*Work supported by Contract N00014-67-A-0013-0018 with the Office of Naval Research.

†Present address: The Perkin-Elmer Company, 2800 Metropolitan Place, Pomona, California 91766.

[1]R. R. Ries, R. A. Damerow, and W. H. Johnson, Jr., Phys. Rev. 132, 1662 (1963).

[2]E. G. Johnson and A. O. C. Nier, Phys. Rev. 91, 10 (1953).

[3]A. O. Nier, in *Nuclear Masses and Their Determination,* edited by H. Hintenberger (Pergamon, London, 1957), p. 185.

[4]J. L. Benson and W. H. Johnson, Jr., Phys. Rev. 141, 1112 (1966).

[5]M. C. Hudson, Ph.D. thesis, University of Minnesota, 1969 (unpublished).

[6]J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 1 (1965).

[7]D. Kerr and K. Bainbridge, Can. J. Phys. 49, 756 (1971).

[8]A. H. Wapstra, in *Proceedings of the Third International Conference on Atomic Masses,* edited by R. C. Barber (University of Manitoba Press, Winnipeg, Canada, 1968), p. 156.

[9]E. R. Cohen and J. W. M. Du Mond, in *Proceedings of the Second International Conference on Nuclidic Masses,* edited by W. H. Johnson (Springer-Verlag, New York, 1964), p. 152.

[10]B. N. Taylor, W. H. Parker, and D. N. Langenberg, Rev. Mod. Phys. 41, 375 (1969).

[11]B. S. Dzhelepov, R. B. Ivanov, M. A. Milhailova, L. N. Moskuin, O. M. Nazarenko, and V. P. Rodionov, Izv. Akad. Nauk SSSR Ser. Fiz. 31, 568 (1967) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 31, 563 (1967)].

[12]S. A. Baranov, Yadern. Fiz. 7, 727 (1968) [transl.: Soviet J. Nucl. Phys. 7, 442 (1968)].

[13]H. van Klugten and E. W. Koopman, Physica 40, 253 (1968).

[14]S. Bjornholm, J. Dubois, and B. Elbek, Nucl. Phys. A118, 241 (1968).

[15]H. C. Britt and J. D. Cramer, Phys. Rev. 185, 1553 (1969).

[16]R. E. Chrien *et al.*, Nucl. Data B4(No. 6), 577 (1970).

[17]P. Matussek *et al.*, Nucl. Data B4(No. 6), 577 (1970).

[18]R. Middleton and H. Marchant, in *Proceedings of the Second International Conference on Nuclidic Masses,* (see Ref. 9), p. 329.

PHYSICAL REVIEW C VOLUME 7, NUMBER 4 APRIL 1973

Nuclear Orientation Studies of the Decays of ^{187}W and ^{185,191,193}Os†

K. S. Krane* and W. A. Steyert

Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

(Received 22 December 1972)

Angular distributions have been measured for γ rays emitted following the decays of ^{187}W and ^{185,191,193}Os nuclei polarized at low temperatures in iron. The decay of polarized spin-1/2 nuclear levels was found to show isotropic angular distributions to three parts in 10^4, in keeping with angular momentum theory, and purity of the accepted nuclear spin values. The magnitudes of the magnetic moments of the ^{187}W and ^{193}Os ground states have been deduced to be $(0.688\pm0.021)\mu_N$ and $(1.30\pm0.19)\mu_N$, respectively, assuming saturation of the hyperfine field at the nucleus; the magnitude of the magnetic moment of the ^{191}Ir 171-keV level has been similarly deduced to be $(3.27\pm0.12)\mu_N$, based in part on the observation that the nuclear spin-lattice relaxation time associated with decays from that level is less than 0.1 sec. $E2/M1$ multipole mixing ratios have been deduced for a number of ^{187}Re and ^{193}Ir γ rays, and the multipole characters of several of the β radiations emitted by ^{187}W and ^{193}Os have been obtained; these multipolarities are discussed in terms of the nuclear structure. The use of polarized ^{191}Os as an absolute γ-ray anisotropy thermometer is discussed.

I. INTRODUCTION

The observation of the angular distribution of radiation emitted by nuclei polarized at low temperatures is a convenient means of investigating fundamental nuclear symmetries as well as of gathering data on nuclear properties such as spins, moments, and radiation multipolarities.[1] We report here an investigation into the γ rays emitted by ^{187}W and ^{185,191,193}Os polarized at $T\sim20$ mK in iron. The magnetic moments of the ^{187}W and ^{193}Os ground states and the 171-keV ^{191}Ir 5-sec excited state have been deduced from the observed angular distributions; the latter measurement was confirmed to be characteristic of the ^{191}Ir level rather than of the ^{191}Os parent by our observation that an upper limit of 0.1 sec can be set on the nuclear-spin-lattice relaxation time associated with decays from that level. Mixing ratios of a number of γ rays following the decays of the parent states have been deduced, and multipolarities of the unobserved β-radiation fields have been obtained.

In addition, angular distributions of γ rays from a number of spin-$\frac{1}{2}$ levels were measured; vanishingly small anisotropies were observed for γ rays from the spin-$\frac{1}{2}$ levels.

II. DECAY SCHEMES

$^{187}W \to {}^{187}Re$. This decay is illustrated in Fig. 1, taken primarily from the measurements of Bisgard *et al.*,[2] Herman, Heighway, and MacArthur,[3] and Brabec, Maly, and Vobecky,[4] all of whom measured the K-conversion coefficients and deduced the γ-ray multipolarities. Additional levels have been identified by resonance fluorescence[5] and by inelastic deuteron and α scattering.[6] The Nilsson assignments of the ^{187}Re intrinsic states given in Fig. 1 represent the consensus of the various investigations; major components of the 511- and 686-keV levels are probably K-2 γ vibrations built on the ground state and the 206-keV level, respectively.

