of the pairing energy with the j value of the individual nucleons in the pair. In many cases, the common j value for the individual nucleons in the pair is the same as the j value for the preceding odd nucleon. In other cases, the pairing may take place in a higher j value level. This is possible if one follows the assumption of Mayer and Jensen[13] that the pairing energy increases as the j value of the pairing particles increases. In certain circumstances, it would thus be energetically favorable to pair in a high j-value state. Mayer and Jensen have indicated a possible ordering of shell model states in this region. From this ordering, one can determine the j value in which each pair is formed. Attempts have been made to correlate P_n values either to the j value of the odd neutron or to the j value given by the Mayer-Jensen scheme. In neither case are consistent correlations apparent.

[13] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, Inc., New York, 1955).

Proton pairing energies are plotted in Fig. 9 as a function of Z. Values with a common neutron number are connected by a straight line. A decrease in the proton pairing energy is noted for values of Z beyond $Z=50$. This change was indicated in the neutron pairing energy at $N=50$ in the previous paper. Over-all correlation to either the j value of the pair or to the j value from the scheme of Mayer and Jensen is poor. The decrease from $Z=50$ to 52 corresponds to a j value decrease. This may indicate that the relationship between pairing energy and j value is good only near a shell closure.

ACKNOWLEDGMENTS

The authors wish to thank Professor A. O. C. Nier for his continued support and encouragement of this work. We wish to acknowledge the aid of J. L. Benson who helped to make some of the measurements. We are also indebted to R. B. Thorness for his aid in design and construction of the mass spectrometer.

PHYSICAL REVIEW VOLUME 132, NUMBER 4 15 NOVEMBER 1963

Properties of Radioactive Re^{189}†

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(Received 3 April 1963; revised manuscript received 19 July 1963)

The new isotope Re^{189} has been produced by fast-neutron irradiation of osmium and by the (α,p) reaction on tungsten. The rhenium was separated chemically from the target material. Beta-ray, gamma-ray, and internal conversion spectra have been measured. The mass assignment is confirmed by the observation of eleven electromagnetic transitions in the Os^{189} daughter, including the 30.8-keV isomeric transition (6h), all of which were known from the decay of Ir^{189}. Rhenium-189 has a half-life of 23.4 ± 1.0 h and emits beta-ray groups with end-point energies 1000, 780, and 725 keV, and probably others. Results of coincidence measurements lead to some new information about the level scheme of Os^{189}. The effects of the expected rotation-particle coupling between low-lying $K=1/2$ and $K=3/2$ bands in Os^{189} are discussed.

I. INTRODUCTION

A CONSIDERABLE number of activities have been tentatively assigned to the isotope Re^{189} in the course of the last several years, but little definite information about this nucleus and its decay has been available. We have conducted experiments leading to the production and identification of this isotope and have studied its decay to levels in Os^{189}.

Previously existing knowledge of some features of the level structure of Os^{189} has been helpful in the identification of Re^{189}. In turn, the results of this work add to the available information about the level scheme of Os^{189}. The decay of Ir^{189} to Os^{189} has been studied by Diamond and Hollander,[1] by Kane,[2] and recently, by Harmatz, Handley, and Mihelich,[3] and by Lerohl.[4] An isomer of Os^{189}, decaying by $M3$ radiation to the ground state, was characterized by Scharff-Goldhaber, Alburger, Harbottle, and McKeown[5] and further investigated by Newton.[6] At least two low-lying levels of Os^{189} have been studied in Coulomb excitation experi-

† Supported by the U. S. Atomic Energy Commission and by the National Science Foundation.

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[1] R. M. Diamond and J. M. Hollander, Nucl. Phys. 8, 143 (1958).

[2] W. R. Kane, thesis, Department of Physics, Harvard University, Cambridge, Massachusetts [Technical Report 3-9,1959 (unpublished)].

[3] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 128, 1186 (1962); referred to as HHM.

[4] J. K. Lerohl, thesis, Ohio State University, Columbus, Ohio, 1962 (unpublished).

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

[6] J. O. Newton, Phys. Rev. 117, 1529 (1960).

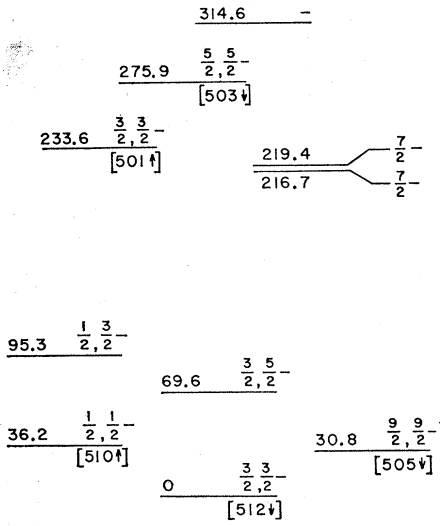

FIG. 1. Levels in Os^{189}. The level scheme, the K quantum numbers, angular momenta, and parities (given as K, I, π), and the intrinsic state assignments $[Nn_z\Lambda\Sigma]$ are those deduced by Harmatz, Handley, and Mihelich from their work on the decay of Ir^{189} and from the work of previous investigators. Energies are in keV.

ments by Rester, Moore, Durham, and Class[7] and by McGowan, Robinson, Stelson, and Ford.[8] A level diagram, adapted from Harmatz, Handley, and Mihelich, is shown in Fig. 1.

To complete the introduction, we briefly review previous reports on Re^{189} and indicate their most likely interpretation in the light of present knowledge. In 1950, Lindner and Coleman[9] searched for products of double neutron capture in rhenium that had been irradiated in a reactor. Two previously unknown activities were encountered, with half-lives $\sim$150 day and $\geq$5 yr.[10] Beta end-point energies of 0.2 and 0.75 MeV, respectively, were determined by aluminum absorption measurements. It was assumed that one of the two activities probably was due to Re^{189}. At present, however, it appears likely that the $\sim$150-day half-life belonged to electron-capturing 165-day Re^{184}, produced through the reaction $Re^{185}(n,2n)$, and that the electron spectrum consisted of conversion electrons. The longer half-life observed by Lindner remains unexplained.

Turner and Morgan[11] analyzed worn tungsten exit strips from the Berkeley 60-in. cyclotron. The rhenium fraction contained a 50-day activity, ascribed to Re^{184}, and a 155-day activity with a complex beta spectrum, as determined by aluminum absorption. It was assumed that the latter activity consisted of a mixture of Re^{183} (at that time believed to have a half-life of 120–140 days) and a 250–300-day activity assigned to Re^{189}. This isotope was thought to have been produced by the reaction $W^{186}(\alpha,p)$; 1.0-MeV gamma rays and a beta spectrum with an end-point energy of 0.16 MeV were observed. Turner and Morgan assumed that they had prepared the same 240-day rhenium isotope that had been found by Wilkinson and Hicks[12] in cyclotron exit strips and at first erroneously assigned to Re^{183}. Actually, since Wilkinson and Hicks obtained their 240-day activity also from alpha bombardments of tantalum, it could not have been due to an isotope of mass 189 and remains unassigned at present. Most probably, Turner and Morgan were dealing with the two isomers of Re^{184}, of half-lives 34 day and 165 day.

