Gamma-ray angular distributions and parity tests in the decays of polarized ^{173}Lu and ^{174}Lu^{m,g}†

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Angular distributions of 18 γ rays have been measured following the decays of ^{173}Lu and ^{174}Lu^{m,g} polarized at low temperatures in the ferromagnetic cubic Laves-phase metal $ZrFe_2$. The magnetic moments of the oriented parent states are deduced to be $|\mu(^{173}\mathrm{Lu})| = (2.34 \pm 0.09)\mu_N$, $|\mu(^{174}\mathrm{Lu}^g)| = (1.94 \pm 0.28)\mu_N$, and $|\mu(^{174}\mathrm{Lu}^m)| = (2.34 \pm 0.33)\mu_N$. The spin of the 1518-keV level of ^{174}Yb is shown unambiguously to be 6. Multipole mixing ratios are deduced for a number of ^{173}Yb and ^{174}Yb γ rays, and several interband $E2/M1$ mixing ratios are compared with values deduced from a Coriolis mixing calculation. The 0°–180° asymmetries of the angular distributions of some of the strongly hindered ^{174}Yb transitions have been observed in a search for the presence of parity mixing effects; no such effects were seen. A possible empirical correlation between γ-ray hindrance and the magnitude of parity-violating effects is pointed out.

RADIOACTIVITY ^{173}Lu, ^{174}Lu^m, ^{174}Lu^g; measured $\gamma(\theta)$ from polarized nuclei; deduced magnetic moment μ, γ-ray multipole mixing ratios, $\delta(E2/M1)$, $\delta(M2/E1)$, $\delta(E3/E1)$, g_K, g_R, J, Coriolis mixing, no observable parity violation.

I. INTRODUCTION

The predicted parity-violating weak component of the nucleon-nucleon interaction has been tested in recent years with great accuracy and with varying degrees of success. The theoretical basis for such studies and a summary of experimental results to date have been given in the recent review article by Gari.[1] In heavy nuclei, these tests have consisted primarily of radioactive decay studies of two types: the forward-backward angular distribution asymmetry of γ rays from polarized nuclei and the circular polarization of γ rays from unoriented nuclei. The choice of a particular nucleus for investigation is dictated, in part, by a number of constraints which are independent of nuclear structure considerations, such as the ease of polarization or the γ-ray branching intensities. However, one common characteristic of most of the studies in heavy nuclei has been the selection of γ-ray transitions whose emission probabilities are strongly retarded relative to standard estimates. Here, the underlying assumption is that the retardation of the "regular" component will not similarly affect the parity-violating "irregular" component; this leads to a relative enhancement of the irregular component. This assumption is not yet directly supported by theoretical calculations (which have been unsuccessful owing to the lack of information on the form of the parity-violating internucleon potential and to the complexity of the nuclear structure considerations in heavy nuclei); however, from a purely pragmatic viewpoint, reasonable success has been obtained by choosing retarded transitions for investigation, indicating at least an indirect relationship between the γ-ray hindrance and the presence of enhanced parity-violating effects.

An indication of the nature of this relationship is given in Fig. 1, in which we show some selected results[2] of studies of parity violation in heavy nuclei. The abscissa shows the hindrance (H_W) of the lowest regular multipole order of the γ radiation relative to Weisskopf estimates. (The regular matrix elements are reduced as the square root of H_W.) The ordinate shows the ratio ϵ of the irregular-to-regular γ-ray matrix elements of the same (lowest) multipole order, assuming that the parity-violating effect involves only interference of like multipoles (for example $E1$ and $M1$) rather than different multipoles ($E1$ and $E2$). The data shown in Fig. 1 are consistent with an approximately linear relationship on the log-log plot with a slope of the order of $\frac{1}{4}$; that is, a change in H_W of four orders of magnitude gives rise to a change in ϵ of one order of magnitude.

We note also that for an unhindered transition, we would expect ϵ of the order of the relative amplitude F of the parity-violating weak Hamiltonian, which is generally taken as $F\sim 10^{-7}$ to 10^{-6}, a value consistent with Fig. 1.

The 992-keV γ ray of ^{174}Yb (see Fig. 2) is emitted from a level having a half-life of the order of 10^{-3} s, and must therefore be strongly hindered. There is, however, some uncertainty regarding the spin-parity assignment of the level; previous data are consistent with either 6^+ of 7^- assignments, with either $M1+E2$ or $E1+M2+E3$ multipolarity, respectively, for the 992-keV transition.[3] The respective hindrances of the lowest multipolarity for these two possibilities are $H_W(M1)=10^{11}$ and $H_W(E1)=0.5\times 10^{13}$. Based on the relationship illustrated in Fig. 1, we might therefore expect an observable parity-violating component in this transition. In particular if the 7^- assignment were correct, an ϵ of 10^{-2} might result.

We have therefore undertaken a study of the decay of oriented ^{174}Lu^m, which populated the ^{174}Yb level in question, in order to confirm this spin assignment and to determine the asymmetry of the angular distribution of the 992-keV γ transition. The feasibility of polarizing Lu dissolved into a ferromagnetic environment at low temperature has been demonstrated in a previous publication.[4] From an analysis of the γ rays of ^{174}Lu^g and ^{173}Lu, which were also present in our samples, the magnetic moments of all the parent states were obtained and multipole mixing ratios for many of the ^{173,174}Yb γ rays were deduced. Similar nuclear structure studies of the γ rays emitted by ^{171,172}Lu will be discussed in a subsequent report.[5]

II. DECAY SCHEMES

The decays of ^{174}Lu^{g,m} and ^{173}Lu are illustrated in Figs. 2 and 3. γ-ray energies and intensities in the decays of the ^{174}Lu have been previously measured by Kantele, Liukkonen, and Sarmanto,[6] and further information on the branching intensities of γ rays in ^{174}Yb may be obtained from a similar study of the ^{174}Tm decay,[7] which populates the same ^{174}Yb levels as do some of the ^{174}Lu^{g,m} decays. The multipolarities of transitions in ^{174}Lu populated by the isomeric ^{174}Lu^m decay were determined by conversion coefficient studies done by Gizon and Godart[8] and by Kartashov *et al.*[9] Angular correlation studies of the ^{174}Yb γ rays have been done by Schmidt, Mihelich, and Funk[3] as well as by Prask *et al.*[10] and Gidefeldt *et al.*[11] A compilation of data relating to the ^{174}Lu^{g,m} decays has recently been given in Nuclear Data Sheets.[12]

