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Experimental Test of the Kumar-Baranger Pairing-Plus-Quadrupole Force Model in the $A = 190$ Region Through $E2$-$M1$ Mixing Amplitudes*

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The $E2/M1$ multipole mixing ratios $\delta(\gamma)$ of γ transitions in even-even osmium and platinum isotopes have been measured in order to test the predictions of the pairing-plus-quadrupole theory of Kumar and Baranger. The mixing ratios $\delta(\gamma)$ were determined from directional-correlation measurements on γ transitions in ^{186,188,190}Os (populated in the decay of ^{186,188,190}Ir and in ^{194,196}Pt (populated in the decay of ^{194,196}Au). The radioactive iridium isotopes were produced by Re(α, xn) reactions, and the gold isotopes were produced by Pt(d, xn) reactions. The equipment employed for the γ-γ directional-correlation measurements consisted of two coaxial 30-cc Ge(Li) detectors and appropriate electronic equipment for high-resolution pulse-height analysis and timing analysis. The observed directional correlations were analyzed in terms of the appropriate $E2/M1$ mixing ratios, which are defined explicitly. The following results were obtained (predictions of the Kumar-Baranger theory are listed in square brackets): $\delta(^{186}\text{Os}, 630\text{ keV}) = -(10^{+15}_{-4})$ [−14.7], $\delta(^{186}\text{Os}, 773\text{ keV}) = -(13^{+9}_{-6})$ [−13.5], $\delta(^{188}\text{Os}, 478\text{ keV}) = -12.3 \pm 2.8$ [−9.5], $\delta(^{188}\text{Os}, 635\text{ keV}) = -6.9 \pm 3.2$ [−10.5], $\delta(^{190}\text{Os}, 371\text{ keV}) = -8.5 \pm 1.0$ [−7.6], $\delta(^{190}\text{Os}, 569\text{ keV}) = -9.0 \pm 1.5$ [−9.9], $\delta(^{194}\text{Pt}, 293\text{ keV}) = +14.3 \pm 2.1$ [+19.9], $\delta(^{196}\text{Pt}, 333\text{ keV}) = -5.7 \pm 0.3$ [−101.4]. Except for the 333-keV transition in ^{196}Pt the agreement of the experimental mixing ratios with the values and signs predicted by the Kumar-Baranger model is excellent.

I. INTRODUCTION

The nuclei of the osmium and platinum isotopes are situated in a transition region between the nuclei possessing large equilibrium deformations in the range $150 < A < 180$ and the spherical nuclei near the doubly magic ^{208}Pb. Knowledge of the static and dynamic properties of the excited states of such nuclei would provide insight into the details of their structure, and would provide a basis for the evaluation of various microscopic and phenomenological nuclear models.

In recent years, much effort has been expended in the study of energy levels, electromagnetic mul-

tipole moments, and transition probabilities of even-even nuclei in the transition region. The results of such studies have indicated that these nuclei are described by neither of the previously well-established phenomenological descriptions of nuclear structure; a description in terms of rotations about a permanent equilibrium deformation does not provide a good approximation of the excited energy levels, and the model of harmonic vibrations about a spherical equilibrium shape is inadequate to explain the substantial quadrupole moments observed in this region. Thus, even for the lower excited states of such nuclei, it is necessary either to consider a model which takes into account higher-order interactions of rotational and vibrational modes of excitation, or to attempt a microscopic description of the properties of these nuclei.

Recent experimental evidence has indicated that the transition from deformed to spherical nuclear shapes in the region of $A = 190$ is a gradual one, as opposed to the sharp onset of nuclear deformations in the neighborhood of $A = 150$. It is thus to be expected that a systematic study of the properties of nuclei in the $A = 190$ region would indicate a slow variation in those properties; the manner of this variation would be an indication of the extent to which various effects must be considered in attempting to construct a satisfactory model of the structure of the nucleus.

