Decay Scheme of Re^{183} and Rotational Bands of Daughter Nucleus W^{183}†

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The electron-capture decay of 70-day Re^{183} has been studied, principally by conversion electron spectroscopy at 0.1% resolution. All but one of the eighteen gamma transitions identified in the present study have been seen by others from beta decay of Ta^{183} to the same daughter nucleus W^{183}. The transition intensities of the present study suggest an assignment of 5/2+ to Re^{183}. New information on $M1-E2$ mixing ratios for some of the gamma transitions is obtained.

INTRODUCTION

RHENIUM-183 was first produced and studied by Hicks and Wilkinson,[1] who characterized it as an electron-capturing isotope of ~240 days half-life, but we now prefer a half-life of 70 days.[2] Der Mateosian and Goldhaber[3] have produced a 5.5-second isomer of beta-stable W^{183}, and Campbell and Goodrich[4] report gamma rays of 0.12 and 0.17 Mev for this isomer. Recently, Poë[5] measured these gamma rays as 0.105 and 0.155 Mev. From their high-resolution beta- and gamma-spectroscopic studies of the beta-emitter Ta^{183}, Murray, Boehm, Marmier, and DuMond[6] have obtained extensive information on the levels of the daughter nucleus W^{183}, and from these data Kerman[7] has made a theoretical analysis of the W^{183} level scheme based on the Bohr-Mottelson[8] rotational model. The majority of the prominent gamma transitions in W^{183} are of the $M1-E2$ mixed type, and Kerman has calculated expected mixing ratios. The data of the present paper allow us to assign numerical values or limits for some of these mixing ratios on the basis of L-subshell conversion coefficients. In addition, the data give information regarding the electron-capture transitions themselves.

INSTRUMENTS AND EXPERIMENTAL PROCEDURE

The most extensive and useful measurements in the study of Re^{183} were made with uniform-field permanent-magnet beta spectrographs, described previously by Smith and Hollander.[9] Samples were usually prepared by electrodeposition of the activity onto 0.010-inch diameter platinum wires. Electron lines were detected photographically on glass-backed Eastman No-Screen x-ray plates with 25 μ emulsion thickness. The resolution achieved in these experiments (full width at half-maximum) was about 0.1%.

Some beta spectroscopic measurements were also carried out at about 3% resolution, using the annular-focusing thick-lens solenoidal spectrometer developed and described by O'Kelley.[10] The resolution of this instrument was not sufficient to achieve a separation of the close-lying lines in many regions of the spectrum, hence the lens spectrometer measurements were of value only in providing supplementary intensity checks.

Gamma spectroscopic and coincidence measurements were attempted with NaI(Tl) scintillation detectors, but no really useful additional information on Re^{183} decay other than half-life[2] was obtained by these means, again because of insufficient energy resolution.

The Re^{183} was produced by thick-target irradiations of tantalum foils by alpha particles from the Crocker 60-inch cyclotron. Incident energies of 48 and 28 Mev were employed in separate experiments. Foils were bombarded in the intense internal beam of the cyclotron in a special probe assembly with direct cooling by water which circulated behind the foils at high pressure.

The initial steps of the carrier-free chemical separation procedure involved a distillation of the rhenium (probably as volatile oxybromides) from concentrated sulfuric acid solution according to the method of Gile, Garrison, and Hamilton.[11] The distillate was trapped in cold 15N nitric acid and the nitric acid and bromine removed by evaporation. The resulting sulfuric acid solution was partially neutralized with ammonium hydroxide to about pH 2 and then transferred to a small electroplating cell[9] with a 0.010-inch platinum wire cathode, which served as the beta-spectroscopic source after cathodic electrodeposition at a current density of about six amperes per square decimeter. Sources for the

