On the Decay of ^{165}Dy

E. Bashandy *, N. Ibrahiem and G. El-Sayad

Nuclear Physics Department, Atomic Energy Establishment, Cairo, U.A.R.

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The internal conversion electron spectrum of transitions in the decay of (139 min) ^{165}Dy to ^{165}Ho has been studied using a high resolution iron-free double focusing β-ray spectrometer. In addition to γ rays previously reported eight new γ rays, mostly in the low energy region, have been observed. A decay scheme involving 17 excited levels is proposed for ^{165}Ho. Multipolarity data, obtained from the measurements of absolute or ratios of conversion coefficients of γ rays, were utilized for assigning possible spins and parities to the levels of ^{165}Ho. The experimental level structure is discussed in the light of nuclear models.

The level structure of ^{165}Ho has been studied experimentally [1–9] through the β decay of the ground state of ^{165}Dy and the electron capture decay of ^{165}Er. A large number of γ-ray transitions following the decay of ^{165}Dy was observed, whereas the electron capture decay of ^{165}Er led directly to the ground state of ^{165}Ho. Coulomb excitation experiments, by Nathan and Popov [10], revealed γ transitions of energies 150 ± 10, 510 ± 15 and 690 ± 15 keV. Diamond et al. [11] performed Coulomb excitation on ^{165}Ho by heavy ions. They found transitions of energies 520 ± 15, 575 ± 15 and 705 ± 15 keV. According to their level scheme studies, states of collective character were preferentially excited. Thus, besides rotational levels up to $17/2-$ based on the ground state, other levels interpreted as being of γ-vibrational character were observed.

The isotopes ^{165}Dy and ^{165}Ho belong to a mass region of nuclei having an ellipsoidal equilibrium shape. The unified nuclear model developed by Bohr and Mottelson is valid for ^{165}Ho, and a simple type of excitation is then possible [12]. The nucleus rotates in space without changing its shape or its intrinsic configuration. The structure of the observed rotational bands implies that the equilibrium shape of the nucleus is mainly axially symmetrical. The lowest collective excitations of strongly deformed nuclei correspond to rotations with the shape preserved. It is also expected that these nuclei exhibit collective excitations corresponding to vibrations about the equilibrium shape [13]. In odd A-nuclei the competitions between vibrational and single-particle states and the increase Coriolis mixing between single-particle states decrease the probability that they could be distinguished.

In view of the uncertainties found in the available data and the lack of detailed information, it was decided to extend the study of γ transitions in ^{165}Ho especially in the low energy data region using a high resolution β-ray spectrometer. With better knowledge of the excited states, intrinsic and rotational in ^{165}Ho, the experimental results are to be recompared with the predictions of the nuclear models applicable to this nucleus.

1. Experimental Procedures

The conversion electron spectra of γ rays following the decay of ^{165}Dy were studied by means of a 50 cm radius, iron-free double focusing β-ray spectrometer [14]. An end window G. M. counter was used as detector. The counter window was ~ 2 mg/cm^2 thick mica.

* Present address: Department of Physics, Faculty of Engineering, P.O. Box 1098, Tripoli, Libya.

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Dysprosium activities were produced by thermal neutron bombardment of natural dysprosium oxide with a purity of 99.9%, over a period of 5 hours in the U.A.R. reactor at Inchass. Due to the short half-life (139 min) in all about 20 irradiations were performed in a flux of $\sim 10^{13}$ neutrons/cm$^2\cdot$sec.

For the internal conversion studies dysprosium oxide was uniformely sputtered on aluminium foil of thickness ~ 1 mg/cm^2. The sputtered material was distributed in a rectangular form of dimensions 0.2×2 cm^2. The thickness of the material deposited was estimated to be $\sim 100\ \mu$g/cm^2. Due to the large cross-section for the formation of ^{165}Dy from the stable nucleus ^{164}Dy (28% natural abundance) activities other than ^{165}Dy can safely by neglected [7]. The 1.25 min isomeric level at 108 keV in ^{165}Dy was allowed to decay for about one hour before the start of the measurements.

1.1. The Internal Conversion Spectrum

The conversion electron spectrum following the decay of ^{165}Dy was investigated in the iron-free double focusing β-ray spectrometer. The study of ^{165}Dy decay was initiated by scanning the conversion electron spectrum in the energy range 0.040 to 1.2 MeV. The measurements were followed up in a repetitive way to scan: 1) the various line groups observed on the survey, 2) line groups previously reported and 3) line groups predicted by our proposed decay scheme. In some of these latter studies improved counting statistics were obtained. Each source was counted for more than three half-lives, which was as long as the majority of the sources were counted.