$^{185}Os \to {}^{185}W$. Figure 2 illustrates this decay, based on the work of Plajner *et al.*[7] Since the ^{185}Os parent state has spin $\frac{1}{2}$, no nuclear alignment was obtained; the decay scheme is presented only in order to place those lines in the γ-ray spectrum resulting from this decay, and thus to identify the γ rays expected to show vanishing anisotropies.

$^{191}Os \to {}^{191}Ir$. The relatively simple decay of ^{191}Os is illustrated in Fig. 3. An accurate value for the $E2/M1$ mixing ratio of the 129-keV γ ray is necessary for a precise determination of the orientation of levels preceding this transition. Table I lists the previously measured values of δ, along with the average value taken for the present work; this value of δ corresponds to the angular

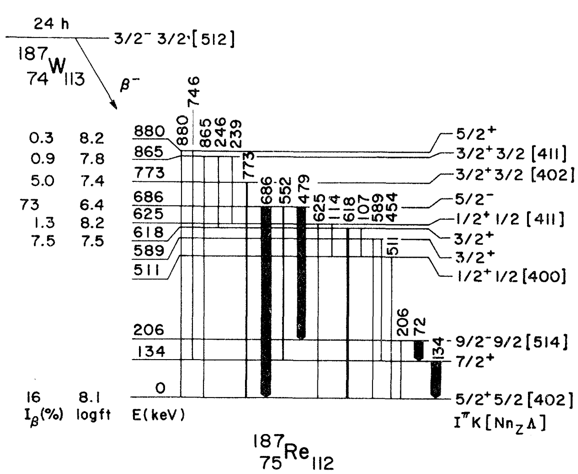

FIG. 1. Decay scheme of ^{187}W to levels of ^{187}Re.

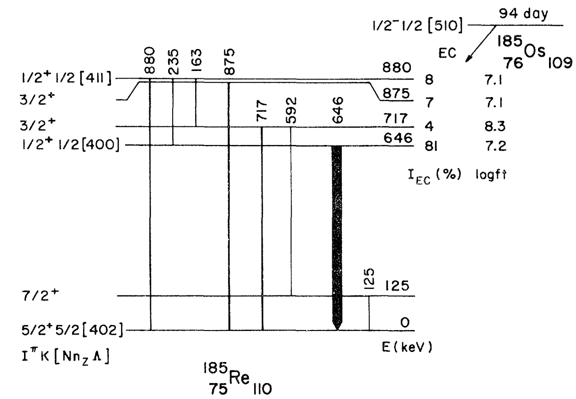

FIG. 2. Decay scheme of ^{185}Os to levels of ^{185}W.

distribution coefficients

$$A_2(129) = +0.942 \pm 0.009,$$

$$A_4(129) = +0.093 \pm 0.005.$$

$^{193}Os \to {}^{193}Ir$. Figure 4 illustrates this decay scheme, taken from the work of Price and Johns,[8] and of Berg, Malmskog, and Bäcklin.[9] References to other decay and reaction studies may be found in Refs. 8 and 9. Possible Nilsson intrinsic assignments are indicated in Fig. 4; however, it has not yet been established that deformed single-particle states provide a basis for understanding the ^{193}Os nucleus superior to that of spherical single-particle states. Avida, Burde, and Molchadzki[10] have obtained good agreement between experimental transition moments and those calculated using single-particle states coupled to a spherical phonon-excited core. Berg, Malmskog, and Bäcklin[9] have obtained better agreement for the transition probabilities between the low-lying even-parity levels with the Nilsson model rather

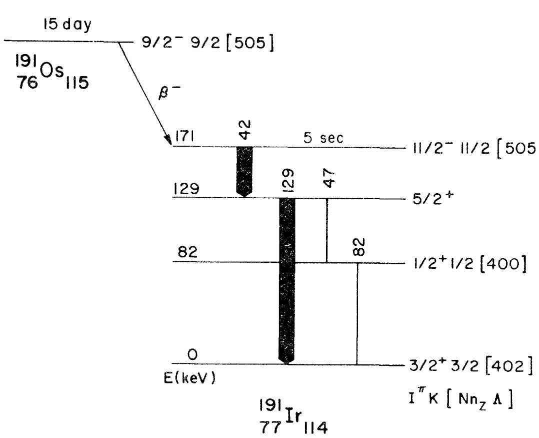

FIG. 3. Decay scheme of ^{191}Os to levels of ^{191}Ir.

than with the core excitation model. Bäcklin, Berg, and Malmskog[11] have suggested an interpretation in which the even-parity levels are characteristic of deformed particle states, while the odd-parity levels show a spherical character; such a situation results from the shallow minima in the potential energy function for nuclei in this mass region where the gradual transition takes place from deformed to spherical equilibrium shapes.

Figures 5 and 6 illustrate sample γ-ray spectra.

III. EXPERIMENTAL DETAILS

Alloys of Fe(Os) and Fe(W) were prepared by melting spectroscopically pure Os or W metal with 99.99% pure Fe. The resulting alloys, containing $\frac{1}{4}$ at.% of the impurity metal, were then rolled into $\frac{1}{8}$-mm foils. Disks of 6-mm diam were cut from the foils and irradiated in the thermal column of the Los Alamos Omega West reactor (flux $= 3\times10^{12}$ neutrons/cm^2 sec) for periods of several hours. Following the irradiation, the samples were annealed in vacuum for 10–15 min at 900°C. In some cases, a small amount of ^{54}Mn in HCl solution was dried on the surface of the foils; in these cases, the samples were annealed in a hydrogen-argon atmosphere for 2 h at 900°C and then for 2 h at 1100°C. The ^{54}Mn served as an absolute γ-ray anisotropy thermometer. Surface contamination was removed by etching away the outer 10% of the foils.

