Studies of Decay Schemes in the Osmium-Iridium Region. II. Decay of 12-Day Ir^{190}†

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Spectra of the gamma rays and internal conversion electrons emitted in the decay of 12-day Ir^{190} have been studied in detail. Internal conversion spectra were obtained with the aid of double-focusing and intermediate-image beta spectrometers, and a permanent-magnet spectrograph. Gamma-ray spectra were obtained by means of photoelectric conversion, employing a double-focusing spectrometer, and by scintillation techniques.

These measurements of the energies and relative intensities of gamma rays and internal conversion electrons give internal conversion coefficients for a number of transitions. These data, coupled with coincidence studies of gamma rays, support the level scheme reported by Nielsen *et al.* for Os^{190} and establish new, odd-parity levels at 1384, 1568, and 1876 kev. An upper limit of 2×10^{-5} is set on positron branching in the decay of Ir^{190}. Relative electron capture transition probabilities for the decay of Ir^{190} to Os^{190} and ratios of reduced transition probabilities for electromagnetic transitions from a number of levels of Os^{190} follow from these results. They are compared with the predictions of the strong-coupling model and the asymmetric rotor model. The half-life of Ir^{190} was found to be 12.3 ± 0.4 days. Even-A iridium-osmium total disintegration energies are found to rise substantially above the values predicted by semiempirical mass formulas, suggesting a possible effect of the change in the nuclear deformation in this region.

INTRODUCTION

OSMIUM 190 merits interest by virtue of the position it occupies in the transition region[1] between the highly deformed nuclei, whose energy levels are well described in terms of the unified, or strong coupling model,[2] and the spherical nuclei, whose energy levels exhibit properties typical of the near-harmonic, or weak-coupling region.[3]

Levels of Os^{190} are excited in the decays of 3-minute Re^{190}, the 3-hour and 12-day isomers of Ir^{190}, and the 10-minute isomer of Os^{190}.

From studies of the 10-minute isomer of Os^{190}, Aten, DeFeyfer, Sterk, and Wapstra[4] suggested the existence of a sequence of three rotational levels, based on the ground state, with energies of 187, 548, and 1048 kev, and an isomeric level at 1662 kev.[5]

Scharff-Goldhaber, Alburger, Harbottle, and McKeown,[6] in a further study of the gamma rays and internal conversion electrons emitted by this isomer, established the rotational nature of all four levels, and determined that the isomerism of Os^{190} arises from a 38.4-kev K forbidden $M2$ transition from a 10− state at 1700 kev to the 8+ rotational state at 1662 kev. The energies of the rotational levels were shown to deviate substantially from a simple $I(I+I)$ dependence.

Sunyar[7] has measured directly the lifetimes of the first two rotational levels, obtaining 3.5×10^{-10} sec and 4×10^{-11} sec, respectively, for the first and second excited levels.

A second 2+ level in Os^{190}, at 557 kev, has been reached via Coulomb excitation by Barloutaud, Lehmann, and Leveque,[8] and by McGowan and Stelson.[9] The latter report reduced transition prob-

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[1] G. Scharff-Goldhaber, *Proceedings of the University of Pittsburgh Conference on Nuclear Structure, June 6–8, 1957*, edited by S. Meshkov (University of Pittsburgh and Office of Ordnance Research, U. S. Army, 1957).

[2] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat. fys.-Medd. **27**, No. 16 (1953).

[3] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).

[4] A. H. W. Aten, G. D. DeFeyfer, M. J. Sterk, and A. H. Wapstra, Physica **21**, 740 (1955).

[5] For the sake of consistency and clarity in discussing the results of previous work we adopt more recent numerical values, and in some instances round them off in the text.

[6] G. Scharff-Goldhaber, D. E. Alburger, G. Harbottle, and M. McKeown, Phys. Rev. **111**, 913 (1958).

[7] A. W. Sunyar, *Proceedings of The Second United Nations International Conference on the Peaceful Uses of Atomic Energy*, (United Nations, New York, 1958), Vol. 14, p. 347.

[8] R. Barloutaud, P. Lehmann, and A. Leveque, Compt. rend. **245**, 523 (1957); (private communication).

[9] F. K. McGowan and P. H. Stelson, Bull. Am. Phys. Soc. **3**, 228 (1958); F. K. McGowan, *Proceedings International Congress on Nuclear Physics, Paris, July 7–12, 1958*, edited by P. Guggenberger (Dunod, Paris, 1959), p. 233; (private communication).

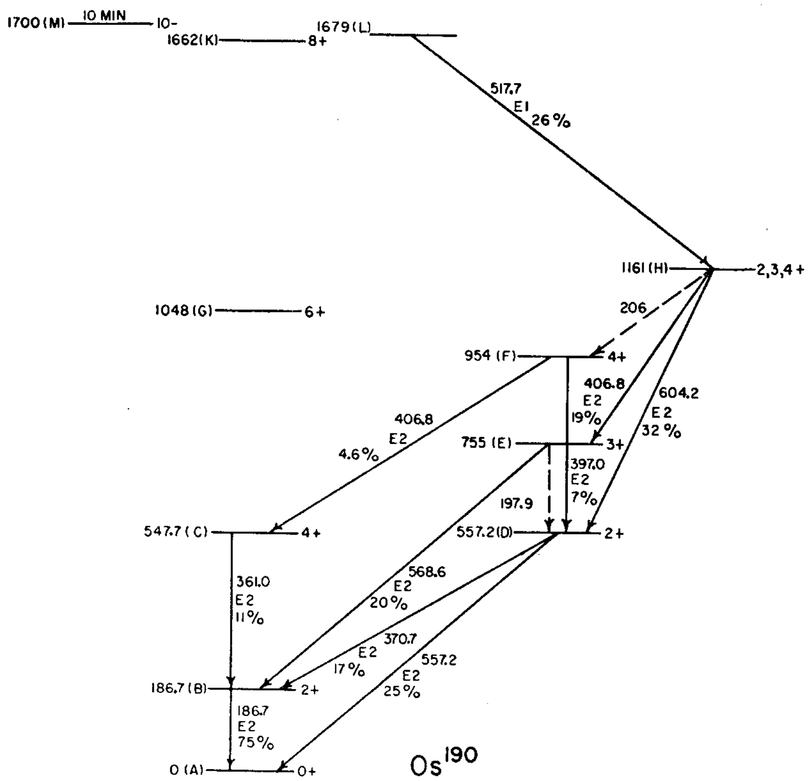

FIG. 1. The level scheme of Os^{190} which was established earlier. In order to facilitate subsequent discussion each level is given a letter designation. Transitions shown are those excited in the decay of Ir^{190}. Their intensities are taken from the work of Nielsen *et al* (see reference 11). Present values for the energies of excited levels and electromagnetic transitions are used.

abilities of 41 and 4.3 relative to a single proton transition for the 371- and 557-kev transitions from the 557-kev level to the first excited state and ground state, respectively, and a reduced transition probability of 79 for the 187-kev transition from the first level of the ground-state rotational band. The latter may be compared with the value of 111 for this quantity which results from the measurements of Sunyar.[7]

Diamond and Hollander,[10] employing 180° permanent magnet spectrographs, have measured the energies of a large number of internal conversion electron groups emitted in the decay of 12 day Ir^{190}. Their observations of transitions with energies of 371 and 557 kev confirmed the existence of the second 2+ level in Os^{190} at 557 kev.

Nielsen, Poulsen, Sheline, and Skytte Jensen,[11] by observing coincidences of gamma rays and internal conversion electrons emitted in the decay of Ir^{190}, have succeeded in establishing additional levels of Os^{190} which account for many of the observed transitions. Their level scheme is shown in Fig. 1. It contains, in addition to the ground-state rotational band and the second 2+ level at 557 kev (level *D*), even parity levels at 755 kev (Level *E*) and 954 kev (Level *F*) which, together with level *D*, were interpreted by these authors as a second rotational band. In addition, they established an even parity level at 1161 kev (Level *H*), and an odd parity level at 1679 kev (Level *L*).

In the present work we have measured by a variety of techniques the energies and relative intensities of the internal conversion electrons and gamma rays emitted in the decay of Ir^{190}. Our results are in agreement with the level scheme for Os^{190} proposed by the Copenhagen group, and establish the existence of several new levels with odd parity.

EXPERIMENTAL PROCEDURE

Preparation of Sources

Ir^{190} was produced both by alpha bombardment of rhenium enriched in Re^{187}(1.8% Re^{185}, 98.2% Re^{187}) and by deuteron bombardment of normal osmium. At energies sufficient for a high yield of Ir^{190} the first process also produces substantial amounts of 41 hour Ir^{188} and 13 day Ir^{189}, and the second 41 hour Ir^{188}, 13 day Ir^{189}, and 74 day Ir^{192}. Both types of bombardments produce shorter-lived activities as well. The utilization of both types of bombardment, studies of the decay of individual radiations and the dependence of their yield upon bombarding energy, and the extensive information existing concerning the radiations of Ir^{192} permitted the assignment of practically every transition observed to a given isotope. For certain extremely weak transitions, however, we could only

[10] R. M. Diamond and J. M. Hollander, Nuclear Phys. 8, 143 (1958).
[11] O. B. Nielsen, N. O. Roy Poulsen, R. K. Sheline, and B. Skytte Jensen, Nuclear Phys. 10, 475 (1959); (private communication).

conclude that they belonged either to Ir^{189} or to Ir^{190}, owing to the similar half-lives of the two nuclides.

The iridium activities were separated from the cyclotron targets with the addition of $IrCl_4$ carrier. Beta spectrometer sources were prepared by evaporation and by electrodeposition methods reported by Ovenden[12] and by Diamond and Hollander.[10]

Procedure in Measuring Internal Conversion Spectra

Internal conversion spectra were obtained using a 30 cm double-focusing beta spectrometer,[13] an intermediate-image beta spectrometer,[14] and a 180° permanent magnet spectrograph.

1. The double-focusing spectrometer was employed to obtain spectra in the region below 900 kev of sources produced by both types of bombardment described above. This instrument has a transmission of 0.8% at full aperture, with a corresponding aberration line breadth at half-maximum of 0.25%. Runs were ordinarily made at full aperture, with a source width and detector slit width of 0.125 inch, which gave, together with electron energy losses in the source, a line breadth of approximately 0.6% in the vicinity of 500 kev, and increasing somewhat at lower energy. Certain runs were made at higher resolution, using a smaller spectrometer aperture and detector slit, and an especially thin electroplated source, giving line breadths of 0.20 to 0.25% in the region above 100 kev. The transmission of the window of the detector, a Geiger-Müller counter, was determined by comparing measured intensities of the strong internal conversion lines of Thorium *B* (Pb^{212}) and its descendants with the results obtained by other researchers.[15]

A rotating coil device,[16] driven by a stabilized frequency power supply, served to measure the magnetic field of the spectrometer. As only relative field measurements were attempted with this device, a momentum calibration was performed by collecting Thorium *B* (Pb^{212}) on the iridium beta spectrometer sources and intercomparing the strong lines of Ir^{189} and Ir^{190} with certain of the precisely measured internal conversion lines of Thorium *B* and its descendants.[17,18] Further checks on this calibration were provided by measurements of the momenta of Auger electrons and by a critical absorption experiment which gave the result that the energy of a strong transition of Ir^{189}, determined as 69.64 kev from our measurements, is greater than the *K* ionization energy of tungsten (69.51 kev).[19]

2. The intermediate image spectrometer, because of its high transmission, was used to obtain internal conversion spectra in the region from 600 to 1400 kev. For reasons of intensity, sources produced by deuteron bombardment of osmium were employed here. Runs were made with the spectrometer adjusted to give a transmission of 4.5% and a corresponding aberration line breadth of 1.6%. This, together with effects of source size and electron energy loss in the source gave a line breadth of 2.5% at 604 kev. Other features of the arrangement and operation of this instrument remained unchanged from earlier work.[14]

3. The 180° permanent magnet spectrograph was employed in checking certain results obtained in the beta spectrometer runs. Several 12 to 14 day exposures were made of iridium produced by deuteron bombardment of osmium and electroplated on 5 mil platinum wire.

