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CONVERSION ELECTRONS OF ^{188}Re FOLLOWING NEUTRON CAPTURE

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Abstract: Conversion electrons of ^{188}Re following neutron capture in ^{187}Re were measured with the beta spectrometer at the FRM reactor. In the energy range between 8 keV and 300 keV, 53 conversion lines were found. Multipolarities were determined for 39 transitions. A level scheme containing 11 levels with spins and parities is proposed.

E | NUCLEAR REACTIONS ^{187}Re ($n_{thermal}$, ce); measured E_{ce}, I_{ce}. ^{188}Re deduced levels, J, π, cc. Enriched target.

1. Introduction

The ^{188}Re nucleus is expected to be deformed and it is interesting to test to what extent simple predictions based on the rotational model can be verified experimentally.

Previous investigations [1-4]) of levels in ^{188}Re were based on the study of the decay of ^{188}W and the 18.6 min isomer of ^{188m}Re. Recently Burson *et al.* [5]) and Takahashi *et al.* [6]) have established part of the level scheme of ^{188}Re. Gamma radiations and conversion electrons following neutron capture in ^{187}Re have been measured by several groups [7-9]).

In order to extend the level scheme of ^{188}Re we have restudied the conversion electron spectrum of ^{188}Re following neutron capture in ^{187}Re with the double focussing beta spectrometer at the Munich research reactor. These data have been combined with very preliminary data of the ^{187}Re(n, γ) spectrum [10]) which have been measured with the curved crystal spectrometer at Risø.

2. Source and apparatus

The source was prepared following a method proposed by Maier [11]) and Mahlein [12]). A quantity of 30 mg of enriched Re (99.22 % ^{187}Re + 0.78 % ^{185}Re) obtained from Oak Ridge was dissolved in H_2O_2. The solution was dried, and the oxides so obtained were evaporated under vacuum onto a rotating aluminium foil

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(0.2 mg/cm^2) to obtain a 1×8 cm^2 target. The target and backing were heated to about 300° C, and the oxides were reduced with H_2. The resulting target thickness was 0.47 mg/cm^2.

The beta spectrometer used in this measurement has been described elsewhere[13-15]. The detector was a proportional counter operated with continuously flowing methane. The window of the counter was made of formvar foil (50 $\mu g/cm^2$).

3. Measuring procedure

The total spectrum was scanned in steps of 0.9 G · cm from 8 keV to 800 keV. At each point, the number of conversion electrons was counted for 1 min. More detailed measurements of the conversion electron spectrum were performed in the electron energy regions 8-225 keV, 8-300 keV and 150-300 keV with a counting time of 4 min per point. The value of 300 keV was adopted as an upper limit, since no lines were found above this energy in the previous 1 min run.

In order to investigate lines with very low energy, the target was biased (−12 kV) to pre-accelerate electrons emerging from the source [16]. Thus, it was possible to measure conversion electrons having zero primary energy and to study under improved conditions the spectrum up to 60 keV. This experiment was performed three times, once with 1 min and twice with 4 min measuring times.

A few lines are present from the decay of the isomeric state with a half-life of 18.6 min. The ratio of the intensity of these lines with the reactor on to the intensity with the reactor off was determined. Shortly after the reactor was shut down, measurements of the L_1 and M lines of the 63.58 keV transition, of the M line of the 92.46 keV transition and the K line of the 105.87 keV transition were begun.

The K, L_2, L_3, M and N line of the 155.03 keV transition in ^{188}Os were recorded after the isomer of ^{188}Re had decayed appreciably.

4. Results

All our experimental results are given in tables 1 and 2. Brief comments may clarify how these data were obtained.

The spectrum was plotted for each of the seven runs, an example of which is shown in fig. 1. The background was subtracted graphically and the approximate positions and heights of the lines were determined from the plots. These positions and heights were used as initial parameters in a computer program for a least-squares fit [17]. The parameters which are necessary for the determination of the line shape were deduced from the more intense lines, particularly from the 155.03 keV transition of ^{188}Os.

4.1. ENERGY OF THE CONVERSION LINES

The energy of the electron lines for each run are based on a calibration using the following preliminary, but sufficiently precise, gamma energies [10]: 63.583, 105.862, 141.757, 155.045, 207.849, 227.082 and 290.669 keV.