A half-life of $\geq$25 years has been found by Johnson in reactor irradiated natural rhenium.[13] This activity may have resulted from double neutron capture by Re^{187}, and may be the same long-lived activity that had been obtained by Lindner.[10]

Possible double-neutron capture by Re^{187}, leading to the formation of Re^{189}, has been carefully studied by Smith,[14] who irradiated rhenium for 16 days in the high thermal flux (1.80×10^{14} n/cm^2 sec) of the Materials Testing Reactor at Arco, Idaho. Ninety days after irradiation, no counts above background could be observed from the sample, leading to the conclusion that either (1) the thermal-neutron capture cross section of Re^{188} is less than 2 b, while it would be expected to be of the order of 10^3 b, or (2) the half-life of Re^{189} is shorter than 5 days or longer than 100 years, so that the decay of this isotope would have escaped detection under the circumstances of the experiment.

Short half-lives also have been ascribed to Re^{189}. Butement[15] has suggested that a 17-min rhenium activity produced with 23-MeV bremsstrahlung on osmium may be due to Re^{189} or Re^{191} from a (γ,p) reaction. Very probably, he was dealing with 19-min Re^{188m}, discovered soon afterward.[16] Aten and de Feyfer[17] obtained a 9.75-min rhenium activity by bombardment of osmium with fast neutrons from 26-MeV deuterons on brass, and assigned this half-life to mass number 189, 190, or 192. It is now clear that they produced 10-min Re^{191} through the reaction $Os^{192}(n,pn)$.

Beta systematics make a long half-life unlikely for Re^{189}. The ground-state spin and parity of this nucleus are expected to be 5/2+, in analogy with Re^{183}, Re^{185}, and Re^{187}. The ground state of Os^{189} has spin 3/2 and odd parity. The beta decay of Re^{189} is, therefore, pre-

[7] D. H. Rester, M. S. Moore, F. E. Durham, and C. M. Class, Nucl. Phys. **22**, 104 (1961).
[8] F. K. McGowan, P. H. Stelson, and R. L. Robinson, in *Electromagnetic Lifetimes and Properties of Nuclear States*, edited by P. H. Stelson, Nuclear Science Ser. Report No. 37, National Academy of Sciences, National Research Council, Publ. 974 (1962), p. 119. F. K. McGowan, R. L. Robinson, P. H. Stelson, and J. L. C. Ford, Bull. Am. Phys. Soc. **8**, 548 (1963).
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[13] N. R. Johnson, Phys. Rev. **129**, 1737 (1963).
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[16] J. W. Mihelich, Phys. Rev. **89**, 907 (1953); A. Flammersfeld, Naturforschung **8a**, 217 (1953).
[17] A. H. W. Aten, Jr., and G. D. de Feyfer, Physica **19**, 1143 (1953).

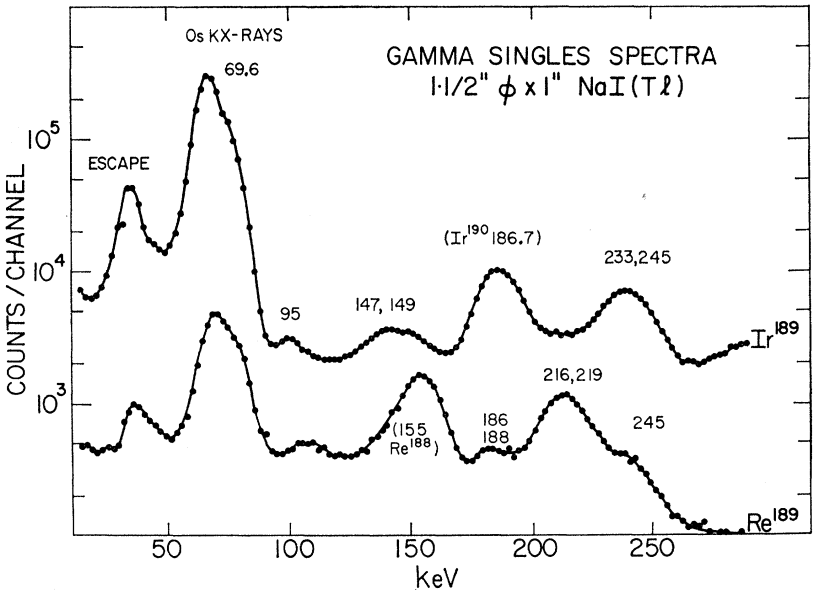

FIG. 2. The scintillation gamma-ray spectrum of Re^{189} (lower curve) is compared with that of Ir^{189} (upper curve). Contaminants of Re^{188} and Ir^{190} were present, and their contributions are labeled.

sumably first-forbidden, with an expected logft of 7 ± 1. The decay energy predicted by Way and Wood and by Yamada and Matumoto is approximately 1.0 MeV.[18] Hence, a half-life of a few hours to a few days is expected.[19,20]

II. SOURCE PREPARATION

Samples of Re^{189} were first produced[21] by irradiation of osmium metal[22] with neutrons from the bombardment of beryllium with the 20-MeV deuteron beam of the Brookhaven 60-in. cyclotron, leading to the reactions $Os^{189}(n,p)Re^{189}$ and $Os^{190}(n,pn)Re^{189}$. The target material was taken up in concentrated nitric acid, rhenium carrier was added, and the solution was evaporated to dryness to drive off osmium as the tetroxide. The process was repeated several times, and the final residue, dissolved in hydrochloric acid, was transferred to Mylar foil and evaporated for counting.

Stronger rhenium sources, suitable for electron spectrometry, were produced by the bombardment of tungsten with alpha particles, through the reaction $W^{186}(\alpha,p)Re^{189}$. Stacked foil tests showed that the desired reaction is entirely suppressed by (α,pn) when the alpha-particle energy exceeds 30 MeV, but that a fair (α,p) yield is obtained for 20 MeV$\leq E_\alpha \leq$30 MeV. Thin (0.002-in.) tungsten foils,[23] covered with aluminum absorbers, were bombarded with the external alpha-particle beam of the 60-in. cyclotron, and a copper probe to which a 0.005-in. tungsten target foil had been hard soldered[24] was exposed to the internal beam.

