Moore, and P. von Brentano, Phys. Rev. 165, 1312 (1968).

[8] C. F. Moore, J. G. Kulleck, W. R. Coker, R. G. Clarkson, J. J. Kent, and W. J. Courtney, Nucl. Instr. Methods 79, 353 (1970).

[9] H. Weidenmüller, Nucl. Phys. A99, 289 (1967).

[10] D. Robson and A. M. Lane, Phys. Rev. 161, 982 (1967).

[11] A F. R. de T. Piza and A. K. Kerman, Ann. Phys. (N.Y.) 43, 363 (1967).

[12] J. P. Bondorf, P. von Brentano, and P. Richard, Phys. Letters 27B, 5 (1968).

[13] P. Richard, N. Stein, C. D. Kavaloski, and J. S. Lilley, Phys. Rev. 171, 1308 (1968).

[14] B. L. Anderson, J. P. Bondorf, and B. S. Madsen, Phys. Letters 22, 651 (1966).

[15] E. Grosse, P. von Brentano, H. J. Glockner, C. F. Moore, Max-Planck Institut für Kernphysik, Annual Report 1968 (unpublished), p. 49.

[16] E. D. Earle, G. A. Bartholomew, I. Bergquist, A. J. Ferguson, and G. Van Middelkoop, Bull. Am. Phys. Soc. 15, 76 (1970).

[17] P. Mukherjee and B. L. Cohen, Phys. Rev. 127, 1284 (1962).

[18] J. Barwick and R. Tickle, Phys. Rev. 161, 1217 (1967).

[19] M. Dost and W. Hering, Max-Planck Institut für Kernphysik, Annual Report, 1967 (unpublished), p. 40.

[20] J. H. Bjerregaard, O. Hansen, O. Nathan, and S. Hinds, Nucl. Phys. 89, 337 (1966).

[21] G. J. Igo, P. D. Barnes, and E. R. Flynn, Phys. Rev. Letters 24, 470 (1970).

[22] J. G. Cramer, P. von Brentano, G. W. Phillips, H. Ejiri, S. M. Ferguson, and W. J. Braithwaite, Phys. Rev. Letters 21, 297 (1968).

[23] J. Alster, Phys. Rev. 141, 1138 (1966).

[24] R. K. Jolly, E. K. Lin, and B. L. Cohen, Phys. Rev. 128, 2292 (1962).

[25] G. A. Peterson and J. F. Ziegler, Phys. Letters 21, 543 (1966).

[26] H. W. Kendall and J. Oeser, Phys. Rev. 130, 245 (1963).

[27] D. S. Onley, J. T. Reynolds, and L. E. Wright, Phys. Rev. 134, B945 (1964).

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Search for Parity Violation in the Gamma Decay of ^{159}Tb Polarized by Dilution Refrigeration*

W. P. Pratt, Jr.,† R. I. Schermer,‡ James R. Sites, and W. A. Steyert
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

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A search for the parity-nonconserving contribution to the γ decay of ^{159}Tb has been made. A complete description of the experimental technique is presented. The angular distribution of the 363-keV line of ^{159}Tb was measured with a pair of Ge(Li) detectors. The ^{159}Gd parent atoms were located in the +453-kG hyperfine field of GdFe$_2$ held at 28 mK by a ^{3}He-^{4}He dilution refrigerator. The resulting 7% polarization of the ^{159}Gd led to a $P_1(\cos\Theta)$ term of $+(2.7 \pm 1.8) \times 10^{-4}$ in the γ-ray angular distribution, where Θ is measured with respect to the nuclear polarization. Thus, for full Tb polarization, the asymmetry would be $+(4.5 \pm 3.0) \times 10^{-3}\, P_1(\cos\Theta)$, peaked in the direction of Tb nuclear spin alignment. This sign of the $P_1(\cos\Theta)$ term is based on an assumed negative moment of the ^{159}Gd parent. We measure the magnitude of this moment to be $(0.22 \pm 0.05)\mu_N$.

