Decay of ^{180}Re: Search for octupole states in ^{180}W

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Study of the decay of 2.45-min ^{180}Re leads to the observation of about 90 γ rays and a number of new levels in ^{180}W. Spins and parities of many of the levels observed are determined using the log*ft* values of positron population and/or the γ-ray depopulation. The allowed unhindered decay from the $(\pi 5/2^+[402\uparrow]$-$\nu 7/2^-[514\downarrow])_{1-}$ ^{180}Re ground state indicates fragmentation of the $(\pi 5/2^+[402\uparrow]$-$\pi 9/2^-[514\uparrow])_{2-}$ configuration among a number of 2^- states in ^{180}W. We find tentative observation of the $K=1^-$ and 0^- components of the octupole vibration. This would establish the excitation energy of all four expected octupole components in ^{180}W.

[RADIOACTIVITY ^{180}Re [from ^{182}W$(p,3n)$, natural targets]; measured E_γ, I_γ, γ-γ coinc.; deduced log*ft*; ^{108}W deduced levels E, J, π.]

I. INTRODUCTION

In a study of the high-spin states in ^{180}W from the ^{181}Ta$(p,2n\gamma)^{180}$W reaction,[1] we observed both the $K^\pi=2^-$ and 3^- components of the octupole vibration. However, no evidence was found for the $K^\pi=0^-$ and 1^- components. Goudsmit *et al.*[2] have shown that the ground state of the 2.45-min positron/electron-capturing ^{180}Re activity must have the configuration $(\pi 5/2^+[402\uparrow]-\nu 7/2^-[514\downarrow])_{1}-$ because of its superallowed decay into the $K^\pi=2^-$ octupole band with an appreciable component of the configuration $(\pi 5/2^+[402\uparrow]-\pi 9/2^-[514\uparrow])_{2}-$. This proton configuration also strongly influences the β decay, with $\log ft=5.0$, to a level of 1832 keV, and it might be expected to influence the β decay to other 2^- levels. Although Goudsmit *et al.*[2] failed to identify the $K^\pi=0^-$ and 1^- octupole components, the large β decay Q value of 3828 keV suggests that they might be populated from the ^{180}Re decay. Identification of these components would allow a study of the interactions among all four of the octupole bands and a comparison with the study of Neergård and Vogel,[3] who have predicted the detailed properties based on microscopic calculations. With these purposes in mind, we have reinvestigated the decay of ^{180}Re.

II. EXPERIMENTS

Single detector γ-ray spectra were accumulated using a 15% coaxial Ge(Li) detector and a low-energy photon (LEP) pure Ge detector. Gamma-gamma coincidence spectra were also obtained using two 10% coaxial Ge(Li) detectors. Three-parameter coincidence data (E,E,t) were stored event by event on magnetic tape. Absorbers of 0.22-g/cm^2 Cd and 0.48-g/cm^2 Cu were used with the coaxial detectors to reduce the low-energy counting rates. Energy resolution was 2.0 to 2.5 keV full width at half-maximum (FWHM) at 900 keV for the coaxial detectors and 550 eV at 100 keV for the LEP detector.

Sources of ^{180}Re were produced by the ^{182}W$(p,3n)^{180}$Re reaction using 27-MeV protons from the Livermore cyclograaff. Target foils were natural W metal of 102 mg/cm^2 (coaxial detectors) or 51 mg/cm^2 (LEP detector). The sources were hand carried from their irradiation position in the external beam to the γ-ray spectroscopy detectors located outside the irradiation area. Longer-lived background activities were almost entirely due to other Re isotopes. These activities were held to a minimum in the single detector γ-ray spectrum measurements by using a new W foil for each irradiation. (About 40 sources were used in accumulating the singles spectrum.) Under these conditions, background activities in percent of the ^{180}Re activity at the start of data accumulation were as follows: 19-h ^{181}Re, 0.3%; ^{182}Re, 0.15% (mostly 12.7 h); 38-d ^{184}Re, 0.02%.

In the singles γ-ray spectrum experiments, two 4096-channel spectra, separated in time by 2.5 to 3.3 min, were accumulated for each source. The computer code GAMANAL[4] was used for analysis of the spectra. Gamma rays which exhibited the proper 2.45-min decay in these spectra were assigned to ^{180}Re decay. Our data are most consistent with a half-life of 2.38 min for ^{180}Re, in good agreement with previously published values.[5]

Only one spectrum was accumulated in the coincidence experiment. A 180° detector geometry was used, with the detectors separated by ~5 mm of Pb shielding, and with the sources axially located in a 5-mm diameter hole in the shield.

The spectra in coincidence with 50 γ-ray energy gates were generated by off-line sorting of the event-mode data; coincidences due to chance and to the Compton continuum underlying the γ-ray peaks were subtracted during the sorting process.