The γ-ray spectrum from the ^{173}Lu decay has been studied by Kurcewicz *et al.*,[13] and γ-ray

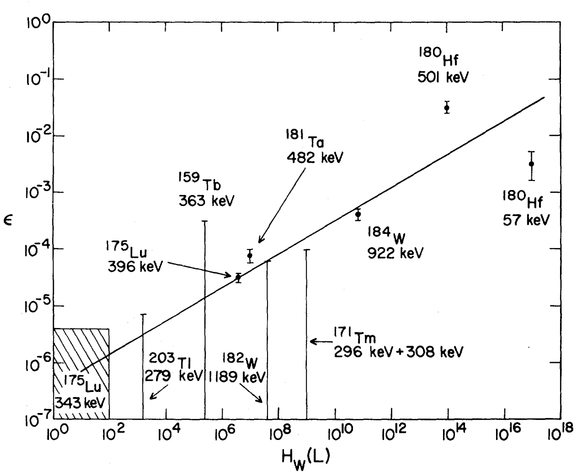

FIG. 1. The qualitative relationship between the lowest-order irregular-to-regular multipole mixing ratio $\epsilon=\langle \bar{\pi}'L\rangle/\langle \pi L\rangle$ and the hindrance H_W of the πL regular multipole relative to Weisskopf estimates. The solid line indicates the general trend of the data and has a (log-log) slope of approximately $\frac{1}{4}$. Data represented are derived from numerous studies (Ref. 2) and include results from γ-ray asymmetry experiments using polarized nuclei (^{159}Tb, ^{171}Tm, ^{180}Hf, ^{184}W) as well as circular polarization studies (^{159}Tb, ^{171}Tm, ^{175}Lu, ^{180}Hf, ^{181}Ta, ^{182}W, ^{203}Tl).

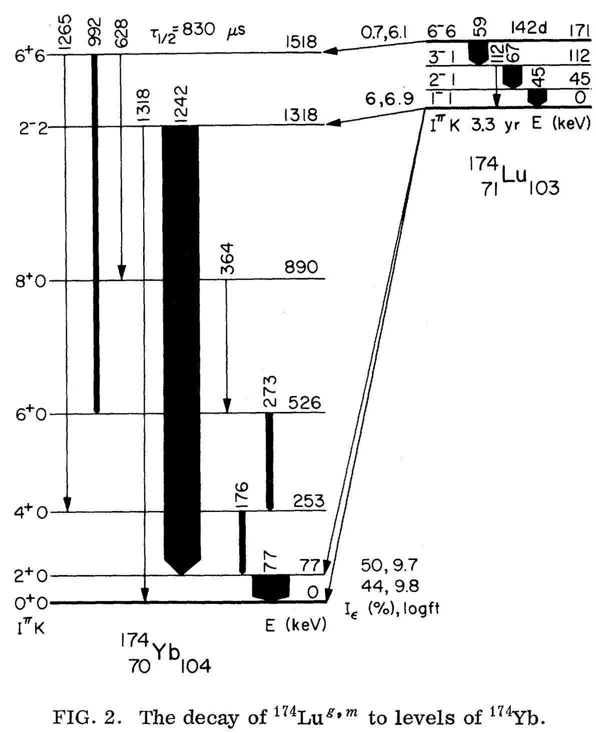

FIG. 2. The decay of ^{174}Lu^{g,m} to levels of ^{174}Yb.

multipolarities may be deduced from internal conversion intensities measured by Kartashov *et et al.*[14] Previous γ-ray angular distribution studies include determination of the $E2/M1$ mixing ratios of γ rays from Coulomb-excited levels of the ground-state rotational band by Ashery, Blaugrund, and Kalish[15] and γ-γ and e-γ angular correlation studies of the 272-79-keV cascade by Hornshoj and Deutsch.[16] References to other experiments may be found in the recent compilation in Nuclear Data Sheets.[17]

The spin-parity assignment of the ^{174}Yb level at 1518 keV has not previously been unambiguously determined. Considerations based on pairing calculations lead one to expect states of spin 6^+ or 7^- at this energy. Studies of the decays of ^{174}Tm and ^{174}Lu^m have been interpreted as providing indirect evidence in support of either assignment. Preliminary evidence for the 7^- assignment was based on the failure to observe the 1265-keV γ transition.[18,19] Later studies[6,7] of the decays showed this 1265-keV transition which tended to favor the 6^+ assignment. (It should be noted that the difficulty in correctly identifying the 1265-keV peak results from the additional presence of 992 + 273 keV coincidence summing.) Data derived from (d,p) reactions were shown to be consistent with either spin-parity assignment.[20] Angular correlation measurements of the 992-273-keV cascade are inconsistent with the 7^- assignment if $E1+M2$ multipolarity is assumed for the 992-keV transition.[11] However, as was shown by Schmidt, Mihelich, and Funk,[3] the angular correlation data are consistent with $E1+M2+E3$ multipolarity and thus with a 7^- assignment. Model-dependent consideration of the γ-ray hindrance per degree of K forbiddeness favors the 6^+ assignment over the 7^-. In summary, although a preference for the 6^+ assignment is indicated by the various experimental

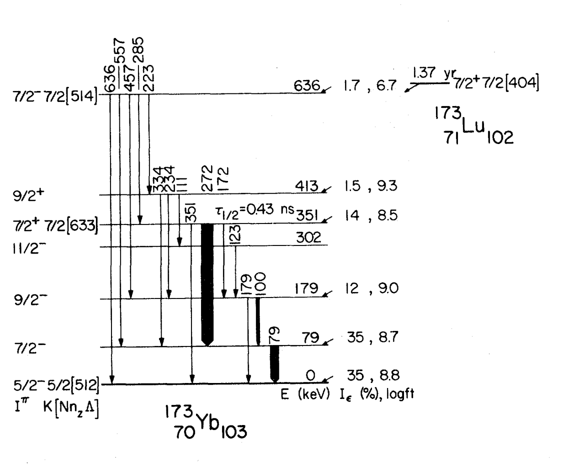

FIG. 3. The decay of ^{173}Lu to ^{173}Yb.

results, in no case has it been possible to exclude completely the possibility of a 7^- assignment. The present results, however, when combined with the previous angular correlation results, lead to a unique 6^+ assignment.

