Nuclear-orientation measurement of parity admixture in the 501-keV gamma transition in $^{180}Hf^{m}$†

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The effect of the parity nonconserving nuclear force on the 501-keV γ transition of ^{180}Hf has been confirmed by a remeasurement of the angular distribution asymmetry of the radiation emitted by $^{180}Hf^{m}$ polarized at temperatures down to 16 mK. A difference of 1% was observed between the γ-ray intensities parallel and antiparallel to the nuclear polarization direction. When the results of the present study are averaged with previous nuclear polarization experiments and compared with the results of circular polarization experiments, it is deduced that the parity mixing can be uniquely assigned to an irregular $\tilde{E}2$ multiple, rather than to a higher order irregular multiple such as $\tilde{M}3$. Assuming a vanishing $\tilde{M}3$ component, the present study yields $\epsilon = \langle\tilde{E}2\rangle/\langle M2\rangle = -0.026 \pm 0.002$, and the global average from all measurements is $\epsilon = -0.030 \pm 0.002$.

[NUCLEAR STRUCTURE ^{180}Hf; 501-keV transition, parity mixing.]

I. INTRODUCTION

The current-current theory of weak interactions of Feynman and Gell-Mann[1,2] suggests that the strangeness-conserving nonleptonic weak interaction will contribute to the internucleon potential and will result in small parity impurities in nuclear states.

In the past there have been numerous experimental studies of this effect in nuclei, either by searching for decays which would be absolutely forbidden except for the parity-nonconserving interactions, or else by searching for evidence of interference between the parity-conserving and possible nonconserving multipoles in the nuclear electromagnetic radiation field. Numerous theoretical computations of parity nonconserving effects have likewise been attempted. The experimental and theoretical situation has been most recently summarized by Gari,[3] and previous reviews have been given by Hamilton[4] and Henley.[5] Discussions of a more pedagogic nature regarding weak interactions and their relationship to possible parity nonconserving effects in nuclei may be found in the works of Blin-Stoyle[6] and Commins.[7]

The 501-keV γ ray emitted in the decay of $^{180}Hf^{m}$ provides a particularly striking case of the interference between the regular parity-conserving and the irregular parity-nonconserving multipoles. This case has been studied previously by observing the circular polarization of the radiation from an unpolarized sample,[8-10] and during the initial phase of the present studies the results of a similar experiment on the angular distribution asymmetry from a polarized sample were published.[11] We decided, therefore, to attempt an independent confirmation of the effect under somewhat varied conditions, in particular by varying the nuclear environment and by reaching lower temperatures. Although, as discussed below, these objectives were only partly realized, we did succeed in attaining somewhat greater sensitivity to the higher-order irregular multipoles, and were thus able to assign the parity impurity uniquely to an admixture of irregular $\tilde{E}2$ radiation and eliminate the possibility of the presence of higher-order irregular multipoles ($\tilde{M}3$, etc.).

The theory of this experiment is given in Sec. II, and experimental procedures are described in Sec. III. Section IV concerns data reduction, and the results are treated in Sec. V.

II. THEORY

The theoretical basis for parity mixing in nuclear levels has been given by numerous previous works[3-7] and need not be reproduced here. We note only that the ratio of the irregular to the regular amplitude is expected in first order to be equal to FR, where F gives the relative amplitude[12] of the weak Hamiltonian ($\sim 10^{-7}$) and R contains the nuclear-structure dependent factors describing the overlap of the admixed nuclear wave functions.

The ^{180}Hf level scheme is illustrated in Fig. 1.[13] The 8^- ($K=8$) isomeric level decays to the 6^+ level of the $K=0$ ground-state rotational band by means of the 501-keV transition, which is of mixed $E3/M2$ multipolarity, with $\langle E3\rangle/\langle M2\rangle = +5.3\pm 0.3$.[11] The parity nonconserving interaction is expected to admix a small 8^+ component into the 1.142 MeV 8^- level (a similar admixture of a 6^- component into the 0.641 MeV 6^+ level is neglected for the present discussion). To the extent that this admixture may be treated by standard methods of first-order perturbation theory, the close spacing between the 8^- level and the 8^+ level at 1.084 MeV tends to magnify the admixture (i.e., increase R); in addition, the regular (parity conserving) $E3$ and $M2$ components of the 501-keV radiation field are strongly hindered, resulting in a relative enhancement of any possible irregular component which is not similarly hindered.