Energy calibrations were based on the ^{180}W γ rays of 233.98, 744.78, 902.84, 1006.41, 1117.24, and 1129.09 keV which were measured in the ^{181}Ta(p, $2n\gamma$) experiments,[1] and which are prominent in the ^{180}Re decay spectrum. We used standard γ-ray sources of ^{56}Co, ^{133}Ba, ^{152}Eu, and ^{182}Ta for energy nonlinearity and efficiency calibrations.

III. RESULTS

The γ-ray spectra obtained during the first count are shown in Fig. 1. The lines at 365.5 keV and at 1121.4, 1189.2, 1221.5, and 1231.1 keV are impurities from ^{181}Re and ^{182}Re, respectively. Spectra in coincidence with the 2^+-0^+ transition (103.6 keV) in the ground-state band, the 902.8-keV γ ray that depopulates the octupole $K^\pi = 2^-$ level at 1006.4 keV, and the 1013.7- and 1117.3-keV γ rays that depopulate the $K^\pi = 2^+$ level at 1117.2 keV, are shown in Fig. 2. Table I summarizes the data and shows for comparison (on an independent intensity scale) the γ-ray intensities reported by Goudsmit *et al.*[2]

Using the energy and coincidence data in Table I together with existing information about the ^{180}W levels,[1] we have constructed the decay scheme shown in Fig. 3 for ^{180}W levels populated by ^{180}Re decay. The strongly populated level at 1831.71 keV was established in the early studies[2] of ^{180}Re decay. None of the other levels above 1233 keV have been reported previously.

The three states at 1587.25, 1632.90, and 1814.9 keV are the only states we find in the region between 1.0 and 2.0 MeV that could possibly belong to the $K^\pi = 0^-$ or $K^\pi = 1^-$ octupole bands. Although they are only weakly populated in the ^{180}Re decay, these levels are quite firmly established by our γ-ray energy and coincidence data. The 1632.90-keV state cannot be the same level as the one observed at 1634.56 keV and interpreted as $K^\pi = 3^-$ in the ^{181}Ta(p, $2n\gamma$)^{180}W study[1] because the decay modes are entirely different.

There is evidence that all three of these states were populated in the ^{181}Ta(p, $2n\gamma$)^{180}W reaction.[1] The 1483.6-, 1529.8-, and possibly the 1786.4-keV γ rays reported in Ref. 1 agree in energy with γ rays which depopulate the levels at 1587, 1633, and 1815 keV, respectively. Also, the 808.9-keV γ ray which depopulates the 1815-keV level appeared in coincidence with the 902.8-keV γ ray. These data indicate that the populations of the three levels in the ^{181}Ta(p, $2n\gamma$) reaction were as follows, relative to the population of the $K^\pi = 2^-$ band head at 1006 keV: 4% (1587-keV level), 3% (1633-keV level), and 4% (1815-keV

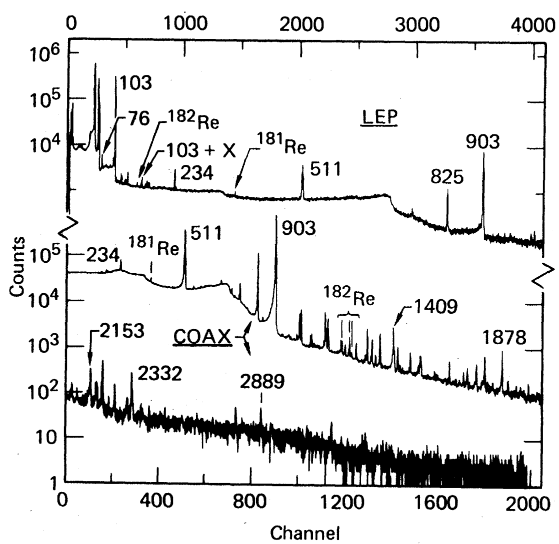

FIG. 1. Gamma-ray spectra obtained with a pure Ge (LEP) detector (top scale) and a coaxial Ge (Li) detector (bottom scale, 0–4096 channels overlapped). Energy calibrations are approximately 0.25 keV/channel (LEP) and 1.00 keV/channel (coax).

