Low-K two-quasiparticle states in ^{180}Ta

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Excited states in ^{180}Ta, populated in the ^{180}Hf(p,n) and $(d,2n)$ reactions, were investigated by in-beam γ-ray and conversion-electron spectroscopy. In addition to the excited two-quasiparticle bands with $K^{\pi}=0^{-}$ and 1^{-} known from previous work, we have identified six other low-lying two-quasiparticle bands with $K \leqslant 4$. At intermediate K, 12 previously unkown levels were identified that could, however, not be associated reliably with rotational bands. These levels might be of significance in connection with the as yet unresolved problem of the stellar production mechanism for the 9^{-} isomer of ^{180}Ta. At higher K we observe only levels known from the previous in-beam γ-spectroscopic studies with heavier projectiles, but suggest for some levels a different ordering into rotational bands based on band-mixing considerations. We also report a deuteron spectrum measured in the ^{181}Ta$(p,d)^{180}$Ta reaction with high resolution and statistics. This spectrum served for configuration assignments and yields an energy of 78 ± 1 keV for the 9^{-} isomer in ^{180}Ta.

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I. INTRODUCTION

The nuclear structure of the doubly odd nucleus ^{180}Ta is of current interest in connection with the nucleosynthesis of this isotope. The ^{180}Ta species found in nature, with an abundance of 0.012%, is a quasistable 9^{-} isomer ($t_{1/2} > 10^{15}$ yr) at an excitation energy of approximately 78 keV, whereas the 1^{+} ground state decays with a half-life of 8 h. In spite of considerable experimental and theoretical efforts, the production and survival of the spin-trap isomer in nucleosynthesis is not clear [1,2]. One open question is the extent of the coupling of the isomer and the ground state in the photon bath of the stellar environment via resonant excitation of higher-lying excited levels. An understanding of this problem requires a detailed knowledge of the nuclear structure of ^{180}Ta.

The experimental knowledge on the nuclear excitations of ^{180}Ta available before 1996 is summarized in Ref. [3]. Excited states were studied in proton and neutron transfer on targets of ^{179}Hf and ^{181}Ta. The intrinsic levels observed in ^{180}Ta are essentially restricted to those due to the coupling of the proton ground state of ^{181}Ta with the intrinsic neutron states and the coupling of the neutron ground state of ^{179}Hf with the intrinsic proton states. Furthermore, these investigations do not provide information on the γ decay of the identified levels. Recently, excited states in ^{180}Ta were studied with in-beam γ-ray spectroscopic methods following compound reactions with ^{7}Li and ^{11}B ions [4–6] and deep-inelastic reactions [7]. In these investigations many low-lying two-quasiparticle states and their associated rotational bands were identified, but due to the nature of the reactions used preferentially excitations with high K (the projection of the spin on the nuclear deformation axis) are populated. Below $K=4$ only two excited two-quasiparticle states were observed, which were already known from the previous transfer experiments.

In order to identify the two-quasiparticle states in ^{180}Ta with low and intermediate K we have performed in-beam γ-ray and conversion-electron spectroscopy following the (p,n) and $(d,2n)$ reactions [8]. The results of these investigations are reported in the present paper. In addition, we present the results of an earlier high-resolution measurement of the deuteron spectrum in the reaction ^{181}Ta$(p,d)^{180}$Ta [9] that is an essential help in the assignment of two-quasiparticle configurations to the levels observed in ^{180}Ta.

II. EXPERIMENTAL METHODS AND RESULTS

The ^{180}Hf$(p,n)^{180}$Ta reaction is expected to dominate at proton bombarding energies below 10 MeV, as compared to the Coulomb barrier for this reaction of ≈ 13 MeV. We, therefore, chose the $(d,2n)$ reaction for our first measurements. In a later measurement of the excitation functions for the (p,xn) reactions, we found that the (p,n) reaction at $E_p \approx 9$ MeV is most favorable for the investigation of the low-spin-level structure of ^{180}Ta [10,11]. In this section, we will first present some results obtained in the $(d,2n)$ reaction followed by a more detailed discussion of the results obtained in the (p,n) reaction. The deuteron spectrum measured in the ^{181}Ta$(p,d)^{180}$Ta reaction will then be presented and in a final subsection we will give a graphical summary of the band structure observed in ^{180}Ta.

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TABLE I. Energies of selected γ rays in ^{180}Ta.

Transition $(I^\pi,K)_i$	$(I^\pi,K)_f$	E_γ (keV) Present work[a]	Ref. [4]	Ref. [5]
4^-,0	3^-,0	83.86	83.9	83.9
5^-,0	4^-,0	101.64	101.5	101.7
0^-,0	1^+,1	107.71	107.8	107.6
6^-,0	5^-,0	127.84	127.8	127.6
7^-,0	6^-,0	138.19	138.0	138.3
8^-,0	7^-,0	171.30	171.2	170.9
4^-,4	3^-,1	177.68		
3^-,1	4^-,0	226.04		
2^-,1	3^-,0	243.74		
1^-,1	2^-,0	252.39	252.5	252.1
1^-,1	0^-,0	315.63	315.8	315.4
2^-,1	1^-,0	347.53	347.8	346.8
3^-,1	2^-,0	373.07	373.5	372.8
5^+,4	4^+,4	121.44	121.1	121.8
4^+,4	3^+,1	409.14	409.1	408.8
8^+,8	9^-,9	100.75	100.7	100.6
6^-,6	7^-,7	111.32	111.0	111.1
7^+,7	8^+,8	179.12	179.0	178.9
9^+,8	8^+,8	196.35	196.3	196.2
6^-,6	7^+,7	217.88	218.0	
10^+,8	9^+,8	221.22	221.3	221.1
7^-,7	8^+,8	285.60	285.7	285.3

[a]Estimated accuracy ± 0.05 keV.

A. $\gamma\gamma$ coincidences following the ^{180}Hf$(d,2n)^{180}$Ta reaction

A target of 8 mg/cm^2 HfO_2 enriched to 94.3% in ^{180}Hf was bombarded with 12.4 MeV deuterons at the cyclotron of the PSI (Villigen, Switzerland). Gamma-gamma coincidences were measured using a setup containing five Compton-suppressed Ge detectors [12]. A total of ≈ 5 million twofold coincidences were recorded in list mode, sorted with an appropriate time window into a $4k \times 4k$ matrix and analyzed with the interactive RADWARE package [13].

In addition to the $(d,2n)$ reaction, we observed the deuteron breakup reactions leading to ^{181}Hf, ^{180}Hf, and ^{179}Hf. Using the precisely known energies of γ rays in ^{181}Ta (from the radioactive decay of ^{181}Hf), ^{180}Hf, and ^{179}Hf, we derived accurate energies for the strong γ rays in ^{180}Ta listed in Table I. For comparison the energies reported in Refs. [4,5] are also included in the table. We note in this connection a problem with the γ-ray energies reported by Saitoh *et al.* [5]: the energies of the $\Delta I = 1$ and $\Delta I = 2$ transitions within rotational bands are inconsistent, with, e.g., a systematic discrepancy of ≈ 0.4 keV for the energies between ≈ 250 keV and ≈ 500 keV.

For all weak γ rays our $\gamma\gamma$ coincidences measured in the (p,n) reaction provide better information, apart from a few transitions between high-spin states, due to much better counting statistics. We will, therefore, only discuss two examples of the $(d,2n)$ data and include the results in the tables presented in the following section.

The γ-ray spectra in coincidence with the 100.8 keV $8^+ \rightarrow 9^-$ transition measured in the (p,n) and $(d,2n)$ reactions are shown in Fig. 1. This comparison illustrates the much better counting rates obtained in the (p,n) reaction (see also Fig. 3), but also the enhancement of the population of the states with increasing spin in the $(d,2n)$ reaction: the 179.1 and 285.6 keV γ rays result from the decay of levels with spin 7, whereas the 196.4 and 338.0 keV γ rays depopulate levels with spin 9 and 8, respectively.

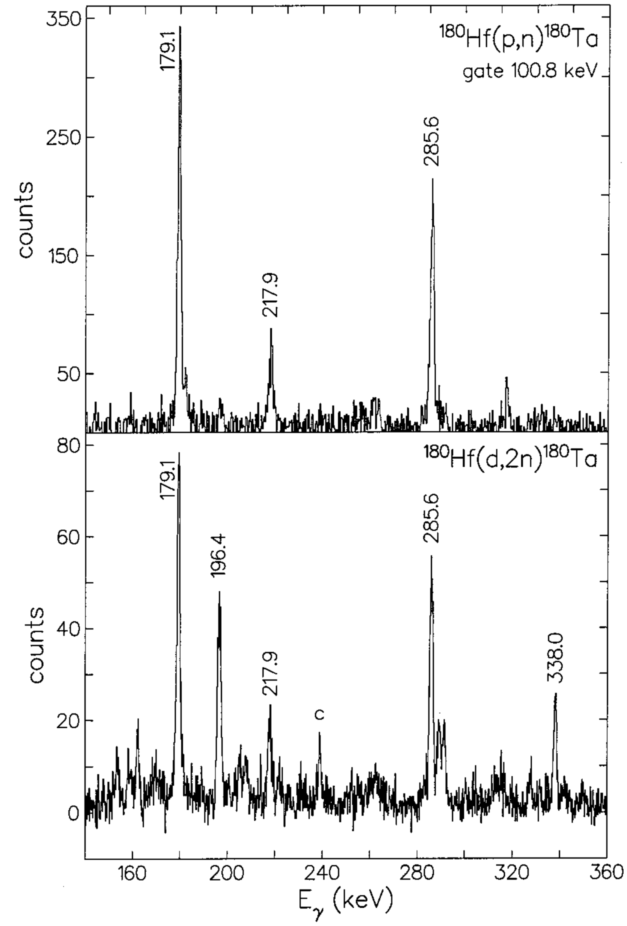

FIG. 1. Gamma-ray spectra in coincidence with the 100.8 keV $8^+ \rightarrow 9^-$ transition measured in the (p,n) and $(d,2n)$ reactions.

To illustrate the limit for the identification of $\gamma\gamma$ coincidences imposed by the energy resolution, we show in Fig. 2 the γ ray spectra in coincidence with 217.2 and 217.9 keV transitions. The peaks resulting from the γ rays in coincidence with the gate transitions are labeled by the γ-ray energies.

B. $\gamma\gamma$ coincidences following the ^{180}Hf$(p,n)^{180}$Ta reaction

Gamma-gamma coincidences following the (p,n) reaction were measured at the Bonn cyclotron with a coincidence setup containing five Compton-suppressed Ge detectors. A 9 mg/cm^2 thick target of HfO_2 enriched to 94.3% in ^{180}Hf was bombarded with 8.9 MeV protons. A total of ≈ 15 million twofold coincidences in ^{180}Ta were accumulated during an effective time of data accumulation of 4 days. Again, the list-mode data were sorted into a $4k \times 4k$ matrix and analyzed with the RADWARE package [13].

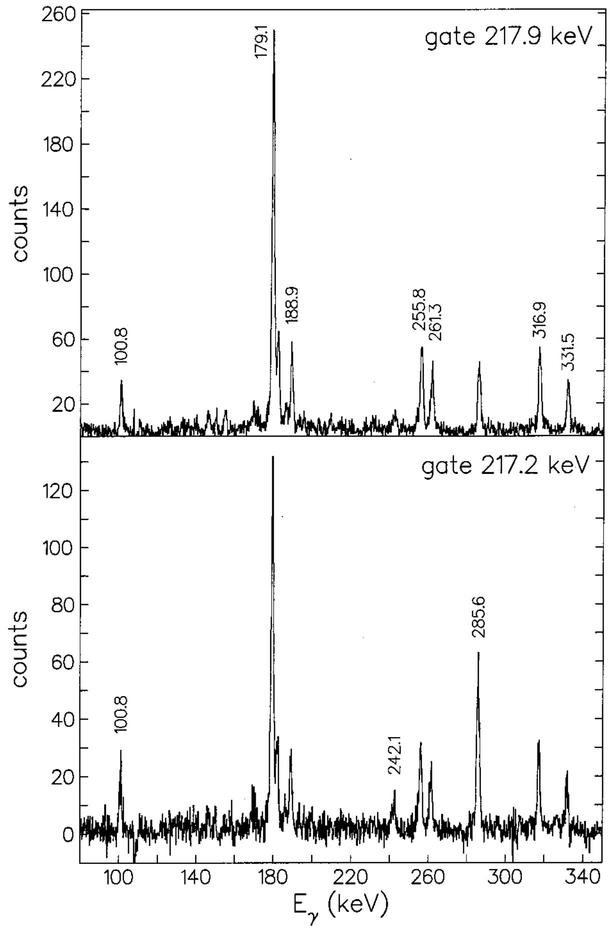

FIG. 2. Gamma-ray spectra in coincidence with 217.2 and 217.9 keV transitions measured in the $(d,2n)$ reaction.

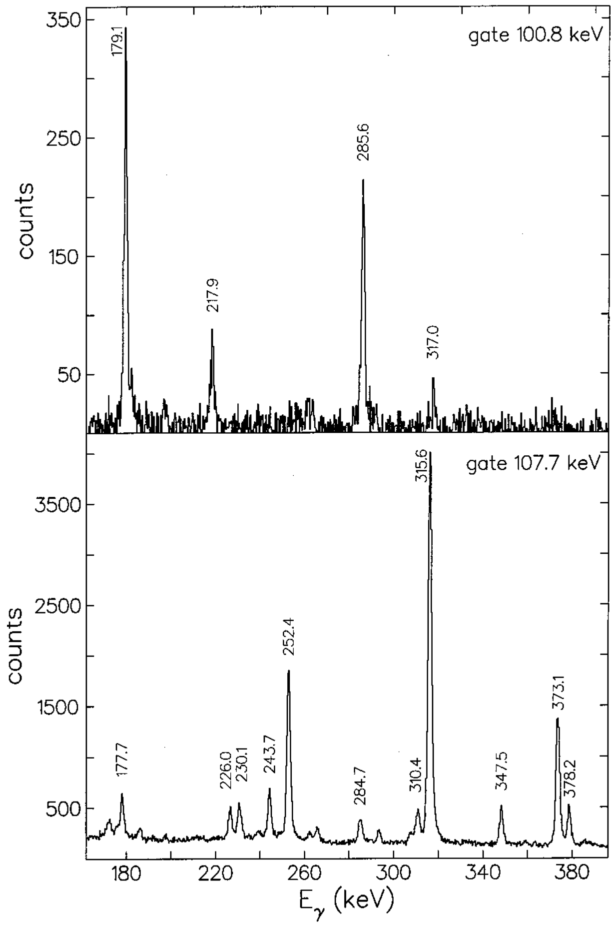

FIG. 3. Gamma-ray spectra in coincidence with the 100.8 keV $8^+ \to 9^-$ and 107.7 keV $0^- \to 1^+$ transitions.

As an illustration of the quality of our data and our reasoning for the assignment of the γ rays in the level scheme of ^{180}Ta, we show some γ-ray spectra in Figs. 3–6. Sections of the γ-ray spectra in coincidence with the transitions from the bandheads of the first-excited $K^\pi = 0^-$ band to the ground state (107.7 keV γ ray) and the first-excited $K^\pi = 8^+$ band to the 9^- isomer (100.8 keV γ ray) are shown in Fig. 3. The figure illustrates the predominant population of low-spin states in the (p,n) reaction. The rotational members of the 0^- band decay by $\Delta I = 1$ intraband $M1$ transitions and, therefore, all γ rays populating this band are observed in coincidence with the 107.7 keV transition. Similarly, all γ rays from the high-spin states populated in the (p,n) reaction, which are observed in our $\gamma\gamma$ coincidence spectra, proceed via the 8^+ level.

The rotational band most strongly populated in the (p,n) reaction is the first-excited $K^\pi = 1^-$ band with its bandhead at 423 keV. The members of this band decay by $\Delta I = 1$ intraband $M1$ transitions and by $M1$ transitions to the 0^- band (e.g., the 252.4, 315.6, and 373.1 keV γ rays in Fig. 3). The depopulation of the three lowest members of the $K^\pi = 1^-$ band is shown in Fig. 4. Most significant is the predominant decay by the intraband transitions, in particular for the 2^- level. This feature will be used below in the identification of the 4^- member of this band and discussed in Sec. III D 1.

