forbiddenness[21]; formula (3) shows in addition that also $M1$ transitions are essentially forbidden; one should notice that the ground state of Li^6 is predominantly $S=1, L=0$, as the value of its magnetic moment shows. This implies, as already remarked, a particularly small value for the matrix element $\langle a|\mathbf{S}|b\rangle$.

We conclude by stating that, of course, in the above discussion we have looked for evidence in favor of the proposed rule; however, once this is established, the reverse use can be made of it; namely to help in establishing the spins and parities of the excited states; in addition, as already remarked, the particularly simple form of the matrix element (3) will give valuable information on the structure of the nuclei considered here.

[21] A. Gamba and V. Wataghin, Nuovo cimento **10**, 176 (1953); see also Gell-Mann and Telegdi, reference 3. Compare this last paper for a discussion of the application of the $E1$ rule to photonuclear reactions.

ACKNOWLEDGMENTS

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Decay Scheme of 50-Day Re^{184}†

C. J. GALLAGHER, JR.,* D. STROMINGER, AND J. P. UNIK
Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California

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A detailed study of the radiations of Re^{184} decay is given. The decay is found to be complex, with most of the direct decay populating the 2+ and 3+ levels at 904 and 1006 kev in W^{184}. A decay scheme is presented which includes all of the strong transitions, but several weak transitions remain unplaced. Several tests of the unified-model predictions are made.

Data on the K-Auger electrons of tungsten are given.

Some incidental studies of Re^{183} are also presented. The half-life value of Re^{183} is found to be 71 days, in disagreement with previous values.

INTRODUCTION

THE 50-day electron-capture isotope Re^{184} was discovered by Fajans and Voigt.[1] Wilkinson and Hicks[2] reported the 50-day half-life. Several electron-spectroscopic investigations at low resolution have been carried out,[2,3] but no decay scheme has been determined. The study presented here is based largely on the results of high-resolution electron spectroscopy and gamma-gamma coincidence measurements.

INSTRUMENTS AND EXPERIMENTAL PROCEDURES

The present electron-spectroscopic studies of Re^{184} were made on two permanent-magnet spectrographs with magnetic fields of 99 and 350 gauss.[4] These permanent-magnet spectrographs were carefully calibrated by using the conversion electrons of Re^{183} for the low-energy field and Bi^{206} for the high-energy field. The gamma-gamma coincidence measurements were made by using the fast-slow coincidence circuit described elsewhere.[5] The chance coincidence rate was always less than 10% of the true coincidence rate. Precautions were taken to insure that coincidences were not due to a Compton-degraded photon from one NaI(Tl) crystal striking the other NaI(Tl) crystal. Singles and coincident gamma spectra were studied by use of $1\times1\frac{1}{2}$-inch NaI(Tl) scintillation crystals with 50-[6] and 100-channel[7] differential-pulse-height analyzers.

The rhenium activities used in these studies were prepared by two methods. The sources used for electron-spectroscopic studies were prepared by the irradiation of a thick (~0.12-inch) tungsten plate in the intense low-energy deuteron beam of the Livermore A-48 accelerator.[8] The Re^{184} was apparently produced by barrier penetration reactions, because the deuteron energies

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* Present address: Norman Bridge Laboratory of Physics, California Institute of Technology, Pasadena, California.

[1] K. Fajans and F. Voigt, Phys. Rev. **58**, 177 (1940).

[2] G. Wilkinson and H. G. Hicks, Phys. Rev. **77**, 314 (1950).

[3] R. G. Wilkinson, reported in reference 10.

[4] W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956).

[5] D. Strominger, Ph.D. thesis, University of California Radiation Laboratory Report UCRL-3374, June, 1956 (unpublished).

[6] A. Ghiorso and A. E. Larsh, reported in University of California Radiation Laboratory Report UCRL-2647, July, 1954 (unpublished).

[7] This 100-channel gamma analyzer is a commercial model manufactured by the Pacific Electro-Nuclear Company, Culver City, California.

[8] Birdsall, Clark, Jopson, Livdahl, Smith, and Van Atta, Bull. Am. Phys. Soc. Ser. II, **2**, 187 (1957).

TABLE I. Transitions in W^{184} following Re^{184} decay. Conversion coefficients listed are normalized and depend on the absolute values of the coefficients in parentheses. Two values were used for normalization, because the high- and low-energy ranges were measured separately. The uncertainty in the photon intensities is about 20%.