A small parity-nonconserving interaction between nucleons results from the current-current theory of weak interactions proposed by Feynman and Gell-Mann.[1] Assuming the presence of such an interaction, the nuclear states are not eigenstates of parity, and small parity impurities can be expected. The impurity amplitude F is estimated to be on the order of 10^{-6} to 10^{-7}.[2,3]

There are several possibilities for experimental measurements of the existence and extent of the parity-nonconserving amplitude. One type of experiment is to look for the presence of decays forbidden by parity. Studies of the α decay from excited states of O^{16} have placed a 3×10^{-13} upper limit on F^2.[4] The other type of experiment is to look for correlations which would not be present if parity were conserved. These experiments study F itself. To date, these experiments have examined the circular polarization of γ rays from unpolarized sources,[5,6] or the angular distribution of γ rays with respect to the polarization of neutrons captured by the nuclei.[7] In both cases the effect was enhanced by choosing γ decays in which a parity-conserving decay mode was hindered with respect to a parity-nonconserving mode. Some of these experiments give strong evidence for weak interactions between nucleons.

We used a different method to study γ-decay parity nonconservation. Our experiment was to measure the correlation between the angular distribution of the γ decay from ^{159}Tb and the polarization of the ^{159}Gd parent nucleus. (The ^{159}Gd-^{159}Tb decay scheme[8] is shown in Fig. 1.) We also picked a transition (the 363-keV line) in which we expect the parity-conserving mode ($E1$) to be hindered with respect to the principal parity-nonconserving modes ($M1$ and $E2$). To achieve significant polarization, it was necessary to cool our source to a few hundredths of a degree and to utilize the large internal field of a ferromagnetic host.

METHOD

The experimental apparatus was designed to allow two stationary detectors to count the γ activity from a thin disk of material held at very low temperatures in a rotating magnetic field. The counting rate of the 363-keV γ ray of interest was then measured as a function of rotation angle.

Sample

The sample itself was GdFe$_2$. The gadolinium was thus placed in a magnetic enviroment where it sees a high internal field. In particular, the compound GdFe$_2$ has a hyperfine field of +453 kG,[9] somewhat higher than other gadolinium compounds.

Natural gadolinium and iron were reacted and cut to the proper shape before the gadolinium was activated. The sample was cut down to a thin disk (0.9 cm diam, 0.012 cm thick), using a spark plane. A very sharp x-ray pattern with lattice constant $a_0 = 7.3916 \pm 0.0003$ was obtained from this material. The pattern showed no evidence of mixed phases. This thin-disk geometry serves three purposes. (1) The demagnetization effect is minimized by a thin disk oriented with a diameter parallel to the applied field. (2) A large surface-to-volume ratio is useful, since the high neutron cross section of ^{155}Gd and ^{157}Gd results in self-shielding. (3) Thermal contact to a thin disk is relatively simple.

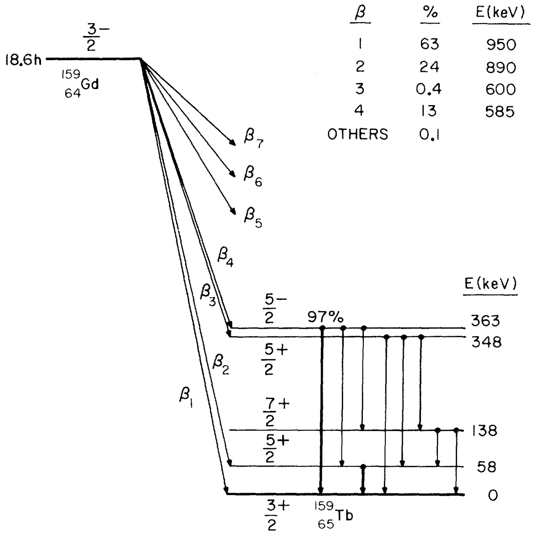

FIG. 1. Principal decay modes of ^{159}Gd. The irregular $M1$-$E2$ admixture to the 363-keV $E1$ transition is studied in this experiment. The proximity of a $\frac{5}{2}^+$ level [413↑] to the $\frac{5}{2}^-$ level [532↑] suggests a significant parity impurity in the 363-keV level. The ground state has a [411↑] assignment.