Several levels populated in the (p,n) reaction decay predominantly to the 1^+ ground band. The rotational members of this band decay by intraband transitions and thus the γ rays populating these levels are not in coincidence with the 107.7 keV $0^- \to 1^+$ transition. Up to the 4^+ member of the ground band the depopulating $\Delta I = 1$ intraband $M1$ transitions have too low energies and γ ray intensities to be detected in our coincidence setup, and therefore excited states populating predominantly these levels can only be identified in the $\gamma\gamma$ coincidence measurement if they are populated by sufficiently strong γ transitions. As an example, we show in Fig. 5 the corresponding γ-ray spectra for the two lowest members of the first-excited $K^\pi = 1^+$ band with its bandhead at 320 keV. The figure demonstrates in particular the weakness of $\Delta I = 1$ $M1$ transitions in this band: the γ rays populating the 371 keV 2^+ level and depopulating the 320 keV 1^+ level are not in coincidence. This $K^\pi = 1^+$ band, which was not known from the previous work, is one of the most strongly populated bands in the (p,n) reaction (see Table V).

The established band with the highest K decaying to the ground state is a $K^\pi = 4^+$ band with its bandhead at 520 keV. This band is a promising candidate to be involved in the transformation from the 9^- isomer to the 1^+ ground state by inelastic photon scattering or Coulomb excitation [14]. In

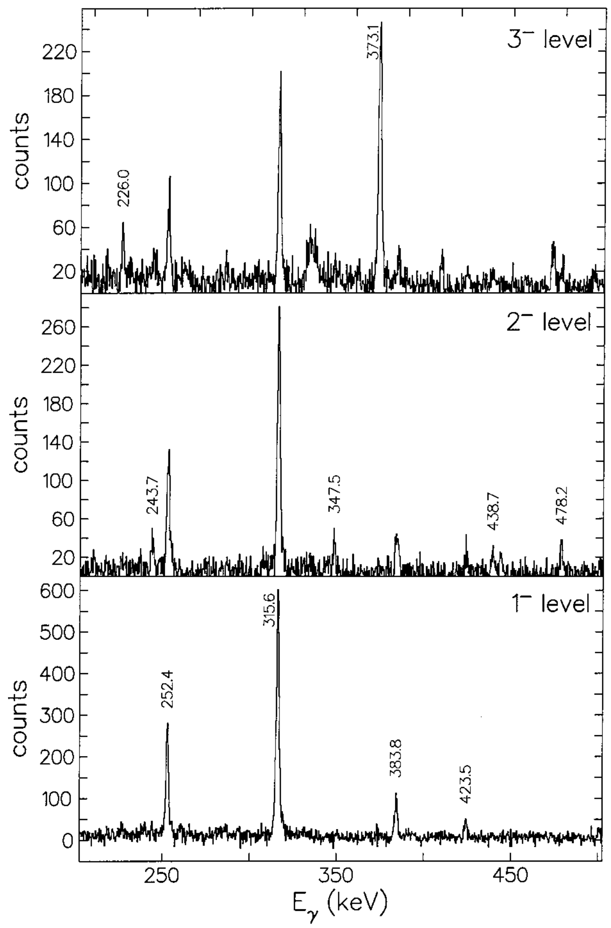

FIG. 4. Gamma-ray spectra in coincidence with γ rays populating the 423 keV 1^- level (gates on 230.1, 284.7, and 453.3 keV γ-rays), the 478 keV 2^- level (gates on 310.3 and 398.8 keV γ-rays) and the 544 keV 3^- level (gates on 177.7 and 265.2 keV γ-rays). In each spectrum the γ rays depopulating the populated level are marked by their energies.

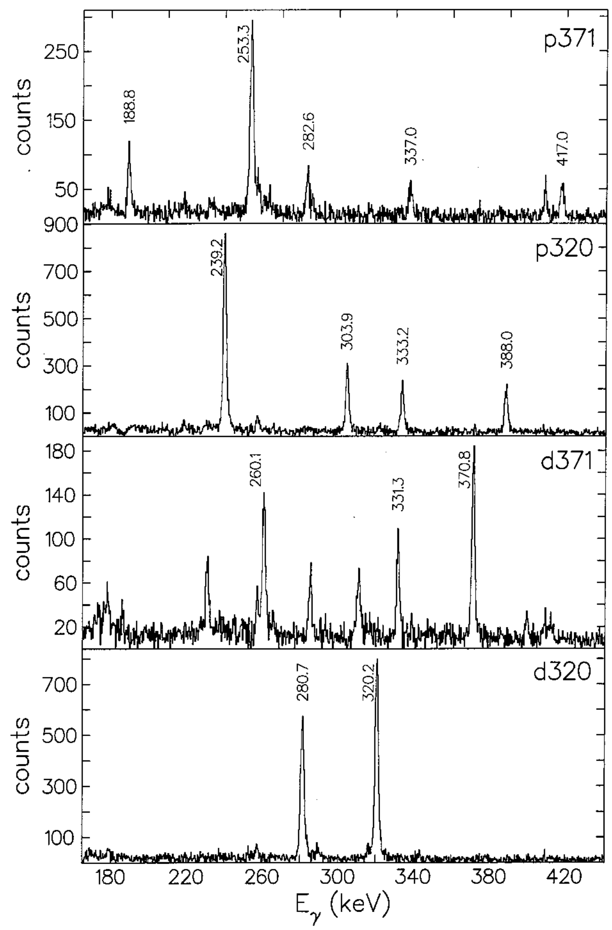

FIG. 5. Gamma-ray spectra in coincidence with γ rays populating and depopulating the two first members of the $K^\pi=1^+$ band in ^{180}Ta at 320 and 371 keV. The spectra shown were created with gates on the peaks marked in the figure by their γ-ray energies.

Fig. 6, we show a section of the γ ray spectrum in coincidence with the 409 keV transition depopulating the 520 keV 4^+ level, as observed in the (p,n) and $(d,2n)$ reactions. A comparison of these two spectra provides some information on the spins of the populated levels, as discussed below.

The γ rays observed in the (p,n) and $(d,2n)$ reactions can be categorized in three groups listed for reasons of clearness in separate tables: (1) γ rays populating and depopulating the ground band and the first-excited $K^\pi=0^-$ and $1^\pm$ bands with the exception of the 520 keV 4^+ level (bands with low K); (2) γ rays from levels depopulating via the $K^\pi=4^+$ band with the 520 keV level as bandhead (bands with intermediate K); (3) γ rays leading to the 179 keV 8^+ level (bands with high K).

The properties of the bands with low K are summarized in Table II. The γ-ray intensities listed in the table were derived, when possible, from the γ-ray spectra in coincidence with γ rays populating a given level. For those levels, for which we do not observe populating γ rays, intensity estimates were obtained from the coincidences with γ rays depopulating the level populated by the γ ray under consideration. This requires a knowledge of relative depopulation intensities that can have large uncertainties, and therefore these γ-ray intensities are listed in Table II in parentheses and should be considered as indicative values.

Most of the levels listed in Table II are only identified in the $\gamma\gamma$ coincidences by depopulating γ rays. It is clear that we do not observe the transitions to the lowest two members of the ground band for all those levels that are only populated by γ rays too weak to be observed with the $\gamma\gamma$ coincidence setup used in the present experiment. Consequently, we miss the levels that are only populated and depopulated by such γ rays. This might be a reason for our failure to identify the higher-lying $K^\pi=0^-$ bands predicted by theory (see Table VIII).

The bands with intermediate and high K are listed in Tables III and IV, respectively. Levels for which only one deexciting γ ray is observed in the $\gamma\gamma$ coincidences are only included in the tables if the coincidences are observed in both the (p,n) and $(d,2n)$ reactions (except for a few γ rays known from the previous work as indicated in the tables).

We note here that we observe, in three cases, levels with the same energy in the different K regions: (1) A level at 809.3 keV listed in Tables II and III; (2) a level at 892.6 keV

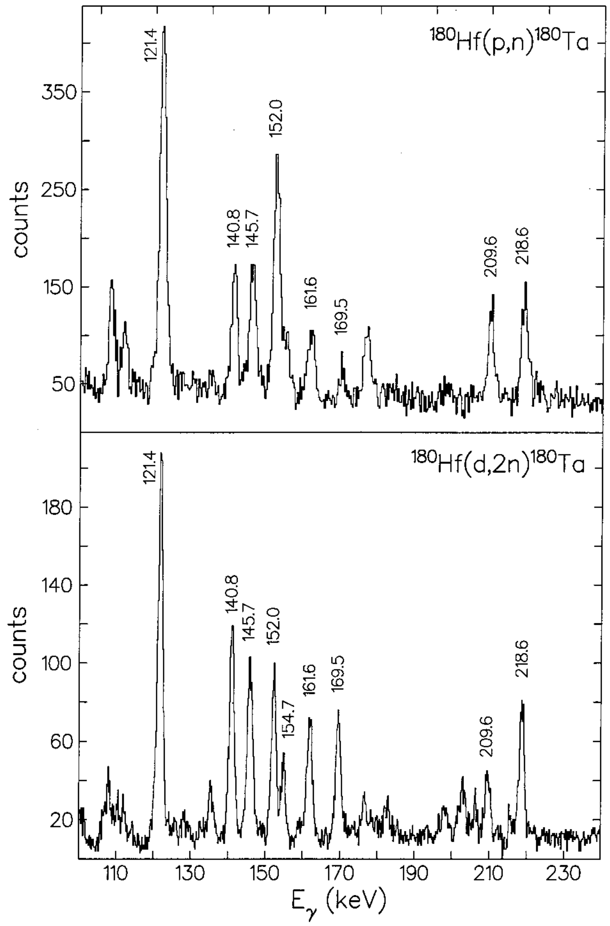

FIG. 6. Gamma-ray spectra in coincidence with the 409 keV γ ray depopulating a 4^+ level at 520 keV, observed in the (p,n) and $(d,2n)$ reactions.

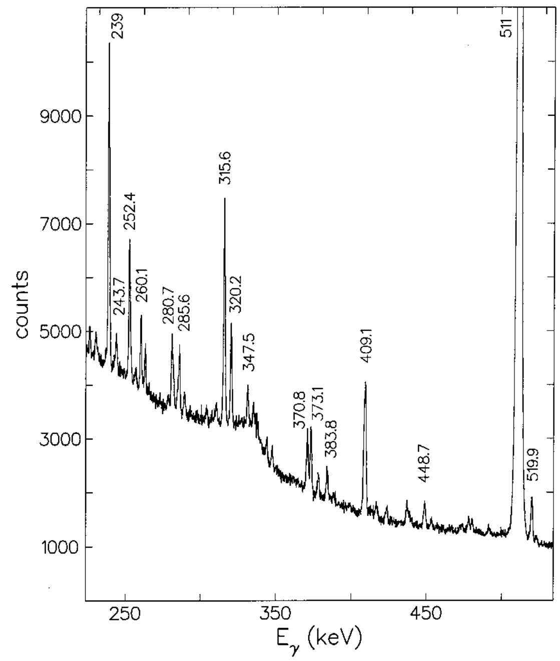

FIG. 7. Singles γ-ray spectrum following the reaction of 9.1 MeV protons with ^{180}Hf measured with a LEPS detector placed at 55° to the beam direction.

listed in Tables II and IV, which might also appear in Table III (892.9 keV level); (3) a level at 907.3 keV listed in Tables II and IV. The latter two levels are particularly interesting since they could provide a link between the 1^+ ground state and the 9^- isomer. However, we should emphasize that the energies of the levels listed in Table IV have an error of ± 1 keV and therefore the identification of these levels with those of Tables II and III is uncertain.

The configuration assignments given in Tables II–IV will be discussed in detail in Sec. III. The listing of the intensities, with separate normalization for each level, emphasizes the physics of the decay, but conceals the strength of population of the various bands observed in the (p,n) reaction, which is important for a judgment of the reliability of the proposed assignments. We, therefore, show in Fig. 7 a singles γ-ray spectrum in the region of the strong γ rays resulting from the decay of the first-excited $K^\pi = 1^+$, 2^+, and 1^- bands to the ground and first-excited $K^\pi = 0^-$ band. Apart from the 239 and 511 keV lines, all reasonably strong lines belong to ^{180}Ta. The 239 keV peak results predominantly from the decay of the 238.6 keV level in ^{179}Ta, which collects almost the total intensity of the $(p,2n)$ reaction.

The spectrum shown in Fig. 7 was used for the normalization of the intensities of γ-rays in ^{180}Ta populating the ground and 0^- bands and for the determination of *K* conversion coefficients described in Sec. II C.

Table V contains a list of γ-ray intensities for the bands that are most strongly populated in the ^{180}Hf$(p,n)^{180}$Ta reaction. For each level the transition is listed for which the intensity was normalized to 100 in Tables II–IV.

C. Conversion-electron experiments

Conversion electrons were recorded with an iron-free orange spectrometer at the Bonn cyclotron. Singles electron spectra are measured with this spectrometer by stepping the current over the region of interest. The pulse height from the electron detector (NE102 plastic scintillator viewed with a photomultiplier), and the time relative to the beam pulse are recorded on magnetic tape and analyzed off-line. For the measurement of $e^-\gamma$ coincidences, four Compton-suppressed Ge detectors are placed behind the target opposite to the spectrometer. Gamma-ray spectra are measured in coincidence with electrons of a given energy by selecting these electrons at a fixed spectrometer current. The targets used in these measurements were ≈ 400 μg/cm^2 thick layers of HfO_2 enriched to 98.3% in ^{180}Hf on ≈ 30 μg/cm^2 carbon foils.

A singles electron spectrum is shown in Fig. 8. The spectrum shown in the lower part displays electrons that are delayed by more than ≈ 3 ns with respect to the pulsed beam of the cyclotron. The steep rise of the total spectrum at low electron energies results from δ electrons. The strong 239 keV lines in the delayed spectrum result predominantly from the 239 keV isomer in ^{179}Ta. Table VI contains a list of *K* conversion coefficients for the strong peaks of Fig. 8, which

TABLE II. Transitions for levels in ^{180}Ta with low K observed in the ^{180}Hf(p,n) and ^{180}Hf$(d,2n)$ reactions.