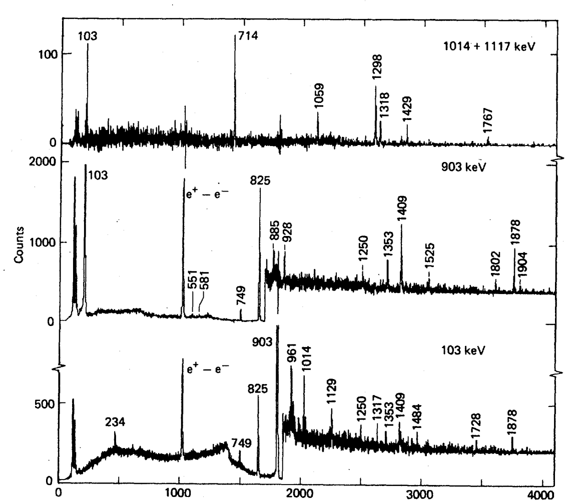

FIG. 2. Gamma-ray spectra in coincidence with three different energy gates, showing γ rays which populate the ground-state band, the octupole band head at 1006 keV (903-keV gate), and the 2^+ band head at 1117 keV (1014-+ 1117-keV gates). The changes which occur in the ordinate scale in the region between channels 1500 and 2000 are by a factor of 20 in the 903-keV gated spectrum and by a factor of 10 in the 103-keV gated spectrum. A constant of 20 counts per channel has been added to the data from the 903- and 103-keV gates in order to eliminate negative numbers arising from the chance coincidence subtractions.

TABLE I. Gamma rays from ^{180}Re decay.

$E_\gamma(\Delta E)$ (keV)[a]	$I_\gamma(\Delta I_\gamma)$ Goudsmit *et al.*[b]	$I_\gamma(\Delta I_\gamma)$ This work[c]	Coincidence γ rays (keV)	Transition E_i	Transition E_f
75.99	~0.7	19 (1)	104, 749, 903, (1353)	1082	1006
(102.51)[d]		(1.7)[d]		1185	1082
103.567	23.0(25)	2390 (70)	234, 511[e], 749, 825, 903, (970) 1014, 1121, 1130, 1250, 1318, (1332), 1353, 1409, (1484) (1529), 1727, (1766), 1877	104	0
131.54		11.7(5)			
173.91(7)		10 (2)	None		
178.74(9)		7.7(8)	1250	1185	1006
233.983	0.5(1)	85 (3)	104, (551), 669, 745, 749, 825 (847), 895, (1250), (1333), 1353, 1477, (1802)	338	104
511[e]			104, 511[e], 570, 669, 825, 903, 1006		
550.52(4)		18.1(15)	104, (745), 903	1633	1082
580.8(1)		12 (2)	(828), 848, 903, (935)	1587	1006
599.0(1)		16 (2)	(104), 234, 1129	1832	1233
626.7(2)		6.4(23)		1633	1006
668.80(3)		44 (3)	234, (749), (825), (1333), (1353), (1878)	1006	338
699.7(2)		10 (3)	None	(2532	1832)
714.43(3)		30(2)	1014, 1117	1832	1117
744.84(4)	[0.7(2)]	28 (2)	104, 234, (551), 749, (1353)	1082	338
749.34(1)	1.4(4)	120 (4)	(76), 104, 234, 745, 903	1832	1082
782.6(2)		2.9(10)		2416	1633
808.9(3)		3.1(6)		1815	1006
825.36(1)	11.8(5)	1070 (30)	104, (234), 511[e], 903, (971), 1006, 1052	1832	1006
828.5		4 (2)[f]		(2416	1587)
847.80(9)		3 (1)	581, 1484, (1587)	1185	338
		4.5(10)		2435	1587
(895.26)[d]		7.6[d]	234, (1651)	1233	338
902.838	100	9690 (290)	104, 162, 511[e], 551, (581), (627) 749, (809), 825, 929, 1250 (1333), 1353, 1409, 1429, (1516), (1525), 1802, (1816), 1878, (1904)	1006	104
935.2(2)		3.5(9)	(581), (903)	2523	1587
995.14(8)		7.6(8)	104, 234, 1129	2228	1233
1006.31(2)	0.6(1)	53 (2)	511[e], 825, (1409)	1006	0
1013.73(2)	1.2(3)	79 (3)	104, 714, 1059, 1298, 1318, 1405, 1429, (1767)	1117	338
1036.0(3)		1.1(4)			
1052.42(5)		9.9(6)	104, 825, 903	2884	1832
1059.42(4)	0.20(7)	12.7(7)	(104), 1014, 1117	2177	1117
1069.4(2)		3.3(6)	104, (1711)	2884	1815
1082.6(3)		1.5(5)			
1110.7(2)		5.9(7)		2228	1117
1117.28(2)	0.7(2)	67 (2)	714, 1059, 1298, 1318, (1405), 1429, 1767	1117	0
1129.14(2)	0.6(2)	48 (2)	104, 599, 995, 1183, 1203 (1290), 1651	1233	104
1145.4(4)		1.1(6)		2228	1082
1183.11(5)		12 (1)	1129	2416	1233
1202.6(1)	0.27(8)	8.6(7)	1129	2435	1233
1250.22(4)		6 (1)	104, 179, 903	2435	1185
		6 (1)		2257	1006
1290.0(1)		4.2(6)		2523	1233