After the disk had been cut, it was coated on one side, first with 1000 Å of iron and then with 10 000 Å of lead, by vacuum evaporation. The lead surface was then tinned with Wood's metal for mechanical and thermal contact.

Just prior to an experimental run the GdFe$_2$ disk was placed in the thermal column of the Los Alamos Omega West reactor for 24 h. The thermal neutron flux was 3×10^{12} n/cm^2 sec. The activation of interest is $^{158}\text{Gd} + n \rightarrow {}^{159}\text{Gd}$. The half-life τ of ^{159}Gd is 18.6 h, and thus the experiment must be assembled and the data taken within a very few days after the sample is removed from the reactor. The activation of other Gd isotopes leads to products which neither heat the sample excessively nor have γ lines close to the line of interest. At the start of the series of runs we had 2000 counts per sec in each counter from the 363-keV line, indicating a source strength of about 0.1 mCi.

Magnets

The external field necessary to polarize the GdFe$_2$ was achieved with superconducting coils. In order to identify a small asymmetry in the γ distribution, it is necessary to at least reverse the magnetic field to eliminate errors which might arise from different counting efficiencies of the two counters or from geometric placement of the counters with respect to the source. At low temperatures, however, it would be unwise to simply reverse the field, because hysteresis of the ferromagnetic sample would result in a good deal of unwanted heat. With a rotating field, on the other hand, it is possible to keep the sample magnetically saturated while the field is changing. Also, with a rotating field the Gd polarization adiabatically follows the field, but with a reversing field, long spin-lattice relaxation times could cause a time lag in polarization. A continuously rotating field was preferred to a field intermittently rotated by 180° because of the simplicity of operation and the possible elimination of some systematic errors.

The actual magnet and counter arrangement is shown schematically in Fig. 2. The magnets produce a field rotating in the plane of the thin disk sample when two sinusoidal currents 90° out of phase with one another are applied to the two pairs

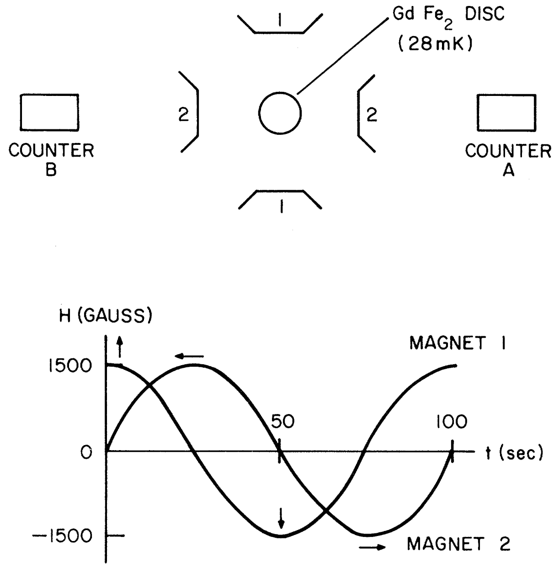

FIG. 2. Schematic of source, magnet, and counter arrangement. Actual magnets are two superconducting Helmholtz pairs. The resulting 0.01 Hz rotating 1500-Oe field provides a rotating ^{159}Gd polarization. The direction of the magnetic field is indicated by arrows on the H versus t graph.

of coils. Experimentally, it was found that a rotating field of 1000 G or more produced little or no heating of the sample, and it is therefore assumed that 1000 G is sufficient for saturation. During an actual data run, an external field of 1500 G was used.

The magnet coils were approximately elliptical in shape and were wound with copper-clad niobium titanium wire. The current needed for 1500 G was about 7.5 A. The magnet currents, and thus the field direction, were synchronized with the channel advance of two multichannel analyzers used in the multiscale mode for data storage.

