cubic fermi, respectively, is only slightly below the value of 0.158 nucleons per cubic fermi which characterizes most spherical nuclei.[15,36] Thus, nuclear matter elongates but does not change in central density as it departs from the closed-shell structure.

The intrinsic quadrupole moments were found to be $(11.47\pm0.13)\times10^{-24}$ cm^2 for U^{238} and $(9.83\pm0.16)\times10^{-24}$ cm^2 for Th^{232} and agree very well with the results of De Wit *et al.*[14] as shown in Table VI.

ACKNOWLEDGMENTS

I would like to thank Professor H. L. Anderson for suggesting this problem and for his generous assistance and encouragement in the preparation, execution, and interpretation of this experiment. I would also like to thank my collaborators Richard D. Barton, Clifford K. Hargrove, E. P. Hincks, James D. McAndrew, Madhu S. Dixit, Harlan J. Evans, and Dan Kessler for their effort and support during the course of the experiment. I am indebted to I. L. Fowler and H. L. Malm of the Chalk River Nuclear Laboratories of Atomic Energy of Canada Ltd. for the fabrication of the Ge(Li) detector and for helping to mount it. I am grateful for the technical assistance rendered by Rudy Gabriel, J. P. Legault, John Lillberg, William Miles, Paul Plowe, and John Redfern. I would also like to thank Frank Castorf and Mrs. Serena Torres for their computer programing assistance. And, finally, I thank Mrs. Ann Scott for her patience in typing the many drafts of this paper.

PHYSICAL REVIEW VOLUME 180, NUMBER 4 20 APRIL 1969

Studies of Os^{189}: Gamma Rays, Lifetimes, and Mössbauer Effect*

M. C. Gregory,† B. L. Robinson, and S. Jha
Case Western Reserve University, Cleveland, Ohio 44106
(Received 21 October 1968)

The γ-ray energies and intensities in the decay of iridium-189 have been measured with Ge(Li) and Si(Li) detectors, and the internal-conversion coefficients of 15 lines have been estimated. The mean life of the 276-keV state was found to be less than 0.4 nsec by electronic means. Limits were established for the mean life of the 95.3-keV state by the Mössbauer effect (greater than 0.2 nsec) and by electronic means (less than 0.4 nsec). The mean life of the 69.6-keV level was found to be 2.35 ± 0.06 nsec, and a single line of corresponding width was observed in the Mössbauer effect. The nuclear Zeeman effect gave the magnetic moment of the 69.6-keV state as 0.965 ± 0.020 μ_N, with $E2/M1=0.57\pm0.21$ and an internal magnetic field of 1.085 ± 0.052 MG acting on the osmium nucleus in a dilute iron alloy. The electromagnetic properties of the 69.6-keV level are completely consistent with its pure rotational character.

I. INTRODUCTION

THE level structure of osmium-189 and the properties of its excited states have not been well studied. The level structure is inferred from the studies of the radioactive decay of 24-h rhenium-189 [1,2] and 13.3-day iridium-189.[1,3] Although transition energies have been measured accurately by β-ray spectroscopy and internal-conversion ratios have been estimated, high-resolution γ-ray studies have not been carried out. From Coulomb excitation work[4–6] the $B(E2)$ values for the 69.6-, 95.3-, 219.4-, and 233.6-keV levels have been extracted.

The partial level scheme of osmium-189 is shown in Fig. 1. The ground state of osmium-189 is $\frac{3}{2}-$, its magnetic dipole moment is $+0.6566$ μ_N, and its electric quadrupole moment is $+0.91\pm0.10$ b.[7] The 69.6-keV level ($\frac{5}{2}-$) is interpreted to be the first rotational state built on the ground state. Its mean life has not been directly measured but it is estimated to be 2.4 nsec, based upon the $B(E2)$ value extracted from Coulomb excitation and the multipolarity mixture ratio extracted from internal-conversion data. The 36.3-keV state ($\frac{1}{2}-$) is supposed to be an intrinsic state.[7a] No measurement of its lifetime has been made, but the 36.3-keV transition to the ground state is an almost pure $M1$ transition. The 95.3-keV state has been interpreted as the first rotational state built on the 36.3-keV intrinsic state. Its lifetime is inferred to be 0.86 nsec,

* From the Ph.D. thesis of M. C. Gregory, Case Western Reserve University, 1968.

† Present address: Lawrence Radiation Laboratory, Livermore, Calif.

[1] A. Artna, Nucl. Data **1B**, 85 (1966).

[2] B. Craseman, G. T. Emery, W. R. Kane, and M. L. Perlman, Phys. Rev. **132**, 1681 (1963).

[3] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **128**, 1186 (1962).

[4] D. H. Rester, M. S. Moore, F. E. Durham, and C. M. Class, Nucl. Phys. **22**, 104 (1961).

[5] F. K. McGowan, P. H. Stelson, R. L. Robinson, and J. L. C. Ford, Oak Ridge National Laboratory Report No. ORNL-3425, 1963, p. 26 (unpublished).

[6] A. Z. Hrynkiewicz, B. Sawicka, J. Styczen, S. Szymczyk, and M. Szawlowski, Acta Phys. Polon. **31**, 437 (1967).

[7] G. Himmel, Z. Physik **211**, 68 (1968).

[7a] *Note added in the proof.* P. Kienle *et al.* have studied the Mössbauer effect with the 36.3-keV γ ray. The mean life and the magnetic moment of the 36.3-keV state are (0.72 ± 0.04) nsec and $+(0.226\pm0.029)$ μ_N, respectively (private communication).

again based upon Coulomb excitation and internal-conversion data. It is presumed that some interband mixing[1,2] should occur in the states of this nucleus, but in view of the fact that the higher members of the rotational bands have not been observed, the assignment of a pure rotational character to the 69.6- and 95.3-keV states must be regarded as tentative.