Procedure in Measuring External Conversion Spectra

Photoelectric conversion spectra were taken with the double-focusing beta spectrometer and converter foils of tantalum and thorium. An 11.5-mg/cm² tantalum foil and 8.3- and 29-mg/cm² thorium foils, 0.156 inch wide and 1.050 inch long, were used. The gamma emitting material occupied a space 0.080 inch in diameter and 0.160 inch long in a Teflon capsule 0.125 inch in diameter situated in an aluminum cup with a 0.020-inch thick wall adjacent to the converter foil. The full spectrometer aperture and a 0.125-inch counter slit were used.

The breadths of photoelectric conversion lines in this arrangement varied rapidly with energy and foil thickness. The 517-kev line of Ir^{190}, for example, converted in the 11.5-mg/cm² tantalum foil, had a breadth of 1.4%.

It is well known that owing to the energy dependence of the rather large anisotropy in the angular distribution of photoelectrons with respect to the direction of propagation of the incident gamma ray, and to scattering of the photoelectrons in the converter foil, a knowledge of the total photoelectric cross section alone is insufficient for the determination of gamma-ray intensities from the intensities of photoelectric conversion lines. In certain geometries, gamma-ray intensities may be calculated with the use of results of recent measurements of the dependence of the angular distribution of photoelectrons[20] upon the energy of the incident photon and the atomic number,

[12] P. J. Ovenden, Prods. Finishing **10**, 62 (1957); Nature **179**, 39 (1957).

[13] A. A. Bartlett and K. T. Bainbridge, Rev. Sci. Instr. **22**, 517 (1951).

[14] D. E. Alburger, Rev. Sci. Instr. **27**, 991 (1956).

[15] A. I. Zhernovoi, E. M. Krisyuk, G. D. Latyshev, A. S. Remennyi, A. G. Sergeev, and V. I. Fadeev, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 682 (1957); [translation: Soviet Phys.-JETP **5**, 563 (1957)]; V. D. Vorobev, K. I. Ilin, T. I. Kolchinskaia, G. D. Latyshev, A. G. Sergeev, Yu. N. Trofimov, and V. I. Fadeev, Izvest. Adak Nauk (S.S.S.R.) Ser. Fiz. **21**, 954 (1957) [translation: Bull. Acad. Sciences (U.S.S.R.) **21**, 956 (1957)].

[16] Model 722S Rawson-Lush rotating coil gaussmeter. Rawson Electrical Instrument Company, Cambridge, Massachusetts.

[17] G. Lindström, Arkiv Fysik **4**, 1 (1952); Phys. Rev. **87**, 678 (1952).

[18] K. Siegbahn and K. Edvardson, Nuclear Phys. **1**, 137 (1956).

[19] R. D. Hill, E. L. Church, and J. W. Mihelich, Rev. Sci. Instr. **23**, 523 (1952).

[20] S. Hultberg, Arkiv Fysik **15**, 307 (1959); S. Hultberg and Z. Sujkowski, Phys. Rev. Letters **3**, 227 (1959).

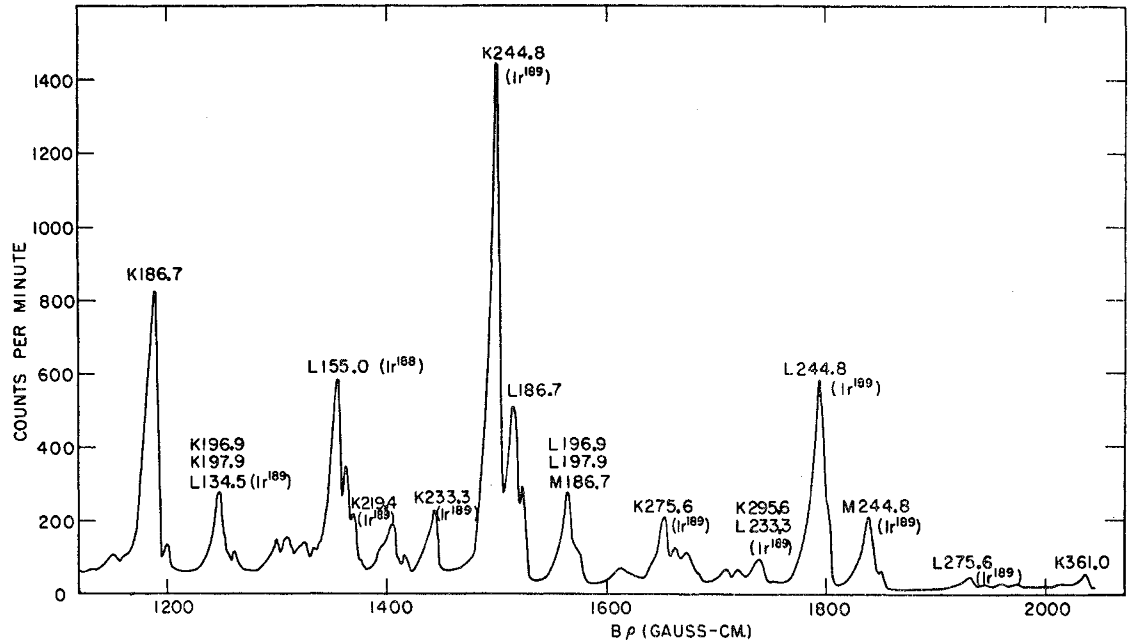

FIG. 2. The internal conversion spectrum of Ir^{190} and other iridium isotopes—low-energy region. Source produced by alpha bombardment of Re^{187}.

and existing knowledge of electron scattering. The approach followed here, however, has been to determine empirically the spectral response of the entire experimental arrangement for gamma rays. This was done with the use of nuclides for which the intensity ratios of the gamma rays emitted are precisely and reliably known; namely, Na^{24}, Na^{22}, and Hf^{180m}. For Na^{24}, the intensity ratio of the 1.368- and 2.754-Mev gamma rays deviates from unity by less than one part per thousand.[21] For Na^{22}, adoption of the value 9.9% for the electron capture branching ratio[22] and small corrections for three quantum annihilation and annihilation in flight gave the value 1.780 for the ratio of the intensity of the 511-kev annihilation radiation to that of the 1277-kev gamma ray. For Hf^{180m}, the rotational nature of the first four excited levels ensures that the intensities of the lowest three transitions, with energies of 93.3, 216.0, and 332.4 kev, will stand in a one to one ratio. However, the next highest transition, with an energy of 443.6 kev, is in cascade with a 57.6 kev $E1$ transition, which competes with a 501 kev $E3$ crossover transition. Two measurements of the intensity of the latter give 20 and 15%, respectively.[23,24] The adoption here of 18% for this value, and of corrections for internal conversion[24a] give for the relative intensities of the gamma rays:

$$I(443.6):I(332.4):I(216.0)=0.976:1.153:1.000.$$

Measurements of the intensity ratios of the photoelectric conversion lines of each of these nuclides were used to construct curves giving the relative spectral response of the apparatus for gamma rays. This was done not only for the customary adoption of line area as a measure of intensity but also using the peak height for this purpose. The latter criterion for intensity is useful when conversion lines are weak compared with background or are incompletely resolved from one another.

The uncertainty in the intensity calibration is estimated to be 7% above 511 kev and 10% below this energy.

Scintillation Spectrometer Studies

Gamma rays were also studied with the aid of sodium iodide detectors ranging in size from $1\frac{1}{2}$-inch diameter ×1-inch length to 5-inch diameter ×4-inch length, multichannel pulse-height analyzers, and coincidence circuits.

RESULTS

Internal Conversion Electron Spectra

The transition energies and relative intensities of the internal conversion electrons of Ir^{190} are presented

[21] L. V. Gustova, B. S. Dzhelepov, P. E. Ermolov, and O. V. Chubinskii, Izvest. Akad. Nauk (S.S.S.R.) Ser. Fiz. 22, 211 (1958) [translation: Bull. Acad. Sciences (U.S.S.R.) 22, 208 (1958)].

[22] R. Sherr and R. H. Miller, Phys. Rev. 93, 1076 (1954).

[23] G. Scharff-Goldhaber, M. McKeown, and J. W. Mihelich, Bull. Am. Phys. Soc. 1, 206 (1956).

[24] V. S. Gvozdev, L. I. Rusinov, Yu. I. Filimonov, and Yu. L. Khazov, Nuclear Phys. 6, 561 (1958).

[24a] *Note added in proof.*—Theoretical internal conversion coefficients were used for these corrections.

in Table I. Errors in the energy determinations are estimated to be 0.05% for the 186.7-kev transition, 0.1% for the other strong transitions, and 0.2 to 0.3% for the weaker transitions, depending on the intensity. For comparison, transition energies determined by Diamond and Hollander[10] by means of 180° permanent magnet spectrographs or scintillation techniques, and the results of Nielsen *et al.*,[11] for the relative intensities of K-shell internal conversion electrons (renormalized to percent of the K internal conversion line of the 186.7-kev transition) and K/L ratios are also shown.

Upper limits are given for the internal conversion electron intensities of the transitions above 1000 kev, for a serach of this region, carried out on the intermediate image spectrometer, failed to reveal any internal conversion electrons.

In these measurements the decay of well-resolved internal conversion peaks gave a half-life of 12.3±0.4 days for Ir^{190}.

Typical portions of the internal conversion electron spectrum, taken on the double focusing spectrometer, of Ir^{190} and other isotopes produced by the alpha bombardment of Re^{187} are shown in Figs. 2 and 3. Several internal conversion lines of particular interest, from a source produced by the deuteron bombardment of osmium, are shown in Fig. 4.

Photoelectric Conversion Spectra

The relative intensities of the gamma rays of Ir^{190}, determined by the method of photoelectric conversion, employing the double-focusing beta spectrometer, are presented in Table II. A typical photoelectric conversion spectrum is shown in Fig. 5. The Ir^{190} used in these measurements was produced by deuteron bombardment of osmium. The values listed represent averages from runs utilizing both thorium and tantalum converter foils. The experimental K-shell internal conversion coefficients listed were calculated from the results of Tables I and II by assuming a value of 0.0138 for the K-shell internal conversion coefficient

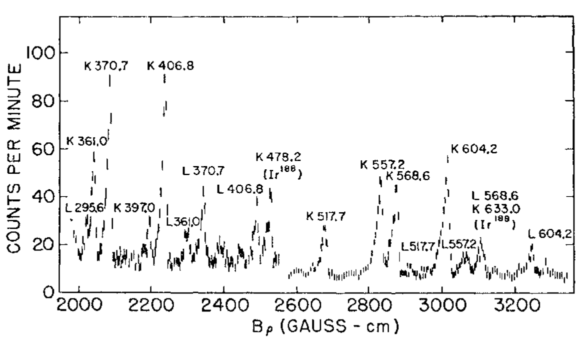

FIG. 3. The internal conversion spectrum of Ir^{190} and other iridium isotopes—high-energy region. The two portions of the spectrum (joined at $\beta\rho=2550$ gauss cm) are from two sources of different strengths, both produced by the same alpha bombardment of Re^{187}. The scale has been adjusted to show the heights of individual peaks in the two regions in their correct ratio.