III. EXPERIMENTAL DETAILS

A. Sample preparation

As in our previous work,[4] samples were prepared by introducing the Lu isotopes as impurities in the cubic ferromagnet $ZrFe_2$, where they substitute for the Zr. The Lu activity was prepared by bombarding a natural Yb foil with 15-MeV deuterons at the Lawrence Berkeley Laboratory 88-inch cyclotron. After the short-lived activities had decayed for several months, the foil, along with a small amount of Lu metal carrier, was arc melted with iron in an argon atmosphere. Next this iron-lutetium alloy was arc melted with Zr to form $(Zr_{0.96}Lu_{0.04})Fe_2$, which was subsequently annealed at 900°C in vacuum. The Yb is volatile and insoluble in $ZrFe_2$ and thus evaporates away during the melting, so only the Lu remains in the $ZrFe_2$. This was confirmed by neutron activation analysis of the alloys. The sample used in the 4-mK measurement was neutron activated at the Los Alamos Omega West reactor to produce ^{177}Lu^g which acted as a thermometer isotope; because of the known decay and moment of ^{177}Lu^g it provides an accurate value of H/T (H is the hyperfine field at a Lu nucleus, T is the temperature). This sample was large, being a somewhat flattened 0.7-cm sphere, with its flattened side soldered with indium to the cold finger.

B. Apparatus

For the 20-mK measurements the sample was mounted on a cold finger attached directly to a ^{3}He-^{4}He dilution refrigerator. For the measurements at 4 mK the sample was attached to a gold-cerium magnesium nitrate adiabatic demagnetization stage.[21] The ferromagnetic sample, lying in the horizontal plane, was polarized using two pairs of superconducting Helmholtz coils perpendicular to each other. Except in the case of the parity studies, each pair had its axis in the horizontal plane and produced $0.36T$ at the sample. A 40-cm^3 Ge(Li) detector was mounted along the axis of each of the Helmholtz pairs. (A typical γ-ray spectrum taken with these detectors is shown in Fig. 4.) Thus, as one or the other of these pairs was activated, the nuclei were polarized toward one detector and perpendicular to the other. For the parity experiment both detectors were located along the axis of one of the pairs, and the polarization was rotated by 180° between each counting period so that a given detector was alternately at 0° and 180° with respect to the nuclear polarization direction.[4]

C. Data analysis

The γ-ray counting rates at 0° and 90° relative to the alignment axis were analyzed according to the relationship

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

where the geometrical correction factors Q_k correct for the 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 is the nuclear magnetic dipole moment, H is the hyperfine field, I is the nuclear spin, k_B is the Boltzmann constant) and on the temperature T, the deorientation coefficients U_k correct 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.

For parity-conserving radiation, only even values of k are permitted in Eq. (1), and for such radiations

$$A_k = \frac{F_k(LLI_fI_i) + 2\delta F_k(LL'I_fI_i) + \delta^2 F_k(L'L'I_fI_i)}{1+\delta^2}\,, \qquad (2)$$

where the γ-ray mixing ratio δ is given in the phase convention of Krane and Steffen.[22]

The 0°-180° asymmetry characteristic of parity mixing is defined by

$$A = \frac{W(0°) - W(180°)}{W(0°) + W(180°)} = \frac{Q_1B_1U_1A_1 + Q_3B_3U_3A_3}{1 + Q_2B_2U_2A_2 + Q_4B_4U_4A_4}\,. \qquad (3)$$

For the present work, we obtain for the 992-keV γ ray at $T = 20$ mK

$$A(992) = 0.67\epsilon\,, \qquad (4)$$

where ϵ is the amplitude mixing ratio of the lowest irregular and regular multipoles ($\tilde{E}1/M1$ in this case). Similarly, for the 1242-keV γ ray

$$A(1242) = 0.19\epsilon\,, \qquad (5)$$

where now $\epsilon = \tilde{M}1/E1$.

IV. RESULTS AND DISCUSSION

A. γ-ray anisotropies

In Table I are shown the anisotropies of the angular distributions of the γ rays following the ^{173}Lu and ^{174}Lu^{m,g} decays. (The designations $T = 20$ mK and $T = 4$ mK indicate only a convenient label for distinguishing data obtained without the demagnetization stage from data obtained with it. These temperatures represent the nominal value at the cold finger measured in other studies; the average

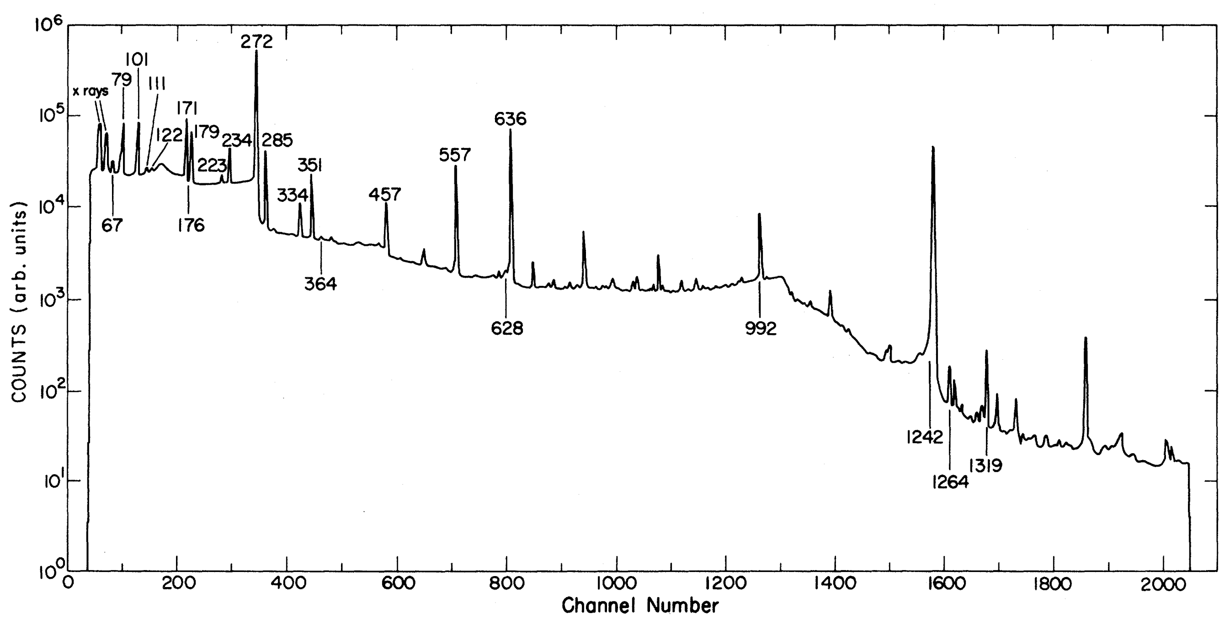

FIG. 4. γ-ray spectrum from the decays of ^{173}Lu, ^{174}Lu^{g}, and ^{174}Lu^{m}. The peaks are labeled with γ-ray energies in keV; those labeled above the spectrum correspond to the ^{173}Lu decay, and those labeled below the spectrum to the ^{174}Lu decays.