It has long been known[1] that γ transitions between the lower excited states of heavy even-even nuclei are dominantly of a collective nature, and thus the electric quadrupole ($E2$) component is heavily favored over any competing magnetic dipole ($M1$) component allowed by angular momentum selection rules. However, small admixtures of $M1$ radiation have been observed in such transitions, and the relative amount of this admixture is a measure of the applicability of the collective interpretation of nuclear levels. In addition, it is desirable that any detailed theory of nuclear structure should provide a means of computing the amount of this $M1$ admixture to be expected on the basis of that particular model.

The most successful theoretical approach to date in understanding the structure of nuclei in this region is that of Kumar and Baranger.[2] Employing a microscopic description of the nuclear interaction, a detailed calculation has resulted in a set of predictions[3] concerning the energy levels and the static and dynamic electromagnetic multipole moments of nuclei in the mass region $182 < A < 196$. In particular, the magnitudes and relative phases of the matrix element of $M1$ transitions in these nuclei have been computed.[4]

In order to provide a means of testing the predictions of the Kumar-Baranger model and to provide a sense of direction for future models, we have undertaken a systematic investigation of the $E2/M1$ mixing amplitudes of γ transitions between the lower excited states of even-even osmium and platinum nuclei. These mixing ratios have been determined by measuring γ-γ directional correlations using high-resolution Ge(Li) detectors and multichannel coincidence and routing techniques. In order to provide a basis for a meaningful comparison with the theory, results will be presented in terms of ratios of explicitly defined reduced matrix elements.

II. OSMIUM-PLATINUM NUCLEI

A representation of the lower excited states and of the γ transitions of the even-even osmium and platinum nuclei is given in Fig. 1.[5] The present paper describes measurements on γ transitions in ^{186,188,190}Os and ^{194,196}Pt; the states of ^{192}Os and ^{192}Pt are presented for completeness. Recent investigations into the structure of these nuclei have resulted in a well-established set of energy levels. Studies by means of high-resolution conversion-electron and γ spectroscopy of the decays of the appropriate iridium and gold isotopes have yielded a reasonably complete understanding of the structure of the energy levels of these nuclei.[6-10]

The gradual transition of nuclear properties which occurs in these nuclei is readily apparent upon inspection of the systematics of the lower excited states. The spacing of the levels of ^{186}Os indicates that this nucleus may be of a "rotational" nature, with portions of the ground-state rotational band and the $K = 2$ γ-vibrational band shown. However, toward the upper end of this region of nuclei, the structure becomes more "vibrational" in nature, as typified by the proximity of the 4^+ state and the second excited 2^+ state, normally interpreted as members of the two-phonon vibrational triplet.

In order to investigate the possible rotational nature of the states of ^{186,188}Os, studies have been carried out by means of $(\alpha, 2n)$ and $(\alpha, 4n)$ reactions[11,12]; such reactions preferentially populate states of the ground-state rotational band,[13] and in fact a set of rotation-type levels up to a 10^+ state have been found to occur in both nuclei. However, the energy spacing of these levels differs considerably from what one would expect on the basis of the simple $I(I+1)$ rule, and even the inclusion of a term proportional to $[I(I+1)]^2$ does not appreciably improve the fit.[14]

Similarly, the spacing of the levels at the upper end of the region deviates from what one would expect on the basis of harmonic or near-harmonic

vibrations. In addition, this interpretation is unable to account for the observed quadrupole moments,[15-17] which would vanish for pure vibrational levels. Further indication of the inability of the vibrational interpretation to describe the structure in this region adequately is the occurrence of a rotationlike band (up to an 8^+ state) reported to occur in ^{194}Pt, populated by the decay of a high-spin isomer of ^{194}Ir.[18]

Such considerations are evidence of the failure of the phenomenological model of Bohr and Mottelson[19] as a means of understanding nuclear structure in the transition region. Attempts have been made to consider phonon admixtures in the structure of the $2^{+\prime}$ states of the osmium nuclei,[20] and such efforts have revealed a small one-phonon admixture in the $2^{+\prime}$ state, this admixture increasing with decreasing deformation. However, such mixed phonon states cannot explain the presence of $M1$ transitions.