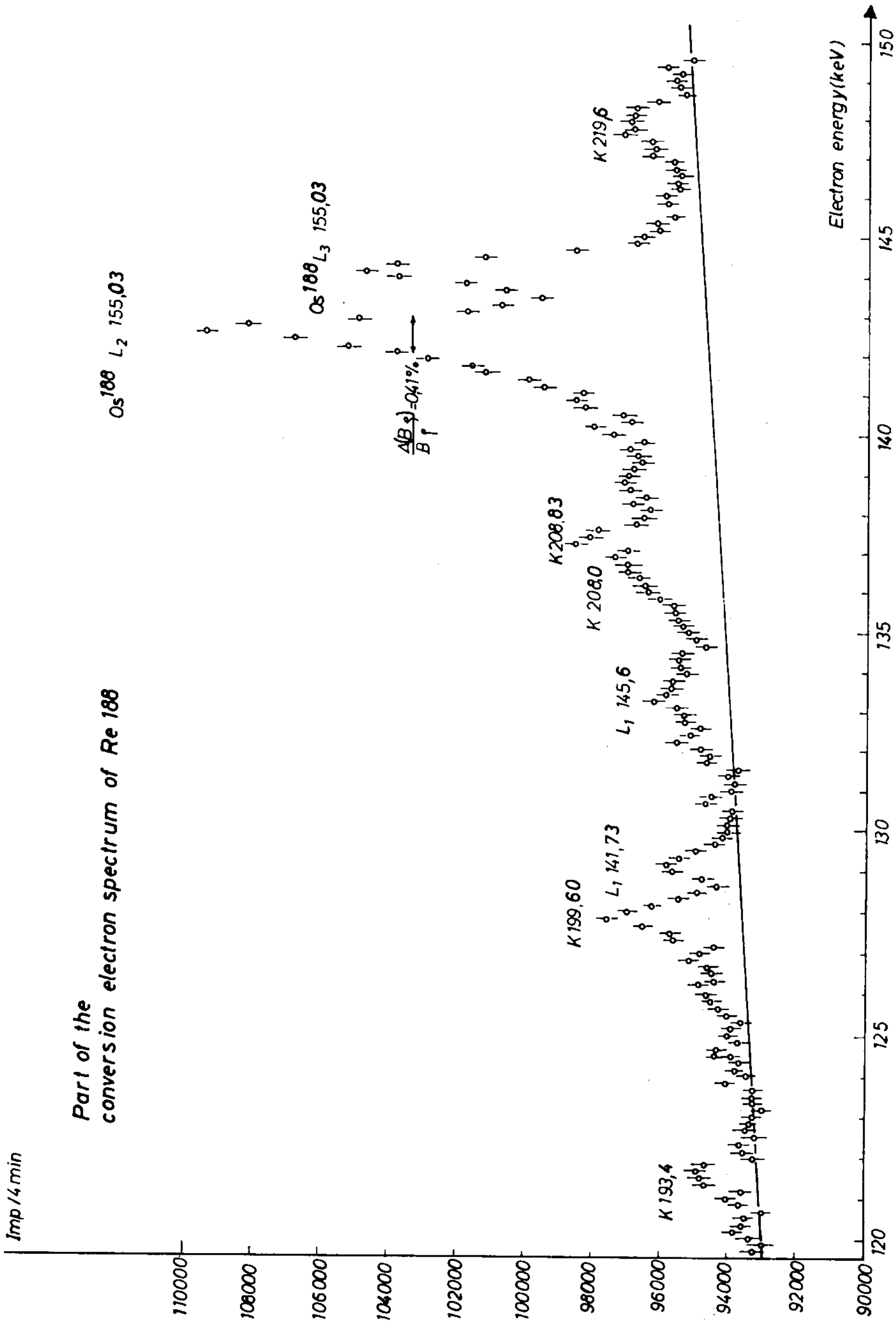

Fig. 1. Part of the conversion electron spectrum of ^{188}Re.

