KERNFORSCHUNGSZENTRUM

KARLSRUHE

Oktober 1963

KFK 191

Institut für Neutronenphysik und Reaktortechnik

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KARLSRUHE

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Nuclear Physics **48** (1963) 422—432; © *North-Holland Publishing Co., Amsterdam*

THE LEVEL STRUCTURE OF Re^{187}

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Received 11 February 1963

Abstract: The transitions and levels of Re^{187} populated by W^{187} beta decay have been investigated by using prompt and delayed gamma-gamma coincidence techniques. The relative intensities of the gamma rays are given. The experimental reduced transition probabilities are compared with the theoretical predictions of the unified model.

1. Introduction

The lower energy levels of the strongly deformed odd-mass nuclei between the closed shell $N = 82$ and the double closed shell $Z = 82$, $N = 126$ are successfully described as being single particle states in an axially symmetrical potential, with rotational states based upon them [1,2]. The nucleus Re^{187} is near the upper limit of this region. The deformation compared to that of somewhat lighter nuclei has already markedly decreased. This fact makes the assumption of strong coupling uncertain. Exact knowledge of the excited states of Re^{187} thus furnishes a useful contribution to the investigations on the validity of the model for the boundary regions.

The level structure of Re^{187} has been investigated by many authors [3-13] via the beta decay of W^{187} (half-life 24 h). Sufficient energy is available for this decay to excite states in the daughter nucleus up to some 1300 keV. Level schemes have been worked out by Germagnoli and Malvicini [4], Cork *et al.* [5], Dubey *et al.*[7], Vergnes [8], Gallagher *et al.*[9] and Arns and Wiedenbeck [10]. All studies reported till now show agreement in the energies of a major number of transitions. With the exception of gamma rays at 72, 134, 206, 480, 552 and 686 keV originating from transitions between energy levels at 134, 206 and 686 keV there are, however, considerable discrepancies as to the position of most transitions in the decay scheme, so that the level structure is not yet well established. In conventional Coulomb excitation experiments gamma rays with energies of 134 keV, 167 keV and 301 keV were observed [14-19]. The result of these experiments is a level at 301 keV which is de-excited by a ground-state transition and a cascade through the level at 134 keV. Only in one of the papers [10] on the decay of W^{187} is the occurrence of gamma lines at 167 keV and 301 keV reported. Coulomb excitations with 14-20 MeV α-particles [20] point to the possible existence of two gamma-vibrational levels with energies of 511 keV and (880 ± 20) keV, respectively.

The 206 keV level is a metastable state with a half-life of [3] 5.5×10^{-7} sec. The half-life of the excited state at 134 keV is [21] $(1.04 \pm 0.14) \times 10^{-11}$ sec.

According to measurements made by Meggers *et al.*[22]) and by Segel and Barnes [23]) the ground state spin of Re^{187} is $\frac{5}{2}$. Spin and parity of the excited levels have been the subject of several investigations [8-13]). The results are contradictory in part (cf. ref.[24])).

In view of the inconsistencies in the experimental data reported till now it was deemed useful to re-examine the level structure of Re^{187}.

2. Experimental Procedure

In this work the gamma rays following beta decay of W^{187} were investigated using sum coincidence and gamma-gamma coincidence techniques. The main features of the apparatus have been described in a previous paper [25]). The effective resolving time for the coincidence measurements was about 6 nsec. Angular correlation experiments are reported in a separate article [24]).

Sources were prepared from tungsten powder of 99.98 % purity and irradiated in the Karlsruhe research reactor. The gamma ray spectrum was followed for a period of several weeks. No impurity activities were found to be present in the sources. In order to avoid interferences from the very small amount of long-lived W^{181} contained all data were taken early in the decay of each source.

3. Results

3.1. COINCIDENCE MEASUREMENTS

A total of 34 sum coincidence and gamma-gamma coincidence measurements was carried out in various energy ranges †. The results are summarized in table 1 and some of the spectra are presented in fig. 1.

