Gamma-ray angular distributions in the decays of polarized ^{171,172}Lu†

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Angular distributions of numerous γ rays have been measured following the decays of ^{171,172}Lu polarized at low temperatures. The magnetic moments of the Lu ground state are deduced to be $|\mu(^{171}\mathrm{Lu})| = (2.04\pm 0.10)\mu_N$ and $|\mu(^{172}\mathrm{Lu})| = (2.26\pm 0.10)\mu_N$. Spin assignments are deduced for several levels in ^{172}Yb. $E2/M1$ and $M2/E1$ mixing ratios are deduced for many of the ^{171}Yb and ^{172}Yb transitions and are compared with expectations based on the intrinsic character of the nuclear levels.

[RADIOACTIVITY ^{171}Lu, ^{172}Lu; measured $\gamma(\theta)$ from polarized nuclei; ^{171,172}Lu-deduced magnetic moment μ; ^{171,172}Yb-deduced multipole mixing ratios, $\delta(E2/M1)$, $\delta(M2/E1)$, g_K, g_R, J^π, Coriolis mixing.]

I. INTRODUCTION

The study of the angular distribution of γ radiation from oriented nuclei has yielded considerable insight into the properties of nuclear levels and their radiations. In particular, the static nuclear electromagnetic moments and the multipole characters of the radiation fields may be accurately determined. This information is essential for understanding the structure of the low-lying levels. In recent publications[1,2] we have reported investigations of the decays of polarized ^{173,174,177}Lu; angular distributions of numerous γ rays were measured, and nuclear magnetic moments and γ-ray multipole mixing ratios were deduced. From these parameters it was possible to draw conclusions regarding the structure of the nuclear levels. In the present work we report on a similar investigation of the decays of ^{171,172}Lu. Although the level schemes populated in these decays are reasonably well established, measurement of the γ-ray multipole mixing ratios can yield further insight into the structure of the various levels and their identification with Nilsson-model configurations. Determination of these mixing ratios as well as the nuclear magnetic dipole moments of ^{171,172}Lu is the goal of the present work.

II. DECAY SCHEMES

The decays of ^{171}Lu and ^{172}Lu are illustrated in Figs. 1 and 2. The γ-ray spectrum of the ^{171}Lu decay to levels of ^{171}Yb has recently been investigated with high precision by Bonch-Osmolovskaya *et al.*[3] Previous studies of the γ ray and internal conversion electron intensities, with corresponding determination of the transition multipolarities, include those of Kaye,[4] Barneoud *et al.*,[5] and Balalaev *et al.*[6] Identification of the ^{171}Yb levels with the appropriate Nilsson configuration has followed from the single-particle transfer reaction studies of Burke *et al.*[7,8] The Coriolis mixing of various ^{171}Yb intrinsic states has been previously investigated by Lindblad, Ryde, and Barneoud[9] by means of the energies of rotational levels populated in the (α, xn) reaction. The various investigations of the ^{171}Yb level schemes have been recently summarized in the Nuclear Data Sheets.[10]

The ^{172}Lu decay scheme is considerably more complex. This decay has been studied by Sen and Zganjar[11] and by Balaleav *et al.*[12] Transition multipolarities have been deduced from the internal conversion data (for example, that of Kaye[13]); internal conversion coefficients have been deduced by Sen and Zganjar[11] from their γ-ray data in conjunction with previous conversion electron measurements. Additional multipolarities for a number of transitions have been derived from numerous angular correlation studies.[14-21] The intrinsic characters of the ^{172}Yb levels have been studied in single-particle transfer reactions by Burke and Elbek[22] and by O'Neil and Burke.[23] The γ-ray transition probabilities have been studied in comparison with expectation based on the intrinsic characters of the states by Moroz *et al.*,[24] Belt *et al.*,[25] Sen and Zganjar,[11] and by Reich, Greenwood, and Lokken[26] in the ^{172}Tm decay to ^{172}Yb. Level and multipolarity assignments have been summarized in the recent compilation of the Nuclear Data Sheets.[27]

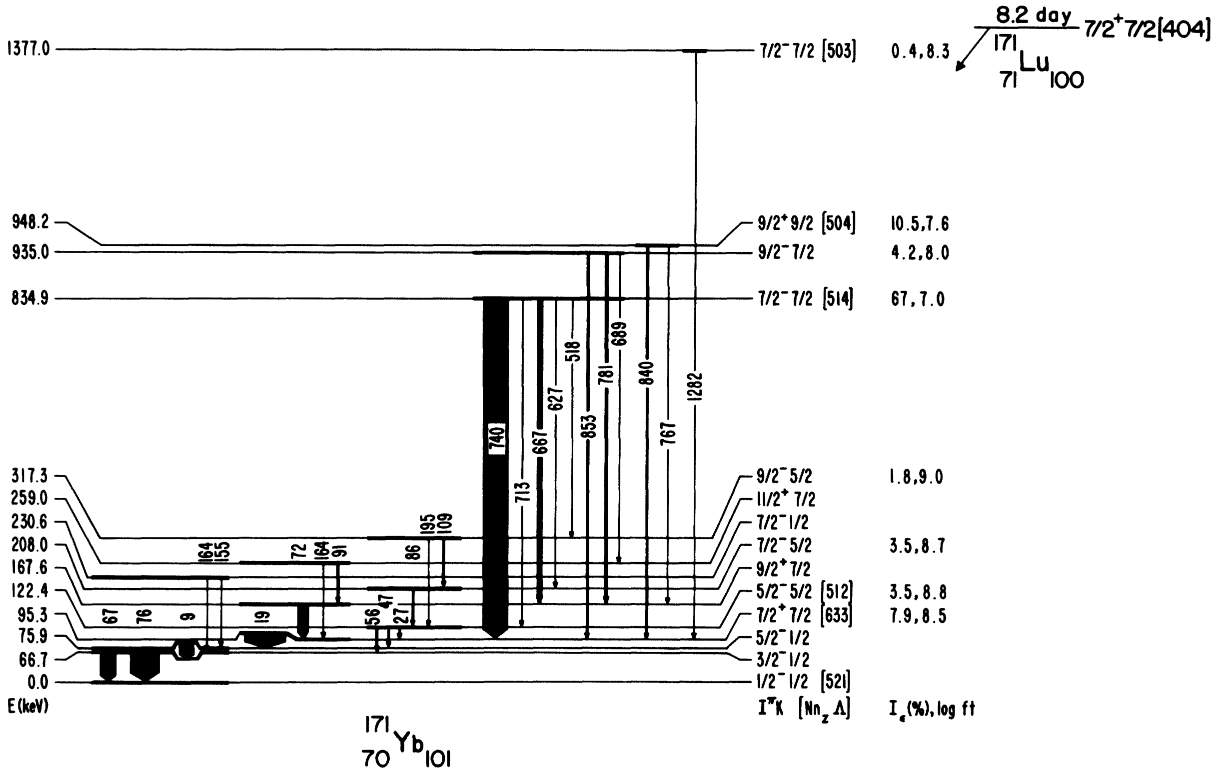

FIG. 1. The decay of ^{171}Lu to levels of ^{171}Yb.

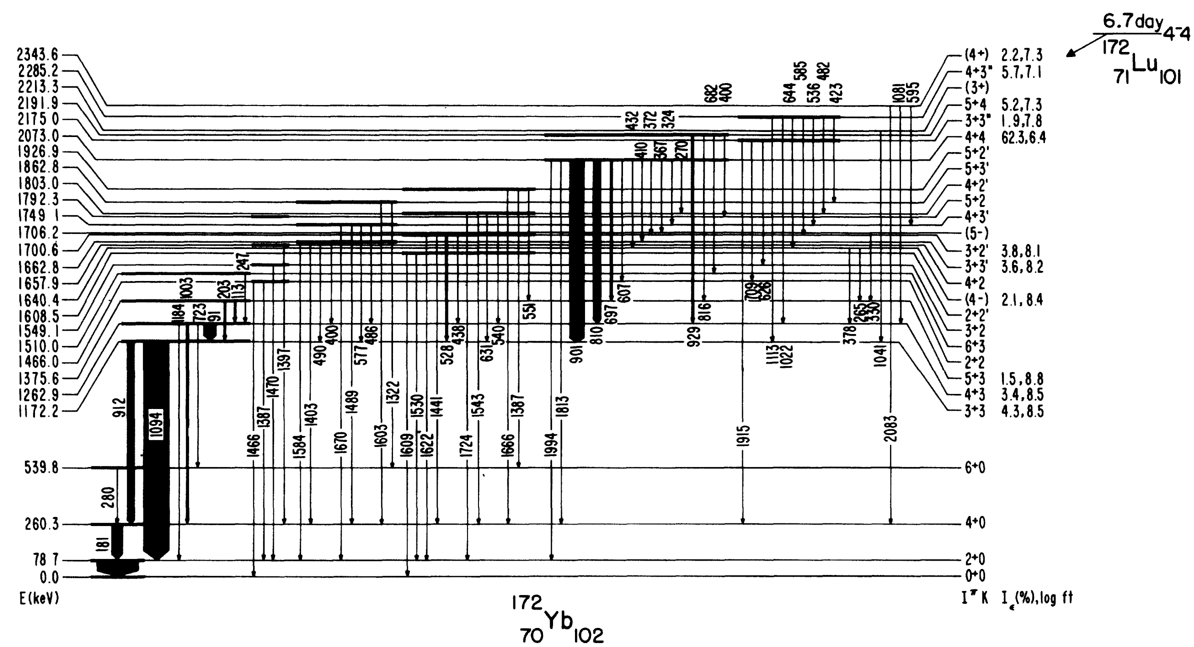

FIG. 2. The decay of ^{172}Lu to levels of ^{172}Yb.

III. EXPERIMENTAL DETAILS

A. Sample preparation

The Lu activity was produced by irradiating a natural Yb foil with 4 μA-h of 17 MeV deuterons at the Los Alamos Tandem van de Graaff. The (d,n) and $(d,2n)$ reactions result primarily in the production of ^{171,172,173,174}Lu; the half-lives of the ^{171,172}Lu (~ 7 day) relative to those of ^{173,174}Lu (~ 1 yr) result in the dominance of the former activity. As in our previous work,[1,2] polarization of the sample was achieved by introducing the Lu as an impurity into the compound $ZrFe_2$ to form $(Zr_{0.96}Lu_{0.04})Fe_2$. Further details of the sample preparation are given in our previous work.[1,2] A small quantity of ^{177}Lu^g activity was introduced by neutron activation; in this way the ^{171,172}Lu magnetic moments could be deduced by direct comparison with the known ^{177}Lu^g moment.