The states of the rotationlike bands in the osmium nuclei are well approximated by the model of rotations of an axially asymmetric nucleus.[21] The departure from axial symmetry is indicated by the ratio of the energies of the first two excited 2^+ states, and on the basis of this parameter, the calculated level energies of the ground-state band are in good agreement with experimental results; however, the agreement is not as good for the members of the $K=2$ γ-vibrational band, particularly in ^{186}Os, which would be expected to be the most rotational nucleus of the investigation. A similar result is obtained by considering the rotation-vibration interaction for deformed nuclei.[14]

The failure of the phenomenological models to provide a satisfactory accounting of the structure of the nuclei in the transition region has prompted a detailed investigation of nuclear deformations on a microscopic level. Detailed descriptions of the states of ^{188}Os in terms of quasiparticle excitations have been given,[7] but such effects are not expected to be present in the lower excited states considered in this work.

A consideration of nuclear deformations on the basis of the anisotropic harmonic oscillator including a residual pairing interaction[22] has shown that, with respect to γ vibrations, the nuclear potential has a very shallow minimum; these nuclei are "soft" with respect to γ vibrations. Thus the assumption of a *permanent* equilibrium deformation (possibly zero), implicit in most phenomenological models, may not be valid.

The theoretical calculations of Kumar and Baranger[2] have involved detailed predictions concerning the structure of nuclei in this particular mass region. Their calculation consists of residual pairing and quadrupole interactions applied to spherically symmetric independent-particle wave functions (assumed to be harmonic oscillators). Choosing an appropriate set of single-particle levels, the parameters of the calculation are the proton and neutron pairing force strengths, determined from experimental odd-even mass differences; the strength of the quadrupole force and the effective

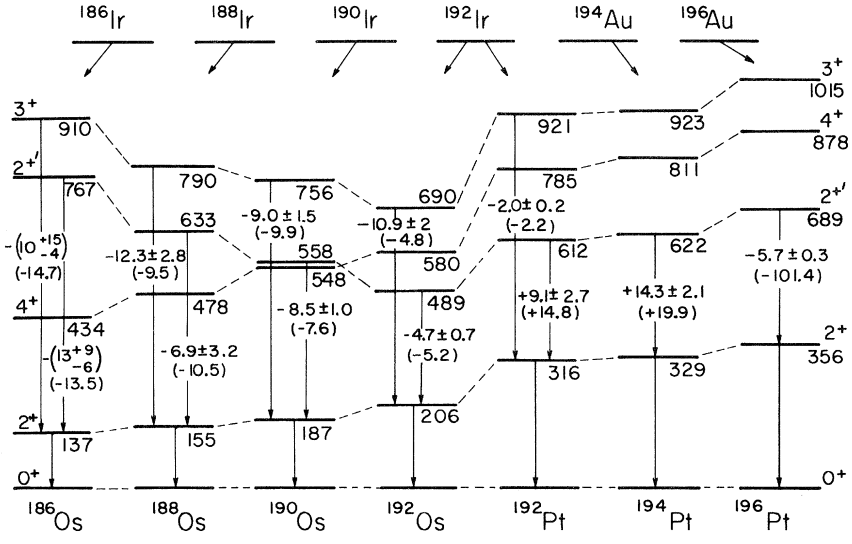

FIG. 1. Experimental and theoretical values for the $E2/M1$ mixing ratios of lower collective transitions in osmium and platinum isotopes. The theoretical values shown below the measured values are those of Kumar (see Ref. 4). Results for the $2^{+\prime}$-2^+ transition in ^{192}Os (Ref. 33) and for the 3^+-2^+ transition in ^{192}Os and both transitions in ^{192}Pt (Ref. 37) have been included.

charge, determined from experimental intrinsic quadrupole moments, and a core inertial parameter, determined from the experimental moments of inertia. The selection of these parameters is made by fitting the entire region from the doubly magic $A=132$ ($Z=50$, $N=82$) to the doubly magic $A=208$ ($Z=82$, $N=126$). The microscopic calculation makes possible a computation of the seven functions of the deformation parameters β and γ (the potential energy, three moments of inertia, and three vibrational parameters) which appear in Bohr's collective Hamiltonian; the results are obtained numerically. The advantage in this calculation lies in the fact that the coupling between the rotational, β-vibrational, and γ-vibrational modes is treated exactly, and no assumptions need be made regarding the separability of the various modes.

