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Decay of Os^{182} and Os^{183}. II. Coincidences, Conversion Coefficients, and Decay Schemes*

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The 382-kev transition in Re^{183} was shown to have a conversion coefficient of $(1.09\pm0.14)\times10^{-2}$ which established the transition as $E1$. The half-life of the state from which this arises was found to be $(7.7\pm0.5)\times10^{-9}$ sec from delayed coincidence measurements, indicating a hindrance factor of 3×10^{6} relative to the single particle value. Other transition multipolarities were assigned from their conversion coefficients, L subshell and K/L ratios as obtained from the preceding paper. Amongst these the 170.72-kev isomeric transition in Os^{183} was identified and shown to be $M4$ with a hindrance factor of 12. Decay schemes for Os^{183} and Os^{183m} are established and good agreement is obtained between the proposed spins and parities and those suggested by the scheme of energy levels in a spheroidal potential as calculated by Nilsson.

1. INTRODUCTION

In a preceding paper,[1] hereafter denoted by (I), measurements on the gamma-ray and conversion line spectra from certain osmium activities were described. The activities were produced by bombarding tungsten with alpha particles of various energies and later separating them chemically. Three main activities attributable to the decay of osmium isotopes were seen. These had half-lives in hours of 13.67±0.1, 9.9±0.3 and 21.1±0.3 and were assigned to the decay of Os^{183}, Os^{183m}, and Os^{182}, respectively.

In this paper further analysis of the data on conversion lines is made in order to obtain transition multipolarities. A measurement of the internal conversion coefficient of the 382-kev transition is reported. This measurement shows that the 382-kev transition is of the electric dipole type; such transitions are frequently found to be much slower than single particle transitions. A measurement was therefore made of the lifetime for decay of this radiation; it indeed proved to be slower than a single particle transition by a factor of about 10^{6}. Other coincidence measurements are also reported. Decay schemes are postulated and discussed in terms of the unified nuclear model.[2,3]

2. MEASUREMENT OF TRANSITION MULTIPOLARITIES

2.1 The Conversion Coefficient of the 382-kev Transition

The K-conversion coefficient of the 382-kev transition was measured relative to the conversion coefficients for the 569-kev and 1064-kev transitions occurring in Bi^{207} decay. These conversion coefficients have been measured previously by McGowan and Campbell,[4] by Ricci[5] and by Wapstra.[6] The values used here for the two conversion coefficients are 0.0164±0.002 and 0.103±0.010 for the 569-kev and 1064-kev transitions, respectively.

The method of measurement required preparation of sources of Os^{183} and Bi^{207} having approximately equal gamma intensities. Gamma spectra of the two sources were taken under identical geometrical conditions and the relative intensities of the 382-kev, 569-kev, and 1064-kev transitions were obtained by the method given in (I). The K lines of these transitions were then compared in intensity by use of the lens spectrometer; bias curves were taken to ensure 100% detection efficiency for the 382-kev K line and for higher energy electrons. From these results and assuming the values for the Bi^{207} conversion coefficients given above it was possible, after correcting for the decay of the Os^{183}, to obtain the conversion coefficient of the 382-kev gamma ray. The value obtained, combining the estimated errors for this experiment and the errors in the Bi^{207} conversion coefficients, is

$$\alpha_K(382)=(1.09\pm0.14)\times10^{-2}.$$

The values obtained by interpolation from the theoretical calculated points[7,8] are 1.15×10^{-2}, 3.2×10^{-2}, 8.8×10^{-2}, and 1.1×10^{-1} for $E1$, $E2$, $E3$, and $M1$ transitions, respectively. From the experimental value above it seems most likely therefore that the 382-kev transition is of the electric dipole type.

2.2 Deductions from L Subshell Ratios and K/L Ratios

If one assumes the accuracy of the present theoretical calculations of conversion coefficients it is usually

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

[3] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).

[4] F. K. McGowen and F. C. Campbell, Phys. Rev. **92**, 523 (1953).

[5] R. A. Ricci, Physica **23**, 693 (1957).

[6] A. H. Wapstra, Arkiv Fysik **7**, 279 (1954).

[7] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57ICCKI, issued by University of Illinois, Urbana, Illinois (unpublished)].

[8] M. E. Rose, *Internal Conversion Coefficients* (North Holland Publishing Company, Amsterdam, 1958).

TABLE I. K/L ratios, L subshell ratios, conversion coefficients, multipolarity assignments and relative intensities of transitions in Os^{183} decay. The errors in the conversion coefficients are likely to be of the order of ±20% except where otherwise indicated. $I(\gamma)$ is the relative intensity of the gamma-ray and $I(t)$ the relative intensity of the transition; for energies greater than about 200 kev these are equal within the accuracy of measurement. α_K and α_K(th) are the measured and the theoretical K-conversion coefficients[a] for the suggested multipolarities.

E kev	K	L_1	L_2	L_3	$I(\gamma)$	$I(t)$	α_K	α_K(th)	Multipolarity
114.44	4.2	1.00	0.15	0.06	0.27	1.19	1.5	3.0	$M1+(4\pm1)\%\ E2$
145.39	5.1	1.00	0.17	0.066	2.3×10^{-2}	6.1×10^{-2}		1.52	$M1+(6\pm2)\%\ E2$
151.02	4.2 ± 1.3	1.00						1.40	$M1$
167.90	6.6 ± 1	1.00	0.13		0.11	0.25	0.71	1.05	$M1+(6\pm3)\%\ E2$
197.10	5.6 ± 2	1.00						0.68	$(M1)$
236.20	b	1.00	0.28[c]	0.28[c]	0.07	0.07	3.10^{-2} [e]	3.5×10^{-2}	$E1$
259.83	3.8 ± 1.5		1[c,d]	1[c]	3.3×10^{-3}			8.6×10^{-2}	$E2$
381.76	8.2 ± 0.3	1.00	0.21	0.14	1.00		$(1.09\pm0.14)\times10^{-2}$	1.12×10^{-2}	$E1$
496.1	5.1 ± 0.2	1.00			≤0.05		2.2×10^{-2}	1.65×10^{-1}	$M2$
477.2					≤0.07		4×10^{-3}		
736.9					$\leq5\times10^{-3}$		2.1×10^{-2}		Not $E1$ or $E2$
807.8					1.5×10^{-2}		$(1\pm0.3)\times10^{-2}$		$E2$, $M1+E2$ or $E3$
851.1	6.5 ± 0.3	1.00			3.0×10^{-2}		1.7×10^{-2}	1.35×10^{-2}	$M1$
887.5 889.4					1.5×10^{-2}		$(2\pm0.7)\times10^{-2}$		$M1$ or $M2$