The samples were cooled to $T \sim 20$ mK using a ^{3}He-^{4}He dilution refrigerator and polarized in an external field of 3 kG provided by either of two perpendicular pairs of superconducting Helmholtz coils. Data were accumulated simultaneously at 0 and 90° relative to the applied field using two 40-cm^3 Ge(Li) detectors. The counting rates of the individual peaks at 0 and 90° were analyzed according to the relationship

$$W(\theta) = \sum_k Q_k B_k U_k A_k P_k(\cos\theta), \qquad (1)$$

where the orientation parameters B_k describe the orientation of the initial state and depend on the hyperfine splitting $\mu H/Ik_B$, the deorientation coefficients U_k correct for the effects of unobserved intermediate β and γ radiations, and the angular distribution coefficients A_k describe the properties of the observed γ ray. The γ-ray mixing ratios are defined according to the convention of Krane and Steffen,[12] in which the interference term in the expression for A_k is always written with a + sign. The geometrical correction factors Q_k correct for the finite detector size. Only k = even terms contribute to the present investigation, and the maximum, k_{max}, is two for the ^{187}W and ^{193}Os decays. For these decays only the 0 and 90° raw counting rates were necessary to obtain the desired information. For the ^{191}Ir investigation $k_{max} = 4$, and an additional piece of data was required, namely the "warm" unpolarized counting rates to be used for normalization.

The hyperfine fields of W, Os, and Ir impurities in Fe are given in the compilation of Koster and Shirley[13] as

$$\text{Fe(W)}:\ H = -643 \pm 13\ \text{kG},$$
$$\text{Fe(Os)}:\ H = 1100 \pm 20\ \text{kG},$$
$$\text{Fe(Ir)}:\ H = -1403 \pm 20\ \text{kG}.$$

The rather slow approach to magnetic saturation possibly owing to magnetostriction in the vicinity of impurity atoms in Fe has been discussed by Aharoni[14]; the effective hyperfine field at the impurity nuclei does not lie parallel to the applied field but rather on the average along the generator of a cone whose axis is parallel to the applied field. The half angle of the cone decreases with increasing applied field, and is predicted to be of

TABLE I. Previously measured values of the 129-keV $E2/M1$ mixing ratio.

Method [a]	Value [b]	Reference
e^-	0.39 ± 0.02	c
ME	$-0.36^{+0.04}_{-0.01}$	d
e^-	0.39 ± 0.02	e
ME	-0.398 ± 0.020	f
e^-	0.37 ± 0.03	g
CE	-0.46 ± 0.04	h
Av.	-0.39 ± 0.01	

[a] e^-: conversion coefficient; ME: angular distributions following Mössbauer effect; CE: angular distributions following Coulomb excitation.

[b] Values without sign explicitly given are for magnitude of δ only.

[c] E. P. Mazets and Yu. V. Sergeenkov, Izv. Akad. Nauk SSSR Ser. Fiz. 30, 1193 (1966) [transl.: Bull. Acad. Sci. USSR, Phys. Ser. 30, 1244 (1966)].

[d] F. Wittman, Z. Naturforsch 19a, 1409 (1964).

[e] Z. Plajner, V. Brabec, O. Dragoun, and L. Malý, Czech. J. Phys. 17B, 703 (1967).

[f] A. V. Davydov, G. R. Kartashov, and Yu. V. Khrudev, Yadern. Fiz. 7, 735 (1968) [transl.: Soviet J. Nucl. Phys. 7, 447 (1968)].

[g] S. G. Malmskog and A. Bäcklin, Arkiv Fysik 39, 411 (1969).

[h] R. Avida, I. Ben-Zvi, P. Gilad, M. B. Goldberg, G. Goldring, K. H. Speidel, and A. Sprinzak, Nucl. Phys. A147, 200 (1970).