The angular distribution of γ radiation from an oriented nucleus is described by[14]

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

where the Q_k correct for the finite geometry, the

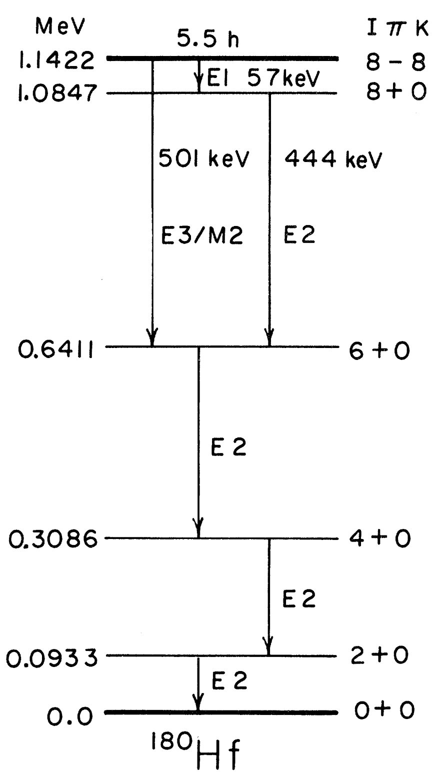

FIG. 1. Decay scheme of ^{180}Hf^m.

orientation parameters B_k depend on the temperature and on the orienting interaction, the U_k correct for loss of orientation arising from unobserved intermediate transitions, and the A_k describe the properties of the observed γ ray. The P_k are Legendre polynomials, and θ is the angle between the axis of orientation and the direction of emission of the γ ray. For the 501-keV transition, all $U_k=1$. The parity mixing is evidenced only in the terms with odd k, which vanish in the absence of parity mixing. For odd k, considering only the lowest-order irregular multipole,

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

where the F_k are the F coefficients. Here, ϵ is the ratio of the irregular to regular matrix elements, in this case $\langle \tilde{E}2\rangle/\langle M2\rangle$, and δ is the $\langle E3\rangle/\langle M2\rangle$ mixing ratio. The asymmetry α is defined as

$$\alpha = 2\frac{W(180^\circ) - W(0^\circ)}{W(180^\circ) + W(0^\circ)}$$

$$= -2\,\frac{Q_1B_1A_1 + Q_3B_3A_3}{1 + Q_2B_2A_2 + Q_4B_4A_4}\,. \qquad (3)$$

In the present experiment the asymmetry α of the 501-keV γ ray has been determined and the irregular-to-regular mixing ratio ϵ has been deduced.

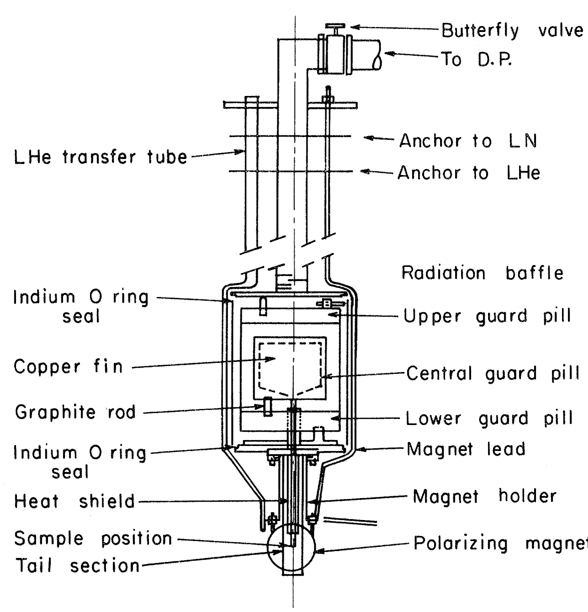

FIG. 2. The low-temperature cryostat and Dewar system.

III. EXPERIMENTAL

A. Low temperature apparatus

The low temperatures necessary to polarize the nuclei were produced by the demagnetization of chromium potassium sulfate (chrome alum) salt prepared in a glycerin slurry. Thermal contact to the salt slurry was achieved by means of 16 sheets of 0.13 mm copper foil. A schematic view of the apparatus is shown in Fig. 2.

The salt pill was cooled in thermal contact with a bath of liquid helium pumped to 1 K, and was demagnetized from a field of 50 kG, reaching a temperature of 10 mK, as determined by a $^{60}Co(Fe)$ thermometer.

