Submitted to Physical Review C

LBL-2354
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January 1974

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

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KEYWORD ABSTRACT

RADIOACTIVITY ^{177m}Lu, ^{177g}Lu; measured $\gamma(\theta)$ from polarized nuclei; deduced magnetic moment μ, hyperfine field H of impurities in $ZrFe_2$, relaxation time, γ-ray multipole mixing ratios, $\delta(E2/M1)$, $\delta(M2/E1)$, g_K, g_R, Coriolis mixing; deduced no observable parity violation.

NUCLEAR ORIENTATION STUDY OF THE DECAY OF ^{177m}Lu†

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Abstract

Angular distributions of 37 γ rays were observed following the decays of 161-day ^{177m}Lu and 6.8-day ^{177g}Lu polarized at low temperatures in the ferromagnetic cubic Laves-phase compound $ZrFe_2$. The magnetic moment of the ^{177m}Lu was deduced to be $|\mu| = 2.74 \pm 0.21\ \mu_N$, in excellent agreement with the value $\mu = +2.71\ \mu_N$ computed assuming the ^{177m}Lu to be the three-quasiparticle state $\{7/2^+[404]_p, 9/2^+[624]_n, 7/2^-[514]_n\}$. The magnetic hyperfine fields of Lu, Ta, Sc, and Co in $ZrFe_2$ were deduced from the corresponding γ-ray anisotropies. Decays proceeding through the 1.1-sec ^{177m}Hf were observed to show characteristic relaxation times of $T_1 \approx 6.7$ sec. The E2/M1 mixing ratios of numerous intraband transitions in ^{177}Lu and ^{177}Hf were deduced, and the corresponding $(g_K - g_R)/Q_o$ values were computed. Several interband M2/E1 mixing ratios were deduced and were compared with calculations based on the Nilsson model including first-order Coriolis mixing. The 0°-180° asymmetries of

several ^{177}Lu transitions were observed in an effort to see if parity mixing effects might be present due to the particularly close-lying opposite parity states of ^{177}Lu; no effects were seen to the limit of 2×10^{-4}.

I. INTRODUCTION

The study of the angular distribution of γ radiation emitted following the decay of polarized nuclei provides insight into the static and dynamic nuclear electromagnetic matrix elements as well as into the strength and character of the electromagnetic interactions of the nucleus with its environment.[1] The order to investigate the properites of the transitions which follow the decay of ^{177m}Lu and to study the means which can be used to polarize Lu, we have observed the angular distributions of γ rays following the decays of ^{177m}Lu and ^{177g}Lu polarized at low temperatures in a matrix of $ZrFe_2$. We report here the deduced γ-ray multipole mixing ratios, the magnetic hyperfine fields of Lu and a number of other impurities in $ZrFe_2$, and the first direct measurement of the magnetic moment of a three-quasiparticle state.

In order to achieve observable nuclear polarization at the ultralow temperatures which can readily be attained in the laboratory, the nuclei must be subjected to magnetic fields of the order of at least 10^5 Oe. It is well known that the hyperfine fields at nuclei of the rare earths in Fe, for example, may amount to 10^6 Oe; however, the lack of solubility of the rare earths in Fe makes sample preparation a difficult process, and generally necessitates implantation techniques. In a previous study[2] we reported the decay of Yb polarized in Au; the rare earths have high solid-solubilities in Au, which acts as medium to permit the rare earths to experience their full paramagnetic fields, which may amount to 10^7 Oe. However, due to the tri-valency of the Lu ion, the electronic structure of Lu is characterized by a filled 4f shell, and hence Lu has a

vanishing field in Au. In previous studies we have observed substantial hyperfine fields as well as considerable solid solubilities of Hf[3] and Er[2] in the cubic ferromagnet $ZrFe_2$. In the present study, we have succeeded in dissolving and polarizing Lu in $ZrFe_2$.

A number of isomers in nuclei of the $A \approx 175$ mass region have been identified as three-quasiparticle states.[4] In general the identification of these states is based on a consideration of the couplings of the low-lying Nilsson quasiparticle states which can give rise to the appropriate spin and parity. A measurement of the magnetic moment of such a state provides a direct test of the suggested coupling scheme. Although the moment of a three-quasiparticle level in ^{177}Hf may be deduced from the cascade-to-crossover ratios of the transitions in the rotational band built on the level,[5] we report here the first direct (model-independent) measurement of the moment of a three-quasiparticle isomer.

In addition, there are a number of highly retarded E1 γ transitions between the rotational levels built on the various intrinsic states of ^{177}Lu and ^{177}Hf. It is generally assumed that such highly retarded transitions are good candidates for the observation of effects due to weak parity non-conserving forces in the nuclear Hamiltonian.[6] The general assumption is that the nuclear structure effects which give rise to the hindrance of the "regular" transition do not also produce a large hindrance of the "irregular" transition which arises from a possible parity admixture in the nuclear levels. Such effects are also likely to be enhanced by the close proximity of the odd- and even-parity levels of the same spin; in the ^{177}Lu level scheme, corresponding opposite-parity levels are separated by only a few keV. In search of possible

parity non-conserving effects, we have observed the forward-backward asymmetries of a number of γ rays following the decay of ^{177m}Lu.

II. ^{177m}Lu DECAY SCHEME

The decay of ^{177m}Lu to levels of ^{177}Lu and ^{177}Hf has been the subject of numerous investigations. Investigations of the rather complex spectrum of γ rays were done by Alexander, Boehm, and Kankeleit[7] using a bent-crystal spectrometer, and by Blok and Shirley[8] using a Ge(Li) detector. These decay studies have established the spectrum of rotational states built on the intrinsic Nilsson single-particle states as shown in Fig. 1. Although the population of rotational bands to such high spins is not uncommon (for example, numerous such bands are seen in (α, xn) reactions), it is unusual to have a radioactive decay scheme involving such states, and thus the decay of ^{177m}Lu provides an opportunity to observe numerous nuclear properties not generally observable in radioactive decay studies. A precise determination of the γ-ray branching intensities was done by Haverfield, Bernthal, and Hollander.[9] Included in the γ-ray spectrum are a number of weak interband E1 transitions, in addition to the E2 and E2/M1 intraband transitions. The considerable deviations of the intensities of these transitions from the rotational-model predictions (Alaga branching rules) were discussed by Alexander et al.,[7] and a calculation of the effect of Coriolis-type mixing on the E1-intensities was done by Bernthal and Rasmussen,[10] who were able to obtain good agreement between the observed intensities and a three-parameter fit. Other studies of the transition multipolarities were performed by Kartashov, Troitskaya, and Shevelev,[11] who determined the internal conversion electron intensities in the ^{177m}Lu

decay, and by West, Mann, and Nagle,[12] who did a similar study of the decay of ^{177}Ta to ^{177}Hf. The angular distributions of the γ rays following the decay of ^{177m}Lu aligned in neodymium ethyl sulfate were observed by Blok and Shirley,[13] and the angular correlations of γ rays in the $9/2^+$[624] band of ^{177}Hf were studied by Hübel et al.[14] and interpreted in terms of the intrinsic electromagnetic structure of the band. Numerous internal conversion[12,15-19] and angular correlation[12,20-24] studies of the decay of ^{177g}Lu have been done; as shown in Fig. 1, only a few of the low-lying ^{177}Hf levels are populated in this decay. Studies of transition multipolarities in ^{177}Lu have been done by Balodis et al.[25] following neutron capture, by Kristensen et al.[26] following the ^{177m}Lu decay, and by Johansen et al.[27] in the ^{177}Yb decay.

III. EXPERIMENTAL DETAILS

A. Sample Preparation

Lutetium, zirconium, and iron metals were arc-melted together in an argon atmosphere to form $(Lu_{0.05}Zr_{0.95})Fe_2$ which was subsequently vacuum annealed at 1100°C for 24 hours. Disc-shaped sections 5 mm in diameter and 1/2 mm thick were cut from the buttons. One disc (sample I) was irradiated for 60 hours in the Los Alamos Omega West Reactor in a region where the flux was 2×10^{12} neutrons/cm^2/sec. The irradiated disc was allowed to decay for 4 months in order to allow the decay of the intense ^{177}Lu ground state ($\tau_{1/2}$ = 6.8 d); thus when this sample was studied the only significant activities were decays from the ^{177m}Lu ($\tau_{1/2}$ = 161 d) plus trace ^{60}Co, ^{182}Ta, and ^{46}Sc impurities. Following the studies on sample I, a second disc (sample II) from the original button was irradiated for 5 minutes in the identical reactor location. It was immediately taken from the reactor and cooled to allow study of ^{176m}Lu ($\tau_{1/2}$ = 3.7 h) and ^{177}Lu ground state ($\tau_{1/2}$ = 6.8 d). In both experiments a small foil of Fe, with minute quantities of ^{54}Mn dissolved in it, was indium soldered to the same upper cold finger as the source. The ^{54}Mn anisotropy served as a thermometer to measure the Lu source temperature.