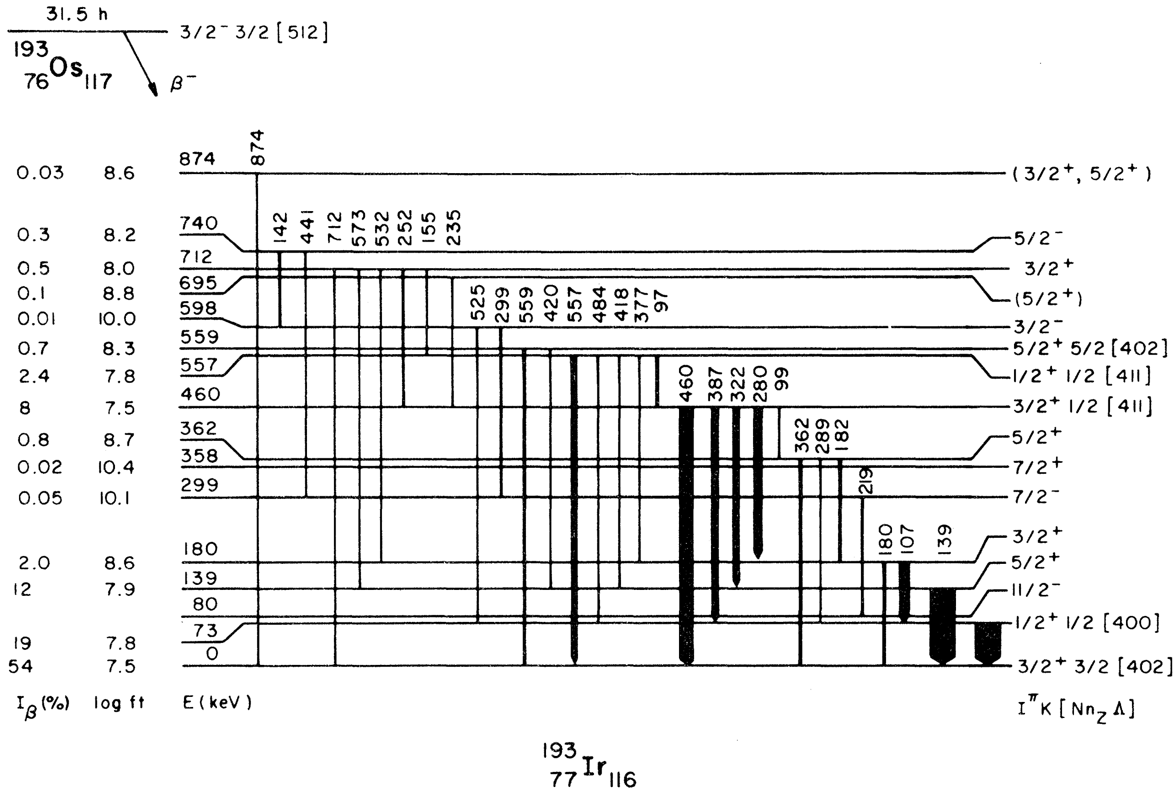

FIG. 4. Decay scheme of ^{193}Os to levels of ^{193}Ir.

order 10° for applied fields of a few kilogauss.[14] Such effects have been noted by Ben-Zvi *et al.*[15] in measurements of perturbed angular correlations following Coulomb excitation of W. A number of different impurities in Fe show[16] cone angles of 10° in fields of 2 to 3 kOe. We used 3 kOe in the present experiments. A 10° cone angle would result in a 5% underestimate of a nuclear moment deduced from a measurement of the product μH.

Additional problems associated with the preparation of microscopically homogenious Fe(Os) and Fe(Ir) alloys have been studied by perturbed-angular-correlation measurements by King, Grabowski, and Scharenberg.[17] For some Fe(Ir) alloys they see too small a perturbation, resulting in a moment measured to be too small. Improper alloy preparation would also cause us to measure too small a moment; however, the remaining nuclear structure parameters are independent of H, since they are deduced from relative angular distributions of two or more γ rays.

IV. RESULTS

$^{187}W \rightarrow {}^{187}Re$. The orientation parameter B_2 of the ^{187}W was deduced from the angular distribution of the 479-keV pure-$E2$ transition which follows

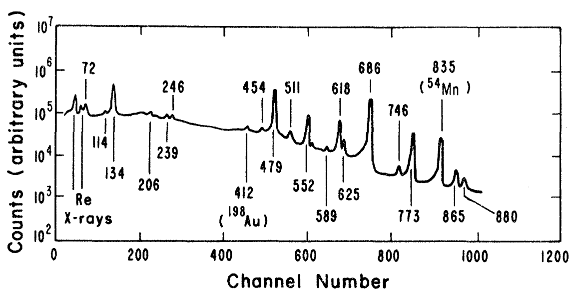

FIG. 5. γ-ray spectrum from the decay of ^{187}W.

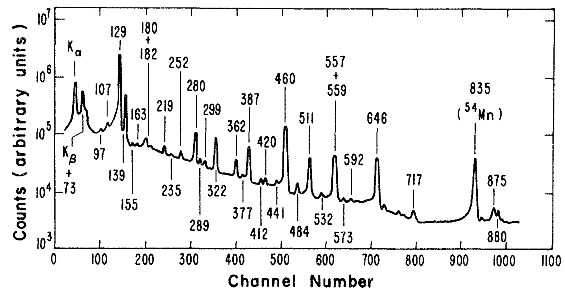

FIG. 6. γ-ray spectrum from the decays of $^{185,191,193}Os$.

the $\frac{3}{2}$ - $\frac{5}{2}$ Gamow-Teller β decay. From the B_2 thus obtained and the temperature deduced on the basis of the ^{54}Mn γ ray ($T \sim 20$ mK), the hyperfine energy splitting obtained is

$$\Delta = 10.8 \pm 0.2 \text{ mK},$$

and thus (assuming the saturated value $H = 643$ kG)[13]

$$|\mu| = (0.688 \pm 0.021)\mu_N .$$

This value compares quite well with the value[18] $\mu = (+0.6564 \pm 0.0003)\mu_N$ for the $\frac{3}{2}^-[512]$ ground state of ^{189}Os, suggesting the choice of the positive sign for the above measured value. The measured angular distributions of the various ^{187}Re γ rays were corrected for the appropriate B_2 and also for solid angle, and the resulting U_2A_2 values are given in Table II. On the basis of the published branching intensities,[2-4] appropriate values of U_2 were computed, permitting the γ-ray A_2 values to be deduced; these A_2 values and the corresponding γ-ray mixing ratios are presented in Table II. The results are in general in good agreement with the results of conversion coefficient measurements[2-4,19]; the 134-keV mixing ratio is in agreement with a value deduced from angular distribution measurements following Coulomb excitation.[20]

Based on the 239- and 246-keV mixing ratios derived from conversion coefficient measurements,[2-4] the U_2 values for the first-forbidden β decays populating the 865-keV level may be computed; averaging the results for the two transitions we obtain

$$U_2 = +0.28 \pm 0.06 .$$

This value may be compared with the theoretical expression for a $\frac{3}{2}^-$ - $\frac{3}{2}^+$ β decay

$$U_2 = |\alpha_0|^2 + 0.2|\alpha_1|^2 - 0.6|\alpha_2|^2, \qquad (2)$$

where $|\alpha_L|^2$ represents the fraction of the β intensity of total angular momentum L. While the present results do not lead to a unique result for the β multipolarity, they do indicate that a substantial fraction ($\gtrsim 40\%$) of the β-radiation field carries the larger angular momentum values, i.e., $L = 1$ and $L = 2$; the extreme values consistent with the present results are $|\alpha_1|^2 > 0.8$ if $|\alpha_2|^2 = 0$, or else $|\alpha_2|^2 > 0.4$ if $|\alpha_1|^2 = 0$.

