Isomer Re^{188m}†*

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Two new transitions in Re^{188m} were found which are responsible for the 18.7-min half-life of this isomer. The energies and branching ratios of these transitions which originate from a 6− state at 171.9 keV, are 2.4 keV (57%) and 15.9 keV (43%). Their multipole orders are $M3$. Each transition is followed by an $M1$ transition, of 105.9 and 92.4 keV, respectively, both terminating in the first excited (2−) state at 63.58 keV, which decays by an $M1$ transition to the ground state. The ground state and the first two excited states appear to be members of a rotational band with $K=1-$, whereas the 3rd and 4th excited states can be interpreted as composed of the same proton orbit as that of the ground state, but of different neutron orbits. The thermal neutron activation cross section of Re^{187} leading to the isomer was found to be 1.25 ± 0.25 b.

I. INTRODUCTION

IN the course of a study of energy levels of the odd-odd isotopes of Re and Ir[1] we became interested in the decay of Re^{188m}. A 22-min activity produced by neutron capture in Re^{187} had been assigned to this isomer by Mihelich.[2] He used scintillation spectrometers to study its photon spectrum, singly and in coincidence, and 180° permanent magnet spectrographs to investigate its conversion electron spectrum. He found two transitions in cascade, of 105 and 63.5 keV. His results, however, did not enable him to determine the multipole orders of these two transitions. Consequently, the isomeric lifetime could not be ascribed to either one of them.

Flammersfeld[3] independently discovered Re^{188m} by slow neutron irradiation of natural rhenium, and assigned to it an 18.7-min half-life. His assignment was confirmed by Herr[4] by means of a Szilard-Chalmers separation of the 16.7-h Re^{188} daughter. Flammersfeld studied the radiations of Re^{188m} by means of absorption in Al, brass, and Pb and concluded that the isomer decays by a ~60-keV transition. On the basis of the Goldhaber-Sunyar diagram relating the multipole order with the energy and half-life of an isomeric transition, he suggested that this transition might be $E3$ or $M3$. For the production cross section of Re^{188m} with thermal neutrons, Flammersfeld deduced a value $\sigma=1.0$ b by comparing it with the production cross section of Re^{188}.

A recent study by Roy[5] on the decay of W^{188} makes it appear highly probable that the 63.5-keV transition depopulates the first excited state of Re^{188}. A precision measurement of the energy of this transition carried out by Hardell and Nilsson[6] with a Re^{188m} source by means of a bent crystal diffraction spectrometer, yielded the value 63.7 ± 0.1 keV.

While our work was in progress, a crystal spectrometer determination of the low-energy part of the capture gamma-ray spectrum of $Re^{187}+n$ was reported by Schult *et al.*[7] These authors observed that three of the transitions found, with energies of (63.581 ± 0.003) keV, (92.447 ± 0.006) keV, and (105.960 ± 0.008) keV, occur also in the gamma-ray spectrum of Re^{188m}.[8] They concluded that none of the three lines is identical with the isomeric transition, since their intensities after a reactor bombardment with $T\gg\tau_{1/2}(Re^{188m})$ are reduced to $<\frac{1}{10}$ when the reactor is turned off. No coincidences between the 106- and 92-keV transitions were found, and also no definite evidence for 106–63-keV coincidences was obtained, in contrast to Mihelich's result. Hence, it was thought possible that all three transitions are in parallel. This was given as a possible explanation for the lack of crossover transitions with intensities >15%. From the relative intensities of the conversion electron lines, and of the K x rays, the authors concluded that the 63- and 106-keV transitions are probably $M1$, whereas the lack of conversion electrons from the 92-keV transition suggested to them that this transition is probably $E1$.

The 16.7-h ground state of Re^{188} is known[9] to decay by beta emission to Os^{188} with a total disintegration energy of 2.116 MeV. The most intense beta branches lead to the (0+) ground state (78%) and first excited (2+) state (20%) at 155 keV, while weak beta branches populate a number of higher excited states up to 1.950 MeV. The logft values of the two most intense beta

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* This work is an extension of material originally reported at an Am. Phys. Soc. meeting at Pasadena, California [K. Takahashi, M. McKeown, and G. Scharff-Goldhaber, Bull. Am. Phys. Soc. 8, 595 (1963)].
‡ On leave of absence from the University of Tokyo, Tokyo, Japan.
[1] G. T. Emery, W. R. Kane, M. McKeown, M. L. Perlman, and G. Scharff-Goldhaber, Phys. Rev. **129**, 2597 (1963).
[2] J. W. Mihelich, Phys. Rev. **89**, 907A (1953).
[3] A. Flammersfeld, Z. Naturforsch. **8a**, 217 (1953).
[4] W. Herr, Z. Naturforsch. **7a**, 819 (1952).
[5] J. C. Roy, Can. J. Phys. **40**, 677 (1962).
[6] R. Hardell and S. Nilsson, Nucl. Phys. **39**, 286 (1962).
[7] O. W. B. Schult, B. Weckermann, T. v. Egidy, and E. Bieber, Z. Naturforsch. **18a**, 61 (1963).
[8] A 92-keV line reported by Mihelich in a private communication was listed in the table by J. M. Hollander, I. Perlman, and G. T. Seaborg, Rev. Mod. Phys. **25**, 469 (1953), but omitted in a later edition of the table.
[9] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 59–3–123.

branches suggest a spin and parity assignment 1− for the ground state of Re^{188}. K. O. Nielsen and O. B. Nielsen,[10] using an isotopically pure source of Re^{188}, were able to support this assignment by showing that the shapes of these two beta branches are of the forbidden, nonunique type. A recent direct measurement[11] confirms spin 1.

Our program for the study of Re^{188m} was as follows:

(a) We planned to establish which of the transitions of 63.5, 106, and 92 keV (if present) are in coincidence and to determine their multipole orders.

(b) If none of these transitions should have the expected octupole character, a search for a hitherto unknown transition was to be undertaken. From Mihelich's[2] work it appeared that the energy of such a transition $E_{IT} \lesssim 30$ keV.

(c) The possibility of a hidden transition originating from a high-spin isomeric state is indicated by the large production ratio for slow neutron capture found by Flammersfeld: $\sigma_{Re^{188}}:\sigma_{Re^{188m}} \sim 75:1$. Therefore we planned to remeasure this ratio.

(d) We also intended to redetermine the half-life of Re^{188m}.

As will be seen, the mode of isomeric decay of Re^{188m} is considerably more complex than we had anticipated. The results obtained complement in a very interesting way the meager information so far available on rotational spectra and "Nilsson levels" of odd-odd nuclei.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source Preparation

Unless otherwise stated, an electroplating solution was prepared from natural rhenium by dissolving 500-mg Re metal powder in conc. HNO_3, heating to dryness, adding NH_4OH to neutralize, again heating to dryness, and dissolving in 100-cc 5% *n* H_2SO_4, to which 0.5-cc HF were added. 1–2 cc of this solution were irradiated for 1 min in the Brookhaven Reactor. The irradiated Re was then electroplated on 1-mil Cu backing, using 150 mA for 30 sec.