Initial and final states	Gamma-ray energy (kev)	Photon intensity	Conversion coefficients K	L_I	L_{II}	L_{III}	Total	Decay fraction	Multipolarity
(a)	97.33±0.05	...		weak	weak	...[b]	...	...	$(M1+E2)$
BA	111.20±0.06	14	...[c]	...	(0.72)[d]	0.46	2.6	52	$E2$
(a)	210 ±20	...						...	$(E1)$
GE	230 ±20	~0.4					...	0.4	$(E1)$
(a)	241.1 ±0.2								
FD	250 ±20	~0.8					...	0.8	$(E1)$
CB	252.84±0.1	~0.6	0.08	weak	weak	weak	0.15	0.7	$E2$
GD	330 ±25	~0.3					...	0.3	...
DC	540 ±40	~0.3					...	0.3	$(E2)$
EC	642.4 ±0.6	~0.5	0.008				0.008	0.8	$(M1+E2)$
(a)	788.3 ±0.8	...	weak				...	...	...
DB	792.7 ±0.8	40	0.009	0.001			0.010	40	$(M1+E2)$
EB	895.2 ±0.9	15	0.006				0.006	15	$(E2)$
DA	904.3 ±0.9	45	(0.0045)[e]	weak			0.0045	45	$(E2)$
	K x-rays	100							

[a] Not assigned in decay scheme.
[b] L_{III} 97.33 masked by L_{II} and L_{III} 99.07 (Re^{183} decay).
[c] Correction factors excessively large for this line.
[d] Value used for normalization of conversion coefficients of low-energy lines. Rose's value of α_{LII} was used.
[e] Value used for normalization of conversion coefficients of high-energy lines. Sliv's value of α_K was used.

were ≤ 7.6 Mev, which is below the Coulomb barrier for (d,xn) reactions in tungsten. After the plate was allowed to cool for several months, it was dissolved in a 90% conc. HNO_3—10% conc. HF solution. The solution was then digested for several hours in a steam bath to remove the HF. After digestion, yellow WO_3 precipitated, leaving the rhenium in solution as ReO_4^-. Because no carrier had been added, some of the ReO_4^- had been occluded in the WO_3 precipitate. To improve the yield, the WO_3 was dissolved in $6N$ NH_4OH and then reacidified with NHO_3, reprecipitating the WO_3. The supernatant liquid containing the ReO_4^- was concentrated, and the ReO_4^- was isolated from any WO_4^- remaining in solution by the anion exchange procedure of Huffman, Oswalt, and Williams.[9] Rhenium sources were then prepared by the cathodic deposition of the carrier-free rhenium activity on 0.010-inch platinum wires in the plating cell described by Smith and Hollander.[4]

The sources used for scintillation spectrometer studies were prepared by irradiating 0.001-inch natural rhenium foils in the fast neutron beam of the Berkeley 60-inch cyclotron. These sources were essentially free of the interfering radiations of Re^{183}. The neutron beam is produced by stripping ~15 Mev deuterons in a beryllium block. The sample was shielded on both sides with $\frac{1}{4}$-inch cadmium absorbers, to reduce the number of thermal-neutron-induced reactions. After bombardment, the foil was allowed to cool for two months to permit the 92.8-hr Re^{186} [10] produced by the $Re^{187}(n,2n)Re^{186}$ reaction to decay. No purifying chemistry was performed, because charged-particle reactions had been eliminated by thick shielding foils. The high purity of the foil, the long cooling period, and small cross sections were effective discrimination against the products of any (n,xp) reactions.

EXPERIMENTAL RESULTS

The complex long-lived rhenium spectrum of Re^{183} and Re^{184} which was observed in the permanent magnet studies presented a difficult problem of analysis. However, because of the careful studies by Murray *et al.* (hereafter referred to as MBMD)[11] on the levels of W^{183} populated by Ta^{183} decay, and the equally thorough studies by Thulin *et al.* (hereafter referred to as TRGSH)[12] on the decay of Re^{183}, it was possible to determine which of the many lines observed belonged to Re^{184}.

The transitions of Re^{184} are shown in Table I. The photon intensities were determined from the scintillation spectrometer measurements. These transitions were so assigned only after the internal-conversion line spectrum of the long-lived rhenium isotopes had been carefully analyzed, and the many transitions of Re^{183} accounted for. We list only visual intensities for the conversion lines in several cases where the intensities, if calculated, would be subject to excessively large corrections from either the photographic-efficiency or photographic-blackening corrections. The lines observed on the photographic plate were related to numerical intensities by the method of Mladjenović and Slätis.[13]

In addition to the transitions reported in Table I,

[9] Huffman, Oswalt, and Williams, University of California Radiation Laboratory Report UCRL-3324, February, 1956 (unpublished).
[10] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[11] Murray, Boehm, Marmier, and DuMond, Phys. Rev. **97**, 1007 (1955).
[12] Thulin, Rasmussen, Gallagher, Smith, and Hollander, Phys. Rev. **104**, 471 (1956).
[13] M. Mladjenović and H. Slätis, Arkiv Fysik **8**, 65 (1954).

evidence was obtained from the scintillation spectrometer studies for other gamma rays with energies higher than 900 kev. These transitions are very weak and they could not be resolved from the 900 kev transitions or from one another. For that reason they are not included in Table I.

Because there exists considerable confusion in the literature regarding the previously reported transitions of Re^{184} and half-lives of the neutron-deficient isotopes of rhenium in general, it seems worthwhile to discuss them here.