The polarizing magnets consisted of two pairs of perpendicularly oriented superconducting Helmholtz coils, made of 0.11 mm Nb-Ti wire wound on a Fiberglas form. The control sequence for the polarizing magnets is illustrated in Fig. 3. The charging and discharging of the magnets were controlled by a ramp generator and timer, and the two magnet controls could be arranged to be 90° or 180° out of phase, such that the effect of the ramps would be to rotate the field by 90° or 180°. The applied field strength was 2.0 kOe.

B. Detectors and data acquisition

The γ rays were observed using Ge(Li) detectors of approximately 40 cm^3 active volume. Either two detectors at 180° to each, or four detectors at 90° apart, were used to collect the data. The detector preamplifier pulse was fed to a pole-zero compensated high-rate linear amplifier (HRLA). The slow pulse from the HRLA was used for energy discrimination, and the fast pulse was used for pileup rejection, in which pileup events and slow rise-time pulses resulting from partial charge collection were rejected. Energy discrimination was done using single-channel analyzers, with the fast pulse from the pileup rejector as a strobe. The resulting pulse was routed and digitized in an analog-to-digital converter, and finally was stored in the memory of a PDP-7 computer and written onto magnetic tape.

C. Sample preparation

The cubic ferromagnet $ZrFe_2$ provides a convenient environment in which to polarize Hf impurities. Dilute Hf impurities experience a magnetic hyperfine field in $ZrFe_2$ of 200± 20 kG.[15] [Early attempts were made to prepare a sample of Hf(Fe), in which the Hf is expected to experience a hyperfine field larger by a factor of 3. Activated $^{180}Hf^m$ metal was arc-melted with Fe to prepare Hf(Fe) alloys with 0.01-0.1 at.% Hf. The resulting alloys were rolled into foils and cooled in the low-temperature apparatus. The effective field on the Hf was deduced to be in the neighborhood of 200 kG; this reduced effective hyperfine field is likely due to the presence of a substantial fraction ($\frac{2}{3}$) of the Hf impurity atoms in nonmagnetic sites.] The compound $Hf_{0.1}Zr_{0.9}Fe_2$ was prepared in an arc furnace in an argon atmosphere, using Fe and Zr metals of 99.99% purity, along with Hf enriched to 87% in ^{179}Hf. The alloy was produced by first melting together Zr and Fe in stoichiometric ratios to make $ZrFe_2$; the resulting ingot was remelted several times to assure homogeneity. An x-ray powder diffraction spectrum of a portion of the ingot is

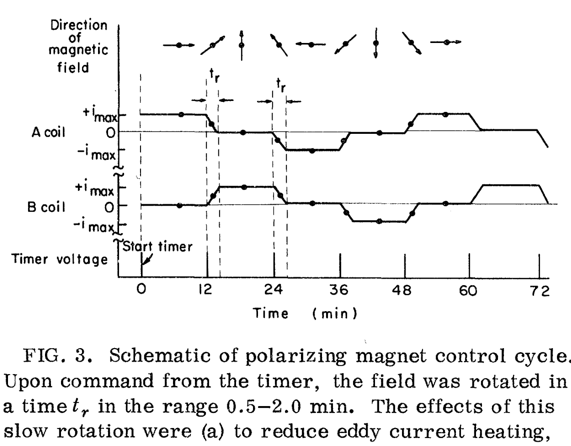

FIG. 3. Schematic of polarizing magnet control cycle. Upon command from the timer, the field was rotated in a time t_r in the range 0.5–2.0 min. The effects of this slow rotation were (a) to reduce eddy current heating, and (b) to maintain the sample in magnetic saturation. The field directions are defined such that when $i_A > 0$, the field is in the direction of detector 1 and when $i_B > 0$, in the direction of detector 2.

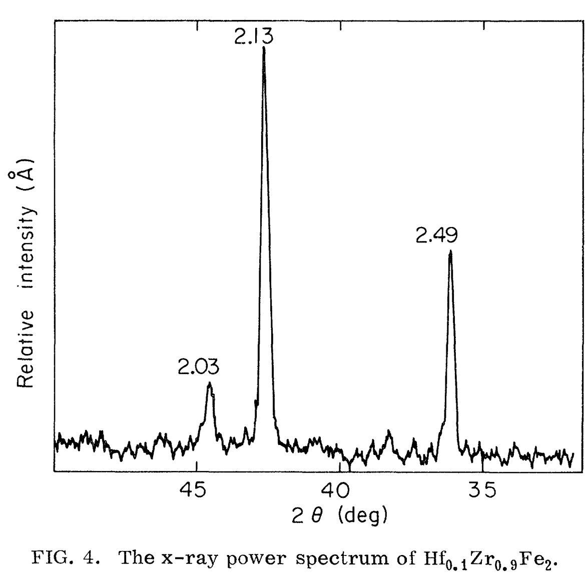

FIG. 4. The x-ray power spectrum of $Hf_{0.1}Zr_{0.9}Fe_2$.