In a platinum crucible, the tungsten targets were dissolved in hydrofluoric acid and a small quantity of nitric acid, to which rhenium and osmium carriers had been added. The solution was evaporated to dryness. Nitric acid and more osmium carrier were added and the solution was boiled to dryness again, more thoroughly to drive off osmium activities. The residue, primarily WO_3, was dissolved in 6N KOH, and tungstic acid was precipitated with HCl. After centrifuging, the supernatant was decanted, made strongly acidic with HCl, and then Re_2S_7 was precipitated with H_2S. The centrifuged precipitate was washed with distilled water and dissolved in 1M NaOH. After removal of insoluble hydroxides by repeated precipitation of $Fe(OH)_3$, Re_2S_7 was reprecipitated with H_2S from strong HCl. Alternatively, the first Re_2S_7 precipitate was washed and taken up in a drop of H_2O_2 to form perrhenic acid. Rhenium was then electroplated from a solution of perrhenic acid in 0.1N HCl onto thin gold-plated copper foils, for measurements in the beta-ray spectrometer.

III. IDENTIFICATION AND HALF-LIFE OF RHENIUM-189

The identification of the isotope is based on the combination of modes of production, specific rhenium

[18] K. Way and M. Wood, Phys. Rev. 94, 119 (1954); M. Yamada and Z. Matumoto, J. Phys. Soc. Japan 16, 1497 (1961).

[19] We are indebted to Dr. C. L. McGinnis for first pointing out this argument to us.

[20] A recent publication by Blichert-Toft [P. Blichert-Toft, Phys. Letters 3, 130 (1962)] again raises the possibility of a long-lived Re^{189}. If such an activity exists it is presumably an isomer of very high spin.

[21] B. Crasemann, G. T. Emery, and W. R. Kane, Bull. Am. Phys. Soc. 7, 353 (1962).

[22] Spectroscopically pure osmium sponge from Johnson, Matthey and Company, Ltd., London, England.

[23] Obtained from the Varlacoid Chemical Company, New York, New York.

[24] We are indebted to Dr. J. Bigeleisen for performing this operation for us.

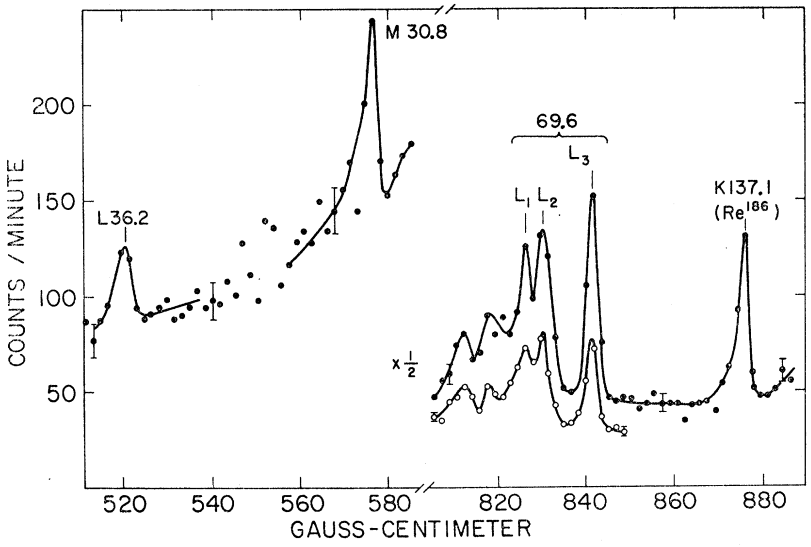

FIG. 3. Low-energy sections of internal conversion-electron spectrum of Re^{189}. Open circles represent counts obtained 25 h after counts shown by dots.

chemistry performed on the targets, and the gamma scintillation spectrum (Fig. 2). The identity of Re^{189} is confirmed by the observation, discussed below, of conversion electrons from many of the electromagnetic transitions in Os^{189} known from previous studies[1-3] of the decay of Ir^{189}.

The identification[21] of 23-h Re^{189} has been confirmed by Baró and Flegenheimer,[25] who produced the activity by the irradiation of Os with fast neutrons, and by the reaction $Os^{192}(d,\alpha n)Re^{189}$.

The half-life was determined by integrating areas under the 217- and 219-keV gamma-ray peaks in scintillation spectra that were recorded at intervals over periods of approximately five days each, using sources from three different bombardments (one Os+n, two W+α). The result obtained for the half-life of Re^{189} is 23.4±1.0 h.

IV. INTERNAL CONVERSION-ELECTRON SPECTRUM

The conversion-electron spectrum was measured with a double-focusing spectrometer[26] at 0.4% resolution. Electroplated sources from two different bombardments were employed. Lines from Re^{182}, Re^{183}, Re^{186}, Re^{188}, and Os^{183} were also observed. Spectra were recorded repeatedly, and the characteristic half-life was used in cases of doubt to identify lines that belong to Re^{189}. The only competing activity with a comparable half-life was 17-h Re^{188}, whose decay properties are well known.

The detector was a flow counter with a 580-$\mu g/cm^2$ window. The primary energy calibration of the spectrometer was based on the lines of the thorium active deposit and of Cs^{137}. As secondary standards, well known conversion lines of Re^{183},[27] Re^{186},[26,28] and Re^{188} [28,29] were used.

Sections of conversion-electron spectra are shown in Figs. 3, 4, and 5. Line shapes were obtained from several of the most intense and clearly resolved lines in various parts of the spectrum, and line-shape parameters as functions of magnetic rigidity were calculated. These semiempirical line shapes were fitted to all peaks. Relative conversion-electron intensities were calculated from the areas under the peaks, corrected for source decay and for counter-window absorption.[30] The results of the analysis are summarized in Table I.

V. ELECTRON-ELECTRON COINCIDENCES

The level scheme of Fig. 1, derived largely by analysis of sums and differences of transition energies found in Ir^{189} decay, is ambiguous in that there are two possible places for the 245.0-keV transition (314.6 −69.6=245.0 and 275.9−30.8=245.1 keV). To help resolve this ambiguity, coincidences were sought, with a source of Ir^{189}, between internal conversion electrons from the 245.0- and 69.6-keV transitions. The measurement was made with a magnetic lens coincidence spectrometer,[31] using plastic scintillators as detectors. The fast-slow coincidence circuit had a resolving time of 40 nsec. The result was negative (0±4% of 245-keV transitions were found to be in coincidence with 70-keV

[25] G. B. Baró and J. Flegenheimer, Radiochimica Acta **1**, 2 (1962).
[26] G. T. Emery, W. R. Kane, M. McKeown, M. L. Perlman, and G. Scharff-Goldhaber, Phys. Rev. **129**, 2597 (1963).
[27] J. J. Murray, F. Boehm, P. Marmier, and J. W. M. DuMond, Phys. Rev. **97**, 1007 (1955); see also Ref. 3 and references given there.
[28] B. Lindström and I. Marklund, Nucl. Phys. **40**, 329 (1963).
[29] R. L. Graham, J. S. Geiger, R. A. Naumann, and J. M. Prospero, Can. J. Phys. **40**, 296 (1962).
[30] D. Saxon, Phys. Rev. **81**, 639 (1951).
[31] T. R. Gerholm, Rev. Sci. Instr. **26**, 1069 (1955).