On the basis of our measurements we are forced to conclude that the 626 keV gamma ray which has been observed by most previous authors is not a ground state transition or a transition to the 206 keV metastable state, but a transition to the first excited state at 134 keV. Thus a level must be postulated at 760 keV. This conclusion is in agreement with the papers of Dubey [7]) and Arns and Wiedenbeck [10]). It is contradictory, however, to the results of Vergnes [8]) and Gallagher *et al.*[9]). The recent detailed investigation made by Maack Bisgård *et al.*[11]) allows no statement as regards the 626 keV transition. According to the present study the 760 keV level is most probably fed by a 106 keV gamma ray proceeding from a level at 866 keV and de-excited, parallel to the 626 keV-134 keV cascade, by a weak direct decay to the ground state. This result is consistent with the data of Arns and Wiedenbeck. Mack Bisgård *et al.* failed to observe a transition at 760 keV. In the level scheme proposed by Gallagher *et al.* a gamma ray at 106.61 keV is ascribed to a transition between levels at 618.2 and 511.6 keV. As such a transition is not in contradiction to our results the possibility that the

† The gamma ray spectrum which is obtained by means of a conventional single crystal spectrometer shows the existence of well established gamma transitions at 72, 134, 480, 552, 619, 686, 775 and 866 keV (see refs. [10, 11])).

TABLE 1

Summary of the coincidence measurements

Energy range (keV)	Coincident gamma ray energies (keV)															
	X 72	106	134	206	247	480	514	552	619	626	686	732	760	775	777	86[illegible]
a) Sum coincidences																
463–481	+		+													
527–553	+		+													
551–569	+		+													
607–629	+		+													
664–688	+		+					+								
760–786	+		+							+						
848–892†	+	+	+		+				+			+	+			
900–970	+		+												+	
b) Prompt gamma-gamma coincidences																
60–84†	+		+					+								
90–110†	+		+			+		+		+	+		+			
120–148†	+		+			+		+		+		+			+	
160–178	+		+				+				(+)					
171–189	+		+								(+)					
193–221	+		+													
213–227	+		+													
222–246	+		+				+		+							
239–255	+		+				+		+							
262–290	+		+													
288–308	+		+													
314–336	+		+													
343–367	+		+													
371–397	+		+													
401–429	+		+													
420–450	+		+													
455–487	+		+													
512–538	+		+													
531–559	+		+													
562–592	+		+													
590–650	+	+	+		+											
659–693	+		+													
717–757	+	+	+													
c) Delayed gamma-gamma coincidences																
60–84	+					+		(+)								
120–148	+					+		(+)								
456–504	+		+	+												

† The spectrum is shown in fig. 1.

