Levels in ^{186}Os as Populated from Decay of 15.8-h ^{186}Ir†

K. J. Hofstetter*
Cyclotron Institute and Department of Chemistry, Texas A & M University, College Station, Texas 77843, and Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506

T. T. Sugihara
Cyclotron Institute and Department of Chemistry, Texas A & M University, College Station, Texas, 77843

D. S. Brenner
Jeppson Laboratory, Clark University, Worcester, Massachusetts 01610
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The level scheme of ^{186}Os as populated by the decay of 15.8-h ^{186}Ir has been studied using Ge(Li) detectors in singles and coincidence spectrometers. The coincidence data confirm essentially all of the previously known intraband and interband transitions assigned to the ground-state band (to the 6^+ level), the γ band (to the 7^+ level), and to the $I=4$, 5, and 6 members of a two-phonon $K=4$ band. Coincidence data also establish levels in keV at 1194.45, (4^+); 1461.09, 4^+; 1480.3, 4^+; 1628.3, 5^-; 1775.8, 6^+; 1812.5, 5^+; 1875.40, 4^+; 2056.38, (5^+, 6^+); 2081.21, 4^+; 2377.3, (5^+, 6^+); and 2771.7, 4^+. The I^π assignments are based on multipolarities determined from internal-conversion coefficients. Additional levels based on energy sums are tentatively proposed at 1582.3, 2661.2, 3041.3, 3151.7, 3268.8, and 3413.6 keV. The 15.8-h ^{186}Ir state is believed to have $I^\pi=5^+$ and an argument is presented based on the β-decay pattern that $K=1$.

I. INTRODUCTION

Level schemes for ^{186}Os have been reported by several research groups. Emery *et al.*[1] at Brookhaven National Laboratory and Harmatz and Handley[2] at Oak Ridge National Laboratory have used high-resolution conversion-electron spectrometers to study the spectrum of internal-conversion electrons accompanying the decay of 15.8-h ^{186}Ir to levels in ^{186}Os. Sugihara, Keenan, and Perlman[3] combined the internal-conversion electron data with Ge(Li) γ-ray singles measurements to extract multipolarity information for the 127 transitions thought to follow the decay of ^{186}Ir. In each of these studies, a decay scheme was proposed based on energy sums, decay patterns, and multipolarities. A group at CERN has reported γ-ray data but has not proposed a decay scheme.[4] Fogelberg[5] has recently discussed mixing between the γ-vibrational band and the ground-state band in ^{186}Os in a study of ^{186}Ir and ^{186}Re decay. In this work we emphasize coincidence spectra obtained with two Ge(Li) detectors which have helped to resolve some of the ambiguities of the previous works.

Studies of reaction γ rays produced in the ^{184}W(α, $2n$)^{186}Os and ^{186}W(α, $4n$)^{186}Os reactions[6,7] have led to the firm assignment of members of the ground-state rotational band up to the 6^+ member. These levels are at 137.15 (2^+0), 433.91 (4^+0), and 868.70 (6^+0) keV; $I^\pi K$ are given in parentheses. The energy of the 8^+0 level is less clearly established but is probably 1420.13 keV. All of the decay studies of ^{186}Ir agree that ^{186}Os has a $K=2$ γ-vibrational band with levels at 767.38 (2^+2), 910.33 (3^+2), 1070.25 (4^+2), 1275.30 (5^+2), 1490.93 (6^+2), and 1752.28 (7^+2) keV. To simplify references to these levels we continue the practice of Refs. 1 and 3 and assign letters as follows: $A-E$ for the 0^+, 2^+, 4^+, 6^+, and 8^+ members, respectively, of the ground-state rotational band, and $F-K$ for members of the γ band in order of increasing energy. Other levels are also identified by a letter.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source Preparation

Rhenium metal powder, enriched to 96.7% in ^{185}Re, was used as the target for 40-MeV α-particle irradiations in the external beam of the Texas A & M variable-energy cyclotron or the Yale University heavy-ion accelerator. Sources of ^{186}Ir were produced by the ^{185}Re(α, $3n$)^{186}Ir reaction. The α-particle energy incident on the target ($\approx$35 MeV) was chosen to minimize the interference from ^{185}Ir and ^{187}Ir which have half-lives comparable to that of ^{186}Ir.[3] Some 41-h ^{188}Ir was also present from the ^{187}Re(α, $3n$)^{188}Ir reaction. For a typical experiment the charge collected on the target holder ranged from 5–30 μA h. The target preparation and irradiation procedures for the

Yale experiments were the same as those described in Ref. 3.

Iridium was chemically separated from the irradiated targets using the procedure of Sugihara, Keenan, and Perlman[3] during preliminary irradiations. Very little interfering activity was found to be eliminated by the chemical separation; hence for the majority of sources used, no analytical chemistry was performed.

B. γ-Ray Singles Measurements

The earlier γ-ray study,[3] which was done for the most part in 1965–66, used small-volume planar Ge(Li) detectors (4–5 cm^3) of moderate energy resolution and multichannel analyzers with limited storage capacity. Since Ge(Li) γ-counting systems have improved significantly in efficiency and resolution in the past few years, we felt it appropriate to reinvestigate the singles γ-ray spectrum of ^{186}Ir.

The detectors used in the present study included (1) a 33-cm^3 detector fabricated as a right circular cylinder with one open end which gave a resolution of 2.2 keV [full width at half maximum (FWHM) at 1332 keV], (2) a 6-cm^2 planar detector with a drifted depth of 9 mm and a resolution of 1.2 keV for the 122-keV γ ray of ^{57}Co, and (3) two 20-cm^3 coaxially drifted detectors which are described in the next section. Detector (1) was used for spectra taken at Clark University while (2) and (3) were used at Texas A & M University.