TABLE I. Internal conversion electrons from Re^{189}.

Electron energy (keV)	Shell	Relative intensity[a]	Transition energy (keV)	Mean transition energy (keV)	Subshell ratios
27.79±0.05	M_I	178±40	30.84±0.05		
28.33±0.06	M_{III}	550±60	30.79±0.06	30.82±0.04	$M_I:M_{III}=(0.32\pm0.05):1.00$[b]
23.25±0.04	L_I	360±70	36.22±0.04	36.22±0.04	
56.72±0.07	L_I	367±20	69.69±0.07		
57.20±0.07	L_{II}	470±20	69.58±0.07		
58.71±0.07	L_{III}	465±10	69.58±0.07		
66.50±0.14	M_I	52±20	69.55±0.14		
66.80±0.14	M_{II}	108±15	69.59±0.14		
67.10±0.14	M_{III}	115±15	69.56±0.14	69.59±0.05	$L_I:L_{II}:L_{III}=(0.79\pm0.05):(1.01\pm0.05):(1.00)$[c]
82.2 ±0.3	L_I	63±30	95.2 ±0.3		
84.36±0.15	L_{III}	32±24	95.23±0.15	95.23±0.15	
73.19±0.15	K	217±36	147.06±0.15	147.06±0.15	
76.01±0.15	K	72±30	149.88±0.15	149.88±0.15	
112.05±0.20	K	194±25	185.92±0.20		$K/L_I=5.2_{-1.8}^{+3.9}$
172.83±0.20	L_I	37±13	185.80±0.20	185.86±0.15	$L_I/L_{II,III}>1$
114.49±0.10	K	85±22	188.36±0.10	188.36±0.10	
	K	236±244[d]			
203.86±0.10	L_I	36±19	216.83±0.10	216.83±0.10	
145.54±0.10	K	71±16	219.41±0.10	219.41±0.10	
171.16±0.20	K	53±18	245.03±0.20	245.03±0.20	

[a] Corrected for decay and counter-window absorption.
[b] Newton (Ref. 6) found a value of 0.21:1 for the $M_I:M_{III}$ ratio, and an energy of 30.81 ±0.03 keV for this transition.
[c] For this transition the L-subshell ratios of Ref. 2 [(0.53±0.06):(1.05±0.06):1.00] and Ref. 3 [0.63:1.06:1.00] have a somewhat lower relative L_I intensity than is found here. This discrepancy could be explained if the 59.1-keV transition known in Ir^{189} decay were also present in Re^{189} decay; its M-conversion lines would be unresolved from L_I 69.6 and its L-conversion lines would have been obscured in this work by conversion lines of the 46.5-keV transition following Re^{188} decay.
[d] This line hidden under Re^{188} $L_{I,II}$ 155.0.

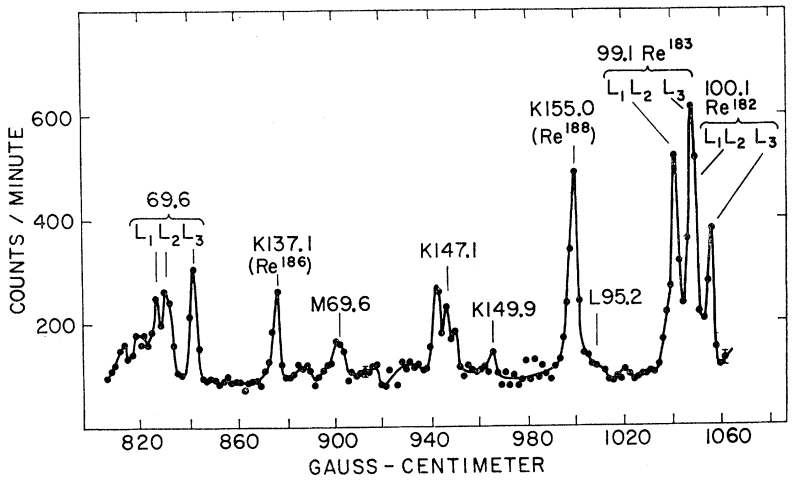

FIG. 4. Section of internal conversion-electron spectrum of Re^{189} and other isotopes produced concurrently.

transitions), indicating that this suggestive energy-sum relation is accidental.[32]

VI. BETA SPECTRUM

The continuous beta spectrum from a number of rhenium sources was measured with an anthracene scintillation crystal (1 in. diam×½ in.) and a 256-channel pulse-height analyzer. The energy scale was determined by measurement of the conversion-electron lines of Cs^{137} and Bi^{207}. For comparison, the beta spectrum of P^{32} was measured under identical conditions. The P^{32} Fermi plot was straight, within statistics, from the end point (1.71 MeV) down to approximately 600 keV. Below this energy, excess counts appeared, due to the escape of scattered electrons.

A typical Fermi plot of the data from a rhenium source is shown in Fig. 6. When the 2-MeV Re^{188} spectrum was subtracted, it became apparent that the Re^{189} beta particles extend to a maximum energyof 1.00±0.05 MeV. Further analysis of these data is not warranted.

[32] In Ref. 3, it was estimated (on the basis of intensities deduced from internal conversion spectrograph measurements with film recording) that the 245.0-keV transition was about five times as intense as the 30.8-keV transition, and, thus, most of the 245.0-keV transitions were assumed to de-excite the 314.6-keV level. The transition intensities of Ref. 2, however, based on conversion lines counted in a double-focusing spectrometer, are completely consistent with all of the 245.0-keV transitions feeding the 30.8-keV level.

