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Nuclear Structure and Parity Mixing in the Decays from Oriented ^{182}Ta†

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Angular distributions of 26 γ rays in ^{182}W have been measured following the β decay of ^{182}Ta oriented at low temperatures in iron. Triple multipole mixing ($E1+M2+E3$) of the 1189-keV γ radiation was inferred by comparison of the present results with those of γ-γ directional correlations and internal-conversion measurements; values deduced for the mixing ratios of the 1189-keV radiation were $\delta(M2/E1)=+0.49\pm0.03$ and $\delta(E3/E1)=-0.64\pm0.05$. $E2/M1$ multipole mixing ratios deduced for other γ transitions were (energies in keV): $\delta(85)=+0.30\pm0.02$; $\delta(114)=+0.31\pm0.02$; $\delta(179)=+0.92^{+0.13}_{-0.07}$; $\delta(1002)=-(8.9^{+2.1}_{-1.8})$; $\delta(1121)=+21^{+19}_{-6}$; $\delta(1157)=-(7.6^{+\infty}_{-4.8})$; $\delta(1231)=-(60^{+100}_{-20})$. The $M2/E1$ mixing ratios deduced were $\delta(222)=+0.007\pm0.005$; $\delta(1274)=+0.42\pm0.04$. The $E3/M2$ mixing ratio of the 960-keV transition was deduced to be $-3.6\leq\delta(960)\leq+0.3$. The allowed β transition populating the 1374-keV level was determined to be (38 ± 23)% Fermi ($L=0$) and $62\mp23)$% Gamow-Teller ($L=1$). In the first-forbidden β transition populating the 1443-keV level, probably all, but at least half, of the β transitions carry one unit of angular momentum, with the remainder carrying two units. The hyperfine splitting of ^{182}Ta in iron was found to be 21 ± 2 mK, corresponding to a ^{182}Ta ground-state magnetic moment of $2.6\pm0.2\mu_N$. Measurements of the parity-nonconserving 0–180° (forward-backward) asymmetry of the 1189-keV γ-ray angular distribution indicated an asymmetry of $(-2.8\pm1.7)\times10^{-4}$; vanishing asymmetries were found for the 222-, 1121-, and 1274-keV γ rays. These results would seem to be in reasonable agreement with the vanishing circular polarization of the ^{182}W γ rays measured elsewhere.

I. INTRODUCTION

The nuclei with mass numbers $180<A<200$ are in a region in which the nuclear shapes are in transition from the strongly deformed nuclei with $A<180$ to the spherical nuclei in the region of the doubly magic ^{208}Pb. This transition is a gradual one (as contrasted with the rather sharp onset of deformation near $A=150$). Thus a systematic study of the nuclei with $180<A<200$ should show a gradual variation of the properties associated with the competing modes of nuclear structure.

A theoretical interpretation of the structure in this region has been accomplished with considerable success by Kumar and Baranger.[1] Using a microscopic description of the nuclear interaction in terms of a quadrupole force coupled to a pairing interaction, they have computed the collective parameters of the Bohr Hamiltonian, and have obtained predictions concerning the energy levels and static and dynamic multipole moments of the positive-parity states of even-even nuclei in the mass region $182<A<196$. In addition, magnitudes and relative phases of the $M1$ and $E2$ matrix elements have been computed,[2] and have been found to be in excellent agreement with $E2/M1$ mixing ratios extracted from directional-correlation measurements.[3]

In order to investigate the structure of the nucleus ^{182}W, which is at the deformed side of the transition region, we have observed the angular distribution of γ radiations from ^{182}Ta oriented in iron at low temperatures, and have deduced multipole mixing ratios of the various γ radiations.

The presence of the weak nucleon-nucleon interaction[4] in the nuclear Hamiltonian gives rise to a small (order 10^{-7}) parity impurity in nuclear states. Such parity impurities may be detected through a forward-backward asymmetry in the γ radiation field from polarized nuclei[5,6] or by measurement of the circular polarization of γ radiations from unpolarized nuclei.[7] The size of the laboratory effect produced by such a parity impurity is in large part dependent upon the retardation by nuclear-structure effects of the "regular" part of the γ transition; previous studies of the angular distribution of γ radiation from polarized nuclei[5,6] have revealed forward-backward asymmetries of greater than 1.5% in the case of ^{180}Hf and less than 10^{-4} in the case of ^{159}Gd. In order to continue the study of parity-violating effects, we have investigated the forward-backward asymmetries of the strongly hindered 222-, 1189-, and 1274-keV transitions in ^{182}W; recent results of circular-polarization measurements[8] indicate a vanishing parity-violating effect for the ^{182}W γ rays.

II. ^{182}W LEVEL SCHEME

The decay scheme of ^{182}Ta to levels of ^{182}W is shown in Fig. 1. Recent Ge(Li)-detector γ spectroscopy measurements[9,10] have placed a large number of transitions in the level scheme corresponding to a ground-state rotational band, a γ-vibrational band, a possible β-vibrational band, and a number of negative-parity bands. The internal-conversion-electron spectrum has been thoroughly investigated[11-14] revealing the multipole intensities and characters of many of the transitions. A number of γ-γ directional-correlation measurements[15-17] have been performed using NaI(Tl) detectors, which are unfortunately not able to resolve many of the lines in the γ-ray spectrum. Recent high-resolution directional-correlation measurements[18] using Ge(Li) detectors, however, have eliminated some of these difficulties.