Detector efficiencies were determined with standard sources distributed by the International Atomic Energy Agency. A number of nuclides whose relative γ-ray intensities are well known were used as secondary intensity standards. The energy calibration was made using well-known lines[1] in ^{186}Ir as internal standards.

The very complex γ-ray spectra, which were collected over periods ranging from 8–50 h, were analyzed by the computer code RAGS.[8] Decay data helped to establish the contribution of impurity lines from ^{187}Ir and ^{188}Ir.

The results can be summarized in the following statements: (1) Energies of higher-energy lines have been determined more accurately. (2) Better values have been obtained for the intensities of some γ rays, particularly weak lines in energy regions where the γ-ray density is high. (3) For the vast majority of the 127 γ rays reported in Ref. 3 the redetermined intensities have caused no significant change in the multipolarity assignments.

Since the emphasis in this paper is on coincidence spectroscopy, the detailed results of γ-ray energies, intensities, and multipolarities obtained in singles spectra are given in the Appendix. These data, which constitute "best" values for the transitions listed, supersede those values reported previously.[3] However, in view of the complexity of the γ-ray spectrum of ^{186}Ir, this list should not be considered exhaustive.

C. γ-γ Coincidence Measurements

Coincidence events among γ rays were recorded with a Ge(Li)-Ge(Li) detector system. Each detector had an active volume of 20 cm^3 and resolution (FWHM at 1332 keV) of 3.3 keV at low counting rates. An aluminum absorber, 2 g/cm^2 thick, was placed in front of each detector to prevent positrons from reaching the detector and giving rise to erroneous coincidence events. The detectors were positioned in a collinear geometry during these experiments. The coincidence measurements were made with a fast-slow coincidence unit and a system of digital gates. Output pulses from the analog-to-digital converter (ADC) of the gating detector were selected by setting digital windows on the spectrum regions of interest. Pulses from the other detector with the proper time relationship to the gating pulses (resolving time 2τ was usually 50 nsec) were selectively routed and stored in the memory of the pulse-height analyzer. Typically, eight gates were set and eight 512-channel coincidence spectra were recorded in each experiment. Intense sources, up to 50 000 counts/sec, were normally used. A baseline restorer reduced gain-shift dependence on counting rate and maintained the energy resolution of 4 keV (at 1332 keV) at these rates. The counting rate was maintained within a factor of 2 over a counting period by periodically replenishing the source. In order to identify background contributions, off-peak gates were set for each peak. The spectrum from each background gate was then subtracted from the corresponding peak gate. The true/chance coincidence ratio for the system was about 30 under these conditions. The digital gating technique has been described in more detail elsewhere,[9] where typical spectra are shown.

Two criteria were used to determine whether a γ ray could be placed with certainty in the level scheme: (1) It must be found in a coincidence spectrum, and (2) proper intensity relationships among transitions implied by a particular cascade must be observed. Table I illustrates the applications of these criteria for the spectra gated by the 435-, 584-, and 1057-keV γ rays.[10]

Relative intensities of selected γ rays in the singles spectrum are listed in column 3 of Table I. Transitions are identified by letters indicating the levels connected (see Fig. 1). The 435-keV

TABLE I. γ-ray intensities (not corrected for internal conversion or accidental coincidences) in singles and coincidence experiments. Normalizations in gated spectra were chosen to simplify comparisons with singles spectrum; see text.

Transition	E_γ (keV)	Singles	435 Gate	584 Gate	1057 Gate
BA	137	66.5(16)	34(3)	4.0(6)	72(10)
ba	208	0.88(11)		1.0(4)	
Xa	277	2.48(12)		3.0(4)	
CB	297	≡100	86(8)		≡100
DC	435	54.3(14)	2.2(2)	1.0(3)	
β^+	511	7.2(8)	5.1(6)		
JD	622	4.9(5)	≡4.9		
FB	630	7.8(14)		≡7.8	
FA	767	8.6(7)		10.1(11)	
cD	943	1.38(7)	1.2(4)		
TD	1188	3.2(4)	3.0(4)		
ZD	1508	1.49(12)	2.0(5)		

transition is the $6^+0 \to 4^+0$ transition *DC*. In the spectrum gated by this transition, listed in column 4, the intensity of the $4^+0 \to 2^+0$ transition *CB* and that of the $2^+0 \to 0^+0$ transition *BA* should be in the cascade ratio. Experimentally the γ-ray intensity ratio *CB/BA* is 2.5 ± 0.4 (internal conversion has not been taken into account). The intensity ratio expected from theoretical internal-conversion coefficients is 2.10. Transitions which feed level *D* such as *JD*, *cD*, *TD*, and *ZD* should have the same relative intensities as in the singles spectrum. This is seen to be the case within experimental error. The normalization of intensities at *JD* was chosen to facilitate the comparison. It is seen also that a majority of the positron intensity goes to the 6^+0 level.

In the spectrum gated by the 584-keV transition, the intensities of transitions feeding level *a* and deexciting level *F* are the same as in the singles spectrum. This clearly establishes the placement of the 584-keV transition as *aF*. In the case of the spectrum gated by the 1057-keV transition, the γ-ray intensity ratio *CB/BA* is 1.4 ± 0.2 instead of the cascade value 2.5 ± 0.4 expected if the 1057-keV transition were the transition *JC*. From energy sums this transition could also be *NB*.[1-3] The coincidence intensity data are consistent with about 75% of the 1057-keV intensity being assigned to *JC*, and 25% to *NB*.

Table II summarizes the coincidence data observed in the decay of ^{186}Ir. In each case, unless otherwise indicated, intensities are those expected for a cascade and the parent level is established.