[a] See reference 8.
[b] K 236.2 obscured by $M1$ line of the 167.90 transition.
[c] These weak lines have to be measured by the comparison method; the accuracy is probably of order ±30%.
[d] The L_1 and L_2 lines are poorly resolved and the comparison method will give the intensity of the stronger of the two.
[e] Assuming the theoretical K/L ratio.

possible to obtain transition multipolarities and mixing ratios from measurements of the ratios of the intensities of the L and M subshell conversion lines. This method is particularly sensitive for low-energy (below about 200 kev) transitions in heavy nuclei. Experimentally the situation is often favorable because the lines are close together in energy and thus relative intensity measurements are good. The K/L ratios are much less sensitive than are the L and M subshell ratios to transition multipolarity but nevertheless in some cases measurement of the K/L ratio is of assistance in determining the multipolarity of a transition. Usually some other information, such as the absolute value of a conversion coefficient, is also required in order that an unambiguous assignment can be given.

(*i*) *The Decay of* Os^{183}

In Table I the relative intensities of the K and L subshells, the relative gamma-ray intensities, the relative transition intensities and the measured and theoretical conversion coefficients are given for some of the transitions assigned to Os^{183}. For information on the other transitions and on the M and N subshell ratios see Table III of (I). Where possible the intensity results are taken from the data of the double focusing spectrometer, or of the lens spectrometer, since these are likely to have the greatest accuracy. In other cases the densitometer method is preferred to the comparison method; the latter seems to give low results for very strong lines. In the region below about 150 kev it is likely that the intensities which we obtain are too low; they deviate by about a factor of two at 40 kev. This is apparent both because the measured conversion coefficients are too low and because the K/L ratios are also too low. The reason for this is not entirely clear; it may possibly be related to source thickness, particularly if the source is not uniformly thick. This reduction of detection efficiency will not appreciably affect deductions about the transition multipolarities from the L subshell ratios since the L lines are close together in energy. However in assessing the gamma intensity of, for example, the 145-kev transition, where the multipolarity can be deduced from the L subshell ratios but the gamma-ray is not directly observed, an empirical correction curve was used to correct the electron intensities; the gamma intensity was then deduced from the theoretical conversion coefficient. There is no obvious reason to suppose that the electron relative intensities will be seriously in error in the high-energy range. The measured conversion coefficients were deduced from the measured gamma-ray and electron intensities together with the value of $(1.09\pm0.14)\times10^{-2}$ for the K-conversion coefficient of the 382-kev transition.

(*ii*) *The Decay of* Os^{183m}

In paper I it was shown that a number of gamma-rays in the region of 1100-kev energy decayed with a half-life of 9.9±0.3 hours. In addition the conversion lines of a transition of energy 170.72 kev and half-life 9.5±0.5 hours were reported. The spacings of the conversion lines showed that this transition occurred in osmium rather than rhenium. It is therefore plausible to assume that all these transitions arise from the decay of the same state which, if this assumption is valid, must be a metastable state of an osmium isotope. For the reasons

TABLE II. Experimental and theoretical[a] relative electron intensities for a 170-kev transition in a nucleus with $Z=76$.

	K	L_1	L_2	L_3	M_1	M_2	N
expt.	1.30	1.00	0.33	1.50	0.38	0.54	0.25
$M3$	2.36	1.00	0.175	0.67			
$M4$	1.41	1.00	0.24	1.51			
$M5$	0.92	1.00	0.27	2.55			

[a] See reference 8.

given in (I) this isotope is taken to be Os^{183}. The isomeric transition is considered first of all. In Table II the measured relative intensities of the conversion lines are compared with theoretical relative intensities[8] for $M3$, $M4$, and $M5$ transitions.

From this comparison it seems almost certain that the transition is $M4$. The fact that the measured K/L ratio is a little low is not surprising since this occurs with other transitions in this region of energy, as has been mentioned before.

From the experimental electron intensities and gamma intensities the ratio of decay by the isomeric transition to total decay of the metastable state is found to be (0.46 ± 0.1). From the half-life of (9.9 ± 0.3) hours for the combined transition a partial half-life of 21.5 ± 4 hours is deduced for the isomeric transition. Taking the theoretical K and L conversion coefficients as 5.8×10^1 and 1.13×10^2, respectively and the experimental $(M+N+\cdots)/L$ ratio of 0.4 a value of $(1.67\pm0.35)\times10^7$ sec is obtained for the partial half-life of the 170.72-kev gamma ray.

We shall now consider the gamma rays arising from the K-capture branch of Os^{183m}. In all, five gamma-rays were assigned to this decay though, as Table III of paper I shows, they are not all assigned with certainty. In no case was it possible to observe more than one line of the L shell because the low-energy transitions were too weak and the high-energy transitions had small conversion coefficients. An attempt was made to estimate the multipolarity of the transitions from the conversion coefficients.