TABLE 1

Conversion electron lines of ^{188}Re

E_γ (keV)	I_γ	$\frac{\Delta I_\gamma}{I_\gamma}$ (%)	Shell	E_e (keV)	ΔE_e (keV)	I_e	$\frac{\Delta I_e}{I_e}$ (%)	Conversion coefficient	Theoretical values E1	E2	M1	Multipole assignment	Remarks
1	2	3	4	5	6	7	8	9	10	11	12	13	14
30.60	(0.2)		$L_{1,2}$	18.21	0.08	6.2	50		0.94	366	23.0	M1+	
			L_3	20.06	0.09	2.0	50		0.58	430	0.26	(2±1) % E2	
46.69	0.13	20	$L_{1,2}$			2.2	80	17±12	0.307	48.5	6.50	M1+	−K 105.87
			L_3			0.5	70	4±3	0.146	52.1	0.0708	<20 % E2	−K 107.45
63.58 [e])	16	15	L_1	51.05	0.04	35.5	20	2.2	0.0963	0.261	2.38	M1+	
			L_2	51.64	0.05	4.1	20	0.26	0.0444	10.8	0.236	(0.40±0.05)	
			L_3	53.11	0.09	1.1	20	0.069	0.0528	10.9	0.0272	% E2	
			M	60.67	0.05	9.5	20	0.59					+K 131.3
			N	62.94	0.07	2.8	20	0.17					
75.0	2.5	10	L_1	62.5	0.2	0.3	80	0.12	0.0663	0.173	1.48	E1	
87.4	0.22	15	K	15.7	0.1	2.3	30	10	0.439	1.07	6.34	M1	
			L_1	75.0	0.2	0.7	40	3	0.0461	0.126	0.943		
92.46	0.5+1.6	15	K	20.78	0.04	10.3	20	(4.9)	0.382	0.961	5.41		doublet
			$L_{1,2}$	80.25	0.09	2.4	20	(1.1)	0.0545	1.98	0.883		92.36 E1 probable
			M	89.66	0.07	1.0	20	(0.5)					92.46 M1
93.6	0.42	10	K	21.9	0.1	1.6	40	3.8	0.370	0.940	5.23	M1+(E2)	
105.87 [e])	3.6	8	K	34.19	0.04	13.1 [b])	20	3.6	0.271	0.741	3.67	M1+	
			$L_{1,2}$	93.37	0.08	2.2	20	0.61	0.0386	1.10	0.598	< 3 % E2	
			M	102.87	0.09	0.9	15	0.25					
107.45	0.52	8	K	35.77	0.04	1.8	25	3.5	0.261	0.720	3.52	M1	
111.67	0.9+0.8	8	K	39.99	0.04	5.6	10	(3.3)	0.237	0.669	3.15		doublet : both M1 probable
114.4	0.20	10	K	42.7	0.2	0.3	40	1.4	0.221	0.636	2.92	M1+E2	
115.3	0.56	10	K	43.6	0.1	1.2	35	2.2	0.218	0.630	2.88	M1(E2)	
131.3	0.81	10	L_1	118.8	0.2	0.33	50	0.41	0.0175	0.0534	0.297	M1	−K 190.44
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