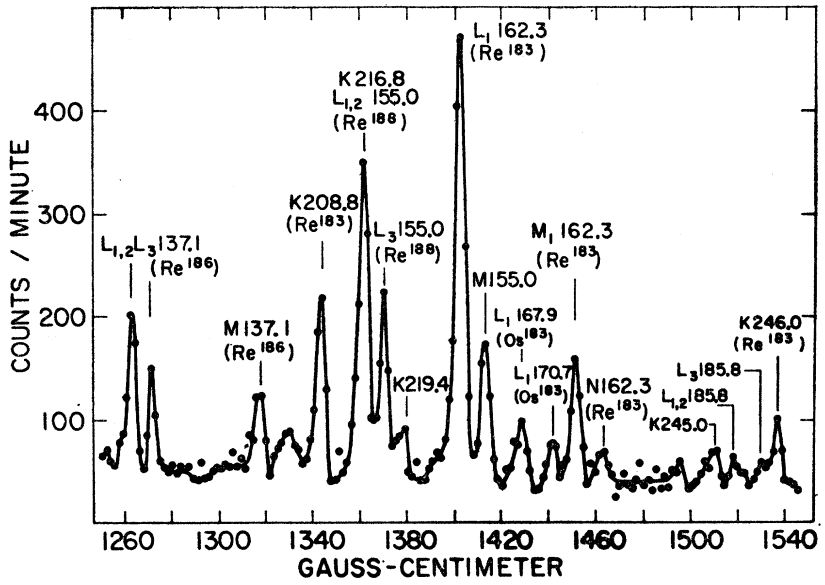

FIG. 5. Section of internal conversion-electron spectrum of Re^{189} and other isotopes.

However, beta-gamma coincidence experiments yielded information about the components of the Re^{189} spectrum, and about the placement of some of the gamma-ray transitions in the level scheme.

VII. BETA-GAMMA COINCIDENCES

Pulses from the anthracene beta detector were observed in coincidence with pulses from gamma rays detected with a sodium iodide crystal. A fast-slow coincidence circuit with a resolving time of approximately 90 nsec was employed. In early runs, the beta coincidence spectrum was recorded with a 256-channel pulse-height analyzer. The most complete data were obtained in later runs, employing the Chase 64×64-channel two-dimensional pulse-height analyzer,[33] in which coincident beta and gamma spectra were recorded simultaneously along the x and y "axes." Beta counting rates near the end point of each spectrum were corrected for finite resolution of the detector, after the method of Owen and Primakoff.[34]

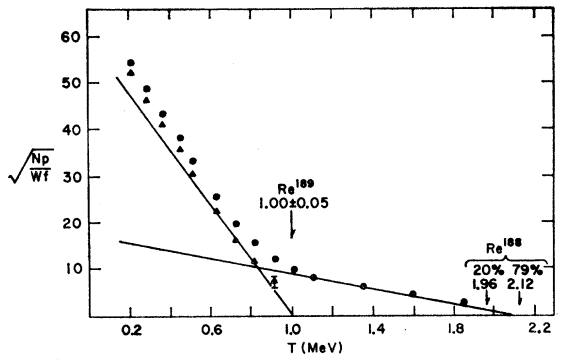

FIG. 6. Fermi plot of beta-ray spectrum of a mixed source of Re^{189} and Re^{188} measured with an anthracene scintillation crystal. The Re^{189} end-point energy found by subtracting the Re^{188} spectrum was consistently 1.00±0.05 MeV for several such measurements.

The most easily analyzed beta spectrum was obtained in coincidence with the 216.8+219.4-keV gamma rays; the combined results of four experiments place the energy end point of the beta branch feeding the 217- and 219-keV levels at 780±20 keV. [cf. Fig. 7(a) for a typical Fermi plot.] The energy difference between the Re^{189} and Os^{189} ground states is therefore 1000±20 keV. Figure 7(b) shows a Fermi plot of the β-spectrum coincident with the 185.9- and 188.4-keV gamma rays. The energy end point is 780±30 keV, which confirms that these gamma rays de-excite the 216.8- and 219.4-keV levels. Beta rays in coincidence with the gamma-ray peak at 150 keV also show, after coincidences due to Re^{188} decay are subtracted, a spectrum with an end point of about 780 keV.

The beta-ray spectrum in coincidence with 245-keV gamma rays has an end point of 725±30 keV [Fig. 7(c)], consistent with the placement of the 245.0-keV transition between the 275.8- and 30.8-keV levels.

Two typical gamma-ray spectra in coincidence with beta particles are shown in Fig. 8. The 216.8- and 219.4-keV gamma-ray peak, prominent in coincidence with 400-keV betas, is reduced by a factor of 12 when the center of the beta window is set on 850 keV, if the curves are normalized at the x-ray peak.

The absolute intensities of some of the individual γ ray peaks (in number of γ rays per Re^{189} disintegration) were derived from a comparison of the β-γ co-

[33] R. L. Chase, Brookhaven National Laboratory Report 3838, 1958 (unpublished); Proc. Inst. Radio Engrs. 47, 464 (1959).

[34] G. E. Owen and H. Primakoff, Phys. Rev. 74, 1406 (1948).

TABLE II. Absolute gamma-ray intensities in the decay of Re^{189}.

Gamma-ray peak[a]	Gamma-ray singles per Re^{189} beta ray	Beta-gamma coincidences per Re^{189} beta ray
"150"	...	0.035±0.015
"187"	0.025±0.010	...
"218"	0.11 ±0.03	0.09 ±0.03
"245"	0.04 ±0.02	$0.03_{-0.01}{}^{+0.02}$

[a] In the gamma-ray scintillation spectrum the "150"-keV peak is due to the 147.1- and 149.9-keV transitions of Re^{189} and the 155.0-keV transition of Re^{188}. The "187" peak is due to the 185.9- and 188.4-keV transitions, and the "218" peak is due to the 216.8- and 219.4-keV transitions, all in Re^{189}.

incidences with the β and γ singles spectra. A source of Au^{198} was counted (β singles, γ singles, and β-γ coincidences) in the same geometry to determine the electron and γ-ray counting efficiencies. The consistency of the procedure was tested by deriving the number of 155-keV γ rays/Re^{188} decay; the number found in this analysis, 0.10±0.02, agrees well with the value (0.105) derived from the decay scheme[35] of Re^{188}. The results for Re^{189} are shown in Table II.

VIII. INTENSITY OF BETA-RAY BRANCHES

The conversion-electron intensities (Table I) may be normalized to the absolute gamma-ray intensities

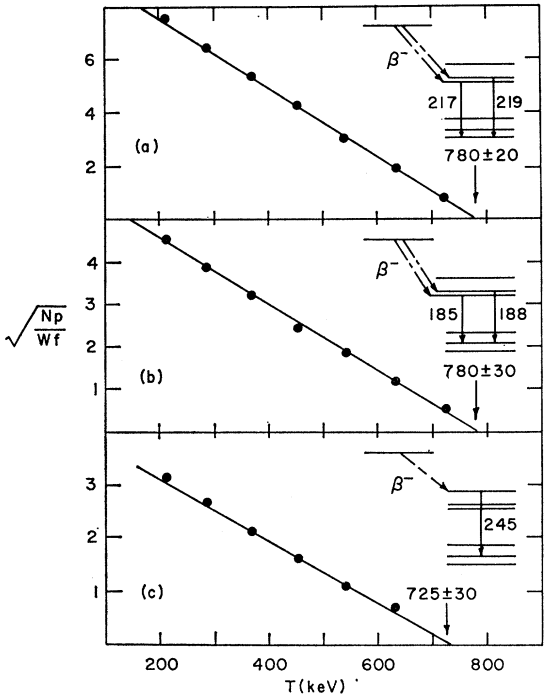

FIG. 7. Fermi plots of Re^{189} beta-ray spectra in coincidence with (a) 216.8- and 219.4-keV gamma rays, with (b) 185.9- and 188.4-keV gamma rays, and with (c) 245.0-keV gamma rays. An anthracene scintillation crystal was the beta-ray detector.