B. Radiation Detection

The radiations from Re^{188m} were studied either with NaI(Tl) scintillation spectrometers or with a Gerholm double-lens electron-electron coincidence spectrometer. This spectrometer was also used to observe electron-gamma-ray coincidences. For this purpose one of the magnetic coils was replaced by a NaI(Tl) scintillation spectrometer.

C. Measurements and Results

a. Scintillation Spectrum and Half-Life of Re^{188m}

Figure 1 shows the photon spectrum of Re^{188m}, obtained 3 min after the end of bombardment [curve (a)]

[10] K. O. Nielsen and O. B. Nielsen, Nucl. Phys. **5**, 319 (1958).
[11] W. M. Doyle and R. Marrus, Nucl. Phys. **49**, 449 (1963).

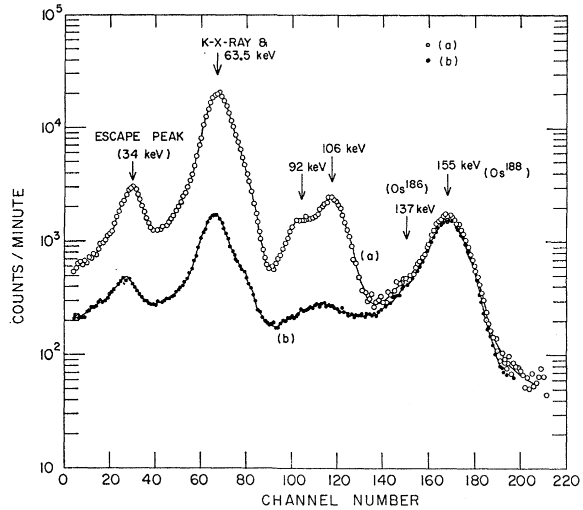

FIG. 1. Photon spectrum of Re^{188m} obtained with a scintillation spectrometer: A cylindrical NaI(Tl) crystal of 1½-in. diameter and ½-in. thickness was used. The source consisted of Re metal powder bombarded in the Brookhaven Reactor and spread onto scotch tape. Curve (a) shows a Re^{188m} (18.7 min) spectrum obtained 3 min after the end of bombardment. Curve (b) shows the 16.7-h Re^{188} background spectrum obtained 103 min later. Comparison of the intensity of the 155-keV transition (see Fig. 13) with the intensities of the 106-, 92-, and 63.5-keV transitions (which were corrected for the 18.7-min decay) permitted the calculation of the thermal neutron production cross section ratio for the two isomers. Upper limits of 0.1 and 0.05%, respectively, for the ($92+63.5 \approx 156$ keV) and ($106+63.5 \approx 169$ keV) crossover transitions were obtained from these curves.

and of Re^{188}, obtained 103 min later [curve (b)]. Curve (a) gives clear evidence of the presence of a γ ray of ~ 92 keV, in addition to the previously known γ rays of 63.5 and 105.9 keV, confirming the result of Schult *et al.*[7,8] Only a very small peak is found at 137 keV, which indicates that the amount of 90-h Re^{186} in our source was negligible. The intensity of the 155-keV transition emitted from 16.7-h Re^{188} is comparable to that of the 106-keV transition. The relative photon intensities are listed in Table I. From these data, together with a knowledge of the multipole orders (Secs. II C.c and II C.d) and branching ratios (II C.d), the isomeric ratio for pile neutron activation may be computed (see Sec. II C.g).

TABLE I. Relative photon intensities from Re^{188m} (corrected for decay) compared with the intensity of the 155.0-keV transition from Re^{188} (16.7 h). The activity was produced by bombarding Re^{187} for 1 min in the Brookhaven reactor.

Transition energy (keV)	Relative intensities	References for energy values
2.4	Not observed	Present work
15.9	<1	Present work
L x ray	60±5	
K x ray and 63.5	100	Refs. 2, 7
92.4	5.0±0.3	Ref. 7
105.9	10.0±1.0	Ref. 7
155.0 (Os^{188})	10.5±1.0	Nuclear data sheets

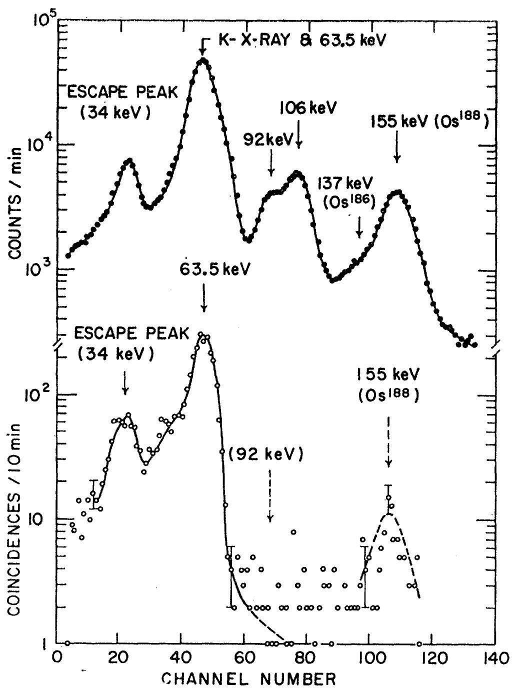

FIG. 2. Photon spectra obtained with a NaI(Tl) crystal of $1\frac{1}{2}$ in. diam and $\frac{1}{2}$ in. thick. The upper curve represents a singles spectrum. The spectrum given by the lower curve was taken in coincidence with a 106-keV γ ray detected by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in. NaI(Tl) crystal. It is seen that the 106-keV transition coincides only with the 63.5-keV transition, but not with the 92-keV transition.

A careful decay measurement of the 63.5-keV peak was taken. When corrected for a 16.7-h background from Re^{188}, $\tau_{1/2}=18.7\pm0.2$ min was obtained, in excellent agreement with the value 18.7 ± 0.3 min reported by Flammersfeld,[3] but somewhat lower than the 22-min half-life found by Mihelich.[2]

b. Gamma-Gamma Coincidence Studies

In order to determine which of the three gamma rays of 63.5, 92.4, and 105.9 keV found in the spectrum of Re^{188m} (see Fig. 1) coincide, the photon singles spectrum was compared with a coincidence spectrum triggered with the 106-keV photopeak (Fig. 2). Only the 63.5-keV peak, together with its escape peak, was found in coincidence, but not the 92-keV peak. Similarly, a coincidence spectrum triggered by 92-keV γ rays showed only the 63.5-keV γ peak, but no 106-keV peak. Table II summarizes the coincidence results. Thus it was shown that Mihelich[2] was correct in stating that the 63.5- and 105.9-keV transitions coincide, and the doubt by Schult *et al.*[7] concerning this point was removed, whereas their statement that the 92.4- and 105.9-keV transitions do not coincide was confirmed. As the decay scheme of W^{188} suggests[5] that the 63.5-keV transition leads to the ground state of Re^{188}, the simplest assumption is that the 105.9- and 92.4-keV transitions depopulate levels of 169.5 and 156.0 keV, respectively. An inspection of the photon spectrum in Fig. 1 shows that there is no indication of crossover transitions: The upper limits for transitions of 156 and 169 keV are 0.1 and 0.05%, respectively.