Initial level[a]		Final level		Transition[b]	
E_{exc} (keV)	I^{π},K	E_{exc} (keV)	I^{π},K	E_{γ} (keV)	I_{γ} (rel.)
0.0[f]	1^{+},1				
39.5[f]	2^{+},1	0.0	1^{+},1	39.5	
107.7[g]	0^{-},0	0.0	1^{+},1	107.7	
110.7[f]	3^{+},1	39.5	2^{+},1	71.2	
130.3[g]	1^{-},0	107.7	0^{-},0	22.7[c]	
171.0[g]	2^{-},0	130.3	1^{-},0	40.6	
184.8[f]	4^{+},1	110.7	3^{+},1	74.1	100
		39.5	2^{+},1	145.3	≈8
234.1[g]	3^{-},0	171.0	2^{-},0	63.2	
310.8[f]	5^{+},1	110.7	3^{+},1	200.2	≈13
		184.8	4^{+},1	126.0	100
318.0[g]	4^{-},0	234.1	3^{-},0	83.9	
320.2 [h]	1^{+},1	0.0	1^{+},1	320.2	100
		39.5	2^{+},1	280.7	66
370.8 [h]	2^{+},1	0.0	1^{+},1	370.8	100
		39.5	2^{+},1	331.3	45
		110.7	3^{+},1	260.1	59
416.2[f]	6^{+},1	184.8	4^{+},1	231.4	36
		310.8	5^{+},1	105.4	100
419.6[g]	5^{-},0	318.0	4^{-},0	101.6	
423.3[i]	1^{-},1	0.0	1^{+},1	423.5	9
		39.5	2^{+},1	383.8	18
		107.7	0^{-},0	315.6	100
		130.3	1^{-},0	293.0	3
		171.0	2^{-},0	252.4	37
447.9 [h]	3^{+},1	39.5	2^{+},1	408.4	100
		110.7	3^{+},1	337.2	25
		184.8	4^{+},1	262.8	32
477.9[i]	2^{-},1	0.0	1^{+},1	478.2	126
		39.5	2^{+},1	438.7	93
		110.7	3^{+},1	367.4	⩽15
		130.3	1^{-},0	347.5	100
		171.0	2^{-},0	307.2	27
		234.1	3^{-},0	243.7	88
544.0[i]	3^{-},1	39.5	2^{+},1	504.6	≈3
		110.7	3^{+},1	433.4	⩽3
		171.0	2^{-},0	373.1	100
		184.8	4^{+},1	359.2	≈2
		234.1	3^{-},0	309.7	5
		318.0	4^{-},0	226.0	13
		423.3	1^{-},1	120.8	≈2
547.5[g]	6^{-},0	419.6	5^{-},0	127.8	
547.8 [h]	4^{+},1	110.7	3^{+},1	437.2	100
		184.8	4^{+},1	363.0	⩽10
		310.8	5^{+},1	237.0	21
549.1 [j]	3^{-},3	171.0	2^{-},0	378.2	100
		477.9	2^{-},1	71.3[c]	
559.4 [k]	2^{+},2	0.0	1^{+},1	559.6	23
		39.5	2^{+},1	519.9	100
		110.7	3^{+},1	448.7	53
		130.3	1^{-},0	429.3	⩽15
		320.2	1^{+},1	239.2	13
		370.8	2^{+},1	188.8	2
600.3[f]	7^{+},1	310.8	5^{+},1	289.6	29
		416.2	6^{+},1	184.0	100
624.1 [k]	3^{+},2	0.0	1^{+},1	624.3	100
		320.2	1^{+},1	303.9	63
		370.8	2^{+},1	253.3	78
		447.9	3^{+},1	176.2	22
		559.4	2^{+},2	64.7[c]	
645.4 [j]	[4^{-},3]	234.1	3^{-},0	411.3	(100)
		544.0	3^{-},1	101.4	(100)
653.4[l]	1^{-},1	0.0	1^{+},1	653.4[d]	
		320.2	1^{+},1	333.2	(51)
		370.8	2^{+},1	282.6	(27)
		423.3	1^{-},1	230.1	(100)
		477.9	2^{-},1	175.5	(28)
658.3[i]	[4^{-},1]	544.0	3^{-},1	114.3	
663.6 [m]	[4^{-},4]	234.1	3^{-},0	429.4	(≈70)
		549.1	3^{-},3	114.5	(100)
676.3[h]	5^{+},1	184.8	4^{+},1	491.4	
		547.8	4^{+},1	128.5	
685.7[g]	7^{-},0	547.5	6^{-},0	138.2	
708.0 [l]	2^{-},1	0.0	1^{+},1	708.0[d]	
		320.2	1^{+},1	387.9	(60)
		370.8	2^{+},1	337.2	(15)
		423.3	1^{-},1	284.7	(100)
		447.9	3^{+},1	260.4	(32)
		549.1	3^{-},3	158.7	(≈6)
708.5 [k]	[4^{+},2]	559.4	2^{+},2	149.1[e]	
721.7 [n]	4^{-},4	544.0	3^{-},1	177.7	(100)
		549.1	3^{-},3	172.6	(≈20)
731.0		171.0	2^{-},0	560.1	(100)
		318.0	4^{-},0	412.9	(55)
735.3[f]	8^{+},1	416.2	6^{+},1	319.1	(100)
		600.3	7^{+},1	135.0	(76)
784.1 [m]	[5^{-},4]	234.1	3^{-},0	550.1	(100)
		318.0	4^{-},0	466.0	(53)
787.8 [l]	[3^{-},1]	370.8	2^{+},1	417.0	
788.2 [o]	3^{-},3	477.9	2^{-},1	310.3	
809.3 [p]	[5^{-},5]	544.0	3^{-},1	265.2	(100)
		658.3	[4^{-},1]	151.0	(100)
857.0[g]	8^{-},0	685.7	7^{-},0	171.3	
876.7 [q]	[2^{-},2]	171.0	2^{-},0	705.5	
		320.2	1^{+},1	556.7	(16)
		423.3	1^{-},1	453.3	(100)
		477.9	2^{-},1	398.8	(13)
880.7		423.3	1^{-},1	456.9	(70)
		559.4	2^{+},2	321.4	(58)
		624.1	3^{+},2	256.6	(100)
892.6		721.7	4^{-},4	170.9	
907.3 [o]	4^{-},3	721.7	4^{-},4	185.6	(100)

TABLE II. (*Continued.*)

Initial level [a] E_{exc} (keV)	I^{π},K	Final level E_{exc} (keV)	I^{π},K	Transition [b] E_{γ} (keV)	I_{γ} (rel.)
		788.2	$3^-,3$	119.3	(27)
915.8		320.2	$1^+,1$	595.6	(100)
		370.8	$2^+,1$	545.2	(22)
		423.3	$1^-,1$	492.4	(42)
935.1		0.0	$1^+,1$	934.9[d]	
		320.2	$1^+,1$	614.8	(70)
		477.9	$2^-,1$	457.0	(100)
951.5		320.2	$1^+,1$	631.3	(95)
		370.8	$2^+,1$	580.7	(100)
		423.3	$1^-,1$	528.0	(89)
977.2[f]	$9^+,1$	735.3	$8^+,1$	241.9	
996.5		370.8	$2^+,1$	625.7	(100)
		447.9	$3^+,1$	548.6	(61)
1030.5[g]	$9^-,0$	857.0	$8^-,0$	173.5	
1037.1		320.2	$1^+,1$	716.8	(100)
		370.8	$2^+,1$	666.2	(84)
1113.1		370.8	$2^+,1$	742.3	(63)
		447.9	$3^+,1$	665.2	(100)
1241.4[g]	$10^-,0$	1030.5	$9^-,0$	210.9	
1447.3[g]	$11^-,0$	1241.4	$10^-,0$	205.9	

[a]For tentative spin-parity and configuration assignments I^{π},K is given in squared brackets.
[b]Estimated accuracy ± 0.1 keV for the energies and $\pm 20\%$ for the intensities. Intensities given in parentheses are only indicative values.
[c]Gamma ray not observed.
[d]Gamma ray only observed in the singles spectrum. Its placement in the level scheme is not confirmed by $\gamma\gamma$ coincidences.
[e]Only observed in the $(d,2n)$ reaction.
[f]$\{\nu 9/2^+[624]-\pi 7/2^+[404]\}K^{\pi}=1^+$ band.
[g]$\{\pi 9/2^-[514]-\nu 9/2^+[624]\}K^{\pi}=0^-$ band.
[h]$\{\pi 9/2^-[514]-\nu 7/2^-[514]\}K^{\pi}=1^+$ band.
[i]$\{\pi 7/2^+[404]-\nu 5/2^-[512]\}K^{\pi}=1^-$ band.
[j]$\{\pi 7/2^+[404]-\nu 1/2^-[510]\}K^{\pi}=3^-$ band.
[k]$\{\nu 9/2^+[624]-\pi 5/2^+[402]\}K^{\pi}=2^+$ band.
[l]$\{\nu 7/2^-[514]-\pi 5/2^+[402]\}K^{\pi}=1^-$ band.
[m]$\{\pi 7/2^+[404]+\nu 1/2^-[510]\}K^{\pi}=4^-$.
[n]$\{\pi 7/2^+[404]+\nu 1/2^-[521]\}K^{\pi}=4^-$ band.
[o]$\{\pi 7/2^+[404]-\nu 1/2^-[521]\}K^{\pi}=3^-$ band.
[p]$\{\pi 7/2^+[404]+\nu 3/2^-[512]\}K^{\pi}=5^-$.
[q]$\{\pi 7/2^+[404]-\nu 3/2^-[512]\}K^{\pi}=2^-$.

are not contaminated by doubly assigned transitions. All transitions listed in the table have predominantly $M1$ multipolarity.

The various weak peaks in the electron spectrum can result, in general, from a superposition of conversion electrons from different atomic shells. Their composition can, in principle, be identified by measuring the coincident γ-ray spectra for a comparison with the corresponding $\gamma\gamma$ coincidence spectra. Unfortunately, most of the electron peaks that cannot be assigned from the singles measurement were too weak to allow an unambiguous assignment from the $e^-\gamma$ coincidence measurements due to lack of counting statistics. Helpful conclusions could only be obtained from two measurements:

(1) A measurement with 102 keV electrons corresponding to the L_1 conversion electrons of 114 keV transitions in tantalum performed following the (p,n) reaction. We assign two transitions with energies of 114.3 keV (658 keV

TABLE III. Transitions for levels in ^{180}Ta with intermediate K observed in the ^{180}Hf(p,n) and ^{180}Hf$(d,2n)$ reactions.

Initial level [a] E_{exc} (keV)	I^{π},K	Final level E_{exc} (keV)	I^{π},K	Transition [b] E_{γ} (keV)	I_{γ} (rel.)
519.8[f]	$4^+,4$	39.5	$2^+,1$	480.3	≈ 1.5
		110.7	$3^+,1$	409.1	100
		184.8	$4^+,1$	335.2	16
		310.8	$5^+,1$	209.1	16
		448.0	$3^+,1$	71.8[c]	
592.0[d]	$[5^{\pm},\ 5]$	519.8	$4^+,4$	72.2[d]	
641.3[f]	$5^+,4$	519.8	$4^+,4$	121.4	
671.9		519.8	$4^+,4$	152.0	
729.4		519.8	$4^+,4$	209.6	100
		641.3	$5^+,4$	88.1	≈ 1
732.8[d]	$[6^{\pm},\ 5]$	592.0	$[5^{\pm},\ 5]$	140.8	
738.4		519.8	$4^+,4$	218.6	100
		641.3	$5^+,4$	96.9	20
787.0[f]	$6^+,4$	519.8	$4^+,4$	267.2	10
		641.3	$5^+,4$	145.7	100
792.4		671.9		120.5	
809.3[g]	$[5^-,\ 5]$	519.8	$4^+,4$	289.4	
863.6		519.8	$4^+,4$	343.8	
883.9		641.3	$5^+,4$	242.6	100
		729.4		154.5	
892.9		738.4		154.5	
894.4[d]	$[7^{\pm},\ 5]$	732.8	$[6^{\pm},\ 5]$	161.6	
938.7		792.4		146.3	
956.4[f]	$7^+,4$	787.0	$6^+,4$	169.4	
991.4		519.8	$4^+,4$	471.5	51
		641.3	$5^+,4$	350.2	100
1042.9		519.8	$4^+,4$	523.1	
1076.9[d]	$[8^{\pm},\ 5]$	894.4	$[7^{\pm},\ 5]$	182.4[e]	100
		732.8	$[6^{\pm},\ 5]$	344.2[e]	83
1100.5		641.3	$5^+,4$	459.2	
1149.5[f]	$8^+,4$	787.0	$6^+,4$	362.3[e]	100
		956.4	$7^+,4$	193.2[e]	53
1204.9		519.8	$4^+,4$	685.2	100
		863.6		341.2	≈ 60

[a]For tentative spin-parity and configuration assignments I^{π},K is given in squared brackets.
[b]Estimated accuracy ± 0.1 keV for the energies and $\pm 20\%$ for the intensities.
[c]See discussion in Sec. III C.
[d]Energy proposed by Dracoulis *et al.* [4,6]. See discussion in Sec. III C.
[e]Only observed in the $(d,2n)$ reaction.
[f]$\{\pi 9/2^-[514]-\nu 1/2^-[521]\}K^{\pi}=4^+$ band.
[g]Tentative assignment: $\{\pi 7/2^+[404]+\nu 3/2^-[512]\}K^{\pi}=5^-$.

TABLE IV. Transitions for levels in ^{180}Ta with high K observed in the ^{180}Hf(p,n) and ^{180}Hf$(d,2n)$ reactions.

Initial level [a] E_{exc} (keV)	I^{π},K	Final level E_{exc} (keV)	I^{π},K	Transition [b] E_{γ} (keV)	I_{γ} (rel.)
78.0 [d]	$9^-,9$				
178.8[e]	$8^+,8$	78.0	$9^-,9$	100.8	
281.0 [d]	$10^-,9$	78.0	$9^-,9$	203.0[c]	
357.9[f]	$7^+,7$	178.8	$8^+,8$	179.1	
375.1[e]	$9^+,8$	178.8	$8^+,8$	196.4	
464.4[g]	$7^-,7$	178.8	$8^+,8$	285.6	
506.3 [d]	$11^-,9$	281.0	$10^-,9$	225.3[c]	
516.7 [h]	$8^+,8$	178.8	$8^+,8$	338.0	100
		357.9	$7^+,7$	158.9	12
575.7 [i]	$6^-,6$	357.9	$7^+,7$	217.9	100
		464.4	$7^-,7$	111.3	50
576.9[f]	$[8^+,7]$	178.8	$8^+,8$	398.1	100
		357.9	$7^+,7$	219.0	50
596.3 [e]	$10^+,8$	375.1	$9^+,8$	221.2[c]	
681.5[g]	$8^-,7$	464.4	$7^-,7$	217.2	
685.5		357.9	$7^+,7$	327.6	
724.4 [h]	$9^+,8$	375.1	$9^+,8$	349.3	$\leqslant 10$
		516.7	$8^+,8$	207.7	100
753.6 [d]	$12^-,9$	506.3	$11^-,9$	247.3[c]	
757.6		575.7	$6^-,6$	181.9	
764.5 [i]	$7^-,6$	464.4	$7^-,7$	300.1	100
		575.7	$6^-,6$	188.9	92
808.0[f]	$[9^+,7]$	375.1	$9^+,8$	433.0[c]	≈ 70
		576.9	$[8^+,7]$	231.2[c]	100
831.5		357.9	$7^+,7$	473.6	100
		464.4	$7^-,7$	367.1	≈ 5
		575.7	$6^-,6$	255.8	81
837.0		575.7	$6^-,6$	261.3	
842.2[e]	$11^+,8$	375.1	$9^+,8$	467.2[c]	100
		596.3	$10^+,8$	245.6[c]	18
867.9		576.9	$[8^+,7]$	291.0[c]	
892.6		575.7	$6^-,6$	316.9	100
		357.9	$7^+,7$	534.9	8
907.3		757.6		149.6	≈ 10
		575.7	$6^-,6$	331.6	100
923.6[g]	$9^-,7$	681.5	$8^-,7$	242.1[c]	
957.3 [h]	$10^+,8$	724.4	$9^+,8$	232.8[c]	100
977.5 [i]	$8^-,6$	464.4	$7^-,7$	512.9[c]	
		575.7	$6^-,6$	402.0[c]	
		681.5	$8^-,7$	295.8[c]	
		764.5	$7^-,6$	213.0[c]	
1017.7		831.5		186.3	

[a]The spin-parity and configuration assignments are adopted from Refs. [4–6] except for the 576.9 and 808.0 keV levels (see discussion in Sec. III D 2). All level energies have an error of ± 1 keV resulting from the uncertainty of the $9^-,9$ level.
[b]Estimated accuracy ± 0.1 keV for the energies and $\pm 20\%$ for the intensities.
[c]Only observed in the $(d,2n)$ reaction.
[d]$\{\pi 9/2^-[514]+\nu 9/2^+[624]\}K^{\pi}=9^-$ band.
[e]$\{\pi 7/2^+[404]+\nu 9/2^+[624]\}K^{\pi}=8^+$ band.
[f]$\{\pi 5/2^+[402]+\nu 9/2^+[624]\}K^{\pi}=7^+$ band.
[g]$\{\pi 7/2^+[404]+\nu 7/2^-[514]\}K^{\pi}=7^-$ band.
[h]$\{\pi 9/2^+[514]+\nu 7/2^-[503]\}K^{\pi}=8^+$ band.
[i]$\{\pi 7/2^+[404]+\nu 5/2^-[512]\}K^{\pi}=6^-$ band.

TABLE V. Selected γ-ray intensities for the rotational bands that are most strongly populated in the ^{180}Hf$(p,n)^{180}$Ta reaction.

Band K^{π}	Initial level E_{exc} (keV)	I^{π}	Transition E_{γ} (keV)	I_{γ}[a]
1^+	320.2	1^+	320.2	50
	370.8	2^+	370.8	39
1^-	423.3	1^-	315.6	100
	477.9	2^-	347.5	11
	544.0	3^-	373.1	41
2^+	559.4	2^+	519.9	56
	624.1	3^+	624.2	12
3^-	549.1	3^-	378.2	14
4^+	519.8	4^+	409.1	98
7^+	357.9	7^+	179.1	25
7^-	464.3	7^-	285.6	23

[a]Estimated accuracy $\pm 20\%$.

$\rightarrow$544 keV levels) and 114.5 keV (664 keV$\rightarrow$549 keV levels) in the level scheme of ^{180}Ta that are in coincidence with 373.1 and 378.2 keV γ-rays, respectively. The intensity ratios of these two γ rays observed in the $\gamma\gamma$ and $e^-\gamma$ measurements are identical, proving that the two 114 keV transitions have the same—almost certainly $M1$—multipolarity. Furthermore, the 151 keV γ-ray (809 keV$\rightarrow$658 keV levels) is in coincidence with delayed conversion electrons indicating that the 809 keV level has a lifetime of several nanoseconds (see also the discussion at the end of this section).