[35] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences-National Research Council, Washington 25, D. C.), NRC 59-3-123.

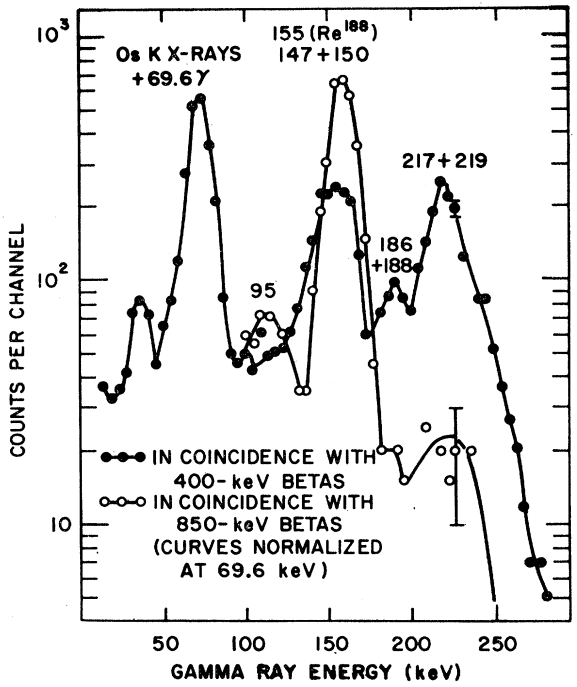

FIG. 8. Gamma-ray scintillation spectra in coincidence with beta rays of 400 keV (filled circles) and 850 keV (open circles) from a Re^{189} source also containing Re^{188}.

(Table II) with the use of theoretical conversion coefficients for the 216.8-, 219.4-, and 245.0-keV transitions, which have been shown[3] to have *E2* multipolarity. The resulting absolute transition intensities are then independent of assumptions about the multipolarities of the other transitions, except where unmeasured conversion or gamma-ray intensities must be estimated. The details, and the results, of these estimates are given in Table III.

The transition intensities of Table III allow estimates to be made of the intensities of the beta-ray branches. These intensity estimates, and the resulting log*ft* values, are shown in Table IV.

IX. LEVELS OF OSMIUM-189

Evidence was found in this work for population (directly or indirectly) in the beta decay of Re^{189} of at least seven of the excited states in Os^{189} shown in Fig. 1. The beta-gamma coincidence results confirm the existence of the 275.8-keV level, and, when taken in conjunction with the internal conversion results, confirm the existence of levels at both 216.8 and 219.4 keV. The result of the electron-electron coincidence measurement, done with an Ir^{189} source, removes some of the evidence for a level at 314.6 keV. The present results do not imply any new states in Os^{189}. No evidence was found for the excitation, in Re^{189} decay, of the 233.6-keV state known from the decay of Ir^{189}. (See Fig. 9.) Transitions of intensity $\leq 1\%$ would not have been seen in this work.

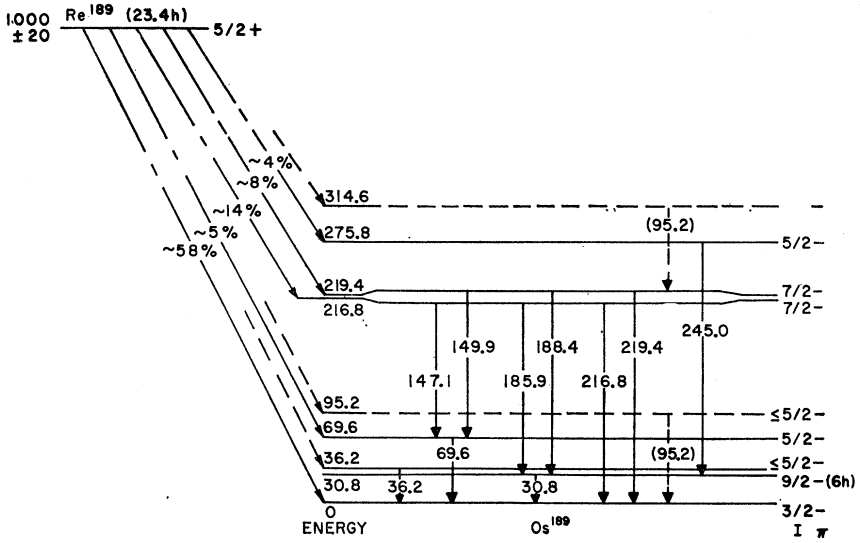

FIG. 9. Decay scheme of Re^{189}. Energies are in keV.

The beta-ray transition logft values which are reasonably well defined by these results (those for the transitions to the ground, 216.8-, 219.4-, and 275.8-keV states) are consistent with a spin change of 0 or 1, and thus consistent with the spin assignments given in Fig. 1, and with the assumption of spin and parity 5/2+ for Re^{189}, as was expected from the data on Re^{185} and Re^{187}.

We review briefly the evidence for the spin assignments given in Fig. 1. The ground-state spin has been measured[36] to be 3/2. The spin of the 30.8-keV state is then 9/2 because of the $M3$ multipolarity of the isomeric transition. Both the 216.8- and 219.4-keV states must then have spin 7/2, since each decays by a $\Delta I \leq 1$ transition to the isomeric ($I=9/2$) state and by a $\Delta I \leq 2$ transition to the ground ($I=3/2$) state. The 69.6-keV state must have $I=5/2$, since it is connected to both $I=3/2$ and $I=7/2$ states by $\Delta I \leq 1$ transitions. It also follows that the 275.8-keV state has spin 5/2, since it decays by a $\Delta I \leq 2$ transition to the $I=9/2$ state and by a $\Delta I \leq 1$ transition to the $I=3/2$ ground state.[2,3]

TABLE III. Estimated electromagnetic transition intensities in Os^{189} following beta decay of Re^{189}. The well-established $E2$ multipolarity of the 245.0-keV transition (Refs. 1, 2, and 3), and of the 216.8- and 219.4-keV transitions (Ref. 3) allows the use of theoretical conversion coefficients for these transitions to give the normalization for the internal conversion-electron data. The relative intensities of conversion-electron lines not seen in this work (due to counter-window cutoff or interference of impurity lines) are taken from HHM (Ref. 3). Gamma-ray intensities not measured directly were estimated with the use of the multipolarity assignments given in column 3 and the conversion coefficients of M. E. Rose [*Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958)].