The radiation of about 1100 kev as observed in a sodium iodide spectrometer actually consists of two gamma-rays of energy 1102.0 kev and 1108.1 kev. These could not be resolved in any available gamma-ray spectrometer so that only a mean conversion coefficient for the two could be obtained. This value is $(3.8\pm0.8)\times10^{-3}$ and is to be compared with theoretical values of 1.3×10^{-3}, 3.3×10^{-3}, and 7×10^{-3} for $E1$, $E2$, and $M1$, respectively. Thus it seems likely that the transitions are both $E2$ or that one is $E1$ and the other $M1$. The first of these interpretations seems the more probable. As will be shown later, both of these transitions go to the ground state of Re^{183} and from intensity considerations must be fed directly. Thus if one transition is $E1$ and the other $M1$ these close-lying levels will have to be fed with roughly the same intensity by allowed and first forbidden K-capture branches, which is somewhat unlikely though not impossible. The K-conversion coefficient of the 1034.8-kev gamma-ray is estimated to be $(4.5\pm1.6)\times10^{-3}$ and thus this transition is also likely to be $E2$ or perhaps $M1$.

Since the L_1 line of the 67.26-kev transition is observed but the L_2 and L_3 lines are not it seems likely that this transition is predominantly an $M1$ transition. From the measured electron intensities and this assumption it is possible to estimate the total intensity of this transition. The value obtained is 0.13 relative to the intensity of the combined 1100-kev transition, the error being rather large since the conversion coefficient is not known exactly. This value is to be compared with a value of 0.13 for the relative intensity of the 1034.8-kev transition. The coincidence of these two values is of course due to chance but it seems possible that the two transitions may in fact have the same intensity.

There is no indication as to the multipolarity of the 147.0-kev transition. Intensities relative to that of the 1100-kev complex are estimated to be 0.17, 0.06, or 0.03 if the transition is $E1$, $E2$, or $M1$, respectively.

(*iii*) *The Decay of* Os^{182}

The information regarding the transitions attributed to the decay of Os^{182} is given in Table III. The accuracy of the conversion coefficient measurements is rather less than for the transitions of Os^{183} decay; nevertheless it seems possible to make some multipolarity assignments. The gamma-rays from the two lower energy transitions were not observed; thus, only very approximate estimates of their total intensities can be made; intensity measurements with the permanent magnet spectrographs below about 40-kev electron energy are subject to large errors. The L and M subshell ratios are probably still fairly good however since the lines are close together in energy.

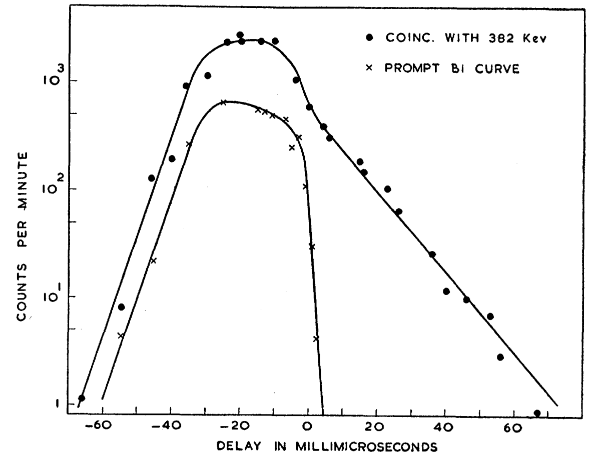

FIG. 1. Coincidence delay spectrum of the 382-kev gamma-ray taken with the K x-rays and higher energy radiation, detected in a $1\frac{1}{2}$-in. diam×1-in. NaI crystals.

TABLE III. K/L ratios, L subshell ratios, conversion coefficients, multipolarity assignments and relative intensities of transitions attributed to Os^{182} decay.

E kev	K	L_1	L_2	L_3	$I(t)$	α_K	α_K(th)	Multipolarity
27.60		1.00	0.23	0.07	(1)			$M1+(0.3\pm0.1)\%\ E2$
55.50		1.00	0.12	0.04	(0.5)			$M1+(0.6\pm0.2)\%\ E2$
180.18		1.00	0.14 ± 0.05		0.7 ± 0.15	$(4\pm2)\times10^{-2}$	7.0×10^{-2}	($E1$)
263.3					0.14 ± 0.03	$(4\pm2)\times10^{-2}$	2.8×10^{-2}	($E1$)
509.9	6.4 ± 0.3	1.00			1.00	$(4\pm1.5)\times10^{-2}$	5.0×10^{-2}	$M1$

3. DELAYED COINCIDENCE MEASUREMENT OF THE HALF-LIFE OF THE 382-kev TRANSITION IN Re^{183}

The electric dipole transitions which are emitted from low-lying nuclear energy levels are forbidden by selection rules on almost any model, and many have been observed experimentally to be much slower than the single particle estimate. For this reason it seemed worth while to attempt to measure the lifetime of the 382-kev transition which was shown in the last section to be of the electric dipole type.

For these measurements a conventional coincidence system of the fast-slow type in conjunction with a 50-channel pulse-height analyzer was used. The resolving time $2\mathcal{T}$ of the fast coincidence circuit was about 30 mμsec and that of the slow circuit was about 4 μsec. The gamma-rays were observed with two 1-in.$\times1\frac{1}{2}$-in. diameter NaI(Tl) crystals. Suitable absorbers were used to prevent or to minimize scattering from one crystal into the other.