To provide a reference line for the energy measurements on ^{165}Dy decay, the conversion lines of the 84 keV transition in ^{170}Yb, the 412 keV transition in ^{198}Hg and the 661 keV transition in ^{137}Ba were carefully measured. The momentum resolution was varying between 0.15 and 0.4%, depending on the accuracy required and in order to decrease the continuous β-ray spectrum as much as possible, in some energy region, without spoiling the statistics. The observed conversion lines were analyzed and several γ transitions are ascribed to the decay of ^{165}Dy, see Table 1. Eight new γ transitions have been observed mostly in the low energy region, see Figs. 1 and 2. This is not surprising, since such high precision, good resolution conversion electron measurements together with high specific activities used were not

Present work: Transition energy (keV)	Present work: State assignment	PERSSON et al. [7]	CRANSTON et al. [5]	KANE et al. [1]	BONHOEFFER et al. [3]	JORDAN et al. [2]
—	1080 → 1037			43.64		
64.3 ± 0.1	566 → 502					
74.8 ± 0.1	420 → 345			75.95		
94.5 ± 0.1	95 → 0	94.68 ± 0.05	94.7	95	95 ± 0.5	94.4 ± 0.2
105.75 ± 0.12	672 → 566					
126.13 ± 0.13	641 → 515					
135.25 ± 0.14	345 → 210					
151.55 ± 0.15	497 → 345					
153.74 ± 0.15	515 → 361					
279.2 ± 0.3	996 → 717	279.6 ± 0.2	279.4	278 ± 4	275 ± 3	279.4 ± 0.8
360.5 ± 0.4	361 → 0	361.5 ± 0.3	361.0	358 ± 4	356 ± 3	361.2 ± 1.0
383.6 ± 0.4	1056 → 672					
450.3 ± 0.5	811 → 361			450		
—	996 → 515	478.7 ± 1.5	480			
497.2 ± 0.6	497 → 0					
502.1 ± 0.9	502 → 0	500.8 ± 1.7				
514.8 ± 0.9	515 → 0	514.2 ± 1.7	515			
—	641 → 95	545.5 ± 1.7	545			
—	566 → 0	565.7 ± 1.7	564	553 ± 5	555 ± 5	
575.7 ± 1.0	996 → 420	575.1 ± 1.8				
582.7 ± 1.5	1080 → 497	587.6 ± 2.0				
621.5 ± 1.5	717 → 95	621.0 ± 2.0	620			
635.3 ± 1.7	996 → 361	633.5 ± 2.1	634	630 ± 5	630 ± 3	634 ± 3
694.9 ± 1.9	1056 → 361	695.0 ± 3.2				
716.8 ± 1.9	717 → 0	715.7 ± 2.4	715	710 ± 4	708 ± 4	710 ± 20
995.5 ± 1.2	996 → 0	995.1 ± 1.2	995	1000 ± 6	985 ± 10	
1037.2 ± 2.0	1037 → 0					1020 ± 30
1055.6 ± 2.0	1056 → 0	1055.6 ± 2.8		1068 ± 4		
1079.6 ± 2.2	1080 → 0	1080.1 ± 3.0	1080			

Table 1. Experimental γ-ray energies (in keV) in the decay of Dy^{165} compared with some earlier results.

Transition energy (keV)	Conversion line	Theoretical values E 1	E 2	E 3	E 4	M 1	M 2	M 3	M 4	Experimental values	Multi-polarity
64.3 ± 0.1	$L_I + L_{II}/L_{III}$	3.13	0.94	0.99	1.04	7.83	3.74	0.72	4.19	2.9 ± 0.5	E 1
74.8 ± 0.1	$L_I + L_{II}/L_{III}$	3.50	0.99	1.04	1.09	7.96	4.19	0.79	3.37	3.38 ± 0.6	M 4
94.5 ± 0.1	K/L	6.21	0.69	0.08	0.01	6.62	3.40	0.92	0.22	6.2 ± 0.8	M 1 + E 2
	$L_I + L_{II}/L_{III}$	1.24	1.89	1.87	1.83	10.12	1.19	1.95	3.15	9.5 ± 1.0	
1037.2 ± 2.0	K/L	7.53	6.14	4.93	0.42	6.58	6.19	5.59	4.95	7.5 ± 1.2	E 1

Table 2. Internal conversion coefficient ratios of the 64, 75, 95 and 1037 keV transitions in Ho^{165}.

undertaken before. The intensities of the internal conversion lines were determined from the measured areas under the peaks, taken into consideration the corrections for the absorption in the mica counter window as well as the corrections for the decay. The electron lines intensities were deduced from measurements relative to the K-conversion lines of the 94.5 and 360.5 keV transitions.