Wilkinson and Hicks[2] examined the conversion-electron spectrum of Re^{184} and reported transitions of energies of 43, 159, 205, and 285 kev. Wilkinson[3] also studied Re^{184} decay and found electron lines corresponding to transitions of 159, 206, 244, 784, and 890 kev. The assignment of these transitions to Re^{184} was made on the basis of the rate of decay of the electron lines.

From our studies we conclude that all of the transitions except the 784- and 890-kev transitions assigned to Re^{184} in previous studies were incorrectly assigned. The low-energy transitions reported are very similar in energy to transitions in Re^{183} (see Re^{183} gamma spectrum, Table VI) and we believe that they should be so assigned. This misassignment could very easily be due to the earlier misassignment of a 120-day half-life to Re^{183} (see discussion of this point in TRSGH, reference 12). The 71-day half-life determined by us explains why these low-energy lines were previously assigned to 50-day Re^{184}. It is also interesting to note that the 120-day half-life reported for Re^{183} is in agreement with the reported half-life of W^{181}.[3,14–17] It seems very likely, therefore, that Re^{181} was produced in the original studies of the rhenium isotopes by Wilkinson and Hicks,[2] but was not so identified. Their assignment of a 346-kev transition to Re^{182} seems to support this conclusion, because no strong 346-kev transition is observed in Re^{182} decay, but a very strong 366-kev transition is observed in Re^{181} decay.[18] The W^{181} formed following Re^{181} decay would then cause the tail in the rhenium decay curves.

COINCIDENCE STUDIES

In the previous section we noted that the 780- and 890-kev transitions were assigned to Re^{184} on the basis of half-life. Besides these, the 111.20- and 252.84-kev transitions can also be definitely assigned to Re^{184}. Coincidences were looked for between these photons, K x-rays, and other photons in the sample to help determine the decay scheme of Re^{184}. Table II summarizes the results of the coincidence experiments.

Delayed coincidence measurements were also made on Re^{184} decay. We were able to set an upper limit of 1.1 mμsec for the half-life of the state giving rise to the 904.3- and 792.7-kev transitions.

A half-life value of 1.3±0.4 mμsec was obtained for the 111.2-kev level. This value was determined by the centroid shift analysis suggested by Bay.[19] A Bi^{207} sample was used to obtain a standard delay curve for the comparison. This value is in agreement with the value of 1.0 mμsec obtained from Coulomb-excitation yield considerations.[20]

DISCUSSION OF RESULTS

Discussion of transitions.—The L_{I} and L_{II} lines of a 97.33-kev transition were observed. The expected L_{III} line is masked by the L_{I} and L_{II} lines of the strong 99.07-kev transition in Re^{183}. On the basis of the relative L-subshell intensities, the transition was assigned as $M1-E2$.

The two most intense low-energy transitions in Re^{184} are the 111.20-kev and 252.84-kev transitions. They were assigned $E2$ multipolarities on the basis of their observed $L_{\mathrm{I}}/L_{\mathrm{II}}/L_{\mathrm{III}}$ ratios. Because we obtained only relative gamma and electron intensities for both of these transitions, we could determine only their relative conversion coefficients. However, it is possible to assume a theoretical conversion coefficient for one of the transitions whose multipolarity is well established, and then calculate the other absolute conversion coefficients from the relative conversion coefficients. The experimental relative conversion coefficients we obtained were normalized against the theoretical conversion coefficient for the L_{II} line of an $E2$ transition of 111.20-kev. The absolute conversion coefficients, so calculated for the other conversion lines of the 111.20- and 252.84-kev transitions, agree within experimental error with the

TABLE II. Gamma-gamma coincidences observed in the decay of Re^{184}.[a]

Transition (kev)	K x-rays	110	210	230	250	330	540	640	790	900
K x-rays	Y	Y	···	···	Y	···	···	···	Y	Y
110	···	···	···	···	Y	···	···	···	Y	Y[b]
250	···	···	···	···	···	···	Y	Y	Y[c]	Y[c]
790	···	···	Y[d]	···	Y	Y[e]	N	N	N	N
900	···	···	···	Y[f]	Y	Y[e]	N	N	N	N

[a] Y = coincidence definitely observed; N = coincidence looked for but not observed.
[b] 25% of 900-kev photons are in coincidence with 110-kev transitions.
[c] ~1% of 790-kev and 900-kev photons are in coincidence with 250-kev photons.
[d] 210–790-kev coincidences are observed in extremely weak intensity.
[e] 0.3% of 790-kev and 900-kev photons are in coincidence with 330-kev photons.
[f] ~1% of 900-kev photons are in coincidence with 230-kev photons.