A typical Ge(Li)-detector gamma-ray spectrum of the decay of sample I is shown in Figure 2. Only the low energy portion of the spectrum is shown, since ^{177m}Lu has no γ-rays of energy greater than 466 keV. Other low-energy γ-rays come from the decays of ^{59}Fe, ^{181}Hf, and ^{182}Ta. The high-energy region contains γ-rays from the ^{46}Sc, ^{59}Fe, ^{60}Co, ^{95}Zr, and ^{182}Ta decays, in addition to the 835-keV ^{54}Mn γ-ray.

B. Apparatus

The essential features of the low-temperature apparatus have been described in a number of previous publications,[1-3] and a recent communication[28] discussed the modifications of the basic system used for studies of time-reversal invariance. The low temperatures necessary to achieve observable nuclear polarizations were achieved using a ^{3}He-^{4}He dilution refrigerator, which is capable of operating at 14 millikelvin (mK) in the absence of a heat load. The sample was polarized using two pairs of Helmholtz coils oriented with their axes at right angles to one another. The modifications of the apparatus which affect the present study are (1) the sample is not soldered directly to the cold-finger, but rather to a copper piece which screws into a threaded copper receptacle soldered to the cold-finger, and (2) the sample cannot be magnetized in two mutually perpendicular directions in the plane of the sample, but rather in one direction in the plane of the sample and in another normal to the sample. These modifications result in (1) a relatively high sample temperature, owing to the poor thermal contact across the screw threads, and (2) a reduced degree of polarization when the magnetization direction is normal to the sample. The applied fields used were 3.6 kOe parallel to the sample plane and 5.7 kOe normal to the sample plane.

The γ rays were observed by using two 40 cm^3 Ge(Li) detectors placed along the axes of polarization. The data were accumulated using a mini-computer-based data acquisition system.[29] The angular distribution anisotropies were determined from peak intensities obtained from the 2048-channel γ-ray spectra, and the forward-backward asymmetries were computed by the computer from integrated peak intensities.

C. Data Analysis

The angular distribution of γ radiation from the decay of an ensemble of oriented nuclei is described by

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

where the geometrical correction factors Q_k correct for the angular resolution of the detectors, the orientation parameters B_k describe the orientation of the initial state, the deorientation coefficients U_k correct for the effect of unobserved intermediate radiations, and the angular distribution coefficients A_k describe the properties of the observed γ ray. The P_k are the Legendre polynomials. The index k is restricted to even values for parity nonviolating radiations, but can take odd values in the case of parity violation. For the present work, the small degree of polarization achieved limits the values of the index to $k \leq 2$.

The angular distribution coefficients are given by

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

for k = even, with δ the γ-ray multipole mixing ratio in the phase convention of Krane and Steffen,[30] and by

$$A_k = \frac{2\epsilon}{1+\delta^2}\left[F_k(LLI_fI_i)+\delta F_k(LL'I_fI_i)\right] \tag{3}$$

for k = odd, with ϵ the irregular-to-regular parity nonconserving multipole mixing ratio[3] (M1/E1, for example).

The forward-backward asymmetry $\mathcal{A}$ is given by

$$\mathcal{A} = \frac{W(0°) - W(180°)}{[W(0°) + W(180°)]} \tag{4}$$

$$= \frac{Q_1 B_1 U_1 A_1}{1 + Q_2 B_2 U_2 A_2} . \tag{5}$$

The asymmetries Q were determined from the forward-backward counting rate differences for magnetization in the plane of the sample.

The reduced degree of polarization obtained for a magnetization direction normal to the plane of the samples necessitated some special care when analyzing the angular distribution anisotropies. Denoting the detectors in directions parallel and perpendicular to the plane of the sample by A and B, respectively, the following four counting rates may be measured:

$$\begin{aligned} W_A^{\parallel} &= \overline{W}_A (1 + c_A B_2), \\ W_A^{\perp} &= \overline{W}_A (1 - \tfrac{1}{2} c_A B_2'), \\ W_B^{\parallel} &= \overline{W}_B (1 - \tfrac{1}{2} c_B B_2), \\ W_B^{\perp} &= \overline{W}_B (1 + c_B B_2'), \end{aligned} \tag{6}$$

where the superscripts indicate whether the applied field is parallel or perpendicular to the plane of the sample, $\overline{W}_i$ represent the isotropic high-temperature counting rates, c_i are constants ($= Q_2 U_2 A_2$), and B_2 and B_2' represent the orientation parameters for external fields respectively parallel and perpendicular to the plane of the sample; i.e., $B_2 \geq B_2'$. Choosing a γ ray of pure multipolarity, for which c_A and c_B may be computed (c_A and c_B differ only in the solid-angle correction factors of the two detectors), these four equations may be solved for the four unknowns $\overline{W}_A$, $\overline{W}_B$, B_2, and B_2'; similarly, once B_2 and B_2' have

been determined, we may determine $\overline{W}_A$, $\overline{W}_B$, c_A, and c_B for the remaining γ rays.

IV. RESULTS AND DISCUSSION

A. Angular Distributions

The results deduced from the anisotropies of the various ^{177}Lu and ^{177}Hf γ rays are presented in Table I. These results were obtained as described above, and will be analyzed for the magnetic moments and γ-ray mixing ratios in succeeding sections. The data have been corrected for the effect of the reduced polarization when the magnetization was perpendicular to the sample. The values of B_2 presented in Table I thus may be assumed to represent fully saturated polarizations in the plane of the sample. For the ^{177m}Lu decays, this effect amounted to a correction of 15-20% relative to the values deduced assuming full saturation when the sample is polarized normal to its plane; this follows from our observed relationship $B_2'/B_2 \approx 0.7$.

The Mn-in-Fe foil used for thermometry purposes[31] was a much thinner sample than the $ZrFe_2$ and thus much more difficult to polarize normal to its plane. We observed $B_2'/B_2 \approx 0.4$ for this sample, and applying the appropriate correction factors to the observed anisotropy of the 835-keV γ ray, we deduced $T = 30.4 \pm 1.0$ mK for the ^{177m}Lu decays (sample I), and $T = 45.6 \pm 3.2$ mK for the ^{177g}Lu decays from sample II.

The irradiation of the ^{177g}Lu sample also produced some ^{176m}Lu activity (3.7 hr), which decays via the 88-keV $2^+ \rightarrow 0^+$ transition of ^{176}Hf. From the known magnetic moment of the 1^- ^{176m}Lu,[32] and from the hyperfine field of Lu in $ZrFe_2$ deduced below, we would expect

$|B_2U_2A_2| < 0.0009$ for the 88-keV γ ray, in agreement with our observed value of

$$B_2U_2A_2\ (88\,\text{keV}) = -\ 0.0013 \pm 0.0020.$$

A comparison of the angular distribution of the 113.0-keV γ ray from sample I (^{177m}Lu decay) with that from sample II (^{177g}Lu decay) can be analyzed to yield the deorientation factor U_2 for the β decay from ^{177g}Lu to the 113.0-keV level of ^{177}Hf. This is possible since a negligible fraction of the 113.0-keV γ rays observed following the ^{177m}Lu decay actually proceed through the ^{177g}Lu level. The deduced value of U_2 is given in Table I; this may be compared with the theoretical value $U_2 = 0.925 - 0.288\,\alpha_2$, where α_2 is the fraction of the beta decays which carry two units of angular momentum (resulting from the B_{ij} first-forbidden matrix element). We thus conclude that $\alpha_2 < 0.17$, indicating that the majority of the 384-keV β-decays carry one unit of total angular momentum.