B. Apparatus

The sample was cooled by contact with a ^{3}He-^{4}He dilution refrigerator. In one set of measurements (referred to as nominally $T = 20$ mK) the sample was soldered directly to the refrigerator. For another set of measurements (nominally $T = 4$ mK) a cerium magnesium nitrate adiabatic demagnetization stage was introduced. Polarization of the cooled sample was achieved using two pairs of superconducting Helmholtz coils with their axes perpendicular to each other. The coils produced a magnetic field of $0.36T$ at the sample. A 40-cm^3 Ge(Li) detector was mounted along the axis of each of the coils. In this way, whenever one of the pairs of coils was conducting, one detector recorded the counting rates at an angle of 0° with the polarization direction, while the other recorded the rates at 90°. A typical γ-ray spectrum is shown in Fig. 3.

Several demagnetizations were performed for each sample, with the amplifier gain and analog-to-digital converter digital base line chosen such as to maximize the energy resolution or counting rates in various parts of the spectrum. Further details concerning the apparatus are found in Ref. 2.

C. Data analysis

The γ-ray counting rates were determined by integrating the various spectra and were analyzed according to the relationship

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

where the geometrical correction factors Q_k correct for detector angular resolution, the orientation parameters B_k describe the degree of orientation of the initial state and depend on the hyperfine energy splitting $\Delta = \mu H / I k_B$ (μ = nuclear magnetic dipole moment, H = hyperfine field, I = nuclear spin, k_B = Boltzmann constant) and on the temperature T, the deorientation coefficients U_k correct

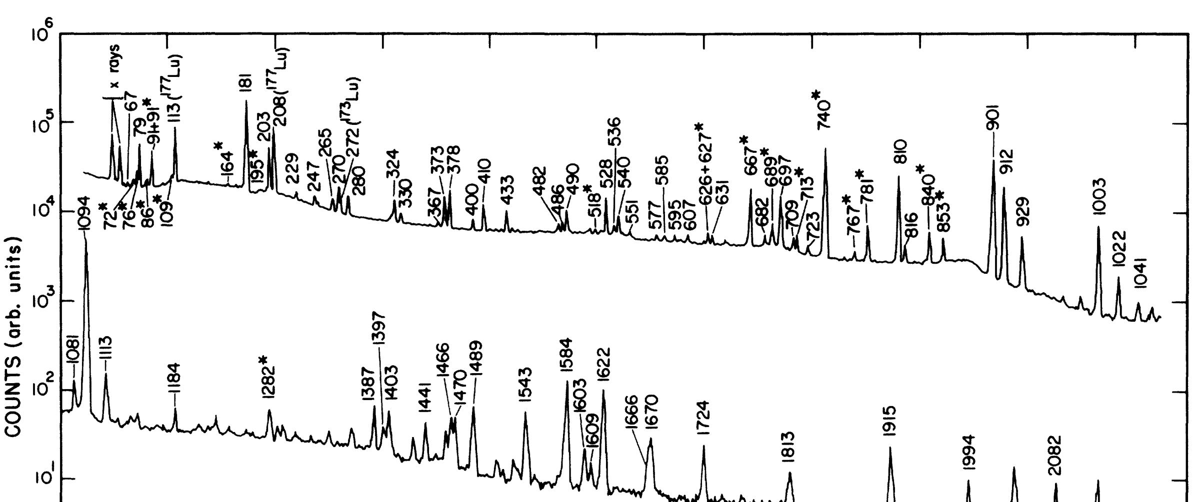

FIG. 3. γ-ray spectrum from the decays of ^{171}Lu, ^{172}Lu, and ^{177}Lu^g (plus some ^{173}Lu impurity). The peaks are labeled with the corresponding energy in keV; peaks with no parent isotope designation follow the ^{172}Lu decay, while those with an asterisk follow the ^{171}Lu decay.

for the effects of unobserved intermediate radiations, and the angular distribution coefficients A_k describe the properties of the observed γ ray. The P_k are Legendre polynomials. The angular distribution coefficients are given in terms of the γ-ray mixing ratio δ, which is defined in terms of emission matrix elements.[28]

In order to deduce the γ-ray mixing ratio from a measured angular distribution, knowledge of the U_k coefficients is required. For this purpose it is beneficial to observe γ rays which are preceded by pure multipole radiation, such as allowed Gamow-Teller β decays. However, as can be seen from Fig. 2, more than 90% of the ^{172}Lu β decays are of the first-forbidden type, whose multipolarity will be mixtures of $L=0$ (for $\Delta I=0$ decays), $L=1$, and $L=2$. A rigorous analysis of the observed angular distributions thus requires a knowledge of the multipole characters of the various β decays. Lacking such knowledge, we must allow for all possible multipolarities by calculating the U_k coefficients with a corresponding uncertainty which allows for all possible β multipolarities.

For $\Delta I=0$ first-forbidden β decay, the deorientation coefficients are given by

$$U_k(\beta)=|\alpha_0|^2+U_k(L=1)|\alpha_1|^2+U_k(L=2)|\alpha_2|^2, \quad (2)$$

where the quantities $|\alpha_L|^2$ give the fraction of the β-decay intensity corresponding to the Lth multipole ($|\alpha_0|^2+|\alpha_1|^2+|\alpha_2|^2=1$). The quantities $U_k(L)$ are angular momentum coupling coefficients.[29] For a $4^- \to 4^+$ decay, for example, $U_2(0)=1$, $U_2(1)=0.850$, and $U_2(2)=0.573$. Thus the $U_k(\beta)$ is not extremely sensitive to the competition between the $L=0$ and $L=1$ multipoles, but a sizable $L=2$ admixture could have a substantial effect on $U_k(\beta)$.

TABLE I. Computed deorientation coefficients for ^{171}Yb levels.

Level energy (keV)	U_2 ^{a}
67	0.488 (41)
76	0.639 (48)
95	0.736 (57)
122	0.726 (54)
168	0.818 (61)
208	0.829 (60)
259	0.870 (7)
317	0.888 (32)
835	0.900 (100)
935	0.925
948	0.918 (7)
1377	0.900 (100)

^{a}Figures in parentheses indicate uncertainty of last digit or digits.

However, the intensity of the $L=2$ component (which arises from the B_{ij} term in the β interaction) can be inferred to be small; this follows from the lack of direct β feeding to the expected $I=6^+$ states of the various ^{172}Yb rotational bands. Given an upper limit on the intensity of the unique first-forbidden $4^- \to 6^+$ decays, one can then use the rotational model (i.e., the Alaga rules[30]) to predict a corresponding upper limit on the $L=2$ admixture in the decays to the 5^+ and 4^+ states of the same rotational band. We have increased this upper limit by a rather arbitrary factor of 3 to try to correct for effects (band mixing) which result in the deviations of the observed[11] γ-ray transition probabilities from the rotational model predictions. The $L=2$ intensities so deduced generally amounted to no more than a few percent. In computing the U_2 values, we have taken into consideration all possible combinations of $L=0$ and $L=1$ β multipolarities, and have used the known γ-ray multipolarities and branching ratios[11,27] to compute the U_k values for each level populated in the ^{171}Lu and ^{172}Lu decays. The U_2 values obtained are given in Tables I and II. The uncertainties quoted result from the uncertainties in the branching ratios and β and γ multipolarities.

Most γ rays can be analyzed using the computed U_2 values of Tables I and II. However, the most

TABLE II. Computed deorientation coefficients for ^{172}Yb levels.

Level energy (keV)	U_2
79	0.224 (12)
260	0.442 (21)
540	0.757 (66)
1172	0.664 (36)
1263	0.764 (45)
1376	0.854 (56)
1466	0.571 (40)
1510	0.851 (57)
1549	0.757 (75)
1609	0.616 (174)
1640	0.819 (40)
1663	0.812 (39)
1701	0.784 (36)
1706	0.916 (20)
1749	0.768 (53)
1803	0.768 (72)
1863	0.861 (80)
1927	0.905 (50)
2073	0.921 (79)
2175	0.869 (36)
2192	0.936 (3)
2213	0.887 (28)
2285	0.921 (79)
2344	0.921 (79)

intense ^{172}Lu β decay populates the 2073-keV 4^+ level of ^{172}Yb. The depopulating γ rays are among the most intense in the spectrum and the anisotropies of their angular distributions have been determined with great precision. The computed U_2, however, has a 10% uncertainty, and would result in a correspondingly large uncertainty in the deduced A_2. (None of the transitions from the 2073-keV level has a sufficiently well-known multipolarity to enable the others to be compared with it.) In order to minimize this uncertainty, we have analyzed the γ rays depopulating the 2073-keV level by comparing their angular distributions with those of γ rays of known multipolarity from lower levels. This procedure is successful because of the large fraction of the ^{172}Lu decays which proceed through the 2073-keV level; hence all subsequent γ-ray angular distributions depend to some extent on the U_2 of the β decay populating the 2073-keV level. We let γ represent a γ ray depopulating the 2073-keV level, and γ_c represent a subsequent γ ray of known multipolarity ($E2$, for example) used for comparison. The measured quantities are then $[B_2U_2A_2]_\gamma$ and $[B_2U_2A_2]_{\gamma_c}$. We let $U_2(\beta)$ represent the deorientation coefficient of the β decay to the 2073 keV level; then, since the transition γ_c is emitted from a level populated indirectly through the 2073-keV level, the U_2 associated with the level which emits γ_c can be written as $a+bU_2(\beta)$, where a and b are constants depending on the branching ratios, etc. (For example, if $\gamma_c = 181$ keV, $a=0.216\pm0.014$, and $b=0.247\pm0.009$.) The ratio of the measured angular distributions of γ and γ_c can then be written

$$\frac{[B_2U_2A_2]_\gamma}{[B_2U_2A_2]_{\gamma_c}} = \frac{A(\gamma)}{A_2(\gamma_c)}\ \frac{U_2(\beta)}{a+bU_2(\beta)}\ ,$$

or

$$A_2(\gamma) = A_2(\gamma_c)\ \frac{[B_2U_2A_2]_\gamma}{[B_2U_2A_2]_{\gamma_c}}\ \frac{a+bU_2(\beta)}{U_2(\beta)}. \tag{3}$$

If we choose γ_c such that $b \geq a$, the uncertainty in the ratio $[a+bU_2(\beta)]/U_2(\beta)$ becomes less dependent on the uncertainty in $U_2(\beta)$. Using the 181-keV ($E2$), 203-keV ($E2$), and 1094-keV ($\delta[E2/M1] = -3.3\pm0.2$) γ rays for comparison, we have used this procedure to reduce the uncertainty in the analysis of the γ-ray angular distribution from the 2073-keV level to the order of 5%.