In the first experiment a single channel analyzer was not available and coincidences were made between the K x-rays plus all higher energy gamma-rays and the 380-kev radiation which was observed on the 50-channel pulse analyzer. The delay curve obtained is shown in Fig. 1. Some knowledge of the decay scheme, shown in Fig. 3, is required in order to interpret this result. If this scheme is assumed and it is further assumed that the 380-kev radiation is the only delayed radiation then it is apparent that the delay curve will contain both prompt and delayed components. The full line drawn through the experimental points is a curve computed from the shape of the "prompt delay curve" assuming equal prompt and delayed components, the half-life for the delayed component being 8×10^{-9} sec. A "prompt delay curve" was obtained by taking coincidences between the K x-rays and 569-kev radiation from a Bi^{207} source, the gain of the photomultiplier being reduced so that the 569-kev radiation gave the same pulse height as the 382-kev radiation did previously. The asymmetry in the prompt curve is partly statistical in origin, arising from the relatively long decay time of the NaI and the large difference in energy of the two radiations. A further reason for it is that a gate was employed on the high-energy side and not on the low-energy side. A curve having nearly the same shape as this "prompt curve" though slightly shifted in position was obtained with the Os^{183} source when coincidences were taken between the K x-radiation plus higher energy radiation and the radiation with energy higher than 382 kev. This radiation corresponded to counts in the top channel of the pulse-height analyzer so that this curve was obtained simultaneously with that for the 382-kev line. The half-life obtained for the 382-kev transition is $(7.7\pm0.5)\times10^{-9}$ sec.

In a second experiment a single-channel pulse-height analyzer was also available and this was used to gate on the 380-kev peak. The K x-ray peak, the 114-kev peak and the 167-kev peaks were observed on the 50 channel analyzer. The results of this are shown in Fig. 2. It can be seen that the delay curves for coincidences with the K x-rays and with the 167-kev radiation show the 8×10^{-9} sec delay while that for 114-kev coincidences does not. This is consistent with the proposed decay scheme of Fig. 3. It should not be inferred from the slope on the delay curve for the 114-kev gamma-ray that this transition has also a lifetime in the 10^{-9} sec region; this slope is almost certainly instrumental.

4. COINCIDENCE MEASUREMENTS AND DECAY SCHEMES

For the slow coincidence measurements a coincidence circuit of resolving time $2\mathcal{T}$ equal to 4 μsec in conjunction with a single-channel analyzer, a 50-channel analyzer of the "Snapper" type and two 1-in.$\times1\frac{1}{2}$-in. diam NaI(Tl) crystals was used. It was hoped to make quantitative measurements with this arrangement. In

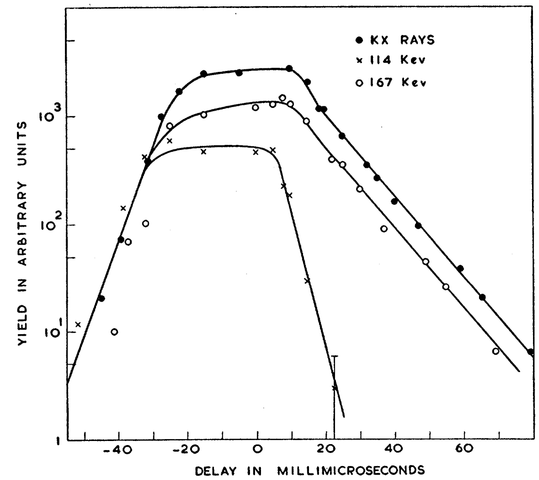

FIG. 2. Coincidence delay spectra of the 382-kev gamma-ray taken with the K x-rays, 114-kev and 167-kev gamma-rays.

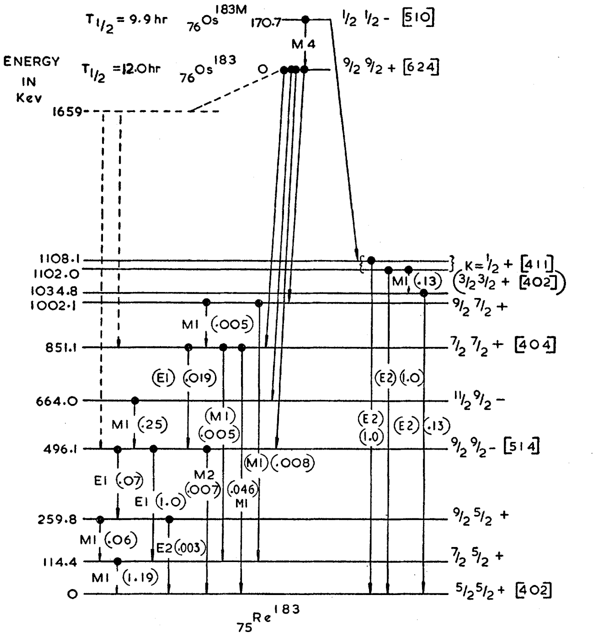

FIG. 3. Proposed decay schemes for Os^{183} and Os^{183m}. The numbers in round brackets are the relative transition intensities. They are taken relative to the intensity of the 382-kev transition for Os^{183} decay and to that of the 1108-kev transition for Os^{183m} decay.

order to do successful measurements with a source having a complicated spectrum, a half-life of about 12 hours and daughter nuclei with similar half-lives it is desirable to take data rather quickly. Unfortunately the electronic system available allowed only rather slow counting rates so that the results are rather rough. Nevertheless they enable some details of the decay schemes to be checked. Care was taken in the measurements to avoid scattering from one crystal into the other. The results will be given in the following sections on the setting up of the decay schemes.