In the absence of detailed high-resolution Coulomb excitation studies and relevant nuclear reaction studies which could yield information on the higher members of the rotational bands, the measurement of the electromagnetic properties of the low-lying levels would be useful. It should be possible to observe the Mössbauer effect with the 36.3- and 95.3-keV γ rays in addition to the 69.6-keV γ ray which has already shown a large Mössbauer effect.[8]

In this paper, we report on the high-resolution γ-ray studies of the decay of iridium-189, which lead to estimates of the internal-conversion coefficients of the γ-ray transitions. The results of electronic lifetime measurements, hyperfine-structure studies with the 69.6-keV γ ray, and the Mössbauer effect with the 95.3-keV γ ray are also reported.

II. PREPARATION OF RADIOACTIVE SOURCES

Iridium-189 was produced mainly by the bombardment of natural rhenium metal with 30-MeV helium ions at the cyclotron of the NASA Lewis Research Center. Targets were allowed to age for about three weeks to permit short-lived activities to decay. The irradiated rhenium targets, annealed at 1000°C for 24 h in a hydrogen atmosphere, served as sources for Mössbauer effect experiments.

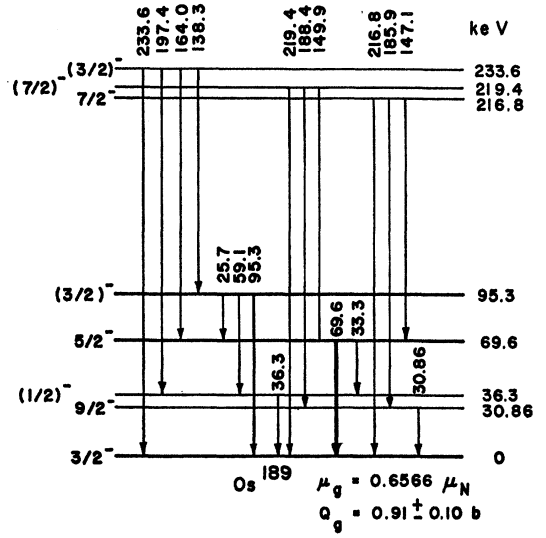

FIG. 1. Partial level scheme of osmium-189.

[8] S. Jha, W. R. Owens, M. C. Gregory, and B. L. Robinson, Phys. Letters **25B**, 115 (1967).

After a source became too weak for Mössbauer spectroscopy, the iridum was separated chemically for other purposes. The rhenium was dissolved in aqua regia, about 10 μg of iridium were added in the form of the chloride, and the solution was then evaporated to dryness. The rhenium was driven off by sublimation of Re_2O_7 in a current of air, leaving an almost carried-free residue of iridium chloride. This radioactive iridium was then taken up in a drop of water and transferred, for example, to a thin sheet (0.1 mm) of plastic scintillator for the conversion-electron–x-ray coincidence studies described below.

Alternatively, a source of iridium-189 was prepared by the bombardment of an iridium foil with 26-MeV protons at the cyclotron of the University of Colorado at Boulder. Platinum-189 (10 h) was produced and allowed to decay to iridium-189. After annealing as above, the iridium foil was used as a source for a Mössbauer study of osmium-189 in the cubic surroundings provided by the iridium metal host lattice as discussed in Sec. V.

Finally, platinum-189 was produced by α bombardment of natural osmium powder. Immediately after the bombardment, the platinum was separated from osmium and iridium; iridium-189 was allowed to grow in the platinum fraction by the decay of platinum-189, and the iridium and platinum were again separated after some length of time. These separations were made by solvent extraction with ethyl acetate.[9] Iridium sources prepared in this way are free of iridium-190 and -192, but do contain the iridium-188 daughter of 10-day platinum-188; however, the iridium-188 has a much shorter half-life than iridium-189 and it can be allowed to decay before the source is used.

III. γ-RAY SPECTROSCOPY

The γ rays emitted by these samples were observed in (a) a 10-cc planar lithium-drifted germanium detector with an aluminum window and (b) a small lithium-drifted silicon detector with a beryllium window.[10] In each case preamplifiers were integral parts of the detectors, and a Tennelec TC-200 amplifier with a TC-250 biased amplifier was used. Spectra were accumulated on a 512-channel pulse-height analyzer.

The relative efficiencies of the detectors were determined by observing the γ-ray spectra of selenium-75, iridium-192, and barium-133, for which the relative intensities of the γ rays are well known.[11–13] The 96- and 66-keV lines of selenium-75 were clearly seen in

[9] G. W. Leddicotte, *The Radiochemistry of Iridium* (Office of Technical Services, U.S. Department of Commerce, Washington, D.C., 1961), NAS-NS-3045.

[10] These detectors were loaned to us by ORTEC, Inc. We are very grateful to Lee Ashcraft.

[11] J. B. Marion, Nucl. Data **4A**, 301 (1968).

[12] P. V. Rao, D. K. McDaniels, and B. Crasemann, Nucl. Phys. **81**, 296 (1966).

[13] W. P. Jones, Nucl. Phys. **A108**, 209 (1968).

TABLE I. Intensities and internal-conversion coefficients.

