LEVELS IN ^{186}Os AS POPULATED BY THE DECAY OF $^{186}\text{Ir}^\dagger$

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Abstract: The excited level scheme of ^{186}Os as populated by the decay of ^{186}Ir has been studied by 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 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^+), 2081.21 (4^+), 2377.3 (6^+) and 2771.7 (4^+) keV. 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. An analysis of the interband transi-

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tion intensities between members of the γ -band and members of the ground-state band indicates that the first-order band-mixing model fits the data. The mixing parameter z_γ is found to have the value 0.087 ± 0.004 for ^{186}Os . The 15.8-h ^{186}Ir state is believed to be a 6^+ state with the Nilsson configuration $\pi \frac{11}{2}^- [505] + \nu \frac{1}{2}^- [510]$.

E

RADIOACTIVITY ^{186}Ir [from $^{185}\text{Re}(\alpha, 3n)$]; measured E_γ , I_γ , $\gamma\gamma$ coinc. ^{186}Os deduced levels, J , π . Enriched targets, Ge(Li)-Ge(Li) coincidence spectrometer.

1. Introduction

Excited level schemes for ^{186}Os have been reported by several research groups. Emery, et al.¹⁾ at Brookhaven National Laboratory and Harmatz and Handley²⁾ 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 . Recently Sugihara, Keenan and Perlman³⁾ 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 recently reported γ -ray data but has not proposed a decay scheme⁴⁾. Many ambiguities remain which can only be resolved by coincidence studies. In this work we emphasize coincidence spectra obtained with two Ge(Li) detectors.

Studies of reaction γ -rays produced in the $^{184}\text{W}(\alpha, 2n)^{186}\text{Os}$ and $^{186}\text{W}(\alpha, 4n)^{186}\text{Os}$ reactions^{5,6)} 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^+), 433.91 (4^+) and 868.70 (6^+) keV; $I^\pi K$ are given in parentheses. The energy of the 8^+ 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, B, C, D, and E for the 0^+ , 2^+ , 4^+ , 6^+ , and 8^+ members, respectively, of the ground-state rotational band and F through K for members of the γ -band in order of

increasing energy.

Because of the recent interest in tests of the ability of the simple band-mixing model to predict transition intensities, we have redetermined the intensities of the strong transitions between members of the γ -band and members of the ground-state band. A single value (0.087 ± 0.004) for the band-mixing parameter z_γ has been found to describe adequately the de-excitation pattern of the γ -band in ^{186}Os .

2. Experimental methods and results

2.1 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 (TAMVEC) or the Yale University Heavy Ion Linear Accelerator. In the TAMVEC irradiations the rhenium powder was wrapped in high-purity aluminium foil which was placed in a water-cooled target holder. Additional cooling was provided by helium gas flowing across the target surface. Sources of ^{186}Ir were produced by the $^{185}\text{Re}(\alpha, 3n)^{186}\text{Ir}$ reaction. The α -particle energy incident on the target (≈ 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 in our sources from the $^{187}\text{Re}(\alpha, 3n)^{188}\text{Ir}$ reaction. Many experimental runs were made; typically the charge collected on the target holder ranged from 5 to 30 μAh . For the irradiations at Yale University, target preparation and irradiation procedures were the same as those described in ref.³⁾.

Iridium was chemically separated from the irradiated targets using the procedure of Sugihara, et al.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.

2.2 GAMMA-RAY SINGLES MEASUREMENTS

The earlier γ -ray study³⁾ which was done for the most part in 1965-66, used small-volume planar Ge(Li) detectors (4-5 cm³) of moderate energy resolution and multichannel analysers with only limited storage capacity (512 or 1024 channels). Since Ge(Li) detector systems (including associated electronics) have been improved significantly in efficiency and resolution, in the past few years, we felt it appropriate to reinvestigate the singles γ -ray spectrum of ¹⁸⁶Ir. The availability of analysers with larger memory size - 2048 and 4096 channels - made it unnecessary to use biased amplifiers or other devices which might introduce non-linearity into the system.

The detectors used in the present study included (1) a coaxially drifted cylindrical detector with an active volume of 33 cm³ and with energy resolution 2.3 keV (FWHM at 1332 keV), (2) a 6 cm² planar detector with a drifted depth of 9 mm and a resolution of 1.2 keV for the 122 keV γ -ray of ⁵⁷Co, and (3) a 20 cm³ coaxially drifted detector which is 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 nucleides whose relative γ -ray intensities are well known were used as secondary intensity standards. The energy calibration was made using well-known lines¹⁾ in ¹⁸⁶Ir as internal standards.

The γ -ray spectra, which were collected over periods ranging from 8 to 50 hours, were analysed by the computer code RAGS⁷⁾. Decay data helped

to establish the contribution of impurity lines from ^{187}Ir and ^{188}Ir .

The results can be summarised in the following statements: (1) Energies of higher-energy lines have been determined more accurately with detectors of higher efficiency and analysers with greater storage capacity. (2) Superior energy resolution and higher efficiency have led to better values 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 are in agreement with the previous work, at least in the sense that no significant change has been made in the multipolarity assignments.

Since the emphasis in this paper is on coincidence spectroscopy, the detailed results of γ -ray energies, intensities and multiplicities obtained in singles spectra are given in the appendix. These data, which constitute "best" values for the transitions listed, supersede those values reported previously³⁾.