			$L_{1,2}$	129.32	0.06	0.6	15	0.27	0.0182	0.312	0.260		
145.2	0.54	10	K	73.5	0.2	0.5	40	0.93	0.121	0.381	1.49	M1+E2	
145.6	0.93	8	K	73.9	0.1	0.9	17	1.0	0.120	0.378	1.48	M1+E2	
155.03 [e]	16 [c]		K	81.16	0.04	4.13	8	0.26	0.10	0.32	1.35	E2	^{188}Os
			L_2	142.53	0.06	3.22 [a]	5	0.20	0.003	0.20	0.02		
			L_3	144.27	0.06	2.56	5	0.16	0.003	0.15	0.002		
			M	152.34	0.06	1.27 [a]	15	0.08					
			N	154.51	0.07	0.45 [a]	10	0.028					
156.47	0.97	8	K	84.80	0.05	1.1	11	1.1	0.0998	0.318	1.21	M1	
157.2	0.60	8	K	85.5	0.1	0.4	50	0.7	0.0986	0.314	1.19	M1+E2	
167.33	2.8	8	K			≦0.4		<0.14	0.0844	0.269	1.00	E1	
188.81	1.95	8	K			≦0.25		<0.13	0.0624	0.197	0.716	E1	
190.44	0.32	15	K	118.76	0.07	0.33	50	1.0	0.0611	0.192	0.700	M1	$-L_{1,2}$ 131.3
193.4	0.9	10	K	121.7	0.1	0.5	45	0.6	0.0588	0.185	0.670	M1	
199.60	1.96	8	K	127.92	0.09	0.85	6	0.43	0.0543	0.170	0.614	60 % M1+(40±15) % E2	
208.0 [e]	8.7	8	K	136.3	0.2	0.23	40	0.026	0.0490	0.153	0.548	E1	
208.83	1.9	8	K	137.15	0.07	0.74	9	0.39	0.0484	0.151	0.540	M1+E2	
219.6	1.25	15	K	147.9	0.1	0.54 [b]	5	0.43	0.0428	0.132	0.471	M1+	
			$L_{1,2}$	207.0	0.2	0.11	10	0.088	0.00605	0.0552	0.0757	<20 % E2	
227.03 [e]	4.4	8	K	155.35	0.08	1.85 [b]	5	0.42	0.0392	0.121	0.428	M1+	
			$L_{1,2}$	214.7	0.3	0.30	20	0.068	0.00556	0.0486	0.0690	<12 % E2	
236.5	3.3	8	K	164.8	0.2	0.24	25	0.073	0.0354	0.108	0.381	E1, E2	
251.23	2.1	10	K	179.55	0.08	0.47	14	0.22	0.0305	0.0924	0.323	M1+E2	
257.2	1.9	10	K	185.5	0.3	0.31	14	0.16	0.0288	0.0871	0.303	M1+E2	
274.7	1.9	10	K	203.0	0.4	0.36	14	0.19	0.0246	0.0736	0.254	M1+E2	
275.9	1.3	10	K	204.2	0.6	0.26	35	0.20	0.0244	0.0728	0.251	M1	
290.8 [e]	9.3	5	K	219.1	0.2	1.76	5	0.19	0.0215	0.0634	0.217	81 % M1+	
			$L_{1,2}$	278.4	0.2	0.24	12	0.026	0.00305	0.0201	0.0352	(19±10) % E2	
299.1	0.3	7	K	227.4	0.5	0.1	50	0.3	0.0201	0.0589	0.201	M1	
339.2	0.7	15	K	267.5	0.7	0.11	25	0.16	0.0150	0.0430	0.144	M1	
362.0	1.4	10	K	290.3	0.7	0.1	40	0.07	0.0127	0.0360	0.120	M1+E2	

[a]) Used for electron intensity calibration.
[b]) Used for gamma intensity calibration.
[c]) Absolute gamma intensity from Nuclear Data [22]).
[e]) Used for energy calibration. — intensity of overlapping line subtracted, + intensity of overlapping line not subtracted.

The energies in table 1 are the weighted averages of the energies measured in the different runs. The gamma energies in table 1 are determined from the electron energies and the electron binding energies [18]).

TABLE 2

Decay of the isomeric state of ^{188}Re

γ-energy	Total intensity with reactor per 100 n captures	Electron shell	$I_{\text{with reactor}}/I_{\text{isomer}}$	Total intensity from isomeric state per 100 n captures
63.58	71±9	L_1	22±3	3.2±0.6
		M	20±8	
92.46	16±3	M	6±3	2.7±1
105.87	21±3	K	15±3	1.4±0.3