sample temperature as determined by the Lu impurities may be somewhat higher, owing to inhomogeneities and poor thermal conduction in the sample.) The 20-mK data represent a simple average of the various individual runs, since the temperature was observed to be quite stable during the course of the measurement. The 4-mK data are those of one typical run of the nine individual runs which were taken at the low temperature; the temperature variation was such that an average could not be taken without accounting for the variation in the orientation parameters. The data have been corrected for the finite detector solid angle, and in the case of the 4-mK data, small corrections have been applied to account for the P_4 term in the angular distribution for certain of the γ rays. Except in the case of the 4-mK 992-keV anisotropy, the latter corrections amounted to no more than twice the quoted uncertainties of the tabulated results.

B. ^{173}Lu magnetic moment

The magnetic moment of the ^{173}Lu was deduced from a separate measurement in which the anisotropy of the 272-keV γ ray was compared with that of the 113-keV γ ray following the decay of 6.7-day ^{177}Lu^g. The latter decay has been the subject of a recent study.[4]

In analyzing these two γ rays, we have used the parameters U_2A_2(113 keV) $=0.337\pm0.010$, based on previous work,[4] and U_2A_2(272 keV), based on our results derived below. The angular distributions of the 113- and 272-keV γ rays then yielded orientation parameters B_2 in the range of 0.68 to 0.78 (the spread in the values results from several independent measurements representing different demagnetizations), corresponding to hyperfine splitting parameters Δ/T in the range 0.74 to 0.84. Although the values of the effective hyperfine field and of the sample temperature may be uncertain, they may be assumed to be identical for the two Lu isotopes in the identical sample, and thus the ratio of the values of Δ/T deduced from the 113- and 272-keV γ rays gives directly the ratio of the magnetic moments.

From the average of several such measurements, we obtain

$$\frac{\mu(^{173}\mathrm{Lu})}{\mu(^{177}\mathrm{Lu}^g)}=1.043\pm0.038,$$

and using the accepted ^{177}Lu^g moment ($\mu=+2.215\mu_N$),[23] it follows that

$$|\mu(^{173}\mathrm{Lu})|=(2.34\pm0.09)\mu_N\,.$$

The ^{173}Lu ground state is characterized as the $\frac{7}{2}^+[404]$ Nilsson state, which also is the ground-

TABLE I. γ-ray anisotropies from the decays of oriented ^{173}Lu and ^{174}Lu^{m,g}.

γ-ray energy (keV)	$B_2U_2A_2$ [a] (20 mK)	$B_2U_2A_2$ [a] (4 mK)	U_2A_2 [a] (20 mK)	U_2A_2 [a] (4 mK)
		^{173}Lu		
79	0.044 (1)	0.251 (4)	0.441 (15)	0.437 (12)
101	0.053 (1)	0.320 (6)	0.532 (21)	0.560 (12)
123	0.033(30)	0.314(100)	0.330(300)	0.580(185)
172	0.008 (1)	0.060 (4)	0.079 (8)	0.096 (4)
179	−0.037 (1)	−0.217 (7)	−0.374 (9) [b]	−0.374 (9) [b]
223	−0.001 (8)	0.089 (44)	−0.011 (76)	0.118 (35)
234	−0.039 (2)	−0.217 (15)	−0.392 (25)	−0.367 (12)
272	−0.027 (1)	−0.135 (1)	−0.267 (11)	−0.245 (4)
285	−0.034 (2)	−0.177 (11)	−0.336 (25)	−0.326 (10)
334	0.031 (6)	0.215 (44)	0.308 (55)	0.299 (28)
351	0.017 (2)	0.124 (15)	0.173 (23)	0.214 (12)
457	0.075 (6)	0.415 (30)	0.755 (68)	0.728 (28)
558	−0.017 (2)	−0.080 (12)	−0.173 (20)	−0.170 (10)
636	0.079 (1)	0.438 (7)	0.788 (33)	0.796 (14)
		^{174}Lu		
67	0.015 (8)	0.082 (15)		
992	0.044 (4)	0.092 (16)		
1242	−0.017 (1)	−0.044 (3)		
1318	−0.044(22)			

[a] Errors in last digit or digits indicated in parentheses.
[b] Value assumed in analysis.

state configuration of ^{175}Lu ($\mu = +2.238\mu_N$)[23] and ^{177}Lu ($\mu = +2.245\mu_N$).[23] Based on the reasonable agreement of our measured ^{173}Lu moment with these values, the sign of the ^{173}Lu moment may be assumed to be positive.

C. ^{173}Yb γ-ray anisotropies

The initial scheme for analyzing the ^{173}Yb γ rays consisted of using the 272-keV anisotropy to deduce the B_2 of the ^{173}Lu, taking the A_2 based on the 272-keV $M2/E1$ mixing ratio deduced by Hornshoj and Deutsch[16] ($0 \leq \delta \leq 0.032$) and taking the U_2 to be that of a predominantly (> 90%) Gamow-Teller type of allowed β decay, since the Nilsson selection rules seem to be systematically quite effective in inhibiting Fermi-type decays in this mass region. When the remaining angular distributions were corrected for the B_2 so deduced, it was found that the resulting values of U_2A_2 for the 179-, 456-, and 636-keV γ rays were 20–30% larger than allowed by theory. Assuming no error in the spin assignments, this indicates that U_2 or A_2 values used for the 272-keV γ ray were too large by 20–30%. For the error to be in the A_2 would require a $M2/E1$ mixing ratio of $\delta = -0.18 \pm 0.01$, which is not consistent with either the measured K-conversion coefficient[14] or with the measured γ-γ or e^--γ correlation.[16] Thus the error must lie in our assumptions regarding the U_2 value. The U_2 value may be reduced by the necessary amount by assuming a substantial (~ 50%) contribution of second-forbidden decays to the β transition, or else by an additional deorientation, introducing an attenuation parameter of 0.7–0.8, which arises from external perturbations acting on the 0.4-nsec 351-keV level. Although we favor the latter explanation, the present studies do not differentiate among any of the possible sources of deorientation of the 351-keV level, and we conclude only that the 272-keV γ ray is not a good indicator of the ^{173}Lu alignment.