2.3 γ - γ COINCIDENCE MEASUREMENTS

Coincidence events among γ -rays were recorded with a Ge(Li)-Ge(Li) detector system. The two detectors employed each had an active volume of 20 cm³ and resolutions (FWHM at 1332 keV) of 3.3 keV at low counting rates. An aluminium absorber, 2 g/cm² thick, was placed in front of each detector to prevent positons from reaching the detector and giving rise to erroneous coincidence events. Initially the detectors were operated at 120° with lead shielding in between to reduce scattering from one detector to the other. Later 180° geometry was adopted, with corresponding increase in efficiency, when it was found that backscattering peaks could be recognized by comparison with off-peak gates⁸⁾.

Coincidence relationships were obtained with a fast-slow coincidence

system and cross-over timing. The resolving time 2τ was usually 50 nsec. Intense sources, up to 50K counts per second, were normally used. A base-line restorer reduced gain shift with counting rate and maintained the energy resolution at 4 keV at these rates. The counting rate was permitted to change by only a factor of two over a counting interval; the source was replenished every half-life. Typically the ^{186}Ir activity produced in an irradiation was useful for about 100 h.

Each amplifier was DC coupled to the ADC of a two-parameter 4096-channel pulse-height analyser and a system of digital gates. Usually spectra were collected with a conversion gain of 1024 channels on the gating detector and 512 channels on the recording detector. The digital gating technique has been described elsewhere⁹⁾.

A portion of the γ -ray singles spectrum of ^{186}Ir taken on the gating detector is shown in fig. 1. The intense 435 keV[†] γ -ray is the $6^+0 \rightarrow 4^+0$ transition. To obtain reliable coincidence information in such a complex spectrum, we set a narrow digital window, approximately 3 keV wide and centered on the photopeak. A "Compton" gate of the same width was set in a structureless higher-energy region to sample the coincidence events occurring as a result of Compton scattering. To obtain coincidence information on the 435 keV γ -ray, for example, the γ -ray gate A and its associated Compton gate B were set (see fig. 1) and the resulting coincidence spectra were obtained as shown in fig. 2. The contribution of spurious events in the spectrum arising from true coincidences with Compton-scattered high-energy lines was removed by subtracting the Compton-gated spectrum from the

[†]To conserve space we adopt the practice of giving the energy of a γ -ray rounded to the nearest keV. A more precise value is given in the appendix. Energies of levels have not been rounded.

peak-gated spectrum. In the 435 keV net coincidence spectrum (i.e., corrected for Compton-gated events), the intensity of the 435 keV γ -ray remaining after subtraction is a measure of the random rate. For a source such that the singles rate in each detector was about 50K counts per second, the true-to-random ratio for all coincident events was typically 10:1. In the net 435 keV gated spectrum, the ratio is 30:1; many random events have been eliminated by the digital gating and Compton-correction techniques.

For a less intense γ -ray such as the 584 keV transition (see fig. 1), the net spectrum is more difficult to obtain since 80% of the events in the 584 keV region arise from scattering. In many experiments, the spectra of several γ -ray gates could be corrected with the spectra from one common Compton gate. Typical of such an experiment are the gates C (551 keV) and D (584 keV) with the common Compton gate E; the resulting coincidence spectra are shown in fig. 3. Difficult γ -ray gates were, for example, in the 706-730 keV region (gates F, G and I) where only 5% of the events resulted from full-energy γ -rays. Nevertheless, careful selection of the off-peak gate H and subtraction from the resulting coincidence spectra have led to reliable coincidence relationships and intensities in this region (see fig. 4). The 277 keV γ -ray presented a different problem in that it is a small, low-energy satellite on the intense 297 keV $4^+0 \rightarrow 2^+0$ transition. In that case a lower energy off-peak gate was set and the results of the coincidence spectra obtained are given in fig. 5.

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. As an example of the latter point, consider the 435 keV γ -ray which is known to be the $6^+0 \rightarrow 4^+0$ transi-

tion . In the spectrum gated by the 435 keV line (fig. 2) are the intense lines at 297 and 137 keV, the well known $4^+0 \rightarrow 2^+0$ and $2^+0 \rightarrow 0^+0$ transitions, respectively. These E2 transitions are in cascade and the ratio of their γ -ray intensities I_{297}/I_{137} should be 2.1:1, when internal conversion is taken into account. This same ratio should be obtained in coincidence with any transition populating the 4^+0 level.

Table 1 summarises coincidence intensities for the spectra gated by the 435, 584, and 1057 keV γ -rays. In the 435-gated spectrum, $I_{297}/I_{137} = 2.5 \pm 0.5$, in good agreement with that expected for a cascade. Similarly in the spectrum gated by the 584 keV γ -ray, the ratio I_{630}/I_{137} is that expected for a cascade. In the spectrum gated by the 1057 keV γ -ray (see fig. 5), however, the ratio $I_{297}/I_{137} = 1.4 \pm 0.3$ is not that expected for a cascade. The 1057 keV transition was placed twice in previous decay schemes^{1,2,3)}. The coincidence evidence supports this. About 70% of the 1057 keV γ -rays populate the 4^+0 level and 30% the 2^+0 level.

Table 2 summarises the coincidence events which have been observed in the decay of ^{186}Ir . In each case, unless otherwise indicated, intensities are those expected for a cascade and the parent level has been established. The letters identifying levels are assigned in a manner consistent with refs.^{1,3)}.