[14] Cork, Nester, LeBlanc, and Brice, Phys. Rev. **92**, 119 (1953).
[15] Bisi, Ferrani, and Zappa, Nuovo cimento **1**, 651 (1951).
[16] Bisi, Ferrani, and Zappa, Nuovo cimento **3**, 661 (1956).
[17] Delbrunner, Heer, Kundig, and Ruetschi, Helv. Phys. Acta **29**, 235 (1956).
[18] Gallagher, Sweeney, and Rasmussen, Phys. Rev. **108**, 108 (1957).
[19] Z. Bay, Phys. Rev. **77**, 419 (1950).
[20] F. K. McGowan and P. H. Stelson, Phys. Rev. **109**, 901 (1958).

theoretical $E2$-conversion coefficients of Sliv and Band[21] and Rose.[22]

The high-energy transitions for which we were able to obtain absolute conversion coefficients are EC, DB, EB, and DA. Because the electron intensities of these high-energy transitions were obtained from a different study, and consequently had a different scale factor than those of the low-energy transitions, the previous normalization could not be used. To normalize these conversion coefficients, we assumed that the K line of the 904.3-kev transition has Sliv's theoretical α_K (0.0045) for an $E2$ of this energy. The results shown in Table I indicate that the data are consistent with the assignment of $E2$ and $M1-E2$ multipolarities to these transitions. We shall discuss later why we used the 904.3-kev transition for normalization.

A very weak and questionable K line is the only evidence for the 788.3-kev transition. Because we cannot resolve the two ~790-kev photon peaks, we estimated what fraction of the 790-kev photon peak would belong to this transition if it had $E1$, $M1$, or higher multipolarity. If the transition is $E1$, the gamma intensity will be about a fourth of the observed peak. On the other hand, if the transition has $M1$, $E2$, or higher magnetic or electric multipolarity, its contribution to the photon peak can be neglected. In the later discussions we assume that the intensity of the 788.3-kev photon can be neglected relative to that of the 792.7-kev photon.

The ~210-, ~230-, ~250-, and ~330-kev photons were detected in the coincidence studies. We believe that an $E1$ assignment is most probably correct for the ~230-kev and ~250-kev transitions, because we failed to observe their K-conversion electron lines although their intensities are large relative to that of the 252.84-kev photon, the conversion electrons of which were seen. The data do not permit an unambiguous multipolarity assignment to the ~330-kev transition.

Decay scheme.—The level scheme proposed for W^{184} is shown in Fig. 1. The first excited state of W^{184} was determined to have an energy of 111.13±0.06 kev from Coulomb-excitation experiments.[23] The energy of this transition is in excellent agreement with the 111.20 ±0.06-kev transition observed in our study and the latter transition is therefore assigned as transition BA.

The coincidence data of Table II show that most of the ~900-kev transitions are in coincidence only with K x-rays. Therefore, the 904.3-kev transition is placed to decay to the ground level (A), establishing level D. Strong 790–110 coincidences were also observed, and the sum, 792.7+111.2=903.9, is equal to transition energy DA within the energy uncertainty of 0.1%, thus further supporting level D.

The coincidence data show that about 25% of the 900-kev photons are in coincidence with 111.20-kev transitions. The strong 895.2-kev transition is therefore placed to establish level E. It can then be seen that the sum, 252.8+642.4=895.2, is equal to transition EB. Because the 252.84-kev transition is in excellent agreement with the expected 4+→2+ rotational spacing, the 252.84-kev transition is placed to establish level C. The observation of 540–250 coincidences also supports this scheme.

The energies of the 1150- and 1230-kev levels are based upon the coincidence measurements and are therefore expected to have uncertainties of 20 kev. Although there is a possibility that these transitions populate levels other than those shown, the present assignment is probably correct. However, because the complexity of the levels observed in W^{184} indicates that high-resolution studies of these weak transitions are required to establish the assignments definitely, we indicate the tentative assignment by dotted lines. The spins and multipolarities of the 1150- and 1230-kev levels are assigned because the 250- and 230-kev transitions are probably $E1$ transitions.

It is interesting to note that the levels of W^{184} have also been studied from Ta^{184} decay by Butement and Poë.[24] In this study, 110-, 160-, 210-, 240-, 300-, 405-, 780-, 890-, and 1180-kev photons were reported with relative intensities 3, 1, 1, 6, 3.5, 10, 1.7, 9, and 5. Unfortunately, the level scheme of W^{184} is too complex to attempt placing these transitions in our level scheme without much ambiguity. This treatment must be deferred until more high-resolution spectroscopy has been performed on Ta^{184} decay.

Primary population and log(ft) values.—The most striking feature of Re^{184} decay is that apparently the total primary electron-capture decay occurs to a group of levels around 1 Mev. Such behavior is difficult to explain on the basis of the single-particle model because the spins of these high-lying levels are similar to spins of

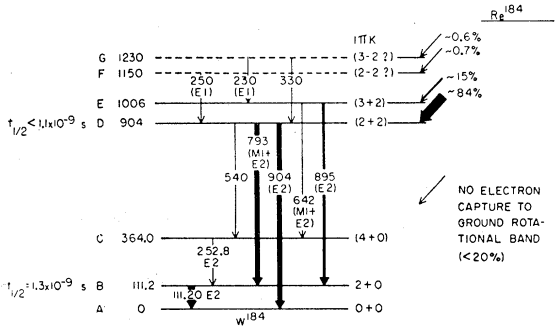

FIG. 1. Partial decay scheme of Re^{184} to the levels of W^{184}.