Similarly, from the 618-keV angular distribution, the U_2 for β decays populating the 618-keV level is computed to be

$$U_2 = +0.08^{+0.10}_{-0.02} .$$

Similar conclusions may be drawn from Eq. (2) for this decay; again, the higher multipolarities must dominate and $|\alpha_1|^2 \sim 1$ if $|\alpha_2|^2 = 0$ or else $|\alpha_2|^2 > 0.5$ if $|\alpha_1|^2 = 0$.

The 589-keV level is populated only through the spin-$\frac{1}{2}$ 625-keV level, and thus the 589- and 454-keV transitions are expected to show vanishing anisotropies, as observed.

At present it is not possible to resolve the U_2 and A_2 contributions to the 746-, 773-, and 880-keV angular distributions.

TABLE II. Angular distribution of γ rays from the decay of ^{187}W.

γ-ray energy (keV)	U_2A_2 [a] (units of 10^{-3})	A_2 [a] (units of 10^{-3})	Mixing ratio δ	Multipolarity
72	193(13)	319(21)	-0.008 ± 0.011	$M2/E1$
134	13(4)	22(9)	$+0.160 \pm 0.006$	$E2/M1$
206	−300(60)	−500(100)	-0.07 ± 0.01	$E3/M2$
239	195(100)	1000(50) [b]	-0.53 ± 0.16 [c]	$E2/M1$
246	−305(70)	−940(100) [b]	$+0.50 \pm 0.15$ [c]	$E2/M1$
454	−300(420)			$E2$
479	−143 [b]			$E2$
552	102(5)	136(7)	$+0.001 \pm 0.005$	$M2/E1$
589	−20(100)			$E2/M1$
618	−24(4)	$-(310^{+60}_{-150})$ [b]	-0.50 ± 0.25 [c]	$E2/M1$
686	−314(10)	−420(13)	-0.008 ± 0.013	$M2/E1$
746	59(33)		$\lvert\delta\rvert < 0.9$ [c]	$E2/M1$
773	43(5)		$\lvert\delta\rvert < 1$ [c]	$E2/M1$
865	13(29)	46(103)	-0.05 ± 0.09	$E2/M1$
880	−113(55)			$E2/M1$

[a] Figures in parentheses are uncertainties in last digit or digits.
[b] Value assumed in analysis.
[c] Magnitude of δ from conversion coefficient measurements (Refs. 2–4); sign derived from present work (phase definition of Ref. 11).

$^{191}Os \to {}^{191}Ir$. From the measured angular distribution of the 129-keV γ ray, using the A_k values given in Sec. II and assuming pure-$E3$ multipolarity for the 42-keV transition, we derive for the ^{191}Ir 171-keV level

$$B_2 = 1.511 \pm 0.015,$$

$$B_4 = 0.778 \pm 0.055.$$

By measuring the time necessary for restoration of anisotropy following application of the external field to an initially unpolarized sample, an upper limit on the nuclear spin-lattice relaxation time (measured at $T \sim 20$ mK) has been determined to be 0.1 sec, indicating that the observed polarization is characteristic of the 5-sec 171-keV ^{191}Ir level, rather than of the parent ^{191}Os level. The above B_k values yield, at a measured ^{54}Mn temperature of 19.2 ± 0.2 mK,

$$\Delta = 30.5 \pm 1.0 \text{ mK}.$$

Assuming the value given above for the magnetic field at full saturation, this corresponds to

$$|\mu| = (3.27 \pm 0.12)\mu_N.$$

(A previous nuclear orientation measurement[21] deduced $|\mu| = (6.3 \pm 1.5)\mu_N$; the discrepancy between the two results is due primarily to the choice of the 129-keV mixing ratio, which was deduced in Ref. 21 to be -0.28 ± 0.06, a value somewhat smaller than those given in Table I.)

No other magnetic moments of $\frac{11}{2}^-[505]$ Nilsson states are available for comparison with the measured value; however, the low-lying $\frac{11}{2}^-$ levels of ^{191}Ir and ^{193}Ir have been suggested[11] to be describable as $h_{11/2}$ spherical shell-model states. The Schmidt limit for the magnetic moment of such a state is $7.8\mu_N$, considerably larger than the presently measured value. One possible explanation for this discrepancy would be a finite deformation of the $\frac{11}{2}^-$ level, and thus the failure of the spherical independent-particle picture to predict the proper magnetic moment. An alternate and possibly more valid explanation may be based on the observations[17,22] that perturbed angular correlation measurements using Fe(Ir) alloys yielded magnetic moments factors of 2–3 smaller than Ni(Ir) alloys; thus, perhaps due to nonsaturation or to microscopic nonhomogeneity, too large a value of H was used in extracting μ from Δ.