(2) A measurement with 228 keV electrons corresponding to the L_1 conversion electrons of 239 keV transitions in tantalum performed following the $(d,2n)$ reaction. In this measurement, we observe γ-rays in coincidence with electrons from the 238.6 keV transition in ^{179}Ta and the 239.2 keV transition (559 keV$\rightarrow$320 keV levels) in ^{180}Ta. Unfortunately, the $\gamma\gamma$ and $e^-\gamma$ measurements were performed at

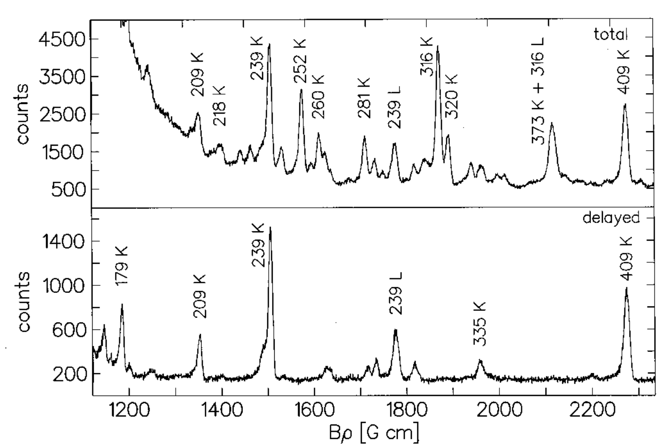

FIG. 8. Singles electron spectrum from $E_{e^-}\approx 120$ keV to ≈ 360 keV measured following the ^{180}Hf(p,n) reaction at a proton bombarding energy of 9.1 MeV. The momentum resolution $\Delta p/p$ is approximately 0.7% corresponding to an energy resolution of ≈ 1.5 keV at 120 keV and ≈ 4.0 keV at 360 keV.

TABLE VI. Comparison of experimental and theoretical *K* conversion coefficients for transitions in ^{180}Ta.

E_γ (keV)	*K* conversion coefficient Exp.[a]	$E1$	$E2$	$M1$
209.1	0.34	0.045	0.149	0.469
252.4	0.29	0.028	0.091	0.280
260.1	0.25	0.026	0.084	0.258
280.7	0.25	0.022	0.069	0.210
315.6	0.16	0.017	0.051	0.153
320.2	0.12	0.016	0.049	0.147
370.8[b]	0.08	0.011	0.033	0.099
373.1	0.09	0.011	0.033	0.098
409.1	0.10	0.009	0.026	0.077

[a]Estimated accuracy $\pm 20\%$.
[b]Corrected for the 315.6 keV L_1 conversion electrons.

different deuteron bombarding energies, thus preventing a quantitative analysis, but $E1$ multipolarity can be excluded for the 239.2 keV transition.

We have also performed $e^-\gamma$ coincidence measurements for some low-energy transitions for which the measurement of $\gamma\gamma$ coincidences is difficult because of their large internal conversion. As an example, we show in Fig. 9 the γ-ray spectrum measured in coincidence with 59.6 keV electrons corresponding to *K*, L_1, or M_1 conversion electrons of 127.0, 71.3, or 62.3 keV transitions in tantalum nuclei, respectively, measured in the $(d,2n)$ reaction. At 60 keV, the conversion-electron spectrum is completely masked by δ electrons and therefore the spectrometer current for this measurement was calculated from the calibration derived from electron peaks with $E \geqslant 83$ keV. The data were analyzed for electrons emitted without time delay with respect to the cyclotron beam (denoted prompt in Fig. 9) and with time delays of more than ≈ 3 ns (denoted delayed in Fig. 9).

Several interesting conclusions can be drawn from this measurement:

(1) The electron gate contains the L_1 conversion electrons of four transitions proposed in the level scheme of ^{180}Ta.

(i) The established 71.2 keV intraband $(3^+,1)\rightarrow(2^+,1)$ transition (111 keV$\rightarrow$40 keV levels).

(ii) The 71.3 keV $(3^-,3)\rightarrow(2^-,1)$ transition (549 keV $\rightarrow$478 keV levels) proposed in the present work. The existence of this transition is based on the observation of the 244, 316, and 348 keV γ rays (see Fig. 4) and the intensities of these three lines suggest $M1$ multipolarity for the 71.3 keV transition.

(iii) A 71.8 keV transition from the 520 keV 4^+,4 isomer to the 448.0 keV 3^+,1 level. This transition is proposed because of the observation of the 263 keV γ ray in the delayed $e^-\gamma$ spectrum. Its existence is supported by the observation of the γ rays depopulating the 448 keV level in the $\gamma\gamma$ spectrum with the 121.4 keV γ ray populating the 520 keV level as gate transition.

(iv) A 72.2 keV transition from a level at 592 keV with tentative spin-parity of 5^+ to the 520 keV 4^+ level proposed by Dracoulis *et al.* [4,6]. The energies of the L_1 and L_2 conversion electrons of a 72.2 keV transition are 0.9 and 1.4 keV higher than the nominal energy of 59.6 keV selected in the $e^-\gamma$ coincidence measurement. The energy resolution at 60 keV, corresponding to the momentum resolution of 0.7%, is 0.8 keV, but at this low energy the electron peaks are expected to be broadened due to scatterings in the ≈ 400 μg/cm^2 thick target, which is confirmed by the detection of the *M* conversion electrons of a 64.7 keV transition described below. We, therefore, conclude that we should detect a large fraction of the 72.2 keV L_1 or L_2 conversion electrons in the measurement under discussion. Dracoulis *et al.* conclude from an intensity balance argument that the 72.2 keV transition must have $M1$ or $E2$ multipolarity if it is the transition connecting a level at 592 keV, with the 141 keV γ ray as its lowest rotational transition, and the 520 keV level. For such a transition the fraction of electron conversion is 11% for the L_1 electrons of an $M1$ transition and 32% for the L_2 electrons of an $E2$ transition. Both the proposed 592 keV level and the 520 keV level are isomeric [4] and we would therefore expect the 141 keV γ ray populating the 592 keV level to be enhanced in the delayed $e^-\gamma$ spectrum relative to the 121 and 146 keV intraband γ rays of the 520 keV

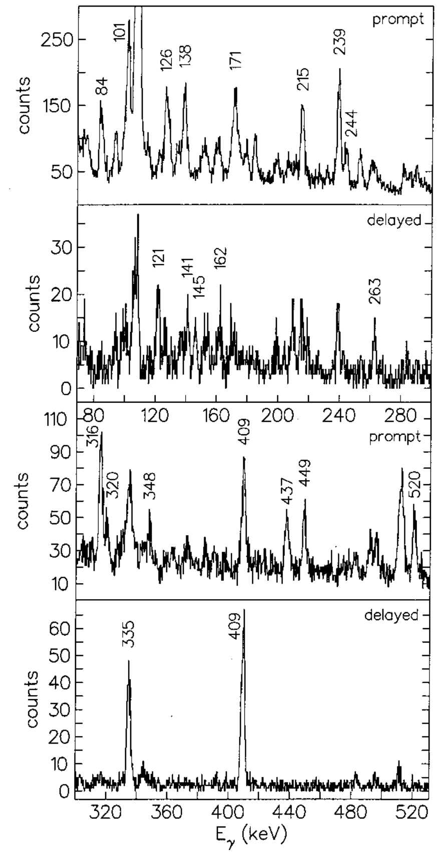

FIG. 9. Gamma-ray spectra measured in coincidence with 59.6 keV electrons following the reaction of 14.0 MeV deuterons with ^{180}Hf. The two spectra shown correspond to coincidences with electrons appearing without time delay with respect to the deuteron beam and with a delay of more than ≈ 3 ns denoted as prompt and delayed, respectively. The spectra were created with the appropriate time windows on the e^--hf TAC without any additional background subtraction.

band as compared to the $\gamma\gamma$ spectrum with the 409 keV gate transition. From the delayed $e^-\gamma$ spectrum and the $\gamma\gamma$ spectrum shown in Fig. 6 we obtain the ratios of counting rates $c(121):c(141):c(146)=100:(63\pm 11):(42\pm 13)$ and $100:(59\pm 3):(41\pm 6)$, respectively. Thus our data do not support the assignment of the 72.2 keV $M1$ or $E2$ transition proposed by Dracoulis *et al.* [4], although the accuracy of the $e^-\gamma$ data is too low to allow an unambiguous conclusion.

(2) The electron gate contains a contribution from the M_1 conversion electrons of the 64.7 keV $(3^+,3)\rightarrow(2^+,1)$ transition (624 keV→559 keV levels). The existence of this transition was first suggested by the observation of coincidences of a 257 keV γ ray populating the 624 keV level with the γ rays depopulating the 559 keV level. The observation of the 239, 449, and 520 keV γ rays in the prompt $e^-\gamma$ spectrum confirms the existence of the 64.7 keV transition and suggests its $M1$ multipolarity.

(3) The remaining γ ray peaks observed in the prompt $e^-\gamma$ spectrum can be explained as resulting from the L_1 conversion electrons of the 71.2 keV $(3^+,1)\rightarrow(2^+,1)$ transition and the K conversion electrons of the 127.8 keV $(6^-,0)\rightarrow(5^-,0)$ transition except for the 215 keV γ ray. In particular, the rather strong 437 keV γ ray observed in the prompt $e^-\gamma$ spectrum confirms its assignment as transition from a level at 548 keV to the 111 keV $(3^+,1)$ level. An unambiguous assignment of the 548 keV level from the $\gamma\gamma$ coincidences alone would have been questionable since it would be based essentially only on the observed 237 keV–126 keV coincidences. The 215 keV γ ray results presumably from the $4^+\rightarrow 2^+$ transition in ^{180}Hf, although we do not understand its origin in the $e^-\gamma$ coincidence spectrum.

The good timing of the electron detector allows the identification of electrons that are delayed with respect to the cyclotron beam by more than ≈ 1 ns. Unfortunately, all levels with nanosecond lifetimes not known from the previous work [4,5] are weakly populated in the (p,n) and $(d,2n)$ reactions, and we could therefore only obtain some rough information on lifetimes from two experiments [8,11]:

(1) In the γ-ray spectra gated by the 373 K conversion electrons the 151, 178, and 265 keV γ rays are observed in coincidence with delayed electrons. Assuming that these delays are due to lifetimes of the 722 and 809 keV levels depopulated by these γ rays we obtain a lifetime range of 1–5 ns for the two levels.

(2) From the time spectra of the conversion electrons of the 111 and 218 keV transitions depopulating the 576 keV 6^-,6 level, we obtain a lifetime of ≈ 10 ns for this level.

D. Levels of ^{180}Ta observed in the ^{181}Ta$(p,d)^{180}$Ta reaction

Levels in ^{180}Ta populated in (p,d) and (d,t) neutron transfer were studied previously by Warde *et al.* [15] and Dewberry and Naumann [16], respectively. These authors measured angular distributions for spin determinations, but the conclusions drawn from these measurements were hampered by the limited resolution (≈ 15 keV) that prevented the separation of several energy doublets. The aim of the present measurement was, therefore, to obtain a spectrum with high counting statistics and sufficient resolution to resolve the expected doublets with separations below 10 keV.

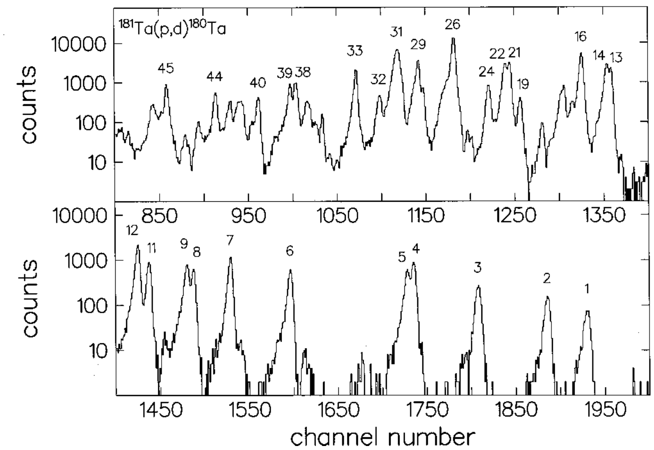

FIG. 10. Deuteron spectrum measured in the (p,d) reaction at 40° with an incident proton energy of 22 MeV.

The ^{181}Ta$(p,d)^{180}$Ta reaction was performed at the tandem accelerator of the LMU/TU München. A target of ≈ 120 μg/cm^2 high-purity (99.99%) natural tantalum on a ≈ 10 μg/cm^2 carbon backing was bombarded with 22 MeV protons. The deuterons were magnetically analyzed with a Q3D spectrometer at a laboratory scattering angle of 40°. The low-energy part of the spectrum up to approximately 1 MeV is shown in Fig. 10. In this energy region, a resolution of 4 keV (full width at half maximum) was achieved, sufficient to resolve levels with a separation of 5 keV (see, e.g., the levels number 13 and 14 in Fig. 10).

The excitation energies of the levels populated in the ^{181}Ta$(p,d)^{180}$Ta reaction were derived by an internal calibration using the precisely known energies from the in-beam γ-ray spectroscopy. The energy calibration was performed with 21 levels from 0 to 788 keV that could be reproduced with a quadratic calibration function with an average deviation of ± 0.5 keV. Among the calibration peaks were six peaks involving the excitation energy of the 9^- isomer, which was used as an additional parameter in the calibration fit. A fit using all six levels yields $E_{exc}(9^-)=78.7\pm 0.5$ keV whereas a value of 77.4 ± 0.5 keV is obtained from the separation of the $(4^+,1)$ and $(8^+,8)$ levels (levels number 4 and 5 in Fig. 10). We therefore adopt a result of $E_{exc}(9^-)=78.0\pm 1.0$ keV, which is somewhat larger than the value 75.3 ± 1.4 keV derived in the most recent compilation from mass differences [3]. Table VII contains a list of the peaks that have a counting rate of 500 or more. We believe that these peaks correspond to levels in ^{180}Ta with the protons occupying the $7/2^+[404]$ orbital.

E. Band structure in ^{180}Ta

In this section we will graphically display the structure of the rotational bands listed in Tables II–IV. A detailed discussion of the adopted assignments will be given in the following sections.

The rotational bands associated with low K are shown for clarity in two separate figures. The first-excited bands with

TABLE VII. Nuclear levels in ^{180}Ta populated in the ^{181}Ta$(p,d)^{180}$Ta reaction.

Peak number	I^{π},K	Excitation energy [a]	Counts at $\Theta_{lab}=40°$	Neutron transferred
1	1^{+},1	0.0*	561	$9/2^{+}[624]$
2	2^{+},1	39.8*	1009	$9/2^{+}[624]$
3	3^{+},1	111.1*	1765	$9/2^{+}[624]$
4	8^{+},8	178.9*	5305	$9/2^{+}[624]$
5	4^{+},1	185.6*	3050	$9/2^{+}[624]$
6	5^{+},1	310.8*	3345	$9/2^{+}[624]$
7	9^{+},8	375.8*	5798	$9/2^{+}[624]$
8	6^{+},1	416.5*	3364	$9/2^{+}[624]$
9	1^{-},1	423.2*	3726	$5/2^{-}[512]$
10		425.8	608	
11	7^{-},7	465.2*	4879	$7/2^{-}[514]$
12	2^{-},1	477.4*	11073	$5/2^{-}[512]$
13	3^{-},1	544.0*	11041	$5/2^{-}[512]$
14	$3^{-},3_1$	548.4*	12556	$1/2^{-}[510]$
15		572.2	743	
16	6^{-},6	576.8*	25142	$5/2^{-}[512]$
17	10^{+},8	596.6*	3637	$9/2^{+}[624]$
18	7^{+},1	600.3*	1687	$9/2^{+}[624]$
19	$[4^{-},3_1]$ [b]	646.3	2024	$1/2^{-}[510]$ [b]
20		654.1	611	
21	$[4^{-},1]$ [b]	658.4*	15725	$5/2^{-}[512]$ [b]
22	$[4^{-},4_1]$ [b]	663.3*	12943	$1/2^{-}[510]$ [b]
23		680.5	1221	
24	8^{-},7	682.7*	3219	$7/2^{-}[514]$
25		717.3	2426	
26	$4^{-},4_2$	722.3*	65900	$1/2^{-}[521]$
27		733.4	2262	
28		758.1	3378	
29	7^{-},6	763.6	18007	$5/2^{-}[512]$
30	$[5^{-},4_1]$ [b]	784.0	12731	$1/2^{-}[510]$ [b]
31	$3^{-},3_2$	788.0*	41177	$1/2^{-}[521]$
32	$[5^{-},5]$ [b]	808.5	2632	$3/2^{-}[512]$ [b]
33	$5^{-},4_2$	836.4	8794	$1/2^{-}[521]$
34	$[2^{-},2]$ [b]	876.5	626	$3/2^{-}[512]$ [b]
35		884.5	528	
36		891.3	1121	
37		895.0	1471	
38	$4^{-},3_2$	907.7	5419	$1/2^{-}[521]$
39		914.5	3695	
40		952.6	2126	
41		973.0	1296	
42	8^{-},6	977.3	1351	$5/2^{-}[512]$
43		986.2	1607	
44		1003.7	2817	
45		1062.6	4177	
46		1075.9	710	
47		1080.0	1344	

[a]The levels used for the energy calibration are marked by an asterisk.