4.1 The Decay Scheme of Os^{183}

The postulated decay scheme is shown in Fig. 3. Consider first the strong transitions (see Table I) having energies of 114.44, 167.90, and 381.76 kev. Both slow and fast coincidence experiments show that all three gamma-rays are in coincidence with one another. Allowing for experimental error, the 381-kev and 114-kev transitions have roughly equal intensities while the intensity of the 167-kev transition is considerably lower. From this it follows that either a 114-kev state or a 381-kev state lies lowest. The fast coincidence measurements show that the 381-kev transition is slow ($T_{\frac{1}{2}} = 7.7\times10^{-9}$ sec). However these measurements also show that coincidences between the 167-kev and the 381-kev gammas have this delay while those between the 114-kev and 381-kev gammas do not (see Fig. 2). The 114-kev transition being $M1$ with very small $E2$ admixture would be expected to be relatively fast so this establishes that the 114-kev state lies lowest. Thus the 381-kev and 167-kev gammas arise from the decay of states at 496.1 and 664.0 kev. Other possibilities seem unlikely from intensity considerations, and the positions of these three states seem fairly certain. With these states as a basis the state at 259.8 kev can also be fixed with fair certainty. This arises partly from the energy sums which in all cases are correct to within ±0.05% and partly from the very satisfactory consistency of the scheme with the measured transition multipolarities. Further support is given by the coincidence measurements which show that the 236-kev gamma ray is not in coincidence with the 381-kev gamma ray.

The 851-kev gamma ray is shown by the coincidence measurements to have no radiation in coincidence with it of a sufficiently high intensity for the transition to be other than a direct ground-state transition. There must then be a level at 851.9 kev. Other transitions from this level and also the level at 1003 kev are assigned only on the basis of energy sums, again correct to within ±0.05%. A little support is however given to the assignment of the 1003-kev level from the fact that the first rotational state of the 851-kev level would be expected at about this energy if the moment of inertia of this band was about the same as that of the ground-state band; as we shall see later the spin of the 851-kev level is expected to be $\frac{7}{2}$. The coincidence measurements are not in disagreement with these transition assignments but cannot be used to support them. It is desirable that further coincidence measurements be made with a more satisfactory arrangement.

A number of other energy sums can be made with the observed transition energies. However it is felt that little confidence can be placed in any further energy levels deduced in this way; the sums, excluding those consistent with the decay scheme of Fig. 3, are given below.

$$736.9 = 477.2 + 259.8,$$

$$1162.9 = 355.45 + 807.8.$$

Finally it should be remarked that the half-life of 13.67±0.1 hours obtained for the Os^{183} activity is not the half-life for Os^{183} decay. This apparent half-life is observed because the ground state of Os^{183} is fed from the isomeric state via the 170-kev $M4$ transition. Correcting for this a half-life of (12.0±0.5) hours is found for the decay of Os^{183}. Because of the rather close values for the half-lives of Os^{183} and Os^{183m} the deviation from linearity up to about 100 hours is not great. Though these results certainly do not prove that there is a curvature in the decay curve they are not inconsistent with there being one. The measurement at 159 hours has too large an error to help in this matter. Foster, Hilborn, and Yaffe,[9] who found a value of (15.4±0.3) hours for the half life of the osmium ac-

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[9] J. S. Foster, J. W. Hilborn, and L. Yaffe, Can. J. Phys. **36**, 555 (1958).

tivity, formed the activity by a different reaction hence they may have formed relatively more of the isomeric state. This might account for the difference in observed half-lives.

4.2 The Decay Scheme of Os^{183m}

The slow coincidence measurements showed that less than 2% of radiation higher in energy than 100 kev is in coincidence with the 1100-kev radiations. The two strong transitions of 1102.0- and 1108.1-kev energy must therefore go directly to the ground state and arise from levels at these energies. The 67.26-kev transition and the 1034.8-kev transition sum up to 1102.1 kev; moreover they have approximately the same intensities. It therefore is possible that they arise from the 1102-kev state. Unfortunately there is no way of telling whether the intermediate state is at 67.26 or at 1034.8 kev.

4.3 The Decay Scheme of Os^{182}

Five transitions attributed to the decay of Os^{182} were observed, but no coincidences between the prominent 509-kev line and the other transitions were seen. Not more than 3% of gamma rays higher in energy than about 100 kev are in coincidence with the 509-kev gamma ray when a coincidence circuit of resolving time $2\tau=4$ μsec is used. This means that either there are no appreciable coincidences with transitions above 100 kev in energy or else that the half-life of such transitions is greater than about 120 μsec. Further discussion of this decay scheme will be given in Sec. 5.2.

5. DISCUSSION

In this section spins and parities will be assigned to some of the postulated energy levels. The level schemes will be discussed in terms of the deformed nucleus model of Nilsson[3] and Bohr and Mottelson.[2]

5.1 Assignment of Spins in the Decay of Os^{183} and Os^{183m}

The decay scheme for Os^{183} and Os^{183m} is given in Fig. 3. The scheme will first be discussed without reference to a particular nuclear model except that the existence of rotational states, for which there is extensive experimental evidence, will be assumed.

Consider the ground-state spin of Re^{183}; this has not been measured directly. The neighboring nuclei $Re_{75}{}^{185}$ and $Re_{75}{}^{187}$ both have measured spins of $\frac{5}{2}$ and the two lowest rotational states of each have been seen in Coulomb excitation.[10] The energies of the first excited states of Re^{183}, Re^{185}, and Re^{187} are 114.44, 125.3, and 134.2 kev, respectively; the ratios of the energies of the second to those of the first excited states are 2.271, 2.26, and 2.24, respectively. The theoretical ratio of second to first excited state is 2.22, 2.286, and 2.40 for the spin K of the base state being $\frac{7}{2}$, $\frac{5}{2}$, and $\frac{3}{2}$, respectively. The systematic behavior of the energies of the first excited states and of the ratios strongly supports the assumption that Re^{183} has spin $\frac{5}{2}$. Moreover the tendency for the ratio to approach the theoretical value as the nuclei became lighter and hence further from the closed shell is as expected. Further evidence is given on the Re^{183} spin from the decay of Re^{183} itself, which has been studied by Thulin *et al.*[11] They find that a spin of $\frac{5}{2}$ best fits the experimental data. In the discussion below we shall assume that this value is correct. Experimentally the parity is not determined but we shall take it here as even for reasons of clarity; later it will be shown that even parity is predicted by the Nilsson model.