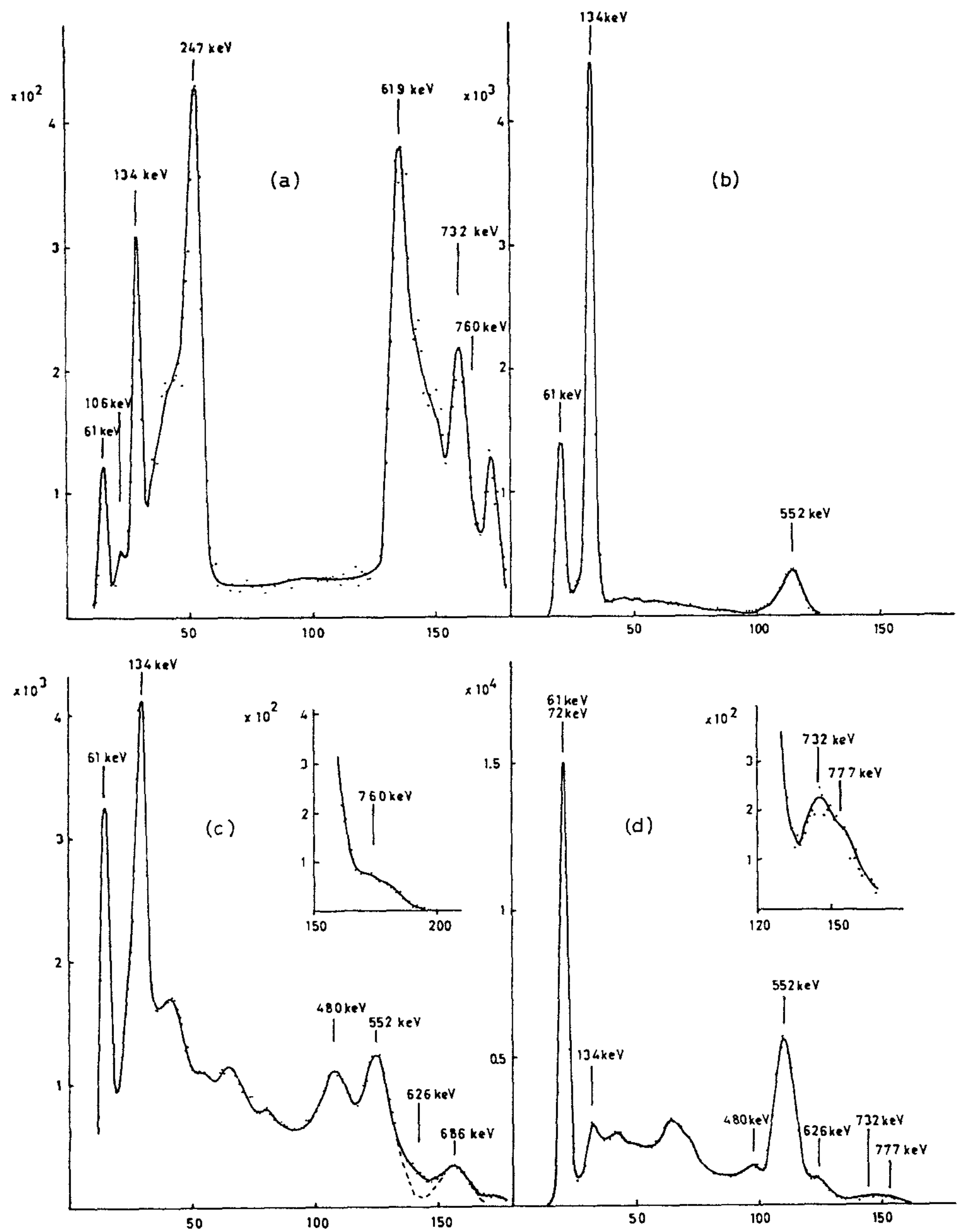

Fig. 1. (a) Sum coincidence spectrum corresponding to the energy range 848 to 892 keV. (b) Spectrum of gamma rays coincident with the energy range from 60 to 84 keV. (c) Spectrum of gamma rays coincident with the energy range from 90 to 110 keV. The energy scale differs from that in (b) and (d). (d) Spectrum of gamma rays coincident with the energy range from 120 to 148 keV.

106.61 keV gamma ray is different from that observed in the present study cannot be ruled out.

Obviously, the gamma rays at 619, 775 and 866 keV correspond to ground state transitions. Both the sum coincidence and the gamma-gamma coincidence measurements clearly indicate the cascade relationship between the 619 keV photons and a gamma ray at 247 keV. The results obtained by Gallagher *et al.*, Arns and Wiedenbeck and Maack Bisgård *et al.* are thus confirmed. In agreement with the investigation of Arns and Wiedenbeck the present experiments point to the existence of a weak line at 732 keV which is interpreted as being a transition from the 866 keV level to the first excited state. Furthermore, a weak gamma ray seems to exist at 777 keV. It, too, was found to be in coincidence with the 134 keV transition. This result necessitates the placing of a level at 911 keV. High lying states in this energy region are to be expected from beta ray measurements performed by Dubey *et al.* and Maack Bisgård *et al.* The data of these studies show agreement as to the presence of a low energy beta transition with a maximum energy of about 330 keV. Maack Bisgård *et al.* have suggested that this beta group may possibly be resolved into two groups with end-point energies at about 400 keV and 250 keV, respectively. If this assumption is correct, the 400 keV beta ray would populate a level at about 910 keV. It should be noted that Maack Bisgård *et al.* failed to observe both the 732 keV and the 777 keV gamma ray.

A weak line was found at 514 keV. Most probably this transition can be identified with the gamma ray seen by other authors at 511 keV in conversion electron measurements and in Coulomb excitations with 14-20 MeV α-particles. According to the papers of Dubey *et al.* and Gallagher *et al.* the 511 keV line reaches the ground state. The spectra obtained in the present study are in favour of such a proposal.