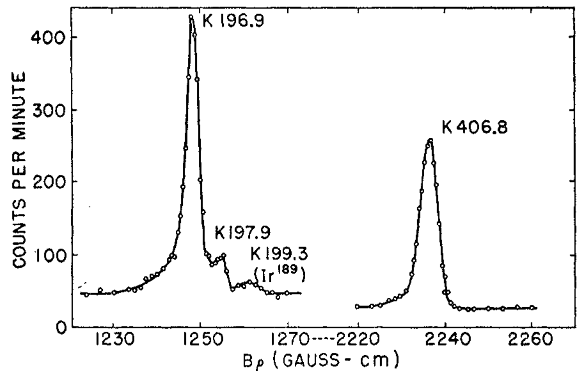

FIG. 4. Individual internal conversion lines of transitions of Ir^{189} and Ir^{190} with energies in the vicinity of 197 kev and 407 kev. Source produced by deuteron bombardment of osmium.

of the 557.2-kev transition. This is the value calculated by Sliv and Band[25] for a pure $E2$ transition. The transition proceeds from the 2+ level at 557.2 kev to the 0+ ground state of Os^{190} (see Fig. 1). Measured internal conversion coefficients are compared with theoretical values[25] in Fig. 6.

Scintillation Spectra

The complexity of the gamma rays of Ir^{190} is such that all that can be said concerning scintillation spectra in the region below 900 kev is that they are in qualitative agreement with the higher resolution photoelectric conversion results. In the region between 900 and 1500 kev, however, spectra taken with a 2×3-inch NaI detector reveal the presence of four incompletely resolved peaks. These are found with Ir^{190} sources produced both by alpha bombardment of Re^{187} and deuteron bombardment of osmium, and appear to follow the decay of Ir^{190}. The relative intensities of these four gamma rays were determined by fitting the shape of the 1277-kev peak of Na^{22} to the observed Ir^{190} spectrum. The energies and relative intensities thus obtained are listed in Table III. The uncertainty in the intensities of the three higher energy gamma rays relative to that at 1020 kev is estimated to be 25%, and the uncertainty in the intensity of the 1020-kev gamma ray relative to that at 186.7 kev also at 25%. The upper limits for the internal conversion coefficients in Table III, calculated, as in Table II, with the assumption of the pure $E2$ value of 0.0138 for the K-shell internal conversion coefficient of the 557.2-kev transition, fix the multipole order of the 1020-kev transition as $E1$, and limit the choice of multipole orders for the remaining transitions to those shown.

[25] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 Part I [translation: Report 57ICC K1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)]; Part II (1958) [translation: Report 58ICC L1)].

TABLE I. Transition energies and relative intensities of internal conversion electrons of Ir^{190}. Experimental K/L ratios are compared with K/L ratios derived from the tables of internal conversion coefficients of Sliv and Band.[a] Transition energies are compared with those determined by Diamond and Hollander[b] and relative intensities and K/L ratios with the results of Nielsen *et al.*[c]

Transition energy (kev) Present work	Diamond and Hollander[b]	I_K Present work	I_K Nielsen *et al.*[c]	I_L Present work	K/L Present work	K/L Nielsen *et al.*[c]	Theory
186.7±0.1	186.7	100±5	100	86±4	1.16±0.07	1.20	1.18($E2$)
196.9±0.2	···	19±2	22}	4.5 ±3.3[d] (196.9 and 197.9 combined)	$4.8^{+12}_{-2\ 0}$ (196.9 and 197.9 combined)	···	6.02($M1$)
197.9±0.4	···	2.5 ±0.4	···}				1.28($E2$)
205.9±0.6	206.2	~2.1	3.1	···	···	···	···
223.8±0.6	···	2.0 ±0.4	···	···	···	···	···
294.6±0.3	···	4.5 ±0.5	3.4	1.9 ±0.4	2.4±0.9	···	2.27($E2$)
361.0±0.4	361.2	4.9 ±0.5	3.9	1.9 ±0.4	2.6±0.6	2.9	2.86($E2$)
370.7±0.4	371.4	7.3 ±0.6	5.6	2.2 ±0.3	3.3±0.6	2.9	2.94($E2$)
397.0±0.8	···	1.5 ±0.3	1.9	0.5 ±0.2	3.0±0.9	3.1	3.14($E2$)
406.8±0.4	407	7.0 ±0.4	6.1	1.7 ±0.2	4.1±0.6	3.5	3.22($E2$)
517.7±1.0	520–530	1.9 ±0.3	1.2	0.26±0.1	7.3±2.0	>4.5	6.45($E1$)
557.2±0.6	558	3.6 ±0.3	3.2	0.77±0.1	4.7±0.8	≳4.3	4.09($E2$)
568.6±0.6	568	3.1 ±0.3	2.6	···	···	≳3.4	···
604.2±0.6	600–620	3.5 ±0.3	3.6	0.76±0.1	4.6±0.8	~5	4.30($E2$)
725 ±2	~700	0.11±0.03	···	···	···	···	···
767 ±2	760	0.13±0.03	···	···	···	···	···
827 ±2	~800	0.09±0.03	···	···	···	···	···
1020 ±10	~1000	<0.028[e]	···	···	···	···	···
1150 ±15	···	<0.024	···	···	···	···	···
1330 ±15	···	<0.016	···	···	···	···	···
1430 ±15	···	<0.011	···	···	···	···	···

[a] See reference 25. [b] See reference 10. [c] See reference 11.
[d] Because the L-shell internal conversion electrons of the 196.9- and 197.9-kev transitions were unresolved from one another, a combined L-shell internal conversion intensity and K/L ratio is given for the two transitions.
[e] A search in the region above 1000 kev failed to disclose any internal conversion electrons above background.

Coincidence Measurements

In order to determine the role of the high-energy transitions in the level scheme of Os^{190}, gamma-ray coincidence measurements were carried out for the 827, 1020, and 1330-kev transitions, which are reasonably well resolved by scintillation techniques, and whose photopeaks are relatively free from Compton background arising from other transitions.

Establishment of Level I

In the spectrum coincident with the 827-kev gamma ray, strong peaks, approximately equal in intensity,

TABLE II. Relative intensities of gamma rays of Ir^{190} determined by photoelectric conversion utilizing a double focusing beta spectrometer. Experimental K-shell internal conversion coefficients are calculated from the relative gamma-ray intensities and the results in Table I, with the assumption of a pure $E2$ internal conversion coefficient for the 557.2-kev transition. Experimental internal conversion coefficients are compared with theoretical values from the tables of internal conversion coefficients of Sliv and Band.[a]

Energy (kev)	Intensity	K-shell internal conversion coefficient: Experimental	K-shell internal conversion coefficient: Theoretical	Assumed multipole order
186.7	153±23	0.25 ±0.04	0.204	$E2$
196.9}[b]	21±4	0.38 ±0.07	{0.177 ($E2$)	$M1+E2$?
197.9}			{0.69 ($M1$)	$E2$?
223.8	15±5	0.05 ±0.02	0.0421	$E1$
361.0	42±5	0.044 ±0.009	0.0374	$E2$
370.7	77±10	0.036 ±0.006	0.0352	$E2$
397.0	21±5	0.028 ±0.008	0.0299	$E2$
406.8	97±13	0.027 ±0.004	0.0280	$E2$
517.7	119±15	0.0059±0.0009	0.0060	$E1$
557.2	100±13	assumed	0.0138	$E2$
568.6	94±12	0.013 ±0.002	0.0132	$E2$
604.2	143±18	0.0094±0.0018	0.0115	$E2$
725	10±3	0.0051±0.0015	0.0030	$E1$
767	<8 (not observed)	>0.0059	0.0070	$E2$?
827	16±3	0.0022±0.0009	0.0024	$E1$

[a] See reference 25.
[b] Because the 196.9 and 197.9-kev gamma rays were unresolved in the photoelectric conversion spectra, the sum of their gamma-ray intensities, and a combined K-shell internal conversion coefficient, $[I_{eK}(196.9)+I_{eK}(197.9)]/[I_\gamma(196.9)+I_\gamma(197.9)]$, are listed. From the latter, and from the relative K-shell internal conversion electron intensities of the two transitions a lower limit of 0.26 follows for the K-shell internal conversion coefficient of the 196.9-kev transition, independent of the multipole order of the 197.9-kev transition. If the 197.9-kev transition has pure $E2$ character, the K-shell internal conversion coefficient of the 196.9-kev transition is 0.46±0.16.

appear at the positions of the 186.7, 370.7, and 557.2-kev gamma rays, and a weaker peak, about one fourth as intense, at the position of the 294.6-kev gamma ray. An examination of the branching ratios of the low-lying levels of Os^{190} (see Fig. 1) shows that approximately equal intensities for the 186.7, 370.7, and 557.2-kev transitions can arise only from excitation of level D (557.2 kev). If the possibility of contributions from the neighboring gamma rays with energies of 196.9, 361.0, and 568.6 kev is considered—although the energy calibration of the coincidence spectrum should have been sufficient to distinguish a sizeable contribution of any of these—the same conclusion is reached, that the excitation of no other known level would give rise to a combination of these three pairs of gamma

TABLE III. Energies and relative intensities of higher energy gamma rays of Ir^{190} determined from measurements with a 2 in.×3 in. NaI detector. The upper limits on the experimental K-shell internal conversion coefficients are calculated from the relative gamma ray intensities and the results of Table I with the assumption of a pure $E2$ internal conversion coefficient for the 557.2-kev transition. Experimental internal conversion coefficients are compared with theoretical values from the tables of Sliv and Band.[a]

Energy (kev)	$(I/I_{557})\times100$	K-shell internal conversion coefficient Experimental	Theoretical	Multipole order
1020±10	10±2.5	<0.0020	0.0016	$E1$
			0.0039	$E2$
1150±15	3.2±1	<0.0058	0.0013	$E1$
			0.0031	$E2$
			0.0066	$E3$
			0.0067	$M1$
1330±15	1.9±0.6	<0.0067	0.0010	$E1$
			0.0024	$E2$
			0.0048	$E3$
			0.0046	$M1$
1430±15	0.9±0.3	<0.0092	0.00087	$E1$
			0.0021	$E2$
			0.0041	$E3$
			0.0074	$E4$
			0.0038	$M1$
			0.0090	$M2$

[a] See reference 25.

rays having the same ratio of intensities. The direct feeding of level D by the 827-kev transition is therefore assumed, which requires the placing of a new level at 1384 kev (level I). The placement of the 294.6-kev transition between level I and the previously established level L (1679 kev)[11] follows immediately from their energy difference and from the present coincidence results.