If we do not take into account the very extensive experimental evidence for the existence of rotational states both in neighboring nuclei and in many other nuclei, then it is possible to assign two sets of spins to the 114-, 259-, and 496-kev levels. These spins, deduced from the measured transition multipolarities are $7/2+$, $9/2+$ and $9/2-$ or $3/2+$, $1/2+$ and $1/2-$, respectively. However the evidence for the existence of the rotational states now seems so strong that in suitable circumstances it can now be used as a good guide in assigning spins. A very brief description of the main features of rotational states is now given. The rotational states based on a state of angular momentum K have successive angular momenta $K+1$, $K+2$, etc. Except in nuclei very close to the edge of a rotational region, the energy, relative to that of the base state, of a state of angular momentum I is given to a good approximation by the expression $E(I)=\hbar^2/2\mathfrak{J}[I(I+1)-K(K+1)]$ where $\mathfrak{J}$ is an effective moment of inertia and $K\neq\frac{1}{2}$. Another important feature is that the $E2$ transition probabilities are very considerably enhanced, often by as much as a factor of 10^2, over the single particle values. Now the 114- and 259-kev levels, as was mentioned earlier in this section, have an energy ratio very close to that of the theoretical value for $I=\frac{5}{2}$. Moreover the observed $E2/M1$ ratios for the 145- and 114-kev transitions are about 5×10^{-2} whereas the ratio expected if both have single particle matrix elements is about 1×10^{-4}; this suggests that the $E2$ matrix elements may be enhanced. Thus the evidence strongly favors the conclusion that the 114- and 259-kev levels are rotational levels of the ground state and therefore have spins $7/2+$ and $9/2+$, respectively. It might be remarked here that the observation of any anisotropy in the angular correlation between the 167-kev and 381-kev gamma rays would prove the proposed spin sequence, since if the 496-kev level has spin $\frac{1}{2}$ the correlation must be isotropic.

Since the 167-kev transition from the 664-kev level is

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[10] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

[11] S. Thulin, J. O. Rasmussen, C. J. Gallagher, W. G. Smith, and J. M. Hollander, Phys. Rev. **104**, 471 (1956).

also $M1$ with a relatively large $E2$ admixture it is plausible to assume that this arises from the first rotational state of the 496-kev level; it therefore has spin $11/2-$. Usually one finds that the values of $\hbar^2/2\mathfrak{J}$ for different bands do not differ markedly, thus the fact that the value of 15.26 kev for this band is rather close to that of 16.35 kev for the ground-state band also gives support for the assignment. The fact that no transitions are observed to the ground or first excited states gives further support.

The decay of the 851-kev state to the ground state by an $M1$ transition establishes it as having spin $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ with even parity. The decay to the first excited state by a transition that is not $E1$ or $E2$ effectively eliminates the $\frac{3}{2}$ possibility. Decay is observed to the 496-kev level in competition with much higher energy $M1$ transition. From lifetime consideration this transition could hardly be $M2$; it must therefore be $E1$. If this is so then $\frac{5}{2}$ is also ruled out and the spin of the 851-kev state must be $7/2+$. It then seems likely that the 1003-kev state, which decays by $M1$ transitions to the 851- and 114-kev states but not to the ground state, is the first rotational state of the 851-kev state. It will therefore have spin $9/2+$. This band has an acceptable value of $\hbar^2/2\mathfrak{J}$ of 16.77 kev.

We now consider the possible spins of the Os^{183} ground state. Since radiation of energy 1440 kev is observed in the decay of Os^{183} the energy available for the decay must be more than this. Predictions from β systematics are not reliable in this region. The Coryell systematics[12] predicts a total decay energy of 1.4 ± 0.4 Mev whilst the Way and Wood[13] systematics suggests a decay energy of about 2 Mev. From a consideration of $\log_{10}(ft)$ values observed in other nuclei it would seem very likely that the $\log_{10}(ft)$ value for decay to the "1440-kev state" should lie between 5 and 8. This implies that the total decay energy to the ground state of Os^{183} lies between about 1.5 and 2.7 Mev.

The $\log_{10}(ft)$ values for decay to the 496-kev state with these extreme decay energy values are 5.8 and 7.4, respectively. While it would be unsafe to conclude from this that the decay to the 496-kev state is first forbidden, allowed decay cannot be excluded, it seems very likely that the spin change is not greater than unity since first forbidden transitions with $\Delta I=2$ almost always have $\log_{10}(ft)$ greater than 7.4. Thus the ground state of Os^{183} has spin $7/2\pm$, $9/2\pm$, or $11/2\pm$. The value of $7/2\pm$ can be excluded since the isomeric state decays by an $M4$ transition. If this state had spin $1/2\mp$ it would almost certainly decay by $E3$ radiation and if it were $15/2\mp$ then the levels in Re^{183} fed by the decay of the isomeric state would have to decay by multiple gamma-ray cascades rather than by direct ground-state transitions as observed. It seems likely that the value $11/2\pm$ can also be excluded since decay is observed to the 851-kev state with $\log_{10}(ft)$ values for the extreme decay energies of 6.8 and 7.7. Again it appears likely that the spin change is not greater than unity, which excludes $11/2\pm$ for Os^{183}. Thus the most probable value for the spin of Os^{183} is $9/2\pm$ and that of the isomeric state $1/2\mp$.

Consider now the spins of the states at 1102 and 1108 kev. Assuming equal population of these states the $\log_{10}(ft)$ values for the extreme decay energies are 5.0 and 7.1. Thus the decay can either be allowed or first forbidden with spin change not greater than unity. The spins can therefore be $1/2\pm$ or $3/2\pm$. Since the decay to the ground state by $E2$ transitions is observed then, with our previous parity convention, the spins must be $1/2+$ or $3/2+$.