Transition energy (keV)	Relative γ-ray intensity	Relative electron intensity a	b	Internal-conversion coefficient a	b	Theoretical conversion coefficients c $M1$	$E2$	Multipolarity mixture ratio $E2/M1$ a	b
				L conversion					
25.7	0.5	15		3.19		42.3	2006		
36.3	11.8	423	500	3.58	4.24	16.1	362		
56.6	3.3	44		1.33		4.10	41.0		
59.1	26.3	395							
59.3		36							
69.6	62.1	2100	1900	3.38	3.06	2.24	15.0	0.10	0.07
				K conversion					
95.2	5.1	15	67						
95.3		75							
138.3	1.1	13	53	1.19	4.91	1.90	0.444	0.95	
147.1	1.4	13	53	0.96	3.95	1.59	0.365	1.2	
149.9	0.1	6	20	0.64	2.13	1.51	0.355	3.2	
164.0	0.1	11	12	1.15	1.22	1.17	0.283	0	0
180.5	0.5	3.2	10	0.64	2.00	0.895	0.218	0.61	
185.9	9.2	18	57						
188.4		6.3	8						
197.4	3.7	8.5	14	0.229	0.385	0.698	0.176	8.4	
206.3	1.2	4.6	9	0.371	0.726	0.617	0.155	1.1	
216.8	6.2	15	13	0.242	0.205	0.540	0.143	3.0	5.4
219.4	6.4	13	12	0.204	0.183	0.523	0.139	4.8	7.4
233.4	5.0	13	6	0.259	0.120	0.441	0.110	1.2	32
244.8[d]	100	100	100				0.100		
275.7	8.8	14		0.158		0.297	0.083	1.9	

[a] Reference 3.
[b] Reference 14.
[c] Reference 15.
[d] This transition ($\frac{5}{2}-$ to $\frac{9}{2}-$) is taken as a pure $E2$ transition with the theoretical K-shell conversion coefficient. All intensities were normalized to this line.

both detectors and served as the normalization points for intercalibrating them.

The pulse-height spectra observed in these detectors are shown in Figs. 2 and 3. The energies and relative intensities of the γ rays emitted by iridium-189 are given in Table I.

The internal-conversion electrons emitted by iridium-189 have been observed in a permanent-magnet photographic β-ray spectrometer[3] and in a double-focusing β-ray spectrometer.[14] The results are summarized in Table I. Internal-conversion coefficients were computed assuming that the 245-keV line is a pure $E2$ transition with the theoretical value[15] of the K-conversion coefficient, $\alpha_K=0.100$. Theoretical values for the $E2$ and $M1$ internal-conversion coefficients are given in Table I for each γ ray, and estimates were made of the multipolarity mixing ratios and entered in the last column of the table. Note that the values obtained for the L-shell internal-conversion coefficients fell consistently outside the range of the theoretical coefficients. This could well be due to systematic errors in the estimation of the intensity of the low-energy electron lines.

IV. LIFETIME MEASUREMENTS

The lifetimes of the 69- and 95-keV levels were measured by a delayed coincidence technique[16] involving x-ray–conversion-electron coincidences. The 4π electron counter was fabricated of a sandwich of 0.1-mm

[14] G. Y. Sychikov, O. D. Kovrigin, G. D. Latyshev, G. D. Lodarenko, and V. N. Novikov, Izv. Akad. Nauk SSSR Ser. Fiz. **30**, 162 (1966).
[15] R. S. Hager and E. C. Seltzer Nucl. Data, **4A**, 1 (1968).
[16] R. E. Bell, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), Chap. XVII.

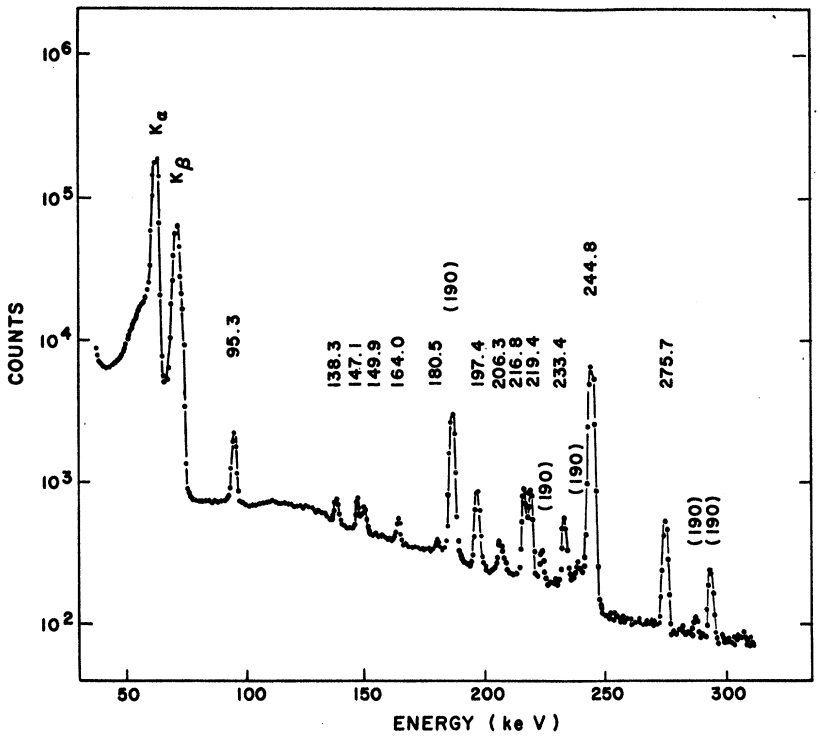

FIG. 2. γ-ray spectrum in germanium detector.