[21] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation by P. Axel, Report 57 ICC Kl, issued by Physics Department, University of Illinois Urbana, Illinois (unpublished)].

[22] M. E. Rose (privately circulated tables). Also M. E. Rose and G. H. Goertzel, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Appendix IV, p. 905.

[23] Chupp, Clark, DuMond, Gordon, and Mark, Phys. Rev. **107**, 745 (1957).

[24] F. D. S. Butement and A. J. Poë, Phil. Mag. **46**, 482 (1955).

states much lower in energy, but can perhaps be understood in terms of the K forbiddenness predicted by the unified model.[25–27] In order to obtain an idea of the strength of the K forbiddenness, we calculated a lower limit of the logft value to state B. From our absolute upper limit of 20% decay to ground, and assuming a 1300-kev decay energy and an L_I/K ratio of 0.13,[28] we calculated[29] a logft value of ≥ 8.7, compared with the usually observed logft of 7.5 for a first-forbidden transition. This indicates a hindrance of at least 20 for the decay.

The reported primary branching, 84% to level D, 15% to level E, was deduced from the ratio of the total intensity of the high-energy transitions to the observed K x-ray intensity reported in Table I.

Level D was assigned a spin of 2 because it decays to levels A, B, and C. Level E is assigned spin 3 because it decays to B and C, but not to A. The states have been assigned positive parity because the normalized absolute conversion coefficients discussed previously are consistent with $E2$ and $M1-E2$ multipolarities. No normalization other than that used leads to results that are consistent with all of the data.

The branching ratios from, and energies of, states E and D provided a check on the applicability of the wave functions of the unified model to the high-energy states through comparison of the experimental and theoretical reduced transition probabilities. In Table III these data are compared. The agreement of the experimental and theoretical values for the ratios DB/DA and DC/DA supports our assignment of spin 2 to this level; while EC/EB is in reasonable agreement with the theoretical value based on the assumption that E has spin 3, and suggests that K is a good quantum number for these states. We assumed that all transitions were pure $E2$; the absolute conversion coefficient for DB suggests it has some $M1$ mixing, which would tend to reduce the experimental ratio DB/DA in Table III. EC and EB probably also have some $M1$ mixing; we have not attempted to determine these mixing ratios because the uncertainties in the intensities are too large to make such a calculation meaningful. Angular correlation studies of these transitions would be very useful in determining the amount of $M1-E2$ mixing in these transitions.

TABLE III. Comparison of experimental and theoretical reduced transition probabilities for $E2$ de-excitation of the high-energy states of W^{184}. All transitions were assumed to be pure $E2$.

K, π initial state	Transitions compared	Reduced transition probability calculated	Theoretical	Experimental
2,+	DB/DA	$\frac{B(E2;2,2\text{—}2,0)}{B(E2;2,2\text{—}0,0)}$	1.43	1.72
2,+	DC/DA	$\frac{B(E2;2,2\text{—}4,0)}{B(E2;2,2\text{—}0,0)}$	0.072	0.08
2,+	EC/EB	$\frac{B(E2;3,2\text{—}4,0)}{B(E2;3,2\text{—}2,0)}$	0.40	0.28

From the observed primary decay of Re^{184} to 2+ and 3+ and not to ground, it is probable that Re^{184} has a spin of 2 or 3. Because the logft to state D, calculated by assuming a decay energy of 400 kev to this state, is ~ 7.1, decay is probably first-forbidden, suggesting negative parity for this state.

It is interesting to note here that the Bohr-Mottelson unified model[25] makes specific predictions regarding primary beta populations to members of a rotational band. From the paper of Alaga *et al.*,[27] the intensity of primary beta decay should be

$$\frac{ft(i\rightarrow f)}{ft(i\rightarrow f')}=\frac{\langle I_iLK_iK_f-K_i|I_iLI_fK_f\rangle^2}{\langle I_iLK_iK_f-K_i|I_iLI_{f'}K_f\rangle^2}.$$

From a consideration of the expressions for the beta-decay f factors for first-forbidden, non-unique electron capture decay, which Hoff and Rasmussen[29] have shown to be

$$f=\tfrac{1}{2}\pi g_K{}^2q_K{}^2,$$

and using the curves of Brysk and Rose[28] to evaluate the necessary parameters, one can see that the above expression provides a method for the calculation of electron capture decay energies, if we assume (1) that the unified-model wave functions are a valid description of the states in question, (2) that the beta decay proceeds only through operators corresponding to an angular momentum change of one unit, and (3) that the initial and final spins are known.

