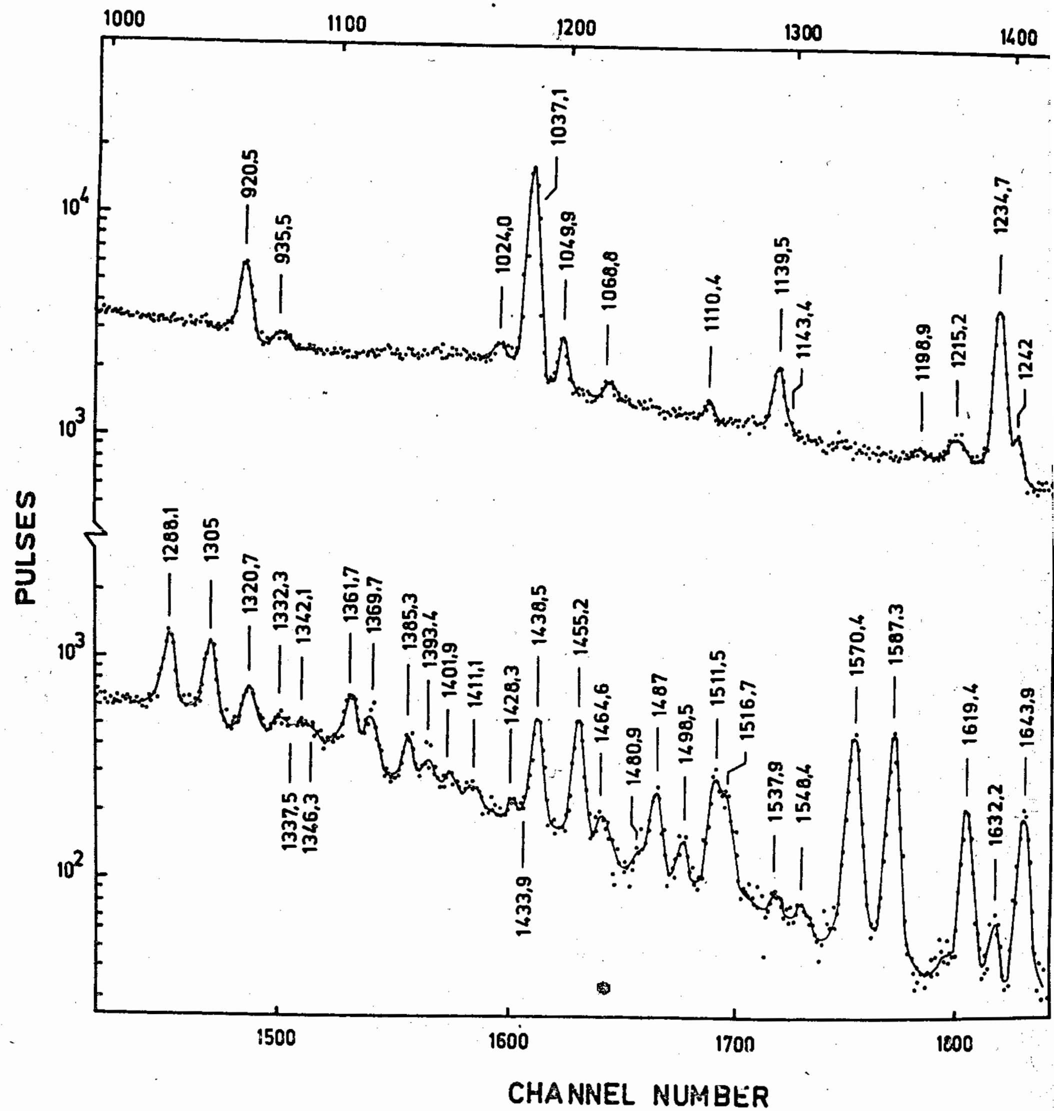

Fig. 3. Gamma-ray spectrum of ^{167}Yb (high energy part), measured with a 6.3 cm^3 detector. (Absorber: 8 mm Pb , 1 mm Cd , 1 mm Cu).