We attempted to measure the half-life of the 63.5-keV (2−) state using a fast-slow coincidence circuit

TABLE II. Summary of results of gamma-gamma coincidence measurements showing the absence of 92–106-keV coincidences.

Triggering gamma ray (keV)	Coincident gamma rays (keV)	Relative photon intensities
K x and 63.5	*K* x rays and 63.5	100[a]
	92.4	5.6 ± 0.5
	105.9	11.5 ± 1.0
92.4	*L* x rays	130 ± 20[a]
	63.5	100
	105.9	$\lesssim 1$
105.9	*L* x rays	80 ± 15[a]
	63.5	100
	92.4	$\lesssim 1$

[a] No correction was made for the *K*- and *L*-shell fluorescence yields.

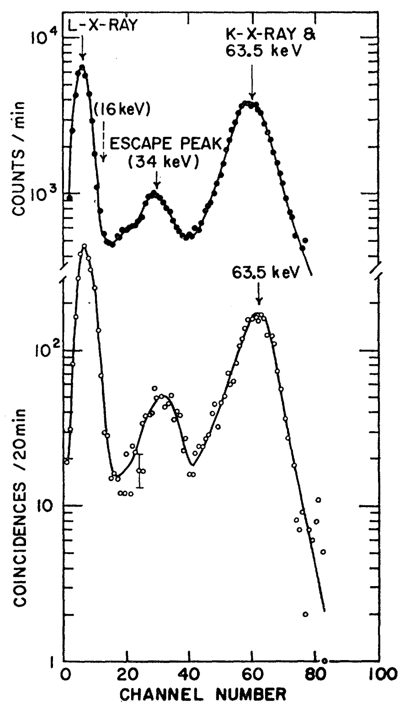

FIG. 3. Determination of the multipole order of the 63.5-keV transition. The upper curve shows the low-energy part of the scintillation spectrum of Re^{188m}. The lower curve shows the coincidence spectrum triggered with the 106-keV photopeak. The *L*-conversion coefficient of the 63.5-keV transition was obtained by comparing the areas of the *L* x-ray peak with the 63.5-keV photopeak. To detect the triggering γ rays a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in. NaI(Tl) crystal was used whereas the spectra presented in the figure were obtained with a crystal with $\frac{1}{2}$ in. diam and $\frac{1}{8}$ in. thick. From the upper curve an upper limit of 0.7% was obtained for the intensity of an unconverted 16-keV transition (see Sec. II C.e).

(whose resolving time $2\tau=1\times10^{-7}$ sec). Coincidences between the K x rays from the conversion of the 106 and 92.4-keV transitions and L x rays (which are mainly due to the 63.5-keV transition) were studied. An upper limit of $\tau_{1/2}(63.5)<2\times10^{-8}$ sec was found.

The next step in our investigations was the determination of the spins and parities of these three levels, which will be described in II C.c and II C.d.

c. Determination of the Multipole Order of the 63.5-keV Transition

To determine the L-conversion coefficient of the 63.5-keV transition we measured the ratio of L x rays to 63.5-keV γ rays. Since the 63.5-keV γ rays and the K x rays of Re (61 keV) are not resolved by our scintillation counter, we measured the photon ratio in coincidence with the 106-keV γ ray.

Figure 3 presents the results: In the upper part, the low-energy singles spectrum from Re^{188m} is given, which is to be compared with the coincidence spectrum triggered by 106-keV gamma rays as shown below. The numerical results are given in Table II. It is seen that in the coincidence spectrum the "63.5-keV" peak—because it is free from K x rays—has shifted slightly to the right and is less pronounced, compared to the L x-ray peak, than in the singles spectrum. After the proper correction for the L-shell fluorescence yield ($\omega_{LL}=30\%$)[12] has been made, a value of 2.7 ± 0.5 is obtained for the L-conversion coefficient of the 63.5-keV transition. In Table III this value is compared with the theoretical values given by Rose[13] for various

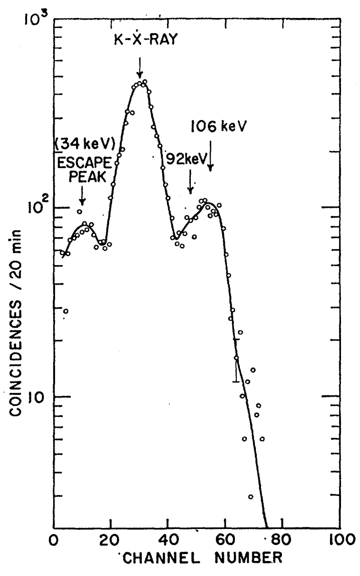

FIG. 4. Determination of the K-conversion coefficients of the 106- and 92-keV transitions by observing the photons coinciding with the L-conversion electrons of the 63.5-keV transition. This measurement was carried out with the Gerholm coincidence spectrometer. Only a mean value for the K-conversion coefficients of the two transitions was obtained in this way, but, taken together with the relative K and L conversion electron and photon intensities $[I_{\gamma106}/I_{\gamma92}=2$(see Table I)$]$, it furnished individual values for the conversion coefficients. The pulse-height spectrum was obtained with a $1\frac{1}{2}$-in.$\times1\frac{1}{2}$-in. NaI(Tl) crystal.

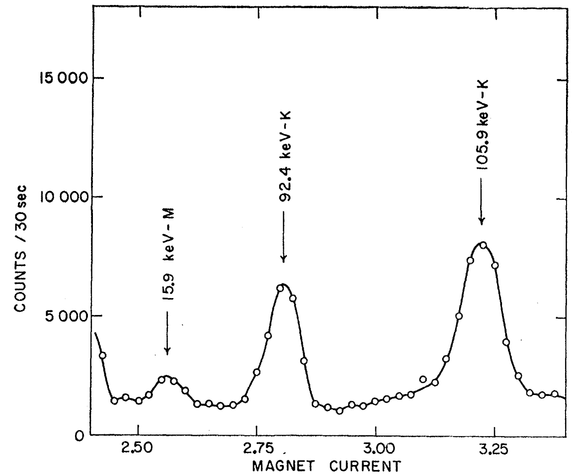

FIG. 5. Part of the conversion electron spectrum obtained with 25.5-kV preacceleration in the Gerholm spectrometer. A circular Re^{188m} source of 3 mm diam plated on 1-mil Au foil was used. The 16.7-h background was subtracted from the measured spectrum. The curve was corrected for the 18.7-min decay.

TABLE III. Conversion coefficients and multipole order assignments for the 63.5-, 92.4-, and 105.9-keV transitions.