IV. RESULTS

A. γ-ray anisotropies

The measured angular distributions of the ^{171}Yb and ^{172}Yb γ rays are summarized in Tables III and IV, respectively. The 4 mK results represent an average over several demagnetizations and over several runs within each demagnetization. The 20 mK data represent an average over several different runs. For both cases, the different runs were made using various gain and baseline settings in order to optimize the results for a particular region of the γ-ray spectrum. No variation in anisotropy resulting from temperature variations was observed among the various groups of data, and hence the anisotropies have been averaged directly assuming no B_2 variation. Corrections have been made for the solid angle factor Q_2. From the observed counting rates $W(0°)$ and $W(90°)$ (normalized by the isotropic warm counting rates), the coefficients of the P_2 and P_4 terms in the angular distributions were deduced. The $B_4U_4A_4$ terms are small (in nearly all cases vanishing within 1 standard deviation) and can provide no additional insight into the characteristics of the ^{171,172}Lu decays or the ^{171,172}Yb γ rays. Hence we will base our analysis only on the $B_2U_2A_2$ values.

TABLE III. ^{171}Yb γ-ray angular distributions.

$E\gamma$ (keV)	Initial state E (keV)	$I^\pi K$	Final state E (keV)	$I^\pi K$	$B_2U_2A_2(\times 10^3)$ (4 mk)	(20 mk)
67	67	$\frac{3}{2}^-\frac{1}{2}$	0	$\frac{1}{2}^-\frac{1}{2}$	−200(101)	−132(26)
72	168	$\frac{9}{2}^+\frac{7}{2}$	95	$\frac{7}{2}^+\frac{7}{2}$	170 (50)	70(24)
86	208	$\frac{7}{2}^-\frac{5}{2}$	122	$\frac{5}{2}^-\frac{5}{2}$	284 (56)	41(17)
109	317	$\frac{9}{2}^-\frac{5}{2}$	208	$\frac{7}{2}^-\frac{5}{2}$	255 (42)	40(50)
164 [a]	259	$\frac{11}{2}^+\frac{7}{2}$	95	$\frac{7}{2}^+\frac{7}{2}$	−103 (67)	−88(25)
195	317	$\frac{9}{2}^-\frac{5}{2}$	122	$\frac{5}{2}^-\frac{5}{2}$	−172(105)	−76(35)
518	835	$\frac{7}{2}^-\frac{7}{2}$	317	$\frac{9}{2}^-\frac{5}{2}$	540 (90)	103(53)
627	835	$\frac{7}{2}^-\frac{7}{2}$	208	$\frac{7}{2}^-\frac{5}{2}$	−230 (50)	−27(14)
667	835	$\frac{7}{2}^-\frac{7}{2}$	168	$\frac{9}{2}^+\frac{7}{2}$	86 (4)	26 (2)
689	948	$\frac{9}{2}^-\frac{7}{2}$	259	$\frac{11}{2}^+\frac{7}{2}$	106 (14)	37(11)
713	835	$\frac{7}{2}^-\frac{7}{2}$	122	$\frac{5}{2}^-\frac{5}{2}$	407 (19)	126(16)
740	835	$\frac{7}{2}^-\frac{7}{2}$	95	$\frac{7}{2}^+\frac{7}{2}$	−253 (1)	−60 (1)
767	935	$\frac{9}{2}^+\frac{9}{2}$	168	$\frac{9}{2}^+\frac{7}{2}$	−108 (38)	−24(23)
781	948	$\frac{9}{2}^-\frac{7}{2}$	168	$\frac{9}{2}^+\frac{7}{2}$	−260 (6)	−55 (6)
840	935	$\frac{9}{2}^+\frac{9}{2}$	95	$\frac{7}{2}^+\frac{7}{2}$	566 (9)	155 (8)
853	948	$\frac{9}{2}^-\frac{7}{2}$	95	$\frac{7}{2}^+\frac{7}{2}$	204 (11)	68(12)
1282	1377	$\frac{7}{2}^-\frac{7}{2}$	95	$\frac{7}{2}^+\frac{7}{2}$	−366 (53)	−50(12)

[a] Possible doublet—the 164-keV transition can also connect the 231-keV and 67-keV levels.

TABLE IV. ^{172}Yb γ-ray angular distributions.

E_γ (keV)	Initial state E (keV)	Initial state $I^\pi K$	Final state E (keV)	Final state $I^\pi K$	$B_2U_2A_2$ ($\times 10^3$) (4 mk)	$B_2U_2A_2$ ($\times 10^3$) (20 mk)
79	79	2^+0	0	0^+0	29 (8)	−9 (2)
91	1263	4^+3	1172	3^+3	336(13)	98 (4)
181	260	4^+0	79	2^+0	−131 (2)	−38 (1)
203	1376	5^+3	1172	3^+3	−248 (5)	−66 (2)
247	1510	6^+3	1263	4^+3	−275(35)	−70(11)
265	1640	(4^-)	1376	5^+3	75(31)	−21(10)
270	2073	4^+4	1803	$4^+2'$	−380(30)	−106 (4)
280	540	6^+0	260	4^+0	−213(19)	−58 (6)
324	2073	4^+4	1749	$4^+3'$	−366(15)	−108 (6)
330	1706	(5^-)	1376	5^+3	−312(33)	−97(13)
367	2073	4^+4	1706	(5^-)	199(75)	−23(40)
372	2073	4^+4	1701	$3^+2'$	−502(10)	−143 (3)
378	1640	(4^-)	1263	4^+3	−219 (9)	−69 (3)
400	1663	$3^+3'$	1263	4^+3	70(40)	30(15)
410	2073	4^+4	1663	$3^+3'$	−488(13)	−146 (4)
432	2073	4^+4	1640	(4^-)	−343(18)	−93 (6)
482	2285	$4^+3''$	1803	$4^+2'$	−303(42)	−83(17)
486	1749	$4^+3'$	1263	4^+3	−267(35)	−95(12)
490	1663	$3^+3'$	1172	3^+3	−310(16)	−74 (6)
528	1701	$3^+2'$	1172	3^+3	−261 (9)	−67 (3)
536	2285	$4^+3''$	1749	$4^+3'$	−226(39)	−94(16)
540	1803	$4^+2'$	1263	4^+3	−195(17)	−72 (8)
551	1927	$5^+2'$	1376	5^+3	−111(97)	−75(26)
577	1749	$4^+3'$	1172	3^+3	278(90)	56(42)
585	2285	$4^+3''$	1701	$3^+2'$	240(71)	67(32)
595	2344	(4^+)	1749	$4^+3'$	−263(74)	−119(32)
607	2073	4^+4	1466	2^+2	−182(60)	−66(22)
631	1803	$4^+2'$	1172	3^+3	90(43)	59(23)
682	2192	5^+4	1510	6^+3	165(50)	86(28)
697	2073	4^+4	1376	5^+3	84 (6)	29 (3)
709	2175	$3^+3''$	1466	2^+2	−112(38)	−58(16)
810	2073	4^+4	1263	4^+3	−266 (3)	−75 (2)
816	2192	5^+4	1376	5^+3	−327(45)	−97 (9)
901	2073	4^+4	1172	3^+3	112 (2)	37 (2)
912	1172	3^+3	260	4^+0	−141 (3)	−40 (2)
929	2192	5^+4	1263	4^+3	253 (9)	84 (5)
1003	1263	4^+3	260	4^+0	123 (6)	39 (3)
1022	2285	$4^+3''$	1263	4^+3	−299(18)	−93 (7)
1041	2213	(3^+)	1172	3^+3	−268(55)	−104(19)
1081	2344	(4^+)	1263	4^+3	−272(67)	−50 (9)
1094	1172	3^+3	79	2^+0	196 (1)	63 (1)
1113	2285	$4^+3''$	1172	3^+3	430(13)	140 (4)
1184	1263	4^+3	79	2^+0	−145(39)	−44(13)
1387	1466	2^+2	79	2^+0	172(20)	58 (7)
1403	1663	$3^+3'$	260	4^+0	162(19)	61 (6)
1441	1701	$3^+2'$	260	4^+0	222(23)	79(10)
1466	1466	2^+2	0	0^+0	−226(18)	−80 (8)
1470	1549	3^+2	79	2^+0	73(23)	15 (8)
1489	1749	$4^+3'$	260	4^+0	141(12)	48 (5)
1543	1803	$4^+2'$	260	4^+0	134(14)	50 (5)
1584	1663	$3^+3'$	79	2^+0	−134 (9)	−32 (3)
1603	1863	$5^+3'$	260	4^+0	−90(40)	−22(15)
1622	1701	$3^+2'$	79	2^+0	−123(11)	−32 (3)
1666	1927	$5^+2'$	260	4^+0	−180(35)	−48(12)
1670	1749	$4^+3'$	79	2^+0	−215(20)	−67 (9)
1724	1803	$4^+2'$	79	2^+0	−240(23)	−64 (8)
1813	2073	4^+4	260	4^+0	179(34)	33(15)
1915	2175	$3^+3''$	260	4^+0	−168(19)	−39 (9)

TABLE IV *(Continued)*

	Initial state		Final state			
E	E		E		$B_2U_2A_2(\times 10^3)$	
(keV)	(keV)	$I^{\pi}K$	(keV)	$I^{\pi}K$	(4 mk)	(20 mk)
1994	2073	4^+4	79	2^+0	−65(34)	−16(15)
2083	2344	4^+	260	4^+0		−115(13)

B. ^{171}Lu magnetic moment

The ^{171}Lu decay provides no unique means of determining the orientation parameters of the initial state. We observe only mixed $E2/M1$ transitions following the Gamow-Teller β decay to the 948-keV state, and the $E1$ transitions (for example from the 835- and 935-keV states which are known from conversion coefficient measurements to contain vanishingly little $M2$ admixtures), follow first-forbidden β decays whose multipole characters are uncertain. (The $E2$ transitions between the low-lying rotational states with $\Delta I = 2$ are not suitable due to the large uncertainties of their angular distributions.) Since, in general, $M2/E1$ mixing is less probable than $E2/M1$ mixing, we have selected two $E1$ (possibly plus $M2$) transitions, 740 keV and 781 keV, to determine the initial state orientation. These transitions have been selected because a $\Delta I = 0$ transition is considerably less sensitive to a given amount of $M2/E1$ mixing than is a $\Delta I = \pm 1$ transition. [For example, ignoring the δ^2 terms in A_2, $A_2(781) \approx -0.440 - 0.603\delta$, while $A_2(853) \approx +0.303 - 1.871\delta$; thus an uncertainty of 0.5% in the $M2$ intensity causes an uncertainty of 10% in $A_2(781)$ and 40% in $A_2(853)$.] Assuming the 740-keV transition to be pure $E1$ and the 781-keV transition to have $|\delta(M2/E1)| \leq 0.06$ (based on the measured conversion coefficients[10]), we obtain the following values for the ^{171}Lu orientation parameters:

$$E_\gamma = 740 \text{ keV:} \quad B_2(4 \text{ mK}) = 0.640 \pm 0.070,$$
$$B_2(20 \text{ mK}) = 0.153 \pm 0.016,$$
$$E_\gamma = 781 \text{ keV:} \quad B_2(4 \text{ mK}) = 0.644 \pm 0.053,$$
$$B_2(20 \text{ mK}) = 0.137 \pm 0.016.$$