1.2. Internal Conversion Coefficients and Transition Multipolarities

Accurate conversion intensities, K/L and L-subshell ratios of most transitions are determined. In order to determine the multipole orders of the transitions, the values of conversion coefficients were compared with theoretical ones interpolated from the tables calculated by SLIV and BAND [15]. The multipole orders of the low transitions have mainly been deduced from conversion electron intensity ratios of different shells or subshells, see Table 2. The sensitivity of the conversion ratios to multipolarity, however, decreases with increasing energy. Therefore, multipolarities of the γ rays above 300 keV, for which the relative γ intensities have been measured [7], were determined from the comparison of absolute conversion coefficients with the theoretical ones, see Table 3. The conversion electron and the photoelectron measurements result in a relative determination of the conversion coefficients. One can normalize these values to an absolute scale by measuring one of the conversion coefficients absolutely. This was done by comparison with the known conversion coefficient of a transition in the same source. In this investigation we have assumed that the 361 keV γ ray is pure M2 as was proved previously [7].

2. Results and Discussion

The internal conversion spectrum of the transitions in ^{165}Ho was measured several times. According to the conversion data 25 γ transitions were found. The transition energies obtained are in good

Transition energy (keV)	Theoretical values E 1	E 2	E 3	E 4	M 1	M 2	M 3	M 4	Experimental values	Multi-polarity
502.1 ± 0.9	0.0046	0.0127	0.0324	0.0808	0.0273	0.0840	0.2180	0.5545	0.0044 ± 0.0009	E 1
514.8 ± 0.9	0.0043	0.0118	0.0300	0.0743	0.0255	0.0777	0.1991	0.4988	0.013 ± 0.002	E 2
575.7 ± 1.0	0.0034	0.0091	0.0224	0.0532	0.0192	0.0564	0.1379	0.3288	0.018 ± 0.003	M 1
621.5 ± 1.5	0.0029	0.0076	0.0183	0.0424	0.0151	0.0452	0.1072	0.2470	0.027 ± 0.005	E 1
635.3 ± 1.7	0.0028	0.0073	0.0174	0.0400	0.0151	0.0427	0.1004	0.2994	0.017 ± 0.003	M 1
694.9 ± 1.9	0.0023	0.0059	0.0137	0.0304	0.0120	0.0327	0.0741	0.1626	0.014 ± 0.003	E 3
716.8 ± 1.9	0.0021	0.0055	0.0120	0.0278	0.0111	0.0301	0.0673	0.1458	0.0023 ± 0.0004	E 1
995.5 ± 1.2	0.0013	0.0032	0.0056	0.0138	0.0050	0.0120	0.0250	0.0500	0.0015 ± 0.0003	E 1
1055.6 ± 2.0	0.0010	0.0024	0.0050	0.0097	0.0043	0.0107	0.0205	0.0382	0.004 ± 0.0009	M 1
1079.6 ± 2.3	0.0010	0.0023	0.0048	0.0092	0.0041	0.0099	0.0193	0.0355	0.0038 ± 0.0009	M 1

Table 3. K-conversion coefficients and multipolarities for some transitions in ^{165}Ho.

[15] L. A. SLIV and I. M. BAND, Tables of Internal Conversion Coefficients, Alpha-Beta and Gamma-Ray Spectroscopy, Appendix 5, ed. K. SIEGBAHN, North Holland Publishing Co., Amsterdam 1965.

agreement with the previous results [1–3, 5, 7], see Table 1. In addition eight new transitions of energies 64.3, 105.75, 126.13, 135.25, 153.74, 383.6, 497.2 and 1037.2 keV have been observed, see Figs. 1, 2, and 3. The 151.5 keV transition was previously proposed by NATHAN and POPOV [10]. Other transitions, such as the 43.64, 478.7, 454.5 and 565.7 keV could not be observed in our measurements.