In view of the above discussion, we have chosen to use the pure-$E2$ 179-keV transition. Here the β decay is of the first-forbidden type, and we assume the $L=2$ contribution to the decay (the B_{ij} term) to contribute less than 10% (5 ± 5%) of the decay intensity, in which case $U_2A_2 = -0.374 \pm 0.009$, where we have taken into account the population of the 179-keV level through the 351-keV level, including its apparent dealignment.

Using the 179-keV γ-ray anisotropy, we obtain values for the orientation parameter of the ^{173}Lu to be $B_2 = 0.100 \pm 0.004$ for the 20-mK data, and $B_2 = 0.55 \pm 0.02$ for a typical run of the 4-mK data. These orientation parameters correspond respectively to $\Delta/T = 0.215 \pm 0.005$ and $\Delta/T = 0.62 \pm 0.02$. These deduced splittings suggest that the data obtained using the demagnetization stage has an effective sample temperature only a factor of 3 lower than that obtained without the demagnetization, rather than a factor of 5 as expected. The source of this discrepancy, which may have arisen from the failure of the large low conductivity sample to achieve a uniform temperature of 4 mK, is not clear; however, the deduced γ-ray parameters are not affected.

The deduced mixing ratios of the ^{173}Yb γ rays are summarized in Table II. These values represent an average of the 20- and 4-mK results. The transitions from the 636-keV level have been analyzed by assuming the 285-keV transition to be pure $E1$, with a possible admixture of $M2$ less than 0.25% (i.e., $|\delta(M2/E1)| < 0.05$).

The $E2/M1$ mixing ratios of the 79- and 101-keV transitions in the ^{173}Yb ground-state rotational band have been measured previously by both angular correlation and conversion coefficient techniques. In a measurement of the γ-ray angular distributions following Coulomb excitation, Ashery, Blaugrund, and Kalish[15] deduced $\delta(79) = -0.161 \pm 0.022$ and $\delta(101) = -0.238 \pm 0.021$, in agreement with the present values; however, the γ-γ angular correlation results of Hornshoj and Deutsch[16] indicate $\delta(79) = -0.26 \pm 0.01$. Internal conversion data derived[17] from L-subshell ratios yield $|\delta(79)| = 0.237 \pm 0.007$ and $|\delta(101)| = 0.205 \pm 0.020$. Thus there exists an apparent small discrepancy among the various results for $\delta(79)$.

The presently measured values of the $E2/M1$ mixing ratios of the three transitions from the 636-keV level are in agreement with the values deduced[17] from the K-conversion coefficient [$|\delta(457)| = 0.65^{+0.45}_{-0.65}$, $|\delta(557)| = 2.0^{+1.6}_{-0.6}$, $|\delta(636)| = 1.1^{+0.5}_{-0.4}$]. Based on the ratio of Clebsch-Gordan coefficients (Alaga rules), we expect these three mixing ratios to be of relative magnitudes $\delta(457) : \delta(557) : \delta(636) = +3.2 : +1.8 : 1$, whereas the

TABLE II. Mixing ratios of the ^{173}Yb γ rays.

γ-ray energy (keV)	Multipolarity	δ
79	$E2/M1$	−0.161(19)
101	$E2/M1$	−0.191(11)
123	$E2/M1$	−0.17 (11)
172	$M2/E1$	$+0.008 \pm 0.005$
223	$M2/E1$	-0.003 ± 0.027
234	$M2/E1$	-0.060 ± 0.017
334	$M2/E1$	-0.012 ± 0.015
351	$M2/E1$	-0.019 ± 0.012
457	$E2/M1$	$+1.0^{+0.7}_{-0.3}$
558	$E2/M1$	$+1.84 \pm 0.10$
636	$E2/M1$	$-(0.80^{+0.50}_{-0.35})$

observed ratio is $-1.2:-2.3:1$. This discrepancy may be studied in terms of possible Coriolis mixing of the various ^{173}Yb intrinsic states. For the sake of the present calculation we will assume only the 636-keV level to be subject to Coriolis mixing, which we take to be of first order. [Although the states of the ground-state rotational band could also be considered in this type of calculation, the good agreement between the level energies of the ground-state band[17] and the prediction of the rotational $I(I+1)$ formula and between the observed and predicted reduced transition probabilities[17] suggests that such effects, if present, are small.] We therefore consider the mixing of a $K=\frac{5}{2}^-$ state into the $\frac{7}{2}^-[514]$ level. This $K=\frac{5}{2}^-$ state cannot be identified with the ground state, since then we would expect to observe corresponding admixture of $\frac{7}{2}^-[514]$ into the ground-state band. Burke, Alford, and O'Neil[24] have identified a $\frac{9}{2}^-$ state at 1168 keV which they assign to the $\frac{5}{2}^-[523]$ band. The $\frac{7}{2}^-$ state of this band would be expected some 100 keV lower in energy, and hence about 400 keV above the $\frac{7}{2}^-[514]$ level. Since no other negative parity states of $K \geq \frac{5}{2}$ have been identified in the ^{173}Yb level scheme below ~2 MeV, this state seems to be a reasonable candidate for Coriolis mixing with the $\frac{7}{2}^-[514]$. We then obtain (cf. Ref. 4)

$$\psi_i = |I_i M_i K_i\rangle - [(I_i+K_i)(I_i-K_i+1)]^{1/2} A_- |I_i M_i K_i'\rangle ,$$

$$\psi_f = |I_f M_f K_f\rangle ,$$

where $I_i=\frac{7}{2}$, $K_i=\frac{7}{2}$ (identified with the $\frac{7}{2}^-[514]$ Nilsson state), $K_i'=\frac{5}{2}$ (the $\frac{5}{2}^-[523]$ Nilsson state), $I_f=\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$, and $K_f=\frac{5}{2}$ (the $\frac{5}{2}^-[512]$ Nilsson state). The quantity A_- is a Coriolis matrix element of the form $(\hbar^2/2\mathscr{I})\langle K_i'|j_-|K_i\rangle/[E(K_i)-E(K_i')]$. The reduced multipole matrix elements may then be written as:

$$\langle I_f \| M(M1) \| I_i\rangle = \sqrt{8}\,(0.167 M_0^{(1)} + 1.647 M_1^{(1)}) , \quad (6a)$$