Electronics

A block diagram of the electronics used is shown in Fig. 3. The field rotation was controlled by a Hewlett-Packard 203A variable-phase function generator operating at 0.01 Hz. The two sine-wave outputs were set to a 90° phase difference and each controlled a separate power amplifier.[10] Two large 12-V storage batteries were used for the amplifier power supplies. The phase difference, current amplitudes, and current zero points were set by plotting the two currents with an X-Y recorder and making adjustments until the recorder drew a circle of the proper size and position.

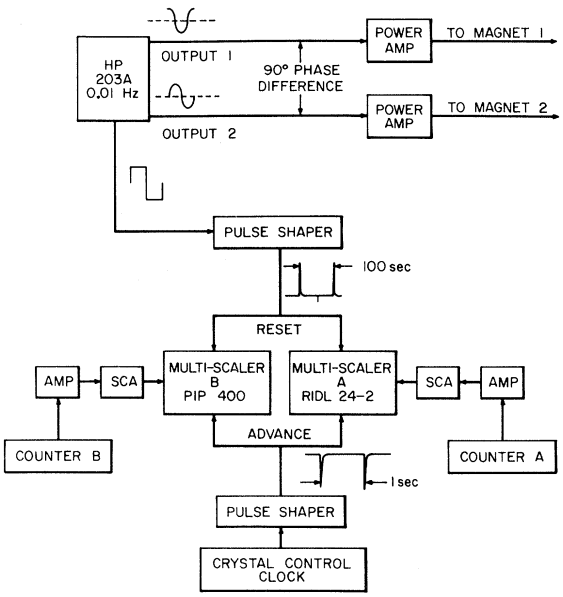

FIG. 3. Block diagram of electronics. Pulses from counters A and B are cyclically stored in 100 channels of the multiscalers as the source polarization is rotated in the rotating 1500-Oe magnetizing field.

The γ-ray counting was done with two 40-cc^3 Ge(Li) detectors made by Nuclear Diodes. The detectors were oriented 180° apart in the plane of the rotating field. They were each about 9 cm from the Gd source. The output of the detectors was fed into single-channel analyzers (SCA) set on 363 keV with a window of 5 keV, which encompassed ≈80% of the peak counts. The output of these analyzers went into two multichannel analyzers operating in the multiscale mode.

The Hewlett-Packard function generator has synchronous square wave outputs as well as the sine outputs. One of these square waves was differentiated and rectified and was used to reset the storage channel advances of the multiscalers to zero. The channel advance itself was controlled by a Beckman 7361-11 crystal-controlled universal timer which was set to give one pulse every second. These pulses were then adjusted to the proper shape and magnitude to trigger the channel advance. Thus, the γ-ray count from each of the two detectors was stored successively in the two multiscalers with each channel corresponding to a different field direction. Approximately 100 channels were required for a complete field rotation.

After data had been accumulated for the proper length of time, the storage contents were recorded on paper tape which was in turn converted to punched cards for analysis. Periodically, the SCA's were set to register the background slightly above the 363-keV peak. For these runs the window was about 15 keV wide to provide a better counting rate.

Cryogenics

The low temperatures necessary for polarization of the Gd nuclei were achieved with a ^{3}He-^{4}He dilution refrigerator. The refrigerator used is capable of cooling an experiment to 14 mK in continuous operation without an external heat load. The ^{3}He circulation rate is typically 5×10^{-5} mole per sec.

One difficult part of the cryogenics is to achieve good thermal contract between the dilution refrigerator mixing chamber and the radioactive source. The thermal contact agent must be able to transfer the one or two ergs per sec of heat generated by the sample activity. At the same time, the contact agent cannot contain electrical paths which enclose significant areas, because the rotating field causes eddy-current heating. Also, the sample must be easily removable so that it can be put back in the reactor.