Transition energy (keV)	Intensity: transitions per Re^{189} beta decay	Multipolarity
30.8	0.15	$M3$[a]
36.2	0.03_7	$(M1+0.4\%\ E2)$[b]
69.6	0.11	$(68\%\ M1+32\%\ E2)$[c]
95.2	0.03_6	$(92\%\ M1+8\%\ E2)$[b,d]
147.1	0.03_1	$(50\%\ M1+50\%\ E2)$[b]
149.9	0.02_0	$E2$[b]
185.9	0.02_7	$M1$[b]
188.4	0.01_9	$(33\%\ M1+67\%\ E2)$[b]
216.8	0.08_7[e]	$E2$[b]
219.4	0.03_7[e]	$E2$[b]
245.0	0.03_5	$E2$[b,d,f]

[a] Refs. 5 and 6.
[b] Ref. 3.
[c] The mixing fraction given is that of Ref. 2. Reference 3 is in close agreement, giving (71% $M1$+29% E2). It has been pointed out to the authors that there may be nuclear penetration effects in the $M1$ internal conversion which would make these deductions of the mixing ratio from the L-subshell ratios invalid. H. Ikegami (private communication).
[d] Ref. 2.
[e] Comparison of conversion-line intensities for the 219.4-, 188.4-, and 149.9-keV transitions with data on Ir^{189} decay (Refs. 2 and 3) seems to show more K219.4 intensity relative to K188.4 and K149.9 in Ir^{189} decay than in Re^{189} decay. Thus, possibly some of the 219.4-keV transition intensity in Ir^{189} decay should be assigned to a transition between the 314- and 95-keV levels (see Fig. 1). Because of large uncertainties in measured conversion-line intensities for the 216.8-keV transition, these intensities, relative to K185.9 and K147.1, which de-excite the same state, were taken to be the same as those measured by HHM in Ir^{189} decay.
[f] Ref. 1.

TABLE IV. Intensities of beta-ray branches in the decay of Re^{189}. The intensity values are derived in part from the beta-gamma coincidence results, and in part from the intensities of electromagnetic transitions in Os^{189}. The intensity of the ground-state branch is inferred from the difference between the total beta-ray intensity and the intensity of the electromagnetic transitions ending in the ground state.

Excitation energy of final state (keV)	End-point energy of branch (keV)	Intensity (in percent of Re^{189} decays)	logft
0	1000±20	58±25	7.2
69.6	930±20	5±3	8.2
216.8	783±20	14±6	7.4
219.4	781±20	8±4	7.7
275.8	724±20	4±2	7.8

[36] K. Murakawa and S. Suwa, Phys. Rev. 87, 1048 (1952).

Unfortunately, no similar argument fixing the spins of the 36.2- and 95.2-keV states seems possible with present experimental evidence, but it is clear that the spin of each level is less than or equal to 5/2, and, from the existence of a $\Delta I \leq 1$ transition between the two levels in Ir^{189} decay,[2,3] that the two spins are within one unit of each other. The $M1$, $E2$, and $M3$ multipolarity of all observed transitions implies the same parity for all the states shown in Fig. 1. From a comparison with the Nilsson diagram, the common parity is taken to be odd; the present discussion of the level scheme is independent of this over-all parity.

Recently, McGowan, Robinson, Stelson and Ford have measured $B(E2)$ values for Coulomb excitation of the 69.6-keV and 95.2-keV states, and of an $I=7/2$ state at about 219 keV.[8] The $B(E2)$ values are, respectively, 0.63, 0.20, and 1.10, in units of $10^{-48}\ e^2\ 1\ cm^4$. The relatively large values for excitation of the 69.6-keV and "219-keV" states might be taken to imply considerable rotational character for these excitations. Let us assume, as a first working hypothesis, that the $I=5/2$ (69.6 keV) and $I=7/2$ (219.4 keV, or possibly, 216.8 keV) states are members of a $K=3/2$ rotational band based on the ground state. The properties of this band, if it is a band, are different from the lowest order rotational predictions in the following ways: (1) The ratio (1.7) of the $B(E2)$ values for excitation of the $I=7/2$ and $I=5/2$ states does not agree with the ratio (0.56) predicted for zeroth-order rotational excitations in a pure $K=3/2$ band. While the $B(E2)$ value for excitation of the $I=7/2$ state implies, assuming $K=3/2$, an intrinsic quadrupole moment of about the same magnitude as is found in Os^{188} and Os^{190}, the $B(E2)$ value for excitation of the $I=5/2$ state implies an intrinsic quadrupole moment only about 60% as large as is found in neighboring even-mass nuclei. (2) If K were a good quantum number for the states involved, one would expect that the relative reduced intensities of the beta-ray branches from Re^{189} to the Os^{189} ground state ($K,I=3/2,\ 3/2$), 69.6-keV state (3/2,5/2), and either the 216.8- or 219.4-keV state (3/2, 7/2) would obey the strong-coupling intensity rules.[37] The experimental results and the rule predictions are shown in Table V; there appears to be a real disagreement. (3) Finally, the experimental energy ratio $E_{7/2}/E_{5/2}$ is 3.15 (or 3.11_5), while the rotational prediction is 2.4. This is a much larger deviation from the first-order $I(I+1)$ spacing than is usually found, even larger than the quite sizable deviations in $K=3/2$ bands in Ir^{189} and Ir^{191}. These, and some other, more typical, ratios are shown in Table VI.

TABLE V. Comparison of Re^{189} reduced beta-ray intensities for branches to the "ground-state band" of Os^{189}. The ground state of Re^{189} is assumed to be $I=K=5/2$, and the intensity-rule predictions (Ref. 37) are made under the assumption of $L=1$ decay to levels of a $K=3/2$ band in Os^{189}.

Spin of final state	Energy of final state (keV)	Relative reduced intensity, $(ft)^{-1}$ Theoretical assuming $K_f=3/2$	Measured
3/2	0	1	1
5/2	69.6	0.43	$0.10_{-0.05}{}^{+0.20}$
7/2	216.8 or 219.4	0.071	$0.6_{-0.2}{}^{+0.7}$ and $0.30_{-0.15}{}^{+0.50}$

TABLE VI. Experimental energy ratios, $(E_{7/2}-E_{3/2})/(E_{5/2}-E_{3/2})$, for levels of $K=3/2$ bands in some deformed nuclei. For unperturbed bands the ratio is expected to be 2.40.