$^{193}Os \to {}^{193}Ir$. This decay unfortunately provides no convenient means of determining the orientation of the parent level. The pure-$E2$ 299- and 219-keV γ rays are preceded by the mixed $E2/M1$ 142-keV γ ray, the multipolarity of which has not been precisely determined. A lower limit may be obtained for B_2 by assuming pure $M1$ character, and we thus obtain $B_2 \geq 0.60$, corresponding to $|\mu| \geq 1.1\mu_N$. This value is considerably larger than the above deduced value of 0.68 for the $\frac{3}{2}^-[512]$ ^{187}W state, possibly indicating a spherical single-particle character of the ^{193}Os ground state, since the Schmidt value is $|\mu| = 1.9\mu_N$. [Coriolis mixing of the ^{193}Os ground state with the nearby $\frac{1}{2}^-[510]$ Nilsson state cannot account for the discrepancy since the known $\frac{1}{2}^-[510]$ levels in neighboring nuclei have small moments in the range $(0.06–0.2)\mu_N$.] Averaging the conversion-coefficient measurements of Refs. 8 and 9, an upper limit of 20% may be set on the $E2$ intensity of the 142-keV transition, in which case we obtain from the 299- and 219-keV angular distributions

$$B_2 = 0.68 \pm 0.08,$$

corresponding at $T = 19.2 \pm 0.2$ mK, to

$$\Delta = 34.8 \pm 5.2 \text{ mK}.$$

At full saturation of H, this yields

$$|\mu| = (1.30 \pm 0.19)\mu_N.$$

The measured $B_2U_2A_2$ values for the ^{193}Ir γ rays are presented in Table III. Since the relative uncertainty in the above B_2 value is larger than that for most of the γ-ray angular distributions, the uncertainties in the deduced multipole mixing ratios will result primarily from the uncertainty in our assumed B_2. This situation would be great-

TABLE III. Angular distribution anisotropies from the decay of oriented ^{193}Os.

γ ray (keV)	$B_2U_2A_2$ [a] (units of 10^{-3})
107	38(10)
139	197(1)
155	−12(20)
180	70(5)
182	1(5)
219	−51(2)
235	154(9)
252	−117(2)
280	−68(1)
289	−137(4)
299	47(4)
322	40(1)
362	178(1)
377+379	−9(12)
387	111(1)
418+420	−95(3)
441	−153(6)
460	47(1)
532	−351(8)
557+559	4(1)

[a] Figures in parentheses are uncertainties in last digit or digits.

ly improved if values of μ or $\delta(142)$ were to become available.

The deduced γ-ray multipole mixing ratios are summarized in Table IV. In some cases it was possible to deduce δ independently of B_2, by comparing the angular distributions of γ rays deexciting a given level with one of known multipolarity. This has been done for the 362-, 460-, 559-, and 712-keV levels, in the former case using the pure-$E2$ 289-keV transition, and in the latter three cases using the mixed $E2/M1$ 322-, 420-, and 252-keV transitions, respectively. Measurements of the 322-139-keV angular correlation have been done by Gustafsson *et al.*,[23] Avida *et al.*,[24] and Badica *et al.*[25] Using $\delta(139) = -0.34 \pm 0.01$,[8,9] we compute values of $\delta(322)$ from the angular correlation data in the range

$$\delta(322) = +0.157 \pm 0.025,$$

and thus the 322-keV transition may be employed to analyze the remaining γ rays depopulating the 460-keV level (460, 387, 280 keV). The 420-139-keV correlation has been measured by Avida *et al.*[24]; we have corrected their correlation coefficients for the pure-$E2$ 418-keV transition and extracted the value of $\delta(420)$ given in Table IV. The 420-keV transition was then employed to analyze the 559-keV transition. Similarly, from the 252-460- and 252-387-keV correlations measured by Badica *et al.*,[25] we have extracted a value for $\delta(252)$ [using the present values of $\delta(460)$ and $\delta(387)$], thus permitting analysis of the 155- and 532-keV transitions.

The present results for the transitions from the 180-keV level (180, 107 keV) are best interpreted by choosing the positive sign for $\delta(107)$, where the magnitude of δ determined from the conversion coefficient is as given in Table IV. This then leads to the value given in Table IV for $\delta(180)$, which is in good agreement with the results deduced from the conversion coefficients,[8,9] but in poor agreement with the results of directional correlation measurements.[25]

The present results for the 155-keV transition confirm the $\frac{3}{2}^+$ assignment for the 712-keV level. The $\frac{5}{2}^+$ assignment for the 695-keV level is consistent with the present data for the 235-keV transition, but a possible $\frac{3}{2}^+$ assignment cannot be ruled out. The multipole character of the 235-keV transition may be determined based on an estimate of the U_2 value for β decays to the 695-keV level; from the systematic U_2 values given in Table V, we estimate $U_2 \approx 0.3 \pm 0.1$, which yields the value given in Table IV for $\delta(235)$.

The deduced mixing ratios given in Table IV are in good agreement with those derived from the conversion coefficients of Berg, Malmskog, and Bäcklin[9] and of Price and Johns,[8] but are in rather poor agreement with an earlier measurement of Cothern *et al.*[26] for a number of transition multipolarities.

Table V summarizes the deduced β-decay depolarization coefficients for the ^{193}Os first-forbidden decays. These results in general indicate substantial contributions from the $L=2$ (B_{ij}) term in the various β fields. However, it should be noted that the deduced U_2 values depend directly

TABLE IV. $E2/M1$ multipole mixing ratios of ^{193}Ir γ rays.

γ-ray energy (keV)	δ [a]
107	$+0.141 \pm 0.010$ [b]
139	-0.34 ± 0.01 [b]
155	$+0.29 \pm 0.04$
180	$-(0.67^{+0.24}_{-0.14})$
182	$+0.191 \pm 0.010$
235	$-0.07 \geq \delta \geq -0.33$ [c]
252	$-0.07 \leq \delta \leq +0.07$ [d]
280	$+0.060 \pm 0.033$
322	$+0.157 \pm 0.025$ [d]
362	-0.185 ± 0.013
387	-0.21 ± 0.07
420	$+0.27 \pm 0.01$ [d]
441	-0.37 ± 0.04
460	-0.54 ± 0.04
532	$+0.8 \pm 0.4$
559	$+0.153 \pm 0.011$

[a] Phase convention of Ref. 11.

[b] Magnitude of δ from conversion coefficient studies (Refs. 8 and 9); sign from present work.