A summary of the levels of ^{182}W populated by the decays of ^{182}Re and ^{182}Ta and by ^{180}Hf(α, $2n$) reactions is given in Ref. 9. The K assignments given for the levels in Fig. 1 were made[9] on the basis

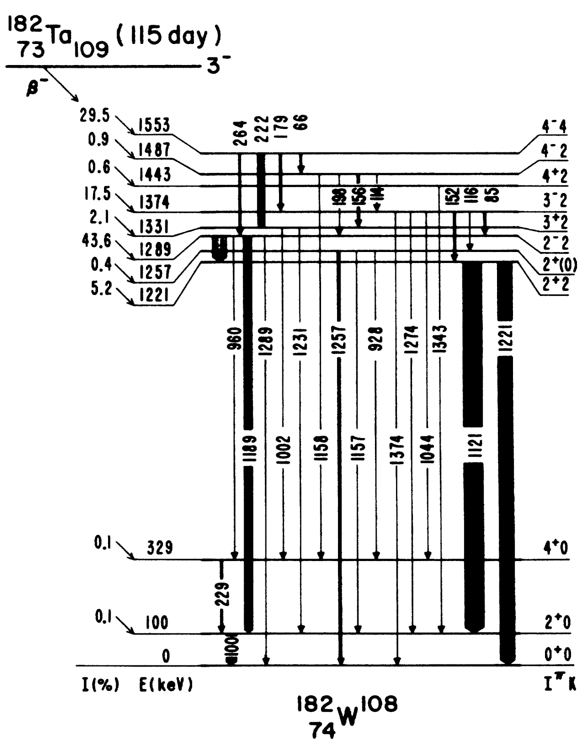

FIG. 1. Decay scheme of ^{182}Ta to levels in ^{182}W.

of reduced transition probabilities from the states populated in the β decays of ^{182}Re and ^{182}Ta. These assignments include the $K=0$ ground-state rotational band [populated up to the 10^+ level in (α, $2n$) reactions]; a $K=2$ γ-vibrational band composed of the 1221-, 1331-, and 1443-keV levels; a $K=2$ negative-parity band (levels at 1289, 1374, and 1487 keV); and the band head of a $K=4$ negative-parity band at 1553 keV. The transition probabilities for the 1257-keV level would be consistent with $K=0$ or 1, and this level has been postulated to be the 2^+ state of the $K=0$ β-vibrational band.[9]

III. EXPERIMENTAL DETAILS

A. Source Preparation

Radioactive ^{182}Ta was obtained by subjecting naturally occurring Ta metal (99.99% ^{181}Ta) to an integrated thermal-neutron flux of 10^{19} neutrons/cm^2. An alloy of 0.07 at.% ^{182}Ta in iron was prepared by melting the irradiated Ta with 99.99% pure iron; the alloy was then rolled to a foil 0.1 mm thick. An oval-shaped sample 8 mm × 4 mm was then cut from the foil and used for the experiment. Before melting, a small amount of ^{54}Mn (from HCl solution) was placed on the surface of the iron so that the 835-keV ^{54}Mn γ ray could be employed for thermometry.[19] The final sample consisted of 25 μCi of ^{182}Ta and 0.7 μCi of ^{54}Mn.

B. Apparatus

The ^{182}Ta nuclei were polarized by subjecting the sample to an external polarizing magnetic field at ultralow temperatures. The external magnetic field of 2 kG was produced by a pair of superconducting Helmholtz coils. Two pairs of coils with their axes oriented at right angles to one another were used.

A ^{3}He-^{4}He dilution refrigerator was employed to achieve the low temperatures necessary for ob-

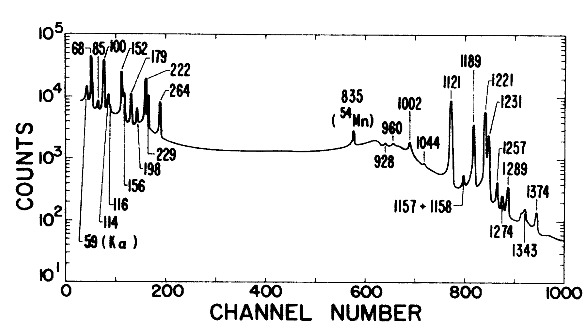

FIG. 2. Ge(Li) detector γ-ray spectrum of the decay of ^{182}Ta. (Energies are in keV.)

servable anisotropic angular distributions of γ rays. Our sample was maintained in thermal equilibrium at 24 ± 2 mK. At this temperature, with the large hyperfine field of Ta in Fe (−656 kG[20]), a nuclear polarization of 75% was achieved. More complete discussions of the experimental low-temperature apparatus have been published previously.[21,22]

The γ rays were observed using two 40-cm^3 coaxial Ge(Li) detectors oriented at right angles (each detector along the axis of one of the pairs of Helmholtz coils). The output of the shaping amplifier for each detector was digitized using a pair of analog-to-digital converters (ADC) operating in the 1024-channel mode. The digitized pulses were stored in the memory of a minicomputer, and the complete spectrum could be printed out at the end of each counting interval using a standard Teletype printer. A sample γ-ray spectrum is shown in Fig. 2.

By passing current through the appropriate pair of coils, the field could be oriented in the direction of either detector. In addition "warm" ($T > 150$ mK) data were taken to be used for normalization. In this way, the normalized counting rates $W(0°)$ and $W(90°)$ were obtained for each detector.

For measurements of the forward-backward asymmetries, the two detectors were placed 180° apart, and the magnetic field direction alternated between pointing at either detector in 5-min intervals. (Between counting intervals the field was rotated by 180° in approximately 1 min, with the source foil kept in magnetic saturation; in this way hysteresis and eddy-current heating were avoided.[22]) Data analysis was performed on-line by the computer which analyzed the peak counting rates, corrected for background and gain shifts, and computed the 0–180° asymmetries.

C. Data Analysis

The angular distribution of γ radiation from an ensemble of oriented nuclei is given by[23]

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

in terms of orientation parameters B_k which describe the orientation of the initial level, deorientation parameters U_k which correct for effects of unobserved intermediate radiations, and angular-distribution coefficients A_k which describe the properties of the observed γ ray. The Q_k correct for the finite solid angle of the radiation detector.[24] The Legendre polynomials P_k are functions of the angle θ, defined with respect to the direction of nuclear polarization. Explicit expressions and numerical values for the B_k, U_k, and A_k are given in the work of Krane.[25] Equation (1) is normalized so that $W(\theta) = 1$ at high temperatures.