III. DECAY SCHEME OF ^{186}Ir

The decay scheme which best fits the experimental data is shown in Fig. 1. Coincidence evidence is emphasized but energy sums, intensity balance, and multipolarity assignments have also been taken into account. Coincidence data are indicated by a circle at the head of the transition arrow. Levels belonging to the ground-state and γ-vibrational bands and a set of levels which may constitute a two-phonon $K = 4$ band[2,3] have been drawn as heavy lines. Transitions between members of the ground-state and γ-vibrational bands are as given previously[3] and are not repeated here.

The evidence in support of the various levels which have been proposed here and in previous work is presented below. The level energies and their uncertainties are based whenever possible on the conversion electron data of Ref. 1; otherwise, the γ-ray energies of this work were used.

A. Low-Lying Collective Levels

The existence of the collective levels *B*, *C*, *D*, *F*, *G*, *H*, *I*, *J*, and *K* is well supported by the coincidence data. The 8^+0 member *E* of the ground-state band was placed at 1453.12 keV in Refs. 1 and 2, and the $8^+0 \to 6^+0$ transition was taken to be the 584-keV *E*2 γ ray. However, the coincidence data clearly indicate that the 584-keV γ ray originates from a level at 1351.82 keV and populates the 2^+2 member *F* of the $K = 2$ γ-vibrational band. Reaction studies[6,7] show that the $8^+0 \to 6^+0$ transition is a 551-keV γ ray; the 8^+0 level is then at 1420 keV.

Several attempts were made to identify by coincidence the $8^+0 \to 6^+0$ transition but no useful information was obtained. The 551-keV γ ray in ^{186}Ir decay is weak and lies in a region in which there are many closely spaced γ rays. The coincidence data are inconclusive. Recent systematics for energies of rotational levels[11,12] suggest that the 8^+0 level in ^{186}Os should be at about 1420 keV. Our results are consistent with this prediction but do not confirm it. The 8^+0 level is evidently only sparsely populated in the β decay of ^{186}Ir.

No direct coincidence confirmation has been obtained for the 7^+2 level *K*. Its deexciting transitions are too weak to permit γ-ray gates to be set successfully. Yamazaki, Nishiyama, and Hendrie[7] have recently analyzed energy systematics of ground-band and γ-band states in even-even osmium nuclei.

The level N at 1194.45 ± 0.14 *keV*. The coincidence data show that the 760-keV transition and part (25%) of the 1057-keV transition feed the levels *C* and *B*, respectively. Both γ rays are found to be *E*2 and the transition *NA* was not observed. These facts suggest that the level *N* should be 3^+ or 4^+. A weak 284-keV γ ray may be the transition NG and a 427-keV transition which corresponds to the energy difference NF, decays with a half-life characteristic of ^{187}Ir (≈ 11 h). Intensity balance indicates that N is fed by β decay. The ratio of $B(E2)$ values, $B(E2, NC)/B(E2, NB) = 2.8$, is consistent with an $I^{\pi}K$ assignment of $4^{+}2$ for N, as predicted by the Alaga rules for an adiabatic rotor.

The level a at 1351.82 ± 0.20 keV. Coincidence data establish this level from the 584 → F → B cascades. The transitions aF (584 keV) and aG (442 keV) are both $E2$. Level a populates only the $K = 2$ γ-vibrational levels and not the ground-state band. This suggests that a is 3^{+} or 4^{+} and of high K. The $B(E2)$ ratio $B(E2, aG)/B(E2, aF) = 1.2$ is consistent with $4^{+}4$ or $3^{+}3$ for level a. Intensity balance indicates that this level is fed primarily by β decay and that hence $4^{+}4$ is the more likely assignment. The assignment of the 584-keV γ ray as the transition ED in Refs. 1 and 2 is clearly