$$\langle I_f \| M(E2) \| I_i\rangle = \sqrt{8}\,(0.399 M_0^{(2)} + 1.626 M_1^{(2)}) \quad (6b)$$

for 457 keV;

$$\langle I_f \| M(M1) \| I_i\rangle = \sqrt{8}\,(0.471 M_0^{(1)} + 1.667 M_1^{(1)}) , \quad (6c)$$

$$\langle I_f \| M(E2) \| I_i\rangle = \sqrt{8}\,(0.632 M_0^{(2)} + 0.259 M_1^{(2)}) \quad (6d)$$

for 557 keV;

$$\langle I_f \| M(M1) \| I_i\rangle = \sqrt{8}\,(0.866 M_0^{(1)} - 1.225 M_1^{(1)}) , \quad (6e)$$

$$\langle I_f \| M(E2) \| I_i\rangle = \sqrt{8}\,(0.645 M_0^{(2)} - 1.579 M_1^{(2)}) \quad (6f)$$

for 636 keV.

The quantities $M_0^{(L)}$ represent the intrinsic transition moments of the basis states

$$M_0^{(L)} = \langle K_f | M'(L) | K_i\rangle , \quad (7)$$

while $M_1^{(L)}$ includes the intrinsic transition moment involving the admixed state

$$M_1^{(L)} = -A_- \langle K_f | M'(L) | K_i'\rangle . \quad (8)$$

The relationships between the unperturbed and first-order perturbed transition moments can be deduced by examining the relative reduced transition probabilities of the three transitions from the 636-keV level. The experimental values are compared with theoretical values in Table III. The ratios obtained using the Alaga rules are those which follow from imposing $M_1^{(L)}=0$ in Eqs. (6a)–(6f). It can be seen that a substantial admixture $M_1^{(1)}$ is required to bring the $M1$ intensities into agreement, while only a small $M_1^{(2)}$ admixture gives reasonable agreement with experiment for the $E2$ intensities. This is in qualitative agreement with conclusions based on the variations in

TABLE III. Ratios of reduced transition probabilities of γ transitions from the 636-keV level of ^{173}Yb.

	Expt.	Alaga rules	Coriolis-coupled	
$\frac{B(M1,\ 457\ \text{keV})}{B(M1,\ 557\ \text{keV})}$	1.3 ± 0.4	0.13	1.5	$M_1^{(1)}/M_0^{(1)}=-1.0$
$\frac{B(M1,\ 557\ \text{keV})}{B(M1,\ 636\ \text{keV})}$	$0.22^{+0.08}_{-0.04}$	0.30	0.24	
$\frac{B(E2,\ 457\ \text{keV})}{B(E2,\ 557\ \text{keV})}$	$0.37^{+0.18}_{-0.24}$	0.40	0.26	$M_1^{(2)}/M_0^{(2)}=-0.05$
$\frac{B(E2,\ 557\ \text{keV})}{B(E2,\ 636\ \text{keV})}$	$0.55^{+0.24}_{-0.12}$	0.96	0.73	

magnitude and phase of the mixing ratios themselves—from an inspection of Eqs. (6a)–(6f) it is seen that only the $M_1^{(1)}$ and $M_0^{(2)}$ terms can reproduce the observed variations in δ. In fact, using the values of $M_1^{(L)}/M_0^{(L)}$ shown in Table III, we deduce $\delta(457):\delta(557):\delta(636) = -0.52 : -1.5 : 1$, which reproduces rather well the observed ratio within the accuracy of the experimental values.

We note briefly that the ratio $M_1^{(1)}/M_0^{(1)} = -1.0$ is consistent with values expected on the basis of Nilsson model calculations. The matrix element of j_- between the $\frac{7}{2}^-[514]$ and $\frac{5}{2}^-[523]$ states has been computed by Bunker and Reich[25] to be 3.7, and thus $A_- \cong 0.1$, using a value of $\hbar^2/2\mathcal{G} = 11$ keV.

An estimate of the ratio between the intrinsic $M1$ probabilities can be obtained from the values of $\sum B(M1)$ computed by Bunker and Reich[25]; they obtain for $g_s = 0.6(g_s)_{\text{free}}$, $\sum B(M1, \frac{7}{2}^-[514] \to \frac{5}{2}^-[512]) = 0.000\,25$, and $\sum B(M1, \frac{5}{2}^-[523] \to \frac{5}{2}^-[512]) = 0.082$. Thus

$$\frac{\langle K_f|M'(M1)|K_i\rangle}{\langle K_f|M'(M1)|K_i\rangle} = \left(\frac{0.082}{0.000\,25}\right)^{1/2} = 18$$

and

$$\left|\frac{M_1^{(1)}}{M_0^{(1)}}\right| \approx (0.1)(18) = 1.8\,,$$

in reasonable agreement with the deduced value of 1.0. We conclude that both the magnitudes of the reduced transition probabilities and the phases of the transition multipole moments are adequately accounted for by a first-order calculation of the effect of Coriolis mixing in the 636-keV level, and that such a calculation gives parameters which are consistent with those expected on the basis of the Nilsson model.

D. ^{174}Lu magnetic moments

The magnetic moment of the ^{174}Lu ground state may in principle be deduced from either the 1242- or 1318-keV angular distributions. The 1318-keV transition is of pure $M2$ multipolarity, but its low intensity gives rise to a substantial uncertainty in the deduction of the orientation parameter. On the other hand, the angular distribution parameter A_2 for the 1242-keV transition is not known with sufficient accuracy to yield a precise measurement of $B_2(^{174}\text{Lu}^g)$; the angular correlation data of Schmidt *et al.*[3] give $\delta(M2/E1) = +0.05 \pm 0.09$, $\delta(E3/E1) = +0.19 \pm 0.08$, corresponding to $A_2 = -0.25 \pm 0.13$. Each of these two γ rays yields a deduced value of B_2 with an uncertainty of the order of 50%. Averaging the two values of B_2 thus obtained from the 20-mK data, we obtain $B_2 = 0.118 \pm 0.036$, and from a comparison with the ^{173}Lu results we obtain the ratio of the $^{174}\text{Lu}^g$ and ^{173}Lu magnetic moments as $\mu(174g)/\mu(173) = 1.01 \pm 0.17$. From the 4-mK data, using the 1242-keV γ ray only, we obtain $B_2 = 0.31 \pm 0.11$ and $\mu(174g)/\mu(173) = 0.65 \pm 0.18$. Averaging the 20- and 4-mK results and using the value of $\mu(173)$ deduced above, we obtain