3. The decay scheme of ^{186}Ir

The decay scheme which best fits the experimental data is shown in fig. 6. 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 previously³⁾ 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.

3.1 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.^{1,2)} and the $8^+0 \rightarrow 6^+0$ transition was taken to be the 584 keV E2 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 show that the $8^+0 \rightarrow 6^+0$ transition is a 551 keV γ -ray; the 8^+0 level is then at 1420 keV.

Several attempts were made to identify by coincidence that $8^+0 \rightarrow 6^+0$ transition but no useful information was obtained. The 551 keV γ -ray in ^{186}Ir decay is weak and lies in a region (see fig. 1) in which there are many closely spaced γ -rays. The coincidence data (fig. 3) are inconclusive. Recent systematics for energies of rotational levels^{10,11)} 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 beta decay of ^{186}Ir ; evidence is presented later that I^π for ^{186}Ir ground state is 6^+ , which is consistent with

this conclusion.

It should be noted that 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.

3.2 THE LEVEL N AT 1194.45 ± 0.14 keV

The coincidence data show that the 760 keV transition and part (30%) of the 1057 keV transition feed the levels C and B, respectively. Both γ -rays are found to be E2 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 might be the transition NG. A 427 keV transition which would correspond to NF decays with a half-life characteristic of ^{187}Ir (≈ 11 h). Intensity balance suggests that N must be fed by beta decay. The ratio of B(E2) values $B(E2, NC)/B(E2, NB)$ is 2.8. This corresponds to an $I^{\pi}K$ assignment of 4^{+2} for N, as predicted by the Alaga rules for an adiabatic rotor. Some degree of K-forbiddenness seems likely for the transitions NC and NB.

3.3 THE LEVEL a AT 1351.82 ± 0.20 keV

The coincidence spectrum for the 584 keV γ -ray is given in fig. 3 (gate D). The 208 keV γ -ray ($b \rightarrow a$) and 277 keV γ -ray ($X \rightarrow a$) populate level a while the 630 and 767 keV γ -rays arise from the depopulation of level a to level F. All four γ -rays are in coincidence, as is seen by comparing the spectrum in coincidence with gate D to the background gate E. Coincidence data establish this level from the $584 \rightarrow F \rightarrow B$ cascade. The cascade $442 \rightarrow G \rightarrow B$ confirms this assignment. 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 beta decay and that hence 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 incompatible with the coincidence data.

3.4 THE LEVEL Q AT 1461.09 ± 0.19 keV

This level is established by the cascade $1027 (M1) \rightarrow C \rightarrow B$. Other de-exciting 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 beta decay, its I^π value is probably 4^+ .

3.5 THE LEVEL e AT 1480.3 ± 0.3 keV

The spectrum in coincidence with the 713 keV γ -ray is shown in fig. 4 (gate G). In the background gate H, both the 630-636 and 767-773 keV regions have doublet character. In the 713 keV gated spectrum, only the 767 and 630 keV γ -rays are present. The coincidence cascades $570 \rightarrow G \rightarrow B$ and $713 \rightarrow F \rightarrow B$ establish this level. Transitions de-exciting 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.

3.6 THE LEVEL b AT 1560.0 ± 0.5 keV

Three cascades, $208 \rightarrow a \rightarrow F$, $489 \rightarrow H \rightarrow C$, and $650 \rightarrow G \rightarrow B$, support the existence of the level b. All three de-exciting 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 beta decay.

3.7 THE LEVEL c AT 1812.5 ± 0.5 keV

The cascades $321 \rightarrow J$, $352 \rightarrow Q$ and $944 \rightarrow D$, each followed by its characteristic de-excitation pattern, firmly establish level c. De-exciting 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 beta decay.

3.8 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 conclusion that R is 4^+ , in agreement with previous studies^{1,3}).

3.9 THE LEVEL T AT 2056.38 ± 0.24 keV

The cascade $1188 \rightarrow D$, followed by its characteristic de-excitation pattern, establishes this level. Other de-exciting γ -rays are TK (306 keV), TJ (565 keV, M1/E2), TI (781 keV) and TC (1622 keV, E2). This leads to the conclusion that T is 5^+ .

3.10 THE LEVEL U AT 2081.21 ± 0.20 keV

The spectrum in coincidence with the 730 keV is shown in fig. 4 (gate I). From comparison with the background gate, the 584 keV γ -ray is an obvious coincidence. Somewhat less visible is the fact that the 630 and 767 keV γ -rays are also in coincidence. The multiplet character of each region has been removed but the evidence is not as convincing as that from the 713 keV gate. This is because the 713 keV γ -ray directly

populates level F while the 730 keV γ -ray populates level a which then de-populates to a variety of levels, one of these being level F. Four cascades are observed: 730 (M1/E2) $\rightarrow$ a, 1172 (E2/M1) $\rightarrow$ G, 1314 (E2) $\rightarrow$ F, and 1647 (E2) $\rightarrow$ C, each followed by its characteristic de-excitation pattern. Other de-exciting transitions are Uc (269 keV, M1) and UH (1011 keV, M1). An assignment of 4^+ is implied for U.

3.11 THE LEVEL f at 2771.7 ± 1.0 keV

The 1701 keV γ -ray (M1) was found to be in cascade with the $636 \rightarrow 297 \rightarrow 137$ de-excitation path; this provides the basis for level f. Other de-exciting transitions are fc (960 keV, E2/M1) and fC (2340 keV). The level f is probably 4^+ .