The uncertainties in the values obtained from the 740-keV transition result primarily from the uncertainty in the U_2 for the 835-keV level, while the uncertainties of the 781-keV values result from the uncertainties in $A_2(781)$ owing to possible $M2/E1$ mixing. From the average of the above values we deduce

$$\Delta/T = 0.70 \pm 0.04 \quad (4 \text{ mK}),$$
$$\Delta/T = 0.27 \pm 0.01 \quad (20 \text{ mK}).$$

Uncertainties in the hyperfine interaction of Lu in $ZrFe_2$ make impossible the direct determination of the magnetic moment from the above orientation parameters. However, the presence of $^{177}Lu^g$ in our samples makes possible a direct comparison of the ^{171}Lu and $^{177}Lu^g$ moments in a manner independent of the hyperfine field and the temperature. From the angular distribution of the 113-keV γ ray of the $^{177}Lu^g$ decay, we determine

$$B_2(4 \text{ mK}, \ ^{177}Lu^g) = 0.699 \pm 0.019,$$
$$B_2(20 \text{ mK}, \ ^{177}Lu^g) = 0.181 \pm 0.009,$$

which yield

$$\Delta/T = 0.76 \pm 0.02 \quad (4 \text{ mK}),$$
$$= 0.30 \pm 0.01 \quad (20 \text{ mK}).$$

The ratio of the Δ/T value deduced for the ^{171}Lu to that deduced for the $^{177}Lu^g$ then gives directly the ratio of the magnetic moments:

$$\frac{\mu(^{171}\text{Lu})}{\mu(^{177}\text{Lu}^g)} = 0.92 \pm 0.05 \quad (4 \text{ mK}),$$
$$= 0.90 \pm 0.04 \quad (20 \text{ mK}),$$

and using the $^{177}Lu^g$ moment ($\mu = +2.245\mu_N$),[31] we obtain

$$|\mu(^{171}\text{Lu})| = (2.04 \pm 0.10)\mu_N.$$

It should be noted that the ratio of the Δ/T values deduced for the 4 mK and 20 mK data would indicate a ratio of 2.5 between the temperatures corresponding to the 4 mK and 20 mK data, rather than the expected factor of 5. We interpret this discrepancy as arising from a thermal gradient across the sample and its solder connections to the cold finger in the 4 mK runs, leading to an effective sample temperature of perhaps 8 mK. At 20 mK the sample thermal conductivity is much larger, and the gradient much smaller. We point out, however, that the 4 mK operating temperature with the demagnetization stage and the 20 mK operating temperature without it have been observed in other experiments by means of both resistance and γ-ray thermometry.

C. ^{172}Lu magnetic moment

Although there is no unique sequence of pure-multipole radiations emitted in the ^{172}Lu decay

TABLE V. Deduced ^{172}Lu orientation parameters.

γ-ray energy	B_2 (4 mK)	B_2 (20 mK)
181	0.662(34)	0.191(11)
203	0.690(45)	0.184(12)
247	0.802(102)	0.209(36)
280	0.698(87)	0.190(26)
607	0.446(147)	0.162(54)
1184	0.510(161)	0.155(53)
1466	0.662(70)	0.234(29)
1670	0.625(72)	0.195(29)
1724	0.698(94)	0.186(29)

which might serve as a means of deducing the B_2 of the parent state, there are a number of pure $E2$ transitions which can be employed in conjunction with the computed U_2 values (Table II). These are listed in Table V along with the corresponding deduced values of B_2 for the 4 mK and 20 mK data. Averaging the values of Table V we obtain

$$B_2(4\text{ mK}) = 0.668 \pm 0.028,$$

$$B_2(20\text{ mK}) = 0.191 \pm 0.009,$$

from which follow

$$\Delta/T = 0.639 \pm 0.027 \quad (4\text{ mK}),$$

$$= 0.275 \pm 0.007 \quad (20\text{ mK}).$$

As was done above for the case of ^{171}Lu, the ^{172}Lu magnetic moment can be deduced from a direct comparison of the ^{172}Lu hyperfine splitting with that of ^{177}Lu^g. From the ratio of the deduced hyperfine splittings we obtain

$$\frac{\mu(^{172}\text{Lu})}{\mu(^{177}\text{Lu}^g)} = 0.965 \pm 0.048 \quad (4\text{ mK}),$$

$$= 1.048 \pm 0.044 \quad (20\text{ mK}).$$

Averaging the two results and employing the known ^{177}Lu^g magnetic moment ($\mu = 2.245\mu_N$),[31] we obtain

$$|\mu(^{172}\text{Lu})| = (2.26 \pm 0.10)\mu_N .$$

The most precise of the coefficients of the P_4 terms deduced from the measured angular distribution is that of the 1094-keV γ ray, for which $B_4U_4A_4 = 0.015 \pm 0.001$. Using the computed U_4 value for the 1172-keV level ($U_4 = 0.245 \pm 0.076$) along with the A_4 value appropriate for the deduced 1094-keV mixing ratio, we deduce from the 4 mK data

$$B_4 = 0.100 \pm 0.031.$$

The B_2 value deduced above corresponds to

$$B_4 = 0.082 \pm 0.007,$$

in good agreement with the former value.

D. ^{171}Yb mixing ratios

Using the measured values of $B_2U_2A_2$ given in Table III, along with the deduced B_2 and computed

TABLE VI. Mixing ratios of ^{171}Yb γ rays.

	E_γ (keV)	$(I^\pi K)_i$	$(I^\pi K)_f$	$A_2(\times 10^3)$	δ [a]	$\lvert\delta\rvert$ [b]
$\Delta K=0$ Rotational intraband transitions ($E2/M1$)	67	$\frac{3}{2}^- \frac{1}{2}$	$\frac{1}{2}^- \frac{1}{2}$	−976(242)	$+2.0^{+5.0}_{-1.2}$	0.70 ± 0.03
	72	$\frac{9}{2}^+ \frac{7}{2}$	$\frac{7}{2}^+ \frac{7}{2}$	483(91)	−0.10 ± 0.06	0.276 ± 0.08
	86	$\frac{7}{2}^- \frac{5}{2}$	$\frac{5}{2}^- \frac{5}{2}$	464(84)	−0.07 ± 0.05	0.24 ± 0.04
	109	$\frac{9}{2}^- \frac{5}{2}$	$\frac{7}{2}^- \frac{5}{2}$	447(74)	−0.08 ± 0.04	0.22 ± 0.05
Interband transitions ($E2/M1$)	518	$\frac{7}{2}^- \frac{7}{2}$	$\frac{9}{2}^- \frac{5}{2}$	920(179)	$+1.2^{+1.7}_{-0.7}$	0.5 ± 0.2
	627	$\frac{7}{2}^- \frac{7}{2}$	$\frac{7}{2}^- \frac{5}{2}$	−366(89)	+1.3 ± 0.3	0.8 ± 0.2
	713	$\frac{7}{2}^- \frac{7}{2}$	$\frac{5}{2}^- \frac{5}{2}$	734(97)	−2.1 ± 0.4	$1.4^{+0.4}_{-0.3}$
	767	$\frac{9}{2}^+ \frac{9}{2}$	$\frac{9}{2}^+ \frac{7}{2}$	−181(61)	−0.34 ± 0.08	$0.7^{+0.3}_{-0.2}$
	840	$\frac{9}{2}^+ \frac{9}{2}$	$\frac{7}{2}^+ \frac{7}{2}$	995(55)	$-0.51^{+0.11}_{-0.07}$	0.5 ± 0.2
($M2/E1$)	667	$\frac{7}{2}^- \frac{7}{2}$	$\frac{9}{2}^+ \frac{7}{2}$	157(20)	+0.003 ± 0.014	$0.07^{+0.03}_{-0.07}$
	689	$\frac{9}{2}^- \frac{7}{2}$	$\frac{11}{2}^+ \frac{7}{2}$	188(25)	+0.015 ± 0.016	0.11 ± 0.03
	853	$\frac{9}{2}^- \frac{7}{2}$	$\frac{7}{2}^+ \frac{7}{2}$	357(27)	−0.029 ± 0.014	<0.10
	1282	$\frac{7}{2}^- \frac{7}{2}$	$\frac{7}{2}^+ \frac{7}{2}$	−516(88)	$+0.12^{+0.32}_{-0.13}$	<0.14

[a] We show only the solution for δ which gives best agreement with $|\delta|$ deduced from internal conversion data; the alternate solution has been discarded.

[b] Magnitude of δ as determined from internal conversion coefficients (Refs. 4–6, 10).

TABLE VII. Mixing ratios of $\Delta K=0$ and 1 ^{172}Yb γ rays.

E_γ (keV)	$(I^\pi K)_i$	$(I^\pi K)_f$	A_2	$\delta(E2/M1)$ [a]
91	4^+3	3^+3	0.672(46)	-2.4 ± 0.2
324	4^+4	$4^+3'$	−0.589(30)	$+0.40 \pm 0.14$
400	$3^+3'$	4^+3	0.153(59)	0.00 ± 0.04 or $-(9^{+6}_{-2})$
410	4^+4	$3^+3'$	−0.793(33)	$+0.94^{+0.26}_{-0.10}$ or $+1.6^{+0.2}_{-0.4}$
482	$4^+3''$	$4^+2'$	−0.486(71)	$+0.08^{+0.18}_{-0.11}$ or $+0.82^{+0.20}_{-0.26}$
486	$4^+3'$	4^+3	−0.573(67)	$+0.40^{+0.36}_{-0.22}$
490	$3^+3'$	3^+3	−0.532(37)	$+0.13^{+0.06}_{-0.05}$ or $+1.0 \pm 0.1$
528	$3^+2'$	3^+3	−0.476(31)	$+0.05 \pm 0.04$
536	$4^+3''$	$4^+3'$	−0.422(64)	-0.02 ± 0.09 or $+1.0 \pm 0.2$
540	$4^+2'$	4^+3	−0.411(49)	-0.04 ± 0.07 or $+1.0^{+0.2}_{-0.1}$
551	$5^+2'$	5^+3	−0.317(110)	$+1.1 \pm 0.3$ or -0.18 ± 0.15
577	$4^+3'$	3^+3	0.499(150)	-0.10 ± 0.08
585	$4^+3''$	$3^+2'$	0.387(103)	-0.04 ± 0.06 or $-(4.3^{+1.4}_{-0.9})$
595	$(4^+3''')$	$4^+3'$	−0.505(99)	$-(0.8^{+0.3}_{-0.4})$ or $+0.12^{+0.28}_{-0.16}$
631	$4^+2'$	3^+3	0.227(74)	$+0.05 \pm 0.04$ or $-(7.0^{+2.6}_{-1.5})$
682	5^+4	6^+3	0.310(72)	$+0.09 \pm 0.05$ or $+36^{+\infty}_{-23}$
697	4^+4	5^+3	0.142(10)	-0.012 ± 0.007
709	$3^+3''$	2^+2	−0.243(54)	$+16^{+13}_{-5}$
810	4^+4	4^+3	−0.421(17)	-0.026 ± 0.024
816	5^+4	5^+3	−0.536(44)	$+0.35 \pm 0.25$
901	4^+4	3^+3	0.187(8)	$+0.066 \pm 0.005$
929	5^+4	4^+3	0.422(17)	-0.070 ± 0.009
1022	$4^+3''$	4^+3	−0.503(51)	$+0.11^{+0.13}_{-0.09}$ or $+0.75 \pm 0.17$
1041	$(3^+3''')$	3^+3	−0.519(72)	$+0.11^{+0.12}_{-0.09}$ or $+1.0^{+0.3}_{-0.2}$
1081	$(4^+3''')$	4^+3	−0.312(54)	-0.17 ± 0.07
1113	$4^+3''$	3^+3	0.749(69)	-0.26 ± 0.05 or $-(2.1^{+0.3}_{-0.2})$