The model has been applied to a calculation of energy levels, and static and dynamic multipole moments of a number of lower excited states of even-even tungsten, osmium, and platinum nuclei. In the last paper describing the techniques of the calculation,[2] predictions for the energy levels, $B(E2)$ values, and magnetic dipole and electric quadrupole moments were compared with current measurements. Good agreement was reported between theory and experiment for the energy levels, $B(E2;\ 0^+ \rightarrow 2^+)$ and $B(E2;\ 2^+ \rightarrow 4^+)$ values, and magnetic moments of the first excited states. Agreement in the case of $B(E2)$ values for other transitions was not as good, although few measurements were available for comparison. Recent measurements of static quadrupole moments of the first excited states of ^{186,188}Os by Mössbauer techniques[15] have been in fair agreement with the predictions, and measurements by reorientation effect in Coulomb excitation have been in good agreement with the theory for ^{190,192}Os [16] and ^{194,196}Pt.[17] The predictions of substantial quadrupole moments for the latter nuclei, normally assumed to be near harmonic in structure and thus to have vanishing quadrupole moments, must be considered a particular success for the theory; similarly the theory successfully predicts the change in sign of the quadrupole moment between the osmium and platinum nuclei.

Magnitudes and signs of $E2$ and $M1$ transition matrix elements have been calculated by Kumar[4] in terms of matrix elements of the Bohr-Mottelson[23] electromagnetic multipole operators; conversion to the value of the mixing ratio δ extracted from angular-correlation data is performed as described by Kumar,[4] with the restriction that the sign convention for δ chosen by Kumar is opposite to the one used in this work. The direct comparisons of measured values of δ will be with these calculated values.

III. EXPERIMENTAL TECHNIQUES

As is shown in Fig. 1, the excited states of the osmium isotopes are populated by the β decay of the appropriate iridium isotope, and those of the platinum isotopes by the β decay of gold.

The radioactive sources used for these measurements were produced by bombardments at the Argonne National Laboratory 60-in. cyclotron. The iridium isotopes ^{186,188,190}Ir were produced by (α, xn) reactions on thin (0.001-in.) foils of rhenium metal in naturally occurring isotopic abundances (37% ^{185}Re, 63% ^{187}Re). α energies of 23–25 MeV were used to produce sources in which the primary activities were the 41-h ^{188}Ir and 12-day ^{190}Ir; 35-MeV α particles were used to produce the 16-h ^{186}Ir activity, along with ^{188}Ir. Contaminants were observed from the γ spectra, particularly due to ^{189}Ir, but caused no difficulties in the measurement with the high-resolution Ge(Li) detectors.

The radioactive foils were dissolved in hot nitric acid, which was then evaporated to dryness, and the residue taken up with hydrochloric acid under gentle heat. The radioactive liquid was then placed in a small (2-mm diam by 10-mm height) cylindrical glass ampule. A number of sources were made with activities increasing by successive powers of 2; thus at the end of each half-life, a new source could be obtained of approximately the original activity.

The isotopes ^{194,196}Au were produced by (d, xn) reactions at 12–15 MeV on thin (0.025-in.) foils of platinum metal (33% ^{194}Pt, 34% ^{195}Pt, 25% ^{196}Pt). The resulting activities were principally 39-h ^{194}Au and 6-day ^{196}Au. The foils were dissolved in aqua regia, which was used as the source liquid.

The measurement was performed in an automatic angular-correlation apparatus employing two high-resolution 30-cc coaxial Ge(Li) detectors. The details of the apparatus have been described in a previous paper.[24] The γ-γ directional correlations were measured by counting the coincidences between two selected γ transitions (direct measurements) and the accumulating of routed multichannel-analyzer coincidence spectra (indirect measurements). In the latter case, gating the multichannel analyzer in coincidence with selected regions of the Compton background made possible the measurement of the effects of Compton-scattered radiation on the directional correlations investigated. In addition, the indirect method made it possible to observe simultaneously the directional correlations between the gating transition and all of the γ rays of the coincidence spectrum. This is particularly

important in view of the short half-lives of many of the isotopes investigated in this work.