TABLE I. *(Continued.)*

$E_\gamma(\Delta E)$ (keV)[a]	$I_\gamma(\Delta I_\gamma)$ Goudsmit *et al.*[b]	This work[c]	Coincidence γ rays (keV)	E_i	E_f
1298.44(2)	0.47(9)	37 (1)	104, 1014, 1117	2416	1117
		<3		2532	1233
1314.2(1)		4 (1)		2547	1233
1317.85(3)	0.30(7)	19 (1)	1014, 1117	2435	1117
1333.4(1)		5.8(6)	(745)	2416	1082
1352.80(2)	0.37(8)	30 (2)	104, 234, 903	2435	1082
1405.2(1)		6.7(7)		2523	1117
1409.40(2)	1.2(1)	50 (2)	104, 903	2416	1006
1429.22(4)[g]	0.26(8)	11 (2)	903, 1014, 1117	2547	1117
		4 (1)		2435	1006
1449.2(2)		1.7(6)		2532	1082
1477.3(3)		1.4(5)		1815	338
1483.69(4)	0.29(6)	11 (1)	104, 848, (935)	1587	104
1516.0(5)		5 (1)		2523	1006
1525.14(6)		8.1(5)	(104), 903	2532	1006
1529.30(6)	0.32(6)	8.4(5)	(104)	1633	104
1561.0(4)		0.6(4)			
1587.2(2)		1.9(4)		1587	0
1595.5(3)		1.1(4)			
1651.45(6)		7.1(5)	104, 1129	2884	1233
1678.0(3)		2.2(6)		(2910	1233
1694.0(4)[h]		1.4(8)			
1711.3(2)		2.5(4)		1815	104
1727.8(1)		6.1(8)	104	1832	104
1766.74(6)	0.15(4)	9.2(9)	1014, 1117	2884	1117
1792.3(3)		1.8(5)	None	(2910	1117)
1801.75(5)	0.2(1)	15.2(10)	104, 903, (745)	2884	1082
1815.6(3)		1.8(4)	(903)		
1839.6(2)		1.8(4)			
1877.70(3)	0.25(3)	22.4(10)	104, 903	2884	1006
1903.6(1)		3.1(4)	(903)	(2910	1006)
1939.1(2)		1.1(3)			
1991.1(2)		2.1(4)			
2027.2(4)	0.04(2)	1.4(4)			
2066.9(4)		1.3(3)			
2073.5(2)	0.084(30)	2.5(4)		2177	104
2096.0(2)		1.3(3)			
2142.2(3)		1.7(3)			
2153.24(6)	0.11(2)	9.2(6)		2257	104
2165.7(4)		0.4(2)			
2176.9(1)		3.6(4)		2177	0
2182.3(1)		2.9(3)			
2196.0(5)		0.3(2)			
2204.64(4)	0.13(2)	15.3(7)			
2232.9(2)		1.3(3)			
2258.4(1)	0.05(2)	4.4(4)			
2312.1(2)		1.9(4)		2416	104
2331.87(6)	<0.12(2)	9.1(5)		2435	104
2408.4(3)	0.02(2)	0.6(2)			
2475.5(3)		0.7(2)			
2780.6(2)		1.4(2)		2884	104
2889.8(2)		1.6(3)			
3340.7(5)		0.6(2)			

TABLE I. (*Continued.*)

[a] Errors in the least significant digits are shown in parentheses. They reflect only the statistical uncertainties in peak positions. Approximately 50 eV should be added in quadrature for γ rays below 1500 keV, and 100 eV for γ rays above 1500 keV, in order to include systematic errors.

[b] Reference 2. These authors also report γ rays which we do not confirm at 1024.9, 1228, (1545), 1820.5, 1838.4, 1867.4, 2033.6, 2241.9, and 2341 keV.

[c] Intensities are the number of γ rays per 10 900 Re decays. Errors include our estimate of systematic errors. The statistical errors on intense lines (104, 825, and 903 keV) are much smaller than the errors shown.

[d] Energy and intensity from Ref. 1.

[e] $e^+ - e^-$ annihilation radiation.

[f] This line was seen marginally only in coincidence data.

[g] Complex peak. From coincidence data the γ rays to the 1117- and 1006-keV levels have energies of 1429.5(2) and 1428.8(1) keV, respectively.

[h] This peak might be due to the pair effect of the 2204.6-keV γ ray with single 511 escape.

level). The Hauser-Feshbach calculation discussed in Ref. 1 predicts populations of the $K^\pi = 0^-$ and 1^- bands which agree well with the above observations.

The level at 1814.9 keV agrees very closely in energy with a level that is strongly populated in the (d,d') reaction.[6] Our coincidence data support the decay of this level to the 4^+ and 2^+ members of the ground-state band and also to the $K^\pi = 2^-$ octupole band head at 1006.4 keV. A weak γ ray of 1815.6 keV suggests that the 1814.9-keV level might also decay to the ground state. Because of the low intensities, the data are not good enough to reject this possibility completely. However, both the energy fit, which is off by 2 standard deviations, and the coincidence data, which show weak evidence of coincidences between the 1815.6- and 902.8-keV γ rays, suggest that the 1815.6-keV γ ray does not depopulate the 1814.9-keV state.