3.12 THE NEW LEVEL X AT 1628.3 ± 0.5 keV AND ELIMINATION OF A LEVEL V AT 2152.06

The 277 keV coincidence spectrum is shown in fig. 5 where the 584 keV γ -ray is much more intense than in the associated background spectrum. The 630 and 767 keV γ -rays are enhanced with respect to their respective background regions. The cascade $277 \rightarrow a \rightarrow F$ places a level at 1628.3 keV. The 277 keV transition is E1 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 de-exciting V to positive parity states are not E1 and hence must be assigned elsewhere. The evidence to support level V becomes weak and V is dropped from the present decay scheme. Another E1 transition de-populating X is XH (558 keV). Level X is fed only by beta decay and is probably a 5^- state of high K.

3.13 THE NEW LEVEL Y AT 1775.8 ± 0.5 keV

A level is proposed at 1775.8 keV because of the 706 (E2) $\rightarrow$ H transition path. This conclusion is based on the coincidence data given in fig. 4 (gate F). In the background gate H, the 630-636 keV region has obvious doublet character while in the 706 keV gate only the 636 keV γ -ray is present. The 933 keV γ -ray is easily seen in the 706 keV gate. Both the 636 and 933 keV γ -rays de-excite level H. Level Y possibly de-excites to J also by a 284 keV transition. Level Y is probably a 6^+ , high-K state, fed directly by beta decay. It may be the 6^+ member of the K=4 band.

3.14 THE NEW LEVEL Z AT 2377.3 ± 0.6 keV

The 1508 keV M1 transition is found by coincidence to populate level D (see fig. 2); this places a level at 2377.3 keV. Other de-exciting transitions are ZT (321 keV, E2), Zc (565 keV, M1/E2) and ZJ (885 keV, M1). An assignment of 6^+ is implied by these data.

3.15 OTHER LEVELS

Coincidence data support the existence of all of the levels described above. A number of other levels are proposed (see table 3) which are based on energy sums alone. To obtain these levels, the coincidence-established levels and unassigned transitions were combined by the method of Bäcklin¹²⁾. Before proposing a level we required (1) that there be a minimum of 3 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.

4. Discussion

4.1 ENERGIES OF THE 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-workers¹³⁾. However, the odd-even shift in level energies predicted by this model for the γ -band was found experimentally to have the wrong sign¹⁾.

A more recent attempt to fit ^{186}Os levels by the phenomenological variable-moment-of-inertia (VMI) model¹¹⁾ has been quite successful. The extension of the VMI model to include the γ -band requires a total of 5 parameters. Das, et al.¹⁴⁾ have found that only 4 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 et al.¹⁵⁾ also leads to good agreement with experiment.

The pairing-plus-quadrupole (PPQ) model of Baranger and Kumar¹⁶⁾ makes no assumptions about equilibrium shape unlike the phenomenological VMI model. Unfortunately PPQ calculations are available for only a few of the levels in ^{186}Os .

Comparisons among the several models are summarised in table 4.

4.2 ANALYSIS OF INTERBAND TRANSITION INTENSITIES

Reduced transition probabilities can provide a more sensitive test of the adequacy of models than do level energies. All of the transitions expected between members of the γ -band and the ground-state band (up to the 6^{+2} level) have been observed. Special attention was devoted to minimizing the experimental errors in determining the intensities of these interband transi-

tions.

Because the simple first-order band-mixing model^{17,18)} appears to account for interband transition intensities in strongly deformed nuclei such as ¹⁶⁶Er, ¹⁷⁴Hf, ¹⁷⁸Hf, and ¹⁸⁰Hf, we have analysed the ¹⁸⁶Os data in that context.

In the model the reduced transition probability is given to first order by¹⁹⁾

$$B(E2; K=2, I_{\gamma} \rightarrow K=0, I_g) = 2 \langle I_{\gamma} 22-2 | I_g 0 \rangle^2 |M_1^{\gamma}|^2 [1 + z_{\gamma} F(I_{\gamma}, I_g)]^2.$$

Here M_1^{γ} is the leading order matrix element that connects the γ band with the ground-state band, z_{γ} is the band-mixing parameter, and $F(I_{\gamma}, I_g)$ is the spin-dependent part of the correction term. The value of the quantity $F(I_{\gamma}, I_g)$ for various values of I_{γ} and I_g is taken from ref.¹⁹⁾ and reproduced in table 5 for convenience.

A useful way of analysing all of the interband transition intensities is by means of a Mikhailov plot²⁰⁾. We define the quantity $R(I_{\gamma}, I_g)$ to be

$$R(I_{\gamma}, I_g) \equiv \left\{ \frac{[B(E2; K=2, I_{\gamma} \rightarrow K=0, I_g)]_{\text{relative}}}{2 \langle I_{\gamma} 22-2 | I_g 0 \rangle^2} \right\}^{1/2}.$$

The relative $B(E2)$ is taken to be $(\gamma\text{-ray intensity})/E_{\gamma}^5$. In a plot of $R(I_{\gamma}, I_g)$ against $F(I_{\gamma}, I_g)$, a straight line of slope z_{γ} should be obtained if the first-order mixing model adequately describes the data. Since only the slope is of interest, the various $R(I_{\gamma}, I_g)$ values for different I_{γ} have been normalised for the $\Delta I = 0$ transitions for even I_{γ} . In the case of $I_{\gamma} = 3$, $R(3_{\gamma}, 2_g)$ is normalised to $R(2_{\gamma}, 0_g)$ since $F(3_{\gamma}, 2_g)$ and $F(2_{\gamma}, 0_g)$ are equal. For $I_{\gamma} = 5$ no normalisation is possible and such data have been omitted.