B. Magnetic Moments of Three-Quasiparticle States

By averaging the results for the various E2 transitions emitted in the decay of ^{177m}Lu to states of ^{177}Lu, we obtain $B_2(^{177m}\text{Lu}) = 0.221 \pm 0.007$. At a deduced temperature $T = 30 \pm 1$ mK, this corresponds to $\Delta(^{177m}\text{Lu}) = 3.60 \pm 0.13$ mK, where the hyperfine parameter Δ gives the energy splitting of adjacent magnetic substates ($\Delta = \mu H/Ik_B$). Similarly, for the ground state decay, $B_2(^{177g}\text{Lu}) = 0.097 \pm 0.003$, and at $T = 45.6 \pm 3.2$ mK, $\Delta(^{177g}\text{Lu}) = 9.66 \pm 0.68$ mK.

The magnetic moment of the isomer may then be deduced from the ratio of the splitting parameters, as

$$|\mu(^{177m}Lu)| = |\mu(^{177g}Lu)| \frac{\Delta(^{177m}Lu)}{\Delta(^{177g}Lu)} \frac{23/2}{7/2}$$

$$= 1.23 \pm 0.10 \; |\mu(^{177g}Lu)| . \tag{7}$$

The ground state moment has been determined to be $\mu = 2.236\ \mu_N$,[32] and thus

$$|\mu(^{177m}Lu)| = 2.74 \pm 0.21\ \mu_N .$$

This value may be compared with the value computed assuming the isomer to be a three-quasiparticle state, namely the one-proton, two-neutron combination of the Nilsson states $\{ 7/2^+[402]_p,\ 9/2^+[624]_n,\ 7/2^-[514]_n \}$. The magnetic moment of a deformed nuclear level is given by[33]

$$\mu = g_R I + (g_K - g_R) \frac{K^2}{I+1} \tag{8}$$

where g_R and g_K are the g-factors associated with the rotational and intrinsic structure, respectively. The intrinsic g-factor for a compound state is determined by

$$K g_K = \sum_i K_i\, g_{K_i} , \tag{9}$$

where in the present case we sum over the three constituent states. The intrinsic g-factors of the constituent states are given by

$$K_i\, g_{K_i} = K_i\, g_{\ell_i} + (g_{s_i} - g_{\ell_i}) \langle s_z \rangle_i . \tag{10}$$

The g_ℓ values used are $g_\ell = 1$ for protons and $g_\ell = 0$ for neutrons; we take $g_s = 0.6\, g_s^{free}$, where $g_s^{free} = 5.585$ for protons and $g_s^{free} = -3.826$ for neutrons. The expectation values of s_z were computed using the

Nilsson wave functions[34] with a deformation of $\eta = 5.04$.[35] For the three constituent states which comprise the ^{177}Lu isomer, we compute $\langle s_z \rangle = -0.453$ for the state $7/2^+[404]_p$, $\langle s_z \rangle = +0.417$ for $9/2^+[624]_n$, and $\langle s_z \rangle = -0.378$ for $7/2^-[514]_n$. The intrinsic g-factor of the isomer is then computed to be $g_K = 0.225$. Using $g_R = 0.347 \pm 0.028$,[35] we compute $\mu = +2.71 \pm 0.03\,\mu_N$. This value is in excellent agreement with the experimental value, and suggests that the experimental value is likely to be positive.

The moment of the 1.1-sec isomer of ^{177}Hf may not be determined from the present work; since the lifetime is not sufficiently greater than the expected nuclear spin-lattice relaxation time T_1, decays from the ^{177m}Hf will show anisotropies characteristic of the ^{177m}Lu. However, the influence of the ^{177}Hf state is evidenced in the increased B_2 of the ^{177m}Hf relative to that of the ^{177m}Lu (Table I); the average value of this parameter is $B_2(^{177m}\text{Hf}) = 0.262 \pm 0.004$. This value is of course an "effective" value and is not directly characteristic of the splittings of the magnetic substates of the ^{177m}Hf level. The relaxation time T_1 may be estimated from the relationship of the observed B_2 to that expected for the ^{177m}Lu and ^{177m}Hf levels. The latter may be estimated from the computed value of $\mu(^{177m}\text{Hf}) = 8.27\,\mu_N$, assuming the ^{177m}Hf level to be the three-quasiparticle state $\{7/2^+[404]_p, 9/2^-[514]_p\ 7/2^-[514]_n\}$; this calculated value of the moment is in agreement with the $(g_K - g_R)$ value deduced by Chu et al.[36] from the γ-ray branching ratios following the decay of a higher-lying five-quasiparticle isomer in ^{177}Hf. The hyperfine field of Hf in $ZrFe_2$ has been measured to be $H = 200 \pm 20$ kOe,[3,37] and thus at a temperature $T = 30$ mK, we would

expect $B_2(^{177m}Hf) = 0.45$ in the case of full saturation. If we assume the effect of the relaxation to be given by an approximately exponential behavior e^{-t/T_1}, then the observed B_2 may be related to the expected values as follows:

$$B_2(^{177m}Hf,\ obs.) \approx \frac{T_1}{T_1+\tau}\,(0.98)\,B_2(^{177m}Lu) + \frac{\tau}{T_1+\tau}\,B_2(^{177m}Hf,\ sat.)\ , \tag{11}$$

where τ is the mean lifetime of the ^{177m}Hf and where the factor 0.98 has been introduced into the first term to account for the depolarizing effects of the $^{177m}Lu \rightarrow {}^{177m}Hf$ beta decay. Inserting the appropriate values yields

$$T_1 \approx 6.7 \text{ sec.}$$

This value may be compared with, for example, the relaxation time of ^{60}Co in Fe, which has similar values of g and H; for that case, $T_1 \approx$ 40 sec at T = 30 mK.[38] It has been observed that different impurities in Fe have relaxation times which can be related as $T_1\,T(gH)^2 \approx$ const.;[39] we would thus expect $T_1(^{177m}Lu) \approx 0.5\,T_1(^{60}Co)$ at a given T, which gives qualitative agreement with the deduced value. Our previous experiments[3,28] with Hf in $ZrFe_2$ have indicated no relaxation effects with characteristic times larger than ≈20 seconds, and we therefore conclude that the value deduced above represents a reasonable estimate for the relaxation time of Hf in $ZrFe_2$.

C. Hyperfine Fields in $ZrFe_2$

Owing to the long irradiation time necessary for sample I, numerous impurities present only in microscopic quantities were activated. These

are indicated in the γ-spectrum of Fig. 2. From the angular distributions of the γ rays of the well-established decay schemes of these isotopes, the hyperfine fields listed in Table II have been deduced. In the present work we have employed the decays of ^{46}Sc(889 keV), ^{60}Co(1173, 1332 keV), and ^{182}Ta(156, 222, 264, 1189, 1221 keV), together with the above-deduced splitting of the ^{177g}Lu. Also shown in Table II are some previously measured hyperfine fields of impurities in $ZrFe_2$. The previous results[40] for I in $ZrFe_2$ are subject to some uncertainty, owing to the production of the I by fission and to the lack of annealing to eliminate the subsequent lattice damage. The field for Np was deduced from the previously measured hyperfine splitting of ^{239}Np in $ZrFe_2$ by assuming the ground state moment of ^{239}Np to be equal to that of ^{237}Np.[32] A comparison of the impurity fields in $ZrFe_2$ with those in Fe indicates no systematic relationship between corresponding values; a systematic dependence of H on the atomic number Z (such as has been observed for various solutes in Fe[41]) is difficult to deduce, owing to the paucity of results across a complete group of elements. The $ZrFe_2$ hyperfine field results range from the anomalously large values for Er (which overlaps with the free-atom value) and for Np (with the value for Np in Fe as yet unknown, but most likely lying near to zero, since the neighboring elements U and Pu have fields in Fe of -520 and +620 kOe, respectively[42]), to the reduced value observed for Hf. The actual value of the hyperfine field results from contributions due to core-electron and conduction-electron polarizations; in the case of the $ZrFe_2$ alloys, however, it is also likely that weak solute-solute interactions are present, since the presence of a few atomic percent

of solute may slightly alter the expected characteristics of a dilute alloy. Thus, the present results demonstrate that many of the rare earths have both large solid solubilities and sizeable nuclear polarizations in $ZrFe_2$.