[c] Based on U_2 value estimated from systematics of other levels.

[d] Value assumed in analysis from angular correlation data (Refs. 22-24).

TABLE V. Deorientation coefficients and multipolarities of ^{193}Os first-forbidden β decays, assuming $B_2 = 0.68 \pm 0.08$.

Decay to level	U_2	Multipole character
I^π, E (keV)		
$\frac{5}{2}^+$, 139	0.321 ± 0.044	$\lvert\alpha_2\rvert^2 = 0.50 \pm 0.05$
$\frac{3}{2}^+$, 180	0.232 ± 0.061	$\lvert\alpha_0\rvert^2 \leq 0.55$
$\frac{5}{2}^+$, 362	0.416 ± 0.052	$\lvert\alpha_2\rvert^2 = 0.39 \pm 0.06$
$\frac{3}{2}^+$, 460	0.232 ± 0.022	$\lvert\alpha_0\rvert^2 \leq 0.5$
$\frac{5}{2}^+$, 559	0.284 ± 0.033	$\lvert\alpha_2\rvert^2 = 0.54 \pm 0.04$
$\frac{5}{2}^+$, 695	$U_2 \geq 0.18$	$\lvert\alpha_2\rvert^2 \leq 0.6$
$\frac{3}{2}^+$, 712	0.43 ± 0.11	$\lvert\alpha_0\rvert^2 \leq 0.7$

on the assumed value of B_2; thus a more precise value of the magnetic moment μ of ^{193}Os would improve considerably the present U_2 values.

γ-anisotropy from spin-$\frac{1}{2}$ levels. A number of γ rays in these isotopes originate from spin-$\frac{1}{2}$ levels. From general considerations, no 0–90° γ-ray anistropy is expected. This is tested to the limits indicated in Table IV.

V. DISCUSSION

The sign of the presently deduced value of the ^{193}Ir 139-keV mixing ratio is characteristic of the intrinsic nuclear structure according to the relationship for a γ transition within a rotational band[27]:

$$\operatorname{sgn}\delta = \operatorname{sgn}\left(\frac{g_K - g_R}{Q_0}\right), \tag{3}$$

where g_K and g_R are the intrinsic and rotational g factors, respectively, and Q_0 is the intrinsic quadrupole moment. Based on the tabulated values[18] of $\mu(\frac{3}{2}^+)$ and $\mu(\frac{5}{2}^+)$, we deduce $g_K = -2.4$ and $g_R = 0.28$; i.e., $(g_K - g_R) < 0$. Since $\delta < 0$, this implies $Q_0 > 0$, and thus the ^{193}Ir nucleus is prolate in shape. [Analysis of the 107-keV mixing ratio leads to the same conclusion, assuming that the factor $(1+b_0)$, which enters into the right-hand side of Eq. (3) when $K=\frac{1}{2}$, does not change the sign. Analysis of the 129-keV transition, the ^{191}Ir analog of the 139-keV transition, indicates that the ^{191}Ir nucleus is likewise prolate.] While there is perhaps some question as to the precise validity of Eq. (3) in this mass region where the assumption of axial symmetry of the nuclear deformation may not be valid, the measured ^{191,193}Ir quadrupole moments are also positive,[18] in agreement with the above conclusions.

In the case of ^{187}Re, the measured quadrupole moment is positive, and the magnetic moment indicates that $(g_K - g_R)$ is likewise positive;[18] the positive value of $\delta(134)$ is thus likewise in agreement with Eq. (3).

The interpretation of the deduced β-decay multipolarities in terms of the nuclear structure is not as straightforward. The present results in general indicate that the larger multipolarities dominate the first forbidden β-radiation fields. Since the applicability of the Nilsson single-particle assignments is questionable in this mass region, such an effect probably cannot be ascribed to selection rules based on the asymptotic quantum numbers.

One possible qualitative explanation would be the hindrance of the $L=0$ or $L=1$ components of the β-radiation field in decays to rotational states having 1 or 2 units of rotational angular momentum, respectively. This would account for most of the levels populated in the ^{193}Os β decays. In addition, the $L=0$ and $L=1$ components would be expected to be hindered relative to the $L=2$ components in decays to $K\pm 2$ vibrational states. Significant vibrational admixture has been suggested[8] for the $\frac{1}{2}[400]$ intrinsic state, and thus the β decays to the 180- and 362-keV levels should show this effect. A possible $K+2$ component in the $\frac{5}{2}[402]$ state would explain this result for decays to the 559-keV level. However, a more quantitative interpretation of the β-decay multipolarities must await both a more detailed knowledge of the character of the nuclear wave functions in this mass region as well as a difficult extraction of the first-forbidden β-decay matrix elements.

A demonstration of the possible use of ^{191}Os as a source for an absolute γ-ray anisotropy thermometer is illustrated in Fig. 7. The large hyperfine splitting and spin of the polarized ^{191}Ir level

TABLE VI. 0–90° anisotropies measured for γ rays originating from polarized spin-$\frac{1}{2}$ levels.

Isotope	γ energy (keV)	Anisotropy[a] (units of 10^{-4})	Polarization[b]
^{187}W	511	-6 ± 9	15%
^{187}W	625	$+5\pm 8$	30%
^{185}Os	646	-3 ± 4	10%
^{193}Os	73	2 ± 2	50%

[a] Anisotropy $=[W(0)-W(90)]/[W(0)+W(90)]$.
[b] Polarization $=[N(\uparrow)-N(\downarrow)]/[N(\uparrow)+N(\downarrow)]$.