The Mikhailov plot for ¹⁸⁶Os is shown in fig. 7. If we assume that there is no M1 contribution to the $\Delta I = 0$ and ± 1 transitions²¹⁾, the data are fit by a straight line of slope $z_{\gamma} = 0.087 \pm 0.004$. The $2_{\gamma} \rightarrow 4_g$ (334

keV) and $5_{\gamma} \rightarrow 6_g$ (406 keV) transitions have not been included in evaluating the slope because of the large errors in their intensities. These transitions are weak and lie in an energy region of very closely spaced γ -rays.

Also shown in fig. 7 are similar plots for ^{184}Os and ^{188}Os . The $R(I_{\gamma} I_g)$ values have been arbitrarily displaced for the three nucleides to avoid overlapping of points. The data for ^{184}Os are from ref.⁴⁾ and ²²⁾ and for ^{188}Os from ref.²³⁾. Here the z_{γ} values are found to be 0.019 ± 0.012 and 0.145 ± 0.014 , respectively, for ^{184}Os and ^{188}Os . There appears to be a smooth trend in z_{γ} in this transition region, indicating increasing mixing of rotation and vibration in the less deformed nuclei. It is somewhat surprising that a simple first-order model should work so well for ^{186}Os ; the many low-lying 4^+ , 5^+ and 6^+ states might be expected to mix strongly with the $K=2$ states. The behaviour of the Os transition nuclei is in sharp contrast to the nuclei near $N=90$ in which even the inclusion of β -band mixing in obtaining z_{γ} does not provide complete agreement with the model¹⁷⁾.

4.3 SPIN OF ^{186}Ir

Log ft values for populating states in ^{186}Os from ^{186}Ir decay are shown on the decay scheme (fig. 6). Errors derived from uncertainties in intensity balance are estimated to be no more than ± 0.3 log ft units.

The β -decay pattern indicates that the spin of ^{186}Ir must be 5, 6 or 7. In ref.¹⁾ the assignment made was $7^{(-)}$ and the Nilsson configuration proposed was $\pi \frac{7}{2}^{+}[404] + \nu \frac{7}{2}^{-}[514]$. The CERN group⁴⁾ suggests 6^{-} and the configuration $\pi \frac{3}{2}^{+}[402] + \nu \frac{9}{2}^{-}[505]$. The Nilsson assignments are based on the ground-state orbitals of odd-A Ir and Os isotopes.

In this work we propose that ^{186}Ir is 6^{+} and the Nilsson configuration $\pi \frac{11}{2}^{-}[505] + \nu \frac{1}{2}^{-}[510]$. In nuclei isotonic with ^{186}Ir , such as ^{185}Os , ^{183}W

and ^{181}Hf , the ground-state orbital is believed to be $\frac{1}{2}^-$ [510]. An intense β -decay branch occurs to the 6^+0 level D while the 8^+0 and 7^+2 levels E and K are only weakly populated (if at all). Only one negative parity level is appreciably populated by β -decay. These observations are not consistent with either the assignment $I=7$ as in ref.¹⁾ or the negative parity assignment in refs.¹⁾ and ⁴⁾; 6^+ is a more satisfactory assignment. The only suitable proton orbital is then $\frac{11}{2}^-$ [505]; its energy changes dramatically with deformation²⁴⁾. This orbital has been observed as an isomeric state in the odd-A iridium isotopes²⁵⁾.

A 1.7-h isomer of ^{186}Ir has been reported^{4,26,27)} whose decay populates levels of spin as high as 4 in ^{186}Os . From log ft values, a spin of 2 was estimated for 1.7-h ^{186}Ir ²⁷⁾. The CERN group⁴⁾ chemically milked ^{186}Ir from a parent ^{186}Pt source and found that ^{186}Pt decay preferentially populated a 1^+ state in ^{186}Ir which decayed to the 1.7-h state by an E1 transition. The conclusion of the CERN group is 2^- for the 1.7-h ^{186}Ir and the Nilsson configuration $\pi\frac{5}{2}^+$ [402] - $\nu\frac{9}{2}^-$ [505]. We suggest as an alternative $\pi\frac{5}{2}^+$ [402] - $\nu\frac{1}{2}^-$ [510]. No isomeric transition has been observed between the 1.7-h and 15.8-h states and it is not known which is the ground state.

4.4 CHARACTER OF EXCITED LEVELS IN ^{186}Os

The analysis of the nature of ^{186}Os levels other than those belonging to collective bands is done in terms of the independent quasiparticle model of Soloviev²⁴⁾. Available neutron and proton orbitals are listed in table 6 in approximate order of relative energy above the Fermi energy. The sequence has been adapted from a similar table for ^{188}Os (ref.²³⁾). We assume that ^{186}Os and ^{188}Os have approximately the same deformation. The quasiparticle orbitals extend over a range of about 600 keV in a region

high density of Nilsson states. Hence we can expect appreciable Coriolis mixing which will remove the uniqueness of Nilsson assignments. Nevertheless several two-quasiparticle assignments can be made which are consistent with decay patterns.