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[1] H. G. Hicks and G. Wilkinson, Phys. Rev. **77**, 314 (1950).
[2] There is serious disagreement concerning the correct half-life value for Re^{183}. B. J. Stover [Phys. Rev. **80**, 99 (1950)] lists the value 120 days without citing supporting evidence. S. E. Turner and L. O. Morgan [Phys. Rev. **81**, 881 (1951)] suggest a value of 155 days in their work. Dr. Donald Strominger has recently followed the decay of the prominent 162-kev gamma peak in a sample containing Re^{183} and finds a half-life of 70±10 days. We have used this 70-day value for ft-value calculations.
[3] E. der Mateosian and M. Goldhaber, Phys. Rev. **76**, 187(A) (1949).
[4] E. C. Campbell and M. Goodrich, reported in Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[5] A. J. Poë, Phil. Mag. **46**, 611 (1955).
[6] Murray, Boehm, Marmier, and DuMond, Phys. Rev. **97**, 1007 (1955).
[7] A. K. Kerman, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 15 (1956).
[8] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953); in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. 17.
[9] W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956).
[10] G. D. O'Kelley, California Research and Development Company Report MTA-38, May, 1954 (unpublished).
[11] Gile, Garrison, and Hamilton, J. Chem. Phys. **18**, 995 (1950).

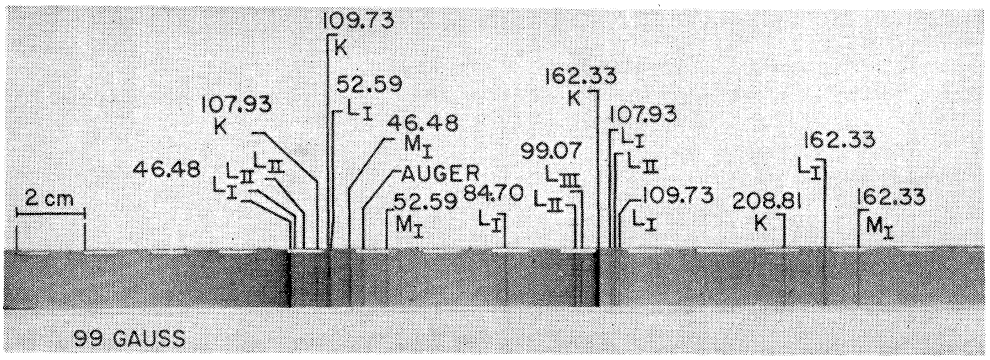


FIG. 1. Photographic plate from the 99-gauss permanent magnet spectrograph. Source mainly Re^{183} with some Re^{184}. Some of the stronger lines are labeled.

solenoidal spectrometer were prepared in a similar manner on copper cathodes.

EXPERIMENTAL RESULTS

After decay of the shorter-lived rhenium activities, the electron spectrum of Re^{183} could be studied with interference only from a relatively small amount of 50-day Re^{184}. A reproduction of one of the spectrograms is given in Fig. 1, with some of the more intense electron lines labeled. The level scheme of Murray *et al.*[6] as drawn by Kerman[7] with his spin assignments is shown in Fig. 2.

Electron lines corresponding to most of the transitions reported by Murray *et al.*[6] were observed, and in addition a weak K line of the transition FB, not reported by them, was seen.

Tables I and II summarize the electron line intensity data from our experiments. On reading the film a rough visual estimate of line intensity was made, and the corresponding letter symbols are to be seen in Table I.

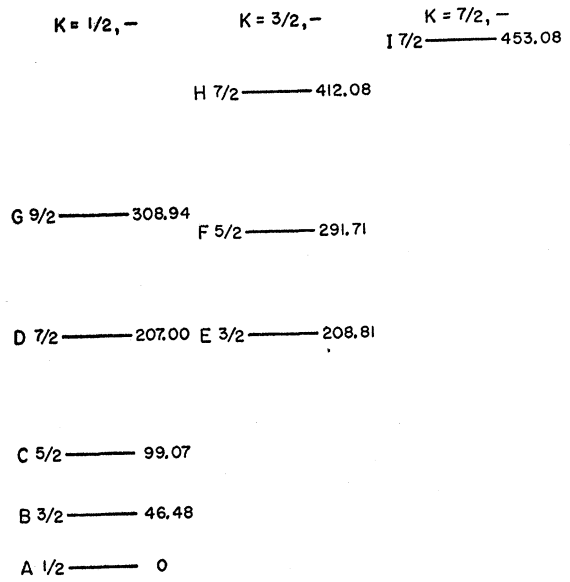


FIG. 2. Level scheme of W^{183} from Murray *et al.*[6] with rotational band assignments according to Kerman.[7]