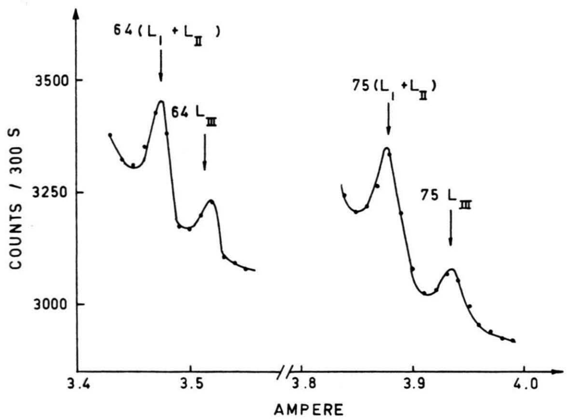

Fig. 1. The L-conversion lines of the 64 and 75 keV transitions in ^{165}Ho.

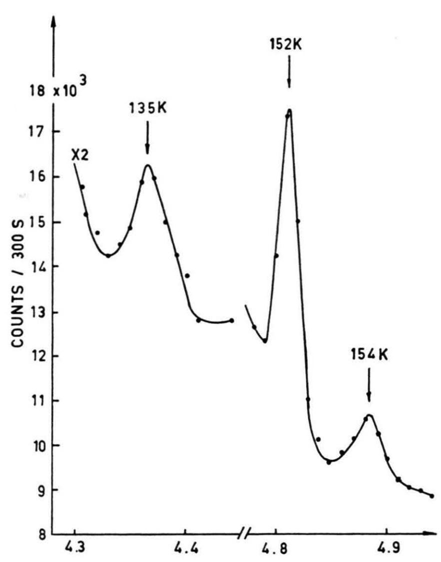

Fig. 2. The internal K-conversion electron lines of the 135, 152, and 154 keV transitions.

The proposed ^{165}Ho level scheme populated by the decay of ^{165}Dy is shown in Fig. 4. This scheme involves 17 excited states. The level energies are based on the energy sums of the γ-ray cascades and

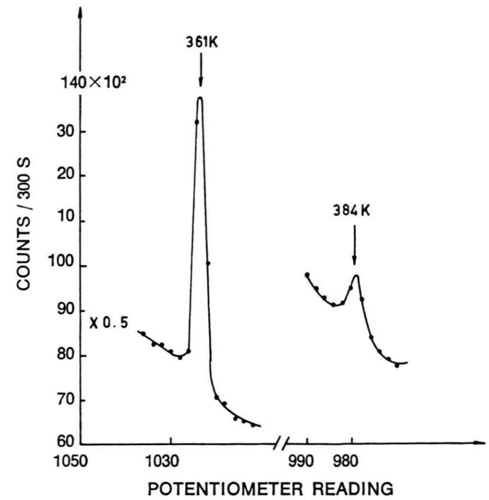

Fig. 3. The internal K-conversion electron lines of the 361 and 384 keV transitions.

coincidence measurements [6, 8]. Spin and parity informations were derived from the multipolarities of γ transitions, Coulomb excitation results [10] and the log ft values [7].

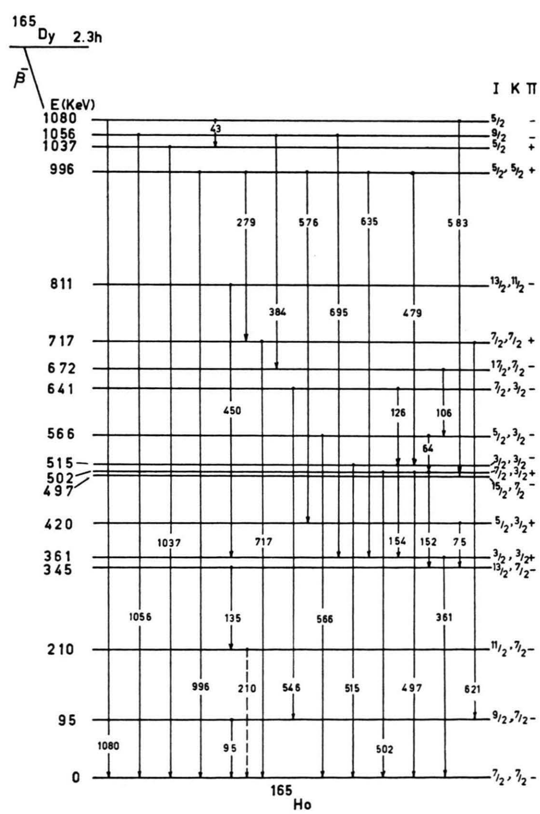

Fig. 4. Level scheme of ^{165}Ho populated in the decay of ^{165}Dy.

