Mixing Ratios of Transitions in the Decay of Ir^{192}*

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Mixing ratios of the 485-keV transition in Os^{192} and the 296-, 308-, and 604-keV transitions in Pt^{192} populated from the decay of Ir^{192} were measured using the γ-γ directional-correlation method. In addition, the 468-316-keV, 589-612-keV, 885-316-keV, and 1063-316-keV γ-γ directional correlations in Pt^{192} have been remeasured. Coaxial and planar Ge(Li) detectors and NaI(Tl) scintillation detectors were used in different combinations depending on the energy resolution required for a particular measurement. The results for the mixing ratios are $\delta_{485}=+(10.9_{-1.5}^{+2.1})$, $\delta_{296}=-(9.1_{-1.7}^{+2.7})$, $\delta_{308}=-(9.9\pm1.0)$, and $\delta_{604}=+(2.0\pm0.2)$. The over-all agreement of the signs, as well as the absolute values of the mixing ratios with predictions of the pairing-plus-quadrupole model of Kumar and Baranger, is good.

INTRODUCTION

THE main collective features of the excited states in even-even Os and Pt nuclei have been explained by phenomenological models such as the vibrational model[1] or the asymmetric rotor model.[2] Many quantitative predictions of these models are, however, not verified by experiment.[3] In addition, the nonzero static quadrupole moments for the first excited 2^+ states in Pt isotopes, which should vanish in the assumption of harmonic vibrations, have been reported recently.[4]

If only the collective modes of excitation are considered, there can be no $M1$ radiation competing in $E2$ transitions (see, e.g., Ref. 5). To be able to account for the observed $E2$-$M1$ mixing of the transitions between the "collective" 2^+ states, Tamura and Yoshida considered a model in which the quasiparticle excitations are coupled to the pure collective states.[6] On the basis of this model, they were able to predict the positive sign for the mixing ratios of the $2'^+\rightarrow2^+$ transitions in Pt^{194} and Pt^{196}, in agreement with experiment.[7] The relative phase of the mixing ratio was in this case determined primarily by the sign of the magnetic moments of the admixed quasiparticle states.

In the model proposed by Greiner[8] the formula for the mixing ratio of the $2'^+\rightarrow2^+$ transitions in vibrational nuclei was developed assuming different deformation for protons and neutrons (on the basis of different strength of the pairing force). With parameter f being a small positive number, formula (49) of Ref. 8 predicts a positive sign for the mixing ratio δ of all $2'^+\rightarrow2^+$ vibrational transitions.

The recent pairing-plus-quadrupole model of Kumar and Baranger[9] which was able to predict the quadrupole moments of the 2^+ states of vibrational nuclei in a natural way also allows calculation of the sign and magnitude of the mixing ratios.[10] Comparison of theoretically predicted mixing ratios with those measured experimentally would provide an additional test of the proposed model.

Previous studies of the decay of the 74.2-day Ir^{192} have established the decay scheme shown in Fig. 1. The directional correlation between γ rays emitted in this decay has been measured before using scintillation detectors.[11–15] Because of the inadequate energy resolution of these detectors, the interpretation of measurements involving transitions in the 300- and 600-keV energy regions involved large ambiguities. Utilization of high-resolution Ge(Li) detectors allows complete resolution of the 300- and 600-keV triplets, and thus provides the possibility for more accurate determination of the mixing ratios of the 296-, 308-, and 604-keV transitions in Pt^{192} and the 485-keV transition in Os^{192}.[16] The measured mixing ratios could then be compared with theoretical predictions of the model of Kumar and Baranger.

EXPERIMENTAL PROCEDURE

In the present experiment an automatic γ-γ spectrometer was used for the directional-correlation measurements. A coaxial Ge(Li) detector (ORTEC, 25

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[1] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955); L. Wilets and M. Jean, *ibid.* **102**, 788 (1956).

[2] A. S. Davydov and G. F. Filippov, Nucl. Phys. **8**, 237 (1958); A. S. Davydov and A. A. Chaban, *ibid.* **20**, 499 (1960).