The limits on the summation index k are determined by the angular momenta of the nuclear levels and radiations; for the present case $0 \leq k \leq 4$. For 0–90° anisotropy measurements, only even values of k need be considered; parity impurities are revealed by nonvanishing odd-k terms.

The orientation parameters B_k for a state of spin I depend on the ratio of its hyperfine splitting energy $\Delta = \mu H / I k_B$ and the temperature T. The temperature could be determined independently from the angular distribution of the ^{54}Mn γ ray, and the hyperfine field H of Ta in Fe is known.[20] Thus a determination of the B_k provides a measure of the magnetic moment μ of the parent state. An unambiguous determination of B_k may be obtained from the angular distribution of a γ ray for which U_k and A_k are uniquely determined. In the case of ^{182}Ta, the 264-keV γ ray of ^{182}W is a pure $E2$ transition ($A_2 = -0.448$, $A_4 = -0.304$) which follows a pure Gamow-Teller β transition ($U_2 = 0.905$, $U_4 = 0.681$). The orientation parameters of the parent nucleus, and hence the magnetic moment of ^{182}Ta, were thus determined from the angular distribution of the 264-keV γ ray.

The deorientation coefficients U_k in general depend on the multipolarities and intensities of *all* unobserved intermediate (β and γ) radiations leading to the observed transition. In the case of unobserved γ transitions, it is necessary to include the intensities of the competing internal-conversion mode of decay, as well as to consider the *total* mixing amplitudes (from internal conversion, as well as γ radiation). Values of U_k are then computed by considering a weighted average of the U_k for each branch leading to the observed radiation; the U_k for each branch is the product of the indi-

TABLE I. Deorientation coefficients computed for unobserved transitions leading to levels in ^{182}W. The coefficients U_k were computed for all transitions (γ, as well as internal conversion) populating the appropriate level; the uncertainties are due to uncertainties in branching intensities, multipolarities, and conversion coefficients (Refs. 9–14).

Level (keV)	U_k for all transitions populating level U_2	U_4
100	0.048 ± 0.025	-0.132 ± 0.039
329	0.397 ± 0.038	-0.056 ± 0.050
1221	0.441 ± 0.032	-0.118 ± 0.038
1257	0.469 ± 0.047	-0.118 ± 0.062
1289	0.758 ± 0.038	0.337 ± 0.017
1331	0.772 ± 0.051	0.388 ± 0.113
1374	0.826 ± 0.093	0.496 ± 0.309
1487	0.780 ± 0.039	0.367 ± 0.018

vidual U_k for each member of that branch.[25] The values of U_k computed for levels of ^{182}W are listed in Table I; the error limits are due to uncertainties in experimental conversion coefficients, multipolarities, and branching intensities of the unobserved transitions.[9-14]

The angular-distribution coefficients A_k are written in terms of the multipole mixing ratios defined by Krane and Steffen.[26] In the case of a transition from I_i to I_f containing a triple multipole mixture ($E1+M2+E3$) the A_k are given by

$$A_k=[F_k(11I_fI_i)+2\delta_1F_k(12I_fI_i)+2\delta_2F_k(13I_fI_i)+2\delta_1\delta_2F_k(23I_fI_i)+\delta_1^2F_k(22I_fI_i)+\delta_2^2F_k(33I_fI_i)](1+\delta_1^2+\delta_2^2)^{-1}, \qquad (2)$$

where

$$\delta_1=\frac{\langle I_f\|M2\|I_i\rangle}{\langle I_f\|E1\|I_i\rangle},\qquad \delta_2=\frac{\langle I_f\|E3\|I_i\rangle}{\langle I_f\|E1\|I_i\rangle}. \qquad (3)$$

The F coefficients of Eq. (2) are defined and tabulated in Ref. 25.

[Since the results for the triple multipole mixture will be compared with γ-γ correlation results, it is useful to point out that in a directional-correlation measurement in which the triply mixed transition is the first member in the cascade, the B_k are given by a relationship similar to Eq. (2) with the two terms linear in δ_1 changing sign.]

The computation of the parity-violating odd-k terms has been described in detail previously.[5] In brief, the forward-backward asymmetry $\mathcal{A}$ is calculated (by the computer) as

$$\mathcal{A}=\frac{W(0°)-W(180°)}{W(0°)}\approx 2\frac{Q_1B_1U_1A_1+Q_3B_3U_3A_3}{1+Q_2B_2U_2A_2+Q_4B_4U_4A_4}. \qquad (4)$$

The denominator of Eq. (4) is known from the 0°-90° anisotropy of the angular distributions, and all terms in the numerator except A_1 and A_3 are known. Thus the parity-nonconserving asymmetry depends on the odd-k angular-distribution coefficients, which are given for the case of the 2^--2^+ 1189-keV transition by

$$A_k=\frac{2\epsilon}{1+\delta_1^2+\delta_2^2+\epsilon^2(1+\tilde\delta^2)}[F_k(1122)+\delta_1\tilde\delta F_k(2222)+(\delta_1+\tilde\delta)F_k(1222)+\delta_2F_k(1322)+\delta_2\tilde\delta F_k(2322)], \qquad (5)$$

where δ_1 and δ_2 are defined by Eq. (3), and

$$\epsilon=\frac{\langle I_f\|\tilde M1\|I_i\rangle}{\langle I_f\|E1\|I_i\rangle},\qquad \tilde\delta=\frac{\langle I_f\|\tilde E2\|I_i\rangle}{\langle I_f\|\tilde M1\|I_i\rangle}. \qquad (6)$$