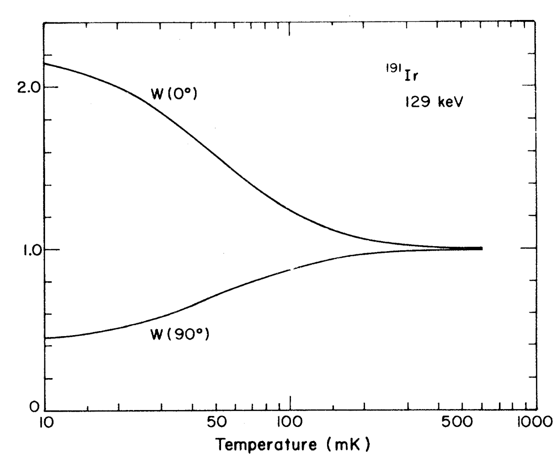

FIG. 7. Counting rates W of the 129-keV ^{191}Ir γ ray at 0 and 90° relative to the orientation axis as a function of the absolute temperature.

result in large anisotropies at relatively high temperatures; thus this isotope would provide an accurate thermometer in the range 30 mK $\leq T \leq$ 200 mK, whereas the more widely used thermometer[28] ^{54}Mn has the 0° counting rate deviating from unity by only 3% at 50 mK and 1% at 100 mK. Other advantages of the use of this thermometer are the lack of sizable β-ray heating and the ability to prepare the isotope as needed by thermal neutron irradiation. The primary disadvantages would be the uncertainty in the presently deduced hyperfine splitting and the problems discussed above associated with lack of understanding of the microstructure of the Fe(Os) and Fe(Ir) systems. Thus at present this should be probably regarded as a relative thermometer, until further study of hyperfine fields in these alloys removes these problems.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge the collaboration of Professor W. Weyhmann during the relaxation time measurements and the assistance of B. T. Murdoch in accumulating the data. Again, D. Hull's expert alloy preparation is appreciated and acknowledged.

---

†Work performed under the suspices of the U. S. Atomic Energy Commission.

*Present address: Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

[1]K. S. Krane, C. E. Olson, and W. A. Steyert, Phys. Rev. C 7, 263 (1973).

[2]K. M. Bisgård, L. J. Nielsen, E. Stabell, and P. Østergård, Nucl. Phys. **71**, 192 (1965).

[3]A. W. Herman, E. A. Heighway, and J. D. MacArthur, Can. J. Phys. **48**, 1040 (1970).

[4]V. Brabec, L. Maly, and M. Vobecky, Izv. Akad. Nauk SSSR Ser. Fiz. 35, 1562 (1971) [transl:: Bull. Acad. Sci. USSR Phys. Ser. 35, 1424 (1971)].

[5]H. Langhoff, Phys. Rev. **159**, 1033 (1967).

[6]K. M. Bisgård and E. Veje, Nucl. Phys. **A103**, 545 (1967).

[7]Z. Plajner, V. Brabec, L. Malý, J. Rízek, and M. Veis, Z. Phys. **237**, 180 (1970).

[8]R. H. Price and M. H. Johns, Nucl. Phys. **A187**, 641 (1972).

[9]V. Berg, S. G. Malmskog, and A. Bäclin, Nucl. Phys. **A143**, 177 (1970).

[10]R. Avida, J. Burde, and A. Molchadzki, Nucl. Phys. **A115**, 405 (1968).

[11]A. Bäcklin, V. Berg, and S. G. Malmskog, Nucl. Phys. **A156**, 647 (1970).

[12]K. S. Krane and R. M. Steffen, Phys. Rev. C **2**, 724 (1970).

[13]T. A. Koster and D. A. Shirley, in *Hyperfine Interaction in Excited Nuclei*, edited by G. Goldring and R. Kalish (Gordon and Breach, New York, 1971), p. 1239.

[14]A. Aharoni, Phys. Rev. **132**, 3794 (1970).

[15]I. Ben-Zvi, P. Gilad, G. Goldring, P. Hillman, A. Swarzschild, and Z. Vager, Phys. Rev. Lett. **19**, 373 (1967).

[16]K. S. Krane, B. T. Murdoch, and W. A. Steyert, Phys. Rev. Lett. **30**, 321 (1973).

[17]W. C. King, Z. W. Grabowski, and R. P. Scharenberg, Phys. Rev. C **4**, 1382 (1971).

[18]V. S. Shirley, in *Hyperfine Interactions in Excited Nuclei*, edited by G. Goldring and R. Kalish (Gordon and Breach, New York, 1971), p. 1255.

[19]E. Bashandy, G. M. El-Sayad, M. R. El-Aassar, and M. Migahed, Atomkernenergie **12**, 59 (1967).

[20]D. Ashery, A. E. Blaugrund, and R. Kalish, Nucl. Phys. **76**, 336 (1966).

[21]J. A. Cameron, I. A. Campbell, J. P. Compton, and R. A. G. Lines, Phys. Lett. **10**, 24 (1964).

[22]P. Sioshansi, D. A. Garber, W. C. King, R. P. Scharenberg, R. M. Steffen, and R. M. Wheeler, Phys. Lett. B **39B**, 343 (1972).

[23]S. Gustafsson, K. Johansson, E. Karlsson, L.-O. Norlin, and R. G. Svensson, Ark. Fys. **34**, 169 (1967).

[24]R. Avida, J. Burde, A. Muchadzki, and Z. Berant, Nucl. Phys. **A114**, 365 (1968).

[25]T. Badica, A. Gelberg, C. Protop, and S. Salageanu, Rev. Roum. Phys. **14**, 471 (1969).

[26]C. R. Cothern, H. J. Hennecke, J. C. Manthuruthil, and R. C. Lange, Phys. Rev. **182**, 1286 (1969).

[27]O. Nathan and S. G. Nilsson in *Alpha- Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 601.

[28]J. R. Sites, H. A. Smith, and W. A. Steyert, J. Low Temp. Phys. **4**, 605 (1971).