[b]Tentative assignment.

$K\leqslant 1$ are shown in Fig. 11. The ground and 0^{-} bands, which are displayed in this figure up to the levels with spin 8, are known from previous work up to $I^{\pi}=16^{+}$ and 13^{-}, respectively.

The higher-lying rotational bands with low *K* are shown in Fig. 12. We note here that several levels are listed in Table II that are not assigned to rotational bands and are, therefore, not shown in the figure.

The levels depopulating via the $K^{\pi}=4^{+}$ band are shown in Fig. 13. Levels not assigned to rotational bands are shown in the right part of the figure. The 4^{+} and $(5^{\pm})$ bands were known from previous work [4–6], all additional levels are new.

The high-spin levels assigned to rotational bands are shown in Fig. 14. Eight additional levels with unknown assignments are listed in Table IV from which three (758, 837, and 868 keV levels) are new, all others known from the previous work of Refs. [4–6].

III. DISCUSSION

The low-lying energy spectrum of the deformed nucleus ^{180}Ta is expected to consist of rotational bands built on two-quasiparticle levels resulting from the coupling of a neutron and a proton outside an even-even ^{178}Hf core. The two valence nucleons occupy Nilsson orbitals, and each set of two orbitals with Ω_p and Ω_n gives rise to a doublet of two-quasiparticle states with $K^{\pm}=|\Omega_n\pm\Omega_p|$. Their relative location is given by the Gallagher-Moszkowski rule stating that the lower-lying level is the one for which the projections of the odd-particle spins are parallel [17].

The two-quasiparticle states in ^{180}Ta below ≈ 1 MeV calculated by Dracoulis *et al.* [4] using a BCS formalism are listed in Table VIII (to avoid negative excitation energies, we have shifted the energies listed by Dracoulis *et al.* by 6 keV). A similar calculation was performed by Saitoh *et al.* [5] who obtain almost perfect agreement between experimental and calculated two-quasiparticle energies. Unfortunately, these authors list only results for the states, for which experimental energies were known, and it is not clear to which extent the agreement was achieved by adjusting the model parameters to reproduce these experimental energies.

The experimental two-quasiparticle states established in the earlier investigations [4,5] and in the present work are also included in Table VIII. The adopted configuration assignments will be discussed below (tentative assignments are indicated by listing the energies in parenthesis). In the comparison of the experimental and calculated two-quasiparticle energies one should note, however, that certain rotational corrections were neglected in the BCS calculation as discussed by Dracoulis *et al.* [4]. According to these authors this may have the effect that the energy of the state with $K=\Omega_n+\Omega_p$ is underestimated if the state with $K=\Omega_n-\Omega_p$ is correctly predicted.

The observed two-quasiparticle states in ^{180}Ta can be divided up into three groups: (1) States with the proton occupying the $7/2^{+}[404]$ orbital (first column of Table VIII). These levels are selectively populated in the neutron transfer from ^{181}Ta. (2) States with the neutron occupying the

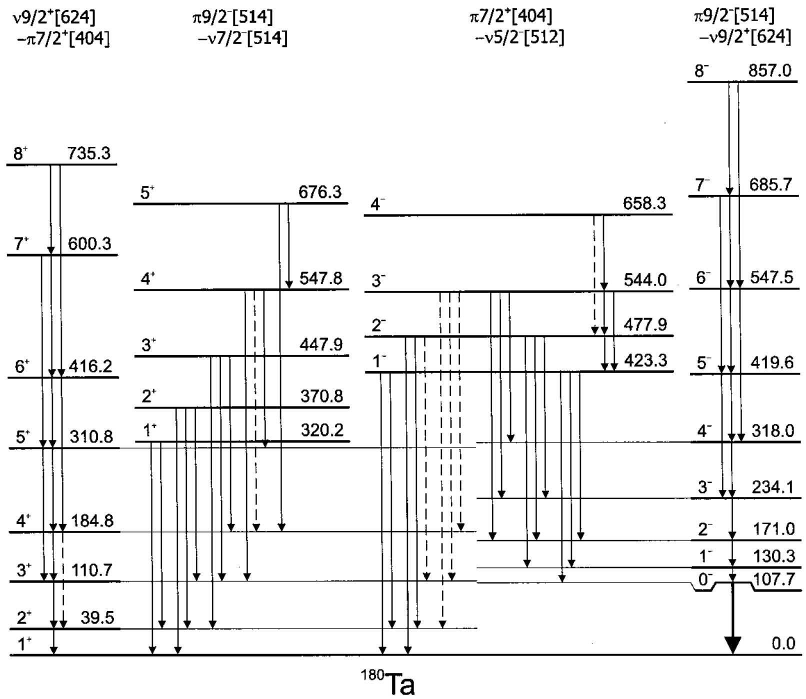

FIG. 11. First-excited rotational bands with $K\leqslant 1$.

9/2$^+$[624] orbital (first row of Table VIII), which are populated in the proton transfer from ^{179}Hf. (3) All other states that are not, or only very weakly, populated in the aforementioned transfer reactions. In the following we will discuss the experimental evidence for the two-quasiparticle states in ^{180}Ta according to this grouping in three separate subsections. In this discussion we will frequently refer to calculated values for the g_K and g_R factors determining the intraband $M1$ transitions. For later use we summarize here the relevant relations.

The expression for the reduced $M1$ transition probabilities within a rotational band (intraband transitions) has the form [18]

$$B(M1;I_i,K\rightarrow I_f,K)=\langle I_iK10|I_fK\rangle^2\langle K|\mathcal{M}(M1,\nu=0)|K\rangle^2. \tag{1}$$

In the odd-odd case the $M1$-matrix elements can be written [19] as

$$\langle K|\mathcal{M}(M1,\nu=0)|K\rangle=\sqrt{\frac{3}{4\pi}}\frac{e\hbar}{2Mc}G^{KK}, \tag{2}$$

with

$$G^{KK}=\Omega_p(g_{\Omega_p}-g_R)+\Omega_n(g_{\Omega_n}-g_R), \tag{3}$$

where the g_Ω are the single-particle gyromagnetic factors and the signs of Ω_p and Ω_n are taken as in $K=\Omega_p+\Omega_n$. It is customary to introduce the two-quasiparticle gyromagnetic

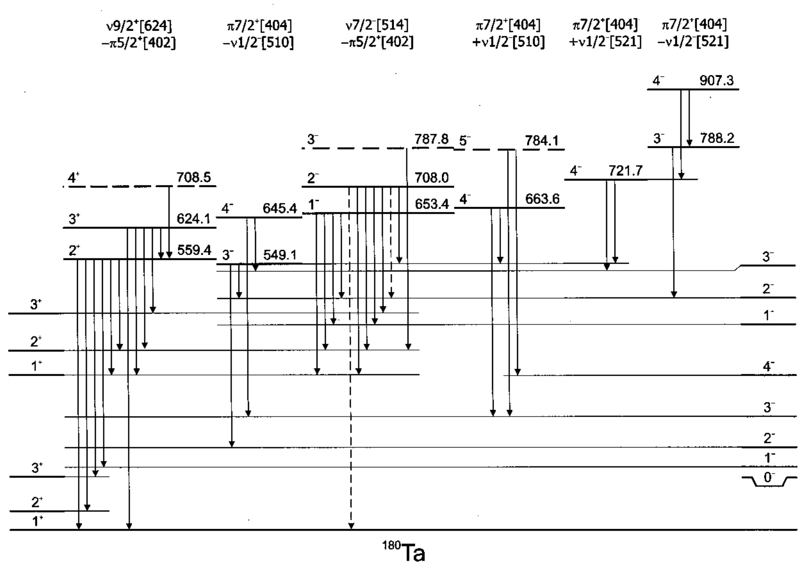

FIG. 12. Rotational bands that decay to the ground and first-excited $K^\pi=1^+$ bands (shown on the left of the figure) and the first-excited $K^\pi=0^-$ and 1^- bands (shown on the right of the figure).

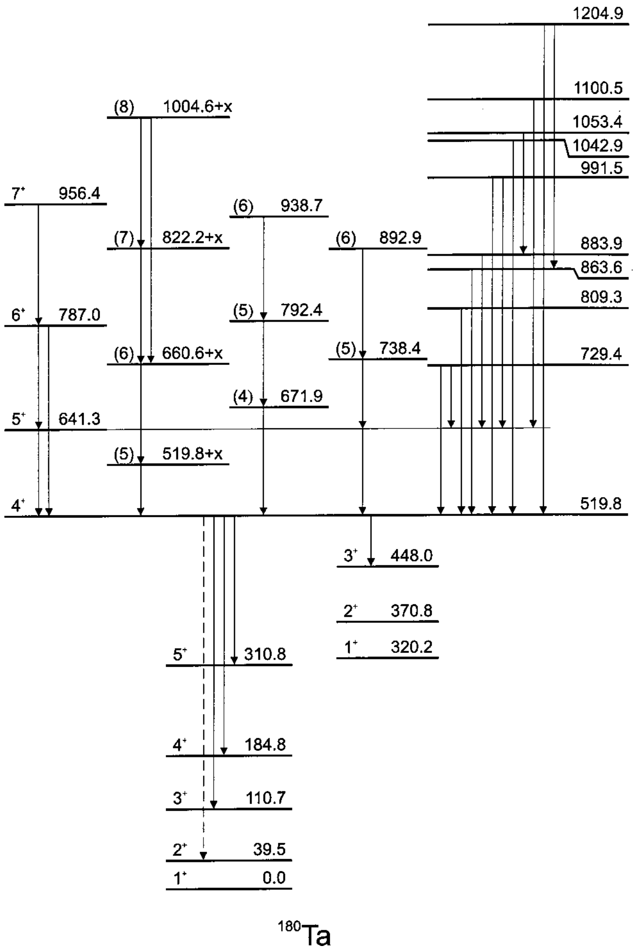

FIG. 13. Levels that depopulate via the 520 keV $I^{\pi},K=4^{+},4$ level.

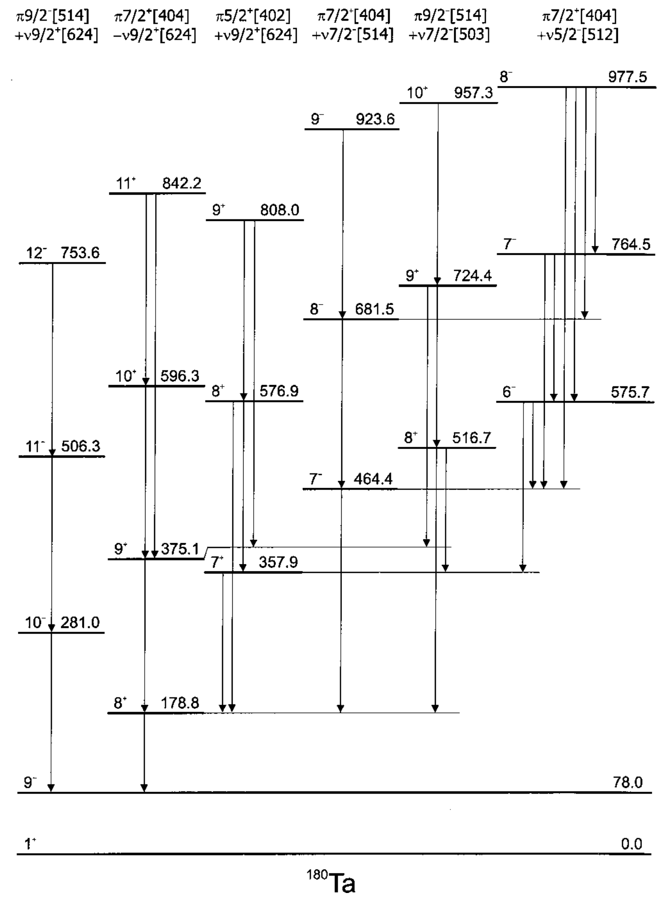

FIG. 14. High-spin rotational bands populated in the ^{180}Hf(p,n) and $(d,2n)$ reactions.

factor $g_K=(\Omega_p g_{\Omega_p}+\Omega_n g_{\Omega_n})/(\Omega_p+\Omega_n)$ to write $G^{KK}=(g_K-g_R)K$ for $K\neq 0$, whereas for $K=0$ one retains $G^{00}=\Omega_p(g_{\Omega_p}-g_{\Omega_n})$ [19]. Calculated values of g_Ω for the single-particle orbitals occupied by the valence particles in ^{180}Ta are listed in Table 3 of Ref. [5] and $g_R=0.26$ is determined in Ref. [4].

Additional corrections to the intraband $B(M1)$ values can result from the rotation-alignment of the unpaired nucleons. These corrections are discussed in Ref. [5] and expressed in terms of a spin dependence of the g_K factors within a rotational band. We will neglect these corrections in the estimates in connection with band mixings discussed below.

In the previous work on ^{180}Ta extensive use has been made of the g_K factors for the determination of configuration assignments [4–6]. Experimental values for g_K were obtained from $B(M1)/B(E2)$ ratios derived from the γ-ray intensity ratios of the intraband $\Delta I=1$ and $\Delta I=2$ transitions, which are in general competitive at intermediate spins. Unfortunately, we do not populate the newly identified bands discussed in Sec. III C to sufficiently high spins to allow the determination of such $B(M1)/B(E2)$ ratios. The configuration assignments proposed for these bands will therefore be based primarily on the comparison of the bandhead energies with the theoretical predictions summarized in Table VIII.

The information on band mixings derived for a few bands from γ-ray branchings will be presented in a final subsection.

A. The $\pi 7/2^{+}[404]\pm\nu\Omega^{\pi}[Nn_3\Lambda]$ configurations

The configurations $\pi_0\pm\nu 9/2^{+}[624]$. (In this subsection we will denote the configuration $\pi 7/2^{+}[404]$ by π_0.) These two configurations with $K^{\pi}=1^{+}$ and 8^{+}—and their rotational bands up to $I^{\pi}=16^{+}$ and 18^{+}, respectively—were established in the earlier transfer and in-beam γ-spectroscopic work.

The configurations $\pi_0\pm\nu 7/2^{-}[514]$. In the earlier work, as well as in our work, only the lower $K^{\pi}=7^{-}$ band could be identified (up to the 13^{-} level in Refs. [4,5]). An observation of the higher-lying $K^{\pi}=0^{-}$ band would be very difficult both in the $(p,n\gamma)$ reaction and the transfer reaction because of its non-yrast character and its low transfer cross section [15].

The configurations $\pi_0\pm\nu 1/2^{-}[510]$. In the in-beam γ experiments a 378.2 keV γ ray is observed in coincidence with 107.7 and 114.5 keV γ rays. We assign this γ ray as transition from a level at 549.1 keV to the 171.0 keV 2^{-} level, populated from a 663.6 keV level by the 114.5 keV γ ray. This assignment is supported by the observation of a 71.3 keV $M1$ transition from the 549 keV level to the 478

TABLE VIII. Two-quasiparticle states in ^{180}Ta up to ≈ 1 MeV. The single-particle energies E_π and E_ν correspond to the average of ^{179}Ta and ^{181}Ta and the average of ^{179}Hf and ^{181}W, respectively. For each two-quasiparticle state the following quantities are listed: First line: $K^{\pm}=|\Omega_n \pm \Omega_p|$ values, with the value for the state with aligned proton and neutron intrinsic spins listed first. Second line: Calculated energies of the corresponding two-quasiparticle states (all energies in keV). Third line: Experimental band-head energies. The two-quasiparticle states that were observed in the present in-beam γ-spectroscopic experiments, but not in the earlier ones, are printed in bold.