[a] The value given for δ is the root of A_2 giving best agreement with the measured conversion coefficients (Ref 27). For cases in which the conversion coefficients do not permit an unambiguous choice to be made, both possible solutions are shown, with the first one given some slight preference.

U_2 values, the angular distribution parameters A_2 were deduced for the mixed $E2/M1$ and $M2/E1$ ^{171}Yb γ rays. In Table VI are shown the average values of A_2 based on the 4 mK and 20 mK data. The A_2 values yield two solutions for the mixing ratio δ; by comparing our results with values of $|\delta|$ deduced from the internal conversion coefficients,[4,6,10] one of the solutions can be discarded due to lack of agreement. The value of δ giving best agreement with the conversion coefficient data is shown in Table VI.

E. ^{172}Yb mixing ratios

The measured ^{172}Yb γ-ray angular distributions, when corrected by the deduced B_2 and computed U_2 values, yield the A_2 coefficients shown in Tables VII and VIII. The values of A_2 represent an average of the 4 mK and 20 mK data. We have again selected the value of δ to be that one of the two roots of A_2 which gives the best agreement with the multipolarities deduced from the internal conversion coefficients.[11,27] As a general rule, the conversion data suggest primarily $M1$ multipolarity for transition between states having $\Delta K=0$ and 1, and $E2$ multipolarity for transitions between states having $\Delta K \geqslant 2$. We have therefore separated these two cases and have listed the corresponding γ rays in Tables VII and VIII. In most cases the uncertainties of the conversion coefficients are too large to permit the extraction of a precise value of $|\delta|$ to compare with the present results. In cases in which the error limits of the conversion coefficients do not permit a unique choice of δ, both values are shown and the value favored somewhat by comparison with the conversion coefficient is noted.

F. ^{172}Yb spin assignments

The spin assignments of the ^{172}Yb levels deduced from the results of the present work are shown in Fig. 2. There are two major differences between the presently proposed spin assignments and those

TABLE VIII. $E2/M1$ mixing ratios of $\Delta K \geq 2$ ^{172}Yb γ rays.

E_γ (keV)	$(I^\pi K)_i$	$(I^\pi K)_f$	A_2	$\delta(E2/M1)$ [a]
270	4^+4	$4^+2'$	−0.592(32)	$+0.40 \pm 0.13$
372	4^+4	$3^+2'$	−0.798(31)	$+1.2^{+0.5}_{-0.3}$
912	3^+3	4^+0	−0.318(21)	-1.9 ± 0.1
1003	4^+3	4^+0	0.250(19)	$+50^{+\infty}_{-29.}$
1094	3^+3	2^+0	0.464(30)	-3.2 ± 0.2
1387	2^+2	2^+0	0.482(53)	$-(2.4^{+0.8}_{-1.5})$
1403	$3^+3'$	4^+0	0.346(31)	$+40^{+\infty}_{-20}$
1441	$3^+2'$	4^+0	0.457(43)	$+10^{+4}_{-3}$
1470	3^+2	2^+0	0.128(38)	$-(7.6^{+1.4}_{-1.0})$
1489	$4^+3'$	4^+0	0.292(29)	$-(24^{+\infty}_{-13})$ or -1.15 ± 0.10
1543	$4^+2'$	4^+0	0.294(35)	$-(22^{+\infty}_{-13})$ or -1.2 ± 0.2
1584	$3^+3'$	2^+0	−0.229(17)	$+18 \pm 3$ or $+0.31 \pm 0.01$
1603	$5^+3'$	4^+0	−0.151(55)	$+12^{+8}_{-3}$ or $+0.24 \pm 0.04$
1622	$3^+2'$	2^+0	−0.225(19)	$+18^{+5}_{-3}$ or $+0.31 \pm 0.01$
1666	$5^+2'$	4^+0	−0.290(45)	$-(6.1^{+1.2}_{-0.9})$ or $+0.33 \pm 0.03$
1813	4^+4	4^+0	0.254(47)	< -18, $> +13$, or $-(1.0^{+0.2}_{-0.1})$
1915	$3^+3''$	4^+0	−0.275(29)	-0.34 ± 0.03 or -2.2 ± 0.2
2083	(4^+3)	4^+0	−0.625(90)	$+0.40 \pm 0.24$

[a] See footnote [a] to Table VII regarding choice of δ.

of Sen and Zganjar.[11] In addition, we are able to propose one additional assignment on the basis of our angular distribution data.

1. 1640-keV level

This level was assigned as 5^- by Sen and Zganjar; the Nuclear Data Sheets compilation[27] suggests 4^- or 5^-. This level is deexcited by means of the 378-keV transition, for which we deduce $A_2 = -0.419 \pm 0.027$. The measured conversion coefficient of $\alpha_K = 0.015 \pm 0.004$ suggests $E1$ multipolarity ($\alpha_K = 0.0097$) with a possible small admixture of $M2$ ($|\delta| = 0.14^{+0.05}_{-0.08}$). From our A_2, we would deduce $\delta = -0.03 \pm 0.04$ if the 1640-keV level is assigned as 4^-, or $\delta = +0.42 \pm 0.02$ for a 5^- assignment. The latter value is in substantial disagreement with the measured conversion coefficient ($\delta = 0.42$ would require $\alpha_K = 0.046$). This supports the 4^- assignment.

The 432-keV transition connects the 2073- and 1640-keV levels. The measured conversion coefficient ($\alpha_K = 0.011 \pm 0.003$) is consistent with multipolarity $E1$ ($\alpha_K = 0.0071$) with a possible small $M2$ admixture ($|\delta| = 0.15^{+0.05}_{-0.07}$). Our angular distribution data yield $A_2 = -0.532 \pm 0.029$. For a 4^- assignment to the 1640-keV level, this A_2 yields $\delta(432) = +0.18^{+0.09}_{-0.07}$, while if the 5^- assignment were correct, the A_2 would indicate $\delta(432) = -(0.9^{+0.3}_{-0.2})$. Again, the latter value is in complete disagreement with the measured conversion coefficient.

We therefore conclude that the 1640-keV level should be assigned as 4^-, and on that basis deduce the $M2/E1$ mixing ratios:

$$\delta(378) = -0.03 \pm 0.04,$$

$$\delta(432) = +0.18^{+0.09}_{-0.07}.$$

2. 1706-keV level

Sen and Zganjar[11] suggested 4^+, 5^+, or 6^+ as the possible assignments for this level, while the Nuclear Data compilation suggested 5^- or 6^-. The conversion coefficients, particularly α_K of the depopulating 1166-keV transition, α_L of the populating 330-keV transition, and α_K of the populating 367-keV transition, indicate $E1$ ($+M2$) multipolarities for these transitions, and therefore suggest negative parity. We have determined the angular distribution parameters of the 330- and 367-keV transitions. For the 330-keV transition we deduce $A_2 = -0.526 \pm 0.046$; this corresponds to $\delta(330) = +0.36 \pm 0.28$ for a 5^- (or 5^+) assignment, and to $\delta(330) = +0.52(4)$ for a 6^- (or 6^+) assignment. For the 367-keV transition, we deduce $A_2 = 0.22 \pm 0.11$, from which we obtain $\delta(367) = +0.04 \pm 0.07$ for a 5^- (or 5^+) assignment and an $E3/M2$ (or $M3/E2$) mixing ratio of $\delta(367) = +0.4 \pm 0.1$ or $\delta(367) < -5$ for a 6^- (or 6^+) assignment. The measured conversion coefficients do not permit the admixtures of the higher multipoles deduced for the spin-6 assignment, and we therefore favor the 5^- assignment, with the corresponding deduced $M2/E1$ mixing ratios

$$\delta(330) = +0.36 \pm 0.28,$$

$$\delta(367) = +0.04 \pm 0.07.$$

TABLE IX. Unplaced γ transitions.

Unplaced γ ray (keV)	Reference transition (keV)	$I(\gamma)/I(\gamma_{ref})$ Present work	Sen and Zganjar [a]
229	203	0.060 ± 0.006	0.065 ± 0.006
233	229	0.60 ± 0.11	1.0 ± 0.3
352	366	<0.16	0.72 ± 0.23
562	551	<0.16	0.27 ± 0.06
862	901	<0.001	0.011 ± 0.005
953	929	<0.015	0.13 ± 0.02
964	929	<0.015	0.052 ± 0.010
991	1002	0.018 ± 0.003	0.021 ± 0.007
1038	1094	<0.0008	0.0032 ± 0.0015
1054	1094	<0.0004	0.0013 ± 0.0002
1062	1094	<0.0004	0.0016 ± 0.0003
1125	1113	<0.013	0.054 ± 0.008
1142	1113	<0.013	0.053 ± 0.021
1145	1113	<0.026	0.25 ± 0.04
1153	1113	<0.013	0.10 ± 0.02
1179	1113	<0.026	0.064 ± 0.017
1593	1603	<0.04	0.28 ± 0.06
1920	1914	<0.025	0.17 ± 0.07

[a] Reference 11.