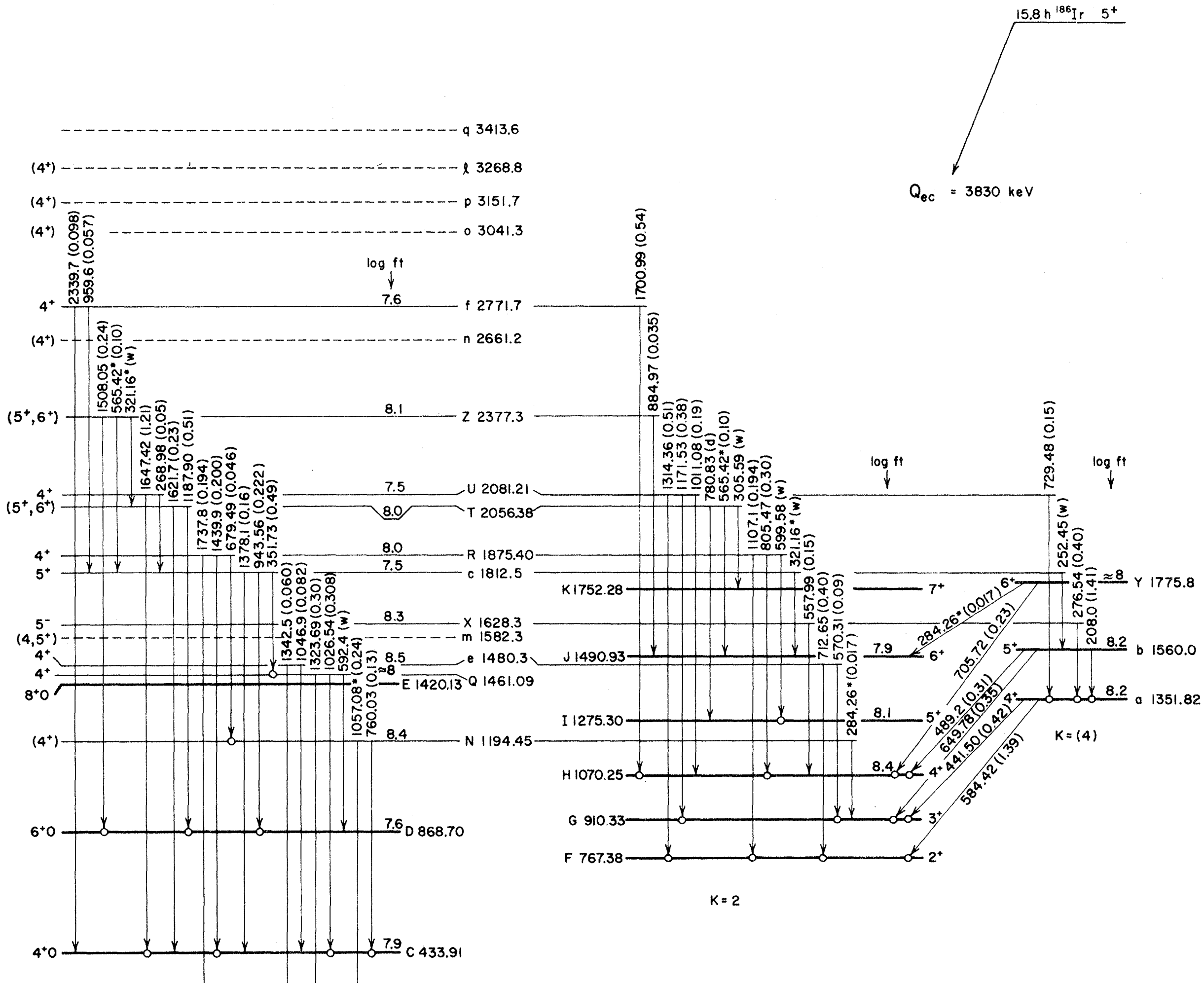

FIG. 1. Level scheme of ^{186}Os from decay of 15.8-h ^{186}Os. Levels drawn with heavy lines are members of the ground-state band, the $K = 2$ γ-vibrational band, and a proposed $K = 4$ two-phonon band. Transitions between members of the ground-state and γ-vibrational bands are not shown here since they have been reported elsewhere (Refs. 1–3). Levels drawn as dashed lines are based only on energy sums. Transitions connecting these levels to other levels are not shown here but are listed in Table III. Transitions whose placement has been confirmed by coincidence spectra are indicated by a circle. Energies are in keV and relative intensities are shown in parentheses adjacent to the γ-ray energy. The intensity scale is that used in the Appendix. The symbols "w" and "d" mean "weak" and "part of an unresolved doublet," respectively. Asterisks identify transitions assigned more than once.

incompatible with the coincidence data.

The level Q at 1461.09 ± 0.19 keV. This level is established by the cascade 1027 ($M1$) → C → B. Other deexciting transitions are QB (1324 keV, $E2$) and QD (592 keV). Since this level populates the 2^+, 4^+, and 6^+ members of the ground-state band but not the $K=2$ band, and is not populated directly in β decay, its I^π value is probably 4^+.

The level e at 1480.3 ± 0.3 keV. The coincidence cascades 570 → G → B and 713 → F → B establish this level. Transitions deexciting level e are eF (713 keV, $E2$), eG (570 keV $E2$), eB (1343 keV), and eC (1047 keV). This pattern suggests I^π for e to be 4^+. In Ref. 3 this level was thought to be 3^- since eF and eG appeared to be $E1$ transitions. The present singles data establish that these transitions are $E2$.

The level b at 1560.0 ± 0.5 keV. Three cascades, 208 → a → F, 489 → H → C, and 650 → G → B, support the existence of the level b. All three deexciting transitions are $E2$ and none go to the ground-state band. These data suggest that b is 5^+ and has a high K value; we propose that it is the 5^+ member of the $K=4$ band. This level is populated by β decay.

The level c at 1812.5 ± 0.5 keV. The cascades 321 → J, 352 → Q, and 944 → D, each followed by its characteristic deexcitation pattern, firmly establish level c. Deexciting transitions cb (252 keV), cJ (321 keV), cQ (352 keV, $E2$), cD (944 keV, $M1$), and cC (1378 keV) are consistent with a 5^+ assignment for c. High K is likely; c is fed primarily by β decay.

The level R at 1875.40 ± 0.20 keV. Coincidence γ rays observed which confirm the level R are at 600 (RI), 679 (RN, $M1$), 805 (RH, $E2/M1$), 1107 (RF, $E2$), 1440 (RC, $M1/E2$), and 1738 (RB, $M1/E2$) keV. The transition multipolarities lead to the conclu-

TABLE II. Coincidences observed in ^{186}Ir decay. Because of background and other factors limiting sensitivity, not all of the γ rays implied by our level scheme could be observed in coincidence experiments.

Gating transition (keV)	Transitions in coincidence (keV)	Parent level Energy (keV)	Parent level Designation
277	137, 584, 630, 767	1628.3	X
352	137, 297, 1027	1812.5	c
421	137, 160, 297, 636, 933	1490.93	J
435	137, 297, 511, 622, 1188, 1508	868.70	D
477	137, 297, 441	910.33	G
489	137, 297, 636, 933	1560.0	b
570	137, 773	1480.3	e
584	137, 208, 277, 630, 767	1351.82	a
622	137, 297, 321, 435	1490.93	J
630–636	137, 277, 297, 441, 584	910.33 and 767.38	G & F
650	137, 297, 511, 773	1560.0	b
679	137, 1057	1875.40	R
706	137, 297, 636, 933	1775.8	Y
713	137, 630, 767	1480.3	e
730	137, 584, 630, 767	2081.21	U
760	137, 297	1194.45	N
767–773	137, 143, 441, 584	767.38 and 910.33	F & G
805	137, 297, 636, 933	1875.40	R
841	137, 297	1275.30	I
933	137, 421, 489	1070.25	H
944	137, 297, 435	1812.5	c
1027	137, 297, 352	1461.09	Q
1057	137, 297 (not in cascade ratio)	1490.93 and 1194.45	J & N
1107	137, 630, 767	1875.40	R
1172	137, 773	2081.21	U
1188	137, 297, 435	2056.38	T
1314	137, 630, 767	2081.21	U
1440	137, 297	1875.40	R
1508	137, 297, 435	2377.3	Z
1647	137, 297	2081.21	U
1701	137, 297, 636	2771.7	f
1738	137	1875.40	R

TABLE III. Levels of ^{186}Os based on energy sums. Exciting and deexciting transitions marked with an asterisk have been placed more than once in the level scheme. Transition energies in parentheses are in keV.