In the case of the direct measurements, the directional correlation was observed by measuring the coincidence counting rate as a function of the angle between the two detectors. A more detailed analysis was required in the case of the indirect measurements, in which it was necessary to extract the coincidence counting rates by computing the peak intensities of the gated γ spectrum.

Corrections for chance coincidences were made for direct measurements by use of a time-to-amplitude converter to separate true and chance coincidences. For the indirect measurements, the number of chance coincidences between the gating transition accepted in one detector and the entire spectrum accepted in the other was counted as in the direct measurements. A chance-coincidence spectrum could then be computed by assuming it to have the energy dependence of the gated γ-ray spectrum from the second detector and to have the correct measured number of total chance-coincidence counts.

A least-squares fit was then made of the counting rates to a function of the form

$$W(\theta) = A'_{00} + A'_{22} P_2(\cos\theta) + A'_{44} P_4(\cos\theta), \tag{1}$$

where

$$A'_{\Lambda\Lambda} = Q_{\Lambda\Lambda} G_{\Lambda\Lambda} A_{\Lambda\Lambda} . \tag{2}$$

The true correlation coefficients $A_{\Lambda\Lambda}$ were extracted from the measured coefficients $A'_{\Lambda\Lambda}$ through knowledge of the geometrical correction factors $G_{\Lambda\Lambda}$ and the perturbation factors $Q_{\Lambda\Lambda}$. The measurement of the $Q_{\Lambda\Lambda}$ factor has been described previously.[24] The perturbation factors $G_{\Lambda\Lambda}$ were due to the time-dependent electric quadrupole interaction which is present in liquid sources, brought about by the interaction of the electric quadrupole moment of the intermediate nuclear level with the (time-dependent) electric field gradient in the liquid.[25] These attenuation factors were measured by observing the correlation in a given source for which the true values of the angular-correlation coefficients $A_{\Lambda\Lambda}$ were well enough established so that the $G_{\Lambda\Lambda}$ factors could be obtained. Generally, the 4^+-2^+-0^+ cascade was used to measure G_{22}, and the $2^{+\prime}$-2^+-0^+ cascade was used to measure G_{44}. Even though the latter involved mixing of multipole orders in the first transition, for the primarily $E2$ collective transitions encountered in this work, the value of the A_{44} coefficient is near enough to the value for pure $E2$ radiation of 0.326 that this serves as a good means to estimate G_{44}. In addition, the relationship[25] between G_{22} and G_{44} for time-dependent quadrupole interactions was used to verify the results. The perturbation factors varied for the different isotopes involved in the measurement, owing to the variations in the quadrupole moments and lifetimes of the 2^+ states; in addition, for different sources of the same isotope, variations were observed for sources of different viscosities.[25] In general, the factors $G_{\Lambda\Lambda}$ were in the range 0.8–1.0, with the larger values (less perturbation) observed for the higher-mass-number isotopes, which show smaller quadrupole moments and shorter lifetimes.

In all cases considered here, mixing of multipole orders was allowed only in the first transition, since the second transition was the 2^+-0^+ $E2$ transition to the ground state. The angular-correlation coefficients $A_{\Lambda\Lambda}$ are then given, for mixed dipole-quadrupole radiation, by

$$A_{\Lambda\Lambda} = B_\Lambda(\gamma_1) F_\Lambda(2202), \tag{3}$$

where the orientation coefficient $B_\Lambda(\gamma_1)$ is

$$B_\Lambda(\gamma_1) = [1+\delta^2(\gamma_1)]^{-1}[F_\Lambda(11 I_1 I_2) - 2\delta(\gamma_1) F_\Lambda(12 I_1 I_2) + \delta^2(\gamma_1) F_\Lambda(22 I_1 I_2)] . \tag{4}$$

The F coefficients $F_\Lambda(LL'I'I)$ are defined and tabulated by Frauenfelder and Steffen.[26]

The mixing ratio δ is given in terms of Bohr-Mottelson electromagnetic matrix elements by

$$\delta(\gamma_1) = k_1 \frac{\sqrt{3}}{10} \frac{\langle I_2 \| \mathfrak{M}(E2) \| I_1 \rangle}{\langle I_2 \| \mathfrak{M}(M1) \| I_1 \rangle} , \tag{5}$$

where the initial state of the transition is written on the right side of the matrix element ($E_1 > E_2$). The energy k_1 of the transition γ_1 is expressed in natural units ($\hbar = m_e = c = 1$). The derivations of the above equations have been discussed in a previous paper.[24]

The measured correlation coefficients were analyzed in terms of Eqs. (3) and (4) to extract the mixing ratio of the γ transition under investigation, given by Eq. (5).