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[4] J. E. Glenn and J. X. Saladin, Phys. Rev. Letters **20**, 1298 (1968).

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[7] S. S. Malik, V. R. Potnis, and C. E. Mandeville, Nucl. Phys. **11**, 691 (1959).

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[13] L. Simons, E. Spring, and G. Wendt, Nucl. Phys. **31**, 452 (1962).

[14] M. W. Johns and M. Kawamura, Nucl. Phys. **61**, 385 (1965).

[15] J. Koch, F. Münnich, and U. Schötzig, Nucl. Phys. **A103**, 300 (1967).

[16] While this work was in progress, it was brought to the author's attention that similar measurements [using Ge(Li) detector] were being made by W. D. Hamilton and K. E. Davies at the University of Sussex, England. The results of their measurements (Ref. 21) are listed in Table II for comparison.

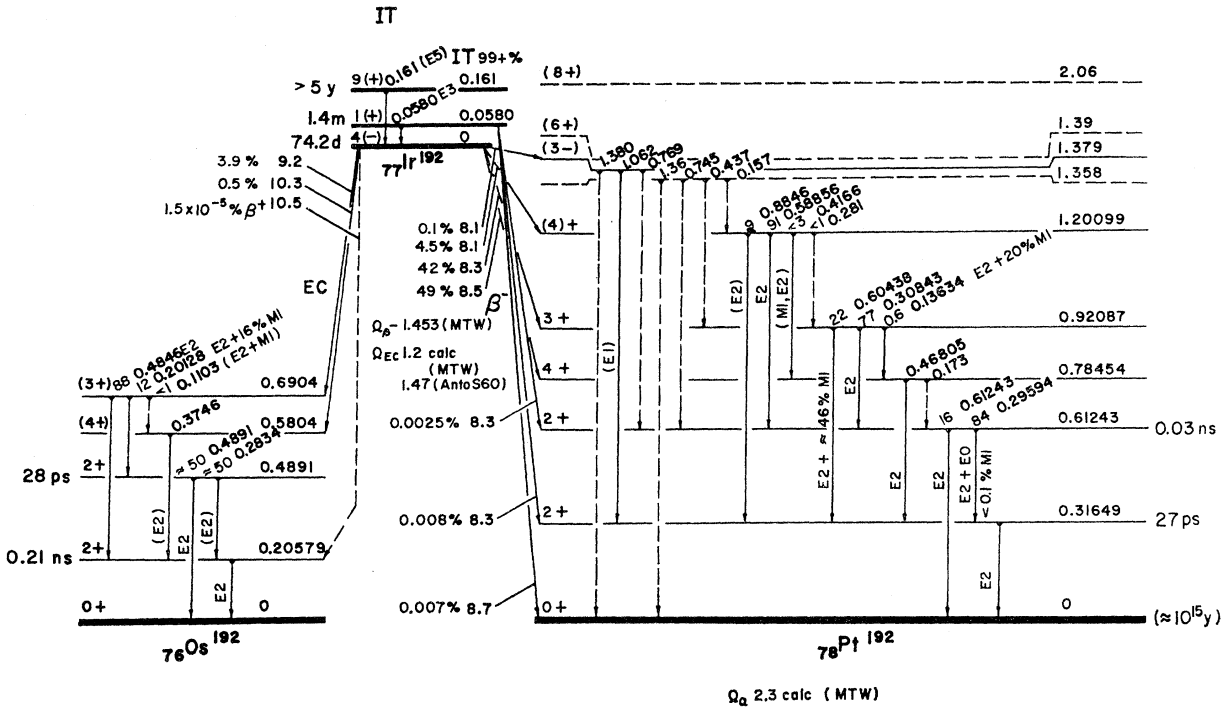

FIG. 1. Decay scheme of Ir^{192} as given in *Tables of Isotopes*, edited by C. M. Lederer, J. M. Hollander, and I. Perlman (John Wiley & Sons, Inc., 1967), p. 372.

cm^3), a planar Ge(Li) detector (RCA SJGG 5/35, 5-mm depletion), and two 3×3 in. NaI(Tl) scintillation detectors were used in different combinations, depending on the energy resolution required for a particular measurement. A conventional coincidence arrangement was utilized with a resolving time of about 70 μsec. The energy resolution of both Ge(Li) detectors was better than 3.5 keV and allowed a complete resolution of the 296-, 308-, and 316-keV triplet (Fig. 2).