$\nu\Omega^\pi[Nn_3\Lambda]$ E_ν (keV)	$\pi\Omega^\pi[Nn_3\Lambda]$ E_π (keV)	$\pi7/2^+[404]$ 0	$\pi9/2^-[514]$ 18	$\pi5/2^+[402]$ 360	$\pi1/2^+[411]$ 568	$\pi1/2^-[541]$ $\approx$650
$\nu9/2^+[624]$		1^+ 8^+	9^- 0^-	7^+ 2^+	4^+ 5^+	4^- 5^-
0		6 136	0 149	324 532	555 695	678 750
		0 179	78 108	358 **559**		
$\nu7/2^-[514]$		7^- 0^-	1^+ 8^+	1^- 6^-	4^- 3^-	4^+ 3^+
205		254 510	339 439	680 798	876 996	950 1100
		464	**320**	**653**		
$\nu1/2^-[510]$		3^- 4^-	5^+ 4^+	3^- 2^-	0^- 1^-	0^+ 1^+
416		485 587	470 614	837 947		
		549 664 [a]	(592 **672**) [b]			
$\nu5/2^-[512]$		1^- 6^-	7^+ 2^+	5^- 0^-	2^- 3^-	2^+ 3^+
442		457 569	436 604	802 938		
		423 576				
$\nu1/2^-[521]$		4^- 3^-	4^+ 5^+	2^- 3^-	1^- 0^-	1^+ 0^+
500		540 618	502 661	888 984		
		722 788	520			
$\nu3/2^-[512]$		5^- 2^-	3^+ 6^+	1^- 4^-	2^- 1^-	2^+ 1^+
723		723 827	704 858			
		(**809 877**) [a]				
$\nu7/2^-[503]$		0^- 7^-	8^+ 1^+	6^- 1^-	3^- 4^-	3^+ 4^+
766		772 896	734 948	636 830	849 1011	
			(517) [c]			

[a]See the discussion in Sec. III A.
[b]See the discussion in Sec. III C.
[c]See the discussion in Sec. III D 2.

keV 2^- level as described in Sec. II C. The 549 keV level is also strongly populated in the neutron transfer reaction and we therefore assign it as the 3^- member of the doublet with the neutron in the $1/2^-[510]$ orbital.

The 4^- member of the 3^- band is expected approximately 100 keV above the 3^- bandhead. At about the same energy one expects the $K^\pi=4^-$ doublet member and the 4^- rotational level of the first-excited $K^\pi=1^-$ band with its 3^- member at 544 keV. All three 4^- levels are expected to be populated in the neutron transfer, and we indeed observe three levels at 646, 658, and 663 keV in this reaction (see Table VII). We associate these levels with those observed in the $(p,n\gamma)$ measurements at 645.4, 658.3, and 663.6 keV. The first two levels decay by 101.4 and 114.3 keV transitions, respectively, to the 544.1 keV 3^-,1 level, and the 663.6 keV level decays by a 114.5 keV transition to the 549.1 keV 3^-,3 level. Although the 4^- assignment for the three levels is not experimentally established, some support comes from the $e^-\gamma$ coincidence measurements that show, that the two 114 keV transitions have the same—most likely $M1$—multipolarity. We will now discuss tentative configuration assignments for the three levels assuming that they indeed constitute the 4^- members of the $K^\pi=1^-$, 3^-, and 4^- bands.

The decay pattern of the $I^\pi=1^-$, 2^-, and 3^- members of the $K^\pi=1^-$ band strongly suggest that the 4^- member decays predominantly by an $M1$ transition to the 3^- member, leaving the 645 and 658 keV levels as candidates for this state. In the neutron transfer reactions, the $K^\pi=1^-$ band is populated by $l=3$ transfer ($5/2^-[512]$ neutron transferred), whereas the $K^\pi=3^-$ and 4^- bands are populated by $l=1$ transfer ($1/2^-[510]$ neutron transferred). The angular distributions observed in the previous neutron transfer experiments indicate $l=3$ transfer for the combined peak at $\approx$660 keV [15,16]. We, therefore, assign the 658.3 keV level as the 4^- member of the $K^\pi=1^-$ band. We note here that the observation of a doublet at 660 keV resolves the problem encountered earlier with the anomalously high intensity of the 4^-,1 state discussed by Dewberry and Naumann [16].

The spin 4 members of the $\pi_0 \pm \nu 1/2^-[510]$ doublet are expected to be strongly coupled by the Coriolis interaction H_c. The matrix element of H_c has the form (see the discussion of ^{166}Ho in Ref. [18]):

$$\langle K=4,I|H_c|K=3,I\rangle = A_0 a\sqrt{(I-3)(I+4)}, \qquad (4)$$

where A_0 is the rotational parameter of the two-quasiparticle doublet ($A_0 \approx 11$ keV) and a is the decoupling parameter of the rotational band associated with the configuration $\nu 1/2^-[510]$. Assuming $a \approx 0.2$ (see, e.g., Table XXVII of Ref. [20]) one obtains a coupling strength of ≈ 6 keV for the 4^- levels, yielding from the experimental energy splitting of the 645 and 664 keV levels an unperturbed energy splitting of ≈ 14 keV and wave functions of $\psi \approx 0.95\psi_{main} \pm 0.32\psi_{admixed}$. As noted by Warde *et al.* [15] the transfer amplitudes for the population of the low-spin members of the $\pi_0 \pm \nu 1/2^-[510]$ configurations are expected to be comparable, which would then yield an intensity ratio for the population of the two mixed 4^- levels of ≈ 4, close to the observed result.

A similar argument can be given for the $M1$ transitions. The $M1$-matrix element of the $(4^-,3) \to (3^-,3)$ transition is proportional to $(g_{K=3} - g_R)$, with a calculated value of 0.76. For the $(4^-,4) \to (3^-,3)$ spin-flip transition the $M1$-matrix element is proportional to $(g_{K=1/2} - g_R)b$, where $g_{K=1/2}$ is the intrinsic g factor and b the magnetic decoupling parameter of the rotational band associated with the configuration $\nu 1/2^-[510]$. Brockmeier *et al.* [21] report for the $\nu 1/2^-[510]$ band in ^{183}W a value of $(g_{K=1/2} - g_R)b = -1.3$. Thus, again, the two $M1$-matrix elements are comparable, and one can, therefore, expect a suppression of the $M1$ transition from one of the mixed 4^- levels to the 549 keV $(3^-,3)$ level as experimentally observed. The 645 keV level decays to the 544 keV $(3^-,1)$ level indicating that it contains a component of the $K^\pi = 1^-$ band. Such an admixture is caused more likely by an effective $\Delta K = 2$ coupling for the $K^\pi = 3^-$ band, and we, therefore, assign the configuration $\pi_0 - \nu 1/2^-[510]$ to the 645 keV level.

We tentatively assign a level at 784 keV as the 5^- member of the $K^\pi = 4^-$ band based on its γ decay and its population in the neutron-transfer reaction.

The configurations $\pi_0 \pm \nu 5/2^-[512]$. The $K^\pi = 1^-$ band with its bandhead at 423 keV has previously been proposed up to the 4^- member at 658 keV [4–6]. Our conversion-electron data confirm the $M1$ multipolarities of the 252, 316, and 373 keV transitions, and the discussion given above supports the assignment of the 658 keV level as the 4^- member of this band. In addition, we observe a level at 809.3 keV, which decays to the 3^- and 4^- members of the $K^\pi = 1^-$ band as expected for the 5^- member of this band. However, its energy is ≈ 30 keV too high, and the $e^-\gamma$ data indicate that the 809 keV level has a nanosecond lifetime making its assignment as 5^- member of the 1^- band unlikely. A tentative assignment for this level will be given below.

The $I^\pi = 6^-$ and 7^- members of the $K^\pi = 6^-$ band were previously proposed by Dracoulis *et al.* [4]. Our observation of a nanosecond lifetime of the 576 keV 6^- level supports its interpretation as a two-quasiparticle bandhead.

Saitoh *et al.* [5] extended the $K^\pi = 6^-$ band up to the 9^- member. The 8^- level decays according to these authors by 210.0 ± 0.1 and 295.0 ± 0.5 keV transitions to the 764.5 keV $(7^-,6)$ and 681.5 keV $(8^-,7)$ levels, respectively, leading to inconsistent excitation energies. We observe a level at 977.5 keV with a depopulation as expected for the 8^- member of the $K^\pi = 6^-$ band. This assignment is supported by the observation of a 977.3 keV level in the neutron transfer experiment.

The configurations $\pi_0 \pm \nu 1/2^-[521]$. In the earlier neutron transfer experiments two strongly excited levels were observed at ≈ 720 keV and ≈ 780 keV with angular distributions characteristic of $l=1$ transfer. As emphasized by Warde *et al.* [15] theoretical estimates suggest that these levels result from pickup of a $1/2^-[521]$ neutron leading to their interpretation as the $(4^-,4)$ (720 keV level) and $(3^-,3)$ (780 keV level) members of the $\pi_0 \pm \nu 1/2^-[521]$ doublet. In addition Warde *et al.* propose the $(5^-,4)$ and $(4^-,3)$ rotational members at 837 and 914 keV, respectively. Our neutron transfer data are in agreement with these assignments yielding the $(4^-,4)$ and $(5^-,4)$ states at about 722 and 836 keV, and the $(3^-,3)$ and $(4^-,3)$ states at about 788 and 908 keV. We note that Warde *et al.* encountered a problem with the intensity of the 908 keV level and mention that the corresponding peak observed in their measurement might contain another unresolved state. We observe indeed a doublet at this energy that could not have been resolved in the earlier measurements.

In the $(p,n\gamma)$ experiment we observe levels at 721.7, 788.2, and 907.3 keV that we assign as $(4^-,4)$, $(3^-,3)$, and $(4^-,3)$ states, respectively. The interpretation of the 721.7 keV level as two-quasiparticle bandhead is supported by its nanosecond lifetime.

The γ decay of the three levels listed in Table II is consistent with the proposed assignments, although the predominant decay of the $(4^-,4)$ and $(3^-,3)$ states to the members of the $K^\pi = 1^-$ band is somewhat surprising. We believe, however, that this unexpected feature can likely be explained by the Coriolis coupling which is, for example, expected to induce large $K=2$ and $K=3$ components into the wave function of the 3^- and 4^- level, respectively (see, e.g., Table III in Ref. [15]). Unfortunately, a quantitative analysis of such effects is as yet not possible due to the lack of experimental information, in particular with respect to the $K^\pi = 2^-$ band with the configuration $\pi_0 - \nu 3/2^-[512]$.

As already noted above, we also observe a 907.3 keV level in the high-spin region (Table IV). Its decay would not be at variance with the assignment as $I^\pi = 4^-$ level, but a proof of the identity of the two 907 keV levels would require the observation of $\gamma\gamma$ coincidences with a common feeding transition as gate, which could not be identified in the present work.

In Table II we list a level at 787.8 keV that is only separated by 0.4 keV from the proposed $(3^-,3)$ level. We will return to this proposal in Sec. III B.

The configurations $\pi_0 \pm \nu 3/2^-[512]$. We observe a level at 809 keV both in the in-beam γ-spectroscopic work and the (p,d) reaction, for which its nanosecond lifetime suggests an assignment as intrinsic state. We tentatively assign the spin 5^- configuration $\pi_0 + \nu 3/2^-[512]$ to this level, based on its γ decay and the predicted energy of this configuration (see the first column of Table VIII). One obvious candidate for its

2^- doublet partner is the level observed at 877 keV for which we, therefore, very tentatively adopt the $\pi_0 - \nu 3/2^-[512]$ configuration.

B. The $\nu 9/2^+[624] \pm \pi\Omega^\pi[Nn_3\Lambda]$ configurations

The configurations $\nu_0 \pm \pi 9/2^-[514]$. (ν_0 denotes the configuration $\nu 9/2^+[624]$.) These two configurations with $K^\pi = 0^-$ and 9^-—and their rotational bands up to $I^\pi = 13^-$ and 21^-, respectively—were established in the earlier transfer and in-beam γ-spectroscopic work.

The configurations $\nu_0 \pm \pi 5/2^+[402]$. The 7^+ and 2^+ members of this doublet were proposed by Warde *et al.* [15] at 361 and 563 keV, respectively. These authors emphasize that the two states are easily identified in the $5/2^+[402]$ proton transfer because of their high yield and the transferred $l=2$. In the previous in-beam γ-spectroscopic work, the 358 keV level was assigned as the 7^+ state although no clear evidence was obtained on the associated rotational levels [4,5]. We will address this problem in Secs. III C and III D 2 below.

We observe levels at 559 and 624 keV with a decay pattern consistent with their interpretation as the first two members of a $K^\pi = 2^+$ band. We note, in particular, two experimental results: (1) positive parity is established for the 559 keV level by the multipolarity of the 239 keV transition to the 320 keV 1^+ level ($M1$ or $E2$); (2) the 624 keV level decays with significant intensity to the 559 keV level, which is not unexpected for the intraband $M1$ transitions of the $K^\pi = 2^+$ band that has a large $(g_K - g_R) = -2.76$. In view of the agreement of the in-beam and transfer reaction results, we consider the assignment of these levels as the first two members of a band based on the configuration $\nu_0 - \pi 5/2^+[402]$ as established. The 4^+ member of this band is proposed at 708.5 keV, but this level is based on a single depopulating γ ray observed only in the $(d,2n)$ reaction and its existence is, therefore, not established beyond doubt.

C. Two-quasiparticle states with the proton and neutron outside the $\pi 7/2^+[404]$ and $\nu 9/2^+[624]$ orbitals

A total of 14 more doublets are predicted in the BCS calculation below an excitation energy of ≈ 1 MeV (Ref. [4] and Table VIII). Until now only four of these 28 states, and their associated rotational bands, had been proposed from experiment. In this section, we will first summarize the evidence for these four states, followed by a discussion of the new states proposed in the present work.

Two 8^+ states at 517 and 577 keV, and their rotational bands up to the 17^+ and 13^+ members, respectively, were proposed by Dracoulis *et al.* [4] and Saitoh *et al.* [5]. These authors assign the configurations $\pi 9/2^-[514] + \nu 7/2^-[503]$ and $\pi 9/2^-[514] + \nu 7/2^-[514]$ to bands with the 517 and 577 keV levels as bandheads, respectively, based on an analysis of g_K factors and aligned angular momenta. Two alternative assignments are discussed in Refs. [4,5]: (1) interchange of the two $K^\pi = 8^+$ configurations, and (2) interpretation of one of the two bands as extension of a $K^\pi = 7^+$ band with the 358 keV 7^+ state as bandhead. The latter possibility was rejected by Dracoulis *et al.* [4] primarily on account of the fast decay of the two 8^+ states to the first-excited 8^+ state at 179 keV in contrast to the delayed decay of the 358 keV 7^+ state. Saitoh *et al.* explain these $8^+ \to 8^+$ transitions for their adopted $K^\pi = 8^+$ configurations by requiring a mixing of the three 8^+ states. This raises the question whether one of the 8^+ states could belong to the 358 keV $K^\pi = 7^+$ band with the enhanced nature of the $8^+ \to 8^+$ transition caused by a $\Delta K = 1$ coupling of this band with the 179 keV $K^\pi = 8^+$ band. We will discuss this possibility in detail in Sec. III D 2 and propose that the level sequence based on the 577 keV 8^+ state represents indeed the extension of the $K^\pi = 7^+$ band.

The 4^+ level at 520 keV, with its rotational band up to the 8^+ member, was observed in the earlier in-beam experiments [4,5]. The spin-parity assignment of this band is established by the $M1$ multipolarities of the 409 and 209 keV transitions from the 520 keV level to the 111 keV 3^+ and 311 keV 5^+ level, respectively, derived from their K conversion coefficients (Ref. [6] and present work).

The two-quasiparticle configuration proposed in Refs. [5,6] for the 4^+ band is based on the experimental value of $(g_K - g_R) \approx 0.6$. Dracoulis *et al.* [4] mention that the angular distribution coefficients A_2 obtained in their measurements favor positive signs of the $E2/M1$ mixing parameters whereas Saitoh *et al.* [5] assume the positive sign for $(g_K - g_R)$ without justifying this choice. The theoretical values of $(g_K - g_R)$ for the levels with spins 4 and 5 listed in Table VIII are given in Table IX. From the two configurations with $K^\pi = 4^+$ and large positive $(g_K - g_R)$, the adopted configuration $\pi 9/2^-[514] - \nu 1/2^-[521]$ leads to better agreement if the correction to g_K resulting from the rotational alignment is included [5,6].