3. 2213-keV level

The 1041-keV transition is assigned as primarily of $M1$ multipolarity on the basis of the K conversion coefficient, indicating possible 2^+, 3^+, or 4^+ assignments for this level. For the 1041-keV transition we deduce $A_2 = -0.519 \pm 0.072$, which yield the following $E2/M1$ mixing ratios, based on the possible spin assignments: $\delta(1041) \approx -0.9$ (2^+), $\delta(1041) = +0.11^{+0.12}_{-0.09}$ (3^+), $\delta(1041) = +0.51 \pm 0.07$ (4^+). The requirement of $M1$ multipolarity imposed by α_K is in somewhat better agreement with the 3^+ assignment and the value of δ presented in Table VII.

4. 2344-keV level

Sen and Zganjar[11] suggest a 4^+ assignment, while the Nuclear Data Sheets compilation indicates 4^+ or 5^+. The 1081-keV transition is of $M1$ multipolarity, as determined by the K-conversion coefficient. Our deduced value of $A_2(1081) = -0.312 \pm 0.054$ would be consistent with a 4^+ assignment if $\delta(1081) = -0.17 \pm 0.07$, or with a 5^+ assignment if $\delta(1081) = +0.34 \pm 0.04$. For the 595-keV transition, the K-conversion coefficient indicates mixed $E2+M1$ multipolarity with $|\delta(595)| = 0.7^{+0.5}_{-0.3}$. For either spin assignment our measured A_2 yields $E2/M1$ mixing ratios in agreement with that deduced from the K-conversion coefficient. We favor the 4^+ assignment based on the analysis of the 1081-keV transition.

It is of interest to note that the present spin assignments suggest the presence of two new rotational bands, one based at 1640 keV and consisting of the levels at 1640 keV (4^-) and 1706 keV (5^-), and another based at 2213 keV and consisting of the levels at 2213 keV (3^+) and 2344 keV (4^+).

G. Unplaced γ rays

Sen and Zganjar[11] report the intensities of a number of γ rays which they were unable to place in the ^{172}Lu decay scheme. Since their means of producing the ^{172}Yb activity [Yb(α,xn)^{172}Hf→^{172}Lu] differed from ours [Yb(d,xn)^{171,172}Lu], a comparison of the γ-ray spectra can possibly provide some insight into the placement of these γ rays. Although in all cases but one the intensities of these questionable transitions were too low to determine angular distribution anisotropies, we have searched various regions of the spectrum for evidence of these unplaced transitions and have, in order to avoid uncertainties associated with absolute detector efficiency calibration, compared their intensities (or upper limits thereon) with those of nearby transitions. The results of this analysis for a number of unplaced transitions are shown in Table IX. Inconclusive results were obtained for other unplaced transitions. With the exception of the 229-, 233-, and 991-keV transitions, we are able to place upper limits on the intensities of these unplaced transitions as much as an order of magnitude lower than that of previous work. Therefore, within these limits, these transitions are excluded from the decay of ^{172}Lu.

The 229-keV transition is the most intense of the unplaced transitions. Our presently determined intensity agrees with that determined by Sen and Zganjar.[11] A transition of this energy and intensity was also reported by Moroz *et al.*[24] [using a sample produced by (α,xn)], and by Harmatz, Handley, and Mihelich[32] [using a sample produced by (p,xn)]; in (n,γ) studies, Alenius *et al.*[33] report a transition of energy 228.1 ± 1.5 keV. It seems, therefore, entirely possible that this transition belongs in the ^{172}Yb level scheme, although it cannot be placed among the existing levels. The intensity of the 229-keV transition was sufficient to permit the determination of its anisotropy and we obtained

$$B_2U_2A_2 = 0.805 \pm 0.070 \quad (4\text{ mK}),$$

$$= 0.214 \pm 0.022 \quad (20\text{ mK}).$$

Assuming this transition to follow the ^{172}Lu decay, we can use our deduced B_2 values and obtain (averaging the 4 mK and 20 mK results)

$$U_2A_2(229\text{ keV}) = 1.18 \pm 0.08.$$

Since the maximum value of U_2 is unity, this suggests that $A_2 \geq 1.1$, which serves to restrict the transition to $\Delta I = \pm 1$; the A_2 for a $\Delta I = 0$ transition cannot be as large as unity. The estimated A_2 in fact yields $\delta \approx +1$ if the transition were $I \rightarrow I+1$, and $\delta \approx -1$ for $I \rightarrow I-1$. We note, moreover, that this transition shows the largest anisotropy of all the γ rays which follow the ^{172}Lu decay; in fact, it is at the limit of the largest possible A_2 values. This suggests the possibility of an isomer (with a half-life of several minutes, to be able to polarize the level) in the ^{172}Yb level scheme with a sufficiently large magnetic moment such that $B_2(^{172}\text{Yb isomer}) > B_2(^{172}\text{Lu})$. It would be of interest to investigate the presence of the 229-keV transition in γ-ray coincidence studies in order to test this speculation.

V. DISCUSSION

A. Magnetic moments

1. ^{171}Lu

In Table X we compare the presently deduced magnetic moment of ^{171}Lu with those of the similar $\frac{7}{2}^+[404]$ ground states of ^{173,175,177}Lu. The present value for the ^{171}Lu moment is seen to be somewhat lower than the remaining values. That this is a real effect and not traceable to, for example, improper alloy fabrication or incorrect sample temperature monitoring, follows from our simultaneous deduction of the ^{171}Lu and ^{173}Lu moments by direct comparison with the ^{177}Lu^g moment in the identical sample. Any effect which would give rise to a lowering of the ^{171}Lu moment would produce a similar effect on the ^{173}Lu moment. The only possible cause of this reduction unrelated to direct nuclear structure effects might possibly be our assumptions regarding the parameters of the decay which were incorporated into our calculation of the U_2 and A_2 values. However, we have tried to include reasonable uncertainties in our U_2 and A_2 values which reflect possible spreads in the values of the decay parameters; such uncertainties are reflected in the ultimate uncertainty derived for the ^{171}Lu magnetic moment.

Since the magnetic moments are relatively insensitive to the rotational g factor g_R, we show in Table X values of the intrinsic g factor g_K, computed from the empirical moments using the representative constant g_R values of 0.35 ± 0.02.[34] The g_K value is related to the nuclear deformation parameter indirectly through the expectation value of the spin of the odd particle along the nuclear symmetry axis. The present results suggest a smaller moment for the ^{171}Lu compared with the other odd-mass Lu isotopes; this corresponds to a smaller g_K value. For $g_S = 0.58\ (g_S)_{\text{free}}$,[35] the minimum value of g_K permitted (corresponding to $\langle s_Z\rangle = -\frac{1}{2}$) for the $\frac{7}{2}^+[404]$ Nilsson state is $g_K = 0.68$, which is just at the limit of the presently measured value. A definite conclusion, based on the present results, in terms of variation in the nuclear deformation g_S or $\langle s_Z\rangle$ may, therefore, not be made unambiguously. We note, however, that other causes (for example, configuration mixing in the nuclear ground states) may be invoked in an attempt to justify this variation in the moments.

TABLE X. Magnetic moments of $\frac{7}{2}^+[404]$ states of odd-mass lutetium isotopes.

Mass number	μ (μ_N)	g_R [a]	g_K
171	(+)2.04 ±0.10	0.35 ± 0.02	0.646 ± 0.037
173	(+)2.34 ±0.09 [b]	0.35 ± 0.02	0.760 ± 0.034
175	+2.2380 ±0.0001 [c]	0.35 ± 0.02	0.722 ± 0.006
177	+2.245 ±0.010 [c]	0.35 ± 0.02	0.725 ± 0.007

[a] Reference 34.
[b] Reference 2.
[c] Reference 31.

TABLE XI. Mixing ratios of common interband transitions in ^{171}Yb and ^{173}Yb.

Initial state	Final state	δ/E_γ (MeV) ^{171}Yb	^{173}Yb
$\frac{7}{2}^- \frac{7}{2}[514]$	$\frac{9}{2}^- \frac{5}{2}[512]$	$+2.3^{+3.3}_{-1.3}$	$+2.2^{+1.5}_{-0.7}$
$\frac{7}{2}^- \frac{7}{2}[514]$	$\frac{7}{2}^- \frac{5}{2}[512]$	$+2.1\pm 0.5$	$+3.3\pm 0.2$
$\frac{7}{2}^- \frac{7}{2}[514]$	$\frac{5}{2}^- \frac{5}{2}[512]$	-2.9 ± 0.6	$-(1.3^{+0.7}_{-0.6})$

2. ^{172}Lu

The 4^- ground state of ^{172}Lu may be accounted for in terms of two intrinsic configurations, either of which might be expected at relatively low energies. These are $\{\frac{7}{2}^+[404]_p + \frac{1}{2}^-[521]_n\}$ or $\{\frac{1}{2}^-[541]_p + \frac{7}{2}^+[633]_n\}$. Since the former configuration is characterized by a larger share of the orbital angular momentum residing with the proton state, that configuration is expected to exhibit a larger moment. The magnetic moment of such a two-particle configuration may be computed according to the relationship

$$\mu = \frac{I}{I+1}\left[g_{s_p}\langle s_z\rangle_p + g_{s_n}\langle s_z\rangle_n + g_{l_p}\langle l_z\rangle_p + g_R\right], \qquad (4)$$

where s and l refer, respectively, to the spin and orbital angular momenta of the particle. For the above configuration, using $\eta = 5.5$ and $g_S = 0.6(g_S)_{\text{free}}$, we obtain $\mu = +2.70\mu_N$ for the $\{\frac{7}{2}^+p,\ \frac{1}{2}^-n\}$ configuration, and $\mu = -0.10\mu_N$ for the $\{\frac{1}{2}^-p,\ \frac{7}{2}^+n\}$ configuration. While the measured value is in much better agreement with the former than with the latter value, the difference between the measured and calculated values can be interpreted as arising from an admixture of the order of 10% of $\{\frac{1}{2}^-p,\ \frac{7}{2}^+n\}$ into the predominately $\{\frac{7}{2}^+p,\ \frac{1}{2}^-n\}$ state.

B. Mixing ratios

1. ^{171}Yb

For the $E2/M1$ mixing ratios of the ^{171}Yb intraband transitions shown in Table VI, the results of the present work are in agreement with the conversion coefficient results only within about 2 standard deviations. We believe this to be a result of the difficulty in analyzing the low energy region of our spectra to extract the anisotropies (see Fig. 3). For these transitions the present work indicates unambiguously the sign of δ, while the more reliable value for the magnitude is probably that deduced from the conversion coefficients. We note that the negative phase of the 86- and 109-keV transitions agrees with our previous work for the corresponding transitions in ^{173}Yb.