Apparently, the gamma rays at 167 and 301 keV which appear in conventional Coulomb excitation experiments are also present in the decay of W^{187}. The intensity of these lines is, however, near the limit of what could be observed with the applied techniques. Evidence was furthermore found for the existence of two previously unreported weak transitions with energies of (320 ± 15) and (365 ± 15) keV, respectively. As to the position of these gamma rays in the decay scheme the data are not conclusive. The 320 keV line is possibly coincident with a gamma ray at about 300 keV. In addition, a weak coincidence seems to exist between photons having the approximate energies 300 keV and 240 keV.

In spite of using a Compton shield several weak lines appeared which, from energy considerations, cannot be ruled out as being due to coincidences between back-scattering and Compton rays. They are clearly different from the photons discussed in the preceding paragraphs. The energies are as follows: 170, 172, 176, 180, 182, 185, 195, 202, 203, 289, 302, 437, 484, 572 and 671 keV. Some of these lines have already been observed by Arns and Wiedenbeck in gamma-gamma coincidence measurements. The possible ordering of levels which is proposed by these authors shows accordingly a more complex structure than the schemes of previous studies. Maack Bisgård *et al.* investigated the influence of various Compton shields and they suggest that the gamma rays reported by Arns and Wiedenbeck are due to spurious coincidences from backscattering events. No further experiments were carried out regarding this point.

The delayed gamma-gamma coincidence measurements clearly indicate that, besides the 480 keV transition, no gamma rays of noticeable intensity feed the metastable state at 206 keV.

3.2. RELATIVE GAMMA RAY INTENSITIES

The relative intensities of the observed gamma rays were determined from the photopeak areas in the measured spectra. The results are listed in table 2. The values have

TABLE 2

Relative intensities of the gamma rays

E_γ (keV)	Unconverted gamma ray relative intensity	E_γ (keV)	Unconverted gamma ray relative intensity
72	56 $\pm$8	619	29.7$\pm$1.6
106	0.36$\pm$0.18	626	4.7$\pm$0.9
134	45 $\pm$5	686	110 $\pm$6
206	4.3 $\pm$1.9	732	1.4$\pm$0.4
247	0.45$\pm$0.09	760	1.3$\pm$0.6
480	100	775	17.6$\pm$1.6
514	$\leqq$3.5	777	0.7$\pm$0.2
552	28.4 $\pm$1.5	866	2.0$\pm$0.6

been corrected for crystal efficiency, peak-to-total ratio, absorption between source and crystal as well as for changes in coincidence efficiency.

4. Discussion

A tentative decay scheme based on the results of the present investigation is shown in fig. 2. The levels at 134, 206 and 686 keV are well established. As regards the excited states at 514, 619, 775 and 866 keV the data seem to be rather conclusive and agreement is found with most of the recent studies. The 301 keV level and its decay to the ground state and to the level at 134 keV are known with certainty from conventional Coulomb excitation experiments. As stated previously, our results indicate that this level is also populated with low intensity in the decay of W^{187}. The levels proposed at 760 and 911 keV are only based on sum coincidence and gamma-gamma coincidence measurements. Their existence should be verified by means of other techniques. A level at 911 keV is favoured by beta ray measurements carried out by previous authors (cf. sect. 3.1.). However, information on the high lying states which are to be expected from these studies in the energy range from 900 to 1100 keV is still lacking. The observed existence of a low energy beta group with an intensity between 5 and 10 % can hardly be explained by the gamma transitions which have been established until now.