In order to attempt to apply the above relationship, we must consider the individual assumptions. From the results shown in Table III it appears that the intensity rules for deexcitation of states D and E come very close to the theoretical values predicted. Therefore, the criterion for K to be a good quantum number seems reasonably well satisfied. Assumption (2) is more difficult[30]: the logft value ~ 7 obtained from rough calculations indicates that there is probably not much contribution from a $\Delta I=2$, yes transition which would have a log$ft\sim 9$. We now consider the third criterion. In this case we know the final spins and K's but we do not know the initial spin and K. We do know, however, that it is probably 2 or 3. Therefore we evaluated the ex-

[25] A. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **26**, No. 14 (1952).
[26] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[27] Alaga, Alder, Bohr, and Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 9 (1955).
[28] H. Brysk and M. E. Rose, Oak Ridge National Laboratory Report ORNL-1830 January, 1950 (unpublished).
[29] R. W. Hoff and J. O. Rasmussen, Phys. Rev. **101**, 280 (1956).
[30] We are indebted to Dr. Sven G. Nilsson for pointing out that assumption (2) can only be considered valid when the logft (for a first forbidden transition) is less than or equal to ~ 6.5.

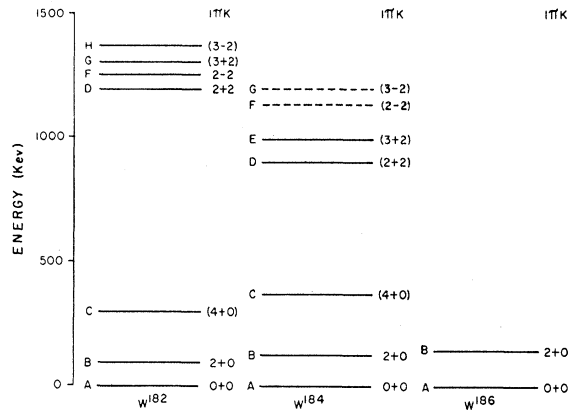

FIG. 2. Comparison of the energies of analogous states in even-mass tungsten nuclei.

pressions for $K_i=I_i=2$, and $K_i=I_i=3$, and then determined what energies, if any, would yield values consistent with the observed decay intensities. A consistent decay energy value was found for each spin, 320 kev to state D assuming $K_i=I_i=2$ and 420 kev to state D, assuming $K_i=I_i=3$. The former value can be ruled out because state G has an energy greater than this: the values of $I_i=3$ and $Q_{EC}=420$ kev to state D, or 1325 to ground, thus seem to be consistent with the theory. It is interesting to note that such spin, parity, and decay energy are all consistent with the observed weak primary decay to states F and G. This energy allows the calculation of logft values of 7.1 and 7.5 to states D and E, respectively.

GENERAL DISCUSSION

The moment of inertia calculated from spacing DE is about 10% greater than the ground-state-band moment of inertia. This result is to be compared with the analogous moment of inertia in W^{182}, which is 10% smaller than that of the W^{182} ground state. We do not believe it possible, from data now known, to determine the cause of this change, but it is possible that such an effect results from the perturbation of the even-spin levels of the $K=2,+$ band by the as yet unobserved states of a near-lying β-vibrational band. These states, because they have the same intrinsic nucleonic wave functions can perhaps couple through the U_3 interaction described by Bohr (reference 25, Chap. V, p. 35). Only even-spin states can couple because the symmetry of the wave functions prevents the appearance of odd-spin states in a β-vibrational band.

TABLE IV. Inertial constants[a] for the positive parity levels of even-even tungsten nuclei.

Nucleus	C (kev)	C' (kev)	D (kev)
W^{182}	16.68	16.77	0.0153
W^{184}	18.53	18.68	0.0237
W^{186}	20.41[b]		

[a] The inertial constants are defined by the relationships: 1. $E_I-E_{I_0}=C\{I(I+1)-I_0(I_0+1)\}$; 2. $E_I-E_{I_0}=C'\{I(I+1)-I_0(I_0+1)\}-D\{I^2(I+1)^2-I_0^2(I_0+1)^2\}$, where E_I is the energy of the rotational state with spin I.
[b] See reference 23.

The results of this study on the levels of W^{184} can be compared with the energies of levels in W^{182} and W^{186}. Unfortunately, only the energy of the rotational 2+, 0 ($I\pi$,K) state in W^{186} has been determined.[23,31,32] In Fig. 2 we compare the experimental data for the energies of analogous levels in the even-even tungsten nuclei. It can be seen immediately that a striking trend exists. In Table IV we compare the inertial constants calculated from these data. The results show that the energies of the 2+ states manifest a marked dependence on the mass number. The increased vibration-rotation interaction also shows this dependence. Such results probably indicate an increased "softening" of the nuclear potential toward shape vibrations as the nuclei move out of the mass region of stable spheroidal deformation. Although the energy of the 2+, 2 state in W^{186} is not known, the increase in energy of the 2+, 0 state between W^{186} and W^{184} indicates an even larger vibration-rotation interaction in W^{186} than in W^{184} or W^{182}. Such a result indicates that the second 2+ state in W^{186} is probably lower in energy than that in W^{184}. However, when we compare the energy of the 2− state that has been observed in W^{182}, and the energy of state F in W^{184}, with the energies of the gamma vibrational states in the same isotopes, then we see that the 2− states appear less perturbed by the variation in mass number. Because there recently has been some suggestion[33] that these states correspond to an octupole vibration, it will be interesting to see if further theoretical investigations explain what appears to be a slower variation of the octupole vibrational potential than that of the gamma-vibrational potential. It must be emphasized that further high-resolution investigations of the negative parity states of W^{184} must be made before the present assignments can be considered definite.