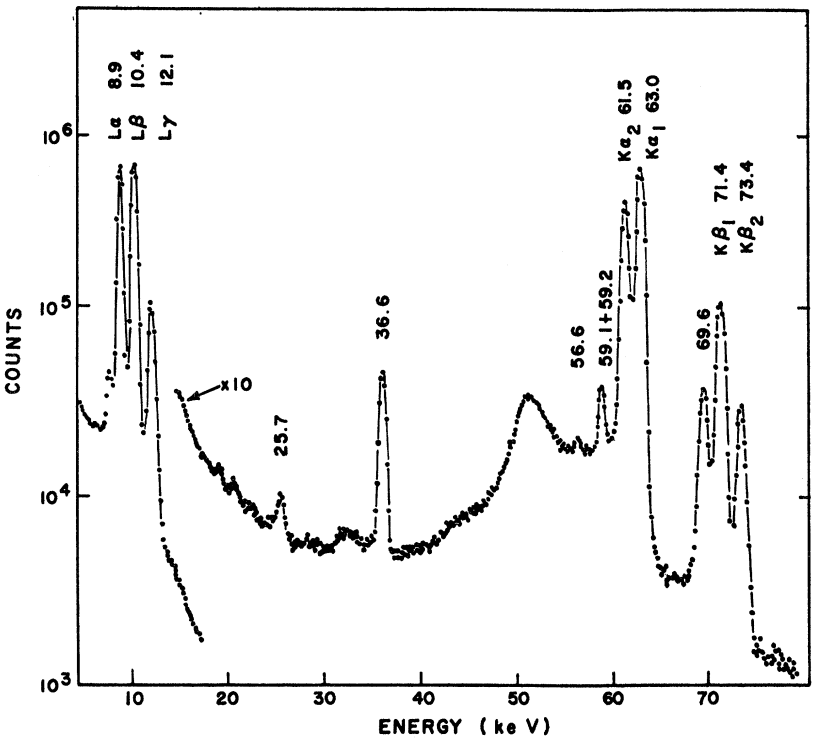

FIG. 3. γ-ray spectrum in silicon detector. [The weak low-energy satellite of the L x-ray group is the Ll x ray of osmium ($L_{III}M_I$) transition.]

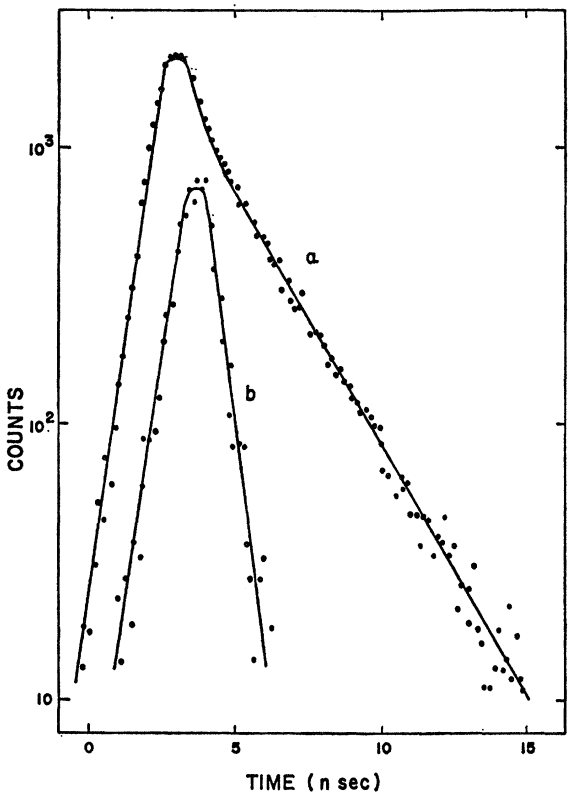

FIG. 4. Delayed coincidence curves: (a) 69.6-keV transition, (b) 95-keV transition.

sheets of plastic scintillator.[17] After depositing the almost-carrier-free source upon one sheet and drying the deposit, the sandwich was fused at about 150°C to form a single transparent scintillator. This was optically coupled to a RCA type 7746 photomultiplier. The x-rays emitted by this source were detected in a Naton-136 plastic scintillator coupled to a similar tube.

Typical delayed coincidence curves are shown in Fig. 4, and the pulse-height spectrum in the 4π electron counter is shown in Fig. 5, where the pulse-height selector settings are indicated for the various experiments.

Since the small plastic scintillator is almost totally insensitive to γ rays, the method was energy-calibrated by making 4π scintillators of barium-133 and cadmium-109 after the technique was developed to the point of reproducibility of pulse height in different source sandwiches. The adequacy of the time resolution at very low energies and at very short times was confirmed by making a 4π detector of iodine-125; the mean life of the 35-keV state in tellurium-125 was found to be 1.4 ± 0.1 nsec, in agreement with previous work.[18]

Using this technique, the mean life of the 69.6-keV level of osmium-189 was measured with three different source sandwiches. By means of a least-squares fit to the exponential part of the delayed coincidence curve, we obtained the following results for these experiments: 2.38 ± 0.05, 2.34 ± 0.05, and 2.32 ± 0.05 nsec. In each of these results the statistical errors are negligible compared to the systematic error due to nonlinearity in the time calibration of the time-to-amplitude converter. We report a final value of 2.35 ± 0.06 nsec for the mean life of the 69.6-keV state.

In two different experiments, only an upper limit of 0.4 nsec could be set for the mean life of the state(s) associated with the 95-keV line(s) as shown in Fig. 4(b). The conversion electrons of the 245-keV transition are by far the most prominent feature of the high-energy electron spectrum of iridium-189: By setting a wide window for high-energy electrons, as shown in Fig. 5(c), we were able to find only an upper limit for the mean life of this transition. We conclude that the 275.8-keV state, from which the 245-keV transition is supposed to originate, has a mean life of less than 0.4 nsec.