Transition energy (keV)		α_K[b]	α_L[b]	Multipole assignment
63.58±0.01[a]	Theoretical values			
	$M1$	···	2.5	
	$E1$	···	0.18	
	$M2$	···	76	
	$E2$	···	21	
	Observed value	···	2.7±0.5[c]	$M1$
92.45±0.01[a]	Theoretical values			
	$M1$	5.5	0.82	
	$E1$	0.38	0.065	
	$M2$	39.0	15.5	
	$E2$	0.87	3.8	
	Observed value	5.9±0.9	0.9±0.2	$M1$
105.96±0.01[a]	Theoretical values			
	$M1$	3.7	0.6	
	$E1$	0.27	0.045	
	$M2$	25	9.2	
	$E2$	0.75	2.0	
	Observed value	3.8±0.5	0.7±0.2	$M1$

[a] Energy values are taken from Ref. 7.
[b] Taken from Ref. 13.
[c] Fluorescence yield of 30% assumed.

[12] Extrapolated from the values given by R. C. Jopson, H. Mark, C. D. Swift, and M. A. Williamson, Phys. Rev. 131, 1165 (1963).

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

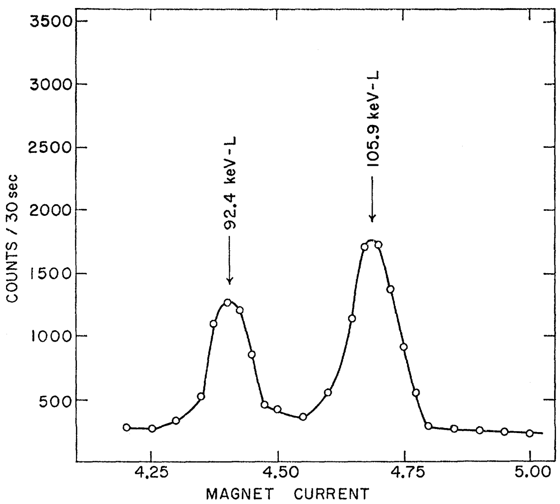

FIG. 6. L-conversion lines of the 92.4- and 105.9-keV transitions obtained with 25.5-kV preacceleration in the Gerholm spectrometer. An electroplated Re^{188m} source of 3-mm diam was used. The 16.7-h Re^{188} background (155-keV K-conversion line) was subtracted from the measured curve, which was also corrected for the 18.7-min decay.

multipole orders, showing that the 63.5-keV transition is unambiguously $M1$, in agreement with Schult *et al.*'s[7] deduction. As the spin of the ground state is 1−, the 63.5-keV state is probably 2−.

d. Determination of the K- and L-Conversion Coefficients of the 106- and 92-keV Transitions

This determination consisted of four steps: (a) measuring the "average" K conversion coefficient $\bar{\alpha}_K$ for the two transitions, (b) determining the relative intensities of their K conversion lines and (c) of their L conversion lines, using as a standard the K conversion line of the 155-keV $E2$ transition from Re^{188} (16.7 h), (d) using the gamma-ray intensity ratio $R_\gamma = I_{106\text{keV}}/I_{92\text{keV}} = 2.0 \pm 0.2$ derived from Table I.

The details and results of these measurements follow:

(a) Figure 4 presents the photon spectrum in coincidence with the 63.5-keV L-electron line. This measurement was carried out with the Gerholm coincidence spectrometer, with one lens being replaced by a NaI crystal. The curve yields a value $\bar{\alpha}_K = 4.5 \pm 0.5$ for the average K-conversion coefficient, whereby $\omega_K = 0.95(\pm 1\%)$[14,15] was used for the K-shell fluorescence yield.

(b) The relative intensities of the 105.9- and 92.4-keV K-conversion lines were determined by comparing their areas (Fig. 5) as measured by the Gerholm spectrometer. In order to obtain these lines, the electrons

TABLE IV. Relative intensities of K- and L-conversion lines of 92.4- and 105.9-keV transitions in Re^{188m}. The K- and L- conversion-line intensities were determined in two separate runs.

Transition energy[a] (keV)	Conversion line	Relative intensity
92.45±0.01	K	1.0
105.96±0.01	K	1.3±0.1
92.45±0.01	L	1.0
105.96±0.01	L	1.5±0.1
155.03±0.02 (Os^{188})	K	0.7±0.1

[a] All values for transition energies are taken from Ref. 7.

were accelerated[16] by means of an electric field of 25.5 kV applied between the source holder and the case of the magnetic lens. As shown in Table IV, the intensity ratio obtained in this way is:

$$R_K = I_{106-K}/I_{92-K} = 1.3 \pm 0.1 .$$

From these data the K-conversion coefficients are

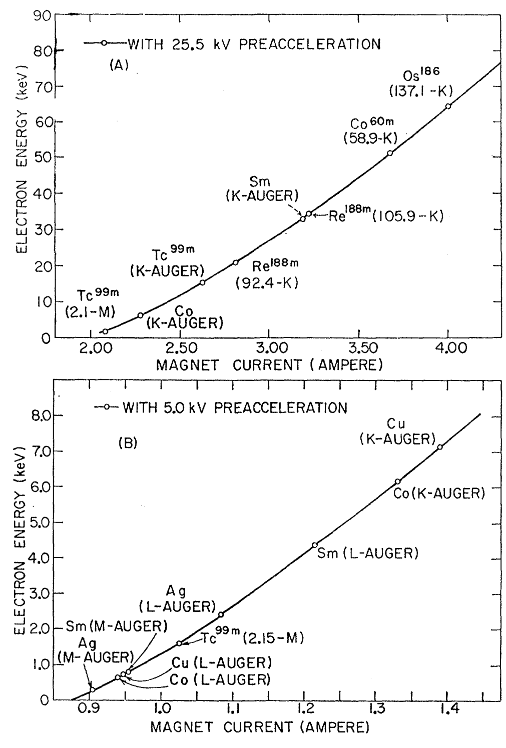

FIG. 7. Calibration curves of Gerholm spectrometer for electrons which were preaccelerated by 25.5 kV [curve (A)] and 5 kV [curve (B)] before entering the magnetic field. Sources of Tc^{99m} (2.1-keV M-conversion line, K-Auger line), Co^{60m} (58.9-keV K-conversion line, K-Auger line), Re^{188m} (92.4 K line, 105.9 K line), Sm^{152} (K-Auger line), and Os^{186} (137.1 K-conversion line) were used to obtain curve (A); in addition to these sources, Ag^{110m} (Ag M-Auger lines), Co^{60m} (Co K- and L-Auger lines) and Zn^{65} (Cu K- and L-Auger lines) were used for the 5-kV calibration curve (B).