IV. RESULTS

A. Nuclear Structure

From the measured counting rates $W(0°)$ and $W(90°)$ (normalized by the isotropic "warm" counting rates), the P_2 and P_4 terms in the angular distributions could be obtained. The correction for the finite solid angle for each detector was applied and the results for the two detectors were averaged. From the angular distribution of the 264-keV γ ray, values of B_2 and B_4 were deduced, as described above; the value deduced for B_2 was

$$B_2=0.705\pm0.023,$$

corresponding to a hyperfine energy splitting of

$$\Delta=21\pm2\text{ mK}$$

at a temperature of 24± 2 mK (deduced from the angular distribution of the ^{54}Mn 835-keV γ ray). Taking the magnetic hyperfine field[20] for Ta in Fe to be −656 kG we compute for the Ta ground-state magnetic moment

$$|\mu|=2.6\pm0.2\mu_N.$$

(Since the magnetic moments of the ground states of a number of odd-odd nuclei in this region are positive,[27] we assume the moment of ^{182}Ta to be positive.) Other than the measurement of μ, the results deduced in this paper do not depend on the value of the hyperfine field.

The above value of B_2 corresponds to a value of

$$B_4=0.082\pm0.005.$$

These values of B_2 and B_4 may then be used to obtain values of the product U_kA_k from the measured anisotropies of each γ ray; results for U_2A_2 and U_4A_4 are presented in Table II. The large values of U_4A_4 (with correspondingly large uncertainties) result from the small value of B_4. Because of these large uncertainties, only the U_2A_2 values were used to extract the mixing-ratio information.

For cases in which the observed γ ray is a pure multipole, the value of A_2 is uniquely determined, and a value of U_2 may be deduced from the experimental value of U_2A_2 and compared with the computed values given in Table I. If the observed γ ray is a mixed multipole, the value of A_2 can be deduced from the experimental U_2A_2, using a value of U_2 obtained either from the analysis of a pure multipole γ ray which depopulates the same

TABLE II. Coefficients of angular distribution of γ rays from oriented ^{182}Ta.

γ-ray energy (keV)	U_2A_2	U_4A_4	Deduced coefficient [a]	Deduced multipole mixing ratios
66 + 68	-0.309 ± 0.017 [b]	-0.12 ± 0.17 [b]	$U_2(1289) = 0.713 \pm 0.045$	...
85	-0.178 ± 0.024	-0.30 ± 0.25	$A_2(85) = -0.216 \pm 0.033$	$\delta(E2/M1) = +0.30 \pm 0.02,\ +20^{+12}_{-5}$ [c]
100	-0.012 ± 0.012	0.16 ± 0.14	$U_2(100) = 0.020 \pm 0.020$	...
114	-0.230 ± 0.021	0.22 ± 0.21	$A_2(114) = -0.295 \pm 0.027$	$\delta(E2/M1) = +0.31 \pm 0.02,\ -7.8 \pm 0.7$ [c]
116	0.256 ± 0.136	0.89 ± 1.49	$U_2(1374) = 0.74 \pm 0.39$	...
152	0.279 ± 0.015	-0.37 ± 0.13	$U_2(1374) = 0.807 \pm 0.044$	$\lvert\alpha_0(\beta)\rvert^2 = 0.38 \pm 0.23,$ [d] $\lvert\alpha_1(\beta)\rvert^2 = 0.62 \mp 0.23$ [d]
156	0.231 ± 0.018	0.37 ± 0.19	$U_2(1487) = 0.74 \pm 0.06$	...
179	-0.714 ± 0.023	0.07 ± 0.09	$A_2(179) = -0.789 \pm 0.025$	$\delta(E2/M1) = +0.92^{+0.13}_{-0.07},\ +1.6 \pm 0.2$ [c]
198	-0.342 ± 0.013	0.16 ± 0.09	$U_2(1487) = 0.763 \pm 0.029$	...
222	0.269 ± 0.013	0.10 ± 0.10	$A_2(222) = 0.299 \pm 0.010$	$\delta(M2/E1) = +0.007 \pm 0.005,\ -5.5 \pm 0.1$ [c]
229	-0.185 ± 0.019	0.17 ± 0.20	$U_2(329) = 0.413 \pm 0.042$	...
264	-0.405 [e]	-0.207 [e]	$B_2(^{182}\text{Ta g.s.}) = 0.705 \pm 0.023$	...
928	-0.059 ± 0.208	2.1 ± 2.1	$U_2(1257) = 0.35 \pm 1.22$	...
960	0.149 ± 0.267	1.4 ± 2.7	$A_2(960) = -0.19 \pm 0.34$	$-3.6 \le \delta(E3/M2) \le +0.3$
1002	0.113 ± 0.031	0.38 ± 0.31	$A_2(1002) = 0.147 \pm 0.041$	$\delta(E2/M1) = -8.9^{+2.1}_{-1.8},\ 0.00 \pm 0.03$ [c]
1044	-0.030 ± 0.300	1.0 ± 3.1	$A_2(1044) = -0.04 \pm 0.36$	f
1121	0.031 ± 0.012	0.09 ± 0.13	$A_2(1121) = 0.070 \pm 0.027$	$\delta(E2/M1) = +21^{+19}_{-6},\ -0.39 \pm 0.02$ [c]
1157 + 1158	-0.016 ± 0.057	0.60 ± 0.57	$A_2(1157) = 0.28 \pm 0.18$	$\delta(E2/M1) = -(7.6^{+\infty}_{-4.8}),\ -(0.61^{+0.34}_{-0.19})$ [c]
1189	-0.628 ± 0.015	0.16 ± 0.15	$A_2(1189) = -0.881 \pm 0.030$	f
1221	-0.224 ± 0.013	0.21 ± 0.14	$U_2(1221) = 0.375 \pm 0.022$	...
1231	-0.071 ± 0.013	0.33 ± 0.17	$A_2(1231) = -0.093 \pm 0.019$	$\delta(1231) = -(60^{+100}_{-20}),\ +0.23 \pm 0.02$ [c]
1257	-0.247 ± 0.030	0.01 ± 0.30	$U_2(1257) = 0.413 \pm 0.050$	...
1274	-0.310 ± 0.042	0.46 ± 0.41	$A_2(1274) = -0.375 \pm 0.057$	f
1289	-0.426 ± 0.042	0.60 ± 0.41	$U_2(1289) = 0.713 \pm 0.071$	...
1343	-0.408 ± 0.090	-0.30 ± 0.85	$U_2(1443) = 0.91 \pm 0.20$	$\lvert\alpha_1(\beta)\rvert^2 = 1.0^{+0.0}_{-0.5}$ [g], $\lvert\alpha_2(\beta)\rvert^2 = 0.0^{-0.0}_{+0.5}$ [g]
1374	-0.625 ± 0.108	0.10 ± 1.05	$U_2(1374) = 0.72 \pm 0.13$	...