By the independent quasiparticle model, the γ -vibrational band can be described as the rotation of a two-particle state. The most obvious two-particle state resulting in a $K^\pi=2^+$ configuration would be $\sqrt{1/2}[510] + \sqrt{3/2}[512]$. Probably, the γ -vibrational band actually contains a large component of two-particle character and this can partially account for the large M1 component to the $3^+2 \rightarrow 2^+2$ 143 keV transition.

The 4^+ levels N (1194.45 keV), Q (1461.09 keV) and e (1480.3 keV) are possibly the two-neutron state $\frac{7^-}{2}[503] + \frac{1^-}{2}[510]$ or $\frac{9^-}{2}[505] - \frac{1^-}{2}[510]$. The former configuration should lie lower in energy and hence N is perhaps the most likely choice. Beta-decay to N would involve changing an $\frac{11^-}{2}[505]$ proton to a $\frac{7^-}{2}[503]$ neutron which corresponds to a first-forbidden unhindered transition. The other two-neutron state should be strongly populated by beta-decay since the transition $\frac{11^-}{2}[505]$ proton to $\frac{9^-}{2}[505]$ neutron should be allowed unhindered. The level e is thus the more likely choice for this configuration.

The only level thus far observed in ^{186}Os which has all of the properties expected of a pure two-particle state is the 5^- level X at 1628.3 keV. Its de-excitation is only to the $K=4$ band. Three possible configurations are the two-neutron configurations $\frac{9^+}{2}[624] + \frac{1^-}{2}[510]$ or $\frac{11^+}{2}[615] + \frac{1^-}{2}[510]$ or the two-proton configuration $\frac{11^-}{2}[505] - \frac{1^+}{2}[411]$, any of which could be populated by a first forbidden unhindered transition.

Baranger and Kumar¹⁶⁾ 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 et al.²⁸⁾ 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 $\hbar^2/2J$ 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 keV²⁹⁾ while in ^{190}Os the 4^+ level at 1163 keV is probably the $K=4$ two-phonon state²⁹⁾. 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).

In a recent note on two-phonon states in deformed nuclei, Soloviev³⁰⁾ points out several of the properties of two-phonon states. One property is the enhanced character of γ -ray transitions depopulating the two-phonon state to levels in the one-phonon band. By analogy to the properties of the quadrupole two-phonon state in ^{154}Gd , Soloviev proposes that there is a decrease in the population rate of two-phonon levels in beta decay.

While the 4^+ , 5^+ and 6^+ levels at 1351.82, 1560.0 and 1775.8 keV do decay to the one phonon $K=2$ band, there is no direct evidence for the decrease in β -decay population rate. The extent of multi-particle mixing into this proposed (221) (221) 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 multi-particle intrinsic states. No useful purpose is likely to be served by attempts at detailed analysis in the present context.

5. Summary and Conclusions

The excited level scheme of ^{186}Os has been elucidated which accommodates about 95% of the transition intensity populated by 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. Although the asymmetric rotor model seems to fit the energies of the $K=0$ and $K=2$ bands better than the symmetric rotor model, it fails in predicting the band head energy of the two-phonon band. Other symmetric rotor models such as the VMI predict the energy levels and spacing very well, which suggests that ^{186}Os is a rotation-vibration type of nucleus.

The transition probabilities between members of the γ -band and members of the ground-state band are described well by a first-order band-mixing calculation. Similar calculations for ^{184}Os and ^{188}Os interband transition intensities show a systematic increase in vibrational mixing with mass number. Unlike the $N=88-90$ region, the trend in the osmium isotopes is continuous. The ground state of ^{186}Ir is believed to be 6^+ . Several non-collective levels in ^{186}Os are discussed in terms of the two-quasiparticle model. The many low-lying 4^+ , 5^+ and 6^+ states are not easy to interpret 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. The β -decay patterns imply high- K character; yet they depopulate into low- K states by $E2$ transitions which should be K forbidden. Some of the high-lying levels could

de-excite by transitions having EO character to low-lying low-K states, in contradiction with their high K character.

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Appendix
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In table 7 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 7.

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 renormalisation of the γ -ray intensity scale relative to the conversion electron data of ref. 1). This renormalisation 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 overall fit to the theoretical conversion coefficients for the inter- and intraband transitions of the ground state and γ -vibrational bands.

The transition energies reported in table 7 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.