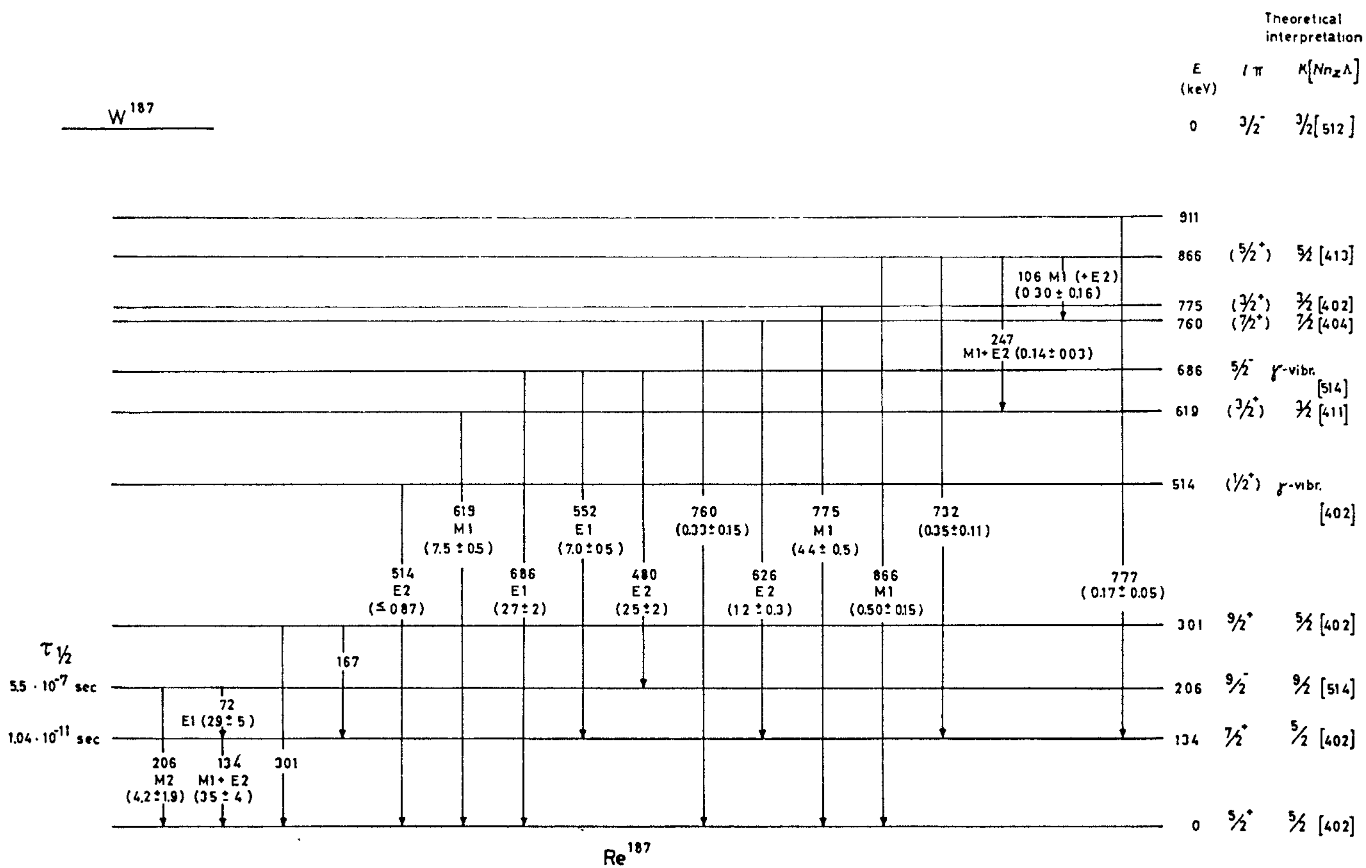

Fig. 2. Tentative level scheme based on the results of the present investigation. The transition multipolarities are adopted from the paper of Gallagher *et al.*[9]) The numbers in parentheses indicate the decay fraction. The values were calculated from table 2 using the total conversion coefficients from ref.[8]) and assuming that 20 % of the primary beta decay feeds the ground state.

It would be an important task to perform a systematic search for transitions proceeding from the quoted high energy region. Possibly the gamma rays at (320±15) and (365±15) keV, appearing in the present investigation, can be associated with the decays of such high lying states.

All spin and parity assignments given in fig. 2 presume spin $\frac{5}{2}$ of the Re^{187} ground state. This assignment can be regarded as well established. Only one $\frac{5}{2}$ orbit is expected by the Nilsson model in this region, i.e. the state $\frac{5}{2}^+$ [402]. The ground state then has positive parity. Spin and parity of the excited levels are based on the gamma ray multipolarities deduced from conversion data[9,11]) and on the observed pattern of transitions from these levels. The assignments $\frac{9}{2}$ and $\frac{5}{2}$ to the levels at 206 and 686 keV, respectively, are confirmed by angular correlation experiments described elsewhere[24]). Table 3 gives a comparison of experimental and theoretical reduced transition probabilities for transitions from some of the excited states.