Beta decay intensities shown in Table II were determined from a detailed intensity balance at each level. In general, we used theoretical values of the conversion coefficients[7] for each γ ray based on its most probable multipolarity. (We used the measured conversion coefficient of Konijn *et al.*[8] for the 902.8-keV γ ray.) Uncertainties in the conversion coefficients had only a minor effect on the intensity balances. The $\log ft$ values in Table II were obtained from the tables of Gove and Martin[9] using the $\beta^+ + e^-$-capture intensities, the β-decay Q value of 3828 ± 60 keV determined by Goudsmit *et al.*,[2] and a ^{180}Re half-life of 2.45 min. We assumed there is no β decay to the ^{180}W ground state. If an upper limit of intensity corresponding to $\log ft = 6.0$ is assumed

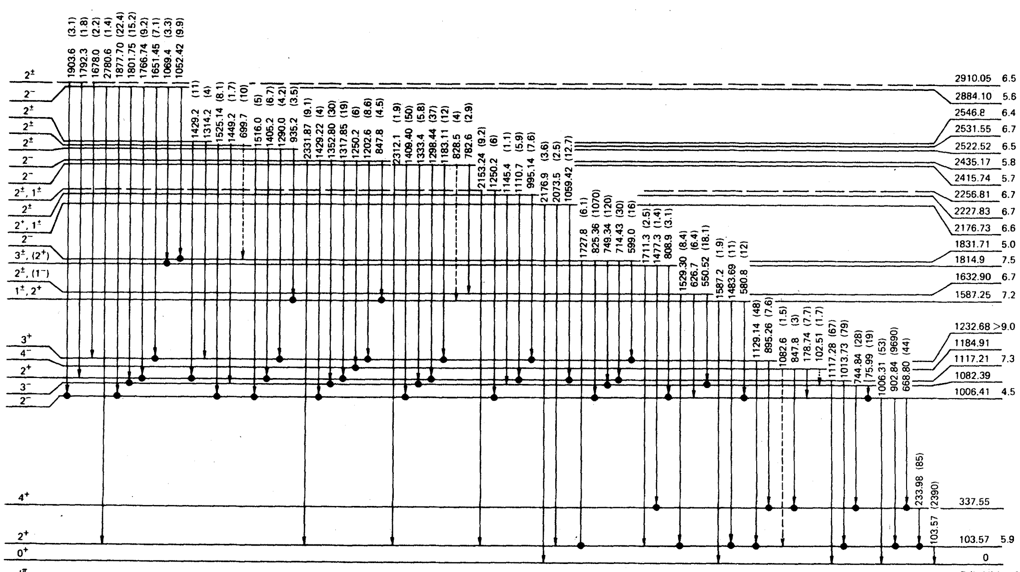

FIG. 3. Decay scheme of ^{180}Re. Gamma-ray intensities per 10 900 Re decays are shown in parentheses following the transition energy label (in keV). A dot at the arrowhead of a γ-ray transition indicates that the γ ray was seen in coincidence with one or more of the γ rays which depopulate the level.

TABLE II. Logft values for ^{180}Re decay to levels in ^{180}W.

Level (keV)	$\beta^+ + K$-cap. Intensity[a]	$\log f_0 t$[b]
103.57	730(430)	5.9
337.55	14(7)	7.5[c]
1006.41	8410(290)	4.50
1082.39	62(20)	6.6[c]
1117.21	12(4)	7.3
1184.91	17(5)	7.1[c]
1232.68	−2(4)	>9.0[d]
1587.25	11(4)	7.2
1632.90	30(3)	6.7
1814.9	3.7(11)	7.5
1831.71	1240(30)	5.0
2176.73	19(1)	6.6
2227.83	15(1)	6.7
2256.81	15(2)	6.7
2415.74	112(4)	5.7
2435.17	82(5)	5.8
2522.52	16(2)	6.5
2531.55	10(1)	6.7[e]
2546.8	17(2)	6.4
2884.10	65(2)	5.6
2910.05	7(1)	6.5

[a] Errors in the least significant digits are shown in parentheses.

[b] Uncertainties in logft's can be inferred from the β-decay intensity errors in column 2. The uncertainty in Q_β introduces an error of 0.02 to 0.04 in logft.

[c] These are at least 2nd forbidden. The logft differences, by ~2σ (337-keV level) and ~3σ (1082- and 1185-keV levels) from the large expected values, are presumably due to unplaced weak γ rays.

[d] $\log f_1 t$.

[e] This logft would be 6.4 if the 699.7-keV γ ray depopulated the 2531.55-keV level.

for the ground-state transition, then the logft's in Table II would increase by a maximum of 0.1.