V. MÖSSBAUER EFFECT

Mössbauer-effect experiments were performed with the 69.6- and 95.3-keV γ rays of osmium-189 using sources of iridium-189. Our earlier work[8] was done at

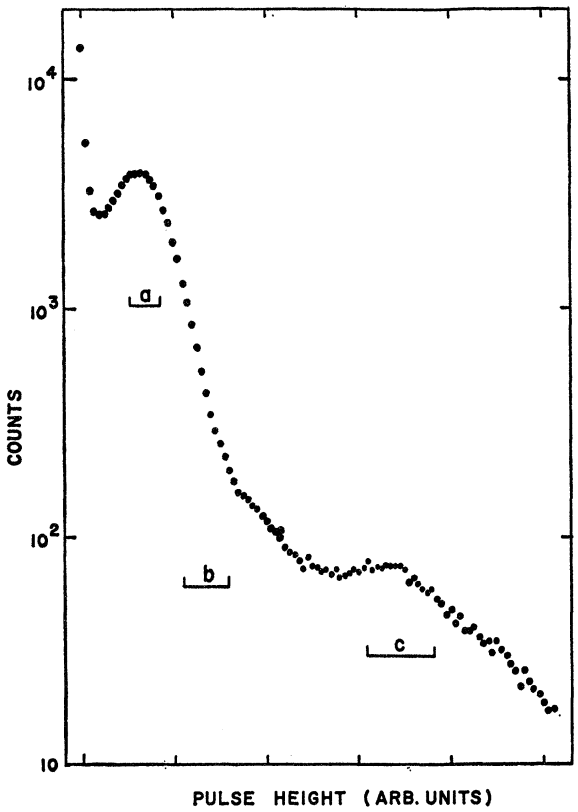

FIG. 5. Pulse-height spectrum in the plastic source sandwich scintillator: (a) single-channel setting for 69.6-keV transition, (b) single-channel setting for 95-keV transition, (c) single-channel setting for 245-keV transition.

[17] Samples of NE 102 were supplied by Harshaw Chemical Co., Cleveland, Ohio.

[18] C. Hohenemser and R. Rosner, Nucl. Phys. **A109**, 364 (1968).

the temperature of liquid nitrogen, but the experiments described here were performed mostly at liquid-helium temperatures in a cryostat described by Kalvius.[19] For the detection of the γ rays, we used a lithium-drifted germanium detector with an area of 4 cm^2 and a thickness of 3 mm. Although the energy resolution was 2.8 keV [full width at half-maximum (FWHM)], the 69.6-keV γ ray was not resolved from the intense K x rays of osmium. After amplification in a biased amplifier, the pulses were selected with a single-channel analyzer set at the position at which the 69.6-keV γ rays were expected to appear. This setting was optimized by a sequence of on-off Mössbauer experiments, in which the transmission of the 69.6-keV γ ray was compared for stationary source and for a very large velocity of the source.

The Mössbauer spectra were observed in the constant-acceleration mode using a Kankeleit drive system[20] and a 400-channel analyzer. The drive system was calibrated by observing the nuclear Zeeman effect in iron-57 with a cobalt-57 source in stainless steel and a metallic iron absorber enriched in iron-57.

The hyperfine patterns observed in these experiments were fitted by a computer program to a sum of Lorentzian-shaped lines in which the linewidth, positions, intensities, multipolarity admixture, and hyperfine constants are least-squares fitted to a linear expansion of the functional by an iterative process until certain convergence criteria are satisfied.[21] The program can be constrained to fit the relative positions and intensities calculated from the theory of hyperfine interactions.

Figure 6 shows the Mössbauer spectrum with the 69.6-keV γ ray using a thick (about 100 mg/cm^2) osmium metal absorber enriched to 87.3% in osmium-189 and a rhenium metal foil source. The solid line in the figure is the computed fit for a single Lorentzian-shaped line with the FWHM of $(5.34\pm0.08)\,\Gamma$, $\Gamma=\hbar/\tau$. With the iridium-189 source in iridium metal and a thin natural osmium metal absorber, a Mössbauer effect of 0.9% was observed with a FWHM of $(2.50\pm0.33)\,\Gamma$. This width corresponds to the measured mean life of the 69.6-keV state when account is taken of the thickness of the absorber, assuming that the Debye temperature is 325°K and that the total internal-conversion coefficient is 8.

Figure 7 shows the Mössbauer spectrum with the 95.3-keV γ ray using the rhenium metal foil source and the thick enriched osmium-189 metal absorber. The FWHM of this absorption line corresponds to a mean life of 129 ± 30 psec. After correcting for the thickness of the absorber assuming an internal-conversion coefficient of 6.7, we find that the value of the mean life is 190 ± 50 psec. This value represents the lower limit for the mean life of this state because the line could have been broadened by hyperfine interactions. We therefore conclude that the mean life of the 95.3-keV state is more than about 0.2 nsec and less than 0.4 nsec.