D. E2/M1 Mixing Ratios

The E2/M1 multipole mixing ratios deduced from the angular distributions of Table I are given in Table III. Except for the lowest transition in each band, the mixing ratios were determined from a direct comparison of the angular distribution of each mixed transition ($I \rightarrow I-1$) with that of the competing E2 cross-over transition ($I \rightarrow I-2$). For the lowest transition in each band, the deorientation parameters U_2 were computed from the multipolarities, branching ratios, and conversion coefficients of the unobserved intermediate radiations. In all cases, the value of δ has been selected as that root of A_2 in best agreement with previous work. The sign of δ is determined according to the definition of Krane and Steffen.[30]

All of the E2/M1 transitions studied in the present work are intraband transitions; for such transitions, the mixing ratios are related to the intrinsic static electromagnetic moments of the band according to the relationship

$$\delta = 0.934 \frac{E_\gamma}{\sqrt{(I+1)(I-1)}} \frac{Q_o}{g_K - g_R} , \qquad (12)$$

where Q_o is the intrinsic quadrupole moment. In Table III we show the deduced value of $(g_K - g_R)/Q_o$ for each transition. It is expected that these values will be constant for all transitions within a given band, and the deduced values are consistent with this assumption.

The mixing ratios for the transitions in ^{177}Lu are in agreement with

those determined by Alexander et al.[7] based on the cascade-to-crossover intensity ratios. The present results serve to determine the sign of the mixing ratios and thus yield an independent determination of the sign of $(g_K - g_R)/Q_o$. The average value of g_K for the $7/2^+[404]$ band of ^{177}Lu is determined to be $g_K = 0.68 \pm 0.07$, assuming $g_R = 0.347 \pm 0.028$ (Ref. 35) and $Q_o = 7.1 \pm 1.2$ b (Ref. 43).

The presently measured mixing ratios of transitions within the $9/2^+[624]$ band of ^{177}Hf are in good agreement with the values determined by Hübel et al.[14] from γ-γ angular correlation measurements, although in the latter it was necessary to apply considerable corrections (often factors of 2 or 3) to the observed correlation coefficients in order to account for the effects of unresolved competing cascades. From the present data we deduced the average value $g_K - g_R = -0.44 \pm 0.03$, assuming $Q_o = 7.6 \pm 0.3$ b (Ref. 43). This value is in agreement with that deduced by Hübel et al., whose work contains a discussion of the interpretation of the g_K and g_R factors.

The mixing ratio of the 9/2-7/2 transition in the $7/2^-[514]$ band of ^{177}Hf as determined from the present work is in good agreement with the γ-γ angular correlation measurement of Hübel et al.[14] ($\delta = -4.8 \pm 0.2$) and Holmberg et al.[18] ($\delta = -4.75 \pm 0.07$), with the nuclear orientation results of Blok and Shirley[13] ($\delta = -4.7\ ^{-0.8}_{+0.4}$), and with the results of the relative internal conversion intensity measurements of Högberg et al.[17] ($|\delta| = 4.5 \pm 0.3$, using appropriately corrected values of the theoretical subshell intensities), but in disagreement with the γ-γ angular correlation results of Hrastnik et al.[21] ($\delta = -3.7 \pm 0.3$) and the e^--γ angular correlation measurements of Törnkvist et al.[15] ($\delta = -3.1 \pm 0.6$).

A discussion of the interpretation of the mixing ratios and magnetic moments of the $7/2^-[514]$ band in ^{177}Hf may be found in the work of Hübel et al.;[14] more recent values of the magnetic moments of the $7/2^-[514]$ state of ^{177}Hf and of the $9/2^+[624]$ state of ^{179}Hf are given in the work of Büttgenbach et al.,[44] along with deduced values of g_K and g_R, which are in good agreement with values deduced in the present work.

E. M2/E1 Mixing Ratios

In Table IV are shown the deduced M2/E1 mixing ratios for transitions in ^{177}Hf. The results for the 291.4- and 292.5-keV transitions were deduced from the anisotropy of the unresolved doublet peak. No variation of the anisotropy was observed between the high-energy and low-energy sides of the peak; hence, we have assumed the two γ rays to have identical anisotropies.

A number of previous studies have been made of the transitions depopulating the 321-keV level. Hrastnik et al.[21] have determined $\delta(71.6) = -0.017 \pm 0.007$ from γ-γ angular correlations, in fair agreement with the present results. The 208-113 keV angular correlation data of West et al.,[12] Holmberg et al.,[18] Thun et al.,[20] and Klema[23] cannot be analyzed to give a unique value of $\delta(208)$, owing to the uncertainties in $\delta(113)$ and in the degree of attenuation of the angular correlation by extranuclear perturbations. For $\delta(113) = -4.7$, these angular correlation data favor small, positive values of $\delta(208)$, as long as the angular correlation coefficient A_{22}, corrected for attenuation arising from perturbations, is less than 0.165 in magnitude. However, the results of Hrastnik et al.,[21] and of Agnihotry et al.[24] ($A_{22} \approx -0.200$) favor negative values of $\delta(208)$ for this value of $\delta(113)$. West et al.[12] observed the 321.3-keV transition to be $15 \pm 2\%$ M2 ($|\delta| = 0.42 \pm 0.04$), based on the internal conversion

coefficients; a similar value follows from the K, L_I, and L_{II} conversion coefficients determined by Grigor'ev.[19] However, as discussed by Holmberg et al.,[16] sizeable nuclear penetration effects are expected for this transition, and thus mixing ratios determined from this method are subject to large uncertainties. A detailed fit of the subshell ratios of the 321-keV transition including penetration effects was done by Agnihotry et al.[24] Their result $|\delta(321)| = 0.17 \pm 0.05$ is in excellent agreement with the present results.

The deviations of the E1-transition probabilities in ^{177}Hf from the predictions of the Alaga intensity rules were discussed by Bernthal and Rasmussen.[10] They were able to fit the $\Delta K = -1$ E1 transitions with a three-parameter Coriolis mixing calculation. Although they assumed all of the transitions to have vanishing M2 components, the M2 components determined in the present work have a negligible effect on the deductions of Bernthal and Rasmussen. Nevertheless, it is of interest to attempt to employ a similar method to examine the M2 intensities as well as the magnitudes and phases of the M2/E1 mixing ratios.

According to the Alaga rules,[45] the relative intensities of transitions from states of an initial intrinsic quantum number K_i to final states K_f are given by ratios of Clebsch-Gordan coefficients. The ratios of the reduced transition probabilities of the M2 transitions depopulating the 321-keV level are computed based on the Alaga rules as follows (experimental values in parentheses):

$$\frac{B(M2, 71 \text{ keV})}{B(M2, 321 \text{ keV})} = 0.22 \quad (11),$$

$$\frac{B(M2, 208 \text{ keV})}{B(M2, 321 \text{ keV})} = 0.72 \quad (67),$$

$$\frac{B(M2, 71 \text{ keV})}{B(M2, 208 \text{ keV})} = 0.31 \quad (0.17).$$

Except possibly in the latter case, the Alaga relationship fails to account for these M2 intensities, and thus we will attempt a Coriolis-type calculation of the transition mixing ratios by considering those states which can mix with the initial and final states. In order to have a convenient means of comparison of the empirical mixing ratios with the computed values, the two must be expressed in terms of the same transition operators. This can be most conveniently done by employing the multipole operators as used for example by Bohr and Mottelson,[46] in terms of which

$$\delta = -0.835\, E_\gamma\, \Delta \,, \tag{13}$$

with

$$\Delta = \frac{\langle I_f \,||\mathcal{M}(M2)\,||\, I_i \rangle}{\langle I_f \,||\mathcal{M}(E1)\,||\, I_i \rangle} \,, \tag{14}$$

where E_γ is the transition energy in MeV, and the M2 and E1 matrix elements are expressed in units of μ_N-cm and e-cm, respectively. The values of Δ deduced from the presently measured mixing ratios are shown in Table IV.