Spins and parities of the levels up to 1232.68 keV are known from previous work. For the other levels we used logft values and γ-ray branchings to deduce the possible spins and parities, as shown in Fig. 3. The levels at 1831.71, 2415.74, 2435.17, and 2884.10 keV are restricted to the unique value $I^\pi = 2^-$ because of the low logft values, indicating allowed β decay[10] from the 1^- ground state of ^{180}Re, and because they all have γ-ray branches to the 3^+ state at 1232.68 keV. All of the remaining levels have uncertain parity based on their logft values, which are consistent with either allowed or first-forbidden β decay. Several of these levels, at 2227.83, 2522.52, 2531.55, 2546.8, and 2910.05 keV, are rather clearly restricted to $I = 2$ because of γ-ray branches to 3^+ and/or 3^- levels and the absence of observable γ branches to the ground-state band. If these levels had $I = 1$, we would expect the high energy ΔK-allowed dipole transitions to the ground-state band to be the dominant mode of decay.

The possible spins for the other five levels above 1233 keV are more ambiguous (see Fig. 3). The two levels at 1587.25 and 1632.90 are particularly interesting because of the possibility that they may be the $I = 1$ and 2 members of the $K^\pi = 1^-$ octupole band (see Sec. IV). Both levels decay to the ground-state band; the 1587.25-keV level decays to both the 0^+ and the 2^+ members, and the 1632.90-keV level decays to the 2^+ member only. This would be consistent with a $K = 1$ assignment for them. However, the other J^π possibilities shown in Fig. 3 cannot be rejected on the basis of the β- and γ-decay properties.

Since the level at 1814.9 keV decays to the 2^+ and 4^+ levels of the ground-state band, but probably not to the 0^+ level, its spin is most likely 3. That interpretation would conflict with the logft value in Table II, which is too low for a β decay with $\Delta I > 1$. However, this discrepancy could easily be due to undetected weak γ rays which populate the 1814.9-keV level, causing our measured logft to be too low.

IV. DISCUSSION

One interesting aspect of the ^{180}Re decay to levels in ^{180}W is the low logft values to five 2^- states with energies of 1006, 1832, 2416, 2435, and 2884 keV. The logft values to these states are 4.5, 5.0, 5.7, 5.8, and 5.6, respectively. It is clear from the low logft values that the allowed unhindered decay from the $(\pi 5/2^+[402\uparrow]-\nu 7/2^-[514\downarrow])_{1^-}$ configuration of the ^{180}Re ground state to the $(\pi 5/2^+[402\uparrow]-\pi 9/2^-[514\uparrow])_{2^-}$ configuration in ^{180}W dominates these decay modes. If one makes the simplifying assumption that these are the only configurations involved in the decay to the five 2^- states, one can calculate the fragmentation of the $(\pi 5/2^+[402\uparrow]-\pi 9/2^-[514\uparrow])_{2^-}$ configuration among these five states. Based on the measured logft values, the percentages of this configuration in the 1006-, 1832-, 2416-, 2435-, and 2884-keV states are 66, 21, 4, 3, and 5, respectively. It is interesting that such a large fraction (approximately 66%) of the $(\pi 5/2^+[402\uparrow]-\pi 9/2^-[514\uparrow])_{2^-}$ configuration is in the 1006-keV state, which is the $K^\pi = 2^-$ component of the octupole vibration. This is somewhat surprising, since the band is known to be quite collective and is expected therefore to be made up from a large number of small contributions of the quasiparticle states. Most of the rest of the $(\pi 5/2^+[402\uparrow]-\pi 9/2^-[514\uparrow])_{2^-}$ configuration (21%) resides in the 1832-keV state. Smaller fractions (but enough to influence the logft values significantly) reside in the other three 2^- states.

States in ^{180}W with possible spin-parity of 1^- and 2^- are observed at 1587.25 and 1632.90 keV, respectively. If these two states are assumed to be members of the same rotational band, a rotational constant $\hbar^2/2\mathcal{J} = 11.4$ keV is calculated in substantial agreement with the value $\hbar^2/2\mathcal{J} = 12.6$ keV calculated from the 2^- and 3^- members of the $K^\pi = 2^-$ octupole band. It is therefore tempting to suggest that the states at 1587.25 and 1632.90 keV are the 1^- and 2^- members of the $K^\pi = 1^-$ octupole band. This interpretation receives support from the possible observation in the (d, d') and the $(p, 2n\gamma)$ studies[1,6] of the 3^- member of the $K^\pi = 1^-$ band. A state observed at 1693.6 keV in the $(p, 2n\gamma)$ reaction decays to the 4^+ member of the ground-state band and corresponds closely in energy to the state at 1692 keV reported in the (d, d') reaction. This energy agrees very well with the predicted energy of the 3^- state in our proposed $K^\pi = 1^-$ band, especially if we allow for some depression of the odd-spin energies due to Coriolis-induced mixing with the $K^\pi = 0^-$ band.