$$|\mu(^{174}\text{Lu}^g)| = (1.94 \pm 0.28)\mu_N\,.$$

In order to deduce the $^{174}\text{Lu}^m$ moment, it is necessary to rely on the 67-keV γ ray emitted in the decay of $^{174}\text{Lu}^m$ to $^{174}\text{Lu}^g$. The decays to ^{174}Yb may not be reliable indicators of the $^{174}\text{Lu}^m$ alignment, since all such decays proceed through the 830-μs level at 1518 keV and may possibly be somewhat deoriented. The multipole mixing ratio of the 67-keV transition may be deduced from the *L*- and *M*-subshell conversion electron measurements of Kartashov *et al.*,[9] who determined a predominantly $M1$ character for this transition, with $E2 = 0.8 \pm 0.2\%$; that is, $|\delta| = 0.09 \pm 0.01$. For $\delta > 0$, the 4-mK result shown in Table I yields $B_2 = 0.53 \pm 0.10$, while for $\delta < 0$, $B_2 = 0.19 \pm 0.03$. To distinguish between these two possibilities, we examine the angular distribution of the 992-keV γ ray; using the results obtained in the following section, we deduce from this γ ray $B_2U_2 = 0.294 \pm 0.050$. The unobserved β decay and the possible dealignment result in a deorientation coefficient U_2 which is less than unity; it follows that the above result sets a lower limit on B_2, and therefore we favor the choice corresponding to $\delta(67) > 0$. This value of B_2 corresponds to $\Delta/T = 0.36 \pm 0.05$. Comparing this value with that deduced for ^{173}Lu yields

$$\frac{\mu(^{174}\text{Lu}^m)}{\mu(^{173}\text{Lu})} = 1.00 \pm 0.14$$

and then

$$|\mu(^{174}\text{Lu}^m)| = (2.34 \pm 0.33)\mu_N\,.$$

The alignment of the 1518-keV level of ^{174}Yb may be altered either by direct reorientation of the level or by perturbations produced by external fields. A direct reorientation of the level seems unlikely in view of the shortness of the lifetime compared with typical values for the nuclear spin-lattice relaxation time, which may be many seconds.[4] On the other hand, perturbation by randomly oriented magnetic fields or electric field gradients is not expected to be large, since the internal magnetic fields are strongly aligned (and hence cannot perturb the angular distribution) and the crystalline electric field gradients are expected to vanish in the limit of a perfect cubic lattice. The assumption of cubicity may not be valid with impurity concentrations of several atomic percent, and so we may well be experiencing such a perturbation. In any case, assuming no loss of alignment during the lifetime of the 1518-keV level, we can obtain a lower limit on the $^{174}\text{Lu}^m$ magnetic moment from the 992-keV angular distribution, from which we obtain $|\mu(^{174}\mathrm{Lu}^m)| \geq (1.87 \pm 0.19)\mu_N$. Since this value, representing a lower limit on the moment, overlaps with the value obtained previously from the 67-keV angular distribution, we are unable to make any definite conclusions regarding perturbations of the 1518-keV level.

The experimental $^{174}\mathrm{Lu}^{g,m}$ moments may be compared with values deduced on the basis of the moments of the neighboring odd-mass nuclei and from a direct calculation using the Nilsson model. The magnetic moment of a two-particle state is given by

$$\mu = \frac{I}{I+1}\left(g_{s_p}\langle s_p\rangle + \langle l_p\rangle + g_{s_n}\langle s_n\rangle + g_R\right), \qquad (9)$$

where $p(n)$ stand for proton (neutron), g_s is the effective spin g factor, and g_R is the rotational g factor. The 1^- ground state of ^{174}Lu is believed to represent the coupling $\{\frac{7}{2}^+[404]_p - \frac{5}{2}^-[512]_n\}$, while the 6^- isomer is the parallel coupling of the same two states. Taking $\eta = 5.5$, we compute $\langle s_p\rangle = -0.453$ and $\langle s_n\rangle = +0.393$. We take $g_s = 0.55(g_s)_{\mathrm{free}}$ as giving the best agreement with the moments of neighboring odd-mass nuclei and compute

$$\mu(^{174}\mathrm{Lu}^g) = +1.85\mu_N,$$

$$\mu(^{174}\mathrm{Lu}^m) = +1.76\mu_N.$$

The computed $^{174}\mathrm{Lu}^g$ moment is in good agreement with the experimental value. The computed $^{174}\mathrm{Lu}^m$ moment is in agreement with the value deduced on the basis of the 992-keV γ ray, and in mild disagreement with the value deduced based on the 67-keV γ ray. Our assumptions regarding the 67-keV transition can be tested by computing the value of $\delta(67)$ based on the rotational model, *viz.*

$$\delta = 0.934\frac{E_\gamma\,(\mathrm{MeV})}{[(I-1)(I+1)]^{1/2}}\,\frac{Q_0}{g_K - g_R}. \qquad (10)$$

The value $g_K - g_R$ is obtained from the parameters used to compute the $^{174}\mathrm{Lu}^g$ moment, and taking $Q_0 = 8$ b, we compute $\delta(67) = +0.058$, a value somewhat smaller than our assumed value of $\delta = +0.09 \pm 0.01$ based on conversion coefficient measurements.[9] If we use the computed value of $\delta(67)$ to obtain the $^{174}\mathrm{Lu}^m$ moment, we obtain $\mu(^{174}\mathrm{Lu}^m) = (1.91 \pm 0.28)\mu_N$ in good agreement with the theoretical value and also with the value obtained from the 992-keV angular distribution. Conversely, using our value of $\mu(^{174}\mathrm{Lu}^m)$ deduced from the 992-keV γ ray, we obtain $\delta(67) = +0.005 \pm 0.029$. Thus assuming no perturbation of the angular distributions proceeding through the 1518-keV level, our data yield values of $\delta(67)$ and $\mu(^{174}\mathrm{Lu}^m)$ which are consistent with the same theoretical parameters.