The K-conversion coefficient of the 635 keV transition was found to be consistent with M1 multiple character with apparent high value. The value obtained $\alpha_K = 0.017 \pm 0.003$ agrees with the result $\alpha_K = 0.018 \pm 0.006$ of PERSSON et al. [7]. However, both results show a high value compared with the theoretical one, see Table 3. This could be explained by probable E0 admixture, also admixture from E2 cannot be excluded.

The spin of the ^{165}Dy ground state was measured by CABEZAS et al. [16] to be 7/2 in agreement with the 7/2+ asignment suggested by MOTTELSON and NILSSON [12]. The ground state spin of ^{165}Ho was measured [17] to be 7/2. Coulomb excitation experiments performed by CHUPP et al. [18], revealed two rotational states in the ground state band with energies 94.7 keV (9/2−) and 204.63 keV (11/2−).

The log ft value of the strong β ray connecting the two ground states indicating [7] an unhindered first forbidden transition the parities of the states should be opposite. From NILSSON diagram [12] for odd-Z nuclei it is predicted that the 7/2− [523] level should be the lowest configuration for $Z = 67$. In this work we have confirmed the existence of five members of the rotational band, superimposed on the $K = 7/2$, $I = 7/2$ ground state, with spins 9/2−, 11/2−, 13/2−, 15/2− and 17/2− at energies 95, 210, 345, 497 and 672 keV respectively. It was difficult to observe the γ ray of energy 210 keV de-exciting the 210 keV, 11/2− level, but the appearance of the 135 keV transition feeding it confirmed its existence and approved the Coulomb excitation suggestion [18]. The 345 keV, 13/2− level is well defined from the feeding and de-exciting transitions. PERSSON et al. [7] have observed a weak γ ray of energy 587 keV, but it was not placed in their suggested decay scheme. The present energy determination revealed a γ ray of energy 582.7 keV instead. This γ transition is found to fit perfectly between the 1080 and the 497 keV levels. Therefore the 497 keV, 15/2− level was excited by the 582.7 keV transition and de-excited by both the 151.5 and 497.2 keV transitions. The 672 keV, 17/2− level was previously observed by Coulomb excitation measurements [11] and in the present investigation it is found to be fed and de-excited by the new γ transitions, 383.6 and 105.75 keV respectively. The experimental data are in fair agreement with the simple rotational formula. Due to the high total intensiy, the 361 keV transition should lead directly to the ground state. The measured internal K-conversion coefficient and the K/L ratio indicate [7] unambiguously M2 multipolarity for the transition. The 361 keV level should therefore possess a spin difference of 2 and opposite parity relative to the ground state 7/2−. As no γ ray was seen leading from the 361 keV state to the 95 keV state, the 3/2+ assignment for the 361 keV level only remains. It is reasonable to assume that this state represents a hole in the 3/2+ [411] orbit. The M2 transition is hindered [7] by a factor of about one hundred compared with the theoretical single-proton transition probability. This slowness of the transition may be explained [7] by the experimentally verified fact that the probabilities for γ transitions between different single particle states are usually smaller for deformed nuclei than for other nuclei. Until this investigation the feeding of the 361 keV level was a complicated question, since it was found [7] that the total intensity of the 361 keV transition is 1280 ± 130, whereas the total intensity of the 635 keV line is 650 ± 60. The direct β decay from the ground state of ^{165}Dy should be classified as second forbidden with a log ft value of ~ 13, excluding the possibility of an appreciable feeding in this way. PERSSON et al. [7] gave a possible explanation that a β branch might exist, feeding going via an undetected low energy transition from a member of the rotational band superimposed on the 361 keV intrinsic level. However, this explanation is very tentative and it is also possible that at least part of the feeding goes via one or several of the γ rays which were not uniquely fixed in the decay scheme. This doubt was ruled out after the present investigation where three γ rays of energies 694.9, 450.3 and 153.74 keV rather than the 635.3 keV transitions were found feeding the 361 keV level. The two levels at 420 and 502 keV assigned as 5/2, 3/2+ and 7/2, 7/2+ [411] rotational states have also been confirmed by one investigation. The 515 keV level is depopulated by a new 153.74 keV transition to the 3/2+, 361 keV level and by a transition to the ground state. It is fed by the 479 and 126.13 keV transitions de-exciting the 996 and 641