The source was prepared by irradiating spectroscopically pure iridium powder with thermal neutrons in the CP-5 reactor at Argonne ($\Phi=10^{13}$ n/cm^2 sec). After allowing the 17.4-h activity due to Ir^{194} to decay, the irradiated Ir powder was dissolved in aqua regia. The diluted solution was used for directional-correlation measurements. The dimensions of the liquid source column inside the cylindrical glass container were 1.5 mm (diameter) and 4 mm (length). The source-detector distance was 5.9 cm for the Ge(Li) and 10.2 cm for the NaI(Tl) detectors.

The coincidence rate was determined at seven different angles, corrected for chance coincidences and, where necessary, for coincidences caused by competing cascades. The directional-correlation coefficients A_{22} and A_{44} were calculated by fitting the experimental data to the directional-correlation function in the form

$$W(\theta)=1+A_{22}P_2(\cos\theta)+A_{44}P_4(\cos\theta),$$

with $A_{kk}=A_k(1)A_k(2)$, where 1 and 2 stand for the first and second transitions in a cascade. Correction for the finite solid angle of the detectors was subsequently applied. The $A_k(1)$ and $A_k(2)$, each depending on only one transition in the cascade, can be expressed in terms of the mixing ratio δ and F_k coefficients[17] as

$$A_k(\gamma)=\frac{F_k(L_\gamma L_\gamma j_\gamma J)+2\delta_\gamma F_k(L_\gamma L'_\gamma j_\gamma J)+\delta^2{}_\gamma F_k(L'_\gamma L'_\gamma j_\gamma J)}{1+\delta^2{}_\gamma},$$

where $\gamma=1$, 2, L_γ and $L_\gamma'=L_\gamma+1$ stand for the multipolarity of transition, and J is the spin of the intermediate state in the $j_1\to J\to j_2$ cascade. Using experimentally determined $A_k(\gamma)$, the mixing ratio δ_γ of the transition γ in a cascade can be calculated.

Some caution is required when one desires to compare experimentally measured mixing ratios with theoretically predicted ones. The definition of the reduced matrix elements and the choice of phase of multipole operators is essential. In the present work the form of

[17] M. Ferentz and N. Rosenzweig, U.S. Atomic Energy Commission Report No. ANL-5324, 1955 (unpublished).

the reduced matrix element was chosen to be the same as that of Biedenharn.[18] The intermediate state J always appears on the right:

$$\delta=\langle j \,||\, L+1 \,||\, J\rangle/\langle j \,||\, L \,||\, J\rangle$$

and j represents initial or final state of the transition. This definition is the same as that of Rose and Brink[19] for the first transition in a cascade. The phase of the (absorption) multipole operators is defined in Ref. 19.

EXPERIMENTAL RESULTS

Preliminary results of the present work were reported at the 1968 Fall Meeting of The American Physical Society.[20] Because of a misprint the δ_{308} given in the abstract should read $-(9\pm1)$ instead of $\delta_{308}=-(12\pm1)$ as printed. In addition, the reported value was not corrected for the summing-up effect discussed below.

Table I gives a summary of the directional-correlation measurements for the cascades involving the 296-, 308-, 485-, and 604-keV transitions. The results of Ref. 21 are included for comparison. The 296-316-keV and the 308-296-keV directional correlations were measured using two Ge detectors. All other cascades were measured using the Ge(coaxial)-NaI detector combination.