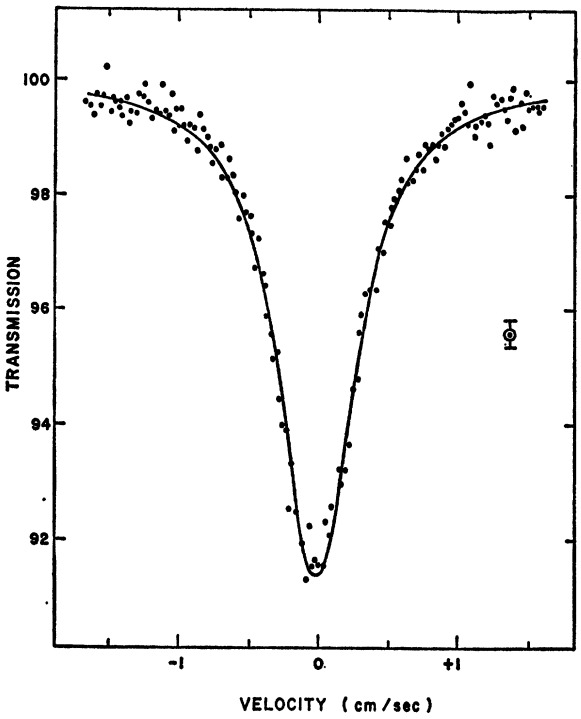

FIG. 6. Mössbauer velocity spectrum with the 69.6-keV line, the source is in rhenium metal foil and thick (about 100 mg/cm^2); enriched (87.3%) osmium metal absorber.

For the study of the magnetic hyperfine splitting of the Mössbauer line of the 69.6-keV γ ray, an absorber of osmium-iron alloy was made. Weighed amounts of very pure metallic iron powder and 3-at.% natural osmium powder were mixed, sintered in a furnace in a hydrogen atmosphere, and then melted in an arc furnace in an argon atmosphere. The pellet so formed was remelted three times, cold-rolled to a thickness of 0.4 mm, and annealed. Using this foil as an absorber and a source of iridium-189 in a rhenium metal host lattice, the magnetic hyperfine structure was observed as shown in Fig. 8. The theoretical intensity distribution for the $E2$ and $M1$ components is shown at the top of the figure. The full line represents the best fit to the experimental data and corresponds to $\mu_e/\mu_g=1.47\pm0.03$, $\delta^2=0.57\pm0.21$, and an effective magnetic field at nucleus of 1.084 ± 0.052 MG. Using the measured magnetic moment of the ground state $\mu_g=0.6566\ \mu_N$, we find that the magnetic moment of the 69.6-keV state is $0.965\pm0.020\ \mu_N$.

Persson *et al.*[22] report the results of Mössbauer experiments with the 69.6-keV γ ray. Their values of the mean life, the magnetic moment, the multipolarity

[19] M. Kelvius, in *Mössbauer Effect Methodology*, edited by I. Gruverman (Plenum Publishing Co., Inc., New York, 1965); Phys. Rev. **137**, B1441 (1965).

[20] E. Kankeleit, Rev. Sci. Instr. **35**, 194 (1964).

[21] R. H. Moore and R. K. Ziegler, Los Alamos Scientific Laboratory Report No. LA-2367, 1960 (unpublished).

[22] B. Persson, H. Blumberg, and M. Bent, Phys. Rev. **174**, 1509 (1968); D. Kucheida, F. Wagner, G. Kaindl, and P. Kienle, Z. Phys. **216**, 346 (1968).

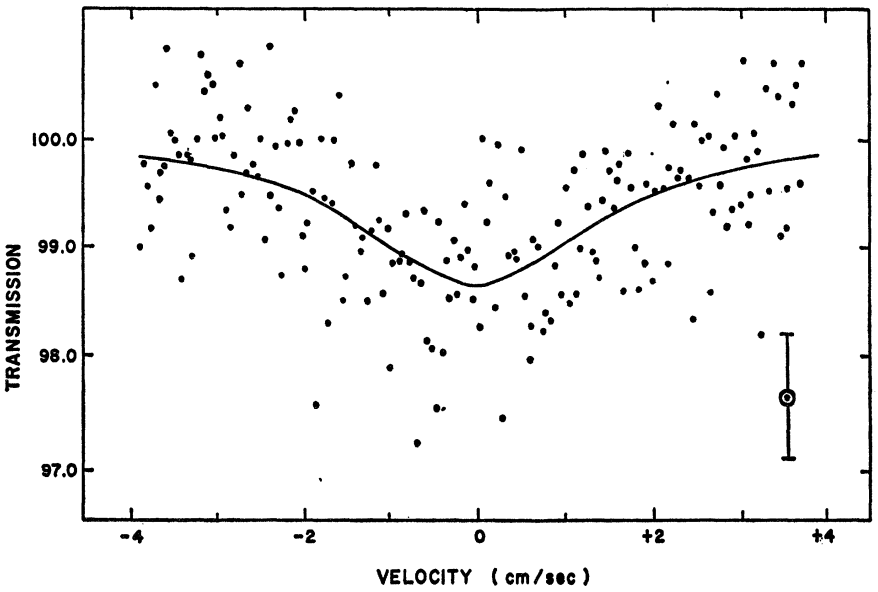

FIG. 7. Mössbauer velocity spectrum with the 95-keV line; conditions similar to Fig. 6.

mixing ratio, and the internal magnetic field are in agreement with our own.

In an attempt to study the electric quadrupole hyperfine interaction, an absorber of osmium disulfide was prepared. A sample of K_2OsO_4 was dissolved in weak hydrochloric acid; upon the addition of Na_2S, a black precipitate formed, which was centrifuged, washed, and dried. Chemical analysis confirmed the presence of sulfur in this precipitate, but attempts to analyze it by x-ray diffraction failed, probably because of the diffuse scattering produced by the extremely fine particles of the precipitate and because of the high atomic number and consequent strong absorption of osmium. An absorber of 20 mg/cm^2 was prepared, and the hyperfine structure shown in Fig. 9 was obtained. Because we are uncertain about the nature of the absorber, we are unable to make any interpretation of this result.