Though none of the spin assignments above can be considered to be conclusively proved it is thought that the probability of their being correct is high. It should be again remarked however that the experimental parity assignments are only relative.

5.2 The Decay of Os^{183} and Os^{183m} and the Nilsson Scheme

It is interesting to see whether the six intrinsic states observed in these decays are fitted well by the single particle levels in a spheroidal potential as calculated by Nilsson.[3] A diagram of these levels is found in Nilsson's article. It has been found by Mottelson and Nilsson[14] that the levels with high angular momentum in odd Z nuclei have to be lowered in energy below their positions in the diagram in order to be in good accord with experimental data. Such a reduction is not surprising since the Coulomb energy of the odd proton is least for the proton being at the edge of the nucleus; it is plausible to suppose that the proton spends more time at the edge when its angular momentum is high than when it is low. Thus in the 50–82 shell the $h_{11/2}$ set of levels should be lowered so that the $h_{11/2}$ spheroidal state occurs about half way between the $d_{3/2}$ and $d_{5/2}$ states and the s, d and d, g doublets should be inverted.

In the discussion below the states will be designated in the conventional way by the quantum numbers I, $\pi[Nn_z\Lambda]$ where I is the spin, π the parity, N the total number of nodes in the wave function, n_z the number of nodal planes perpendicular to the symmetry axis and Λ the projection of the orbital angular momentum along the symmetry axis. Strictly speaking, the asymptotic quantum numbers N, n_z, Λ only apply to the case of infinitely great deformation but in practice the asymptotic wave functions are fairly good approximations to the wave functions for rotational nuclei. Thus it is useful to discuss β and γ transition probabilities in terms of selection rules on the asymptotic quantum numbers. Such selection rules have been

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[12] C. D. Coryell, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, 1953), Vol. 2, p. 305.

[13] K. Way and M. Wood, Phys. Rev. **94**, 119 (1954).

[14] B. R. Mottelson and S. G. Nilsson (Private communication); and Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter **1**, No. 8 (1959).

given by Chasman and Rasmussen[15] and by Alaga.[16] Some of the assignments to the levels in Os^{183} and Re^{183} have been given independently by Mottelson and Nilsson.[14]

Consider first the levels in Os^{183}. The ground state of spin 9/2+ and the isomeric state of spin 1/2− are fitted very naturally by the levels 9/2+ [624] and 1/2− [510] of the Nilsson scheme. The $M4$ transition between these levels is expected to be unhindered. The observed half-life is a factor of 12 slower than the single particle half-life. This is very similar to the observed hindrance factors for other $M4$ transitions and is probably consistent with no violation of the selection rules for this transition.

Coming now to the levels of Re^{183}, the ground state and the two lowest levels can be assigned fairly unambiguously to the Nilsson states 5/2+ [402], 9/2− [514] and 7/2+ [404]. The beta decays to the 9/2− and 7/2+ states would be classified on this basis as first forbidden, unhindered (1*u*) and allowed, hindered (*ah*), respectively. There is a serious violation of the selection rules in the decay to the 7/2+ state so that a considerable degree of hindrance would be expected. In Table IV are shown the experimental $\log_{10}(ft)$ values for decays to the various states assuming that the decay scheme is correct and a total decay energy to the ground state of 2 Mev; this is intermediate between the extreme values previously mentioned. The values of 6.2 and 7.1 for decay to 9/2− and 7/2+ states, respectively, are in reasonable accord with expectations. Decay to the ground state and first excited state of Re^{183} cannot be entirely excluded by the experimental results which are however thought to be consistent, within the errors of measurement, with essentially no decay to these states. Making an allowance of 20% for L capture, the K x-ray intensity computed from the strength of observed transitions is consistent with the observed K x-ray intensity, so that rather little decay can go to the ground state. It is difficult to set a precise upper limit to such a decay intensity owing to uncertainty in the ratio of K to L capture; however it seems most unlikely that more than 20% of the decay can go to this state. Certainly, essentially no decay to the ground state would be expected if the proposed decay scheme is correct. Decay to the first and second excited states would be allowed but twice K forbidden and very considerable degrees of hindrance would be expected.

TABLE IV. $\log_{10}ft$ values for decay to states in Re^{183} from Os^{183} and Os^{183m}, assuming an energy of 2 Mev for decay between the ground states.

Energy of state in kev	Parent	Partial half-life in hours	$\log_{10}ft$
0	183	> 60	>7.2
114.4	183	> 60	>7.1
259.8	183	>600	>8.0
496.1	183	16	6.2
664.0	183	48	6.7
851.1	183	185	7.1
1035	183*m*	>770	>7.7
1102	183*m*	37	6.3
1108	183*m*	37	6.3

TABLE V. Transition energies, partial half-lives and hindrance factors for the gamma rays depopulating the 496-kev state.

Transition kev	Partial $T_{\frac{1}{2}}$ sec	Multipolarity	Hindrance
496	1.2×10^{-6}	$M2$	200
382	8.2×10^{-9}	$E1$	3.2×10^{6}
236	1.2×10^{-7}	$E1$	1.1×10^{7}

In Table V are shown the partial half-lives and hindrance factors, relative to single particle transition probabilities, for the gamma-rays depopulating the 9/2− state. The two $E1$ transitions have very high hindrance factors. These are accounted for partly by the fact that the transitions are K forbidden (usually about a factor of 10^2) and partly by the fact that there are no particle states anywhere nearby which could mix with the various states concerned to give unhindered $E1$ transitions. Sometimes highly hindered $E1$ transitions have anomalous conversion coefficients[17] but in this case no anomalies are observed within the uncertainty of experimental errors. The 496-kev $M2$ transition does not violate the selection rules but nevertheless is hindered by a factor of 200. There are, however, probably too few measured $M2$ transitions so far to evaluate the significance of this result.