The density of the lines was also analyzed on a recording densitometer, and for the more prominent lines it was in this way possible to calculate numerical values for relative line intensities from the densitometer trace, using the method of Mladjenovic and Slätis.[9,12] These photographic intensity comparisons are subject to considerable uncertainty when the electron lines in question are of widely differing energies; however, the numerical estimates of relative L-subshell conversion coefficients should be quite good because of approximate cancellation of factors involving film efficiency and geometry. Hence in Table I we have given no numerical line intensity values, but in Table III we have listed experimental relative L-subshell line intensities, believed to be accurate to $\pm 25\%$. From these subshell ratios and the theoretical conversion coefficients of Rose[13] plotted in Figs. 5 and 6 of the paper of Murray *et al.*[6] we have calculated the $M1-E2$ mixing ratios for the gamma transitions. These are given in Table III as percentage $E2$ character of total photons, along with Kerman's[7] theoretically predicted values of the same quantity.

Table II lists the observed Auger lines. In addition to lines given in Tables I and II, we have seen K(ew), L_I(ew), L_{II}(w), L_{III}(w), and M(w) lines of a 111.2-kev gamma ray which we assign as the $E2$ transition from the first excited state to ground state in W^{184} following electron capture decay of Re^{184}. This transition has been observed in the Coulombic excitation experiments of Stelson and McGowan[14] and Bernstein and Lewis,[15] who quote values of 112 kev and 116 kev, respectively. Of unassigned long-lived lines with greater intensity than "extremely weak" there are only two, at electron energies 46.45 kev (vw) and 52.16 kev (vw).

Using our intensity data supplemented with conversion coefficients and other relative intensities from the work of Murray *et al.*,[6] we have estimated roughly the total intensities of gamma transitions to and from the various levels. From these estimates it appears that the electron capture of Re^{183} mainly populates levels

[12] M. Mladjenovic and H. Slätis, Arkiv Fysik **8**, 65 (1954).
[13] M. E. Rose (privately circulated tables).
[14] P. H. Stelson and F. K. McGowan, Phys. Rev. **99**, 112 (1955).
[15] E. M. Bernstein and H. W. Lewis, Phys. Rev. **99**, 617(A) (1955).

TABLE I. Gamma transitions in W^{183}. The intensity symbols are: s = strong, m = moderate, w = weak, v = very, e = extremely. Ordinary type refers to moderate exposure in 99-gauss magnet. Boldface type refers to long exposure in 216-gauss magnet.

Initial and final states	Gamma-ray energy (kev) (from Murray *et al.*[b])	List of conversion lines observed in Re^{183} decay								
		K	L_I	L_{II}	L_{III}	M_I	M_{II}	M_{III}	N	O
IH	40.97		ew	masked	ew?					
BA	46.48		vs	w	w	ms	ew	ew	w	vw
CB	52.59		ms	w	vw	wm			w	
FE	82.92		ew	ew	masked					
FD	84.70	ew	<m[d]		≤ew[e]	ew				
CA	99.07	vw	vw	ms	ms		<wm[f]	w	vw	
GD	101.94				no lines seen from Re^{183}					
a	102.49				no lines seen from Re^{183}					
HG	103.14				no lines seen from Re^{183}					
DC	107.93	m	wm	≤wm[f]	≤vw[g]	vw				
EC	109.73	ms	wm	≤vw[g]	≤w[h]	vw				
HF	120.38				no lines seen from Re^{183}					
a	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	
FC	192.64	ew, **w**								
HE	203.27				no lines seen from Re^{183}					
HD	205.06				no lines seen from Re^{183}					
EA	208.81	m, **ms**	vw, **m**			**vw**				
GC	209.87				no lines seen from Re^{183}					
IE	244.26				no lines seen from Re^{183}					
FB	245.3[c]	ew								
ID	246.05	w, **ms**	**w**							
FA	291.71	**wm**		**w**			**w**			
HC	313.03	**w**								
IC	354.04	**w**								
HB	365.60				no lines seen from Re^{183}					
IB	406.58				no lines seen from Re^{183}					

[a] Transitions not assigned to decay scheme by Murray *et al.*[6]
[b] See reference 6.
[c] Lines of transition FB were not seen by Murray *et al.*[6] The energy determination for this transition is ours.
[d] 84.70L_I and 142.25K not resolvable.
[e] 84.70L_{III} and 144.12K not resolvable.
[f] 107.9L_{III} and 99.07M_{II} not resolvable.
[g] 107.9L_{III} and 109.7L_{II} not resolvable.
[h] 109.7L_{III} and 111.2L_{II} in W^{184} not resolvable.