TABLE 3

Experimental and theoretical reduced transition probabilities

Energy of initial state (keV)	Reduced transition probability	Theory	Experiment
206	$\frac{B(M2;\ \frac{9}{2}^- \to \frac{7}{2}^+)}{B(M2;\ \frac{9}{2}^- \to \frac{5}{2}^+)}$	0.485	≤ 19 [a])
619	$\frac{B(E2;\ \frac{3}{2}^+ \to \frac{7}{2}^+)}{B(E2;\ \frac{3}{2}^+ \to \frac{5}{2}^+)}$	1.33	[b])
686	$\frac{B(E1;\ \frac{5}{2}^- \to \frac{7}{2}^+)}{B(E1;\ \frac{5}{2}^- \to \frac{5}{2}^+)}$	0.40	0.53±0.06
760	$\frac{B(E2;\ \frac{7}{2}^+ \to \frac{7}{2}^+)}{B(E2;\ \frac{7}{2}^+ \to \frac{5}{2}^+)}$	0.96	$9.5^{+11.5}_{-4.3}$ [c])
775	$\frac{B(E2;\ \frac{3}{2}^+ \to \frac{7}{2}^+)}{B(E2;\ \frac{3}{2}^+ \to \frac{5}{2}^+)}$	1.33	[d])
866	$\frac{B(M1;\ \frac{5}{2}^+ \to \frac{7}{2}^+)}{B(M1;\ \frac{5}{2}^+ \to \frac{5}{2}^+)}$	0.40	$1.2^{+1.0}_{-0.6}$ [e])

[a]) The upper limit is based on an upper limit of [9,24]) 1 % M2 admixture in the 72 keV transition. Using the theoretical transition probability and the transition intensities derived from table 2 the quadrupole admixture is found to be about 4×10^{-2} %.

[b]) Assuming an upper limit of [9]) 15 % E2 admixture in the 619 keV radiation the ratio of intensities of the 485 keV and 619 keV transition is expected to be $I(485)/I\ (619) \leq 0.06$. The present experiments allow to set an upper limit of 0.05 on this ratio. The data are thus consistent.

[c]) Assuming pure E2 radiation for the 626 keV and 760 keV transitions.

[d]) The observed upper limit of [9]) 15 % E2 admixture in the 775 keV transition establishes $I(641)/I(775) \leq 0.08$. The present measurements allow to set an experimental limit of 0.06 on this ratio. The data are thus mutually consistent.

[e]) Assuming pure M1 radiation for the 732 keV and 866 keV transition.

The levels at 134 keV and 301 keV may be characterized with ample evidence as members of the rotational band associated with the ground state configuration. The first intrinsic state occurs at 206 keV and appears to correspond with the $\frac{9}{2}^-$ [514] orbital which is predicted in this region. The 72 keV transition then is $\nu = 1$ K-forbidden.

As regards the higher energy levels only tentative assignments can be made. The 514 keV level is obviously identical with the excited state found by Gallagher *et al.* at 511.6 keV. As has already been pointed out by these authors, it is difficult to interpret this level within the framework of the Nilsson theory. The almost pure E2 decay to the ground state and the absence of a transition to the $\frac{7}{2}^+$ state at 134 keV suggest a spin assignment of $\frac{1}{2}^+$. For energy reasons, only the hole-excitation $\frac{1}{2}^+$ [411] has to be considered for interpretation. The only other intrinsic state of spin $\frac{1}{2}^+$ is the particle-excitation $\frac{1}{2}^+$ [400]. This state, however, should occur at a higher energy than the state $\frac{3}{2}^+$ [402] which is assigned as the 775 keV level. Gallagher *et al.* ascribe the orbital $\frac{1}{2}^+$ [411] and its first rotational state to energy levels at 626 keV and 619 keV, respectively, assuming a large negative decoupling factor. According to subsect. 3.1, we are, however, forced to conclude that the 626 keV gamma ray is not a ground state transition, but a transition to the first excited state at 134 keV. If this result is correct, the level at 626 keV as well as the quoted assignment for the 619 keV level must be discarded. Nevertheless, the 514 keV level appears to be unexplainable as Nilsson state $\frac{1}{2}^+$ [411]. There is no experimental indication of the doublet structure which is characteristic of this configuration and which is very clearly observed in the level schemes of the neighbouring nucleides. Looking for an explanation within the framework of the collective model it seems reasonable to interpret, as suggested by Gallagher *et al.*, the 514 keV level as a gamma-vibrational level based on the ground state. The results of Coulomb excitation experiments performed by Nathan and Popov [20]) are in favour of such a proposal. One of the observed states fits energetically to the level at 514 keV.