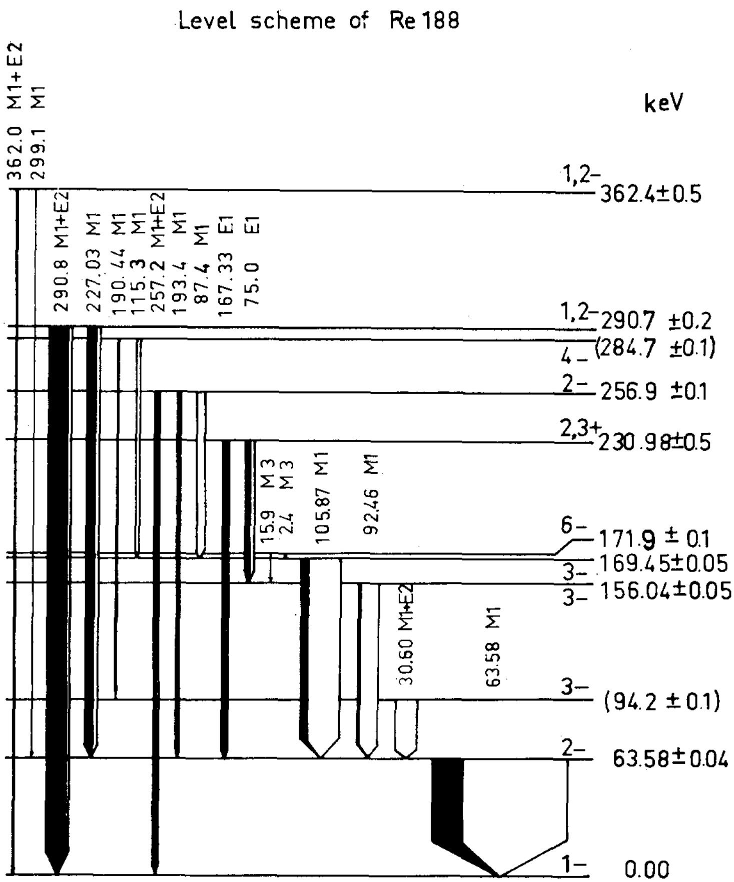

Fig. 2. Level scheme of ^{188}Re. Filled part of the arrows–gamma intensity, open part of the arrows – electron intensity. Level energies in brackets indicate that the level is not well established.

4.2. INTENSITY OF THE CONVERSION LINES

The absolute intensity of the K conversion electron line of the 155.03 keV transition in ^{188}Os is known [5]) and could have been used for the intensity calibration. We have used instead, the sum of the absolute intensities of the L_1, L_2, L_3, M and N conversion lines of the 155.03 keV transition as reported by Burson *et al.* [5]). This was necessary because the absorption of electrons in the window of the proportional counter is negligible for the L, M and N electrons but not for the K electrons of this transition. The intensities I_e listed in table 1 are relative intensities which differ from the absolute intensities (I_e/100 n) by less than 3 %.

4.3. GAMMA INTENSITY

From the K : L ratio and the L subshell ratio, it is known that the 105.87, 219.6 keV, and 227.03 keV transitions are nearly pure M1 transitions (see table 1). We assumed these transitions to be of pure M1 character and calculated their gamma intensities from their calibrated conversion electron intensities using the conversion coefficients of Sliv and Band [19]). In this way, we got a calibration factor for the preliminary relative gamma intensities [10]).

4.4. CONVERSION COEFFICIENTS AND MULTIPOLARITIES

The experimental conversion coefficients were obtained by dividing the calibrated conversion electron intensities by the corresponding calibrated gamma intensities. The multipolarities were assigned by comparison with the theoretical conversion coefficients of Sliv and Band [19]).

Prokofjev *et al.* [8]) found 28 lines in their conversion electron spectrum and determined the multipolarities of seven transitions. These multipolarity assignments are in agreement with our results except for the 208.0 keV transition, for which they have assigned multipolarity E2. Our data, however, clearly show this to be an E1 transition. Apparently Prokofjev *et al.* did not have sufficiently detailed gamma data. For this reason, we feel that an unambiguous assignment of a few weak conversion electron lines as K or L lines was not possible.

5. Comments on a few lines

5.1. TRANSITIONS OF 92.36 keV AND 92.46 keV

These lines are not resolved in our spectrum, but considerations of the electron intensities, the centroid of the unresolved structure and of the gamma intensities indicate that the 92.36 keV transition is of E1 character and the 92.46 keV transition of M1 character. Therefore it is concluded that the 92.46 keV transition is the isomeric transition [1,2]).

5.2. TRANSITION OF 46.69 keV

The $L_{1,2}$ conversion electron line of this transition is superimposed on the K conversion electron line of the 105.87 keV transition and the L_3 conversion line on the K conversion line of the 107.45 keV transition. Knowing the multipolarity of the 105.87 keV transition from our L subshell ratio, we were able to compute the contribution of the L_2 conversion line of the 46.92 keV transition. In the same way we deduced the contribution of the L_3 conversion line to the K peak of the 107.45 keV transition.

5.3. TRANSITION OF 30.60 keV

When using an accelerating potential, two lines appeared which were interpreted as the $L_{1,2}$ and L_3 lines of this transition.

6. Level scheme

The data obtained from the conversion electron measurements and the gamma measurements and the resulting total transition intensities permit the construction of the level scheme (see fig. 2 and ref. [20]) almost independently of the results of other authors [5,6]. In the following, we shall discuss mainly the newly established levels.

6.1. THE LEVELS AT 94.2 AND 284.7 keV

The 284.7 keV level is proposed to be the 4^- level belonging to the ground-state rotational band. The 1^-, 2^- and 3^- levels at 0, 63.58 and 156.04 keV yield the following parameters for this rotational energy formula:

$$E = E_0 + AI(I+1) + BI^2(I+1)^2;$$

$$E_0 = -32.37 \pm 0.03 \text{ keV},$$

$$A = 16.28 \pm 0.02 \text{ keV},$$

$$B = -0.049 \pm 0.002 \text{ keV}.$$

From this it follows that the 4^- level should be situated at 273.9 keV. The relatively strong 115.3 keV transition leading to the level at 169.45 keV suggests a level at 284.7 keV. With the crystal spectrometer at Risø [10], a gamma line has been found which fits between this new level and the 156.04 keV level. An additional transition feeds the level at 94.2 keV which will be discussed later. Since these arguments are weak, we tentatively propose this level at 284.7 keV as the 4^- member of the ground-state rotational band.