[14] *Beta- and Gamma-ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 630.
[15] Wapstra *et al.*, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).
[16] The technique used was similar to that described by M. S. Freedman, F. T. Porter, F. Wagner, Jr., and P. P. Day, Phys. Rev. **108**, 836 (1957).

computed as follows:

$$\alpha_{92K}=I_{92K}/I_{92\gamma}=\bar{\alpha}_K[(1+R_\gamma)/(1+R_K)]=5.9\pm0.9,$$

$$\alpha_{106K}=I_{106K}/I_{106\gamma}=\bar{\alpha}_K[(1+1/R_\gamma)/(1+1/R_K)]=3.8\pm0.5.$$

(c) The intensity ratio $R_L=I_{106L}/I_{92L}=1.46$ (see Table IV) was obtained from the L electron spectrum (Fig. 6). The K electron line of the 155-keV $E2$ transition is not resolved from the 92-keV L-electron line. However, it was measured after the 18.7-min activity had decayed, and, after correcting for the 16.7-h decay, it was subtracted from the L-electron spectrum. Using the average of the measured values given in the literature[9] $\alpha_{155K}=0.30$ and the relative conversion electron intensity

$$R_{155K-106L}=I_{155K}/I_{106L}=0.44$$

and relative γ-ray intensity

$$R_{155\gamma-106\gamma}=I_{155\gamma}/I_{106\gamma}=1.05$$

determined in this work, one obtains

$$\alpha_{106L}=\alpha_{155K}(R_{155\gamma-106\gamma}/R_{155K-106L})=0.7\pm0.2$$

and

$$\alpha_{92L}=\alpha_{155K}(R_{155\gamma-106\gamma}R_\gamma/R_{155K-106L}R_L)=0.9\pm0.2.$$

In Table III these values are compared with the theoretical values, showing that both transitions are $M1$. It thus follows that both the 156.0- and 169.5-keV states in Re^{188} are probably 3−.

Knowledge of the relative γ-ray intensities and experimental K and L as well as theoretical M-conversion coefficients[17] for the 92.4- and 105.9-keV transitions,

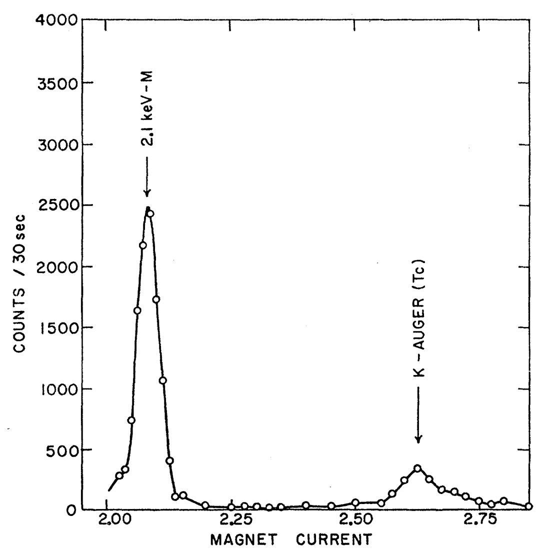

FIG. 8. Low-energy part of the conversion electron spectrum from Tc^{99m} taken with the Gerholm spectrometer. The electrons were preaccelerated by 25.5 kV. The source which had a 3-mm diam was prepared from fission products and electroplated on 1-mil Au foil.

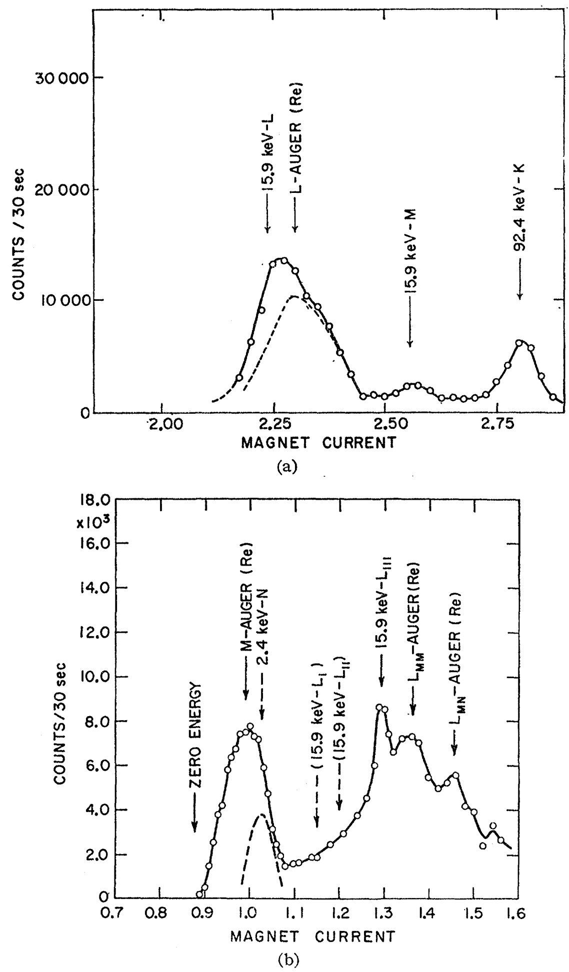

FIG. 9. (a) Low-energy electron spectrum of an electroplated source of Re^{188m} obtained with 25.5-kV preacceleration. The dashed line indicates the L-Auger spectrum obtained from the 16.7-h Re^{188} decay. The position of the 15.9-keV line in the decay scheme was determined by observing the coincidence spectrum with the left-hand and right-hand side of the composite peak consisting of the L-conversion line of the 15.9-keV transition and the L-Auger lines [Fig. 10(a) and (b)], which demonstrates that the 15.9-keV line is followed by the 92.4-keV transition. (b) Low-energy electron spectrum of Re^{188m} accelerated by 5 kV before entering the Gerholm spectrometer. The source was obtained by bombarding a thin Re film obtained by evaporation of Re metal on Mylar with neutrons from the Brookhaven Graphite Reactor. The dashed curve indicates the 2.4-keV N-conversion line which is embedded in the Re M-Auger lines. Evidence for its existence and place in the decay scheme was obtained by an electron-gamma-ray coincidence experiment [see Fig. 11(a) and (b)]. The L_I and L_{II} lines of the 15.9-keV transition, whose positions are indicated by dashed arrows, are too weak to be observed. Comparison with theoretical L-shell ratios (Table V) shows that the multipole order of this transition is $M3$ (see also Fig. 12).

[17] $Z_{eff}=68$ was used for the determination of the M-conversion coefficients, in order to take screening effects into account. [See Y. Y. Chu and M. L. Perlman, Phys. Rev. **135**, B319 (1964).]