Level energy (keV)	Designation		Transitions In (keV)	Transitions Out (keV)
1582.3(2)	*m*	$(4, 5^+)$	*Rm*(293.0), *Zm*(794.2)	*me*(102.1), *mN*(387.9), *mG*(671.8)
2661.2(3)	*n*	(4^+)	···	*nZ*(284.3*, *E*1/*E*2), *nY*(885.0*, *M*1), *nN*(1467.1, *E*2), *nG*(1751.4, *M*1), *nF* (1893.7)
3041.3(4)	*o*	(4^+)	···	*oY*(1264.6, *E*2), *oa*(1690.2*), *oD*(2172.2)
3151.7(5)	*p*	(4^+)	···	*pU* (1071.0, *M*1), *pQ* (1690.2*), *pG*(2242.0), *pF* (2383.7)
3268.8(10)	*l*	(4^+)	···	*lR* (1393.6), *le*[1789.0, (*M*1)], *lG*(2357.3), *lD*(2399.1), *lC*(2835.2), *lB* (3132.2)
3413.6(4)	*q*	···	···	*qU*[1332.3, (*M*1)], *qI*(2138.6) *qD*(2544.3), *qC*(2980.1)

sion that *R* is 4^+, in agreement with previous studies.[1,3]

The level T at 2056.38 ± 0.24 keV. The cascade 1188 → *D*, followed by its characteristic deexcitation pattern, establishes this level. Other deexciting γ rays are *TK* (306 keV), *TJ* (565 keV, *M*1/*E*2), *TI* (781 keV), and *TC* (1622 keV, *E*2). This leads to the conclusion that *T* is 5^+ or 6^+.

The level U at 2081.21 ± 0.20 keV. Four cascades are observed: 730 (*M*1/*E*2) → *a*, 1172 (*E*2/*M*1) → *G*, 1314 (*E*2) → *F*, and 1647 (*E*2) → *C*, each followed by its characteristic deexcitation pattern. Other deexciting transitions are *Uc* (269 keV, *M*1) and *UH*(1011 keV, *M*1). An assignment of 4^+ is implied for *U*.

TABLE IV. Comparison of the energies of collective levels in ^{186}Os with the predictions of models described in the text. Energies are in keV. Asterisks identify level energies used to obtain model parameters.

Level ($I^\pi K$)	Experimental energy (keV) [a]	VMI [b] Ref. 10	MIX − VMI Ref. 13	Rot. − Vib. Ref. 14	PPQ Ref. 15
2^+0	137.15(3)	136.6	137*	137	153
4^+0	433.91(7)	436.3	434*	435	422
6^+0	868.70(10)	870.6	858	864	
8^+0	1420.13(20)	1415.8	1386	1405	
2^+2	767.38(10)	767.4*	767*	768	712
3^+2	910.33(10)	907.3	901	922	993
4^+2	1070.25(10)	1078.4	1070*	1112	
5^+2	1275.30(13)	1275.8	1271	1342	
6^+2	1490.93(13)	1496.1	1501	1590	
7^+2	1752.28(17)	1736.6	1757	1897	

[a] Energies and errors are taken from Ref. 3.
[b] Least-squares fit to experimental level energies.

The level f at 2771.7 ± 1.0 keV. The 1701-keV γ ray (*M*1) was found to be in cascade with the 636 → 297 → 137 deexcitation path; this provides the basis for level *f*. Other deexciting transitions are *fc* (960 keV, *E*2/*M*1) and *fC* (2340 keV, some *E*0). The level *f* is probably 4^+.

The new level X at 1628.3 ± 0.5 keV and elimination of a level V at 2152.06. The cascade 277 → *a* → *F* places a level at 1628.3 keV. The 277-keV transition is *E*1 and was placed in the decay scheme of Ref. 1 as the transition *VR*, level *V* being a 5^- state at 2152.06 keV. The reinvestigation of the singles data indicates that some of the other transitions thought to be deexciting *V* to positive-parity states are not *E*1 and hence must be assigned elsewhere. The evidence in support of level *V* seems to be very weak and *V* is dropped from the present decay scheme. Another *E*1 transition depopulating *X* is *XH* (588 keV). Level *X* is fed only by β decay and is probably a 5^- state of high *K*.

The new level Y at 1775.8 ± 0.5 keV. A level is proposed at 1775.8 keV because of the 706 (*E*2) → *H* transition path. Level *Y* possibly deexcites to *J* also by a 284-keV transition. Level *Y* is probably a 6^+, high-*K* state, fed directly by β decay, possibly the 6^+ member of the $K = 4$ band.

The new level Z at 2377.3 ± 0.6 keV. A coincidence measurement shows that the 1508-keV *M*1 transition populates level *D*; this places a level at 2377.3 keV. Other deexciting transitions are *ZT* (321 keV, *E*2), *Zc* (565 keV, *M*1/*E*2), and *ZJ* (885 keV, *M*1). An assignment of 5^+ or 6^+ is implied by these data.

Other levels. Coincidence data support the existence of all of the levels described above. A number of other levels are proposed (see Table III) which are based on energy sums alone. To obtain these levels, the coincidence-established levels and unassigned transitions were combined by the method of Bäcklin.[13] Before proposing a level we required (1) that there be a minimum of three transitions in or out of the level, (2) that the multipolarity of these transitions form a consistent set, and (3) that intensity balance be maintained.