Establishment of Levels J and N

The spectra coincident with the 1020 and 1330-kev gamma rays are similar to one another in appearance. They both contain only two peaks, of approximately equal intensity, at the positions of the 186.7 and 361.0-kev gamma rays. Clearly this situation can arise only

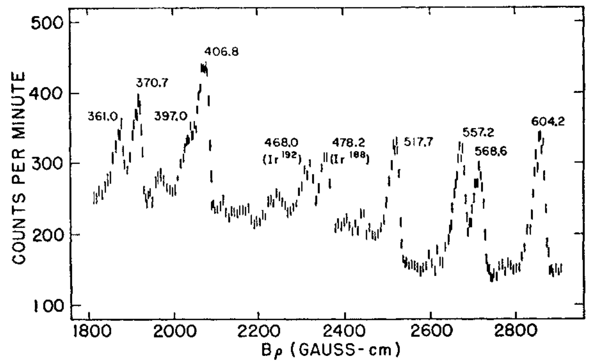

FIG. 5. Photoelectric conversion spectrum of the gamma rays of Ir^{190} and other iridium isotopes. An 8.3-mg/cm² thorium converter foil was used for these measurements. Source produced by deuteron bombardment of osmium.

if both the 1020 and 1330-kev transitions excite directly level C (547.7 kev). This requires the placing of new levels at 1568 (level J) and 1876 kev (level N).

Search for Positrons

Coincidence techniques were also employed in a search for positrons emitted in the decay of Ir^{190}. A search was made for 511-kev annihilation quanta emitted at 180° with respect to one another from a source of Ir^{190} enclosed in copper. The results were negative, yielding an upper limit of 2×10^{-5} on any positron branching in the decay of Ir^{190}.

DISCUSSION

Electromagnetic Transitions

The level scheme of Os^{190}, established from this and previous work, and the electromagnetic transitions

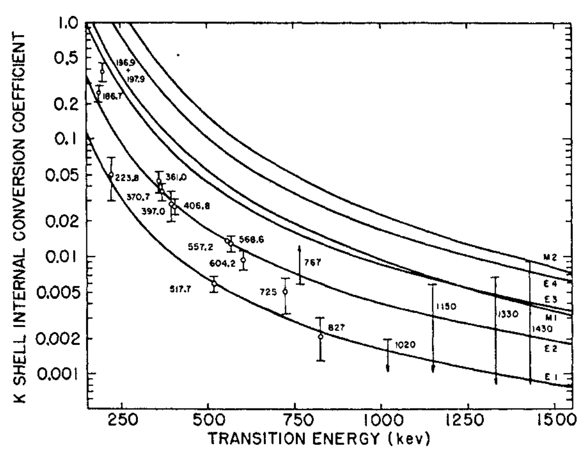

FIG. 6. A comparison of experimentally determined K-shell internal conversion coefficients with the theoretical values of Sliv and Band (see reference 25). In order to calculate internal conversion coefficients from the relative intensities of internal conversion electrons and the relative intensities of gamma rays the theoretical $E2$ value (see reference 25) of 0.0138 was assumed for the K-shell internal conversion coefficient of the 557.2-kev transition.

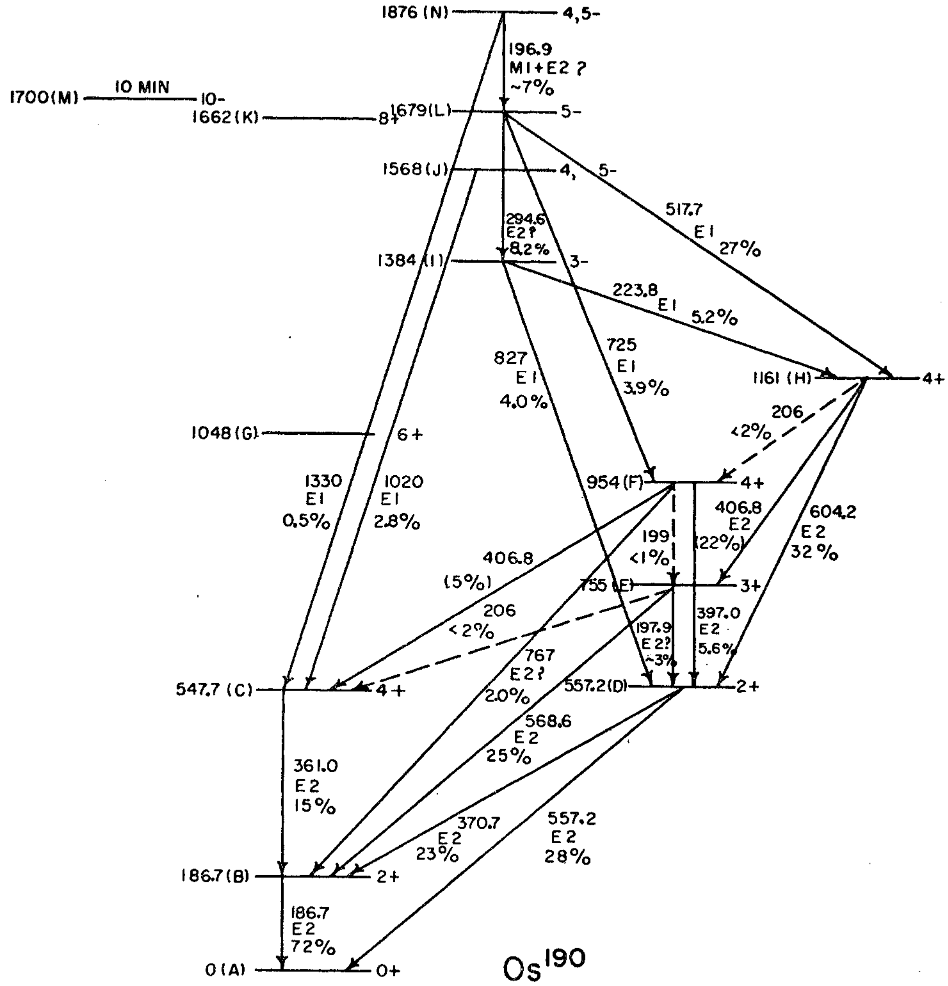

FIG. 7. Proposed level scheme for Os^{190}. Only the electromagnetic transitions excited in the decay of 12 day Ir^{190} are shown. In order to facilitate subsequent discussion each level is given a letter designation.

excited in the decay of 12 day Ir^{190} are shown in Fig. 7. The relative intensities given for the transitions represent transitions per decay of Ir^{190}, in percent, provided that there are no electron capture decays of Ir^{190} to the ground state of Os^{190}. On the basis of the present work the ground state of Ir^{190} appears to have odd parity and a spin of 4, justifying this assumption.

Confirmation of Previous Work

The properties of the energy levels established in previous work, i.e., levels B and C of the ground state rotational band which are also populated in the decay of 10 minute Os^{190m},[6] as well as levels D, E, F, H, and L, which are known from the work of Nielsen *et al.*,[11] are confirmed in the present work. The various energy sums which may be formed from the measured transition energies, the transition intensities, and the internal conversion coefficients which have been determined, are all consistent with previous results.

Placement of 725 and 767-kev Transitions

Two additional transitions have been fitted into the already established level scheme on the basis of the agreement of their measured energies with the energy differences of established levels. The 725-kev transition proceeds from level L (1679 kev) to level F (954 kev). Its measured internal conversion coefficient has large limits of error, as the transition is rather weak, but is closest to the theoretical value for an electric dipole transition. This is consistent with odd parity for level L as postulated by Nielsen *et al.*[11] because of the $E1$ character of the 517.7-kev transition (LH). The 767-kev transition has been placed between levels F and B. Only a lower limit was placed on its internal conversion coefficient, as the gamma ray was not observed in the photoelectric conversion spectrum. This limit, however, suffices to rule out an $E1$ assignment, and is compatible with $E2$ character for the transition.

*The Energy Difference between the 407-*kev *Transitions HE and FC.*

The existence of two transitions with approximately 407-kev energy was postulated by Nielsen *et al.*[11] on the basis of coincidence measurements. They obtained intensities of 19% for transition *HE* and 4.6% for transition *FC*. Only a single line, corresponding to a 406.8-kev transition, was observed in our internal conversion spectrum. This is shown in Fig. 4. The single *K* internal conversion line observed had a breadth of 0.25%, so that the energy difference of the two transitions cannot exceed 0.7 kev provided that the weaker one has at least the indicated intensity. As no new information was obtained on the relative intensities of the two 407-kev transitions, Nielsen's apportioning of the total intensity between the two transitions has been adopted, i.e., of a combined intensity of 27%, 22% has been assigned to the transition between the levels *H* and *E*, and 5% to the transition between levels *F* and *C*.

*Placement of the 206-*kev *transition*

On the basis of the energy differences between established levels there are two possible locations for a 206-kev transition—between levels *H* and *F* and between levels *E* and *C*. Ordinarily a choice between these two possibilities would be furnished by precise values for the energies of the 206-kev transition and of levels *C*, *E*, *F*, and *H*. The precision of the measurement of the energy of the 206-kev transition is limited, however, by its low intensity and the presence in Os^{189} of a transition of similar energy. In addition, the precision with which the energies of levels *C*, *E*, *F*, and *H* are known is limited by the fact that the two 407-kev transitions discussed above, which are so far unresolved, are associated with these levels. The placement of the 206-kev transition either between levels *H* and F or between levels *E* and *C* is, therefore, consistent with the results of the present work. An intensity of approximately 2% for this transition, provided it is *E*2 in character, is indicated by the *K*-shell internal conversion intensity.

*Properties and Placement of the 196.9- and 197.9-*kev *Transitions*

In the work of the Copenhagen group[11] it was suggested on the basis of coincidence measurements that the internal conversion electron group corresponding to a transition energy of 196 kev might arise from more than one transition. In the present work (see Table I) two *K*-shell internal conversion lines from Ir^{190} were observed, with relative intensities of 19 and 2.5, corresponding to transitions of 196.9 and 197.9 kev, respectively. These are shown in Fig. 4. The *L*-shell internal conversion lines of these two transitions were incompletely resolved from the *M*-shell internal conversion lines of the 186.7-kev transition, so that a straightforward measurement of their *K/L* ratios was not possible. However, a combined *K/L* ratio, $[I\epsilon_K(196.9)+I\epsilon_K(197.9)]/[I\epsilon_L(196.9)+I\epsilon_L(197.9)]$ of $4.8_{-2.0}^{+12}$ was calculated for the two transitions by assuming an $(M+N+O)/L$ ratio of 0.32 for the 186.7-kev transition. The latter value for the $(M+N+O)/L$ ratio was adopted from the survey of Listengarten,[26] where this ratio is shown to be fairly constant over a wide range of energies, atomic numbers, and transition multipole orders. In the course of the present work the same value 0.32, was obtained for the $(M+N+O)/L$ ratio for the strong 244.8-kev transition in Os^{189}. The combined *K/L* ratio of 4.8 suggests the existence of a substantial *M*1 or *E*1 admixture in at least one of the two transitions, as the corresponding theoretical *E*2, *M*2, *E*1, and *M*1 *K/L* ratios are 1.28, 3.81, 5.96, and 6.02, respectively. Similarly, the value for the combined *K*-shell internal conversion coefficient, $[I\epsilon_K(196.9)+I\epsilon_K(197.9)]/[I_\gamma(196.9)+I_\gamma(197.9)]$, for the two transitions (see Table II) falls roughly midway between the *E*2 and *M*1 values, and also between the *E*1 and *M*2 values. This result and the relative *K*-shell internal conversion electron intensities of the two transitions give a lower limit of 0.26 for the *K*-shell internal conversion coefficient of the 196.9-kev transition, considerably in excess of the pure *E*2 value of 0.177. Thus the 196.9-kev transition would appear to have mixed $M1+E2$ or alternatively, $E1+M2$ character. The results furnish essentially no information concerning the character of the 197.9-kev transition.