IV. RESULTS

Mixing ratios were measured for the 3^+-2^+ and $2^{+\prime}$-2^+ transitions in ^{186,188,190}Os, and for the $2^{+\prime}$-2^+ transitions in ^{194,196}Pt. The results for the directional-correlation coefficients involving these transitions, and for the mixing ratios δ extracted from these coefficients, are shown in Table I.

In the investigations of the osmium isotopes, the 4^+-2^+-0^+ cascades were also measured, but since these measurements were used to compute the attenuation factors, the results for the directional-correlation coefficients are not presented. In the platinum isotopes, the 4^+-2^+-0^+ cascade could not be measured, in ^{194}Pt because of an unresolved

TABLE I. Results of directional-correlation measurements of γ transitions of osmium-platinum isotopes.

Isotope	Cascade	E (keV)	A_{22}	A_{44}	$\delta(\gamma)$ Present work	$\delta(\gamma)$ Kumar-Baranger
^{186}Os	$2^{+\prime}$-2^+-0^+	630	-0.001 ± 0.052	0.302 ± 0.049	$-(10^{+15}_{-4})$	-14.7
	3^+-2^+-0^+	773	-0.269 ± 0.038	-0.016 ± 0.051	$-(13^{+9}_{-6})$	-13.5
^{188}Os	$2^{+\prime}$-2^+-0^+	478	-0.015 ± 0.014	0.288 ± 0.021	-12.3 ± 2.8	-9.5
	3^+-2^+-0^+	635	-0.312 ± 0.030	-0.003 ± 0.019	-6.9 ± 3.2	-10.5
^{190}Os	$2^{+\prime}$-2^+-0^+	371	0.013 ± 0.010	0.296 ± 0.015	-8.5 ± 1.0	-7.6
	3^+-2^+-0^+	569	-0.288 ± 0.018	0.008 ± 0.023	-9.0 ± 1.5	-9.9
^{194}Pt	$2^{+\prime}$-2^+-0^+	293	-0.127 ± 0.008	0.325 ± 0.010	$+14.3\pm2.1$	$+19.9$
^{196}Pt	$2^{+\prime}$-2^+-0^+	333	0.058 ± 0.007	0.305 ± 0.010	-5.7 ± 0.3	-101.4

transition obscuring the 4^+-2^+ γ ray, and in ^{196}Pt because of the weak population of the 4^+ state. However, the short half-lives of the intermediate states involved in the platinum measurements (~40 psec)[5] made it unlikely that any perturbation was present.

The results given represent weighted averages of several direct and indirect measurements. The indirect measurements in all cases consisted of spectra gated in coincidence with the appropriate 2^+-0^+ transition. All necessary corrections have been applied to the data.

The error limits quoted in the table for the directional-correlation coefficients reflect the statistical uncertainties inherent in the measurement as well as the uncertainties associated with correcting the coincidence spectra for background effects; the influence of the latter source of error was generally predominant. The error limits of the mixing ratios were obtained directly from the error limits of the appropriate correlation coefficient.

The results for ^{186}Os are in disagreement with some older values obtained on the basis of NaI(Tl) measurements. An investigation of the $2^{+\prime}$-2^+-0^+ directional correlation in ^{186}Os populated by the decay of ^{186}Re has yielded the result $\delta(630)=+13^{+5.5}_{-3.0}$, based on the value for the directional-correlation coefficient $A_{22}=-0.129\pm0.017$.[27] Other similar measurements,[28-30] all of which were made with NaI(Tl) detectors, have quoted results for A_{22} in the neighborhood of -0.06, with some overlap occurring with the present results due to the large error limits of the latter.