IV. DISCUSSION

A. Energies of Low-Lying Collective Levels

The transitional character of ^{186}Os has been shown in many experiments. Emery *et al.*[1] compared experimental energies of levels in the ground-state and γ-vibrational bands with the predictions of the Bohr-Mottelson strong-coupling model, the strong-coupling model with rotation-vibration mixing, and several versions of the asymmetric rotor model. The best fit appeared to be obtained by the asymmetric rotor model of Davydov and co-workers.[14] However, the odd-even shift in level energies predicted by this model for the γ band was found experimentally to have the wrong sign.[1]

A more recent attempt to fit ^{186}Os levels by the phenomenological variable-moment-of-inertia (VMI) model[12] has been quite successful. The extension of the VMI model to include the γ band requires a total of five parameters. Das, Dreizler, and Klein[15] have found that only four parameters are needed in their VMI formulation in which the ground-state band and an interacting β- or γ-vibrational band are simultaneously considered. The rotation-vibration model of Faessler, Greiner, and Sheline[16] also leads to good agreement with experiment.

The pairing-plus-quadrupole (PPQ) model of Baranger and Kumar[17] makes no assumptions about equilibrium shape. Unfortunately PPQ calculations are available for only a few of the levels in ^{186}Os.

Comparisons among the several models are summarized in Table IV.

B. Interband Transition Intensities

Reduced transition probabilities for transitions between members of the γ band and the ground-state band in ^{186}Os have recently been analyzed by Fogelberg.[5] He shows that the $B(E2)$ values of $\Delta I = 0$ transitions are too large to lie on a line determined by $\Delta I \neq 0$ transitions in a Mikhailov plot. Since within the errors of the two sets of measurements the intensities we measure for the pertinent transitions, with one exception, have the same values as his intensities, we confirm his conclusion.

The exception is the 1057-keV $6^+2 \rightarrow 4^+0$ transition *JC*. We assign 25% of its intensity to the transition *NB*; Fogelberg considers it to be 100% *JC*. The difference is not large enough to affect the conclusion.

C. Spin of ^{186}Ir Ground State

Logft values for populating states in ^{186}Os from ^{186}Ir decay are shown on the decay scheme (Fig. 1). Errors derived from uncertainties in intensity balance are estimated to be no more than ±0.3 logft units.

The β-decay pattern indicates that the spin of ^{186}Ir is most likely 5. In Ref. 1 the assignment was $7^{(-)}$ and the Nilsson configuration proposed $\pi\frac{7}{2}^+[404] + \nu\frac{7}{2}^-[514]$. The CERN group[4] suggests 6^- and the configuration $\pi\frac{3}{2}^+[402] + \nu\frac{9}{2}^-[505]$.

Both of the above configurations are in conflict with some aspects of the experimental data. Consider the β decay of ^{186}Ir. The logft values for ^{186}Ir ground-state decay are consistent with being allowed hindered or first-forbidden unhindered transitions; yet the above configurations require $\Delta K = 6$ or 7 when, for example, β decay occurs to the 6^+ member of the ground-state rotational band (log$ft = 7.6$). In contrast, the β transition from the ^{176}Lu ground state (7^-7) to the 6^+ member of the ground-state rotational band in ^{176}Hf is characterized by a logft of 18.6,[18] reflecting the K-forbidden nature of this transition.

Another difficulty is that many of the high-lying levels in ^{186}Os which are populated in β decay of ^{186}Ir, in turn, deexcite to low-K states by γ transitions having some $E0$ character. The data seem to imply that the ^{186}Ir ground state has both high spin and low K.

An explanation which is consistent with the data is that the ground state of ^{186}Ir consists of a neutron in a $\frac{1}{2}^-[510]$ orbital coupled to a proton in a $\frac{1}{2}^-[541]$ orbital to give a state with $I^\pi K = 5^+1$ as the lowest-energy member of the coupled-particle rotational band. Such an extreme distortion of a rotational band has not been established by experiment in any nuclide to our knowledge. There are, however, indications that distortions of this type, if not this degree, are associated with coupled-particle rotational bands involving the $\frac{1}{2}^-[541]$ proton orbital. O'Neil and Burke[19] recently reported data on the rotational levels for the $\{\frac{1}{2}^-[541]\pi - \frac{5}{2}^-[512]\nu\}$ configuration in ^{174}Lu as populated by (^{3}He, d) and (α, t) reactions on ^{173}Yb. Their data and theoretical Coriolis coupling calcu-

TABLE V. γ rays assigned to the decay of 15.8-h ^{186}Ir.