In the case of the 604-316-keV cascade the result quoted in Table I includes a correction for the 589-(296)-316-keV coincidences. Because this correction was relatively large (36%), the measurement was repeated using two Ge detectors. The result obtained was $A_{22}=-0.492\pm0.024$ and $A_{44}=-0.044\pm0.040$, in very good agreement with the corrected result measured with the Ge-NaI detector combination. The relatively large errors in the directional-correlation coefficients in the Ge-Ge measurement are due to the fact that the efficiency even of the coaxial Ge detector is relatively poor at 600 keV, and therefore good statistics are hard to obtain.

The directional-correlation coefficients as quoted for the 308-612-keV cascade were corrected for contribution from the 308-(296+316)-keV coincidences. This isotropic contribution was due to coincidences between (1) the 308-keV γ selected in the Ge detector and (2) the sum of pulses from the 296- and 316-keV transitions in the NaI detector. This correction, which was calculated to be 7% in the geometry of the present experiment, has increased the measured value of the mixing ratio δ_{308} by about 11%. This increase is, to a large extent, responsible for a slightly higher value for the mixing ratio of the 308-keV transition, quoted in

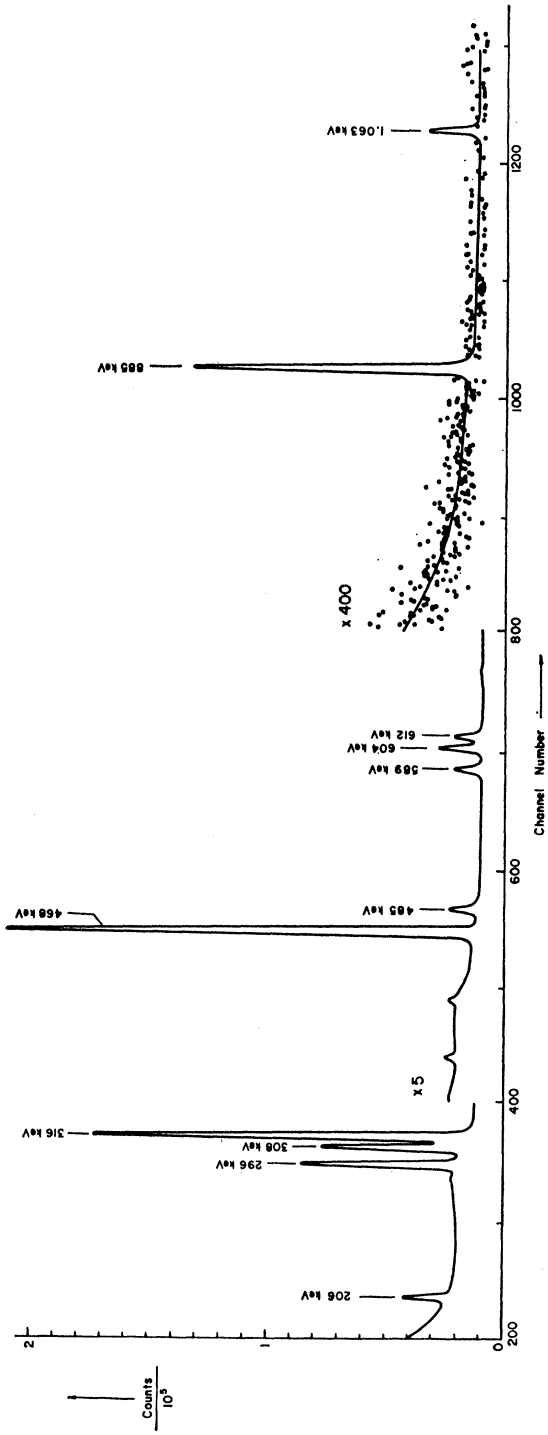

FIG. 2. γ spectrum of Ir^{192} recorded with 5-mm Ge(Li) detector.

[18] L. C. Biedenharn, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Pt. B, p. 732.
[19] H. J. Rose and D. M. Brink, Rev. Mod. Phys. **39**, 306 (1967).
[20] Z. W. Grabowski, Bull. Am. Phys. Soc. **13**, 1468 (1968).
[21] W. D. Hamilton and K. E. Davies, Nucl. Phys. **A122**, 165 (1968).