E. Spin of the 1518-keV ^{174}Yb level

As discussed above and in greater detail by Schmidt *et al.*,[3] the previous data regarding the spin-parity assignment of the 1518-keV level of ^{174}Lu are consistent with 6^+ or 7^- assignments, with a preference for the 6^+ assignment. Based on the angular correlation results, we would expect $A_2(992) = +0.32 \pm 0.02$ for a 6^+ assignment and $A_2(992) = -0.43 \pm 0.11$ for a 7^- assignment. The average of the results for the 992-keV angular distribution is

$$B_2 U_2 A_2(992) = +0.092 \pm 0.016,$$

$$B_4 U_4 A_4(992) = -0.044 \pm 0.017.$$

Since $U_2 > 0$, these results are sufficient to exclude unambiguously the 7^- spin assignment, which demands $A_2 < 0$. Thus the present work in conjunction with previous data uniquely establishes the 6^+ assignment for the 1518-keV level.

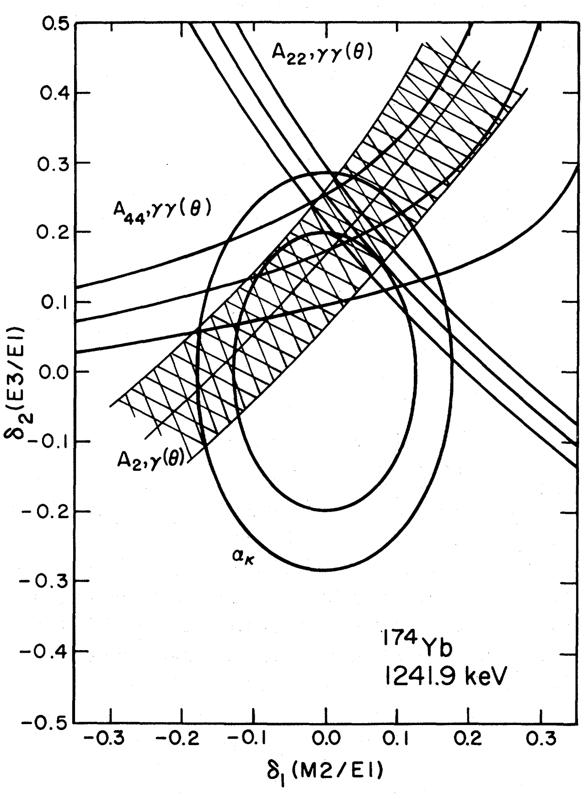

FIG. 5. The mixing ratios $\delta_1(M2/E1)$ and $\delta_2(E3/E1)$ determined from the present measurement of A_2 (cross-hatched region) and from the previous work of Schmidt, Mihelich, and Funk (Ref. 3), from whose work the figure is taken. A_{22} and A_{44} refer to results derived from an angular correlation measurement, and α_K refers to results derived from a conversion coefficient measurement.

F. ^{174}Yb γ-ray anisotropies

The anisotropies of the angular distributions of the ^{174}Yb γ rays are summarized in Table I. The 20- and 4-mK data represent averages over all data runs since the run-to-run temperature variations were small. The mixing ratio of the 992-keV transition cannot be determined directly, owing to possible dealignment in the 1518-keV level. The mixing ratio of the 1242-keV transition can be analyzed directly, although with relatively large error, by a comparison with the 1318-keV angular distribution. Such a comparison yields

$$A_2(1242) = -0.23 \pm 0.12.$$

Assuming the 1242-keV transition to be of $E1+M2+E3$ multipolarity, the multipole mixing ratios $\delta_1(M2/E1)$ and $\delta_2(E3/E1)$ can be determined from a comparison of the results of angular distribution, angular correlation, and conversion coefficient measurements. In Fig. 5 we show such a comparison, in which results derived from the present $A_2(1242)$ are superimposed on previous results given by Schmidt, Mihelich, and Funk.[3] The present results are in good agreement with their results, and the region of overlap can be obtained with slightly more precision than in the previous work:

$$\delta_1(M2/E1) = 0.04 \pm 0.06,$$

$$\delta_2(E3/E1) = 0.20 \pm 0.07.$$

A discussion of the significance of these mixing ratios may be found in the work of Schmidt, Mihelich, and Funk.[3]

G. 0°–180° Asymmetries and parity tests

The forward-backward asymmetries A computed from the experimental counting rates according to Eq. (3), are shown in Table IV. These results have been corrected for uncertainties in the measured asymmetry of the background under the peaks. Although these asymmetries were zero, the statistical uncertainty in measuring that zero is folded into the error reported in Table IV. These results represent an average over 17 runs of typically 50 polarization reversals each; the statistical spread was characterized by a normalized χ^2 lying between 0.5 and 2.0.

The asymmetries yield the following values for the irregular-to-regular parity mixing ratio:

$$\epsilon(992) = (3 \pm 10) \times 10^{-4},$$

$$\epsilon(1242) = (15 \pm 12) \times 10^{-4}.$$

From a comparison with Fig. 1, it can be seen that the $M1$ transition strength of the 992-keV transition, which is hindered by 10^{11}, might be expected to give rise to a value of $\epsilon \sim 10^{-3}$, based on the systematics of other parity-mixing studies. The present result is sufficient to place an upper limit on a possible parity mixing amplitude at about that level, but greater precision is required to obtain confirmation of such an effect.

TABLE IV. 0°–180° asymmetries of ^{174}Lu γ rays.

γ-ray energy (keV)	Asymmetry (units of 10^{-4}) Background near peak	Measured peak	Background-corrected peak
992	-0.7 ± 3.5	0.9 ± 3.8	1.8 ± 6.3
1242	-3 ± 10	-3.0 ± 1.8	-3.0 ± 1.8

V. SUMMARY

The decay of Lu polarized at low temperatures in $ZrFe_2$ was shown in an earlier work[4] to yield considerable information on the nuclear structure of levels populated following the decays of $^{177}Lu^{m,g}$. In the present work a similar investigation was performed relative to the decays of ^{173}Lu and $^{174}Lu^{m,g}$. The nuclear magnetic moments of ^{173}Lu, $^{174}Lu^{m}$, and $^{174}Lu^{g}$ were deduced and shown to be in reasonable agreement with values expected on the basis of the Nilsson model. Multipole mixing ratios for many of the ^{173}Yb and ^{174}Yb γ rays were deduced. A calculation based on Coriolis mixing was shown to account for the deviation of magnitude and phase of several interband mixing ratios from the predictions based on the Alaga rules; the success of this calculation suggests the importance of the phase of the mixing ratio as a nuclear observable. The spin of the 1518-keV level of ^{174}Yb was shown to be 6; although previous studies had shown a preference for this assignment, the present work provides the strongest evidence yet for rejecting a possible spin assignment of 7. A search for 0°–180° γ-ray asymmetries generally associated with parity mixing showed no evidence for any effects at about the 10^{-3} level.

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