[a] $U_2(E)$ indicates the net deorientation coefficient for all transitions populating the level at energy E; $A_2(E)$ indicates the angular-distribution coefficient for the γ ray of energy E.

[b] Results have been corrected for contributions from the 67- and 69-keV $K\beta$ x rays of tungsten.

[c] This root of A_2 for mixing ratio is not consistent with internal-conversion results (Ref. 9).

[d] Multipole character of β transition populating 1374-keV level.

[e] Theoretical values used to deduce orientation parameters.

[f] $M2/E1$ and $E3/E1$ mixing ratios deduced in Sec. V.

[g] Multipole character of β transition populating 1443-keV level.

level, or from the computed values given in Table I. Values of U_2 and A_2 thus deduced are tabulated in column 4 of Table II.

In the analysis of the 68-keV transition, corrections were applied to account for the 67- and 69-keV $K\beta$ x rays of tungsten; the observed $K\alpha$ intensity and the known $K\beta/K\alpha$ ratios[28] were employed for the correction.

The amplitude mixing ratios deduced from the A_2 coefficients (using the phase convention of Ref. 26) are tabulated in column 5 of Table II. For the various γ-ray multipole mixing ratios deduced, in all cases one of the two roots obtained could be discarded upon comparison with results of internal-conversion measurements.[9]

From the angular distributions of the 152- and 1343-keV transitions, the U_2 values were deduced for the β transitions populating the 1374- and 1443-keV levels, respectively; from the values of U_2, the intensity of the multipole component of the β-radiation field carrying L units of angular momentum, $|\alpha_L|^2$, was obtained (normalized such that $\sum_L |\alpha_L|^2 = 1$). Values presented in Table II indicate that most of the allowed β transitions populating the 1374-keV level are probably of the Gamow-Teller type; for the first-forbidden β transition populating the 1443-keV level, our results indicate that all of the transitions carry one unit of angular momentum, but the large experimental uncertainty of the deduced U_2 allows $|\alpha_1|^2$ to be as small as 0.5.

The deduced γ-ray multipole mixing ratios are summarized in Table III.

B. Parity Mixing

Table IV lists the parity-nonconserving forward-backward asymmetries $\mathfrak{a}$ [Eq. (4)] observed for a number of γ transitions in ^{182}W. Data were accumulated for approximately 200 h in thermal equilibrium at 24 mK and for 50 h at 65 mK; the latter warmer data were taken in order to eliminate effects due to the B_3 term in the angular distribution. Results given in Table IV are the averages of results using the two individual detectors.

As a measure of the dispersion of the experimental results, both within a run (lasting about 12 h) and from run to run, the normalized χ^2 value was computed. In general, the χ^2 results ranged between 1 and 2, and thus no significant nonstatistical fluctuations were present.

In order to check for the presence of systematic effects which might give rise to spurious asymmetries (such as source motion or magnetic field effects on detectors and preamplifiers) the forward-backward asymmetry of the 1121-keV radiation was measured. No measurable parity-nonconserving effect is expected in this case, and the vanishing measured asymmetry indicates the lack of systematic errors.

TABLE III. Multipole mixing ratios of ^{182}W γ transitions.

γ-ray energy (keV)	Spin sequence $I^{\pi}_i K_i \rightarrow I^{\pi}_f K_f$	Multipole mixture	Mixing ratio δ	δ Kumar-Baranger calculations
85	$3^-2 \rightarrow 2^-2$	$E2/M1$	$+0.30 \pm 0.02$	
114	$4^-2 \rightarrow 3^-2$	$E2/M1$	-0.31 ± 0.02	
179	$4^-4 \rightarrow 3^-2$	$E2/M1$	$+0.92^{+0.13}_{-0.07}$	
222	$4^-4 \rightarrow 3^+2$	$M2/E1$	$+0.007 \pm 0.005$	
960	$2^-2 \rightarrow 4^+0$	$E3/M2$	$-3.6 \leq \delta \leq +0.3$	
1002	$3^+2 \rightarrow 4^+0$	$E2/M1$	$-(8.9^{+2.1}_{-1.8})$	-35
1044	$3^-2 \rightarrow 4^+0$	$M2/E1$ [a] $E3/E1$ [a]	$+0.4 \pm 0.3$ -0.3 ± 0.2	
1121	$2^+2 \rightarrow 2^+0$	$E2/M1$	$+21^{+19}_{-6}$	$+17$ [b]
1157	$2^+0 \rightarrow 2^+0$	$E2/M1$	$-(7.6^{+\infty}_{-4.8})$	-5 [b]
1189	$2^-2 \rightarrow 2^+0$	$M2/E1$ [a] $E3/E1$ [a]	$+0.49 \pm 0.03$ -0.64 ± 0.05	
1231	$3^+2 \rightarrow 2^+0$	$E2/M1$	$-(60^{+100}_{-20})$	-45
1274	$3^-2 \rightarrow 2^+0$	$M2/E1$ [c]	$+0.42 \pm 0.04$	

[a] See discussion in Sec. V.