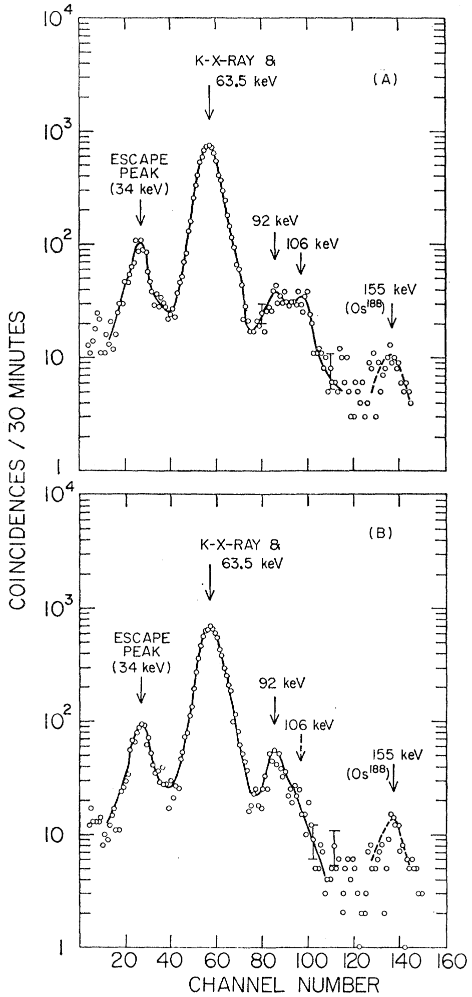

FIG. 10. This figure demonstrates that the 15.9-keV transition coincides with the 92-keV transition, but not with the 106-keV transition. Curve (A) shows the photon spectrum obtained with a $1\frac{1}{2}$ in.$\times 1\frac{1}{2}$ in. NaI(Tl) crystal triggered with the L-Auger electrons from Re^{188m} [magnet current setting 2.35 A; see Fig. 9(a)]. Since the L-Auger line is partly due to the 15.9-keV transition and partly to the 63.5-keV transition, both the 92- and 106-keV transitions coincide with it. Curve (B) triggered mainly with the L-conversion electrons of the 15.9-keV transition [the magnet current for this curve was set at 2.20 A, see Fig. 9(a)], shows a much higher peak at 92 keV than at 106 keV.

permits the computations of the relative intensities of these transitions feeding the 63.5-keV level, $(43\pm5)\%$ and $(57\pm5)\%$, respectively.

Since none of the three $M1$ transitions found can be responsible for the 18.7-min half-life of the isomer, and no γ ray or conversion electron line above $\sim$25 keV was found in the spectrum, a search for low-energy conversion electron lines was undertaken. The parallelism of the 105.9- and 92.4-keV transitions suggests that two competing isomeric transitions take place; for one of these $E\geq 13.5$ keV is therefore expected.

e. Observation of Low-Energy Electron Lines

For this purpose the electrons, before entering the Gerholm spectrometer lens, were accelerated by means of an electric field (25.5 kV), as was mentioned in Sec. II C.d. Figure 5 presents, in addition to the K conversion lines of the 92.4- and 105.9-keV transitions, a peak at $\sim$12 keV, which was tentatively identified as the M-conversion line of a 15.9-keV transition. A search for still lower energy lines thus seemed indicated. The energy calibration of the spectrometer with an accelerating field of 25.5 kV was carried out with a number of conversion lines ranging from 64 keV down to 1.6 keV [Fig. 7, Curve (A)]. The calibration of the low-energy end was carried out with a source of 6-h Tc^{99m}, prepared from fission products (Fig. 8).

A thin Re source was prepared by bombarding 2 cc of Re plating solution for 5 min in the reactor and then electroplating the Re at a 200-mA current for 30 sec. Figure 9(a) shows the low-energy spectrum obtained: in addition to the lines seen in Fig. 5, a wide line is seen, whose right-hand side coincides with the Re L-Auger spectrum (dashed line) found in the decay of the Re^{188} (16.7-h) ground-state decay. The left-hand side is due to L-conversion electrons of the 15.9-keV transition. By observing the gamma spectra in coincidence with the left- and right-hand sides of this composite line (Fig. 10) it was demonstrated that the 15.9-keV transition coincides with the 92-keV transition,[18] while the L-Auger electrons coincide partly also with the 106-keV transition, as they accompany the depopulation of the 63.5-keV level. In order to find electron lines of still lower energy, a very thin Re film ($\sim 10\ \mu g/cm^2$) was deposited on Mylar (0.9 mg/cm^2) by means of an electron-beam evaporator. In order to obtain sufficient resolution at low-electron energies, the accelerating field was reduced to 5 kV. Curve (b) of Fig. 7 shows the calibration curve for this arrangement. In the spectrum shown in Fig. 9(b) the 15.9-keV L_{III} line is partly resolved from the L_{MM} and L_{MN} Auger-electron lines: The L_I and L_{II} conversion electron lines could not be detected. At still lower energies a composite peak due to the Re M-Auger electrons and a 2.4-keV N line is seen. Again, the gamma-ray spectra coincident with the left- and right-hand sides of the line were studied [Fig. 11 (a) and (b)]. The results show that the 2.4-keV transition is in coincidence with the 106-keV transition.

As the two energy-sums, (92.4+15.9) keV, and (105.9+2.4) keV, both equal 108.3 keV, it seemed plausible that the two new transitions originate from a 171.9-keV level and populate the 156.0- and 169.5-keV states which had been identified as 3−. In order to

[18] This conclusion is supported by the results of a γ-γ coincidence experiment, for which the 92.4-keV photopeak was used as trigger; as is evident from the results shown in Table II, the number of L x rays is higher than in the spectrum triggered by the 106-keV photopeak.

determine the spin and parity of the isomeric level, a determination of the multipole order of the 15.9-keV transition was carried out.

f. Multipole Order of 15.9-keV Transition

No indication of a 15.9-keV photopeak was found in the γ-ray spectrum (Fig. 3). An upper limit for the number of unconverted gamma rays per 15.9-keV transition, $I_\gamma < 2\%$, was obtained, excluding an $E1$ assignment. From Fig. 9(b) it was seen that the L_{III} line of the 15.9-keV transition is considerably more intense than the L_I and L_{II} lines. Comparison with the theoretical L-conversion coefficients (Table V) shows that this is only the case for an $M3$ transition.

In order to check this result, we measured the M-conversion lines of the 15.9-keV transition with a double-focusing spectrometer at 0.4% resolution (Fig. 12). The energy calibration was carried out using the well-established K line of the 155.03±0.012-keV transition in Os^{188} (emitted in the decay of Re^{188}). From this measurement the transition energy was found to be 15.93±0.10 keV. The M subshell ratios obtained from this spectrum, which confirm the $M3$ assignment, are given in Table V. The 171.9-keV level, from which the 15.9-keV transition originates, is therefore most probably 6−, and the 2.4-keV transition, which starts at the same level and populates a 3− state as well, must therefore be also an $M3$ transition.

g. Determination of the Isomeric Cross-Section Ratio for Thermal Neutron Capture

As the spin of the isomeric state (6−) differs appreciably from the ground state spin (1−) of Re^{188}, it seemed of interest to reinvestigate the production ratio $R_{capt} = \sigma_{Re^{188}}/\sigma_{Re^{188m}}$ for pile neutron capture. The capturing state of $Re^{187}+n$ is either 2 or 3.[19] One therefore expects $R_{capt} \gg 1$. By comparing the intensity of the 155-keV line from the ground-state (16.7-h) decay with that of the 106-keV transition in Re^{188m} and correcting for