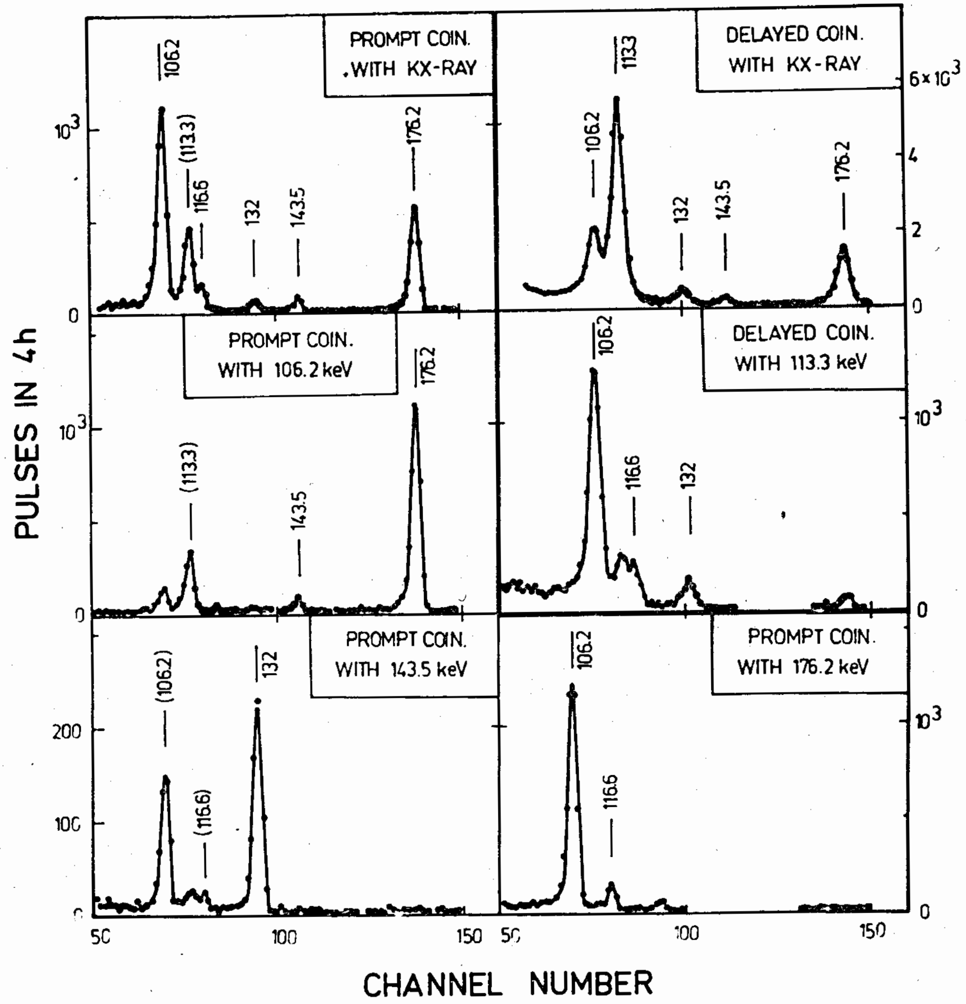

Fig.4. a) Selected parts of the prompt and delayed gamma-gamma coincidence measurements.

Low energy part taken with two germanium detectors of 7 and 22 cm^3. The figures are denoted by prompt or delayed. Not marked lines are from Compton background coincidences, chance coincidences or from ^{169}Yb decay.