It is highly unlikely that any external perturbations caused such a drastic attenuation of the A_{22} coefficient in the present measurement, particularly in view of the agreement between the measured value of $A_{44}=0.302\pm0.049$ and its theoretical value of 0.323. The primary source contributing to the large uncertainty of the A_{22} coefficient was the failure to resolve the 630-keV transition from the 633- and 635-keV transitions in ^{188}Os, since the ^{186}Ir sources contained substantial amounts of ^{188}Ir. These lines of large intensity would be expected to contribute substantially to chance coincidence and Compton background corrections, with the relative contribution increasing in time as the shorter-lived ^{186}Ir decayed. Thus the present work permits a wide range of values for the mixing ratio of the $2^{+\prime}$-2^+ transition in ^{186}Os; however, the 3^+-2^+ transition was clearly resolvable in the spectrum, and this measurement is much more reliable.

Previous γ-γ measurements[31] of cascades in ^{188}Os yielded $\delta(478)=-14^{+11}_{-4}$ and $\delta(633)=-8^{+12}_{-3}$, in good agreement with the present values. However, recent measurements by Coulomb excitation[32] have yielded a value of $|\delta(478)|>30$; the large uncertainties associated with this latter value indicate a preference for the γ-γ directional-correlation data.

The measured values of the mixing ratios for the transitions in ^{190}Os are in fair agreement with the previously reported γ-γ measurements[31] of the $2^{+\prime}$-2^+-0^+ cascade which resulted in $\delta(371)=-14^{+11}_{-4}$, but disagree with results reported in Ref. 31 for the 3^+-2^+-0^+ cascade yielding $\delta(569)=+14^{+\infty}_{-7}$. For the $2^{+\prime}$-2^+ transition, two recent Coulomb excitation measurements have yielded values for $\delta(371)$ of -11 ± 3 [33] and -11^{+6}_{-4}.[32] Both results overlap well with the results of the present work.

In addition to the results given in the table the following directional correlations were measured in ^{190}Os, with the following results:

605–558 keV:
$A_{22}=0.098\pm0.010$,
$A_{44}=-0.001\pm0.016$;
518–605 keV:
$A_{22}=-0.063\pm0.015$,
$A_{44}=0.012\pm0.022$.

These results are consistent with a 5^- assignment for the 1.682-MeV level and a 4^+ assignment for the 1.163-MeV level, consistent with the proposed spin assignments.[8]

The results in the table for the $2^{+\prime}$-2^+ transitions in ^{194}Pt and ^{196}Pt are not in good agreement with results of γ-γ directional correlations using a Ge(Li)-NaI(Tl) detector combination reported recently by

Hamilton[34] who proposes $\delta(294) = +(30^{+39}_{-11})$ in ^{194}Pt, derived from the coefficient $A_{22} = -0.101 \pm 0.014$, and $\delta(333) = -4.03 \pm 0.12$ in ^{196}Pt, derived from $A_{22} = 0.113 \pm 0.005$. The results for ^{194}Pt are subject to a number of corrections arising from the complexity of the decay scheme of ^{194}Au, and the manner of applying such corrections may account for the discrepancy in the measured values of $\delta(294)$. The disagreement in the case of ^{196}Pt is more severe, and in contrast to the ^{194}Pt case, the simplicity of the ^{196}Au decay indicates that the source of this disagreement must lie elsewhere. In the measurement of Hamilton[34] both liquid and metallic sources were employed, and the overlap of the correlation coefficients for the various sources demonstrated that, as assumed in the present work, external perturbations may be neglected. The work of Ikegami *et al.*[35] on γ-γ correlations from the decay of ^{196}Au reached the same conclusion, but their results are in better agreement with the present work, having derived $\delta(333) = -5.0 \pm 0.5$ from $A_{22} = 0.072 \pm 0.004$ using sources of Au in various chemical forms. Earlier results based on directional correlations using two NaI(Tl) detectors gave $\delta(333) = -5 \pm 1$,[36] in agreement with all of the above values.