The 619 keV level possibly corresponds to the hole-excitation $\frac{3}{2}^+$ [411], though this state should appear at a higher excitation energy. Intensity considerations are consistent with this assignment (cf. table 3).

As has been pointed out by Gallagher *et al.*, the 686 keV level, though manifesting some of the expected properties of the hole state $\frac{5}{2}^-$ [532], cannot be described as an intrinsic state in the Nilsson description. It seems probable that this level is a gamma-vibrational state associated with the $\frac{9}{2}^-$ particle excitation at 206 keV. The experimental ratio of reduced transition probabilities for the gamma rays proceeding to the ground state rotational band is in fair agreement with the theoretical prediction (cf. table 3).

Assuming that the transition multipolarities deduced from conversion data [9, 11]) are correct the necessity of placing a level at 760 keV poses a knotty question concerning the theoretical interpretation of this state. In the absence of more information one is somewhat left with speculations. If the 760 keV level has spin and parity $\frac{3}{2}^+$ or $\frac{5}{2}^+$, it could possibly be the particle excitation state $\frac{3}{2}^+$ [402] or the hole-excitation states

$\frac{3}{2}^+$ [422] and $\frac{5}{2}^+$ [413]. However, if it is either of these states, it is not easy to explain the observed branching to the ground state rotational band. An orbital with spin $\frac{9}{2}^+$ is not predicted in this energy region. In addition, a $\frac{9}{2}^+$ assignment would leave unexplained the feeding of this level. As a consequence, only the hole-excitation $\frac{7}{2}^+$ [404] seems to remain as a possible interpretation. According to the selection rules in the asymptotic quantum numbers the M1 transition from this configuration to the ground state rotational band is expected to be very strongly hindered. The E2 decay is also retarded but probably much less. These hindrances may explain a large E2 admixture in the decay to the ground state configuration. However, the experimental ratio of reduced E2 transition probabilities for the 626 keV and 760 keV transitions is at least a factor of 5 larger than is predicted by the simple intensity rules (cf. table 3). Deviations from these rules may sometimes be expected if rotational admixtures in the wave functions contribute a significant part of the matrix elements. Of course, for $\Delta K = 1$ it is found that the E2 transition intensities are not affected if the nuclear deformations for the two states are approximately the same †, but Re^{187} is in a region where intrinsic excitations may occur involving a change of nuclear deformation. Thus, it seems reasonable to assume that the classification $\frac{7}{2}^+$ [404] is not ruled out a priori by the observed deviation from the theoretical prediction. If the assignment to the 760 keV state is correct, the beta decay to this level would be alpha-type first forbidden, hindered.

The 775 keV level is assigned as Nilsson state $\frac{3}{2}^+$ [402]. The failure to observe a transition to the 134 keV state is consistent with this classification (cf. table 3; see also ref. [9])).

A possible interpretation of the 866 keV level is the hole-excitation $\frac{5}{2}^+$ [413]. As a consequence of the low intensities of the 732 keV and 866 keV transitions large errors are involved in the experimental reduced transition probabilities (cf. table 3). The results, therefore, preclude a statement regarding the proposed assignment. If the classification is correct, the beta decay to this level would be first forbidden, unhindered. A calculation of the log ft value from the gamma transition intensities leads to log $ft \approx 7.6$. This value is somewhat greater than is usually encountered for a first forbidden, unhindered transition. Energetically the 866 keV level fits to the second state reported as a result of Coulomb excitation experiments [20]). However, it seems to be more likely that these levels are not identical, in particular if the level observed in Coulomb excitations corresponds to the $\frac{9}{2}^+$ vibration. The evidence found for two weak lines at 807 and 866 keV in conversion electron measurements [11]) is in favour of this assumption.

From the discussion of the levels it seems that, apart from the possible occurrence of two gamma-vibrational states, the observed level structure can be interpreted within the framework of the Nilsson description.

The author would like to thank Professor Dr. K. Wirtz and Dr. K. H. Beckurts for their continued interest and guidance concerning this work.

† An example is provided by the decay of the 480 keV state in Ta^{181}.

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