The reduced matrix elements may be expressed as[33]

$$\langle I_f K_f \,||\mathcal{M}(L)\,||\, I_i K_i \rangle = \sqrt{2I_i+1}\, \langle I_i K_i L (K_f - K_i) \,|\, I_f K_f \rangle \, \langle K_f \,|\, \mathcal{M}'(L) \;\; K_i \rangle \,, \tag{15}$$

where $\mathcal{M}'$ represents the transition operator in the intrinsic system. In the approach employed by Bernthal and Rasmussen,[10] first-order Coriolis mixing of states of $\Delta K = \pm 1$ is considered; specifically,

$$\Psi_i = |I_i M_i K_i\rangle - \sqrt{(I_i+K_i)(I_i-K_i+1)}\; A_- |I_i M_i K_i -1\rangle$$
$$- \sqrt{(I_i-K_i)(I_i+K_i+1)}\; A_+ |I_i M_i K_i +1\rangle ,$$
$$\Psi_f = |I_f M_f K_f\rangle - \sqrt{(I_f+K_f)(I_f-K_f+1)}\; B_- |I_f M_f K_f -1\rangle$$
$$- \sqrt{(I_f-K_f)(I_f+K_f+1)}\; B_+ |I_f M_f K_f +1\rangle . \tag{16}$$

The $A_\pm$ and $B_\pm$ are Coriolis matrix elements of the form $(\hbar^2/2\mathscr{I}) \langle K\pm1 | j_\pm | K \rangle / [E(K)-E(K\pm1)]$. Considering all possible first-order Coriolis-mixed components ($11/2^+$ and $7/2^+$ mixed into $9/2^+$, $9/2^-$ and $5/2^-$ mixed into $7/2^-$), the multipole matrix elements may be expressed as

$$\langle I_f K_f || \mathcal{M}(L) || I_i K_i\rangle = (2I_i+1)^{1/2} \Big\{ M_0^{(L)} \langle I_i\ \tfrac{9}{2}\ L\ -1 | I_f\ \tfrac{7}{2}\rangle$$
$$+ M_1^{(L)} \sqrt{(I_i+\tfrac{9}{2})(I_f-\tfrac{7}{2})}\, \langle I_i\ \tfrac{7}{2}\ L\ 0 | I_f\ \tfrac{7}{2}\rangle + M_2^{(L)} \sqrt{(I_f-\tfrac{7}{2})(I_f+\tfrac{9}{2})}\, \langle I_i\ \tfrac{9}{2}\ L\ 0 | I_f\ \tfrac{9}{2}\rangle$$
$$+ M_3^{(L)} \sqrt{(I_f+\tfrac{7}{2})(I_f-\tfrac{5}{2})}\, \langle I_i\ \tfrac{9}{2}\ L\ -2 | I_f\ \tfrac{5}{2}\rangle + M_4^{(L)} \sqrt{(I_i-\tfrac{9}{2})(I_i+\tfrac{11}{2})}\, \langle I_i\ \tfrac{11}{2}\ L\ -2 | I_f\ \tfrac{7}{2}\rangle \Big\} . \tag{17}$$

The quantities $M_k^{(L)}$ are products of Coriolis matrix elements and intrinsic transition moments:

$$M_0^{(L)} = \langle \tfrac{7}{2} | \mathcal{M}'(L) | \tfrac{9}{2}\rangle ,$$
$$M_1^{(L)} = - A_- \langle \tfrac{7}{2} | \mathcal{M}'(L) | \tfrac{7}{2}\rangle ,$$
$$M_2^{(L)} = - B_+ \langle \tfrac{9}{2} | \mathcal{M}'(L) | \tfrac{9}{2}\rangle ,$$
$$M_3^{(L)} = - B_- \langle \tfrac{5}{2} | \mathcal{M}'(L) | \tfrac{9}{2}\rangle ,$$
$$M_4^{(L)} = - A_+ \langle \tfrac{7}{2} | \mathcal{M}'(L) | \tfrac{11}{2}\rangle .$$

Bernthal and Rasmussen[10] deduced values of $M_0^{(1)} = 5.5\times10^{-3}$, $M_1^{(1)} = 3.4\times10^{-3}$, $M_2^{(1)} = -0.45\times10^{-3}$. Since $M_3^{(1)}$ and $M_4^{(1)}$ vanish identically for L = 1, the E1 matrix elements for all of the transitions studied may be computed from these values and are listed in Table IV along with the deduced values of $\langle M2\rangle$. It should be noted that the absolute phase of the matrix element is an indeterminate quantity, but the relative phases of different matrix elements (either different multipoles or theoretical calculations of different contributions to a single multipole) are definable. Hence the specification of $M_0^{(1)}$ as positive is sufficient to fix the signs of the remaining $M_k^{(1)}$ and $M_k^{(2)}$ values.

Equation (17) may be written in simpler form as

$$\frac{\langle M2\rangle}{(2I_i+1)^{1/2}} = \sum_{k=0}^{4} C_k(I_i, I_f)M_k^{(2)}, \tag{19}$$

where the C_k are given by the coefficients of the appropriate $M_k^{(2)}$ in Eq. (17) and are listed in Table IV.

Although it would be desirable to attempt to fit the eight empirical M2 matrix elements with the five-intrinsic M_k's, this is not possible, owing to the small variation both in the coefficients $C_k (k \geq 1)$ and in the deduced values for the matrix elements of the five transitions in the energy range 291.4-313.7 keV. However, based on the observed small variation in those values, it is apparent that the $C_0 M_0^{(2)}$ term has little influence on the M2 matrix elements, except possibly for the 313.7-keV transition. Thus it is apparent that the principal contribution to $\langle M2\rangle$ for these five transitions comes from having

$$-M_1^{(2)} - M_2^{(2)} + M_3^{(2)} + M_4^{(2)} \approx 1\times10^{-3}. \tag{20}$$

(The $M_k^{(2)}$ are proportional to Coriolis matrix elements of the form $\langle K | j_\pm | K' \rangle (\hbar^2/2\mathcal{J})/\Delta E$, where ΔE is the energy separation between the intrinsic states. This product is estimated to be 0.12, 0.03, 0.03, and 0.08 for $M_1^{(2)}$, $M_2^{(2)}$, $M_3^{(2)}$, and $M_4^{(2)}$, respectively.[4] Additionally, the intrinsic M2 matrix elements $\langle K | \mathcal{M}'(M2) | K' \rangle$ are allowed by the asymptotic Nilsson selection rules[47] for $M_3^{(2)}$ and $M_4^{(2)}$, while the matrix elements are twice n_z-forbidden for $M_1^{(2)}$ and $M_2^{(2)}$. Here we have assumed mixing of the $9/2^-[505]$ and $5/2^-[512]$ states into the $7/2^-[514]$ state, and $7/2^+[633]$ and $11/2^+[615]$ into the $9/2^+[624]$ state.) The small value of $\langle M2 \rangle$ for the 313.7-keV transition could result from $M_0^{(2)} \approx -3\times10^{-3}$; of the five transitions under consideration, this one is the most sensitive to $M_0^{(2)}$ and least sensitive to $M_k^{(2)}$ with $k \geq 1$.

The 321.3-keV result yields (assuming $M_0^{(2)} \approx -3\times10^{-3}$)

$$M_3^{(2)} - M_1^{(2)} \approx +1\times10^{-3}, \tag{21}$$

and from the 71.6-keV transition we obtain

$$M_1^{(2)} + M_2^{(2)} \approx +1\times10^{-3}. \tag{22}$$

However, these results are consistent only with a small (0.03) negative value for $\delta(208.3)$ (i.e., a positive value of $\langle M2 \rangle$). No variation in the matrix elements $M_k^{(2)}$ was able to yield a solution consistent with the observed value of $\delta(208.3)$. [Holmberg et al.[16] attempted to fit the 208.3-keV e^- subshell ratios and e^--γ directional correlation results to determine simultaneously the values of $\delta(208.3)$ and of the nuclear penetration parameter λ_1. Although their deduced results slightly favored

negative values of δ (= -0.004), the deduced relationship between the signs of δ and λ_1 was in disagreement with that preduced on the basis of the Nilsson model. Similarly deduced results of Agnihotry et al.[24] are likewise not conclusive.] We thus conclude that the present results may be taken to give reasonable estimates of the orders of magnitude of the matrix elements $M_k^{(2)}$, but that additional calculations are required for a more complete understanding, particularly of the three transitions depopulating the 321.3-keV level.

F. 0 - 180° Asymmetries

The forward-backward asymmetries $\mathcal{A}$, computed from the experimental counting rates according to Eq. (4), are shown in Table V. The background corrections have been applied assuming the background to have a vanishing asymmetry; this is consistent with the observed asymmetry of the background of $-(1 \pm 1) \times 10^{-4}$ for regions in the vicinity of 160 keV and of 340 keV. The statistical spread of the measured values was characterized by normalized chi-squared values computed to lie in the range 0.5-2.0, indicating a reasonably well-distributed sample.