V. DISCUSSION

In the table the mixing ratios $\delta(\gamma)$ extracted from the angular-correlation data of the present investigation are compared with those calculated by Kumar.[4] Values for the mixing ratios are also shown in the γ transitions of Fig. 1, with the predictions of the Kumar-Baranger theory listed in parentheses below the measured value for each γ transition. To complete the systematic study of this region, results of other investigators for ^{192}Os and ^{192}Pt are also shown.[33,37]

The agreement between the experimental and theoretical results is seen to be quite good, with several of the calculated values lying within the error limits of the measured results. This is perhaps surprising, in view of the poor numerical accuracy to be expected from a calculation of the small $M1$ matrix elements; the computed values are quite sensitive to cancellations among the various small contributions. In fact, such a cancellation has been interpreted by Kumar[38] as the cause of the discrepancy between the theoretical and experimental values for the mixing ratio of the $2^{+\prime}$-2^+ transition in ^{196}Pt.

Particularly satisfying is the successful prediction by the theory of the change in sign of the mixing ratio of the $2^{+\prime}$-2^+ transitions in ^{192}Pt and ^{194}Pt. This is in contrast to other theoretical investigations. By considering different deformations for protons and neutrons, Greiner[39] predicts all $2^{+\prime}$-2^+ mixing ratios to have the same sign (i.e., negative, using the present definition of the matrix elements). Coupling collective states to quasiparticle excitations, Tamura and Yoshida[40] also predict a negative sign for the $2^{+\prime}$-2^+ mixing ratio in the osmium and platinum isotopes. Thus, this prediction of the positive relative phase of the mixing ratio of the $2^{+\prime}$-2^+ transitions in ^{192}Pt and ^{194}Pt constitutes a unique success for the pairing-plus-quadrupole calculations of Kumar and Baranger.

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β Decay and Nuclear Structure in $A = 99$ Nuclei

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An analysis of the β spectrum of Mo^{99} taking into account the correct shape of the outer β group revealed β groups with end points 1214 ±1 (84%), 840 ±5 (2%), 450 ±10 (14%) keV. The shape of the outer β group ($\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$) feeding the 142-keV level in Tc^{99} is expected to be statistical, obeying the ξ approximation. The measured shape-factor coefficient a is -0.01 ± 0.007. On the basis of shell-model matrix elements, the conserved-vector-current prediction for Λ gave a positive value for a, whatever the value of Λ_0. Treating both Λ and Λ_0 as free parameters, a fit to the experimental shape gave $3.4 \leq \Lambda \leq 5$ and $2.3 \leq \Lambda_0 \leq 3.7$. The shape of the inner group (840 keV) was found to be consistent with first-forbidden nonunique character, and within experimental accuracy it was consistent with the shell-model prediction, even though the 514-keV ($\frac{3}{2}^-$) level fed by this β group is considered as arising from the weak coupling of a $p_{1/2}$ proton to the 2^+ first excited state of the core. But the large logft value of this transition may perhaps be explained by a detailed "microscopic" picture of the core.

I. INTRODUCTION

The decay of Mo^{99} has been investigated by many,[1–7] and there is a general agreement on the existence of two β groups with maximum energies of 1230 and 445 keV. Vlasov *et al.*[6] observed a β transition to the ground state of Tc^{99} and two further inner groups which led them to postulate levels at 780 and 1062 keV for Tc^{99}. Cretzu *et al.*[8] could not confirm these additional β groups, but they detected a weak 245-keV β group feeding a level at 1130 keV in Tc^{99}. Further, the spins of levels at 514, 922, and 1131 keV are not uniquely established.[9,10] The absence of β transitions to the ground state and the levels at 140 and 181 keV in Tc^{99} can be understood on the shell-model prediction that these states arise out of $(g_{9/2})^3$ proton configurations. Recently the energy levels of Tc^{99} have been reproduced[11] with configuration interaction of the form $(\nu d_{5/2})^6$ $(\pi g_{9/2})^3$ taking into account admixtures from $p_{1/2}$ proton orbitals. In view of these considerations, a detailed study of the shapes of β groups can contribute some information to the level structure of Tc^{99}. The intense