Energy (keV)	Intensity [a]	Multipolarity	Level assignment
102.12	w		me
119.36	w		
137.15	10.7	E2	BA
143.00	7.0(8)−2 [b]	M1(E2) [c]	GF
146.2	w		
149 [d]	w		
160.02	w		HG
167.05	w		
208.0	1.41(17)−1	E2	ba
219.96	w		
224.13	5.0(10)−2	M1	
234.48	w		
252.45	w		cb
261.23	w		KJ
268.98	5(2)−2	M1	Uc
276.54	4.0(2)−1	E1	Xa
281.3	2.2(8)−2	M1	
284.26	1.7(11)−2	E1 [e]	YJ,nZ,NG
288.80	1.8(9)−2	(M1)	
292.98	w		Rm
296.75	16.1(4)0	E2	CB
302.86	9.5(17)−2	E2/M1 [c]	HF
305.59	w		TK
309.64	1.2(4)−1	M1/E2 [c]	
311.85	w		
321.16	w		cJ, ZT
322.63	w		
326.55 [d]	w		
330.22	5.1(11)−2	E2/M1 [c]	
334.02	2.7(7)−2	M1 [c]	FC
342.50	w		
351.73	4.9(3)−1	E2	cQ
364.90	1.9(3)−1	E2/E1 [e]	IG
387.93	w		mN
403.29	4.9(14)−2	M1	
406.55	5(2)−2	(E2)	ID
420.74	7.0(9)−1	E2	JH
434.78	8.75(23)0	E2	DC
441.50	4.2(5)−1	E2	aG
446.7 [d]	8(4)−2	M1 [c]	
476.90	2.5(6)−1	E2 [c]	GC
489.2	3.1(3)−1	(E2)	bH
542.17	w		
551.43	7(4)−2	M1 [c]	
557.99	1.5(5)−1	E1	XH
565.42	1.0(3)−1	M1/E2 [c]	TJ, Zc
570.31	9(3)−2	(E1/E2)	eG
584.42	1.39(11)0	E2	aF
592.4	w		QD
599.58	w		RI
622.15	7.9(9)−1	E2	JD
630.31	1.26(23)0	E2	FB
636.23	1.78(23)0	E2	HC
649.78	3.5(4)−1	E2 [e]	bG
661.86	8(4)−2	M1/E2	
671.77	w		mG
679.49	4.6(23)−2	M1 [c]	RN
684.81	8(4)−2	M1 [c]	
700.37	6(3)−2		
705.72	2.3(5)−1	E2	YH
712.65	4.0(5)−1	E2 [c]	eF
729.48	1.5(3)−1	M1/E2 [c]	Ua
760.03	1.3(2)−1	E2/M1 [e]	NC
767.30	1.38(11)0	E2	FA
773.06	2.29(11)0	E2	GB
780.83 [d]	w		TI
794.2	w		Zm
805.47	3.0(2)−1	E2/M1 [c]	RH
841.31	1.33(17)0	E2	IC
846.6	1.64(11)0		
884.97	3.5(11)−2	M1 [c]	ZJ,nY
933.18	1.37(11)0	E2	HB
943.56	2.22(11)−1	(M1)	cD
959.6	5.7(11)−2	E2/M1 [c]	fc
1011.08	1.9(2)−1	M1 [e]	UH
1026.54	3.08(11)−1	(M1)	QC
1046.9	8.2(10)−2		eC
1057.08	8.0(8)−1	E2	JC,NB
1071.0	3.4(11)−2	M1 [c]	pU
1107.1	1.94(23)−1	E2	RF
1122.0	1.25(23)−1	(E1)	
1171.53	3.8(6)−1	E2/M1 [c]	UG
1187.90	5.1(6)−1	E2/M1	TD
1264.65	2.0(2)−1	E2	oY
1314.36	5.1(6)−1	E2/(E1) [c]	UF
1323.69	3.0(3)−1	E2 [e]	QB
1332.3	3.9(9)−2	(M1)	qU
1342.5	6.0(6)−2		eB
1363.5	3.8(5)−2		
1378.1	1.6(4)−1		cC
1393.6	5.7(6)−2		lR
1439.9	2.00(17)−1	M1/E2 [c]	RC
1467.1	1.3(3)−1	E2	nN
1508.05	2.4(2)−1	M1	ZD
1597.14	2.2(2)−1	M1	nK
1621.7	2.3(2)−1	E2 [c]	TC
1647.42	1.21(6)0	E2 [e]	UC
1690.2	7.3(11)−2		oa, pQ
1700.99	5.4(2)−1	M1 [c]	fH
1737.8	1.94(17)−1	M1/E2 [c]	RB
1751.36	2.15(11)−1	M1	nG
1789.0	4.5(5)−2	(M1)	le
1829.2 [f]	3.2(13)−2		
1842.6	3.4(9)−2		
1869.0	1.02(14)−1		
1893.7 [f]	6.0(15)−2		nF
1997.1	7.1(14)−2		
2138.6	2.1(4)−2		qI
2144.3	8.4(10)−2		
2165.2	1.53(25)−1		
2172.2	5.6(11)−2		oD
2185.8 [f]	1.62(19)−1		
2242.0	3.7(11)−1		pG
2315.6	5.1(8)−2		

TABLE V *(Continued)*

Energy (keV)	Intensity [a]	Multipolarity	Level assignment	Energy (keV)	Intensity [a]	Multipolarity	Level assignment
2339.7 [f]	9.8(12)−2	Some $E0$	fC	2835.2	2.00(19)−1		lC
2357.3	7.2(11)−2		lG	2853.1	5.7(8)−2		
2383.7	9.6(10)−2	Some $E0$	pF	2866.5	1.5(5)−2		
2399.1	1.04(14)−1	Some $E0$	lD	2912.5	2.5(7)−2		
2544.3	6.7(14)−2		qD	2967.0	2.9(6)−2		
2580.3	2.0(6)−2			2980.1	1.9(4)−2		qC
2733.7	1.5(5)−2	($M1$)		2994.8	1.7(3)−2		
2770.7	9(3)−3			3007.3	3.2(5)−2		
2780.4	8.3(13)−2			3040.3	1.0(3)−2		
2790.2	4.6(7)−2			3074.6	6.6(20)−3		
2805.8	1.5(4)−2			3132.2	1.2(2)−2		lB

[a] γ-ray intensities are normalized to 10.7 for the 137.15-keV γ ray. The symbol w meaning "weak" is used to indicate that the γ-ray intensity is small compared to those of other γ rays in this energy region of the spectrum.

[b] The entry 7.0(8) − 2 is read $(7.0 \pm 0.8) \times 10^{-2}$.

[c] The transition multipolarity differs from that of Ref. 3; see the Appendix for details.

[d] This peak in the spectrum is probably an unresolved multiplet.

[e] The transition multipolarity is different depending on the choice of conversion-electron data, Ref. 1 or Ref. 2.