The observed asymmetries indicate the lack of any substantial effect due to parity mixing to about the level of 2×10^{-4} in the total asymmetries and to about 3×10^{-3} in the peak asymmetries.

The weak interaction, which is present in the nuclear Hamiltonian with a relative amplitude of $\sim 10^{-7}$, is expected to produce small parity impurities in nuclear states. The amplitude of this impurity in the nuclear wave function is enhanced if there are close-lying opposite-parity levels of the same spin. There are four pairs of such

levels in the ^{177}Lu level scheme which are separated by from 1 to 20 keV. These are the corresponding states of the $7/2^+$[404] and the $9/2^-$[514] bands. (The $9/2^-$ band is not populated in the ^{177m}Lu decay, but the levels of that band are shown in the ^{177}Lu level scheme of Fig. 1.) We have observed the asymmetries of the E2 and E2 + M1 transitions depopulating the $11/2^+$, $13/2^+$, $15/2^+$, and $17/2^+$ levels. Furthermore, one might expect to observe the intraband E1 transitions $I_i^+ \rightarrow I_f^-$, but these transitions are not observed in the γ-ray spectrum. (Similar E1 interband transitions are observed in the ^{177}Hf level scheme; in both cases the asymptotic Nilsson quantum numbers are violated.[47]) The possible E1 transitions of ^{177}Lu would be 118 keV ($11/2^+ \rightarrow 9/2^-$), 151 keV ($13/2^+ \rightarrow 11/2^-$), 186 keV ($15/2^+ - 13/2^-$), and 217 keV ($17/2^+ \rightarrow 15/2^-$). Upper limits on the intensities of these unobserved transitions may be obtained from the ^{176}Lu(n, γ) studies of Maier,[48] which indicate that the E1 transition branching intensities are no greater than 0.05% of the 147-keV intensity for the $11/2^+$ level, with corresponding values up to 0.5% for the $17/2^+$ level. These branching intensities can be used to deduce that the E1 transitions are hindered relative to single-particle Weisskopf estimates by at least 10^6. (The corresponding transitions in ^{177}Hf are hindered[7] by at most 10^5.) In Table V are listed the 0° - 180° asymmetries of those regions of the energy spectrum where these E1 transitions might be expected.

The presence of parity mixing in the ^{177}Lu levels would give rise to a forward-backward asymmetry in the γ-ray angular distributions; this would correspond to the presence of a parity-irregular E1 transition admixed into the regular M1 transition, or an irregular M1 trans-

ition mixed into the regular E1. The failure to observe an effect in the vanishingly weak E1 transitions is not surprising. In the case of the M1 transitions, the regular transitions, which are hindered relative to Weisskopf estimates by factors of 30-50, are probably not sufficiently retarded to permit the irregular E1 to compete successfully. Additionally, the single-particle calculation of parity mixing effects done by Michel[49] indicates that admixtures of irregular E1 transitions with M1 are not likely to be found, since the E1 operator commutes with the single-particle parity-odd interaction of the form $\vec{\sigma} \cdot \vec{r}$.

V. SUMMARY

The ferromagnet $ZrFe_2$ was shown to be a suitable environment for polarizing small concentrations of Lu impurities; the magnetic hyperfine field of Lu in $ZrFe_2$ was deduced to be 413 ± 29 kOe. The magnetic moment of the ^{177m}Lu was deduced to be $2.74 \pm 0.21\ \mu_N$, in excellent agreement with the value computed assuming the isomer to be a three-quasiparticle state. The ^{177}Hf γ-rays were observed to exhibit larger degrees of orientation than the ^{177}Lu γ-rays; this difference in orientation enabled the relaxation time of the ^{177m}Hf to be estimated as 6.7 sec. Numerous E2/M1 and M2/E1 γ-ray mixing ratios were deduced and were compared with expectations based on the Nilsson model, including first-order Coriolis mixing for the M2/E1 cases. These comparisons enabled the deduction of numerous intrinsic electromagnetic moments of the Nilsson states. No substantial ($>2\times10^{-4}$) effects of parity mixing on the ^{177}Lu γ-rays were observed, in spite of the close spacings of the ^{177}Lu opposite parity levels.

Acknowledgements

The authors are grateful to Dr. J. Bubernak for a high-resolution analysis of the gamma-ray spectrum of the irradiated sample I and to B. T. Murdoch for assistance in handling the data.

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

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TABLE I. Angular distribution anisotropies from the decay of ^{177}Lu.

γ-ray energy (keV)	$B_2U_2A_2$ [a]	Deduced parameters [a]
71.6 [b]	0.008(4)	A_2(71.6) = 0.086 ± 0.057
105.3	0.193(8)	A_2(105.3) = 0.85(4)
113.0	0.065(2)	A_2(113.0) = 0.375(14)
113.0 [b]	0.035(1)	U_2(384 β) = 0.94(6)
121.6	-0.094(12)	A_2(121.6) = - 0.55(7)
128.5	0.194(6)	A_2(128.5) = 0.85(7)
136.7	0.201(65)	A_2(136.7) = 0.89(29)
136.7 [b]	0.045(9)	A_2(136.7) = 0.56(11)
147.1	-0.108(16)	A_2(147.1) = - 0.55(10)
153.3	0.188(15)	A_2(153.3) = 0.79(7)
159.8	0.150(40)	A_2(159.8) = 0.75(20)
171.8	-0.117(30)	A_2(171.8) = - 0.59(15)
174.4	0.188(9)	A_2(174.4) = 0.77(5)
195.5	-0.079(32)	A_2(195.5) = - 0.42(17)
204.1	0.194(13)	A_2(204.1) = 0.78(6)
208.3	-0.100(1)	A_2(208.3) = - 0.476(20)
208.3 [b]	-0.042(1)	A_2(208.3) = - 0.485(25)
214.4	0.179(9)	A_2(214.4) = 0.72(3)
218.1	-0.120(9)	A_2(218.1) = - 0.52(5)
228.4	-0.091(3)	B_2(^{177m}Hf) = 0.252(12)
233.8	-0.091(6)	B_2(^{177m}Hf) = 0.258(18)
249.7	-0.093(8)	B_2(^{177m}Hf) = 0.292(24)
249.7 [b]	-0.035(1)	B_2(^{177g}Lu) = 0.097(3)

TABLE I (continued)

268.8	-0.082(11)	$B_2(^{177m}Lu)$ = 0.250(32)
281.8	-0.091(2)	$B_2(^{177m}Hf)$ = 0.256(7)
(291.4+292.5)	0.030(36)	$A_2(291.4+292.5)$ = 0.12(14)
296.5	-0.096(11)	$B_2(^{177m}Hf)$ = 0.278(30)
299.0	0.014(22)	$A_2(299.0)$ = 0.06(9)
305.5	-0.005(29)	$A_2(305.5)$ = - 0.02(13)
313.7	0.036(19)	$A_2(313.7)$ = 0.18(9)
319.0	-0.078(3)	$B_2(^{177m}Lu)$ = 0.216(11)
321.3[b]	-0.001(1)	$A_2(321.3)$ = - 0.014(14)
327.7	-0.095(3)	$B_2(^{177m}Hf)$ = 0.256(12)
341.6	-0.103(26)	$B_2(^{177m}Hf)$ = 0.294(73)
367.4	-0.072(13)	$B_2(^{177m}Lu)$ = 0.204(36)
378.5	-0.095(2)	$B_2(^{177m}Hf)$ = 0.262(7)
385.0	-0.092(11)	$B_2(^{177m}Hf)$ = 0.244(32)
413.6	-0.087(4)	$B_2(^{177m}Lu)$ = 0.223(10)
418.5	-0.093(3)	$B_2(^{177m}Hf)$ = 0.268(12)
466.0	-0.071(27)	$B_2(^{177m}Hf)$ = 0.198(76)

[a]Parentheses enclose experimental uncertainty of last digit or digits.

[b]Decay of ^{177g}Lu; all other entries are from ^{177m}Lu decay.

TABLE II. Magnetic hyperfine fields of impurities in $ZrFe_2$.