VI. DISCUSSION

The energies and intensities of the γ rays emitted in the decay of iridium-189 have been measured accurately in this work, but no additional information was obtained about the decay scheme beyond that which was already known. However, we note a discrepancy in the multipolarity mixing ratio of the 69.6-keV γ ray as determined by the total L-shell conversion coefficient ($\delta^2=\sim 0.10$), on the one hand and the intensity of the $\Delta m=\pm 2$ lines in the nuclear Zeeman effect ($\delta^2=0.57\pm 0.21$) and the L-subshell conversion coefficients ($\delta^2=0.43$)[1] on the other.

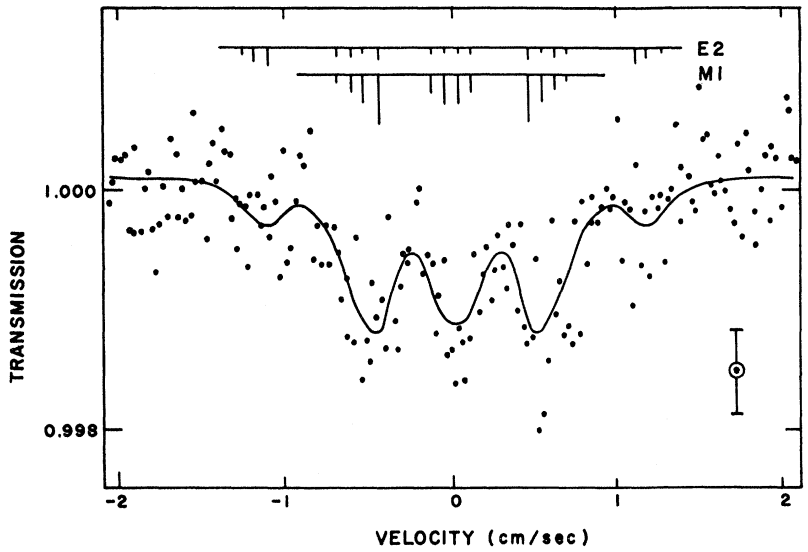

FIG. 8. Nuclear Zeeman effect with the 69.6-keV line: source in rhenium metal, osmium-iron alloy absorber (3-at.% osmium).

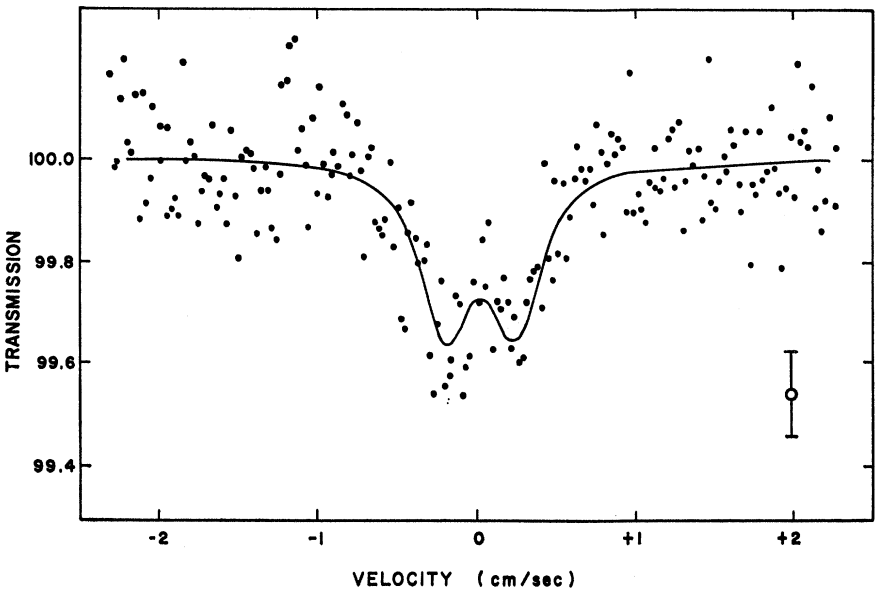

FIG. 9. Electric quadrupole hyperfine interaction with the 69.6-keV line: source in rhenium metal, osmium disulfide absorber.