References

- 1) G. T. Emery, W. R. Kane, M. McKeown, M. L. Perlman and G. Scharff-Goldhaber, Phys. Rev. 129 (1963) 2597
- 2) B. Harmatz and T. H. Handley, Nucl. Phys. 56 (1964) 1
- 3) T. T. Sugihara, J. A. Keenan and M. L. Perlman, Phys. Rev. 181 (1969) 1650
- 4) M. Finger, R. Foucher, J. P. Husson, J. Jastrzebski, A. Johnson, C. Sébille, R. Henck, J. M. Kuchly, R. Regal, P. Siffert, G. Astner, B. R. Erdal, E. Hagebø, A. Kjelberg, F. Münnich, P. Patzelt, E. Beck and H. Kugler, CERN Report 70-29 (1970)
- 5) N. L. Lark and H. Morinaga, Nucl. Phys. 63 (1965) 466
- 6) J. O. Newton, F. S. Stephens and R. M. Diamond, Nucl. Phys. A95 (1967) 377
- 7) W. W. Bowman, Nucl. Inst. Meth. 96 (1971) 135
- 8) R. A. Meyer, Phys. Rev. 170 (1968) 1089
- 9) K. J. Hofstetter and T. T. Sugihara, Nucl. Phys. A140 (1970) 658
- 10) P. C. Sood, Phys. Rev. 161 (1967) 1063
- 11) M. A. J. Mariscotti, G. Scharff-Goldhaber and B. Buck, Phys. Rev. 178 (1969) 1864
- 12) A. Bäcklin, Nucl. Inst. Meth. 53 (1967) 177
- 13) A. S. Davydov and C. F. Filippov, Nucl. Phys. 8 (1958) 237; A. S. Davydov and V. S. Rostovsky, Nucl. Phys. 12 (1959) 58; A. S. Davydov and A. A. Chaban, Nucl. Phys. 20 (1960) 499
- 14) T. K. Das, R. M. Dreizler and A. Klein, Phys. Rev. Lett. 25 (1970) 1626
- 15) A. Faessler, W. Greiner and R. K. Sheline, Nucl. Phys. 62 (1965) 241
- 16) M. Baranger and K. Kumar, Nucl. Phys. A110 (1968) 529

- 17) J. H. Hamilton, Conference of the Academy of Science of the USSR on Nuclear Spectroscopy and Structure of the Atomic Nucleus, Moscow, 1971 (Izv. Akad. Nauk SSSR, Ser. Fiz., to be published)
- 18) W. W. Bowman and T. T. Sugihara, Nucl. Phys. (in press 1971)
- 19) P. O. Lipas, Nucl. Phys. 39 (1962) 468
- 20) R. C. Greenwood, C. W. Reich and S. H. Vegors, Phys. Lett. 33B (1970) 213
- 21) R. F. Casten, J. S. Greenberg, S. H. Sie, G. A. Burginyon and D. A. Bromley, Phys. Rev. 187 (1969) 1532
- 22) P. J. Daly and K. J. Hofstetter, private communication
- 23) T. Yamazaki and J. Sato, Nucl. Phys. A130 (1964) 456
- 24) V. G. Soloviev, Mat. Fys. Medd. Dan. Vid. Selsk. 1 (1961), no. 11
- 25) B. Harmatz and T. H. Handley, Nucl. Phys. A121 (1968) 481
- 26) G. R. Grant and L. Yaffe, Can. J. Chem. 41 (1963) 2533
- 27) N. Zaitseva, J. Zvolsky, Z. Rindina, Z. Stachura, Z. Cheglovski and G. Chulekova, 20th Annual Conf. on Nuclear Spectroscopy and Nuclear Structure, Leningrad (1970)
- 28) N. I. Pyatov, Ark. Fys. 36 (1967) 667; K. M. Zhelezona, N. I. Pyatov and M. I. Cherei, Bull. Acad. Sci. USSR, Phys. Ser. 31 (1967) 546
- 29) A. Faessler, W. Greiner and R. K. Sheline, Nucl. Phys. 70 (1965) 33
- 30) V. G. Soloviev, Sov. J. Nucl. Phys. 10 (1970) 171

TABLE 1
Gamma-ray intensities^{a)} in singles and coincidence experiments

E_{γ} (keV)	Singles ^{b)}	435 Gate ^{c)}	584 Gate ^{d)}	1057 Gate ^{b)}
137.15	57 (3)	27 (3)	4.7(6)	72(10)
208.0	1.1(2)		1.0(4)	
276.54	2.9(3)		3.0(4)	
296.75	≈ 100	69 (7)		≈ 100
434.78	49 (3)	2.0(2)	1.0(3)	
511.0	7.2(8)	3.0(5)		
622.15	5.3(5)	≈ 5.3		
630.31	8.7(10)		≈ 8.7	
767.30	6.9(8)			
943.56	1.5(2)	1.0(4)		
1187.90	2.6(3)	2.5(4)		
1508.05	1.7(2)	2.0(4)		

a) Not corrected for counting efficiency

b) Normalised to 100 for the 296.75 keV γ -ray

c) Normalised to 5.3 for the 622.15 keV γ -ray

d) Normalised to 8.7 for the 630.31 keV γ -ray

TABLE 2
Coincidences observed in ^{186}Ir decay^{a)}

Gating transition (keV)	Transitions in coincidence (keV)	Parent level Energy (keV)	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

TABLE 2 CONTINUED
Coincidences observed in ^{186}Ir decay^{a)}

Gating transition (keV)	Transitions in coincidence (keV)	Parent level	
		Energy (keV)	Designation
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

a) 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.