TABLE V. L-shell and M-shell conversion (electron) ratios for the 15.93±0.10-keV transition[a] and corresponding retardation factors.[b]

Multipole	$L_I/L_{II}/L_{III}$	$M_I/M_{II}/M_{III}/M_{IV}/M_V$	Retardation factor[c]
$E1$	1/1/2.3	1/0.85/1.45/0.40/0.63	10^{15}
$M1$	1/0.09/0.02	1/0.10/0.02/0.004/0.002	10^{14}
$E2$	1/70/120	1/100/140/5/5	10^{10}
$M2$	1/0.04/0.75	1/0.02/0.18/0.003/0.0004	10^{9}
$E3$	1/70/100	1/95/125/20/30	10^{4}
$M3$	1/0.05/8.5	1/0.07/6.5/0.15/0.25	2×10^{3}
Experiment ($M3$)	L_I, L_{II}: hidden L_{III}: observed[d]	M_{II}, M_{IV}, M_V: hidden $M_I/M_{III}\approx 1/5$[e]	

[a] Theoretical values for conversion coefficients are taken from Rose's Tables.
[b] For M-shell conversion coefficients, $Z_{eff}=68$ was used for Re ($Z=75$) in order to take the screening and finite size effects into account.
[c] Retardation factors were obtained by correcting the experimental half-life (18.7 min) for branching and for internal conversion and dividing by the theoretical single-proton gamma-ray half-life deduced from Moszkowski's formulae using $a_0 = 1.45\times10^{-13} A^{1/3}$ cm.
[d] Measured by means of Gerholm spectrometer with 5-kV acceleration.
[e] Measured by means of double-focusing spectrometer.

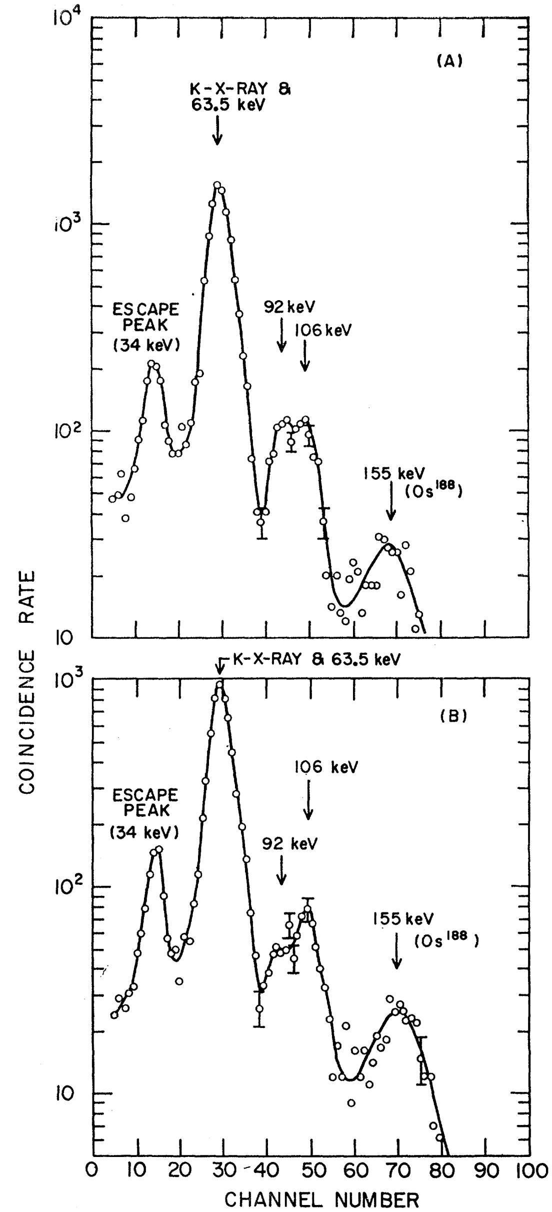

FIG. 11. This figure demonstrates that the 2.4-keV transition coincides with the 106-keV transition, but not with the 92-keV transition. Curve (A) shows the gamma-ray spectrum coincident with M-Auger electrons from Re^{188m}. The triggering pulses correspond to a field current of 0.99 A [see Fig. 9(b)]. The curve represents an 80-min count started 10 min after the end of the neutron bombardment. Curve (B) presents the gamma-ray spectrum coincident with the 2.4-keV N-electron line [I=1.025 A; Fig. 9(b)]. Clearly the 106-keV peak is more intense than the 92-keV peak. The curve represents the combined results from two 80-min runs started 10 min after the end of bombardment.

[19] It has recently been shown by A. Stolovy [Bull. Am. Phys. Soc. 9, 461 (1964)], that $J=3$ for the resonance at 4.42 eV, which is mostly responsible for the thermal neutron cross section in Re^{187}.

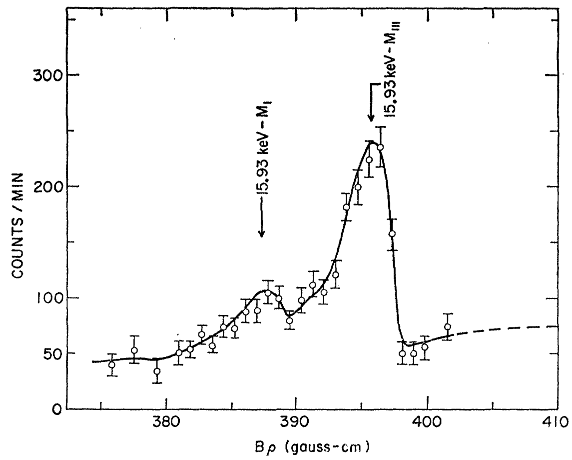

FIG. 12. M-shell conversion lines of the 15.93-keV isomeric transition measured by double-focusing spectrometer. For the energy calibration the well established K line of the 155.03 $\pm$0.012-keV transition in Os^{188} was used, which is emitted from the 16.7-h Re^{188} ground state.

The higher energy portion of the spectrum shown by a dashed line results from data taken in another run. The M-subshell ratios computed from this figure are given in Table V and confirm the multipole order assignment $M3$ obtained from the L-subshell ratios (Fig. 9).

internal conversion, branching ratios and decay constants of the two transitions, one arrives at the value $R_{\text{capt}}=55\pm7$. Using the recently reported value $\sigma_{Re^{188}}=(69\pm7)\times10^{-24}$ cm^2,[20] one obtains $\sigma_{Re^{188m}}=(1.25\pm0.25)\times10^{-24}$ cm^2, in good agreement with Flamersfeld's value of 1.0×10^{-24} cm.