E ($K=3/2, I=3/2-$), F ($K=3/2, I=5/2-$), I ($K=7/2$, $I=7/2-$) and H ($K=3/2$, $I=7/2-$) in roughly the ratio 5:3:0.7:0.2. The only conclusions that can be reached concerning decay of Re^{183} to states B, C, and D of W^{183} are that electron capture to these states is at least less than that to E and could be very small. The uncertainty arises because these states are heavily populated by gamma transitions. Although the lack of information on the total decay energy precludes calculation of ft values, one can deduce that the logft value for the principal electron capture branch (to state E) must be somewhat greater than 6.5, since a lower limit on the decay energy to state E is set by the energy difference between states E and I. Thus, an assignment of first forbidden seems required, which assignment would be consistent with the configuration $K=5/2$, $I=5/2+$ for Re^{183}; such a configuration has been proposed by

TABLE II. Auger lines observed in decay of Re^{183}.

Line	Exptl. energy kev	Theoret. energy[a]	Exptl. Int.
KL_IL_I	45.0_7	45.07	vw
KL_IL_{II}	45.5_4	45.62	ew
KL_IL_{III}	47.0_4	46.96	vw
$KL_{II}L_{II}$	···	46.17	masked
$KL_{II}L_{III}$	47.6_0	47.51	w
$KL_{III}L_{III}$	48.9_4	48.85	vw
$KL_{III}M_{III}$	56.9_4	56.95	ew

[a] Theoretical energies calculated according to formula of I. Bergström and R. D. Hill, Arkiv Fysik **8**, 2, 21 (1954).

TABLE III. $M1-E2$ mixing ratios for the gamma transitions.

Transition	Experimental ratio (this work) $\alpha_{LI}:\alpha_{LII}:\alpha_{LIII}$	Experimental photon percent $E2$ $E2/(E2+M1)$		Theoretical percent $E2$ (Kerman)
		This work Re^{183}	From intensities of Murray *et al.*[a] Ta^{183}	
IH	···	···	1	···
BA	12:2.1:1	1	1	0.6
CB	8.6:1.6:1	2	3	3
CA	···:1.1:1	100	100	100
EB	8.0:1.8:1	23	···	10
FE	···	~20–50	···	20
FD	···	very small	···	0.8

[a] See reference 6.

Mottelson and Nilsson[16] for the naturally occurring isotopes Re^{185} and Re^{187}.

The striking differences in relative gamma-ray intensities between the present observations on Re^{183} and those of Murray *et al.*[6] on Ta^{183} arise from the different population of states by the primary beta process. Our relative conversion line intensities from a common level generally check those of Murray *et al.*[6] to within our experimental error; we do encounter difficulty in that we find a large excess of gamma transitions populating level D over those leaving D if we use Murray's decay fraction percentages, specifically their figure of 65% for the fraction of depopulation of level F which is due to transition FD. The low L_I conversion coefficient of Murray *et al.*[6] for FD as compared with FE also points out the need for additional study on the question of the transitions depopulating level F.

A weak line of the correct energy to be the K line of transition FB was observed. Murray *et al.*[6] did not report this line, but the transition has been suggested as important by Kerman.[7] Using K-conversion coefficients of 0.38 for FB ($M1$) and 0.07 for FA ($E2$), we estimate the photon intensity ratio of FB to FA as ~ 0.1 in disagreement with Kerman's theoretically predicted ratio of 0.55.