Evidently either the 196.9 or the 197.9-kev transition should be placed in the level scheme between levels *E* and *D*. As their 1-kev separation is comparable in magnitude to the errors in the energy differences of other transitions to and from levels *E* and *D*, these energy differences do not decide unambiguously which transition should be placed there. The 197.9-kev transition is favored, however, for the energy difference of the 568.6 (*EB*) and 370.7 (*DB*) kev transitions is 197.9 kev, and of the 604.2 (*HD*) and 406.8 (*HE*) kev transitions—197.4 kev. Furthermore, it appears more reasonable to place the 197.9-kev transition, for which *E*2 character is possible, in the low-energy region of the level scheme in preference to the 196.9-kev transition, which has been shown not to have pure *E*2 character, since all measured *K/L* ratios, and *K*-shell internal conversion coefficients of other transitions from levels below that at 1384 kev are consistent with pure *E*2 character. The 197.9-kev transition has therefore been placed in the level scheme between levels *E* and *D*.

Placement of the 196.9-kev transition between Level *L* (1679 kev) and level *N* (1976 kev), whose existence is required by the coincidence of the 1330, 361.0, and 186.7-kev gamma rays, is suggested both by the energy sums and by the coincidence results by Nielsen *et al.*[11] The latter require that the weaker of the 196.9 and

[26] M. A. Listengarten, Izvest. Akad. Nauk (S.S.S.R.) Ser. Fiz. **22**, 759 (1958) [translation: Bull. Acad. Sciences (U.S.S.R.) **22**, 755 (1958)].

197.9-kev transitions proceed from level E to level D, and the stronger feed level H. While the 196.9-kev transition does not proceed directly to level H in the present level scheme, it nevertheless excites it in the majority of instances via the strong transition LH and the LI–IH cascade.

Upper Limit on Transition FE

The possible existence of a 199-kev transition between levels F and E of Os^{190} is of interest, as a measurement of its intensity would enable a comparison to be made of the reduced transition probabilities of transitions from level F to levels E and D, respectively. The existence of a 199-kev transition in the decay of Ir^{189}, however, permitted only an upper limit of 1% to be set on the intensity of such a transition in the decay of Ir^{190}.

Upper Limits on Transitions HB and HC

Other transitions which were not observed are the possible 974 and 613-kev transitions from level H to the levels B and C of the ground-state rotational band. Upper limits of 1 and 2%, respectively, are set on the intensities of these transitions.

Properties of Transition LI

Coincidence measurements establishing level I and placing transitions LI and ID in the level scheme have already been discussed. Study of transition LI (294.6 kev) is hindered by the presence of the 295.9-kev transition of Ir^{192}, and by the 233-kev transition of Ir^{189}, whose L-shell internal conversion electrons coincide closely in energy with the K-shell internal conversion electrons of the 294.6-kev transition. An internal conversion coefficient for this transition was, therefore, not obtained. An indirect measurement of its K/L ratio was carried out by measuring the K-shell internal conversion intensities of both the 294.6- and 295.9-kev transitions and the total intensity of their incompletely resolved L-shell internal conversion electrons, and then making use of the known K/L ratio of the 295.9-kev transition.[27] The contribution of the L-shell electrons of the 233-kev transition of Ir^{189} required a small additional correction. The resulting K/L ratio, 2.4 ± 0.9, is consistent with the $E2$ value, 2.27, but does not exclude a small $M1$ admixture.

Transition IH

A transition with 223.8-kev energy has been placed between the levels I and H. Its measured internal conversion coefficient is consistent with $E1$ character.

[27] V. M. Kelman, R. Ya. Metskhvavishvili, V. A. Romanov, and V. V. Tukhkevich, Nuclear Phys. 4, 240 (1957); J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 588 (1957) [translation: Soviet Phys.-JETP 6, 455 (1958)].

Transitions Associated with Level I

While the energy sums which may be formed from the transitions associated with level I and their multipole orders testify to the essential correctness of this portion of the level scheme, an inconsistency appears in the gamma-ray spectrum coincident with the 827-kev gamma ray (ID). According to the transition intensities shown in Fig. 7 level I is excited almost exclusively by transition LI (294.6 kev), and hence the 294.6-kev gamma ray should be in almost 100% coincidence with the 827-kev gamma ray (ID) or approximately twice as intense in the coincidence spectrum as each of the 186.7, 370.7, and 557.2-kev gamma rays. In fact, however, it is only about one fourth as intense in the coincidence spectrum as each of these gamma rays. A hypothesis which contradicts none of the experimental evidence is that there exist other, so far undetected, transitions from level I. Transitions with energies of 430, (IF), 629 (IE), 836 (IC), and 1197 kev (IB) are possible. As these would be $E1$ transitions, and thus have small internal conversion coefficients, they might escape detection in the internal conversion spectra. Furthermore, a 629-kev transition would have been masked by the strong 633-kev transition of Ir^{188}. Upper limits of 5, 10, 1, and 1%, respectively, are set on the intensities of possible 430 (IF), 629 (IE), 836 (IC), and 1197 (IB) kev transitions.

A further argument for the possible existence of additional transitions from level I may be proposed on the basis of electron capture transition probabilities. Although level I has odd parity and a spin of 2 or 3, the existing balance of intensities of transitions to and from it indicates only a week ($1\pm2\%$) excitation in the electron capture decay of Ir^{190}, and gives a resulting high log ft value (≥ 8.4). Any further transitions from this level would correspond to a higher electron capture probability and a correspondingly lower log ft value.

The low intensity of the 296-kev peak in coincidence with the 827-kev gamma ray would also result if the lifetime of level I were comparable to the resolving time of the coincidence circuit (2×10^{-7} sec), for then only a fraction, depending on the lifetime, of the 294.6-kev gamma rays would be registered, while the coincidence pattern of the 186.7, 370.7, and 557.2-kev gamma rays would remain unchanged.

Spins and Parities of Energy Levels

Previous Results

Previous studies[6] of the 10 minute isomer of Os^{190} have shown the isomeric level (M) to have odd parity and a spin of 10, and the members of the ground-state rotational band (levels A, B, C, G, and K) to form a 0+, 2+, 4+, 6+, and 8+ sequence of levels. Coulomb excitation experiments[8,9] have demonstrated the 2+ nature of level D. The multipole orders of a number of transitions excited in the decay of 12 day Ir^{190} were

determined from measured K/L ratios and studies of coincidences of gamma rays with internal conversion electrons.[11] These results require that levels E, F, and H have even parity, and level L have odd parity.

Spins and Parities Permitted by Measured Multipole Orders of Transitions

On the basis of the present results little can be added concerning the spins of levels above 557 kev without invoking arguments involving transition probabilities or the predictions of a specific model. The $E2$ nature of transitions FD, EF, HD, and HE serves only to restrict the spins of levels E, F, and H to values from 0 to 4 and to require even parity. The multipole orders of transitions ED, FB, and FC associated with these levels have not been definitely established. On the basis of the $E1$ character of transitions ID and JC, level I must have a spin of 1, 2, or 3 and odd parity and level J 3, 4, or 5 and odd parity. Similarly, spins of 0 to 5 and odd parity are required for level L and spins of 1 to 6 for level N.

Level N and Transition NC

However, if relative transition probabilities are considered, probable spins may be assigned to the levels. While the upper limit on the internal conversion coefficient of transition NC (1330 kev) is consistent with $E1$, $E2$, $E3$, or $M1$ character, three of these possibilities may be eliminated at once. Level N evidently has odd parity, for in common with level L, known to have odd parity, it is strongly fed in the electron capture decay of Ir^{190}. Transition NL(196.9 kev) between these two levels must then be a mixed $M1+E2$ transition for its internal conversion coefficient and K/L ratio are consistent with either $M1+E2$ or $E1+M2$ character. Transition NC to the even parity level at 547.7 kev cannot then have $M1$ or $E2$ character, owing to the opposite parities of the initial and final levels. If transition NC had $E3$ character an $E1$ transition to another member of the ground state band could compete with it. Such an $E1$ transition may be suppressed due to K forbiddenness, but in this instance if level N had a high value of K, a transition to level $D(K=2)$ or other levels above it would be favored. Evidence for excitation of level D, it will be recalled, was not observed in the spectrum of gamma rays in coincidence with the 1330-kev gamma ray (ND or NC). Transition NC is therefore assumed to have $E1$ character, restricting the possible values of the spin of level N to 3, 4, or 5. The absence of a competing 1690-kev transition (NB), on the intensity of which an upper limit of 0.1% is set, eliminates a spin of 3 for level N. The $M1+E2$ character or transition NL then restricts the possible spins of level L to 3, 4, or 5.

Transitions from Levels E and F

Ground-state transitions from levels E and F were not observed. Upper limits of 2 and 1% are set on their respective intensities. These may be compared with intensity sums of 28 and 13%, respectively for all other transitions from the two levels. While there exist even-even nuclei (Pt^{196}, for example) for which ground state transitions from levels with spin 2 and even parity are highly retarded relative to cascade transitions, these are few in number. Spins of 1 or 2 for levels E and F therefore appear rather unlikely. The spin of level E is therefore tentatively restricted to the values 0, 3, or 4, and the spin of level F to 3 or 4, for in the latter case the existence of $E1$ transition LF from level L (spin 3, 4, or 5) rules out a spin of 0.

Spins of Levels E, F, H, and L

Upper limits of 1% are set on the intensities of possible 924 and 1122 kev $E1$ transitions from level L to levels E and D. No transition with 924-kev energy was observed. (An 1150-kev transition with an intensity of slightly less than 1% remains unassigned in the level scheme.) On the other hand, lower energy $E1$ transitions with intensities of 3.9 and 27% arise from level L. A spin of 4 or 5 is, therefore, required for this level. This eliminates the possibility of zero spin for level E, for the two levels are connected by a two-step cascade of $E1$ and $E2$ transitions. The absence of a direct transition between the two levels then eliminates a spin of 4 for either level, requiring that the spin of level E be 3 and that of level L 5. The $E1$ character of transitions LF and LH then fixes the spins of both levels F and H, as 4.

Properties of Level I

Transitions from level I to levels A and B, which would have energies of 1384 and 1197 kev, respectively, were not observed. Upper limits of 0.25 and 0.5%, respectively, are set on the intensities of these two transitions. The choice of spins for level I is thus restricted to 2 or 3, taking into consideration the possibility that an $E1$ transition to level B might be K forbidden. The $E1$ character of transition IH then allows only a spin of 3 for level I. The transition between the 5− level L and the 3− level I must then have pure $E2$ character, which is compatible with the measured K/L ratio (see Table I).