Some further remarks on the decay of the 851-kev level are appropriate. If the decay scheme for this level is correct then the transition to the 496-kev level must be $E1$. A lower limit to the half-life of this gamma ray can be estimated by assuming that the $M1$ transition to ground has the single particle value. This lower limit is 1.4×10^{-12} seconds and gives a hindrance factor of about 50. Such a factor would be unreasonably low since nearly all cases hitherto observed have had hindrance factors greater than 10^3. However the transition 7/2+ [404] to 5/2+ [402] is not allowed by the asymptotic selection rules either for $M1$ or for $E2$ radiation so that it would be expected to be considerably hindered. A transition between the same two Nilsson states is observed in the nucleus Ta^{181} where it is found that the $M1$ and $E2$ transitions are hindered by factors of 3×10^6 and 30, respectively.[14] The presence of the $E1$ transition therefore seems in reasonable accord with present data.

We now consider the levels reached by the decay of the isomeric state. The levels strongly populated are at 1102 and 1108 kev and according to our previous discussion they have spin 3/2 or 1/2 with the same parity

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[15] R. Chasman and J. O. Rasmussen, University of California Radiation Laboratory Report UCRL-3629, 1956 (unpublished).

[16] G. Alaga, Nuclear Phys. **5**, 625 (1957).

[17] S. G. Nilsson and J. O. Rasmussen, Nuclear Phys. **5**, 617 (1958).

as the ground state. There are two possible 1/2+ Nilsson states, 1/2+ [400] and 1/2+ [411], and also a possible 3/2+ state, 3/2+ [402] which are available. The experimental $\log_{10}ft$ values to these states, assuming equal population and 2-Mev total decay energy for Os^{183} ground state, are 6.3. Thus the transition is unlikely to be hindered; first forbidden ($\Delta K \neq 2$) hindered transitions usually have $\log_{10}ft$ values between 7.0 and 8.5.[14] This eliminates the 3/2+ [402] possibility. The level 1/2+ [411] should be fed by an unhindered transition and seems the most likely assignment since it has a decoupling parameter of about −1 which causes the 1/2 and 3/2 rotational states to be nearly degenerate. This Nilsson state, with the characteristic two close levels, has been observed as a ground state in Tm^{171} [10,14] and as an excited state in Ta^{181} [14] and Re^{185}.[14] The level 1/2+ [400], which should also be fed by an unhindered transition has a decoupling parameter of about +0.4 and would not show the close levels as observed. With this interpretation $M1$ transitions to the ground state are K forbidden, which may account for the suggested $E2$ nature of these transitions. It should be noted that the $E2$ transitions are also hindered on the asymptotic selection rules but $E2$ hindrances are often rather small.[14]

Further interpretation of this scheme is rather more fanciful since it is not very well established. However one possible interpretation of the 1035-kev state which qualitatively fits the data is given here. This state, if it exists, appears to have little direct population, being fed mainly from the 1102-kev state. If this state is the 3/2+ [402] Nilsson state, then it will probably be fed by a very weak K-capture branch, since as mentioned above the transition is hindered. However the $M1$ transition from the 1/2+ [411] state to the 3/2+ [402] state is allowed by the selection rules so that this transition may compete well with the ground state transition as is observed.

One may make another bold but precarious assignment with the 147-kev gamma ray, which has not previously been placed in the decay scheme. This is to assume that it arises from the decay of the 5/2+ rotational state of the 1/2+ [411] band to the 3/2+ state of this band by an $M1$ transition. If this were the case it would give values of $\hbar^2/2\mathfrak{I}$ of 15.72 kev and 13.68 kev according as the 1/2+ or 3/2+ state lies lowest. The first of these values is certainly close to those of the other observed rotational bands. This state would have to be fed by an unhindered first forbidden transition with $\Delta I = 2$. The $\log_{10}ft$ value for decay to this supposed state is 7.4 assuming a total decay energy of 2 Mev for the Os^{183} ground state. This is a little low for a $\Delta I = 2$ transition but probably does not exclude the assignment in view of the uncertainties in decay energy.

States, other than the ones reported, which may be populated are 7/2− [523], 1/2− [505] and 1/2+ [400]. It is possible that some of the unassigned transitions arise from the decay of such states. More detailed coincidence work, both γ, γ and e, γ, is required to settle these problems.

5.3 The Os^{182} Decay Scheme

Os^{182} is an even-even nucleus and thus has spin zero in its ground state. It seems unlikely that the 20-hour activity comes from anything other than the decay of the ground state, since isomers in even-even nuclei usually have excitation energies of at least 1 Mev; no radiation attributable to the decay of Os^{182} greater than 509-kev energy is observed.

According to the Coryell[12] systematics the total decay energy is 0.14±0.5 Mev and according to the Way and Wood[13] systematics it is about 1 Mev; since a gamma ray having an energy of 509 kev is observed, the energy must be more than this. The spin of the 13-hour Re^{182} isomer to which the decay of Os^{182} leads is most likely to be 3−.[18] Allowed K capture could lead to levels of spin 0+ and 1+ in Re^{182}. Such states would decay either by direct or cascade transitions to the 3− state; one parity-changing transition, $E1$, $M2$ or $E3$ would have to be involved. Since two $E1$ transitions are probably observed it seems likely that part, at any rate, of the decay is by allowed transitions. Odd parity states could be fed by 1st forbidden transitions. Since no coincidences were observed between the 509-kev gamma ray and the $E1$ gamma rays it is possible also that odd parity states are fed. Further discussion of this decay scheme seems unprofitable at present.

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[18] C. J. Gallagher, J. O. Newton, and V. S. Shirley, Phys. Rev. **113**, 1298 (1959).