[b] Assuming appropriate Kumar-Baranger assignments for the 2^+ vibrational levels.

[c] Assuming $\delta_2(E3/E1) = 0$. See discussion in Sec. V.

The possibility of an asymmetry in the bremsstrahlung or other background radiations was investigated by measuring the asymmetry of both low-energy (250 keV) and high-energy (1140 keV) background regions. The results indicate a vanishing effect for the high-energy background, with the possibility of a small effect in the low-energy background. Because of the large intensities of the 222- and 1189-keV peaks above the background, possible background asymmetries are not expected to be significant.

The 222-keV transition shows a vanishing effect. This $E1$ transition is singly K-forbidden ($\Delta K = 2$), and is hindered relative to Weisskopf estimates by $H_W^{E1} = 2\times 10^5$. For such a relatively small hindrance, parity-nonconserving effects are not expected to appear, since the "regular" $E1$ transition is not hindered sufficiently to allow the "irregular" $\tilde{M}1$ radiation to compete favorably. The small hindrance is also apparent in the small $M2$ amplitude deduced above.

Using the δ_1 and δ_2 values deduced below for the 1189-keV transition ($H_W^{E1} = 0.4\times 10^8$), as well as B_1 and B_3 values deduced from Δ and T, the forward-backward asymmetry $\mathfrak{A}$ of the 1189-keV transition can be written

$$\begin{aligned} T = 24\text{ mK: } \mathfrak{A}(1189) &= +\epsilon[(0.23\pm 0.11) \\ &\quad + \tilde{\delta}(0.08\pm 0.18)], \\ T = 65\text{ mK: } \mathfrak{A}(1189) &= +\epsilon[(0.02\pm 0.03) \\ &\quad + \tilde{\delta}(0.15\pm 0.06)], \end{aligned} \tag{7}$$

where ϵ and $\tilde{\delta}$ are defined in Eq. (6). (The positive values for the asymmetries are obtained assuming B_1 and B_3 are positive, which follows from the negative nuclear hyperfine field and the assumed positive magnetic moment.) The vanishing effect at $T = 65$ mK indicates that the $\tilde{\delta}$ term is not the dominant one; that is, the $\tilde{E}2$ radiation probably does not contribute substantially to the irregular radiation field. For the relative $\tilde{M}1$ contribution, we thus obtain

$$\epsilon(1189) = -(12\pm 9)\times 10^{-4}.$$

Results obtained from measurements[8] of the circular polarization of γ rays from unpolarized ^{182}Ta yield $P_\gamma = -(0.25\pm 0.40)\times 10^{-4}$; assuming all existing parity mixing comes from the 1189-keV transition, this result is equivalent to $\epsilon = -(0.2 \pm 0.3)\times 10^{-4}$. Although the circular-polarization experiment could be observing an accidental cancellation of effects from two or more γ rays, it appears more likely that the present 1189-keV result is experiencing a statistical fluctuation of slightly more than the expected error.

From the 24 mK forward-backward asymmetry of the 1274-keV transition ($H_W^{E1} \leq 3\times 10^7$), we obtain

$$\epsilon(1274) = -(1\pm 4)\times 10^{-4}.$$

TABLE IV. Parity-nonconserving forward-backward asymmetry of γ transitions in ^{182}W.

γ-ray energy (keV)	Asymmetry [a] (units of 10^{-4}) $T = 24$ mK	$T = 65$ mK
222	0.14 ± 0.64	-1.1 ± 2.1
~250 [b]	3.9 ± 2.4	...
1121	0.16 ± 0.72	-2.2 ± 2.0
~1140 [c]	2.0 ± 5.2	...
1189	-2.8 ± 1.7	1.0 ± 3.5
1274	2.6 ± 10.4	-48 ± 24

[a] Defined with respect to the applied field.
[b] Low-energy background.
[c] High-energy background.

V. DISCUSSION

The 1189-keV transition is expected to be primarily of $E1$ multipolarity, for which $A2 = -0.418$, and no amount of $M2$ admixture could bring the observed data into agreement with the conversion coefficient[9,11,12] and directional-correlation[18] results. However, an analysis in terms of $M2+E3$ admix-

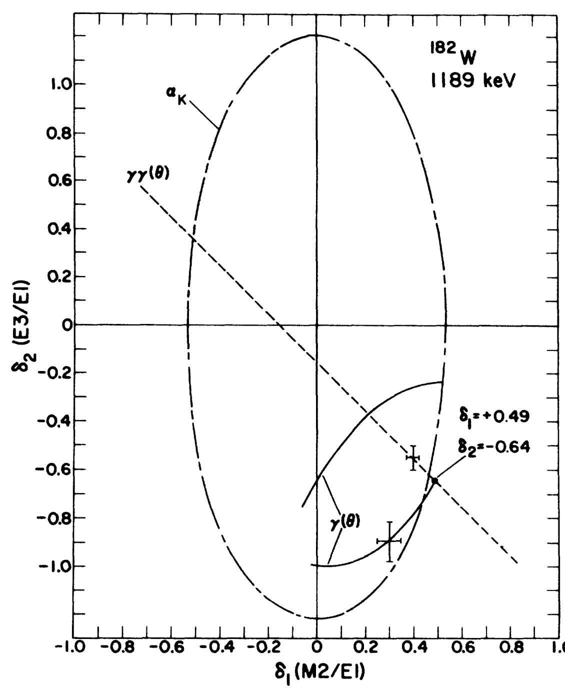

FIG. 3. Relationship between $\delta_1(M2/E1)$ and $\delta_2(E3/E1)$ of 1189-keV γ radiation based on the two roots obtained from the results of the present investigation [$\gamma(\theta)$], directional-correlation studies [$\gamma\gamma(\theta)$, Ref. 18], and K-conversion-coefficient measurements (α_K, Ref. 12).