The absence of $E1$ transitions from the 3− level I to the 2+ and 4+ levels B and C of the ground-state rotational band may be evidence that $K\geq 2$ for this level.

Possible Spins for Level J

Finally, the absence of a 1381-kev transition from level J to level B, on the intensity of which an upper limit of 0.25% is set, allows only spins of 4 or 5 for level J.

Nature of Level H

It should be noted that these arguments regarding the spins of the various levels are independent of any

TABLE IV. Electron capture transitions of Ir^{190} for an assumed decay energy of 1950 kev.

	Level (kev)	Spin	Percent branching to level	Log ft
B	(186.7)	2+	7±5	8.9
C	(547.7)	4+	7±3	8.7
D	(557.2)	2+	6±4	8.8
E	(755)	3+	6±5[a]	8.5
F	(954[a])	4+	7±4	8.5
H	(1161)	4+	24±5	7.7
I	(1384)	3−	1±2	8.8, ≥8.4
J	(1568)	4 or 5−	3±1	8.0
L	(1679)	5−	32±4	6.6
N	(1876)	4 or 5−	7±2	6.2

[a] Percent branching to level calculated with the inclusion of the 206-kev transition between levels H and F.

assumptions concerning the relative intensities of transitions from level H, as its nature remains uncertain. The spin of 4 arrived at for this level does not in itself forbid $E2$ transitions to the second and third members of the ground state rotational band (levels B and C). Sheline[28] has pointed out that the level H might have the character of a two-phonon vibration, in which case transitions to levels of the ground-state rotational band would be forbidden. Alternatively, if this level had intrinsic character, with $K\geq 3$, these transitions would be K forbidden.

The conclusions of these arguments are summarized in the level scheme shown in Fig. 7. Their significance with respect to nuclear models is discussed in a later section.

Decay of Ir^{190} and Re^{190}

Ir^{190}

The electron capture intensities for the decay of Ir^{190} to the various levels of Os^{190} are shown in Table IV. Log ft values have been calculated for an assumed decay energy of 1950 kev. Evidently allowed electron capture transitions excite the odd parity levels L (5−) and N (4 or 5−) in Os^{190}. The ground state of Ir^{190} must therefore have odd parity and a spin of 4, 5, or 6. Level H (4+) is also heavily excited, however, so that a spin of 6 for Ir^{190} appears to be ruled out. Furthermore, the sum of the intensities of electron capture transitions to levels B (2+), C(4+), and D (3+) totals (20±7)%, while the positron branching ratio may be used to set a corresponding upper limit of 8% on the sum of these same transition intensities if Ir^{190} has odd parity and a spin of 5 (see the next section and Table V). The ground state of Ir^{190} must therefore have odd parity and a spin of 4.

Re^{190}

The level scheme established here appears sufficient to account for the observed properties of the beta decay of 2.8 minute Re^{190} to Os^{190}. Aten and DeFeyfer[29] reported an end-point energy of 1.7 Mev for the continuous beta spectrum, and gamma rays of 191, 392, 569, and 830-kev energy, the first three being approximately equal in intensity and the last about one third as intense. The semiempirical mass formulas of Cameron[30] and Levy,[31] whose predictions fall above and below the known values for the decay energies of Re^{186} and Re^{188}, respectively, give 3.1 and 2.7 Mev for the decay energy of Re^{190}. The trend of these decay energies is illustrated in Fig. 8. If the highest energy group in the beta spectrum of Re^{190} excites level I (1384 kev) of Os^{190}, the decay energy is 3.1 Mev, it if excites level H (1161 kev), it is 2.9 Mev. Excitation of level I would account for the appearance of the 830-kev gamma ray (transition ID), and would also produce three unresolved multiplets of gamma rays with average energies approximating the reported energies of 191, 392, and 569 kev, and with intensities $1\frac{1}{2}$ to 3 times that of the 830-kev gamma ray. The possible existence of additional, as yet undetected transitions from level I, discussed earlier, would increase the intensities of the three multiplets somewhat relative to the 830-kev gamma ray. The excitation of level H or the other odd parity levels produces relatively little additional 827-kev gamma radiation. Thus the principal branch of the Re^{190} beta decay must proceed to level I. A branching ratio of 50% for the beta decay of Re^{190} to level I of Os^{190} and a decay energy of 3.0 Mev give a log ft value of 5.3. Evidently this is an allowed transition, requiring the ground state of Re^{190} to have odd parity and a spin of 2, 3, or 4 if the 3− assignment of level I is correct.

Positron Branching Ratio

Limits on High-Energy Electron Capture Branching

The upper limit of 2×10^{-5} set on positron branching in the decay of Ir^{190} may be used both to place upper limits on the intensities of electron capture transitions to low-lying states of Os^{190}, as a test of the correctness

TABLE V. A comparison of experimentally determined intensities of electron capture transitions of Ir^{190} to low-lying levels of Os^{190} with upper limits calculated from the measured upper limit on the positron branching ratio. Intensities are expressed in percent of total transitions.

	Level	Measured intensity	Upper limit on intensity for indicated spin of Ir^{190}			
			2−	3−	4−	5−
A	(0)	⋯	0.6	⋯	⋯	⋯
B	(186.7)	7±5	0.6	0.6	1.4	⋯
C	(547.7)	7±3	54	8	8	8
D	(557.2)	6±4	9	9	31	⋯

[28] R. K. Sheline, Revs. Modern Phys. 32, 1 (1960).

[29] A. H. W. Aten. Jr., and G. D. DeFeyfer, Physica 21, 543 (1955).

[30] A. G. W. Cameron, Chalk River Project Report CRP-690, March 1957, Atomic Energy of Canada, Limited (unpublished).

[31] H. B. Levy, University of California Radiation Laboratory Report UCRL 4713 (July 1956, University of California (unpublished).

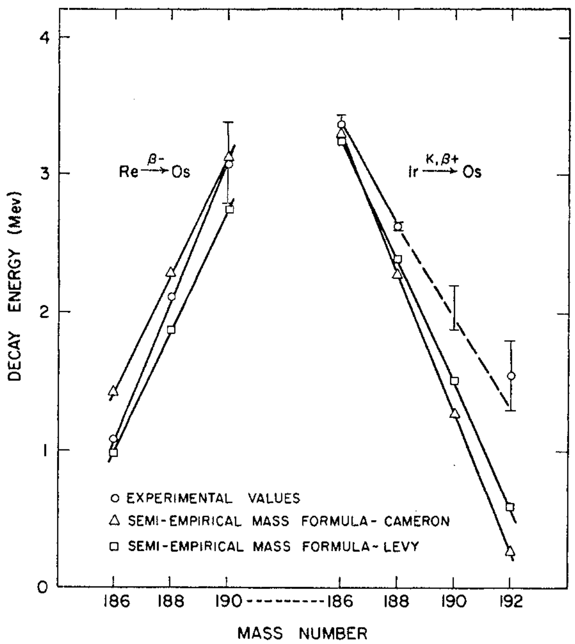

FIG. 8. A comparison of the decay energies of nuclides decaying to the even osmium isotopes with values predicted by the semi-empirical mass formulas of Cameron (see reference 30) and Levy (see reference 31). Experimental decay energies were arrived at from the following sources: Re^{186}; F. T. Porter, M. S. Freedman, T. B. Novey, and F. Wagner, Jr., Phys. Rev. **103**, 921 (1956), $E_{\beta-(\max)}=1.0715\pm0.0013$ Mev. Re^{188}; M. W. Johns, C. C. McMullen, I. R. Williams, and S. V. Nablo, Can. J. Phys. **34**, 69 (1956), $E_{\beta-(\max)}=2.116\pm0.002$ Mev. Re^{190}; (see reference 29), $E_{\beta-(\max)}=1.7\pm0.3$ Mev. The highest energy beta group is assumed to proceed to the 1.384-Mev level of Os^{190}. Ir^{186}; G. Scharff-Goldhaber, D. E. Alburger, and M. McKeown (unpublished), $E_{\beta+(\max)}=1.92\pm0.05$ Mev. The highest energy positron group is assumed to proceed to the 0.434-Mev level of Os^{186}. Ir^{188}; G. Scharff-Goldhaber, D. E. Alburger, and M. McKeown (unpublished), $E_{\beta+(\max)}=1.450\pm0.030$ Mev. The highest energy positron group is assumed to proceed to the 0.155-Mev level of Os^{188}. Ir^{190}; The energy of the uppermost level of Os^{190} excited in the decay of Ir^{190}, at 1.876 Mev, is adopted as a lower limit on the decay energy of Ir^{190}. The upper limit of 2×10^{-5} determined for the positron branching in the decay of Ir^{190} yields an upper limit of 2.2 Mev on the decay energy. Ir^{192}; A value of $Q_{K,\beta+}(Ir^{192})=1.54\pm0.25$ Mev for the $Ir^{192}\rightarrow Os^{192}$ disintegration energy has been calculated from the known disintegration energy of the $Ir^{192}\rightarrow Pt^{192}$ beta decay and the measured masses of Pt^{192} and Os^{192} as follows:

$$Q_{K,\beta+}(Ir^{192})=Q_{\beta-}(Ir^{192})+[M(Pt^{192})-M(Os^{192})]c^2,$$

using the following data: *Nuclear Data Sheets*, compiled by K. Way, F. Everling, G. H. Fuller, N. B. Gore, R. Levesque, J. B. Marion, C. L. McGinnis, and M. Yamada, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C., 1959). $Q_{\beta-}(Ir^{192})=1.453\pm0.005$ Mev; R. A. Demirkhanov, T. I. Gutkin, and V. V. Dorokhov, J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 1217 (1959) [translation: Soviet Phys.-JETP **10**, 866 (1960)], $M(Pt^{192})=192.022561\pm0.000225$ amu, $M(Os^{192})=192.022470\pm0.000160$ amu. A value of 1.95 Mev for the $Ir^{192}\rightarrow Os^{192}$ disintegration energy, based on the discovery of a $1.5\times10^{-5}\%$ positron branch in the decay of Ir^{192} for which $E_{\beta+}=0.240\pm0.010$ Mev, has recently been proposed by S. F. Antonova, S. S. Vasilienko, M. G. Kagansky, and D. L. Kaminsky, J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 379 (1960). This value for the disintegration energy rests, however, on the assumption of 5− spin and parity for the ground state of Ir^{192}, which would require that the positron decay proceed to the 3+ level at 0.691 Mev in Os^{192}. However, the spin of the ground state of Ir^{192} has been shown to be 4 on the basis of studies of the branching ratios of the beta decay of the 1.45 minute isomer of Ir^{192} by G. Scharff-Goldhaber and M. McKeown, Phys. Rev. Letters **3**, 47 (1959), and earlier work on the branching of the beta decay of the ground state of Ir^{192} (see *Nuclear Data Sheets*, cited above). The positron decay of Ir^{192} would then be expected to proceed to the 2+ level of Os^{192} at 0.206 Mev, giving a total disintegration energy: $Q_{K,\beta+}(Ir^{192})=1.468\pm0.010$ Mev, in close agreement with the value arrived at above. *Note added in proof*.—Recent studies by the authors of coincidences of the gamma rays and internal conversion electrons of Ir^{186} with high energy positrons indicate that the predominant positron branch in the decay of Ir^{186} proceeds to the 0.869-Mev level of Os^{186}, rather than to the 0.434-Mev level, as assumed earlier. The total disintegration energy should therefore be 3.81 Mev rather than the 3.37 Mev indicated in Fig. 8.

of the decay scheme, and to place an upper limit on the decay energy of Ir^{190}. On the basis of a large body of experimental evidence the $K/\beta+$ branching ratio for nonunique first forbidden transitions has been shown to fall 30 to 60% above the predictions of Zweifel[32] for allowed transitions and the $K/\beta+$ ratio for unique first forbidden transitions to be close to the value for allowed transitions multiplied by the factor $2(W_0+1)/(W_0-1)$, where W_0 is the maximum positron energy, in units of m_0c^2, including the rest mass.[33] This branching ratio was estimated for transitions to the ground state and levels B, C, and D of Os^{190} for an assumed total disintegration energy of 1950 kev and odd parity and spin 2, 3, 4, or 5 for the ground state of Ir^{190}. The predicted value for an allowed transition was multiplied by a factor of 2 for nonunique first forbidden transitions and by the factor $2(W_0+1)/(W_0-1)$ for unique first forbidden transitions. The values obtained for the $K/\beta+$ branching ratio were combined with the measured upper limit on the positron branching ratio to give the upper limits on electron capture intensities shown in Table V. These serve chiefly to confirm the result that none of the first three excited states of Os^{190} are strongly excited by electron capture transitions. Evidently the large relative error associated with subtracting the intensities of several strong electromagnetic transitions to arrive at a small electron capture transition intensity is responsible for the fact that the electron capture intensity to the 186.7-kev level derived from the measured gamma ray and internal conversion intensities exceeds the upper limit established from the measured positron branching.