shown in Fig. 4. The lines shown are characteristic of $ZrFe_2$ in the face-centered cubic structure; no evidence is seen for other possible phases such as Zr_2Fe (2.35 Å) or $ZrFe_3$ (2.07 Å, 2.25 Å) in the limit of 10% of the $ZrFe_2$. The resulting alloy was then remelted in stoichiometric ratios with Hf and Fe to form $Hf_{0.1}Zr_{0.9}Fe_2$. Disks of the alloy were spark-cut and mechanically polished to thicknesses of 0.6–0.8 mm; the disk diameter was in the range 5–7 mm.

Three different types of samples were employed. In one method, the compound was annealed at 750°C for 12 h following melting in the arc furnace. The compound was then neutron-irradiated for 30 min at a flux of 1×10^{13} neutrons $cm^{-2}\,sec^{-1}$. A second method similarly employed unannealed samples. Finally, the alloy was prepared using previously activated Hf in order to avoid the problems associated with radiation damage following neutron capture. Within experimental error, no differences in nuclear polarization properties were observed between the various ways of sample preparation.

IV. DATA REDUCTION

A. Thermometry

The sample temperature was monitored using a $^{60}Co(Fe)$ thermometer; the anisotropy of the angular distribution of the γ rays following the ^{60}Co decay was used to deduce the temperature.[16] It was also possible to use the ^{180}Hf γ rays for thermometry purposes, since the $^{180}Hf^m$ hyperfine splitting has been previously measured to be 7.9 ± 0.5 mK.[11] The temperature deduced from the ^{60}Co in the 20–30 mK range was consistently 2–3 mK lower than that obtained from the ^{180}Hf. (The ^{60}Co and ^{180}Hf samples were each soldered directly to the cold finger, with the ^{180}Hf at the end of the cold finger and the ^{60}Co somewhat nearer the salt pill. Difficulties encountered in "wetting" the $ZrFe_2$ samples necessitated the use of ordinary "soft" solder with acid flux.) In addition, it proved impossible, despite repeated attempts using various source-mounting arrangements, to cool the Hf sample below 16 mK, even when the cold finger was in the neighborhood of 10 mK. The irreducible thermal gradient was interpreted as arising from a lack of sufficiently good thermal contact between the Hf sample and the cold finger. Thus the temperature deduced from the Hf has been used in analyzing the 501-keV angular distribution asymmetry. Specifically, the angular distribution of the pure $E2$ 444-keV transition has been employed, assuming the unobserved 57-keV transition to be of pure $E1$ multipolarity.[17]

B. Data analysis

The data were written onto magnetic tape in the form of 1024-channel γ-ray spectra. Each spectrum corresponded to the results of counting with a single detector at a given position of the applied field for a period of approximately 10 min.

Following subtraction of an assumed linear background, the spectra were integrated between two selected limits of 444- and 501-keV peaks, and the peak intensities were normalized according to the analyzer live times. The asymmetries were computed according to Eq. (3) by comparing the counting rate for each counting period with the average of those of the previous and subsequent periods having the field directed 180° opposite. Finally, the deduced asymmetries were corrected for small count-rate nonlinearities of the electronics, an effect which results from the high count rates during the early counting periods. These correction factors were deduced empirically from the performance of each detector and associated electronics. An illustration of this nonlinearity is shown in Fig. 5. Such nonlinearities not only can lead to erroneous conclusions regarding the counting rate asymmetry, but they also result in incorrect deductions of the sample temperature.