TABLE V. Photon intensities of transitions of W^{183} observed in Re^{183} decay.

Photon (kev)	Intensity
K x-rays	100.0
108	6.3
160	12.9
210	1.4
250	~0.8

GAMMA SPECTRUM, HALF-LIFE, AND NEW TRANSITIONS OF Re^{183}

In order to obtain the gamma intensity values listed in Table I for Re^{184}, it was necessary to analyze carefully

[31] F. R. Metzger and R. D. Hill, Phys. Rev. 82, 646 (1951).
[32] R. M. Steffen, Phys. Rev. 82, 827 (1951).
[33] R. Sheline, Institute for Theoretical Physics, Copenhagen, Denmark, talk given at the Conference on Nuclear Structure, Pittsburgh, Pennsylvania, June, 1957 (unpublished).

TABLE VI. Transitions in W^{183} following the decay of Re^{183}. The intensity symbols are: s=strong, m=moderate, w=weak, v=very, e=extremely. Ordinary type refers to an exposure in the 99-gauss magnet. Italicized intensities were observed in an exposure in the 216-gauss magnet. Boldface transitions were observed in an exposure in the 350-gauss magnet.

Initial and final states	Transition energy (kev) (from MBMD)[a]	K	L_I	L_{II}	L_{III}	M_I	M_{II}	M_{III}	N	O
IH	40.97		ew	...[b]	ew?					
BA	46.48		vs	w	w	ms	ew	ew	w	vw
CB	52.59		ms	w	vw	wm	ew[c]	ew[c]	w	
FE	82.92		ew	ew	...[b]	ew[c]	ew[c]	ew[c]	ew[c]	ew[c]
FD	84.70	ew	≤m[d]	ew[c]	≤ew[e]	ew			ew[c]	
CA	99.07	vw	vw	ms	ms		<wm[f]	w	vw	
GD	101.94				no lines seen from Re^{183} decay					
g	102.49				no lines seen from Re^{183} decay					
HG	103.14				no lines seen from Re^{183} decay					
DC	107.93	m	wm	≤wm[f]	≤vw[h]	vw				
EC	109.73	ms	wm	≤vw[h]	≤w[i]	vw				
HF	120.38				no lines seen from Re^{183} decay					
g	142.25	≤m[d]								
IG	144.12	≤ew[e]								
DB	160.53	ew								
IF	161.36	ew								
EB	162.33	vvs	ms	w	vw	wm			vw	ew[c]
FC	192.64	ew, *w*								
HE	203.27				no lines seen from Re^{183} decay					
HD	205.06	ew[c]								
EA	208.81	m, *ms*	vw, *m*			*vw*				
GC	209.87	ew?[c]		ew[c]						
IE	244.26	ew[c]								
FB	245.3[j]	ew								
ID	246.05	w, *ms*	*w*							
FA	291.71	*wm*		*w*			*w*			
HC	313.03	*w*								
IC	354.04	*w*	**ew**?[c]							
HB	365.60	**ew**?[c]								
IB	406.58	**ew**?[c]								

[a] See reference 28.
[b] Masked.
[c] Re^{183} lines reported for the first time.
[d] L_I 84.70, K 142.25 superimposed.
[e] L_{III} 84.70, K 144.12 superimposed.
[f] L_{II} 107.93, M_{II} 99.07 superimposed.
[g] Transitions not assigned to the decay scheme by MBMD.
[h] L_{III} 107.93 and L_{II} 109.73 superimposed.
[i] L_{III} 109.73 and L_{II} 111.20 (Re^{184}) superimposed.
[j] Lines of transition *FB* were not seen by MBMD. The energy of this transition was reported by TRGSH.

the gross Re^{183} spectrum. Because these data were not reported by TRGSH, we feel that it might be useful to further studies of this region to report them. The energies and intensities of the gross (composite) gamma peaks of Re^{183} are listed in Table V.

The half-life value of Re^{183} was determined by following the decay of its characteristic K x-ray and 160-kev peaks in a scintillation spectrometer. This decay was followed for more than five half-lives. In both cases the decay was as a simple exponential and a weighted average of the two results yields a half-life value of 71 ± 3 days. This result is in agreement with the value of 67.6 ± 2.5 days obtained by Foster, Hilborn, and Yaffe.[34]

In order to determine the new lines of Re^{184} it was necessary to analyze conversion electron spectra containing many Re^{183} lines. In the process of doing this, we observed evidence for several transitions observed by MBMD in Ta^{183} decay but not reported by TRGSH in Re^{183} decay. For the sake of completeness, we reproduce in Table VI the table of electron lines of transitions in W^{183} observed in Re^{183} by TRGSH with those lines indicated that we report for the first time. Because these transitions do not add materially to the conclusions of TRGSH, we do not attempt to discuss them further here.