A state which is observed at 1814.9 keV with spin $3^{\pm}(2^+)$ corresponds almost exactly with the state observed at 1814 keV in the (d, d') studies of Günther *et al.*[6] This is the most strongly populated state in the (d, d') reaction above the 3^- member of the $K^\pi = 2^-$ band at 1082.39 keV. The (d, d') strength and our observation of γ-ray decay to the 2^+ and 4^+ members of the ground-state band would be consistent with an assignment for the 1814.9-keV state as the 3^- member of the $K^\pi = 0^-$ octupole band. In that case the γ-ray branching to the ground-state band members might agree reasonably well with the Alaga rules,[11] because the $\Delta K = 1$ $E1$ transitions due to any admixed $K = 1$ components in the 1815-keV level are expected to be rather strongly hindered with respect to the $\Delta K = 0$ transitions.[12] The predicted ratio of reduced $E1$ transition probabilities to the 2^+ and the 4^+ members of the ground band is 0.75, in satisfactory agreement with the observed ratio of 1.1 ± 0.4.

The 1814.9-keV level decays to the $K^\pi = 2^-$ octupole band head at 1006.4 keV with an intensity roughly equal to its decay to the ground-state band. This branching requires a hindrance of the $E1$ transitions to the ground band of $\sim 4 \times 10^4$ if we assume an $E2$ strength of one single-particle Weisskopf unit for the $\Delta K = 2$ decay to the $K^\pi = 2^-$ band head. Such a large hindrance for a $\Delta K = 0$ transition weakens the $K^\pi, I = 0^-, 3$ assignment,[12] but it may not be sufficient cause to reject the possibility entirely. In ^{236}U, for example,[5] the transitions from the 688-keV level to the ground-state band appear to be $\Delta K = 0$ $E1$'s with hindrances exceeding 10^6. If the inertial parameter $\hbar^2/2\mathcal{J}$ in this proposed $K^\pi = 0^-$ band is the same as in the $K^\pi = 2^-$ octupole band, then the $K^\pi, I = 0^-, 1$ band head would be at 1688 keV.

Using random-phase approximation (RPA) calculations with an octupole-octupole force and including Coriolis mixing, Neergård and Vogel[3] have been able to reproduce both the approximate energies of band heads and the $B(E3)$ strengths in the 3^- members of the $K^\pi = 0^-$, 1^-, 2^-, and 3^- octupole bands in the rare earth nuclei. In view of the previous qualitative success of these calculations, it may be of value to compare their calculations with the two previously observed[1] octupole bands ($K^\pi = 2^-$ and 3^-) and with the tentatively assigned $K^\pi = 0^-$ and 1^- bands from the present research. Unfortunately, Neergård and Vogel did not report calculations on ^{180}W in Ref. 3. However, the results of a calculation by Neergård on ^{180}W are reported by Günther *et al.*[6] for the $K^\pi = 2^-$ and 3^- bands. For the $K^\pi = 0^-$ and 1^- bands, we have extrapolated the Neergård and Vogel results on Hf and other W isotopes to obtain approximate predictions of the band head energies and the $B(E3)$ values in ^{180}W. The calculated values for the $K^\pi = 0^-$, 1^-, 2^-, and 3^- bands, respectively, are 2000, 1400, 1290, and 1740 keV for the band head energies, and 1, 0.1, 12.4, and 3.8, in units of 10^{-2} e^2b^3, for the $B(E3)$ values to the $I = 3$ states. The systematics in this nuclide region suggest that the extrapolations used for $K = 0$ and 1 might introduce errors of $\leq 10\%$ in the energy predictions and of a factor of 2 or more in the $B(E3)$ predictions. Considering the large uncertainties in these predictions and the uncertainties in extracting $B(E3)$ values from the (d, d') experiments,[6] the agreement between measured $B(E3)$ values and the predictions seems acceptable for our proposed octupole 3^- states.

Recent calculations[1] have been carried out for ^{180}W directly. In these calculations the data available on the $K^\pi = 2^-$ and 3^- octupole bands from in-beam measurements were used with a Coriolis interaction model in an attempt to obtain better estimates for the positions of the missing $K^\pi = 0^-$ and 1^- octupole band heads. The data from the present experiments suggest a disparity of several hundred keV in the positions of these octupole bands when compared to the results of the simple Coriolis interaction calculation of Ref. 1. The calculation was repeated and the additional experimental data from the present study were used to fix the positions of the four octupole band heads. No realistic set of Coriolis interaction matrix elements could be found which would accurately accommodate both the known energies of the octupole bands and the measured rotational spacings in the $K^{\pi}=1^-$ and 2^- bands. Nevertheless, a set of reasonable parameters was obtained which give a best fit to all the experimental data. The calculated values of the lowest-lying states in each octupole band are compared in Table III with the experimental data and with the calculations of Neergård and Vogel.[3]