tures produced a striking solution, in agreement with all data. Figure 3 shows the results of plotting the relationships between $\delta_1(M2/E1)$ and $\delta_2(E3/E1)$ obtained from the internal-conversion[12] (α_k), directional-correlation[18] [$\gamma\gamma(\theta)$], and nuclear-orientation [$\gamma(\theta)$] measurements. A unique solution is obtained from the region in which all three curves intersect, at which point

$$\delta_1(1189) = +0.49 \pm 0.03\,,$$

$$\delta_2(1189) = -0.64 \pm 0.05\,,$$

where δ_1 is the $M2/E1$ mixing ratio and δ_2 is the $E3/E1$ mixing ratio.

Conclusive evidence has been obtained in support of triple multipole mixing in the 1189-keV transition, yielding relative intensities of the multipole components to be 60% $E1$, 15% $M2$, and 25% $E3$. The reduction in the $E1$ transition probability is due to the K-forbiddenness of the transition ($\Delta K = 2$). An octupole vibrational nature of the 1289-keV level would tend to enhance the $E3$ transition probability relative to the $M2$; in addition, a two-quasiparticle contribution to the 1289-keV level also would have the effect of reducing magnetic transition probabilities relative to electric.[29] This is consistent with the observed dominance of the $E3$ over the $M2$ multipole in the 1189- and 960-keV transitions. Additional evidence for $E1$-$M2$-$E3$ mixing in 2^--2^+ transitions in deformed nuclei has been obtained in the cases of ^{178}Hf[30] and ^{180}W.[31]

The present data were examined for the possibility of $E3$ admixtures in the 1044- and 1274-keV transitions from the 3^- state to the 4^+ and 2^+ members of the ground-state band, respectively. Figures 4 and 5 show the results of comparisons of the present data with those obtained from internal-conversion measurements.[9,12] For the 1044-keV transition, Fig. 4, the possibility of nonzero δ_2 values is not excluded. Calculations by Löbner, Smith, and Bunker,[30] based on partial lifetimes and K conversion coefficients, result in the estimates $\delta_1^2 = 0.04^{+0.18}_{-0.02}$ and $\delta_2^2 = 0.49^{+0.21}_{-0.39}$ for the 1044-keV transition. Based on that estimate, we favor the intersection in Fig. 4 having the larger value of δ_2, and conclude

$$\delta_1(1044) = 0.4 \pm 0.3\,,$$

$$\delta_2(1044) = -0.3 \pm 0.2\,.$$

In the case of the 1274-keV transition, Fig. 5, results of the present investigation run nearly par-

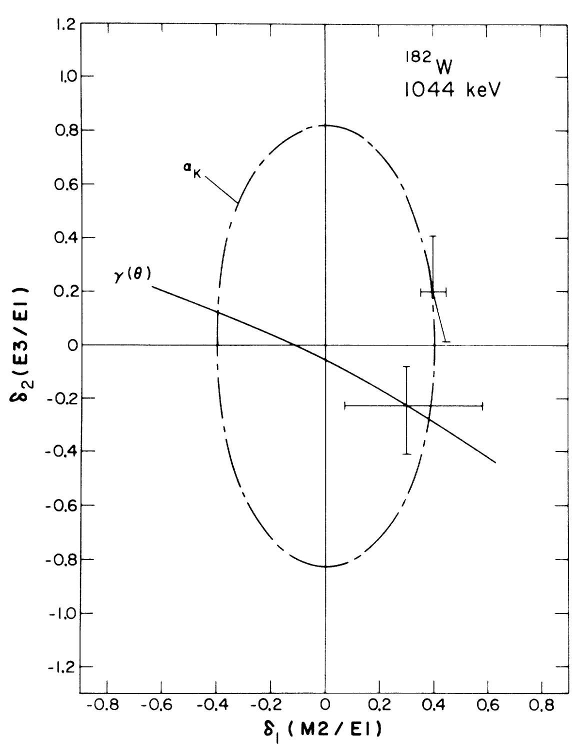

FIG. 4. Relationship between $\delta_1(M2/E1)$ and $\delta_2(E3/E1)$ of 1044-keV γ radiation, based on the present investigation [$\gamma(\theta)$] and K-conversion-coefficient measurements (α_k, Ref. 9).

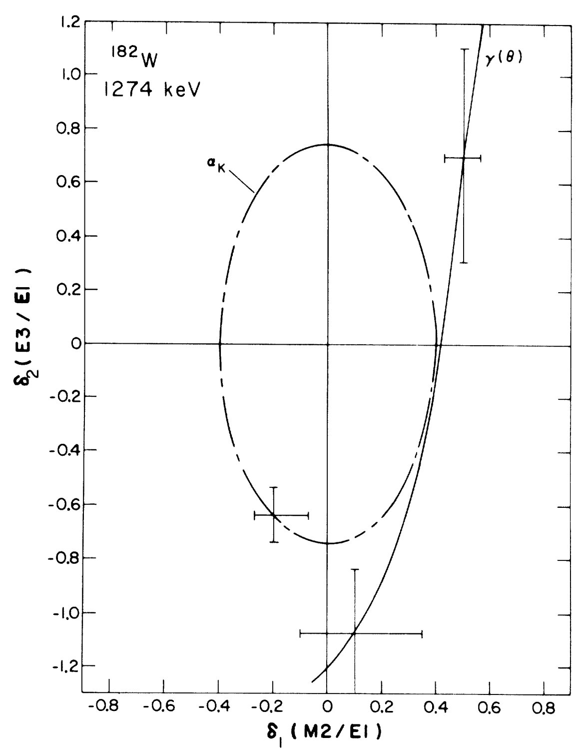

FIG. 5. Relationship between $\delta_1(M2/E1)$ and $\delta_2(E3/E1)$ of 1274-keV γ radiation, based on the present investigation [$\gamma(\theta)$] and K-conversion-coefficient measurements (α_K, Ref. 9).

allel to those of internal-conversion measurements, and values of δ_2 between −1.0 and +0.5 would not be inconsistent with either measurement. However, Löbner, Smith, and Bunker[30] have concluded, based on Alaga intensity rules, that $\delta_2(1274) = 0.0$, and we have adopted that value, for which $\delta_1(1274) = 0.42 \pm 0.04$.