In Table XI we compare the presently measured interband $\frac{7}{2}^-[514] \to \frac{5}{2}^-[512]$ ^{171}Yb transitions with those of ^{173}Yb measured previously.[2] Since the mixing ratio contains an intrinsic dependence on the transition energy, we have tabulated δ/E_γ(MeV) in order to facilitate the comparison. The magnitudes and phases agree remarkably well, indicating that Coriolis mixing of the same levels and of the same amplitude may be invoked in both nuclei to explain the deviations of these Λ-forbidden transitions from the predictions of the Alaga rules (viz., a uniform relative phase and relative magnitudes which are in disagreement with the experimental results).

Since the experimental data involved in the Coriolis calculation are nearly identical to those of our previous work, the calculations need not be repeated here; details may be found in Ref. 2. We summarize by stating that a Coriolis matrix element $A_- \approx 0.1$, which gives the amplitude of mixing of the $\frac{5}{2}^-[523]$ Nilsson state into the $\frac{7}{2}^-[514]$ state, is sufficient to yield excellent agreement between the experimental and calculated magnitudes *and* phases of the mixing ratios.

The two $E2/M1$ transitions from the $\frac{9}{2}^+[624]$ level to the levels of the $\frac{7}{2}^+[633]$ band have both $E2$ and $M1$ components permitted by the selection rules based on the Nilsson assignments. These transitions are thus of predominately $M1$ multipolarity, as opposed to the dominant $E2$ multipolarity of those considered above. By way of comparison, mixing ratios of similar transitions have been measured in ^{177}Hf by West, Mann, and Nagle,[36] who obtained $\delta = +0.22 \pm 0.02$ for the 425-keV, $\frac{7}{2}^+ \frac{7}{2}[633] \to \frac{9}{2}^+ \frac{9}{2}[624]$ transition, and $\delta = +0.9^{+0.2}_{-0.1}$ for the 527-keV, $\frac{9}{2}^+ \frac{7}{2}[633] \to \frac{9}{2}^+ \frac{9}{2}[624]$ transition. (We have reanalyzed the angular correlation results of West *et al.* using the present phase convention and more recent values of the 208-keV $M2/E1$ mixing ratio.[1]) Since all four transitions involve the same Nilsson states, their mixing ratios can be reduced to ratios of intrinsic $E2$ and $M1$ matrix elements by the use of the appropriate Clebsch-Gordan coefficients. The mixing ratio δ may be expressed as follows:

$$\delta = 0.835\ E_\gamma(\text{MeV}) \frac{\langle I_f K_f \| M(E2) \| I_i K_i\rangle}{\langle I_f K_f \| M(M1) \| I_i K_i\rangle}$$

$$= 0.835\ E_\gamma(\text{MeV}) \times \frac{\langle I_i K_i 2(K_f - K_i) | I_f K_f\rangle \langle K_f | M'(E2) | K_i\rangle}{\langle I_i K_i 1(K_f - K_i) | I_f K_f\rangle \langle K_f | M'(M1) | K_i\rangle}, \qquad (5)$$

where we have followed the notation of Nathan and Nilsson.[37] The ratio of intrinsic matrix elements of M' we will refer to as δ'. Then from the transitions connecting the intrinsic states directly we obtain

δ'(425 keV, ^{177}Hf) = -0.77 ± 0.08,

δ'(840 keV, ^{171}Yb) = $-0.91^{+0.19}_{-0.12}$,

indicating quite good agreement. (We have changed the sign of the ^{177}Hf mixing ratios to account for the interchange of initial and final states.) For the transitions involving the first rotational state of the [633] band, we obtain

δ'(527 keV, ^{177}Hf) = $-1.4^{+0.4}_{-0.2}$,

δ'(767 keV, ^{171}Yb) = -0.53 ± 0.12.

Here the agreement is not good. The discrepancy may arise from configuration mixing, and it is interesting to note that the Coriolis matrix element connecting the $\frac{9}{2}^+$[624] and $\frac{7}{2}^+$[633] intrinsic states is quite large,[38] and thus the $\frac{9}{2}^+\frac{7}{2}$[633] state may contain an admixture associated with the $\frac{9}{2}^+\frac{9}{2}$[624] configuration. (This mixing, of course, does not affect the $\frac{7}{2}^+\frac{7}{2}$[633] state.) The admixture is expected to be twice as large in ^{177}Hf as in ^{171}Yb, owing to the factor of 2 difference in the energy separation of the intrinsic states. Moreover, as the sign of the energy difference changes between ^{177}Hf and ^{171}Yb, the mixing is expected to give rise to effects of opposite signs. These expectations are in qualitative agreement with the observed differences in the δ' values.

2. ^{172}*Yb*

In Table XII is shown a comparison of certain of the presently measured ^{172}Yb $E2/M1$ mixing ratios with those measured in previous work. In general the agreement is reasonably good, in view of the various techniques represented. Moreover, the assumptions made in the present work in calculating the U_2 values associated with the ^{172}Lu decay are vindicated by the good agreement obtained, particularly for the 901-, 912-, and 1094-keV transitions. Although there appears to be a discrepancy in sign in the case of the 1003-keV transition, all measured values overlap for infinitely large values of δ. What appears to be a serious discrepancy in the case of the 1584-keV transition may be resolved if, instead of the value -0.074, one selects the larger root of δ from the angular correlation work,[14] namely $+11\pm2$. The internal conversion data[11,27] suggest $E2$ multipolarity, in agreement with this choice. The small discrepancy between the results for the 1387-keV transition may in fact be due to the influence of the 1387-keV transition from the 1927-keV 5^+ level to the 540-keV 6^+ level. The intensity of the latter transition is estimated[11] to be ~5% that of the 2^+-2^+ 1387-keV transition.

The transitions from the $K=3$ band built on the 1172-keV level present an interesting and unusual problem for analysis, since the K assignments forbid both the $M1$ and $E2$ transition multipoles. In order to explain the observed mixing ratios (which suggest 10% $M1$ and 20% $M1$ for the 1094- and 912-keV transitions, respectively), some sort of band-mixing must be invoked. The lowest order admixture permitting both $E2$ and $M1$ transitons would be a $K=2$ component in the ground-state band. This type of band-mixing analysis has been done frequently and with reasonable success to explain the deviation of the $B(E2)$ values of γ-band to ground-state-band transitions from the predictions of the rotational model. (In such an analysis of the ^{172}Yb transitions from the $K=3$ band to the $K=0$ band, the computed $E2/M1$ mixing ratios would be independent of the band mixing amplitude, since the $E2$ and $M1$ components would be proportional to the same mixing parameter.) For the case of the 912-, 1003-, and 1094-keV transitions, this type of analysis would predict $E2/M1$ mixing ratios with relative magnitudes 2.7/1.3/1.0, respectively, and with uniform phases. The magnitudes so predicted are not in agreement with those observed, and this type of analysis is not capable of predicting what is apparently a sort of "resonance" behavior of the 1003-keV mixing ratio. Such behavior depends on the vanishing of the $M1$ term, and therefore probably involves mixing in both initial and final states, which would give rise to two contributions to the $M1$ matrix element.

More detailed attempts at a band-mixing analysis of these transitions have been done by Belt *et al.*,[25] who considered various parametrizations of the mixing in the $K^\pi=3^+$ band. In both the Bohr-Mottelson and Mikhailov calculations, the amount of mixing in the 4^+ state of the $K^\pi=3^+$ rotational band necessary to obtain agreement with the observed transition probabilities differed appreciably from that needed for the 3^+ and 5^+ levels. Moreover, an apparently anomalous cross section for the 4^+ state was noted in the inelastic deuteron scattering studies of Burke and Elbek.[22] It thus appears that a complete interpretation of the $K^\pi=3^+$ band may involve the mixing of many states, and may even include collective contributions.

For most of the K-allowed $E2+M1$ transitions, the results of the present work serve to establish a small upper limit ($\leq$ a few per cent) on the $E2$ components, in agreement with the K assignments. However, the relative magnitudes and phases are again suggestive of K mixing. As an example, we consider the transitions from states of the $K^\pi=4^+$ band based at 2073 keV to states of the $K^\pi=3^+$ band at 1172 keV. For unique K assignments, the ratios of the reduced matrix elements of the $E2$ and $M1$ operators should be proportional to ratios of Cleb-

TABLE XII. Comparison of experimental $E2/M1$ mixing ratios of ^{172}Yb γ rays.

E_γ (keV)	$\delta(E2/M1)$ Present work	Previous work Günther *et al.* (Ref. 15)	Previous work Vukanović *et al.* (Ref. 18)	Others
810	-0.026 ± 0.024	$-0.25^{+0.50}_{-0.13}$	$+0.12 \pm 0.13$	$0.00^{+0.13}_{-0.17}$ [a]
901	$+0.066 \pm 0.005$	$+0.066 \pm 0.011$		$+0.056 \pm 0.015$ [b]; $+0.049 \pm 0.038$ [c]
912	-1.9 ± 0.1	$-(1.2^{+0.7}_{-0.4})$	-1.7 ± 0.2	
1003	$+50^{+\infty}_{-29}$	$-(17^{+\infty}_{-9})$	$>+13, <-13$	
1095	-3.2 ± 0.2	-3.7 ± 0.3	-3.3 ± 0.4	-3.15 ± 0.15 [d]; -3.64 ± 0.15 [a]
1387	$-(2.4^{+0.8}_{-1.5})$			$-(9.3^{+5.0}_{-2.5})$ [e]
1470	$-(7.6^{+1.4}_{-1.0})$			$-(5.6^{+3.0}_{-2.0})$ [e]
1584	$+18 \pm 13$			-0.074 ± 0.020 [c]
1915	-0.34 ± 0.03			-0.10 ± 0.01 [b]

[a] Wagner and Lange, Ref. 20.
[b] Begzhanov *et al.*, Ref. 21.
[c] Stautberg, Shera, and Casper, Ref. 14.
[d] Blumberg *et al.*, Ref. 17.
[e] Lange, Ref. 19.

sch-Gordan coefficients. In Table XIII we compare the measured $E2/M1$ mixing ratios with ratios of the Clebsch-Gordan coefficients $\langle I_i K_i L (K_f - K_i) | I_f K_f \rangle$ for $K_i = 4$, $K_f = 3$, and $L = 1$ or 2 (for $M1$ and $E2$, respectively). (The Clebsch-Gordan coefficient ratios should, in reality, be compared with δ/E_γ, but this introduces only a minor correction.) It is apparent that the relative variations of the observed values of δ are not reproduced well by the predicted ratios; in particular, the phases should have uniform values, in disagreement with those observed. This suggests that a complete interpretation of the $E2/M1$ mixing ratios requires mixing of various intrinsic states. We note that similar conclusions regarding the $K_i^\pi = 4^+$ to $K_f^\pi = 3^+$ transitions were deduced by Sen and Zganjar[11] based on the ratios of reduced transition probabilities.