The contact scheme used is shown in Fig. 4. The mixing chamber of the dilution refrigerator contained a disk of sintered copper to thermally lock the copper body to the cold helium inside. The mixing chamber body was in turn thermally locked to an auxiliary chamber by a press fit from a nylon ring which shrinks when it is cooled. A calibrated carbon resistance thermometer is located in the copper wall of this chamber. The auxiliary chamber was filled with liquid ^{3}He which made thermal contact between another sintered copper disk and a brush of 40 000 No. 49 insulated copper wires. The wires in the brush were combed to minimize electrical contact of the ends with one another, and were surrounded with filter paper to prevent electrical contact with the body of the chamber.

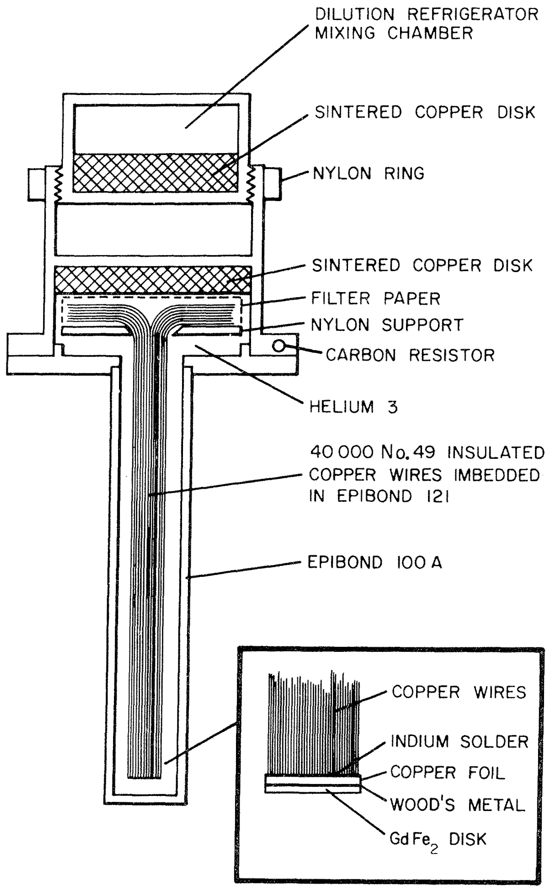

FIG. 4. Thermal contact between the $GdFe_2$ disk and dilution refrigerator. Eddy-current-free contact is provided by large area contact through a ^{3}He bath.

The wires from the brush were brought together and embedded in Epibond 121 epoxy[11] to form a rod about 10 cm long. The end of this rod was machined flat so that the $GdFe_2$ disk could be attached. The bottom piece of the auxiliary chamber was made from a copper flange attached to a hollow Epibond 100A[11] epoxy tail. The two pieces of the auxiliary chamber were vacuum sealed with a lead O ring. Only the tail section was exposed to the rotating field.

The $GdFe_2$ disk was attached to the copper wires as shown in Fig. 4. The bottom of the wire rod was cleaned and attached to a copper foil with indium solder. The bottom of the foil was tinned with Wood's metal. The $GdFe_2$ disk had been previously tinned with Wood's metal, so that after it was irradiated it could be easily attached with a warm hot plate. The sample disk could be removed by dunking it in boiling water to melt the Wood's metal. It was important not to get indium onto the $GdFe_2$, as the indium would activate in subsequent neutron irradiations.

There is always a compromise in this type of experiment between the strength of the source activity and the minimum temperature attainable. However, further development should allow us both higher counting rates and lower temperatures in the radioactive sample. The counting rate will soon be increased by a factor of 4 with a new Dewar system which allows the counters to be placed closer to the source. A higher source strength and lower temperature can hopefully be attained by further improvement in the thermal contact between the source and refrigerator. We feel, however, that extreme low temperatures are not desirable, because the $P_l(\cos\theta)$ angular-distribution term increases at T^{-l}. Second-order effects of a large P_2 term could give a spurious contribution to the measured P_1 term.

ANALYSIS AND RESULTS

Procedure

The data presented here were taken following a single irradiation of the $GdFe_2$. After activation, the source was mounted as described above and the cool-down procedure was begun. From this point, the γ rays were counted continuously for 52 h. This 52-h period, however, was divided into 1- to 5-h data runs, during each of which the temperature and other experimental conditions were nearly constant.