Impurity	$\lvert H(ZrFe_2)\rvert$ (kOe)	$\lvert H(Fe)\rvert$ (kOe)
Sc	400 ± 140[a]	94 ± 3[e]
Co	200 ± 15[a]	288 ± 1[f]
I	220 ± 10[b]	1130 ± 40[f]
Er	8300 ± 1000[c]	2700 ± 400[f]
Lu	413 ± 29[a]	483 ± 60[f]
Hf	200 ± 20[d]	606 ± 70[f]
Ta	322 ± 33[a]	656 ± 13[f]
Np	1370 ± 110[b]	~ 0[g]

[a]Present work.

[b]Ref. 40.

[c]Ref. 2.

[d]Refs. 3 and 37.

[e]D. K. Gupta, A. K. Singhvi, D. N. Sanwal, and G. N. Rao, Phys. Rev. B 7, 2942 (1973).

[f]Ref. 42.

[g]$\lvert H\rvert$ probably small; see discussion in text.

TABLE III. E2/M1 γ-ray mixing ratios deduced from the decays of oriented $^{177m,177g}Lu$.

Nucleus	$K^{\pi}[Nn_z\Lambda]$	$I_i \rightarrow I_f$	Energy (keV)	Mixing Ratio δ: Present work	Mixing Ratio δ: Previous work	$\frac{g_K - g_R}{Q_o}$
^{177}Lu	$7/2^+[404]$	9/2 → 7/2	121.6	+0.54 ± 0.07	± 0.49 ± 0.03[a]	+0.048 ± 0.006
		11/2 → 9/2	147.1	$+0.54^{+0.12}_{-0.09}$	± 0.62 ± 0.09[b]	+0.047 ± 0.009
		13/2 → 11/2	171.8	$+0.59^{+0.31}_{-0.15}$	±0.51 ± 0.04[b]	+0.042 ± 0.014
		15/2 → 13/2	195.5	$+0.41^{+0.19}_{-0.11}$	±0.42 ± 0.07[b]	+0.060 ± 0.019
		17/2 → 15/2	218.1	+0.52 ± 0.05	±0.46 ± 0.05[b]	+0.046 ± 0.005
^{177}Hf	$9/2^+[624]$	11/2 → 9/2	105.3	-0.36 ± 0.04	-0.34 ± 0.02[c]	-0.050 ± 0.006
		13/2 → 11/2	128.5	-0.37 ± 0.06	-0.37 ± 0.02[c]	-0.051 ± 0.008
		15/2 → 13/2	153.3	-0.33 ± 0.05	-0.36 ± 0.02[c]	-0.058 ± 0.007
		17/2 → 15/2	174.4	-0.32 ± 0.04	-0.38 ± 0.03[c]	-0.060 ± 0.008
		19/2 → 17/2	204.1	-0.33 ± 0.05	-0.36 ± 0.03[c]	-0.061 ± 0.008
		21/2 → 19/2	214.4	-0.29 ± 0.02	-0.33 ± 0.04[c]	-0.066 ± 0.005
^{177}Hf	$7/2^-[514]$	9/2 → 7/2	113.0	-4.7 ± 0.2	-4.8 ± 0.2 [c]	-0.0051 ± 0.0002
		11/2 → 9/2	136.7	-3.0 ± 0.7	±2.9 ± 0.4 [d]	-0.0080 ± 0.0020
		13/2 → 11/2	159.8	-2.4 ± 1.0		-0.0097 ± 0.0040

[a] Ref. 26.

[b] Ref. 7.

[c] Ref. 14.

[d] Ref. 19.

TABLE IV. M2/E1 mixing ratios of γ rays in ^{177}Hf.

γ-ray energy (keV)	$(I^{\pi})_i \rightarrow (I^{\pi})_f$	δ	Δ $\left(\frac{\mu_N\text{-cm}}{\text{e-cm}}\right)$	$\frac{\langle E1\rangle^a}{(2I_i+1)^{1/2}}$ (units of 10^{-3} e-cm)	$\frac{\langle M2\rangle}{(2I_i+1)^{1/2}}$ (units of $10^{-3}\mu_N$-cm)	C_0	C_1	C_2	C_3	C_4
71.6	$9/2^+ \rightarrow 11/2^-$	-0.051±0.037	0.85±0.62	+ 5.7	+4.7 ± 3.5	0.34	1.92	2.75	0.67	0.00
208.3	$9/2^+ \rightarrow 9/2^-$	+0.07 ±0.02	-0.40±0.12	+ 8.3	-3.3 ± 1.0	0.60	0.74	2.22	1.21	0.00
291.4	$17/2^+ \rightarrow 15/2^-$	+0.08 ±0.08	-0.33±0.33	-11.4	+3.8 ± 3.8	-0.04	-3.63	-3.73	4.65	4.74
292.5	$19/2^+ \rightarrow 17/2^-$	+0.08 ±0.08	-0.33±0.33	-14.0	+4.6 ± 4.6	-0.11	-3.77	-4.04	5.27	5.49
299.0	$15/2^+ \rightarrow 13/2^-$	+0.11 ±0.05	-0.44±0.20	- 8.8	+3.9 ± 1.7	0.05	-3.42	-3.30	3.99	3.89
305.5	$13/2^+ \rightarrow 11/2^-$	+0.16 ±0.07	-0.63±0.27	- 5.9	+3.7 ± 1.6	0.18	-3.11	-2.67	3.27	4.11
313.7	$11/2^+ \rightarrow 9/2^-$	+0.06 ±0.05	-0.23±0.20	- 2.9	+0.7 ± 0.7	0.38	-2.62	-1.68	2.44	1.68
321.3	$9/2^+ \rightarrow 7/2^-$	+0.17 ±0.01	-0.63±0.04	+ 0.62	-0.39 ± 0.03	0.71	-1.75	0.00	1.43	0.00

[a]Computed, based on the work of Bernthal and Rasmussen (Ref. 10).

TABLE V. 0° -180° asymmetries of ^{177}Lu γ rays.

γ-ray energy (keV)	$I_i^\pi \rightarrow I_f^\pi$	Multipolarity	Asymmetry (units of 10^{-4}) Peak + background	Asymmetry (units of 10^{-4}) Peak
118[a]	$11/2^+ \rightarrow 9/2^-$	E1	-1.3 ± 2.1	
147	$11/2^+ \rightarrow 9/2^+$	E2/M1	-0.6 ± 2.2	-12 ± 44
267	$11/2^+ \rightarrow 7/2^+$	E2	4.0 ± 2.9	28 ± 20
151[a]	$13/2^+ \rightarrow 11/2^-$	E1	-0.5 ± 2.3	
172	$13/2^+ \rightarrow 11/2^+$	E2/M1	0.3 ± 2.2	6 ± 44
319	$13/2^+ \rightarrow 9/2^+$	E2	-1.1 ± 2.9	
186[a]	$15/2^+ \rightarrow 13/2^-$	E1	0.0 ± 2.4	
195	$15/2^+ \rightarrow 13/2^+$	E2/M1	4.7 ± 2.7	95 ± 55
367	$15/2^+ \rightarrow 11/2^+$	E2	-1.4 ± 3.5	-14 ± 35
217[a]	$17/2^+ \rightarrow 15/2^-$	E1	-0.8 ± 2.6	
218	$17/2^+ \rightarrow 15/2^+$	E2/M1		-16 ± 52
413	$17/2^+ \rightarrow 13/2^+$	E2	-0.4 ± 3.0	- 1 ± 9

[a]Suggested E1 transition not actually observed in γ-ray spectra.

Figure Captions

Fig. 1. Decay scheme of ^{177m}Lu to levels of ^{177}Lu and ^{177}Hf, taken from the work of ref. 9. The Nilsson assignments $K^{\pi}[Nn_z\Lambda]$ are indicated for the intrinsic states. The Lu → Hf beta decays are shown as double lines and are labeled with the end-point energy in keV and the relative branching intensity. The ^{177}Hf interband E1 transitions are shown connecting the dashed extensions of the states of the $9/2^+[624]$ and $7/2^-[514]$ bands.

Fig. 2. Low-energy γ-ray spectrum from the decay of ^{177m}Lu. The peaks are labeled by the γ-ray energies in keV. Those peaks labeled below the spectrum are those from the ^{177m}Lu decay; those labeled above the spectrum are from contaminant activities.