TABLE I. Summary of the direction-correlation results for the cascades involving mixed transitions of interest. Results of Ref. 21 are included for comparison.

Cascade (keV)	$A_{22}\pm\Delta A_{22}$	$A_{44}\pm\Delta A_{44}$	Mixing ratio	Ref.
296-316	-0.152 ± 0.016	0.302 ± 0.020	$\delta_{296}=-(9.1_{-1.7}^{+2.7})$	a
	-0.148 ± 0.013	0.292 ± 0.020	$\delta_{296}=-(10_{-1.2}^{+2.0})$	b
308-612	-0.124 ± 0.008	-0.080 ± 0.013	$\delta_{308}=-(9.9\pm1.0)$	a
	-0.094 ± 0.015	-0.023 ± 0.020	$\delta_{308}=-(7.3_{-0.8}^{+1.8})$	b
604-316	-0.492 ± 0.015	-0.051 ± 0.020	$\delta_{604}=+(2.0\pm0.2)$	a
			$\delta_{604}=+(0.74\pm0.06)$	
	-0.480 ± 0.016	$+0.34\pm2.23$	$\delta_{604}=+(2.1_{-0.2}^{+0.3})$	b
589-296	-0.007 ± 0.010	0.018 ± 0.015	$\delta_{296}=+(14_{-5}^{+29})$	a
	-0.012 ± 0.017	0.046 ± 0.023		b
308-296	0.000 ± 0.010	-0.012 ± 0.015	$\delta_{296}=+(9.9_{-2.7}^{+5.8})$	a
	0.029 ± 0.013	0.002 ± 0.020		b
485-206	-0.274 ± 0.011	-0.073 ± 0.015	$\delta_{485}=+(10.9_{-1.5}^{+2.1})$	a

[a] Present work. [b] Reference 21.

Table I, as compared with Ref. 21. The 485-206-keV directional correlation, measured by selecting the 206-keV line in the coaxial Ge detector and the 485 (+468) keV transition in the scintillation detector, was corrected by about 26% to account for background coincidences. This correction was measured by moving the window of the single-channel analyzer above the 206-keV photopeak. The coincident spectrum measured with the 485-keV line accepted in the scintillation detector and Ge spectrum displayed in a multichannel analyzer is presented in Fig. 3.

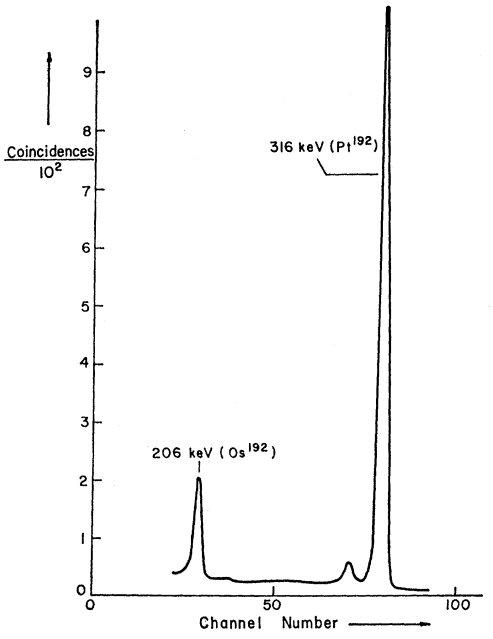

FIG. 3. γ-ray spectrum in coincidence with 485-keV transition (selected in the NaI scintillation detector) recorded with 25-cm^3 Ge(Li) detector.

As can be seen from Table I, the consistency of the results obtained from the measurements of different cascades involving the same transition is very good. In the case of the 589-296-keV cascade the mixing ratio δ_{296} given in the table was calculated assuming that the 589-keV transition is of a pure $E2$ character. When calculating δ_{298} from the measurement of the 308-296-keV directional correlation, $\delta_{308}=-10$ was assumed.