V. RESULTS

The results of this experiment represent data from four different samples, each of which was

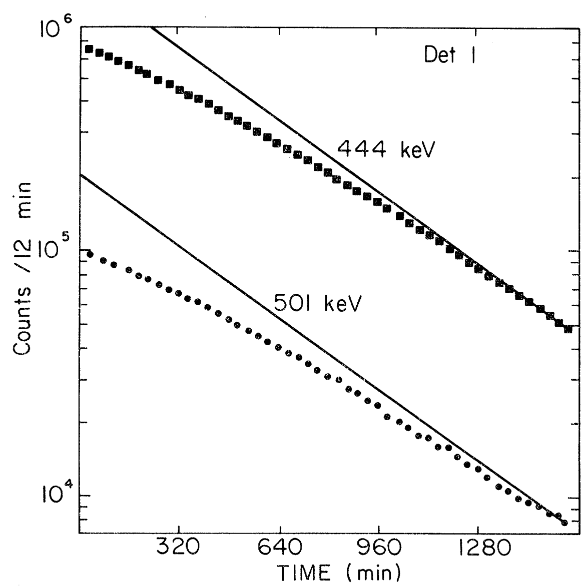

FIG. 5. Integral count-rate nonlinearity of a typical detector. The solid line represents the extrapolation of the data from the region of low counting rates; the points are experimental data.

TABLE I. Parity nonconserving asymmetry of the ^{180}Hf 501-keV γ ray.

Sample No.	Temperature (mK)	Detector No.	Source-to-detector distance (cm)	Detector orientation (deg)	Asymmetry [a]	$\lvert\epsilon\rvert$ [a]
1	16–28	A	22	270		0.0464 (59)
		B	20	0		0.0378 (68)
		C	10	90		0.0464 (64)
		D	11	180		0.0252 (63)
2	16	A	30	180	0.0160 (40)	0.0293 (75)
		E	11	270	0.0100 (28)	0.0184 (52)
		C	12	90	0.0138 (27)	0.0252 (50)
		D	13	0	0.0162 (44)	0.0296 (81)
3	22	A	27	270	0.0111 (30)	0.0244 (67)
		E	10	180	0.0068 (25)	0.0151 (55)
		C	12	0	0.0131 (23)	0.0290 (52)
		D	13	90	0.0111 (33)	0.0244 (73)
4	17	A	17	270	0.0127 (47)	0.0281 (89)
		E	9	90	0.0129 (49)	0.0283 (92)

[a] The statistical uncertainties of the last two digits are indicated in parentheses.

counted during two half-lives. Representative temperatures at which three of the four samples were run were 16, 17, and 22 mK; a fourth sample was observed at temperatures in the range 16–28 mK. The results are summarized in Table I. For sample No. 1, the reasonably rapid warm-up rate necessitated a point-by-point calculation of the parity mixing ratio ϵ; hence no average value of the asymmetry was obtained. The detector code refers to the choice of a selection of detectors available at Lawrence Berkeley Laboratory. The asymmetries are defined according to Eq. (3), and the mixing ratio ϵ was deduced from Eq. (2). The orientation parameters B_1 and B_3 may be either positive or negative according to the sign of the hyperfine splitting parameter Δ; since we deduced the odd-order orientation parameters from the even-order ones (which are always positive, independent of the sign of Δ), the sign of ϵ may not be deduced unambiguously from α. The deduced signs of the moment and hyperfine field[15] indicate, however, that B_1 is positive, and thus that $\epsilon < 0$.

The weighted average value of ϵ based on the data of Table I is $\epsilon = -0.029 \pm 0.002$. Computing the normalized χ^2 value of the 14 individual measurements of ϵ, we obtain $\chi^2 = 2.3$. This value is somewhat large, and perhaps suggests a systematic source of error in the data. A careful examination of each individual data point revealed no systematic effect which could be correlated with the detector identity, its orientation relative to the polarizing magnets, the distance from the cryostat, and so forth. However, the data from sample No. 1 seem to indicate a systematically large value of ϵ, perhaps owing to the different means of handling the data. To account for the possibility of a syste-

TABLE II. Comparison of results on parity nonconservation in the 501-keV transition of ^{180}Hf.

Method [a]	$\epsilon = \langle \tilde{E}2 \rangle / \langle M2 \rangle$	Reference
P_γ	-0.041 ± 0.007	Jenschke and Bock, Ref. 9.
P_γ	-0.033 ± 0.009	Lipson, Vanderleeden, and Boehm, Ref. 10.
P_γ	-0.029 ± 0.006	Kuphal, Ref. 11.
$\gamma(\theta)$	-0.038 ± 0.004	Krane, Olsen, Sites, and Steyert, Ref. 12.
$\gamma(\theta)$	-0.031 ± 0.003	Krane, Olsen, and Steyert, Ref. 17.
$\gamma(\theta)$	-0.026 ± 0.002	Present work.

[a] P_γ = circular polarization of γ radiation from a random source; $\gamma(\theta)$ = angular distribution asymmetry from a polarized source.