III. DISCUSSION

The ground state of Re^{188} may be assumed to consist of the proton orbit $\frac{5}{2}+[402\uparrow]$ found for the ground state of Re^{187} and the neutron orbit $\frac{3}{2}-[512\downarrow]$ found for W^{187}. Following the notation of Gallagher and Moszkowski,[21] the arrows indicate that for the proton orbit the angular momentum component along the symmetry axis $\Omega_p=\Lambda_p+\frac{1}{2}(\uparrow)$, where Λ is the component of the orbital angular momentum along the symmetry axis, and for the neutron orbit $\Omega_n=\Lambda_n-\frac{1}{2}(\downarrow)$. According to the rule proposed by these authors, the intrinsic spins of the proton and neutron tend to be parallel for the ground-state configuration of an odd-odd nucleus, as they are in the deuteron. This leads to $|\Omega_p-\Omega_n|=1-$, in accordance with experiment.

From the fact that each of the two $M3$ transitions is followed by two $M1$ transitions in succession, one may conclude that the level sequence adopted for the decay scheme (Fig. 13) 6$-$, 3$-$, 3$-$, 2$-$, 1$-$, which was so far considered as probable only, is indeed the most plausible one. It is interesting that for the levels at 171, 169, and 0 keV this sequence suggests 3 orbits adjacent in the Nilsson diagram[22] for $82<N<126$, while the proton orbit remains the same. The spin alignment rule is then also fulfilled for the two excited states.

The levels at 63.5 and 156 keV are most naturally interpreted to be members of a rotational band built on the ground state, with $K=1-$. We then find $r_{\text{meas}}=E_2/E_1=1.45$, while the $I(I+1)$ rule gives $r_{\text{theor}}=1.50$ for this ratio. The 3% deviation from this rule contrasts with the value $r_{\text{meas}}/r_{\text{theor}}=1.00$ found in the middle of the deformed region. The deviation is smaller, however, than that found in the isobar Os^{188}, where $r_{\text{meas}}/r_{\text{theor}}=0.89$.[1] Also, the moment of inertia of the rotational band in Re^{188}, while smaller than those found in the deformed region, is considerably larger than that of Os^{188}.

As shown in Table V, the 15.9-keV ($M3$) transition is retarded by a factor of $\sim$2000. The retardation of the 2.4-keV ($M3$) transition is estimated to be 10 to 20 times smaller. These retardation factors fall in the range of expected values for the following reasons: The 2.4-keV neutron transition represents an orbit flip from $\Lambda=3$ to $\Lambda=0$. Morinaga and Takahashi[23] have shown that for $M3$ transitions with $\Delta\Lambda=3$ retardation

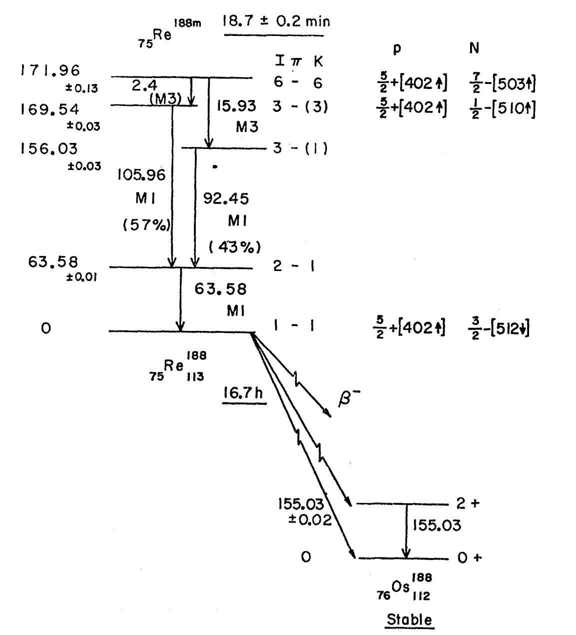

FIG. 13. Decay scheme of Re^{188m}. The energies are given in keV. A part of the decay scheme of Re^{188} (16.7 h) which is relevant for the present work has been taken from Ref. 9. The precise energy values for the three $M1$ transitions are those given in Ref. 7. Please note that the level scheme is not drawn to scale.

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factors $\lesssim 7\times 10^4$ are known. The 15.9-keV transition is K-forbidden: $\nu=\Delta K-3=2$. For each unit of ν a retardation factor between 10 and 100 is found to be the rule, in agreement with the present result. No special search for the 13.5-keV transition from the 169-keV to the 156-keV level was undertaken as this transition is equally K-forbidden as the 106-keV transition ($\nu=1$) with which it competes: It is therefore expected to be $(106/13.5)^3\sim 500$ times weaker. The absence of the 156-keV (<0.1%) and 169-keV (<0.05%) $E2$ transitions is attributed to the preferred role of the competing 92- and 106-keV $M1$ transitions.

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Spin and Magnetic Moment of N^{13}†

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The spin and hyperfine structure separation $\Delta\nu$, of 10-min N^{13} have been measured by the atomic-beam magnetic-resonance technique. The atomic-beam machine was a modified focusing apparatus consisting of a six-pole A magnet, a Goodman-type C magnet, and an approximately uniform-gradient B magnet. This apparatus, which combines the high transmission of focusing machines and the smaller detector area of conventional machines, is described in detail. The N^{13}, in the form of a gaseous molecule, was flushed continuously from the cyclotron target to the apparatus, where neutral atoms were produced in a microwave discharge in the neon carrier gas. The beam was detected on titanium foils heated to approximately 1025°C. The measurements were made in the $^4S_{3/2}$ atomic ground state, but resonances were also observed in the ^2P and ^2D metastable doublets. The final results are $I=\frac{1}{2}$, as expected, and $\Delta\nu=33.347\pm0.020$ Mc/sec from a $\Delta F=1$ measurement. Using the high-precision results on N^{14} and N^{15}, we obtain an average value of $|\mu_I|$, which, corrected for shielding, is $|\mu_I|=0.32212$ (36) nm. Assuming that the sign is negative (as in the case of N^{15}), the sum of the magnetic moments of N^{13} and C^{13} is 0.380 nm, in agreement with the combined predictions of Kurath (for the ordinary part of the magnetic moment operator) and Sachs (for the mesonic current contributions). Further discussion of the result is given.

I. INTRODUCTION

THE study of nuclear magnetic dipole moments has an extensive literature.[1] Experimentally one can make measurements with great precision, but theoretically the situation is not so clear.

The calculation of magnetic moments is very sensitive to small configuration admixtures in the nuclear wave functions.[2] If this were the only uncertainty, then one could use the measured quantities to deduce information about these wave functions. However, it has been shown that the form of the nuclear magnetic dipole operator is sensitive to the strong interactions of the nucleons,[3] i.e., sensitive to meson exchange currents. This differs from the case of electric multipole operators for which the form of the electromagnetic interaction should be independent of the other interactions of the nucleons.[3]

In addition, there has long been speculation about using the same g factors for bound nucleons as for free nucleons.[4] There are large contributions to the nucleon g factors from virtual emission and absorption of mesons, which involve the recoil of the nucleon. In finite nuclei, recoils into occupied momentum states are prohibited by the Pauli principle which could result in a quenching of the g factor. A recent calculation has shown this to be an appreciable effect.[5]

It was pointed out[6] that the meson exchange contribution to a pair of mirror nuclei should be equal and

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