It is of interest to note that the transitions connecting the states of the $K^\pi = 4^+$ band with those of the $K^\pi = 3^+$ band have, with possibly one exception, $E2$ components of at most 1%. The $K^\pi = 3^+$ state at 1172 keV has generally been interpreted[39] as a two-neutron state with the configuration $\{\frac{5}{2}^+[512]_n + \frac{1}{2}^+[521]_n\}$. The 2073-keV state is identified[39] with the two-proton state $\{\frac{7}{2}^+[404]_p + \frac{1}{2}^+[411]_p\}$. The coupling of the intrinsic states and rotational excitations of these two configurations by means of $M1$ transitions is strongly suggestive of mixing of the two configurations. (Such mixing of two-proton and two-neutron configurations has been observed in other nuclei in this mass region.[40]) The mixing, in fact, most likely involves an admixture of the $\Sigma = 0$ counterpart of the 2073-keV level configuration, the $K^\pi = 3^+$ two-proton state $\{\frac{7}{2}^+[404]_p - \frac{1}{2}^+[411]_p\}$ (which may be identified with the 1663-keV level), with the $K^\pi = 3^+$ two-neutron configuration in the 1172-keV state. In this way, the $K^\pi = 4^+$ to $K^\pi = 3^+$ transitions can proceed by merely flipping the spin of the $\frac{1}{2}^+[411]$ proton, and thus the $M1$ nature of the transition is justified. We note in addition that the

TABLE XIII. $E2/M1$ mixing ratios of $K^\pi = 4^+$ to $K^\pi = 3^+$ transitions in ^{172}Yb.

I_i ($K_i = 4^+$)	I_f ($K_f = 3^+$)	E_γ (keV)	δ	$\frac{\langle I_i\, 4\, 2\, {-1} \mid I_f\, 3\rangle}{\langle I_i\, 4\, 1\, {-1} \mid I_f\, 3\rangle}$
4	3	901	$+0.066 \pm 0.005$	0.774
	4	810	-0.026 ± 0.024	1.383
	5	697	-0.012 ± 0.007	2.450
5	4	929	-0.070 ± 0.009	0.408
	5	816	$+0.35 \pm 0.25$	1.120
	6	682	$+0.09 \pm 0.05$	2.197

observed g factor of the 1172-keV level is also indicative of an impurity in the level. The measured value of the g factor is $+0.21 \pm 0.01$,[15,20] while the theoretical value corresponding to the two-neutron configuration would be -0.04. According to the transfer-reaction data of Burke and Elbek,[22] the two-neutron configuration accounts for only 75% of the 1172-keV state. If the other 25% were the $K^{\pi} = 3^+$ two-proton configuration ($g \approx +1$), the expected g factor would agree quite well with the measured value. Thus the assumptions of mixing of two-neutron and two-proton configurations in the 1172-keV level is consistent with the observed static moment and the multipole characters of the populating transitions.

Considering the transitions from the $K^{\pi} = 3^{+\prime}$ ($E = 1663$ keV) to the $K^{\pi} = 3^+$ band, we note that again the $E2$ admixtures are observed to be relatively small, at least as compared with the transitions in which the $M1$ component is K forbidden. Based on transfer-reaction studies, the 3^+ band has been interpreted as arising from coupling of the $\frac{5}{2}^-[512]$ and $\frac{1}{2}^-[521]$ Nilsson states, while the $3^{+\prime}$ band has been interpreted as the $\frac{11}{2}^-[505] - \frac{5}{2}^-[512]$ configuration. Therefore, transitions between these bands would correspond to $\frac{11}{2}^-[505] \to \frac{1}{2}^-[512]$ neutron transitions. Such transitions ought to be highly forbidden, and based on systematics one should find the $E2$ mode to be dominant. As no such case is observed, this suggests either that the assignments are incorrect or that the states contain large admixtures of other configurations.

VI. SUMMARY

As a continuation of earlier work on the nuclear structure information deduced from γ-ray angular distributions following the decays of ^{173}Lu, ^{174}Lu^{m,g}, and ^{177}Lu^{m,g}, we have measured the anisotropies of γ-ray angular distributions following the decays of ^{171}Lu and ^{172}Lu. The nuclear magnetic dipole moments of ^{171,172}Lu have been deduced and compared with expectations based on the Nilsson model. The $E2/M1$ mixing ratios of transitions in ^{171}Yb were compared to transitions connecting the same Nilsson states in ^{173}Yb and ^{177}Hf, and the deviations of the ^{171}Yb mixing ratios from expectations based on the Alaga rules and from the corresponding transitions in ^{177}Hf were shown to be consistent with an interpretation in terms of Coriolis mixing of the various Nilsson states. The ^{172}Yb $E2/M1$ mixing ratios also suggest the necessity of invoking mixing of intrinsic states to explain the relative magnitudes and phases of the mixing ratios of the transitions connecting the various bands.

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[1]K. S. Krane, C. E. Olsen, and W. A. Steyert, Phys. Rev. C 10, 825 (1974).

[2]K. S. Krane, C. E. Olsen, S. S. Rosenblum, and W. A. Steyert, Phys. Rev. C 12, 1999 (1975).

[3]N. A. Bonch-Osmolovskaya, Ts. Vylov, K. Ya. Gromov, and A. Sh. Khaminov, Izv. Akad. Nauk. SSSR Ser. Fiz. 38, 2516 (1974) [Bull. Acad. Sci. USSR Phys. Ser. 38, 45 (1974)].

[4]G. Kaye, Nucl. Phys. 86, 241 (1966).

[5]D. Barneoud, J. Boutet, J. Gizon, and J. Valentin, Nucl. Phys. A138, 33 (1969).

[6]V. A. Balalaev, B. S. Dzhelepov, I. F. Vchevatkin, and S. A. Shestopalova, Izv. Akad. Nauk. SSSR Ser. Fiz. 35, 18 (1971) [Bull. Acad. Sci. USSR Phys. Ser. 35, 16 (1971)].

[7]D. G. Burke, B. Zeidman, B. Elbek, B. Herskind, and M. Olesen, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 35, No. 2 (1966).

[8]D. G. Burke, W. P. Alford, and R. A. O'Neil, Nucl. Phys. A161, 129 (1971).

[9]T. Lindblad, H. Ryde, and D. Barneoud, Nucl. Phys. A193, 155 (1972).

[10]D. J. Horen and B. Harmatz, Nucl. Data Sheets 11, 549 (1974).

[11]D. Sen and E. F. Zganjar, Nucl. Phys. A148, 634 (1970).

[12]V. A. Balalaev, B. S. Dzhelepov, A. I. Medvedev, V. E. Ter-Nersesyants, I. F.Uchevatkin, and S. A. Shestopalova, Izv. Akad. Nauk USSR Ser. Fiz. 38, 681 (1974) [Bull. Acad. Sci. SSSR Phys. Ser. 38, 14 (1974)].

[13]G. Kaye, Nucl. Phys. A108, 625 (1968).

[14]M. M. Stautberg, E. B. Shera, and K. J. Casper, Phys. Rev. 130, 1901 (1963).

[15]C. Günther, H. Blumberg, W. Engels, G. Strube, J. Voss, R.-M. Lieder, H. Luig, and E. Bodenstedt, Nucl. Phys. 61, 65 (1965).

[16]P. Kleinheinz, R. Vukanović, M. Zupancić, L. Samuelsson, and H. Lindström, Nucl. Phys. A91, 329 (1967).

[17]H. Blumberg, K.-H. Speidel, H. Schlenz, P. Weigt, H. Hübel, P. Göttel, H.-F. Wagner, and E. Bodenstedt, Nucl. Phys. A90, 65 (1967).

[18]R. Vukanović, M. Zupancić, H. Å. Lindström, and L. Samuelsson, Ark. Fys. 39, 113 (1969).

[19]J. Lange, in *Angular Correlations in Nuclear Disintegration*, edited by H. van Krugten and B. van Nooijen (Groningen, Rotterdam U.P., 1971), p. 242.

[20]H. F. Wagner and J. Lange, Z. Phys. 242, 292 (1971).

[21]R. B. Begzhanov, A. I. Muminov, N. A. Il'khamdzhanov, U. I. Iuldashev, and A. T. Salikbaev, Izv. Akad. Nauk. Uzb. SSSR, Tashkent Doklady 29, 32 (1972).

[22]D. G. Burke and B. Elbek, K. Dan Vidensk. Selsk. Mat.—Fys. Medd. 36, No. 6 (1967).

[23]R. A. O'Neil and D. G. Burke, Nucl. Phys. A182, 342 (1972).

[24]Z. Moroz, J. Jastrzebski, Z. Preibisz, K. Stryczniewicz, P. Paris, and J. Trêherne, Acta Phys. Pol. 36, 203 (1969).

[25]R. A. Belt, H. W. Kugel, J. M. Jaklevic, and E. G. Funk, Nucl. Phys. A134, 225 (1969).
[26]C. W. Reich, R. C. Greenwood, and R. A. Lokken, Nucl. Phys. A228, 365 (1974).
[27]L. R. Greenwood, Nucl. Data Sheets 15, 497 (1975).
[28]K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).
[29]K. S. Krane, Los Alamos Scientific Laboratory Report No. LA-4677-MS, 1971 (unpublished).
[30]G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, K. Dan Vidensk. Selsk. Mat.—Fys. Medd. 29, No. 9 (1955).
[31]V. S. Shirley and C. M. Lederer, in *Proceedings of the International Conference on Hyperfine Interactions Studied in Nuclear Reactions and Decay, Uppsala, Sweden 1974*, edited by E. Karlsson and R. Wäppling (Upplands Grafiska AB, Uppsala, 1974).
[32]B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 123, 1758 (1961).
[33]G. Alenius, S. E. Arnell, C. Schale, and E. Wallander, Phys. Scr. 3, 55 (1971).
[34]O. Prior, F. Boehm, and S. G. Nilsson, Nucl. Phys. A110, 257 (1968).
[35]Z. Bochnacki and S. Ogaza, Nucl. Phys. 69, 186 (1965).
[36]H. I. West, L. G. Mann, and R. J. Nagle, Phys. Rev. 124, 527 (1961).
[37]O. Nathan and S. G. Nilsson, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 601.
[38]M. E. Bunker and C. W. Reich, Rev. Mod. Phys. 43, 348 (1971).
[39]C. J. Gallagher and V. G. Soloviev, K. Dan. Vidensk. Selsk. Mat.—Fys. Skr. 2, No. 2 (1962).
[40]See, for example, T. L. Khoo, J. C. Waddington, R. A. O'Neil, Z. Preibisz, D. G. Burke, and M. W. Johns, Phys. Rev. Lett. 28, 1717 (1972).