The mixing ratios measured for the 1121-, 1157-, and 1231-keV transitions are in excellent agreement, in terms of magnitude as well as sign, with the predictions of the Kumar-Baranger theory.[2] The apparent agreement in the cases of the 1121- and 1157-keV transitions is dependent on choosing the 1221- and 1257-keV levels to be the Kumar-Baranger $2^{+\prime}$ and $2^{+\prime\prime}$ states, respectively. However, Kumar and Baranger[1] identify the 1221-keV level as the $2^{+\prime\prime}$ level, in which case the presently measured mixing ratios would disagree with the theory; the latter interpretation is supported by $B(E2)$ values observed following Coulomb excitation of ^{182}W.[32] Imposing the choice of the $2^{+\prime}$ state as the γ-vibrational state, as is done for the other isotopes considered by Kumar and Baranger in this mass region, good agreement for the $E2/M1$ mixing ratios is obtained. In the case of the 1002-keV transition, the theory predicts the correct sign but the calculated magnitude of δ is a factor 4 too large. The Kumar-Baranger calculations thus find agreement with experiment (with the appropriate interpretation of the 2^+ levels) for the ^{182}W mixing ratios, as is the case in the osmium and platinum isotopes.[3]

The mixing ratios of the 85- and 114-keV transitions, which connect states of the $K = 2^-$ rotational band, are identical, a result expected for transitions within a rotational band. The 85- and 114-keV transitions both have multipolarities of approximately 10% $E2$ and 90% $M1$, while the 179-keV transition from the 4^- band to the 2^- band ($\Delta K = 2$) is 50% $E2$ and 50% $M1$. These mixing ratios are thus in qualitative agreement with the K assignments of the negative-parity levels.

Excitation of the 1257-keV level by inelastic deuteron scattering[33] favors a $K = 0$ β-vibrational assignment for that level; this is in agreement with our choice of the larger value of δ for the 1157-keV transition, since collective vibrational levels deexcite through enhanced $E2$ transitions.

The present results for the parity-nonconserving amplitude ϵ reveal no effects large enough for definite conclusions at present. The asymmetry measurement technique, however, is thought to be quite free of systematic error, and the results reported can be taken to establish upper bounds on the parity-nonconserving amplitudes.

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Decay of a New 5.8-min ^{150}Tb Activity*

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A new short-lived isomer of ^{150}Tb has been identified. The mass assignment was confirmed by excitation functions and cross bombardments. The 5.8 ± 0.2-min activity is probably a 9^+ state ($\pi h_{11/2}\nu f_{7/2}$) and decays chiefly to an (8^+) state at 2554.4 keV in ^{150}Gd with a log*ft* value of 4.1. No isomeric transition to the 3.1-h ^{150}Tb was observed. The γ-ray spectrum was investigated with Ge(Li) detectors. The 19 γ rays observed were assigned to 10 excited levels (in keV) at 638.05, 2^+; 1134.35, 3^-; 1288.4, (4^+); 1700.9, (5^-); 1936.8, (6^+); 2116.1, (6^+); 2211.2, (7^-); 2392.5; 2554.4, (8^+); and 2906.0. The energy spacing of the positive-parity states in ^{150}Gd suggests a close correspondence to a vibrator model although low-spin members of multiplets corresponding to multiphonon states are not observed. The quasiband representation of Sakai appears also to be a useful way of interpreting these states. Three negative-parity states form a sequence which may correspond to a combination of octupole and quadrupole phonons or an octupole quasiband.

I. INTRODUCTION

Isomerism among Tb nuclides is a common occurrence.[1] For spherical nuclei of $Z=65$, the $h_{11/2}$ proton orbital lies relatively low in energy, while in the deformed region the $\frac{11}{2}^-[505]$ neutron orbital is available to produce low-lying, high-spin odd-odd isomers. At the time this work was begun, only a 3.1-h ^{150}Tb was known[2-4]; its spin was believed to be low, since its decay to ^{150}Gd strongly populated states of spin 4 or less.[3,4] Hence it appeared profitable to search for a high-spin, presumably short-lived isomer of ^{150}Tb.

In addition to gaining insight into the systematics of the odd-odd Tb species, we felt that the decay study of a high-spin ^{150}Tb might reveal interesting new structure information on higher-lying states in ^{150}Gd. A recent γ-ray and conversion-electron study of the reaction[5] ^{151}Eu(p, $2n\gamma$) ^{150}Gd has established levels of spin possibly as large as 5. Insufficient information is available, however, to establish quasiband structure[6] or other evidences of the systematics of collective states in ^{150}Gd. This 86-neutron nucleus might show vibrational character[7] or perhaps resemble the transitional 88-neutron nucleus ^{152}Gd.

In this paper we report the discovery of a 5.8-min ^{150}Tb. Its decay strongly resembles that of 4.2-min ^{152m}Tb in which a large fraction of the β-decay intensity goes to a single high-lying level of high spin in the daughter Gd nucleus.[1] As this manuscript was being prepared, we learned of the work of Arlt and co-workers[8] at Dubna, who have also identified the same nuclide. Their results are in good agreement where the two sets of data overlap. They propose only a partial decay scheme.