Total Disintegration Energy

In order to place an upper limit on the decay energy of Ir^{190}, $K/\beta+$ branching ratios were also calculated for an assumed total disintegration energy of 2200 kev. These gave the result that for this decay energy electron capture transitions to any of the first three excited levels, the sum of whose intensities exceeded 3%, would give rise to a positron branching ratio greater than the experimental upper limit. While the individual electron capture intensities derived for transitions to these levels are small, and subject to large relative errors, certain of

[32] P. F. Zweifel, Phys. Rev. **107**, 329 (1957).

[33] J. Konijn. B. van Nooijen, H. L. Hagedorn, and A. H. Wapstra, Nuclear Phys. **9**, 296 (1958).

these errors drop out in taking their sum, giving a total intensity for electron capture transitions to the three levels of $(20\pm7)\%$. The total disintegration energy of Ir^{190} is therefore deemed to lie between the energy of the uppermost level excited in Os^{190} at 1876 kev and an upper limit of 2200 kev.

The lower limit of 1876 kev on the decay energy of Ir^{190} is considerably higher than that predicted by the semiempirical mass formulas of Cameron[30] (1259 kev) and of Levy[31] (1500 kev). This is shown in Fig. 8, where the experimentally determined decay energies of Ir^{186}, Ir^{188}, Ir^{190}, and Ir^{192} are compared with the predictions of Cameron and Levy. The experimental and predicted decay energies are seen to diverge with increasing mass number, their difference approaching 1 Mev for Ir^{192}. The necessity for sizeable corrections to the semiempirical mass law, in order to take into account contributions arising from the nuclear deformation, has already been pointed out by several authors.[34,35] From this point of view the large discrepancy observed in the present instance between experimental and predicted decay energies may possibly arise from the rapid change of the nuclear deformation with neutron number in this region.

Comparison with Nuclear Models

Deviations from the Strong Coupling Model

Interest in the even isotopes of osmium arises from the fact that they may be expected to exhibit properties intermediate[1,28] between those of the highly deformed nuclei in the strong coupling region $(152\lesssim A\lesssim 182)$ and the spherical nuclei in the near-harmonic region $(192\lesssim A\lesssim 208)$. The deviation of nuclear properties from those predicted by the strong coupling model is found to be large for Os^{190}. The experimental evidence for this which has already been cited is as follows:

1. The levels of the ground-state rotational band not only do not have an $I(I+1)$ dependence of their energy on the spin, but are also not fitted[1,6] by the addition of a correction term[2] arising from the rotation-vibration interaction, proportional to $-I^2(I+1)^2$.
2. A direct measurement of the lifetimes of the second and first excited states of the ground state rotational band[7] gives a ratio of reduced transition probabilities for the $E2$ transitions from these two levels of $0.44_{-0.19}^{+0.55}$, while the strong coupling model predicts a value of 1.43.[2]
3. Coulomb excitation measurements[9] give a value of $9.5_{-1.8}^{+2.9}$ for the ratio of reduced transition probabilities for the $E2$ transitions from the second 2+ state at 557.2 kev to the first excited state and ground state, respectively (the results of the present work give a value of 6.3 ± 1.0) while the strong coupling model predicts a value of 1.43.[2]
4. The K-selection rule appears to be somewhat relaxed with respect to the 38.4 kev $M2$ isomeric transition in Os^{190} (hindrance factor 2.6×10^{-9})[6] as compared with K-forbidden transitions in the highly deformed Hf^{178} [36] and Hf^{180} [37] (hindrance factors 2.6×10^{-14} and 10^{-16}, respectively) while for all three transitions $\nu=\Delta K-L=8$.

The relative intensities determined here for transitions FC and FB (with the inclusion of the data of Nielsen *et al.*[11])afford still one more example of this. If level F is indeed the third member of a gamma vibrational band, as suggested by Nielsen, *et al.* with $I=4$ and $K=2$, then the strong coupling model predicts a ratio of reduced transition probabilities of 2.94 for these transitions, while the experimental ratio is 59 (see Table VII). It is also noteworthy that the ratio of the energy differences between the levels F and D, and levels E and D, respectively, is 2.01, while the strong coupling model predicts the value of 2.33 for the spin sequence 2, 3, 4 in a rotational band, neglecting the rotation-vibration interaction. However, a lowering of the energy of level F might be expected to arise from a repulsion of this level and the neighboring level H, which probably has the same spin and parity.

Comparison with the Asymmetric Rotor Model

It is thus evident that the energy levels of Os^{190} cannot be interpreted in terms of the strong coupling model. Recently Davydov and Filippov[38] have pointed out that in several respects Os^{190} bears out the predictions of the asymmetric rotor model, in which the equilibrium nuclear shape is assumed to be a triaxial ellipsoid. Davydov and Filippov,[38] and Davydov and Rostovsky,[39] on the basis of this model, have calculated the relative positions of even parity levels with spins from 2 to 8 and the relative reduced transition probabilities for electric quadrupole transitions between certain of these levels as functions of γ, the parameter which describes the degree of axial asymmetry of the nucleus. These authors and others[40,41] have compared the predictions of the model with existing experimental results for Os^{190} and other nuclei. The new data obtained in the present work permit a more detailed comparison. Following the method introduced by Mallman and Kerman,[40] we approximate the energy of the nth rotational level with spin I by

$$E_b({}^nI,\gamma,\beta)=A(\beta)\epsilon({}^nI,\gamma)-bA(\beta)[\epsilon({}^nI,\gamma)]^2,$$

[34] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Revs. Modern Phys. **29**, 547 (1957).
[35] F. S. Mozer, Phys. Rev. **116**, 970 (1959).
[36] F. Felber, University of California Radiation Laboratory Report UCRL-3618, 1956 (unpublished); M. Bunker and J. Mize, 1956 (private communication).
[37] G. Scharff-Goldhaber, M. McKeown and J. W. Milhelich, Bull. Am. Phys. Soc. **1**, 206 (1956).
[38] A. S. Davydov and C. F. Filippov, Nuclear Phys. **8**, 237 (1958).
[39] A. S. Davydov and V. S. Rostovsky, Nuclear Phys. **12**, 58 (1959).
[40] C. A. Mallmann and A. K. Kerman, Nuclear Phys. **16**, 105 (1960).
[41] G. R. DeMille, T. M. Kavanaugh, R. B. Moore, R. S. Weaver, and W. White, Can. J. Phys. **37**, 1036 (1959).

where the first term is the energy predicted for the level by the asymmetric rotor model in the absence of the rotation-vibration interaction, and the second term is introduced to correct for the rotation-vibration interaction.

In this expression β is the customary parameter describing the quadrupole deformation of the nucleus and $A(\beta)$ is the function which, for an axially symmetric nucleus, gives the rotational energy of a level with spin I $[E_{rot}=\frac{2}{3}A(\beta)I(I+1)]$ in the absence of the rotation-vibration interaction. The effect of the departure from axial symmetry upon the energies of the rotational levels is contained in the function $\epsilon(^nI,\gamma)$. The quantity b introduced in the second term is an adjustable parameter which should have the same value for all values of the spin.

A comparison of the predicted and experimentally determined level energies of a given nucleus is simplified by taking the ratios of the energies of the various levels ^nI to the energy of the first 2+ state, for these ratios of energies do not depend on β. These ratios are approximated by

$$R_b(^nI)=R_0(^nI)+b\epsilon(^nI,\gamma)[1-R_0(^nI)],$$

where the first term, $R_0(^nI)$, is the corresponding ratio in the absence of a rotation-vibration interaction. The parameters γ and b are then chosen to give the best fit to the ratios of the experimentally determined level energies.

For Os^{190}, these energy ratios were calculated for assumed values of $\gamma=22.2°$ and $b=3.7\times10^{-4}$, which appear to give the best agreement between the predicted and experimentally determined energies of the levels of ground-state rotational band and the second 2+ level. They are presented in Table VI, along with the corresponding ratios of measured energies. The values for the levels of the ground-state rotational band, the second 2+ level, and the 3+ level are seen to be in close agreement, but the energy of the second 4+ level is seen to fall below the energy predicted by the theory by approximately 8%, and the energy of the third 4+ level falls below the theoretically predicted level energy by nearly a factor of 2. While the small deviation of the energy of the second 4+ level (F) might, as observed previously, be attributed to a repulsion of this level and level H, the energy of the third 4+ level (H) clearly does not fit the predictions of the asymmetric rotor model. The ^{34} level predicted by the asymmetric rotor model, it will be noted, would not be expected to appear in the decay of 12 day Ir^{190} for its predicted energy lies in the vicinity of 2 Mev.