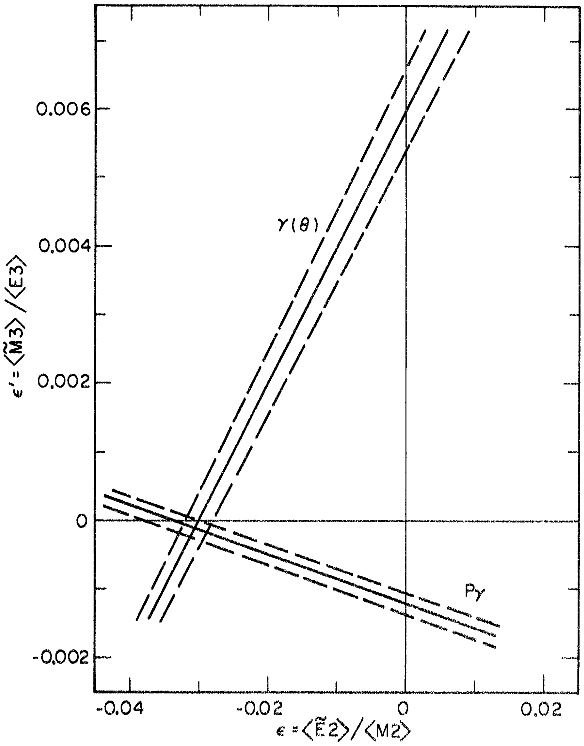

FIG. 6. The relationship between the irregular mixing amplitudes $\epsilon = \langle\tilde{E}2\rangle/\langle M2\rangle$ and $\epsilon' = \langle\tilde{M}3\rangle/\langle E3\rangle$ derived from the average results of circular polarization (P_γ) and angular distribution anisotropy [$\gamma(\theta)$] measurements.

matic error in these results, the uncertainties of the deduced results from sample No. 1 should be increased by a factor of 2. This yields a new average of $\epsilon = -0.026 \pm 0.002$, with $\chi^2 = 1.0$. The final result of the present experiment is compared with those of previous studies in Table II. In doing the comparison, all results have been evaluated using $\delta = +5.3$. The weighted average of the six results to date is $\epsilon = -0.030 \pm 0.002$.

The above deduction of ϵ is based on the implicit assumption that the parity impurity is due solely to the irregular $\tilde{E}2$ multipole. Although the parity impurity is generally ascribed to the presence of the lowest-order irregular multipole, this assumption has not been tested directly. However, from a comparison of the results of the circular polarization studies with those of the angular distribution studies, the nature of the mixing can be determined. Including the two lowest irregular multipoles ($\tilde{E}2 + \tilde{M}3$), the circular polarization can be written as

$$P_\gamma = \frac{2}{1+\delta^2}(\epsilon + \delta^2\epsilon'), \tag{4}$$

where $\epsilon = \langle\tilde{E}2\rangle/\langle M2\rangle$ and $\epsilon' = \langle\tilde{M}3\rangle/\langle E3\rangle$. Similarly, the angular distribution asymmetry can now be written in terms of the coefficients

$$A_k = \frac{2}{1+\delta^2}\{\epsilon[F_k(LLI_fI_i) + \delta F_k(LL'I_fI_i)] + \epsilon'[\delta F_k(LL'I_fI_i) + \delta^2 F_k(L'L'I_fI_i)]\}. \tag{5}$$

Thus each type of experiment yields a relationship between ϵ and ϵ', and from a comparison we can deduce a set of values satisfying both types of results. (It should be noted here that the lower temperatures obtained in the present work relative to previous work provide approximately 60% greater sensitivity to ϵ'.)

In Fig. 6 are illustrated the relationships between ϵ and ϵ' derived from the average results of three circular polarizations and of the angular distribution anisotropy measurements. The intersection of the two curves yields the values

$\epsilon = -0.031 \pm 0.002$,

$\epsilon' = -0.0001 \pm 0.0002$.

The combined result of the two types of measurements thus supports the assumption that the parity impurity arises only from the lowest-order irregular multipole.

The case of ^{180}Hf represents the only nucleus for which consistent evidence of parity nonconservation has been obtained from different methods and from independent investigations. As the summary by Gari[3] suggests, possible evidence has been found in other cases, but there is in general a lack of agreement among the various results. The present results are entirely consistent with the other published results for ^{180}Hf and support the evidence for parity nonconserving effects in this nucleus. The chief value of the present measurement is to confirm the earlier measurements under somewhat altered experimental conditions.

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