We found a strong low-energy transition with the energy 30.60 keV which we assume to be an M1+E2 admixture from the L-subshell ratio. Assuming that this transition leads to the 63.58 keV level indicates a level at 94.2 keV which is connected with the 284.7 keV state by a 190.44 keV transition. The existence of the 284.7 keV level and the transitions discussed above would imply that the 94.2 keV level has spin and parity 3^-. It should be mentioned that the 94.2 keV state is not well established. It seems that this level would be analogous to the 99.38 keV state which has been found [12,20,21]) in ^{186}Re.

6.2. THE 171.9 keV ISOMERIC LEVEL

Because of the low intensity of the isomeric transitions, we did not find the conversion lines of the 2.4 and 15.97 keV transitions as measured by Takahashi *et al.* [6]). We adopted their assumptions about the spin and parity of the level.

We observed the decay of this isomeric level (half-life 18.6 min) when the reactor was shut down. The decrease of the intensity of the following four lines was measured: L_1 63.58, M 63.58, M 92.46 and K 105.87 keV. In this way, we obtained the ratios of the intensities of these three transitions during neutron irradiation to the intensities without irradiation. These ratios, which are given in table 2, are in agreement with the results of Schult *et al.* [7]), who measured the ratio of the gamma intensities. From our intensity ratios and the total intensities of the three transitions during irradiation with neutrons, we determined the part of the intensities of these lines coming from the isomeric state per 100 neutron captures. The 105.87 keV line and the 92.46 keV line are present after the decay of the isomeric level. The sum of both intensities is about equal to the intensity of the 63.58 keV transition as it should be. Thus, the population of the isomeric state is 3.4 ± 0.5 per 100 neutron captures.

6.3. THE 230.98 keV LEVEL

For this level, we obtained a good energy combination: 63.58 keV (level) + 167.33 keV (E1) = 156.04 keV (level) + 75.0 keV (E1). These two E1 transitions determine a new level at 230.98 keV with positive parity and spin 2 or 3. In the level scheme of Prokofjev *et al.*[8]), the 167.33 keV transition populates the 169.45 keV level. This might be also concluded from the experiments of Berestovoi *et al.* [9]), who measured the gamma spectra after neutron capture with delay times of 10 nsec and 20 nsec and found at 10 nsec 3 peaks at 62, 103 and 167 keV. The experimental evidence is not sufficient to rule out either one of these possibilities. Our arguments are based mainly on the energy combination and on the E1 character of the two transitions coming from the 230.98 keV level.

6.4. THE 256.9 keV LEVEL

This level is defined through three rather strong transitions with the energies 257.2, 193.4 and 87.4 keV, which are M1 or M1 + E2 transitions. This implies spin and parity 2^- for the 256.9 keV state.

6.5. THE LEVELS AT 290.7 AND 362.4 keV

The level at 290.7 keV has already been established by Burson *et al.* [5]). The multipole character of the 290.8 keV and the 227.03 keV transitions indicates negative parity and spin 1 or 2. The 290.7 keV level was assumed by Burson *et al.* [5]) to be the head of a rotational band $K = 1^-$ with intrinsic state $p_{\frac{5}{2}+}$ [402], $n_{\frac{3}{2}-}$ [503].

Two transitions with 362.0 keV and 299.1 keV have a difference in energy equal to the first excited state. This yields a level at 362.4 keV with spin and parity 1^- or 2^- defined through the multipole character of the 362.0 keV and the 299.1 keV transitions. If we assume that a band superimposed on the 290.7 keV level has roughly the same moment of inertia as the ground-state band, we should expect the second level of this band close to 364 keV. Remembering that different rotational bands may have somewhat different moments of inertia, we may tentatively conclude that this state is the second level of this band. Under these assumptions, we get for the parameters of the rotational formula

$$E_0 = 254.9 \pm 0.4 \text{ keV}, \qquad A = 17.9 \pm 0.1 \text{ keV}.$$

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