The qualitative observation may be made that transition FD must be quite pure $M1$ on the basis of the extreme weakness of the L_{III} line. Kerman's theoretical estimate for FD is 0.8% $E2$. FE must have considerably more $E2$ admixture than FD, since the L_{II} line of FE is nearly as intense as the L_I line. The percentage $E2$ for FE thus should be around 20–50%, as compared with Kerman's theoretical estimate of 20%. We support Murray's tentative assignment of $M1$ to transition EC, by the observation that the L_{II} line is very weak compared to the K and L_I lines.

DISCUSSION

With our assignment of $K=5/2$, $I=5/2+$ to Re^{183}, we would expect relatively less electron capture directly to the ground rotational band than to the upper bands, since by the K-selection rules decay to the ground band would be of the $\Delta K=2$, yes, unique first forbidden type. The accuracy of the present gamma-ray intensity data is not sufficient to provide a quantitative estimate of the branching to this band, however.

To the extent that K is a good quantum number, the ft values for electron-capture decay to states E, F, and H (in the same rotational band) should be in the ratio of squares of the Clebsch-Gordan coefficients, $(I_i 1 K_i K_f - K_i | I_i 1 I_f K_f)^2$. (These relationships have been given and applied by Alaga, Alder, Bohr, and Mottelson.[17]) With Kerman's[7] term assignments for E, F, and H, this theoretical ratio of ft values is 1:0.43:0.072. Our observation of the surprisingly small electron-capture to state H (4% of that to state E) is in qualitative accord with the theoretical ratio, since this difference does not seem to be explained by decay energy arguments alone.

Another test of this type of intensity relationship can be made with the gamma ray transitions which depopulate level C. The theoretical ratio of reduced transition probabilities[8] of the $E2$ radiation from level C is given by

$$\left(\frac{B_{CA}}{B_{CB}}\right)_{theor}=\frac{(5/2\ 2\ 1/2\ 0|5/2\ 2\ 1/2\ 1/2)^2}{(5/2\ 2\ 1/2\ 0|5/2\ 2\ 3/2\ 1/2)^2}=3.5.$$

Using our determination of 2% $E2$ in transition CB and employing Murray's photon ratio CA:CB=22:24, we find

$$(B_{CA}/B_{CB})_{exp}\approx 3.$$

It is gratifying to see in what detail the unified model for deformed nuclei is able to correlate a large amount of experimental information regarding the states of W^{183}. That the present data accord well with Kerman's predictions gives added confidence in his approach.

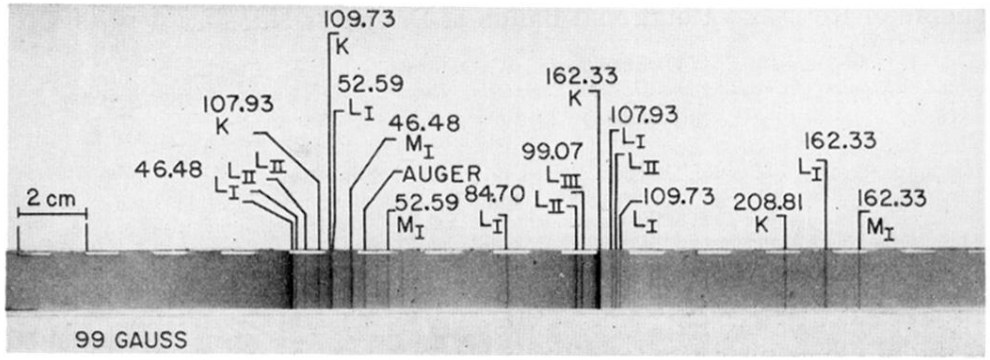
ACKNOWLEDGMENTS

One of us (S. Thulin) wishes to express his gratitude to Professor G. T. Seaborg and others of the University of California Radiation Laboratory for their hospitality and to the Swedish Atomic Committee for a grant. We are grateful to Dr. Aage Bohr, Dr. A. K. Kerman, Dr. S. G. Nilsson, and others associated with the Copenhagen group for sending us useful reports in advance of publication.

We pay tribute to the memory of G. Bernard Rossi, late supervisor of the Crocker 60-inch cyclotron, for the invaluable help which he gave to us in this and in many previous experiments.

[16] B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).

[17] Alaga, Alder, Bohr, and Mottelson, Kgl. Danske Videnskab. Selskab, Mat. fys. Medd. **29**, No. 9 (1955).



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