Reduced transition probabilities were calculated for certain transitions from the results of Davydov *et al.*[38,39] for the same value of γ. Ratios of these are compared in Table VII with corresponding experimental ratios, and with the predictions of the strong coupling model where they can be made. Evidently the experimental results for transitions from the 2+, 3+, and 4+ levels

TABLE VI. A comparison of the measured energies of the levels of Os^{190} with those predicted by the asymmetric rotor model. The energies are expressed as the ratio of the energy of a given level, ^nI, to that of the first 2+ level. In the calculation of these ratios from the asymmetric rotor model the method of reference 40 has been followed. The energy of the nth rotational level with spin I is approximated by

$$E_b(^nI,\gamma,\beta)=A(\beta)\epsilon(^nI,\gamma)-bA(\beta)[\epsilon(^nI,\gamma)]^2,$$

where the first term is the energy predicted for the level by the asymmetric rotor model in the absence of the rotation-vibration interaction, and the second term is introduced to correct for the rotation-vibration interaction.
In this expression β is the customary parameter describing the quadrupole deformation of the nucleus and $A(\beta)$ is the function which, for an axially symmetric nucleus, gives the rotational energy of a level with spin I $[E_{rot}=\frac{2}{3}A(\beta)I(I+1)]$ in the absence of the rotation-vibration interaction. The effect of the departure from axial symmetry upon the energies of the rotational levels is contained in the function $\epsilon(^nI,\gamma)$. The quantity b introduced in the second term is an adjustable parameter which should have the same value for all values of the spin.
The ratio of the energy of a given level ^nI to that of the first 2+ state may be written as

$$R_b(^nI)=R_0(^nI)+b\epsilon(^nI,\gamma)[1-R_0(^nI)],$$

where $R_0(^nI)$ is the corresponding ratio in the absence of a rotation-vibration interaction. Energy ratios were calculated from the above expression with the choice of values of 22.2° for the asymmetry parameter γ and 3.7×10^{-4} for the rotation-vibration interaction parameter b. These values of γ and b appear to give the best agreement of the predicted and measured ratios of the energies of the ^{14}, ^{16}, ^{18}, and ^{22} levels to the energy of the ^{12} level.

Level (^nI)	$E(^nI)$	$R(^nI)=E(^nI)/E(^12)$ Experimental	Theory
$B(^12)$	186.66±0.1	1	1
$D(^22)$	557.2 ±0.5	2.985±0.003	2.990
$E(3)$	755.1 ±1.0	4.045±0.006	3.969
$C(^14)$	547.7 ±0.5	2.934±0.003	2.983
$F(^24)$	954.2 ±1.0	5.112±0.006	5.538
$H(^34)$	1161 ±1.0	6.220±0.007	10.83
$G(^16)$	1048 ±2	5.614±0.011	5.655
$K(^18)$	1662 ±3	8.904±0.018	8.96

D, E, and F agree more closely with the predictions of the asymmetric rotor model than with the predictions of the strong coupling model. There is a disagreement of nearly a factor of 10, however, between the predictions of the model and experiment for the ratio of reduced transition probabilities of transitions HE and HD from the third 4+ level H. Both the energy of this level and the relative intensities of transitions from it thus fail to fit the predictions of the asymmetric rotor model, suggesting either another origin for this level or a deficiency of the model. If the observed 205.9-kev transition is placed at either of its two possible locations in the level scheme, between levels H and F, or between levels E and C, in either case the ratio of the reduced transition probability of the 205.9-kev transition to that of the other transition proceeding from the same level will be substantially larger than the corresponding ratio predicted by the asymmetric rotor model (see Table VII). In view of the deviation of the properties of level H from those predicted for the third 4+ level in the asymmetric rotor model, it would appear to be more probable origin for this transition.

TABLE VII. A comparison of experimental ratios of reduced transition probabilities with values prediced by the strong coupling model[a] and the asymmetric rotor model[b] (for $\gamma=22.2^0$).[c]

Level	Transitions and energies		Level designations: Strong coupling	Level designations: Asymmetric rotor	Ratio of reduced transition probabilities: Strong coupling	Ratio of reduced transition probabilities: Asymmetric rotor	Ratio of reduced transition probabilities: Experimental
$D(557.2)$	DB/DA	370.7/557.2	$(2,2)\to(0,2)/(2,2)\to(0,0)$	$({}^{2}2\to{}^{1}2)/({}^{2}2\to 0)$	1.43	8.52	6.3 ± 1.0
$E(755)$	ED/EB	197.9/568.6	$(2,3)\to(2,2)/(2,3)\to(0,2)$	$(3\to{}^{2}2)/(3\to{}^{1}2)$	...	14.9	23 ± 6
	EC/EB	206/568.6	$(2,3)\to(0,4)/(2,3)\to(0,2)$	$(3\to{}^{1}4)/(3\to{}^{1}2)$	0.40	5.29	≤12.5[d]
$F(954)$	FD/FB	397.0/767	$(2,4)\to(2,2)/(2,4)\to(0,2)$	$({}^{2}4\to{}^{2}2)/({}^{2}4\to{}^{1}2)$	...	57.4	74 ± 32
	FC/FB	406.8/767	$(2,4)\to(0,4)/(2,4)\to(0,2)$	$({}^{2}4\to{}^{1}4)/({}^{2}4\to{}^{1}2)$	2.94	43.5	59 ± 49
	FE/FD	199/397.0	$(2,4)\to(2,3)/(2,4)\to(2,2)$	$({}^{2}4\to 3)/({}^{2}4\to{}^{2}2)$	2.24	1.58	≤5.7
	FE/FC	199/406.8	$(2,4)\to(2,3)/(2,4)\to(0,4)$	$({}^{2}4\to 3)/({}^{2}4\to{}^{1}4)$	...	2.08	≤7.2
	FE/FB	199/767	$(2,4)\to(2,3)/(2,4)\to(0,2)$	$({}^{2}4\to 3)/({}^{2}4\to{}^{1}2)$	...	90.7	≤422
$H(1161)$[c]	HB/HD	974/604.2	$(4,4)\to(0,2)/(4,4)\to(2,2)$	$({}^{3}4\to{}^{1}2)/({}^{2}4\to{}^{2}2)$	...	0.00694	≤0.029
	HE/HD	406.8/604.2	$(4,4)\to(2,3)/(4,4)\to(2,2)$	$({}^{3}4\to 3)/({}^{3}4\to{}^{2}2)$	0.56	0.674	5.1 ± 1.1
	HF/HD	206/604.2	$(4,4)\to(2,4)/(4,4)\to(2,2)$	$({}^{3}4\to{}^{2}4)/({}^{3}4\to{}^{2}2)$	0.196	0.449	≤13.5[d]
$D(557.2)$ $B(186.7)$	DA/BA	557.2/186.7	$(2,2)\to(0,0)/(0,2)\to(0,0)$	$({}^{2}2\to 0)/({}^{1}2\to 0)$	...	0.0667	(0.053 ± 0.012)[e]
$C(547.7)$ $B(186.7)$	CB/BA	361.0/186.7	$(0,4)\to(0,2)/(0,2)\to(0,0)$	$({}^{1}4\to{}^{1}2)/({}^{1}2\to 0)$	1.43	1.44	$(0.44^{+0.55}_{-0.19})$[f]

[a] See reference 2. [b] See reference 39.
[c] A value of $K=4$ has been assumed for the 4+ level H (1161 kev) for the calculation of transition probabilities in the strong coupling model. For the calculation of transition probabilities in the asymmetric rotor model it is assumed to be the ${}^{3}4$ level.
[d] As there are two possible locations in the level scheme for the 206-kev transition, ratios of reduced transition probabilities have been calculated in each case for the entire intensity of the transition and indicated as upper limits. If only one of the two possible 206-kev transitions exists, then the corresponding value in the table represents the actual ratio of reduced transition probabilities.
[e] See reference 9. [f] See reference 7.

On the basis of the present results the asymmetric rotor model appears to be highly successful in describing the properties of the even parity levels of Os^{190}—with the exception of level H. On the other hand, the energy levels of Os^{188} (with the exception of the first and second 2+ levels, and the first 4+ level, which are also predicted by the strong coupling model) appear to bear little relationship to the asymmetric rotor model. In particular, the two 0+ levels of Os^{188} at 1086 and 1765 kev[42] are not predicted by this model. However, it should be recognized that in any process, such as the radioactive decay of a parent nuclide or a particle reaction, only certain of the existing energy levels of a nucleus will ordinarily be excited, owing to the operation of selection rules. The level scheme of Os^{188} has been established chiefly from studies of the decay of Re^{188}, which has a spin of 1, and of Ir^{188}, which probably also has a low spin. Studies of Os^{190}, on the other hand, have involved Ir^{190}, with a probable spin of 4, Re^{190}, with a spin of 2, 3, or 4, and 10 minute Os^{190m} and 3 hour Ir^{190m}, with still higher spins. Therefore, the nonappearance of high-spin levels predicted by the asymmetric rotor model for Os^{188} should not be viewed as a failure of the model, and conversely, the possible existence of additional levels of Os^{190} with low spins (particularly 0+ levels) is not precluded by work done up to this time.

The ratio of the reduced transition probabilities for the transitions from the first 4+ and 2+ levels[7] remains in disagreement with both the strong coupling and asymmetric rotor models.

In view of the comparative success of the asymmetric rotor model, we have investigated whether it is possible to describe the observed odd-parity levels also as part of a rotational spectrum of an asymmetric rotor.

When the nuclear wave function is described as a product of particle, vibrational, and rotational wave functions, the total wave function must be invariant under certain symmetry operations.[43] For the ground state rotational band of an even-even nucleus, the symmetry of the particle and vibrational wave functions is such that the rotational wave function belongs to the symmetry class A.[44] Nuclear octupole vibrations about an axially symmetric equilibrium shape belong to symmetry class B, which requires that the rotational part of the wave function for such states be also of symmetry class B. And for excited particle states of an even-even nucleus, or for an odd-odd nucleus, the particle structure may have either a class A or a class B symmetry. The rotational wave functions must then have symmetry A or B, respectively. For axial symmetry and $K=0$ the levels belonging to class A have spins, 0, 2, 4, . . . , and those belonging to class B have spins 1, 3, 5, ... An example of this difference in the symmetry of the particle structure is apparently seen in the odd-odd nucleus Ho^{166}.[45] The ground state spin and parity is 0−, and the low-lying states at 54 kev (2−) and 82 kev (1−), both of which seem to have $K=0$, are interpreted as members of the ground state rotational bands. It therefore seems that the residual

[42] I. Marklund, B. van Nooijen, and Z. Grabowski, Nuclear Phys. **15**, 533 (1960).

[43] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat. fys.-Medd. **26**, No. 24 (1952).

[44] L. D. Landau and E. M. Lifschitz, *Quantum Mechanics, Nonrelativistic Theory* (Addison-Wesley, Publishing Company, Inc., Reading, Massachusetts. 1958), Sec. 101.

[45] J. S. Geiger, R. L. Graham, and G. T. Ewan, Bull. Am. Phys. Soc. **5**, 255 (1960); R. G. Helmer and S. B. Burson, Phys. Rev. **119**, 788 (1960).

interactions between the odd particles depress the levels of class A relative to those of class B in Ho^{166}.

It is the asymmetric rotor levels of class A which have been calculated by Davydov and Filippov. We have calculated the levels of class B to see whether they fit the odd-parity levels of Os^{190} observed in our work (levels I, J, L, and N). With the assumption of the probable spins attributed to these levels it was not possible to reproduce their relative positions. If level L were to have spin 4, however, rather than the spin 5 tentatively attributed to it, then the positions of the levels could be fitted with a β and γ somewhat different from the Davydov-Filippov β and γ for the ground state band. But then the relative transition probabilities, which are also predicted by the model, did not agree with the observed pattern of transitions between these levels. Neither could the relative spacing of the odd-parity levels of W^{182} be fitted by the model.

While the asymmetric rotor model of Davydov and Filippov agrees, in general, well with the data on the lower energy levels, there is a plausible reason why this simple model might not work as well for rotations based on excited particle or vibrational states. In the latter case there are near-lying particle states which can perturb the level structure and wave functions, while at least the lower members of the ground state rotational band are well separated in energy from states with different particle configurations which might be admixed.

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