The fourth band known from the previous in-beam work is based on an isomer that decays with a half-life of 16 ns to the 520 keV 4^+ state, with six rotational members identified [4,5] (we will denote this band below as isomeric band). Three features of this band can be used for a configuration assignment: (1) The population of the band, both in the reactions with intermediate spin transfer reported in Refs. [4,5] and in the (p,n) and $(d,2n)$ reactions, and its γ decay strongly suggest a $K \geq 4$. (2) Dracoulis *et al.* propose a 72 keV $M1$ transition as a candidate for the decay of the isomer to the 520 keV level. However, as discussed in Sec. II C our conversion-electron data question this proposal. Nevertheless, it seems clear that the connecting transition must have an energy of ≤ 80 keV, which excludes a pure $E2$ transition, and thus a $K^\pi = 6^+$ assignment to the isomeric band, since this would lead to a $B(E2)$ of more than ≈ 20 Weisskopf units. (3) Dracoulis *et al.* [4] and Saitoh *et al.* [5] report an experimental value of $(g_K - g_R) \approx 0.4$ for the isomeric band. Both groups choose the positive sign presumably based on their measured angular distribution coefficients. As is apparent from Table IX, none of the unassigned states with $K = 4$ would be consistent with this value of $(g_K - g_R)$.

It seems now reasonable to assume that the isomeric band has $K=5$ and a bandhead energy between 520 and 600 keV. Unfortunately, none of the possible $K^\pi = 5^\pm$ configurations

TABLE IX. Theoretical values of (g_K-g_R) for the two-quasiparticle states in ^{180}Ta with $K=4$ and 5 predicted below 1 MeV.

K^{π}	Configuration	E_{calc} (keV)	g_K-g_R
4^+	$\pi9/2^-[514]\nu1/2^-[521]$ [a]	502	1.08
	$\pi1/2^+[411]\nu9/2^+[624]$	555	−0.41
	$\pi9/2^-[514]\nu1/2^-[510]$	614	1.41
	$\pi1/2^-[541]\nu7/2^-[514]$	950	0.07
5^+	$\pi9/2^-[514]\nu1/2^-[510]$	470	0.73
	$\pi9/2^-[514]\nu1/2^-[521]$	661	0.99
	$\pi1/2^+[411]\nu9/2^+[624]$	695	−0.57
4^-	$\pi7/2^+[404]\nu1/2^-[521]$ [b]	540	0.40
	$\pi7/2^+[404]\nu1/2^-[510]$ [c]	587	0.08
	$\pi1/2^-[541]\nu9/2^+[624]$	678	−0.63
	$\pi1/2^+[411]\nu7/2^-[514]$	876	−0.15
5^-	$\pi7/2^+[404]\nu3/2^-[512]$	723	0.35
	$\pi1/2^-[541]\nu9/2^+[624]$	750	−0.40
	$\pi5/2^+[402]\nu5/2^-[512]$	802	0.34

[a]Assigned to the 520 keV state.
[b]Assigned to the 722 keV state.
[c]Assigned to the 664 keV state.

can explain the properties of this band [its alignment, its lack of signature splitting, and its (g_K-g_R)] convincingly as discussed in Refs. [4–6]. We, therefore, conclude that a reliable experimental determination of the parity of the isomeric band would be a prerequisite for a reasonably safe configuration assignment.

The lowest rotational band not known from the previous work is the $K^{\pi}=1^+$ band based on the 320 keV state, identified in the present work up to its 5^+ member. $K^{\pi}=1^+$ is established from the $M1$ multipolarities of the transitions from the first two members of the band (320 and 371 keV levels) to the ground band. The assignment of the configuration $\pi9/2^-[514]-\nu7/2^-[514]$ to this band is almost inevitable in view of the theoretical predictions listed in Table VIII.

The γ decay of the 1^+ band by $M1$ transitions to the ground band, and not by intraband $M1$ transitions or $E1$ transitions to the first-excited 0^- band, is somewhat unexpected. The intraband $M1$ transitions are expected to be fast because of the large $(g_K-g_R)=4.6$. On the other hand, the $M1$ transitions to the ground band would be strictly forbidden for the adopted configurations since the electromagnetic moments are one-particle moments. However, the $E1$ transitions to the 0^- band are also expected to be retarded since the $7/2^-[514]\rightarrow9/2^+[624]$ transition involves a spin flip and is, therefore, forbidden by the asymptotic selection rules for $E1$ transitions in deformed nuclei (see Table 5–3 of Ref. [18]), and the intraband $M1$ transitions are hindered by their low energies. Most likely the observed $M1$ transitions can be explained by a mutual mixing of the two 1^+ bands as discussed in Sec. III D 1.

With the assignments discussed so far, all levels listed in Table II up to the 722 keV level are explained except for two levels at 653.4 and 707.9 keV. The spacing of these levels and their γ decay suggest that they constitute the lowest two members of a rotational band with $K=1$. The theoretical predictions leave only one reasonable possibility, the $K^{\pi}=1^-$ band with the configuration $\nu7/2^-[514]-\pi5/2^+[402]$. With this assignment one has to make use of similar considerations as in the previous case to explain the observed γ transitions to the 320 keV 1^+ band and the 423 keV 1^- band: (1) The main component of the $E1$ transitions to the 1^+ band $(5/2^+[402]\rightarrow9/2^-[514])$ vanishes and these transitions must, therefore, proceed via admixtures (e.g., the $\{\nu7/2^-[514]-\pi7/2^+[404]\}K^{\pi}=0^-$ band). (2) The $M1$ transitions to the 1^- band are forbidden because of their two-particle nature, but can be explained by a mutual mixing of the two 1^- bands. It is, therefore, not implausible that the $E1$ and $M1$ transitions become comparable.

The 3^- member of this second-excited 1^- band is expected at ≈790 keV, very close to the level assigned above as $(3^-,3)$ state. We, therefore, tentatively propose levels at 787.8 and 788.2 keV (see Table II), although the energy splitting is too small to establish the existence of two levels. We note, however, that the observed γ decay to the $I=2$ members of the first-excited 1^+ and 1^- bands would be most consistent with the two-level hypothesis.

Two more bands are proposed in Fig. 13 with bandheads at 672 and 738 keV. These assignments are only based on the observed decay of the higher-lying 792, 893, and 939 keV levels to the lower-lying ones of the proposed bands that are most easily explained as intraband $M1$ transitions, yielding tentative assignments of $K=4$ and 5 for the 672 and 738 keV bands, respectively. These assignments are consistent with the intensities of the 152 and 218 keV γ rays depopulating the 672 and 738 keV levels, respectively, observed in the (p,n) and $(d,2n)$ reactions (see Fig. 6).

A configuration assignment for the 672 keV level is at present purely speculative. We have included this band, as well as the isomeric $K=5$ band discussed above, in Table VIII as members of the $\pi9/2^-[514]\pm\nu1/2^-[510]$ doublet, based solely on the assignment proposed for the $K=5$ band by Dracoulis *et al.* [6]. The assignment of the 893 keV level as first-excited member of a band with $K=5$ would be consistent with its γ-ray branching to the $6^-,6$ level at 576 keV (see Table IV) whereas a branching to the $4^-,4$ level at 722 keV (see Table II) would be more easily understandable with an $I,K=5,4$ assignment. Some of the 4^+ and 5^+ levels predicted at these energies are expected to couple strongly by the Coriolis interaction, possibly leading to a $K^{\pi}=4^+$ band with a large $K^{\pi}=5^+$ admixture and increased rotational spacings. We therefore consider, as already indicated above, the 893 keV level as a possible candidate for a level connecting the 1^+ ground state and the 9^- isomer of ^{180}Ta.

D. Gamma-ray branching ratios

In this section we discuss the electromagnetic decay of some selected rotational bands in ^{180}Ta in the context of band couplings. The interband γ-ray transitions are sensitive to band mixings, in particular if the intrinsic transitions are hindered by selection rules, which is the case for almost all transitions between the low-lying two-quasiparticle states in

^{180}Ta. The γ-ray branchings provide in a few cases some insight into the band couplings as discussed in the following sections.

1. First excited $K^\pi=1^+$ and 1^- bands

The relative intensities of the transitions from the first-excited 1^+ and 1^- bands to the ground and first-excited 0^- band, respectively, are listed in Table X. The experimental γ-ray intensities of the $I\to(I-1)$ intraband $M1$ transitions were obtained from the intensities of the γ rays depopulating the levels with spin I and $I-1$ in the coincidence spectra with gates on γ rays populating the levels with spin I. The intensities given in the last column of Table X were calculated assuming $M1$ multipolarity for all transitions and pure K values for the levels involved (leading-order intensities).

The most significant feature of the $M1$ transitions from the first-excited $K^\pi=1^+$ band is the predominance of the interband transitions to the ground band for which, moreover, the branching ratios follow closely the leading-order predictions. The interband $M1$-matrix element can be estimated from the interband to intraband intensity ratio of the $2^+\to 1^+$ $M1$ transitions. For later use we introduce the ratio

$$R(I)=\frac{B(M1;I,K_2\to(I-1),K_1)}{B(M1;I,K_2\to(I-1),K_2)},$$

where K_1 and K_2 are the K quantum numbers of the ground and excited band, respectively. From the intensities listed in Table X one obtains $R(2^+)=0.15\pm0.04$ and with $g_{K_2}=4.9$ for the configuration $\pi 9/2^-[514]-\nu 7/2^-[514]$ assigned to the excited band

$$B(M1;2^+,K_2=1\to 1^+,K_1=1)\approx 0.22\left(\frac{e\hbar}{2Mc}\right)^2.$$

As discussed in Sec. III C the $M1$ transitions between the two 1^+ bands are forbidden. They must result from admixtures of configurations with $K^\pi=0^+$ or 1^+ and with parities opposite to those of the main configurations, which differ from the main configurations of the doublet partner for at most one of the two valence particles. An inspection of Table VIII shows that there is only one possibility, the mutual coupling of the two 1^+ bands. In this case one obtains

$$R(2^+)\approx\left(\frac{g_{K_2}-g_{K_1}}{g_{K_2}-g_R}\right)^2\alpha^2,$$

where α is the amplitude of admixture assumed to be equal for the 1^+ and 2^+ levels. With $g_{K_1}=-3.3$ and $g_{K_2}=4.9$ one obtains from the experimental $R(2^+)$ an amplitude of admixture of $\alpha\approx0.2$ and an interaction strength of $\langle 2^+,K_2=1|H_{int}|2^+,K_1=1\rangle\approx 60$ keV.

We mention here two additional results: (1) In the neutron-transfer reaction described in Sec. II D we obtain an upper limit of 30 counts for the 320 keV level consistent with an interaction-matrix element for the 1^+ levels of up to 75 keV. (2) The two 1^+ bands were also observed in ^{176}Lu at 194 and 339 keV and mixing between these bands was suggested by Balodis *et al.* [22] to account for the unexpectedly strong interband $M1$ transitions. From the γ-ray intensities listed in Ref. [23] one can estimate $R(4^+)\geqslant 0.5$ corresponding to an interaction-matrix element of $\geqslant 50$ keV for the 4^+ level.

TABLE X. Gamma-ray branching ratios for the transitions from the first-excited $K^\pi=1^+$ and 1^- bands of ^{180}Ta.

Band K^π	E_{bh} (keV)	Transitions $(I^\pi K)_i$	$(I^\pi K)_f$	E_γ (keV)	I_γ (exp.)	I_γ (calc.)
1^+	320	1^+1	1^+1	320.2	100	100.0
			2^+1	280.7	66(4)	67.4
		2^+1	1^+1	370.8	100	100.0
			2^+1	331.3	45(3)	39.6
			3^+1	260.1	59(4)	61.4
			1^+1	50.6	1.7(4)	
		3^+1	2^+1	408.5	100	100.0
			3^+1	337.2	25(3)	12.3
			4^+1	262.8	32(3)	37.4
1^-	423	1^-1	0^-0	315.6	100	100.0
			1^-0	293.0	2.9(5) [a]	120.0
			2^-0	252.4	37(3)	25.6
		2^-1	1^-0	347.5	100	100.0
			2^-0	306.9	27(6) [a]	114.6
			3^-0	243.7	88(8)	23.0
			1^-1	54.5	273(50)	
		3^-1	2^-0	373.1	100	100.0
			3^-0	309.9	5(2) [a]	100.3
			4^-0	226.0	13(2)	16.7
			2^-1	66.2	49(10)	

[a]These transitions are very weak and possibly contaminated in the $\gamma\gamma$ coincidence spectra. The listed intensities should perhaps be considered as upper limits.

To trace the origin of the coupling of the two 1^+ states, one has to consider the model used for the description of deformed odd-odd nuclei discussed, for example, by Boisson *et al.* [24]. In this model the two valence nucleons are assumed to strongly couple to the deformed core and to interact with each other through an effective interaction V_{np}. Rotational bands with $\Delta K=0$ are coupled by V_{np} and an additional term representing the coupling of the particle degrees of freedom through the rotational motion. The selection rules for the latter term are violated by the two $K^\pi=1^+$ bands, for which the valence particles are in orbitals with different parities, and thus their coupling must result from the residual interaction V_{np}. This coupling does not affect the branching ratios of the interband transitions in accordance with the experimental observations.

The γ-ray intensities for the $K^\pi=1^-\to 0^-$ interband transitions deviate from the leading-order results. The most significant features are the strong reduction of the $I\to I$ transitions for the odd spins, and the apparent signature dependence of the deviations. This latter dependence is also apparent for the interband-to-intraband intensity ratios with values of $R(I)=1.4(3)\times10^{-3}$ and $11(2)\times10^{-3}$ for the 2^- and 3^- levels, respectively.

We assign the configurations

$$\text{(a)}\quad K^{\pi}=0^{-};\quad \pi 9/2^{-}[514]-\nu 9/2^{+}[624],$$

$$\text{(b)}\quad K^{\pi}=1^{-};\quad \pi 7/2^{+}[404]-\nu 5/2^{-}[512]$$

to the two bands. For these configurations the intrinsic $M1$ transitions are forbidden. The deviations of the γ-ray intensities for transitions between such bands with $|\Delta K|=1$ are usually attributed to their mutual coupling by the Coriolis interaction H_c. In the two-particle case H_c couples bands with $\Delta\Omega=\Delta K$ for one of the two valence particles with the intrinsic configuration of the other particle remaining unchanged [24]. For the configurations (a) and (b) this selection rule is violated and thus the 0^- and 1^- bands cannot couple in first order through the Coriolis interaction.

The low-lying two-quasiparticle states that can lead to the $K^{\pi}=1^{-}\rightarrow 0^{-}$ interband $M1$ transitions via first-order admixtures are the configurations

$$\text{(c)}\quad K^{\pi}=0^{-};\quad \pi 7/2^{+}[404]-\nu 7/2^{-}[514],$$

$$\text{(d)}\quad \pi 7/2^{+}[404]-\nu 7/2^{-}[503],$$

$$\text{(e)}\quad \pi 5/2^{+}[402]-\nu 5/2^{-}[512],$$

$$\text{(f)}\quad K^{\pi}=1^{-};\quad \pi 5/2^{+}[402]-\nu 7/2^{-}[514].$$

The state (f) leads to a renormalization of the g_K factor of band (b) but has in first order no influence on the branching ratios of the $K^{\pi}=1^{-}\rightarrow 0^{-}$ interband transitions. The three $K^{\pi}=0^{-}$ states can couple both to the 0^- and 1^- bands via V_{pn} and H_c, respectively.