With the wave functions derived from these calculations, we can estimate the logft value for the $K^{\pi}, I=1^-, 2$ octupole state tentatively assigned as the level at 1632.9 keV. The calculated wave function for this state is $|1633, I=2\rangle = 0.9992|1^-, 2\rangle - 0.0389|2^-, 2\rangle$. If we assume that the $K^{\pi}=1^-$ octupole band head is essentially unmixed, then we can use the Alaga rules[11] with the observed ft value to the 1587-keV state to determine the β-decay matrix element for the $|1^-, 2\rangle$ component. The ft value for the $|2^-, 2\rangle$ component is determined directly from the observed ft value to the $K^{\pi}=2^-$ octupole band head at 1006 keV. Depending on the undetermined relative signs of the two matrix elements, the calculated logft to the $K^{\pi}, I=1^-, 2$ state is 6.8 or 7.2. This result agrees well with the observed value of 6.7 for the level at 1632.9 keV, and is therefore consistent with the assignment of the 1587.2- and 1632.9-keV levels as the spins 1 and 2 members of the $K^{\pi}=1^-$ octupole band.

TABLE III. Calculated and tentatively observed energies (in keV) of the lowest-lying states in each octupole band in ^{180}W.

	Energy (keV)			
	$K^{\pi}=0^-$	$K^{\pi}=1^-$	$K^{\pi}=2^-$	$K^{\pi}=3^-$
Experiment	1814.9[a]	1587.3	1006.4	1634.6[b]
Calculation[c]	1807[a]	1578	1006.8	1632
Calculation[d]	2100[a]	1400	1290	1740

[a] This is the energy of the K^{π}, $I=0^-, 3$ state. The K^{π}, $I=0^-, 1$ state has not been observed.
[b] See Ref. 1.
[c] Results from a semiempirical Coriolis interaction calculation. See text.
[d] Calculations of Neergård and Vogel (Ref. 3) extrapolated as described in the text. A value of $\hbar^2/2\mathfrak{J}=12.8$ has been assumed for the $K^{\pi}=0^-$ band.

V. CONCLUSIONS

We have identified 11 (and possibly 2 other) new low-spin states in ^{180}W. Low logft values to five 2^- states, including the $K^{\pi}=2^-$ octupole band head, indicate fragmentation of the $(\pi 5/2^+[402]-\pi 9/2^-[514])_{2^-}$ configuration among the five states. Tentative identification of a state at 1814.9 keV as the $K^{\pi}, I=0^-, 3$ octupole vibrational component is compatible with the γ-decay branching and the previously reported[6] strength of excitation in the (d,d') reaction. This assignment is a very speculative possibility, however, and requires confirmation by identification of other members of the rotational band. Two states at 1587.25 and 1632.90 keV and a previously reported state at 1693.6 keV[1,6] have γ-decay branchings, logft's from ^{180}Re β decay, (d,d') excitation (to the 1693.6-keV state), and energy spacings which are fully compatible with their assignments as the spins 1, 2, and 3 members of the $K^{\pi}=1^-$ octupole vibrational band. If these assignments can be finally confirmed, then the energies of all four components of the octupole vibration in ^{180}W would be quite firmly established. In that case, our extrapolations of the calculations in this nuclide region suggest there are significant discrepancies between the microscopic calculations and the observed band head energies, particularly for the $K=0$ and $K=2$ components.

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[1] L. G. Mann, J. B. Carlson, R. G. Lanier, G. L. Struble, W. M. Buckley, D. W. Heikkinen, I. D. Proctor, and R. K. Sheline, Phys. Rev. C 19, 1191 (1979).
[2] P. F. A. Goudsmit, J. Konijn, and F. W. N. de Boer, Nucl. Phys. A104, 497 (1967).
[3] K. Neergård and P. Vogel, Nucl. Phys. A145, 33 (1970).
[4] R. Gunnink and J. B. Niday, Lawrence Livermore Laboratory Report No. UCRL-51061, 1972 (unpublished).
[5] C. M. Lederer and V. S. Shirley, *Table of Isotopes* (Wiley, New York, 1978).
[6] F. Günther, P. Kleinheinz, R. F. Casten, and B. Elbek, Nucl. Phys. A172, 273 (1971).
[7] F. Rösel, H. M. Fries, K. Alder, and H. C. Pauli, At. Data Nucl. Data Tables 21, 291 (1978).

[8]J. Konijn, B. J. Meyer, and G. Van Middelkoop, Phys. Lett. 35B, 567 (1971).
[9]N. B. Gove and M. J. Martin, Nucl. Data Tables 10, 205 (1971).
[10]S. Raman and N. B. Gove, Phys. Rev. C 7, 1995 (1973).
[11]G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 29, No. 9, 2 (1955).
[12]L. Kocbach and P. Vogel, Phys. Lett. 32B, 434 (1970).