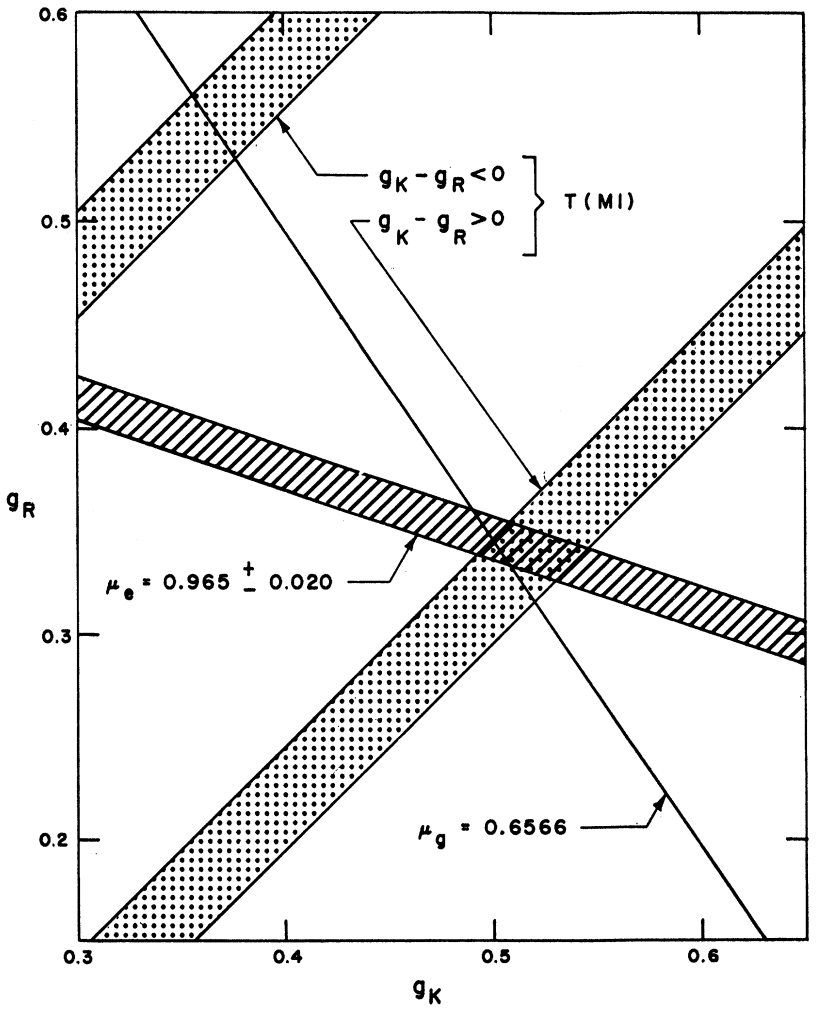

FIG. 10. Interpretation of the ground-state rotational band of osmium-189. The solid line and the hatched band correspond to the observed values of the magnetic moments. The stippled bands correspond to the transition probability for $M1$ radiation; the intersection for $g_K - g_R > 0$ is in accord with the observed positive value of the electric quadrupole moment of the ground state.

From direct electronic measurements we have set an upper limit of 0.4 nsec for the mean life of the 95.3-keV level, and the width of the Mössbauer resonance corresponds to a lower limit of about 0.2 nsec. These data are not in accord with the Coulomb excitation value of $B(E2)$, which corresponds to a mean life of 0.86 nsec. In the decay scheme of Harmatz *et al.*,[3] there are two 95-keV intervals corresponding to the ground-state transition, which we have confirmed by Mössbauer absorption, and to a transition between the 314.6- and 219.4-keV levels. The magnitude of the Mössbauer effect which we have observed implies that relatively little of the 95-keV group of γ rays arises from the ground-state transition, contrary to previous assignments.[1]

We shall conclude by commenting upon the rotational character of the 69.6-keV level. In terms of the rotational model,[23] the magnetic moments of the ground state ($I=K=\frac{3}{2}$) and the first rotational state ($I=\frac{5}{2}$, $K=\frac{3}{2}$) are given by

$$\mu(\text{ground})=3g_R/5+9g_K/10,$$
$$\mu(\text{excited})=13g_R/7+9g_K/14,$$

where g_K is the contribution to the gyromagnetic ratio due to the intrinsic structure and g_R is that due to the collective rotation. From the known values of the magnetic moments, g_R and g_K can, in principle, be determined by a simultaneous solution of these two equations. We prefer to present this solution in a graphical form[24] in Fig. 10, where the solid line corresponds to the ground-state magnetic moment and the hatched band corresponds to the excited-state magnetic moment.

Using the experimental value of the mean life of the 69.6-keV state and the theory of internal conversion, we can find the transition probability $T(M1)$ for the emission of magnetic dipole radiation:

$$1/T(M1)=\tau_{\text{obs}}[(1+\alpha_{M1})+\delta^2(1+\alpha_{E2})].$$

$T(M1)$ is related to $(g_K-g_R)^2$:

$$T(M1)=\frac{4}{3}\frac{E^3}{\hbar^4c^3}\mu_N^2(g_K-g_R)^2\frac{K^2(I+1-K)(I+1+K)}{(I+1)(2I+3)},$$

where μ_N is the nuclear magneton.[23] Then for $\tau=2.35\pm0.06$ nsec, $\alpha_{M1}=2.95$, and $\alpha_{E2}=20.7$, we find

$$(g_K-g_R)^2=\frac{1.16\pm0.03}{9.26+51.0\delta^2}.$$

Using the multipolarity mixing ratio determined from the intensity of the $\Delta m=\pm2$ components in the nuclear Zeeman effect, $\delta^2=0.57\pm0.21$, and taking both positive and negative roots, this result corresponds to the two stippled bands of slope unity in Fig. 10. The intersection of the lower band with the intersection previously determined by the magnetic moments confirms the assumption that the 69.6-keV state is within the limits of this experiment a pure rotational state. The "selection" of the positive root is in agreement with the positive value of the observed electric quadrupole moment and a positive δ.

The next member of the rotational band ($I=\frac{7}{2}$) should occur near 170 keV, and it should display a strong intraband transition to the 69.6-keV state. No such state has yet been suggested, and one would not expect it to be strongly excited in the decay of iridium-189, $I=\frac{3}{2}$. However, Hrynkiewicz *et al.*[6] have observed the γ rays due to heavy-ion Coulomb excitation of osmium-189 and their published γ-ray spectrum shows a peak at about 105 keV, although they take no note of it; this line might be the intraband transition. The existence of this state might be confirmed by a high-resolution γ-ray study of the spectrum of 24-h rhenium-189, $I=\frac{5}{2}$.

ACKNOWLEDGMENTS

We are indebted to Professor D. F. Gibbons of the Center for Study of Materials for his assistance in preparing the iron-osmium alloy. This work would not have been possible without the generous provision of cyclotron time by Dr. R. W. Bercaw of the NASA Lewis Research Center. We are especially indebted to G. W. R. Stroink for his help with the helium cryostat. Professor J. D. McGervey and P. D. Bond made their delayed-coincidence apparatus available, and J. M. Arnold helped in developing the computer programs used for this work.

[23] K. Alder and R. M. Steffen, Ann. Rev. Nucl. Sci. **14**, 403 (1964).

[24] W. R. Owens, thesis, Case Western Reserve University, 1968 (unpublished).