The Coriolis interaction of two bands with $|\Delta K|=1$ gives rise to a mixing of these bands with amplitudes of admixture $\pm c(I)$. In the two-particle case the first-order expression for $c(I)$ is [18,24]

$$c(I)=\epsilon\sqrt{[1+\delta(K_{<},0)](I-K_{<})(I+K_{>})}$$

$$\epsilon=-A_0\langle\Omega_{>}|j_{+}|\Omega_{<}\rangle/\Delta E, \tag{5}$$

where $\Omega_{<}$ and $\Omega_{>}=\Omega_{<}+1$ are the quantum numbers of the valence particle with different configurations in the two interacting bands, and ΔE is the unperturbed energy difference of the bands that are assumed to have identical rotational parameters. The Coriolis coupling of the 1^- band (b) with the band (e) is expected to be negligible, since the coupling-matrix element $\langle 7/2^{+}404|(j_p)_{+}|5/2^{+}402\rangle$ is small and the energy separation is large. The bands (c) and (d) are expected to be coupled to band (b) with comparable strength: band (c) is located close to band (b) but the matrix element $\langle 7/2^{-}514|(j_p)_{+}|5/2^{-}512\rangle$ vanishes in the limit of the asymptotic quantum numbers, whereas the energy separation between the bands (b) and (d) is larger but the matrix element $\langle 7/2^{-}503|(j_p)_{+}|5/2^{-}512\rangle$ is asymptotically allowed. Moreover, these couplings provide a natural explanation for the signature dependence of the γ-ray intensities: the two signature branches of the 0^- bands are split (Newby splitting, see, e.g., Refs. [4,24]) leading to different admixtures for the two signature branches of the 1^- band. Experimental results for the signature splittings of the bands (c) and (d) are known from the neighboring nuclei ^{176}Lu and ^{182}Ta, respectively [23,25]. In both cases the odd-spin members of the 0^- bands are energetically lowered. The coupling of these bands with the 1^- band should lead to an increase of the energy differences $\Delta E=[E(I)-E(I-1)]/2I$ of the 1^- band for even I compared to those for odd I as observed: $\Delta E=13.6$, 11.0, and 14.3 keV for $I=2$, 3, and 4, respectively.

With these couplings the $M1$-matrix element for the interband transitions can be expressed in first order by the *generalized intensity relation* [18]

$$\begin{aligned}\langle K_f,I_f\|\mathcal{M}(M1)\|K_i,I_i\rangle/\sqrt{2I_i+1}\\ =\sqrt{[1+\delta(K_{<},0)]}\langle I_iK_i1K_f-K_i|I_fK_f\rangle\\ \times[M_1+M_2\{I_f(I_f+1)-I_i(I_i+1)\}].\end{aligned} \tag{6}$$

For the $K_i=1\rightarrow K_f=0$ transitions, one obtains

$$\begin{aligned}M_1=\alpha_{a,c}\langle 0_c|\mathcal{M}(M1,\nu=-1)|1_b\rangle\\ +\alpha_{a,d}\langle 0_d|\mathcal{M}(M1,\nu=-1)|1_b\rangle,\end{aligned}$$

$$\begin{aligned}M_2=\alpha_{a,c}\epsilon_{b,c}(\sigma_b)\langle 0_c|\mathcal{M}(M1,\nu=0)|0_c\rangle+\alpha_{a,d}\epsilon_{b,d}(\sigma_b)\\ \times\langle 0_d|\mathcal{M}(M1,\nu=0)|0_d\rangle,\end{aligned} \tag{7}$$

where $\alpha_{a,c}$ and $\alpha_{a,d}$ are the amplitudes of admixture of the bands (c) and (d) in band (a) that are assumed to be independent of the spins, and $\epsilon_{b,c}$ and $\epsilon_{b,d}$ are the spin-reduced amplitudes of admixture of the bands (c) and (d) in band (b) assumed to depend on the signature σ_b of band (b).

The observed suppression of the $I\rightarrow I$ transitions for the odd spins can be explained if M_1 is small [for $K=0\rightarrow K=0$ transitions $B(M1;I\rightarrow I)$ vanishes because the Clebsch-Gordan coefficient $\langle I010|I0\rangle$ is zero]. To obtain an order-of-magnitude estimate of the amplitudes of admixture, we assume $M_1=0$, admixture of only one 0^- band to the 1^- band and 1.0 for the ratio of the intraband $M1$-matrix elements to obtain

$$R(I)\approx\frac{4I^3}{I-1}(\alpha\epsilon)^2.$$

From the experimental $B(M1)$ ratios, one obtains values of $|\alpha\epsilon|\approx 0.7\times 10^{-2}$ and $\approx 1.4\times 10^{-2}$ for $\sigma_b=-1$ (even spins) and $\sigma_b=+1$ (odd spins), respectively. These results have the expected order of magnitude.

Two discrepancies remain: (1) The experimental γ-ray intensity of the $2\rightarrow 2$ transition is too high. As already noted above, this γ ray is very weak and might have been misassigned. (2) For $M_1=0$ the γ-ray intensities of the $I\rightarrow I+1$ transitions listed in the last column of Table X are multiplied by $[(I+1)/I]^2$ leading to discrepancies of factors of ≈ 2 for these transitions. We believe that this could be due to higher-order corrections, e.g., the admixtures of the band (f) in band (a).

2. $K^\pi=7^+$ and 8^+ bands

Five levels with $K^\pi=7^+$ and 8^+ are predicted in the BCS calculations below 1 MeV with the configurations

(a) $K^\pi=7^+$; $\pi 5/2^+[402]+\nu 9/2^+[624]$,

(b) $\pi 9/2^-[514]+\nu 5/2^-[512]$,

(c) $K^\pi=8^+$; $\pi 7/2^+[404]+\nu 9/2^+[624]$,

(d) $\pi 9/2^-[514]+\nu 7/2^-[514]$,

(e) $\pi 9/2^-[514]+\nu 7/2^-[503]$.

These levels are expected to be coupled through the Coriolis interaction [level (a) with (c); level (b) with (d) and (e)] and the residual interaction V_{pn}. The two-quasiparticle states (a) and (c) are established from the previous work at 358 and 179 keV, respectively. Two additional rotational sequences, built on 8^+ levels at 517 and 577 keV, were interpreted in Refs. [4,5] as 8^+ bands with the configurations (e) and (d), respectively. As already mentioned above, Dracoulis *et al.* [4] also considered an interpretation of the 577 keV rotational sequence as an extension of the 7^+ band (a), but rejected this possibility on account of the different partial decay rates of the transitions from the 7^+ and 8^+ states to the 179 keV 8^+ level. We want to show in the following discussion that this lifetime discrepancy can be explained by taking into account the Coriolis coupling of bands (a) and (c), and consequently suggest that the 577 keV level structure might indeed be the extension of band (a).

The $M1$-matrix elements for transitions between bands with $\Delta K=1$ coupled by the Coriolis interaction are described, to first order, by the generalized intensity relation (6). For $K_i=K$ and $K_f=K+1$ the matrix elements M_i have the form

$$M_1=M_0-2(K+1)M_2,$$

$$M_2=\frac{\epsilon}{\sqrt{2}}[\langle K+1|\mathcal{M}(M1,\nu=0)|K+1\rangle - \langle K|\mathcal{M}(M1,\nu=0)|K\rangle] \quad (8)$$

with

$$M_0=\langle K+1|\mathcal{M}(M1,\nu=-1)|K\rangle - \epsilon\sqrt{2}\langle K|\mathcal{M}(M1,\nu=0)|K\rangle. \quad (9)$$

With these relations one can estimate the interband transition rates for the Coriolis coupled bands (a) and (c). For the $M1$ transition from the 358 keV 7^+ level to the 179 keV 8^+ level Eqs. (6) and (8) yield $B(M1;7^+,7\rightarrow 8^+,8)=M_0^2$. Assuming pure $M1$ multipolarity for the 179.1 keV $7^+\rightarrow 8^+$ transition and $\tau(7^+)=60\pm 4$ ns [4,5] one obtains

$$|M_0|=(0.94\pm 0.03)\times 10^{-2}\frac{e\hbar}{2Mc}.$$

The bands (a) and (c) couple through the interaction-matrix element $A_0\langle 7/2^+404|(j_p)_+|5/2^+402\rangle$. For this matrix element a value of ≈ 5 keV is obtained from an analysis of interband transitions between the corresponding $5/2^+$ and $7/2^+$ bands in ^{175}Lu [18]. Assuming this value of the interaction-matrix element for the bands (a) and (c) and $\Delta E\approx 370$ keV, one obtains $|\epsilon_{a,c}|\approx 0.0135$. The intraband $M1$-matrix elements can be estimated with calculated values of g_K yielding ≈ 0.60 and ≈ -0.37 $e\hbar/2Mc$ for the bands (a) and (c), respectively. With these estimates one obtains

$$|M_2|\approx 0.93\times 10^{-2}\frac{e\hbar}{2Mc}.$$

If the 577 keV level is the 8^+ member of band (a), one obtains with these M_i and the relation $B(M1;8^+,7\rightarrow 8^+,8) =(M_1/3)^2\approx(16M_2/3)^2$ for the 398 keV $8^+\rightarrow 8^+$ transition a partial decay rate of $T_\gamma\approx 3\times 10^9$ s^{-1}. Thus the Coriolis coupling of the bands (a) and (c) leads in a natural way to an enhancement of the $(8^+,7)\rightarrow(8^+,8)$ transition compared to the $(7^+,7)\rightarrow(8^+,8)$ transition. It is interesting to note here that (i) the matrix element of 5 keV corresponds to an interaction-matrix element of 20 keV for the 8^+ members of the bands (a) and (c) close to the value of 25 keV suggested by Saitoh *et al.* [5] for the interaction of the 179 and 577 keV 8^+ levels, and (ii) Dracoulis *et al.* [4] have already suggested a mixing of the bands (a) and (c) as an explanation for a possible discrepancy between the measured and calculated (g_K-g_R) values of the band (c).

The mixing of the bands (a) and (c) also gives rise to $E2$ transitions between these bands. The Coriolis coupling leads, to first order, to an I-independent renormalization of the intrinsic $E2$-matrix element M_i,

$$M_i(E2)\Rightarrow M_i(E2)+M_c(E2)$$

with

$$M_c(E2)=\sqrt{6}\epsilon\sqrt{\frac{5}{16\pi}}eQ_0. \quad (10)$$

The induced $E2$ moment is expected to be large compared to the intrinsic moment [18]. With the above estimate of ϵ and $Q_0=679$ fm^2 one obtains $M_c(E2)=7.8$ e fm^2, and an $E2$ transition rate for the 179 keV $7^+\rightarrow 8^+$ transition of $T_\gamma(1+\alpha_{tot})=1.3\times 10^7$ s^{-1} that would account for $\approx 75\%$ of the observed total transition rate. Saitoh *et al.* [5] derive a conversion coefficient of $\alpha_{tot}(179\text{ keV})=0.96\pm 0.10$ from intensity balance considerations that would limit the $E2$ content of the 179 keV transition to at most 25%. One possible explanation for this discrepancy would be that the intrinsic and induced $E2$ moments partly cancel each other. However, the $5/2[402]\rightarrow 7/2[404]$ transition involves a spin flip and an $E2$ transition is therefore forbidden. We consider this $E2$ discrepancy as an indication for mixed configurations of the first-excited $K^\pi=7^+$ and 8^+ bands.

The Coriolis coupling also implies corrections to the rotational energies that amount, to first order, to a renormalization of the rotational parameter A_0 by $\delta A\approx\pm\epsilon^2\Delta E$ [18].

TABLE XI. Gamma-ray branching ratios for intraband transitions of the $K^{\pi}=7^{+}$ band in ^{180}Ta.

I^{π}	$I_{\gamma}[I\rightarrow(I-1)]/I_{\gamma}[I\rightarrow(I-2)]$ [a]			
	Exp.	$K=7_a$	$K=7_b$	$K=8_d$
9^{+}	4.3(7)	0.85	3.24	
10^{+}	3.1(4)	0.44	1.73	5.59
11^{+}	1.1(1)	0.29	1.13	2.76
12^{+}	1.5(3)	0.21	0.82	1.80
13^{+}	0.27(6)	0.16	0.64	1.31

[a]The values in column 2 are experimental results from Ref. [5]. The values in columns 3 to 5 were calculated with $Q_0=679$ fm^2 and $\langle K|\mathcal{M}(M1,\nu=0)|K\rangle=0.60$, 1.5, and 2.0 $e\hbar/2Mc$ for the bands (a), (b), and (d), respectively.

The experimental values of A calculated from the energy differences of the 8^{+} and 9^{+} levels are $A=10.91$, 11.54, and 12.85 keV for the 179, 517, and 577 keV 8^{+} levels, respectively. Under the assumption that the 577 keV level is the 8^{+} member of the 7^{+} band, one would obtain $A_0=11.88$ keV, $\delta A=\pm 0.97$ keV, and with $\Delta E\approx 370$ keV a mixing amplitude of $|\epsilon|\approx 0.05$. Again, this indicates the presence of additional coupling effects.

The previous assignment of the 577 keV 8^{+} sequence as $K^{\pi}=8^{+}$ band with the configuration $\pi 9/2^{-}[514]+\nu 7/2^{-}[514]$ was based on experimental intraband $B(M1)/B(E2)$ ratios which, according to Saitoh *et al.* [5], confirm this assignment. The γ-ray intensity ratios of these transitions are compared in Table XI with the ratios calculated for the $K^{\pi}=7^{+}$ bands (a) and (b) and the $K^{\pi}=8^{+}$ band (d). For band (a) the $I\rightarrow(I-1)$ $M1$ transitions are underestimated by a factor of ≈ 5. However, the agreement is not much better for the 8^{+} band (d) and the experimental data show some scattering casting doubt on their reliability.

The $K^{\pi}=8^{+}$ band based on the 517 keV level is associated in Refs. [4,5] with the configuration (e), based on the comparison of measured and calculated (g_K-g_R) values. Dracoulis *et al.* [4] note one difficulty with this assignment: in the BCS calculation the configuration (e) is predicted 220 keV higher than the observed state, whereas the configuration (d) is predicted 80 keV lower. These authors, therefore, suggest that this could imply an overestimate of the energy of the single-neutron $7/2^{-}[503]$ orbital in their calculation and a corresponding underestimate of the $7/2^{-}[514]$ energy. The 1^{+} doublet partner of the 8^{+} state with the neutron configuration $7/2^{-}[514]$ was identified in the present work at 320 keV in agreement with the calculated energy of Ref. [4], which seems incompatible with the proposed energy changes. We, therefore, adopt the assignment of the configuration $\pi 9/2^{-}[514]+\nu 7/2^{-}[503]$ to the 517 keV 8^{+} level only tentatively.

To summarize this discussion, we believe that the intraband and interband transitions between the five low-lying bands with $K^{\pi}=7^{+}$ and 8^{+} are sensitive to the mixing of all five bands, and therefore a better understanding of these couplings is a prerequisite for reliable configuration assignments based on γ-ray branching ratios. In particular we mention the possible importance of the 7^{+} band (b) that is predicted to be separated from band (a) by only ≈ 100 keV [4,5], but for which so far no experimental information is available. This band is expected to couple strongly to the 8^{+} bands (d) and (e) and these couplings could have a large influence on the interband transitions.

IV. CONCLUSION

The nuclear structure of ^{180}Ta has been studied by in-beam γ-ray spectroscopy following the (p,n) and $(d,2n)$ reactions in which preferentially two-quasiparticle states with low K are populated. We have identified eight new low-lying rotational bands, thereby doubling the number of known levels with their associated bands. Reliable configuration assignments can be made for most of these bands and the experimental bandhead energies agree in general with the values predicted by BCS calculations to better than 100 keV. In spite of this progress, two-thirds of the two-quasiparticle levels predicted below 1 MeV are still unobserved. Moreover, for some of the identified bands the level density is high with several states so far unidentified, and band couplings have a large effect on the γ-ray branchings used for configuration assignments making these assignments uncertain.

One aim of the present investigation had been to search for low-lying states that could be responsible for the experimentally established link between the 1^{+} ground state and the 9^{-} isomer by inelastic photon scattering. We observe levels at 892.6 and 907.3 keV with possible branchings populating both the ground state and the isomer. However, the assignments of the γ rays depopulating these levels are still uncertain and their involvement in the $K^{\pi}=9^{-}$ to 1^{+} transformation is therefore not clear. A unique identification of the decay properties of these levels would require an identification of the weak feeding transitions to be utilized in the $\gamma\gamma$ coincidences that was beyond the sensitivity of our measurements.

In the present work, $\gamma\gamma$ coincidences were measured with five Ge detectors, yielding only limited statistical accuracy. With modern $\gamma\gamma$-coincidence arrays, it should be possible to increase the experimental sensitivity for the identification of the missing two-quasiparticle states by at least two orders of magnitude. Moreover, we believe that such a measurement would also be a promising approach for the identification of the higher-lying intermediate states involved in the coupling of the 9^{-} isomer to the ground state.

Direct experimental information on the location and structure of some of the as yet unidentified states could also be obtained from a study of the ^{179}Hf(α,t) reaction. This would, however, require a high-resolution, high-statistics measurement with a highly enriched ^{179}Hf target. Finally, a high-resolution study of the ^{182}W(d,α) reaction with a polarized deuteron beam would also be valuable. This reaction enables definite spin-parity assignments for low spins and could thus provide information on the 0^{-} states that are difficult to identify in the compound and single-nucleon transfer reactions.

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