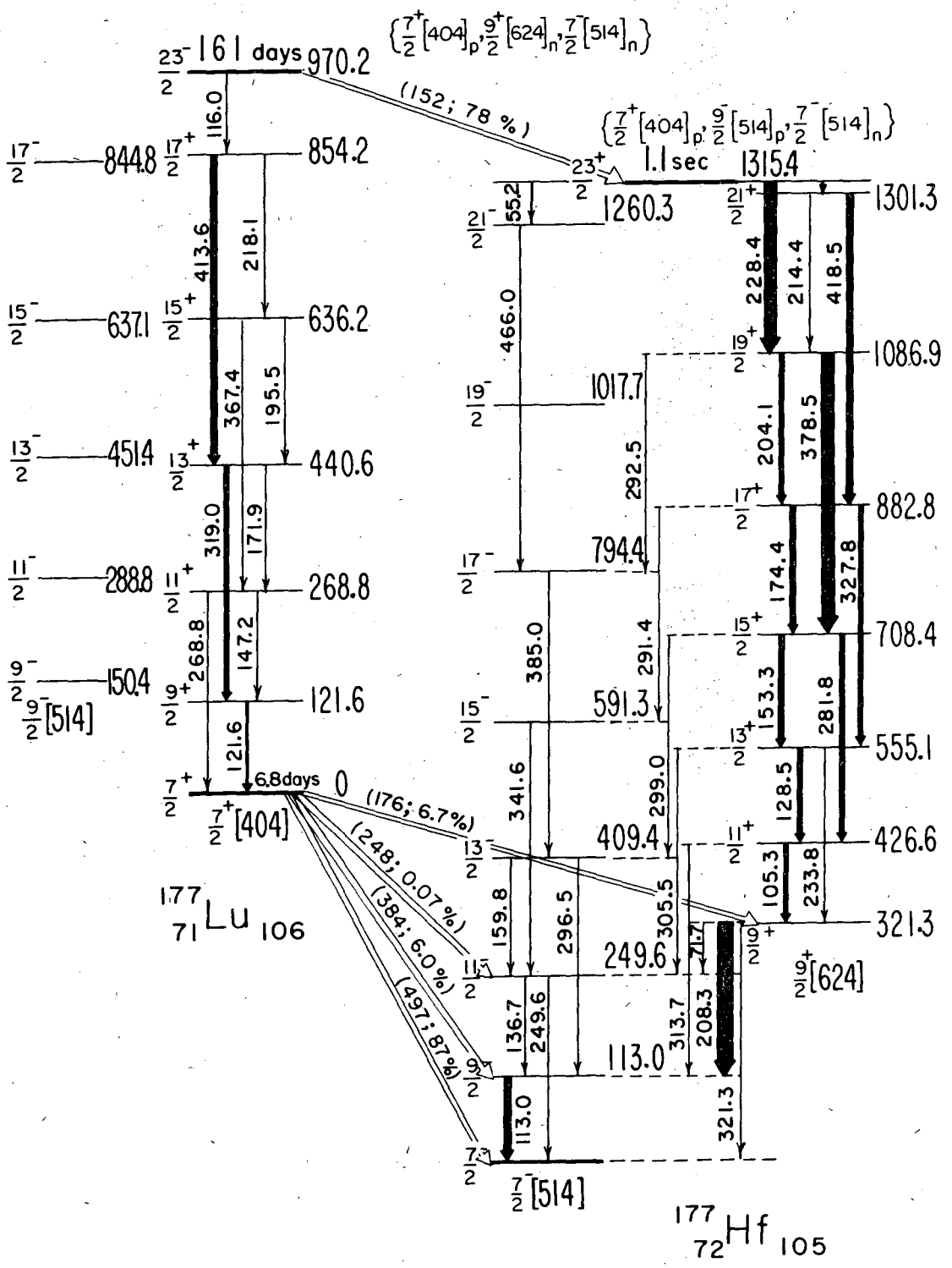
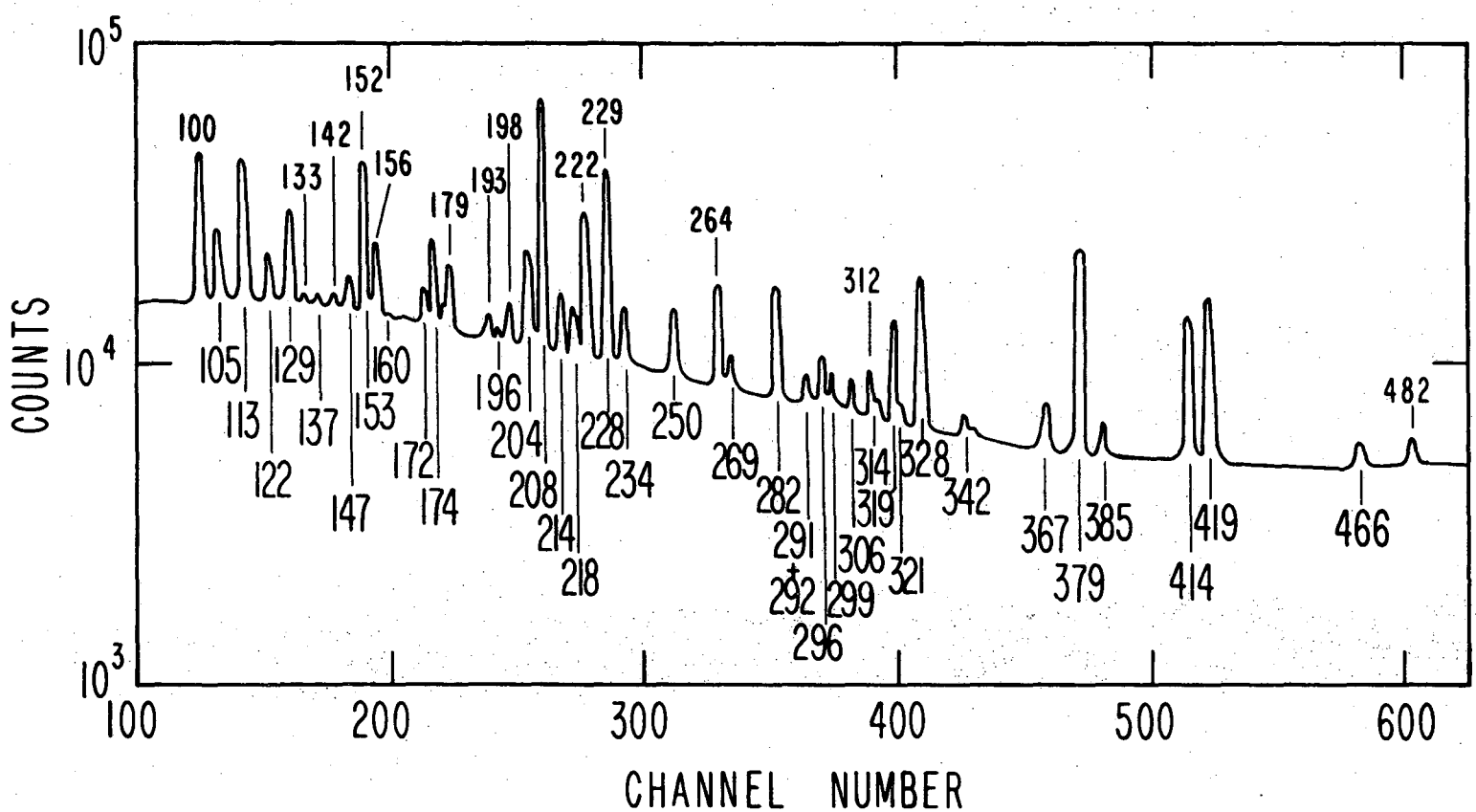

161 days
970.2
(152; 78 %)
1.1 sec
1315.4
844.8
854.2
637.1
636.2
451.4
440.6
288.8
268.8
150.4
121.6
6.8days
0
1260.3
1017.7
794.4
591.3
409.4
249.6
113.0
1301.3
1086.9
882.8
708.4
555.1
426.6
321.3
(176; 6.7%)
(248; 0.07%)
(384; 6.0%)
(497; 87%)
177 71 Lu 106
177 72 Hf 105
XBL741-2136

Fig. 1



XBL741-2135

Fig. 2

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