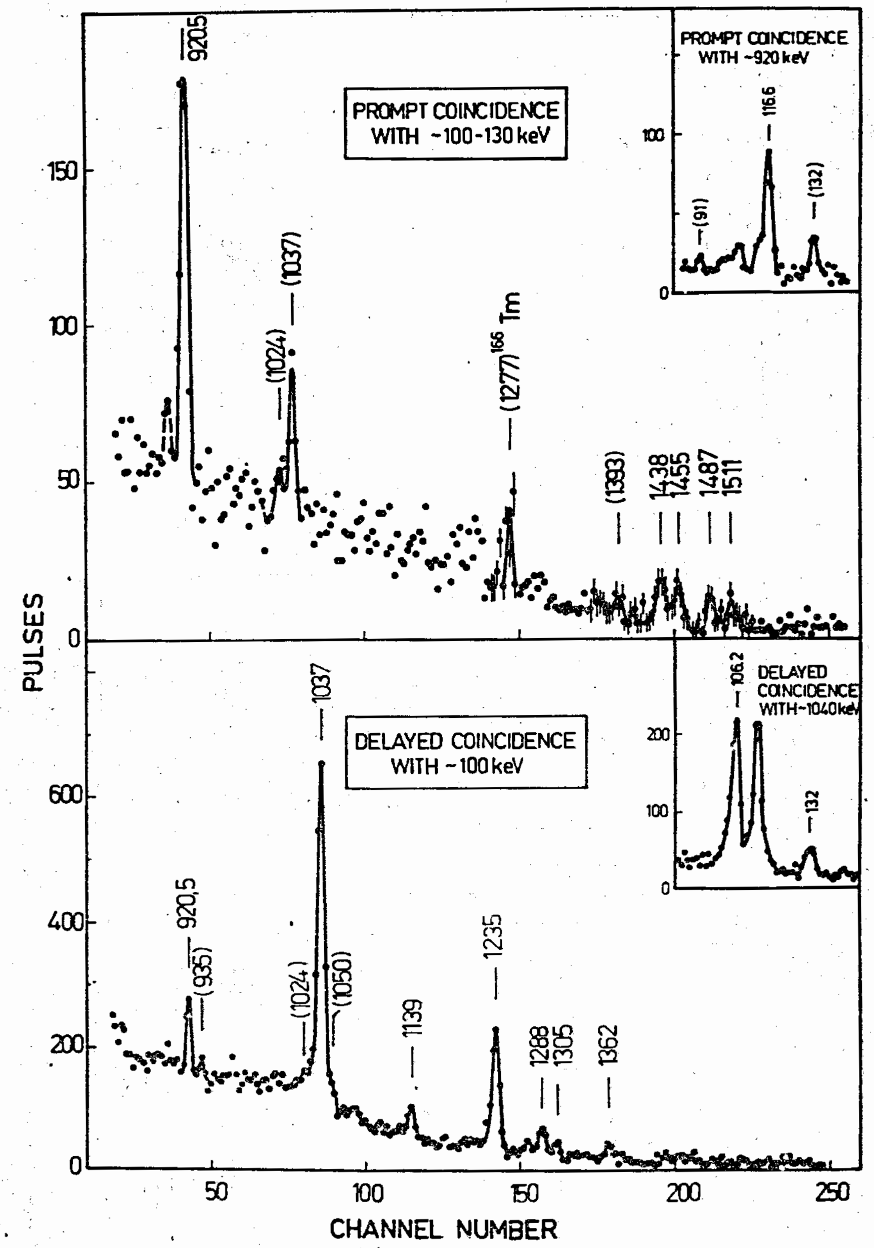

Fig.4 b) Selected parts of the prompt and delayed gamma-gamma coincidence measurements.

High energy part of the gamma-gamma coincidence spectra taken with a germanium detector of 22 cm^3 and a scintillation counter.

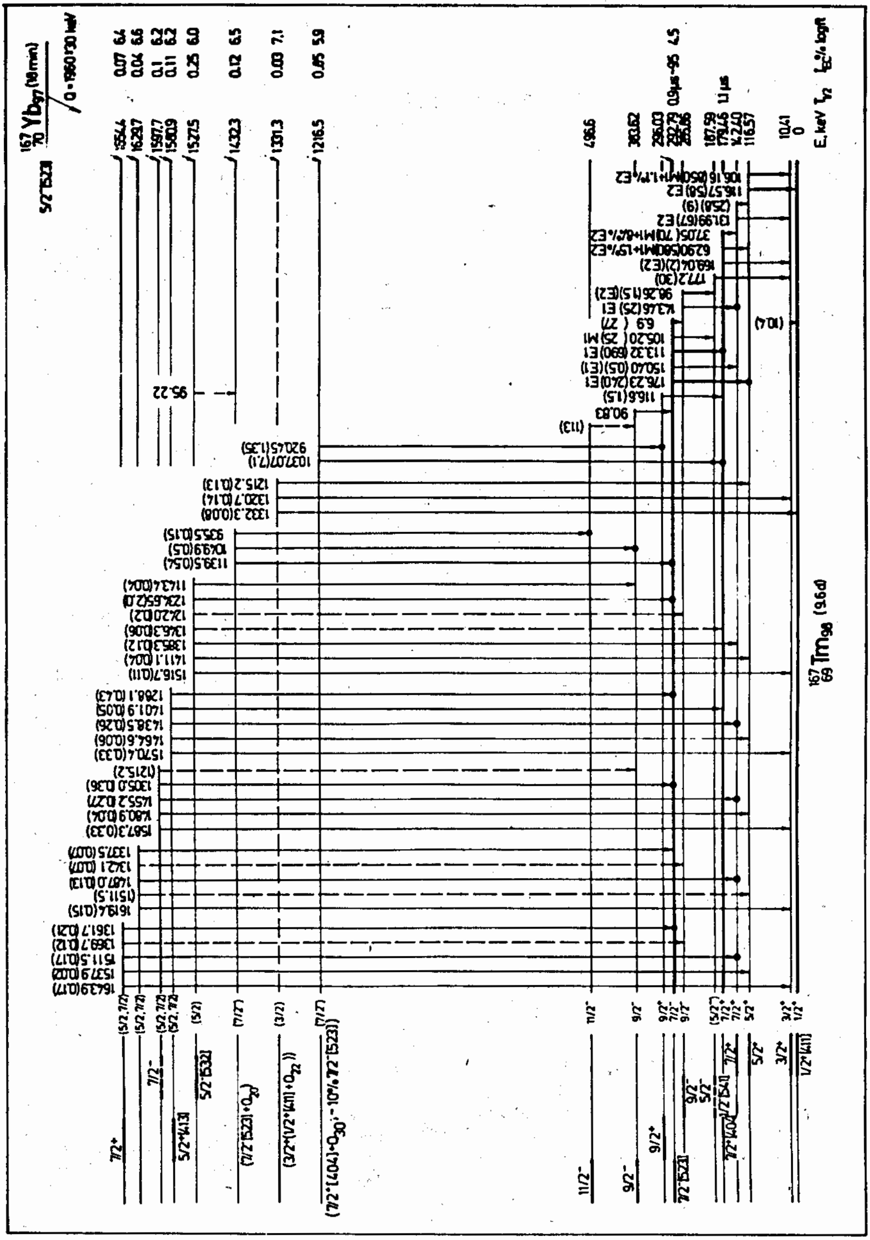

Fig.5. Proposed decay scheme of ^{167}Yb .
Energies are given in keV, total intensities per 1000 decays.
Coincidences are marked by points.