Odd particle	Nucleus	Nilsson orbit	$E_{3/2}$ (keV)	$\frac{(E_{7/2}-E_{3/2})}{(E_{5/2}-E_{3/2})}$	Ref.[a]
n	Gd^{155}	[521↑]	0	2.42	MN
n	Gd^{157}	[521↑]	0	2.38	MN
p	Tb^{157}	[411↑]	0	2.36	MN
p	Tb^{159}	[411↑]	0	2.38	MN
n	W^{183}	[512↓]	208.8	2.45	MN
n	Os^{185}	[512↓]	127.8	2.38	HHM
n	Os^{187}	[512↓]	74.3	2.44_5	HHM
n	Os^{189}	[512↓]	0	3.15 (or 3.11_5)	–
p	Ir^{189}	[402↓]	0	2.65	HHM
p	Ir^{191}	[402↓]	0	2.64	HHM

[a] For cases labeled "MN," references may be found in B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter 1, No. 8 (1959). For cases labeled "HHM," see Harmatz, Handley, and Mihelich, Ref. 3.

X. ROTATION-PARTICLE COUPLING IN OSMIUM-189

As a first step in trying to understand why, in Os^{189}, there should be indications of rotational structure, but large deviations from simple rotational-model predictions, it is natural to try to include the effects of rotation-particle coupling[38] (RPC). If the states at 36.2 and 95.2 keV should be the $I=1/2$ and $I=3/2$ states of a $K=1/2$ band, of the same parity as the supposed $K=3/2$ band, the effects of this $\Delta K=1$ coupling could be very large. Indeed, the classic example of rotation-particle coupling is W^{183}, in which there is mixing between bands which have the same Nilsson orbit assignments as those usually assumed for Os^{189} (see Fig. 1).

Not only may RPC be expected in Os^{189}, but several of the features of the level scheme pointed out in the last section find a qualitative explanation in such coupling. The moderately enhanced $B(E2)$ for excitation of the 95.2-keV state, the anomalous in-band excitation ratio $B(E2,\ 3/2\rightarrow 7/2)/B(E2,\ 3/2\rightarrow 5/2)$, and the anomalous energy ratio $E_{7/2}/E_{5/2}$, can each be produced by suitable admixtures of $K=1/2$ into the $K=3/2$ band, and vice versa. In spite of this qualitative

[37] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 9 (1955).
[38] A. K. Kerman, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **30**, No. 15 (1956).

agreement, however, no detailed fit to the experimental level energies and excitation probabilities can be made.[39] One cannot simultaneously fit the energies of the $I=3/2$ (ground state), 1/2 (36.2 keV), 5/2 (69.6 keV), 3/2 (95.2 keV), and 7/2 (219.4 or 216.8 keV) levels with the assumption of $K=1/2$ and $K=3/2$ bands coupled by RPC.[40]

XI. FINAL REMARKS

Even though the axially symmetric rotational model with RPC included fails to give a detailed account of the low-lying states of Os^{189}, it may still be possible that the rotational model itself is applicable in this region. Studies of even-mass Os nuclei[26] show that low lying $|K-\Omega|=2$ excitations are important features of the level structure. Such excitations may be gamma vibrations, or perhaps evidence of equilibrium gamma deformation.

There is, indeed, one piece of experimental evidence that there are low-lying gamma-vibrational excitations in Os^{189}. The dominant mode of decay of the 275.8 keV ($I=5/2$) state is the 245.0-keV pure $E2$ transition to the $I=K=9/2$ state at 30.8 keV, though several other $M1$, $E2$, or mixed-multipole transitions allowed by the angular momentum selection rules are either weak or unobserved. A limit has been placed[41] on the half-life with which the 245.0-keV transition follows osmium K x rays in Ir^{189} decay; the half-life is less than 5×10^{-10} sec. This limit means that the 245.0-keV transition is at least 10 times faster than the single-proton $E2$ estimate (with radius parameter $r_0=1.2\times10^{-13}$ cm). The enhancement may be taken as evidence that the transition is collective, and since the spin sequence rules out an intraband rotational transition or a beta-vibrational transition, a gamma-vibrational transition is suggested.

Finally, it has been pointed out by Bés,[42] and by Marshalek,[43] that the proximity of the $[510\uparrow]$ and $[512\downarrow]$ bands, and the large Y_{22} matrix element between them, are important factors in the lowering of the gamma-vibrational energy in the osmium region. Thus, it may be expected that for odd-mass osmium nuclei the indirect coupling of these two bands by gamma-vibrational motion has an importance comparable to the direct rotation-particle coupling. This expectation is reinforced by the conclusion of the previous section, that the inclusion of RPC does not lead to complete agreement with the experimental information available on the levels of Os^{189}. Probably more experimental information is needed, however, before a meaningful comparison can be made with the predictions of models which include gamma-vibrational motion (or equilibrium gamma asymmetry).[44]

ACKNOWLEDGMENTS

We wish to thank G. Scharff-Goldhaber for her interest in this work, E. der Mateosian, E. L. Church and J. Weneser for helpful discussions, C. P. Baker and the staff of the Brookhaven 60-in. cyclotron for technical advice and many bombardments, M. McKeown for help with the operation of the double-focusing beta-ray spectrometer, J. G. Giehler for technical assistance, and T. Moffett and J. R. Pond for help with the analysis of the data. We are grateful to F. K. McGowan for transmitting to us results obtained at Oak Ridge National Laboratory. One of us (B.C.) would like to thank M. Goldhaber and the Physics Department of Brookhaven National Laboratory for their hospitality, J. G. Pengra for his collaboration in the preparatory stages of this work, and the National Science Foundation for a grant.

[39] A similar conclusion was reached by the authors of Ref. 8.

[40] That is, one cannot simultaneously fit these five energies by varying the six parameters available if one requires that the experimental $I=5/2$ and 7/2 states are the lowest 5/2 and 7/2 states in the model, and if one requires that the unperturbed moments of inertia of the two bands do not differ by more than a factor of three.

[41] A. Schwarzschild and G. T. Emery (private communication).

[42] D. R. Bés, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **33**, No. 2 (1961).

[43] E. R. Marshalek, University of California, Lawrence Radiation Laboratory Report UCRL-10046, 1962 (unpublished).

[44] An asymmetric rotor treatment of odd-mass nuclei has been given by K. T. Hecht and G. R. Satchler, Nucl. Phys. **32**, 286 (1962), and by others. For many features of nuclear level schemes an asymmetric rotor model is indistinguishable from a model with equilibrium axial symmetry and strong gamma vibrations; see, e.g., L. W. Persson and J. O. Rasmussen, Nucl. Phys. **36**, 666 (1962), and Ref. 26, Sec. IV.