TABLE 3

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	$\underline{I}^\pi$	Transitions	
			In	Out
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*, E1/E2), nY(885.0*, M1), nN(1467.1, E2), nG(1751.4, M1), nF(1893.7)
3041.3(4)	o	(4^+)	...	oY(1264.6, E2), oa(1690.2*), oD(2172.2)
3151.7(5)	p	(4^+)	...	pU(1071.0, M1), pQ(1690.2*), pG(2242.0), pF(2383.7)
3268.8(10)	l	(4^+)	...	lR(1393.6), le(1789.0, (M1)), lG(2357.3), lD(2399.1), lC(2835.2), lB(3132.2)
3413.6(4)	q	...	...	qU(1332.3, (M1)), qI(2138.6) qD(2544.3), qC(2980.1)

TABLE 4

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 ($\underline{I}^{\pi}\underline{K}$)	Experimental energy (keV) ^{a)}	VMI ^{b)} Ref. 11)	MIX-VMI Ref. 14)	Rot.-Vib. Ref. 15)	PPQ Ref. 16)
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

TABLE 5

Spin-dependent factor $F(\underline{I}_\gamma, \underline{I}_g)$ in perturbation correction to the transition probability between an initial γ -band state $\underline{I}_\gamma$ ($K=2$) and a ground-band state $\underline{I}_g$ ($K=0$)¹⁹⁾

Initial state $\underline{I}_\gamma$ ($K=2$)	Final state $\underline{I}_g$ ($K=0$)	$F(\underline{I}_\gamma, \underline{I}_g)$
$\underline{I}_g \mp 2$	I	$\pm(2\underline{I}_g + 1)$
$\underline{I}_g - 1$	I	$(\underline{I}_g + 2)$
$\underline{I}_g$	I	2
$\underline{I}_g + 1$	I	$-(\underline{I}_g - 1)$

TABLE 6

Nilsson orbitals for protons and neutrons in ^{186}Os based on quasiparticle energies calculated for ^{188}Os (ref.²³). Lowest lying orbital is listed at the top of the column.

Quasiproton states	Quasineutron states
$\frac{11}{2}^-$ [505]	$\frac{7}{2}^-$ [503]
$\frac{9}{2}^-$ [514]	$\frac{9}{2}^+$ [624]
$\frac{3}{2}^+$ [402]	$\frac{1}{2}^-$ [510]
$\frac{1}{2}^+$ [400]	$\frac{9}{2}^-$ [505]
$\frac{5}{2}^+$ [402]	$\frac{3}{2}^-$ [512]
$\frac{1}{2}^+$ [411]	$\frac{11}{2}^+$ [615]
$\frac{7}{2}^+$ [404]	$\frac{7}{2}^-$ [514]
$\frac{7}{2}^-$ [523]	$\frac{1}{2}^-$ [521]
	$\frac{7}{2}^+$ [633]
	$\frac{5}{2}^-$ [512]
	$\frac{13}{2}^+$ [606]

TABLE 7

Gamma 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		
2339.7 ^f)	9.8(12)-2	some EO	
2357.3	7.2(11)-2		lG
2383.7	9.6(10)-2	some EO	pF
2399.1	1.04(14)-1	some EO	lD
2544.3	6.7(14)-2		qD
2580.3	2.0(6)-2		
2733.7	1.5(5)-2	(M1)	
2770.7	9(3)-3		
2780.4	8.3(13)-2		
2790.2	4.6(7)-2		
2805.8	1.5(4)-2		
2835.2	2.00(19)-1		lC
2853.1	5.7(8)-2		
2866.5	1.5(5)-2		
2912.5	2.5(7)-2		
2967.0	2.9(6)-2		
2980.1	1.9(4)-2		qC
2994.8	1.7(3)-2		
3007.3	3.2(5)-2		
3040.3	1.0(3)-2		

3074.6

6.6(20)-3

3132.2

1.2(2)-2

1B

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- a) γ -ray intensities are normalised 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 .

Figure Captions

- Fig. 1. Singles γ -ray spectrum of the 400-900 keV region from the decay of ^{186}Ir . Peaks assigned to ^{186}Ir are identified by their energy rounded to the nearest keV. The letters A, B, etc. identify positions of gates set digitally in coincidence experiments. The total counting rate was $\approx 50\text{K}$ counts per sec when this spectrum was taken.
- Fig. 2. Spectra in coincidence with the 435 keV gate A (upper spectrum) and its associated Compton gate (lower spectrum). Only selected regions of interest have been plotted. Arrows indicate the expected positions of peaks whose energy is given in keV in the upper spectrum.
- Fig. 3. Spectra in coincidence with the 584 keV gate D (upper spectrum), 551 keV gate C (middle spectrum) and common Compton gate E (lower spectrum). See also captions of fig. 2.
- Fig. 4. Spectra in coincidence with the 706 keV gate F, 713 keV gate G, 730 keV gate I and common Compton gate H. See also caption of fig. 2.
- Fig. 5. Spectra in coincidence with the 277 keV gate (upper left) and its Compton gate (lower left) and the 1057 keV gate (upper right) and its Compton gate (lower right). See also caption of fig. 2.
- Fig. 6. Level scheme of ^{186}Os from decay of $15.8\text{-h } ^{186}\text{Os}$. Levels drawn with heavy lines are members of the ground-state band, the $\underline{K} = 2$ γ -vibrational band, and a proposed $\underline{K} = 4$ two-phonon band. Transitions between members of the ground-state and γ -vibrational bands are not shown here since they have been reported elsewhere ^{1,2,3}). 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 3. 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.

Fig. 7. Mikhailov plot for transitions between members of the γ -band and members of the ground-state band in ^{184}Os , ^{186}Os , and ^{188}Os . The ordinate function $R(\frac{I}{I}_{\gamma}, \frac{I}{I}_{g})$ is defined in the text. The abscissa is the spin-dependent function whose value is listed in table 5. See text for a discussion of the normalisation method used.

FIG. 5

FIG. 7