[f] This line has a component or components arising from the decay of ^{185}Ir and/or ^{188}Ir.

lations support the assignment of $I^{\pi}K = 3^{+}2$ as the lowest-energy member of the rotational band.

Emery *et al.*[20] have explored the consequences of strong rotation-particle coupling in a two-quasiparticle system in which the proton orbital is $\frac{1}{2}^{-}[541]$ and the neutron orbital either $\frac{1}{2}^{-}[510]$ or $\frac{3}{2}^{-}[512]$. They show in a model calculation that for reasonable values of an effective decoupling parameter, it is indeed possible for the state of lowest energy not to have the minimum angular momentum. While they do not associate their calculations specifically with the 15.8-h state in ^{186}Ir, they conclude that these unusual states are likely to be low-lying excitations.

If we assume a $5^{+}1$ assignment for the 15.8-h state in ^{186}Ir, the predicted ft ratio for allowed, l-forbidden β transitions to the $6^{+}0$ level D and $4^{+}0$ level C is 0.83, in reasonable agreement with the experimental value of 0.5 ± 0.3. β decay to the γ-vibrational band can in turn be explained by assuming that the γ vibration has extensive two-particle character; for example, the two-quasineutron component $\frac{1}{2}^{-}[510]-\frac{3}{2}^{-}[512]$ has been suggested.[21] The large $M1$ component of the 143-keV $3^{+}2 \rightarrow 2^{+}2$ transition supports this idea.

A 1.7-h low-spin isomer of ^{186}Ir has been reported[4,21,22] whose decay populates levels of spin as high as 4 in ^{186}Os. Our experiments were not optimized to detect the decay of this state and we have no data to report.

D. Character of Excited Levels in ^{186}Os

The analysis of the nature of ^{186}Os levels other than those belonging to collective bands could be done in terms of the independent quasiparticle model of Soloviev.[23] The orbitals available for ^{186}Os, however, lie in a region of high density of Nilsson states, hence we can expect appreciable Coriolis mixing which will remove the uniqueness of Nilsson assignments. Baranger and Kumar[17] calculate for ^{186}Os that the first two-quasineutron state should be at 1940 keV and the first two-quasiproton state at 1520 keV. If this is the case, levels N and e are perhaps not intrinsic states but rather collective states such as those suggested by Pyatov and co-workers[24] which result from spin-quadrupole forces. No detailed estimates for ^{186}Os are available.

The levels at 1351.82, 1560.0, and 1775.8 keV have the properties of the 4^{+}, 5^{+}, and 6^{+} members of a $K=4$ rotational band. The inertial parameter $\hbar^2/2\mathscr{I}$ is 20.8 keV compared to 22.8 keV for the ground-state band. Depopulation of these levels is into the $K=2$ band which suggests that a high-K assignment is correct. A two-phonon $K=0$ band has been proposed in ^{188}Os at 1086 keV[25] while in ^{190}Os the 4^{+} level at 1163 keV is probably the $K=4$ two-phonon state.[25] The decay patterns of the two-phonon state in ^{190}Os are very similar to those of the 1351.82-keV level a in ^{186}Os. Level a could be the analogous two-phonon state in ^{186}Os. In the Bohr-Mottelson model, the energy of the two-phonon level should be just twice that of the one-phonon γ-vibrational level. This is nearly the case in ^{186}Os (767.38 and 1351.82 keV). The asymmetric rotor model predicts the energy of the analogous 4^+ state at 2975.8 keV for an asymmetry parameter of 16.51° (the value which provides the best fit to level energies in the γ band). The extent of multiparticle mixing into this proposed[2] two-phonon band will play an important role in determining its decay and population patterns.

For most of the high-lying levels in ^{186}Os extensive configuration mixing is expected to occur as well as multiparticle intrinsic states. No useful purpose is likely to be served by attempts at detailed analysis in the present context.

V. SUMMARY AND CONCLUSION

The level scheme of ^{186}Os has been elucidated which accomodates about 95% of the transition intensity observed in the decay of 15.8-h ^{186}Ir. The collective levels of the $K=0$, $K=2$, and possibly a two-phonon band with $K=4$ are interpreted in the light of existing nuclear models. The asymmetric rotor model, which fits the energies of the $K=0$ and $K=2$ bands better than the symmetric rotor model, fails to predict the band-head energy of the two-phonon band.

The ground state of ^{186}Ir is believed to be 5^+1. The character of many low-lying 4^+, 5^+, and 6^+ states cannot be deduced from decay data or theory since they lie below the expected energies for intrinsic states. Lifetime measurements and charged-particle reaction studies are needed to elucidate the character of these states.

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APPENDIX

In Table V is presented a composite set of singles γ-ray data which we consider to be a "best" set for 15.8-h ^{186}Ir decay. These data result from a critical comparison of the data of Ref. 3 and the γ-ray singles data of this work. In general the two sets of data are in agreement, by which we mean that in most cases transition multipolarities remain the same as in Ref. 3. Those instances where the multipolarity has changed or where the dominant component of a $M1/E2$ mixed-multipolarity transition has changed are identified in Table V.

The changes in multipolarity reflect in part an increase in the amount and an improvement in the quality of the γ-ray data and in part a renormalization of the γ-ray intensity scale relative to the conversion-electron data of Ref. 1. This renormalization involved an upward adjustment of 14% in the γ-ray intensity scale relative to that reported in Ref. 3 and was done because the experimental conversion coefficients derived from the new γ-ray intensity scale provided a better over-all fit to the theoretical conversion coefficients for the interband and intraband transitions of the ground-state and γ-vibrational bands.

The transition energies reported in Table V are taken from the conversion-electron measurements whenever possible, usually those of Ref. 1. For transitions of energy greater than 1800 keV the values reported are based on the γ-ray singles data of this work and are thought to be accurate to ±0.5 keV.

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*Present address: Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506.

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precise value is given in the Appendix. Energies of levels have not been rounded.

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