If one calculates the K-conversion coefficient using theoretical values for pure multipolarities as given by Pauli[22] (in Sliv's approximation) and the mixing ratios as derived from the present measurements, one obtains the values listed in the third row of Table II. The weighted average of the K-conversion coefficients measured in Refs. 23, 24, and 10 is given in the bottom row. As can be seen from Table II, the agreement between calculated K-conversion coefficients, using δ values measured in the present experiment, and experimen-

[22] H. C. Pauli, Purdue University, Lafayette, Ind., 1967 (unpublished).
[23] S. Hultberg, D. J. Horen, and J. M. Hollander, Nucl. Phys. **28**, 471 (1961).
[24] W. F. Frey, J. H. Hamilton, and S. Hultberg, Arkiv Fysik **21**, 383 (1962).

TABLE II. Comparison of the K-conversion coefficients calculated using δ values from the present measurements and experimentally measured by other authors. Theoretical conversion coefficients for pure multipolarities were calculated (in Sliv's approximation) using computer program of Pauli.[a]

Transition (isotope)	296 keV (Pt^{192})	308 keV (Pt^{192})	604 keV (Pt^{192})	485 keV (Os^{192})	Ref.
δ_{expt}	$-(9.1_{-1.7}^{+2.7})$	$-(9.9\pm1.0)$	2.0 ± 0.2	$10.9_{-1.5}^{+2.1}$	
			0.74 ± 0.06		
$(\alpha_k)_{calc}$	$(6.56_{-0.10}^{+0.12})\times10^{-2}$	$(5.90_{-0.03}^{+0.04})\times10^{-2}$	$(1.75_{-0.07}^{+0.10})\times10^{-2}$	$(1.86\pm0.01)\times10^{-2}$	
			$(2.79\pm0.10)\times10^{-2}$		
$(\alpha_k)_{expt}$	$(6.3\pm0.9)\times10^{+2}$	$(5.8\pm0.5)\times10^{-2}$	...	...	b
	$(6.3\pm0.4)\times10^{-2}$	$(5.5\pm0.3)\times10^{-2}$	$(2.0\pm0.1)\times10^{-2}$	...	c
	$(7.2\pm0.3)\times10^{-2}$	$(6.35\pm0.3)\times10^{-2}$	$(2.02\pm0.1)\times10^{-2}$	$(1.88\pm0.1)\times10^{-2}$	d
$\langle(\alpha_k)_{expt}\rangle_{av}$	$(6.8\pm0.2)\times10^{-2}$	$(5.9\pm0.2)\times10^{-2}$	$(2.01\pm0.7)\times10^{-2}$	$(1.88\pm0.1)\times10^{-2}$	

[a] Reference 22.
[b] Reference 23.
[c] Reference 24.
[d] Reference 10.

tally determined K-conversion coefficients is very good for the 296-, 308-, and 485-keV transitions and fair in the case of the 604-keV transition. The K-conversion data exclude the lower value for the mixing ratio ($\delta_{604}=0.74\pm0.6$) of the 604-keV transition.

The directional-correlation coefficients for the 468-316-keV, 589-612-keV, 885-316-keV, and 1062-316-keV cascades in Pt^{192}, which have been remeasured, are listed in Table III. The values of the most recent measurements on these cascades are also given for comparison. The 468-316-keV correlation was measured both with two Ge detectors and with two 3×3-in. NaI(Tl) scintillation detectors. This was done in order to check the solid-angle correction for the Ge-Ge detector combination. These two results agreed well, and the mean values of the correlation coefficients are quoted in Table III.

DISCUSSION

All the measurements reported in Tables I and III are consistent with spin and parity assignments for the levels as given in Fig. 1. Taking into account both directional-correlation and conversion-coefficient measurements, the spin-3 assignment for the 690-keV level

TABLE III. Summary of the directional-correlation coefficients for the remaining cascades in Pt^{192} which have been measured. Some of the recent measurements by other authors are quoted for comparison.