K-AUGER ELECTRONS OF TUNGSTEN

The study of the electron spectrum of the electron-capturing rhenium isotopes provided an excellent opportunity to obtain intensities and energies of many of the K-Auger electron lines of tungsten. These data are listed in Table VII.

The data have been used to test the conclusions of Bergström and Hill[35] regarding the calculation of energies of KL_pL_q-Auger lines. From these energies we calculated a "ΔZ" for each transition. These are in very good agreement with the ΔZ's proposed by Bergström and Hill.[35] These energy data have previously been reported by TRGSH.

[34] Foster, Hilborn, and Yaffe, Can. J. Phys. (to be published).

[35] I. Bergström and R. D. Hill, Arkiv Fysik 8, 21 (1954).

TABLE VII. Energies and intensities of KL_pL_q-Auger electrons of tungsten. The lines observed in plate 1 were mainly from Re^{183} decay; those on plate 2 from Re^{182} decay. The uncertainties in ΔZ are set by those of E_e.

Auger electron	Relative intensities			Plate 1		Plate 2		Average
	Plate 1	Plate 2	Average	Energy (kev)	ΔZ	Energy (kev)	ΔZ	ΔZ
KL_IL_I	1.4±0.3	1.3±0.3	1.3±0.2	45.09±0.05	0.57±0.12	45.07±0.05	0.61±0.14	0.59±0.09
KL_IL_{II}	···	2.7±0.5	2.7±0.5	45.91±0.5[a]	···	45.63±0.05	0.60±0.14	0.60±0.14
KL_IL_{III}	0.9±0.2	2.3±0.5[b]	0.9±0.2	46.93±0.05	0.88±0.14	46.97±0.05	0.76±0.14	0.82±0.10
$KL_{II}L_{II}$		Not seen						
$KL_{II}L_{III}$	2.3±0.5	2.6±0.5	2.5±0.4	47.50±0.05	0.82±0.14	47.51±0.05	0.79±0.14	0.80±0.10
$KL_{III}L_{III}$	1.0[c]	1.0[c]	1.0	48.86±0.05	0.76±0.14	48.85±0.05	0.79±0.14	0.78±0.10

[a] KL_IL_{II}, N_I 46.48 superimposed (Re^{183} exposure).
[b] KL_IL_{III}, K 116.40 superimposed (Re^{182} exposure).
[c] Value used for normalization.

TABLE VIII. Energies and intensities of the KL_pM_q- and KL_pN_q-Auger electrons of tungsten. The limits of error of ΔZ correspond to the limits of error on the electron energies. The intensities are normalized relative to value of 1 for the intensity of the $KL_{III}L_{III}$ intensity in Table VII.

Auger electron	Intensity	Electron energy (kev)	ΔZ	E_e calculated assuming $\Delta Z=1$ (kev)
KL_IM_I	0.6±0.2	54.51±0.05	0.83±0.41	54.49
KL_IM_{II}	0.5±0.2	54.74±0.05	1.09±0.45	54.75
KL_IM_{III}	0.6±0.2	55.03±0.05		55.06
$KL_{II}M_I$			1.07±0.41	55.04
$KL_{II}M_{III}$	0.3±0.1	55.53±0.05	1.89±0.55	55.61
$KL_{III}M_I$	0.5±0.2	56.37±0.05	1.08±0.41	56.38
$KL_{III}M_{II}$	0.7±0.3	56.64±0.05	0.91±0.45	56.63
$KL_{III}M_{III}$[a]	0.9±0.3	56.96±0.05	0.89±0.55	56.95
$KL_IN_I-N_{III}$[a]			···	···
$KL_{II}N_I-N_{III}$	0.5±0.2	57.43±0.05	···	···
$KL_{III}N_I-N_{III}$	0.2±0.1	58.82±0.05	···	···
$KMM-N$	weak bands			
KNN	weak bands			

[a] $KL_{III}M_{III}$, KL_IN's superimposed.

In Table VIII we also list intensities for the KL_pL_q-Auger electrons, again from the two samples. The method of relating intensities to photographic blackening has been described by Mladjenović and Slätis.[13] The uncertainty in the intensities is about 20%.

In a treatment similar to that employed for the KL_pL_q-Auger lines, the energy, ΔZ, and intensity of the KL_pM_q-Auger lines observed are reported in Table VIII. Because of the smaller energy difference between the M_q shells than that between the L_q shells, the limits of error on ΔZ corresponding to the same energy uncertainty are much larger. We do not report a ΔZ for the KL_pN_q-Auger lines in Table VIII because the energy difference is less than the energy uncertainty. The intensity uncertainties are also larger in these cases because the lines are very close-lying, making accurate analyses difficult. Very weak bands corresponding to the KMM- and KNN-Auger lines were also observed, but the energy uncertainty was too great to permit any interpretation of the data.

The over-all trend indicates that ΔZ tends to approach unity as the binding energy of the third electron decreases.

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