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keV levels, respectively. It was found that 3/2 – is the most convenient assignment for the 515 keV level. This is in agreement with the data reported by CRANSTON et al.[5] concerning the direct, allowed β decay, of the 1/2 –, 108.2 keV isomeric level in ^{165}Dy to a level at 516 keV in ^{165}Ho. No single-particle level is accessible with $K = 3/2$ and negative parity in this odd-Z region. The 3/2 – assignment of the 515 keV state might therefore be explained as a 3/2, 1/2 – [541] level associated with $Z > 82$ descending into this energy region for the δ-value in question. Considering the result of Coulomb excitation experiments, NATHAN and POPOV[10] have pointed out a more reasonable explanation. The 515 keV state should thus be a γ-vibrational level associated with the 7/2 – [523] ground state of ^{165}Ho. The 566 keV transition observed[7] from the decay of ^{165}Dy may well be identical with the transition having the same energy, found in the Coulomb excitation[11] studies of ^{165}Ho. This transition is suggested to lead from a level at 566 keV (5/2, 3/2 –) to the ^{165}Ho ground state (7/2, 7/2 –). A γ transition with energy 64 keV was found to de-excite the mentioned level. It is fed by a newly observed 106 keV transition from the 672 keV level. The results of previous[7, 11] measurements indicate that also the 7/2, 3/2 – level at 641 keV is populated in the decay of ^{165}Dy, since a γ ray, having an energy of about 550 keV (543 keV was obtained in the Coulomb excitation studies[11] and 546 keV from the external conversion spectrum[7]), was observed[9] to be in coincidence with the 95 keV transition. This level is confirmed since also a new transition of energy 126.13 keV was found de-exciting it and leading to the 3/2 –, 515 keV level.

It was proved from energy determinations and sum coincidence experiments[8] that there is a level at ~716 keV. This level is de-excited by two γ rays to the 9/2 –, 95 keV state and to the 7/2 – ground state. The multipolarities of γ rays feeding and de-exciting the 717 keV level agree well with the assumed theoretical spin value 7/2. The parities of the 717 keV level and the ground state are opposite and therefore it is proved to agree with 7/2, 7/2 + [404] orbit. A new level is proposed at 811 keV due to the appearance of γ-ray energy of 450 keV. It has been assumed that the 450 keV transition is de-exciting the 811 keV level to the 361 keV level. The 811 keV level is compatible with 13/2, 11/2 – assignment.

The log ft value of the β decay to the 996 keV level indicates an allowed, hindered transition and thus positive parity of that state. According to the multipolarities of the 635 and 996 keV transitions de-exciting the 996 keV level to the 3/2 +, 361 and the 7/2 – ground state respectively, a 5/2 + is assigned to this level. The 635 and 279 keV M1 transitions de-exciting the 996 keV level possess nearly equal intensity in spite of the energy difference[7]. It is therefore possible that the 635 keV transition violates the asymptotic selection rules, whereas the 279 keV transition is unhindered. This situation prevails, assuming the asymptotic quantum numbers, [413] for the 996 keV level and [404] and [411] for the 717 and 361 keV levels, respectively.

Earlier, PERSSON et al.[7] have indicated two levels at 1056 and 1080 keV but they could not give them any definite assignments. The present measurements revealed a third level at 1037 keV which is proposed to compensate the appearance of the 1037 keV transition and to place the 43 keV transition. The latter transition was observed[1] before, but could not be placed in the decay scheme. The log ft values for the β branch feeding the 1056 and 1080 keV levels are 7.0 and 6.4 respectively, indicating either allowed, hindered or first forbidden, unhindered transitions. Therefore the spin values for these two levels could be 5/2, 7/2 or 9/2. In view of the multipolarities of γ transitions de-exciting the 1037, 1056 and 1080 keV levels, spin and parity assignments were assumed to be (5/2 or 7/2 +), (9/2 –) and (5/2, 7/2, or 9/2 –) respectively. These estimates are in fair agreement with single particle levels 5/2 + [402], 9/2 – [514] and 5/2 – [532] (hole state).