Cascade (keV)	$A_{22}\pm\Delta A_{22}$	$A_{44}\pm\Delta A_{44}$	Mixing ratio	Ref.
468-316	0.101 ± 0.003	0.008 ± 0.005	$\lvert\delta\rvert_{468}<7\times10^{-3}$	a
	0.102 ± 0.004	0.005 ± 0.005		b
	0.099 ± 0.019	-0.005 ± 0.026		c
589-612	0.093 ± 0.006	0.006 ± 0.011	$\lvert\delta\rvert_{546}<2.5\times10^{-2}$	a
	0.099 ± 0.019	0.088 ± 0.023		b
885-316	0.055 ± 0.010	0.018 ± 0.015	$\delta_{885}=+(7.5\pm1.5)\times10^{-2}$	a
	0.056 ± 0.010	-0.002 ± 0.026		c
	0.089 ± 0.012	-0.005 ± 0.015		b
1062-316	-0.076 ± 0.012	-0.017 ± 0.020	$\lvert\delta\rvert_{1062}<2\times10^{-2}$	a
	-0.075 ± 0.021	$+0.015\pm0.053$		c
	-0.100 ± 0.016	-0.003 ± 0.019		b

[a] Present work.
[b] Reference 13.
[c] Reference 14.

in Os^{192} is unique. Another possibility which might be considered on the basis of the directional-correlation results only is $I=4$. This, however, would require $\delta_{485}\approx 0.7$ (which is unlikely) and can be excluded on the basis of the conversion-coefficient measurement for the 485-keV transition (see Table II).

The low value for the A_{22} directional-correlation coefficient for the 885-316-keV cascade gives about 0.5% admixture of $M3$ multipolarity in the 885-keV transition. Even considering that the 885-keV $E2$ transition is slow (relative to the 589-keV $E2$ transition, which also originates at the 1200-keV level), this admixture seems to be rather excessive. The results of directional-correlation measurements for the 885-316-keV and the 589-612-keV cascades are also consistent with spin 3 for the 1200-keV level. However, if this were the case, both the 885- and the 589-keV transitions would be predominantly of a dipole character in disagreement with the conversion-coefficient measurements.[10]

The comparison of the experimentally measured mixing ratios with the values predicted by the pairing-plus-quadrupole model of Kumar and Baranger can provide useful information about the validity of the model. The predicted values for the mixing ratios of the 296-, 308-, and 604-keV transitions in Pt^{192} and the 485-keV transition in Os^{192} are[25]

$$\delta_{296}=-14.8,$$

$$\delta_{308}=-9.2,$$

$$\delta_{604}=+2.2,$$

$$\delta_{485}=+4.8.$$

[25] K. Kumar (to be published).

Comparison of these values with the experimental ones, reported in Table I, shows very good agreement for the 308- and 604-keV transitions. The predicted value for the mixing ratio of the 296-keV transition is within 2σ of the value obtained from experiment (σ is the statistical error quoted). The theoretical value for the δ_{485} agrees with regard to the sign but the absolute value is slightly low. $\delta_{485}=+4.8$ (the predicted value) requires $A_{22}(485\gamma\text{-}206\gamma)=-0.35$ and the conversion coefficient $\alpha_k(485)=0.020$, both in disagreement with experimental values. One may wonder, realizing that the experimental value for A_{22} is lower than the predicted one, whether this discrepancy could not be explained by attenuation due to extranuclear fields. However, the relatively short half-life ($t_{1/2}=2.1\times 10^{-10}$ sec) of the 206-keV level in Os^{192} makes the attenuation of the directional-correlation measurement rather unlikely.

The main success of the model of Kumar and Baranger was prediction of the quadrupole moments of the first excited 2^+ states in "vibrational" nuclei, which has been confirmed experimentally.[4] The results reported in the present work show that in the case of Pt^{192} and Os^{192} nuclei the values of the mixing ratios, as predicted by this model, are also in over-all good agreement with experimental findings.

ACKNOWLEDGMENTS

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