Half of the data were taken on the 363-keV line at temperatures around 28 mK. To check for systematic errors, however, data were also taken at higher temperatures where there was no polarization. Data were also taken in a window just above the 363-keV line to check the contribution of bremsstrahlung background. Also, prior to the ^{159}Gd experiment runs were made with a ^{54}Mn source at room temperature to check the equipment for systematic error.

In the computer analyses, data from each run were corrected for the exponential decay during the 100 sec cycle. The data were then Fourier-analyzed by the computer to determine the asymmetry for each counter as described in the following section.

Theoretical Background

Figure 1 illustrates the most relevant features of the ^{159}Gd-^{159}Tb decay. In this experiment the $\frac{3}{2}^-$ ^{159}Gd parent was polarized in the +453-kOe hyperfine field, H_{hf}, of its GdFe$_2$ environment at 28 mK. The 18 h ^{159}Gd parent decays by an allowed Gamow-Teller transition to the 0.16-nsec $\frac{5}{2}^-$ state of ^{159}Tb (0.13 branching ratio). The 363-keV γ ray studied is emitted during the $E1$ transition to the $\frac{3}{2}^+$ ^{159}Tb ground state. This transition is hindered by a factor of 2×10^4 compared with the Weisskopf single-particle estimate.[12]

The long half-life of the $\frac{5}{2}^-$ ^{159}Tb state is attributable to the asymptotic selection rules for $E1$ transitions in deformed nuclei. The $\frac{5}{2}^-$ level is a $[532\uparrow]$ state,[13] while the $\frac{3}{2}^+$ ground state is a $[411\uparrow]$ state.[14] The change of two in n_z between the initial and final states is partially responsible for hindering the $E1$ transition.[15] The interfering irregular $E2$ transition, however, is allowed, while the irregular $M1$ is also hindered. The expected interference term between the regular $E1$ and irregular $E2$ (and possibly $M1$) transition provides the asymmetry under investigation. Specifically, the parity-violating, spin-conserving part of the nuclear-spin Hamiltonian may admix an appreciable amount of the 348-keV $\frac{5}{2}^+$ level because of the relatively small energy denominator in the perturbation expansion. This closeness in energy was a principal factor in the choice of this isotope for investigation. All three states of interest ($\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{5}{2}^-$) are band heads; i.e., they represent the same minimum core rotation with different single-particle states.

The angular distribution of 363-keV ^{159}Tb γ rays can be written in terms of Legendre polynomials of the cosine of the angle θ away from the applied-field direction.[16]

$$W(\theta) = 1 + A_1 f_1^{5/2}(\beta)P_1(\cos\theta) + \tfrac{15}{16} f_2^{5/2}(\beta)P_2(\cos\theta) + A_3 f_3^{5/2}(\beta)P_3(\cos\theta). \tag{1}$$

The $P_2(\cos\theta)$ term is the usual dipole radiation term, while the P_1 and P_3 terms represent parity violation. For Gamow-Teller β decays where one unit of angular momentum is carried away, we find

$$f_1^{5/2}(\beta) = \tfrac{21}{25} f_1^{3/2}(\beta), \quad f_2^{5/2}(\beta) = \tfrac{84}{125} f_2^{3/2}(\beta),$$

and

$$f_3^{5/2}(\beta) = \tfrac{324}{625} f_3^{3/2}(\beta). \tag{2}$$

Here $f_k^{3/2}(\beta)$ and $f_k^{5/2}(\beta)$ are the kth nuclear orientation moments of the $\frac{3}{2}^-$ ^{159}Gd parent and the $\frac{5}{2}^+$ 363-keV ^{159}Tb level. In the case of the ^{159}Gd moments in the magnetic hyperfine field, they are simple functions of β, the hyperfine energy splitting $\mu H_{\text{hf}}/I$ divided by the thermal energy, $k_B T$. Here μ is the previously unknown ^{159}Gd nuclear moment, I is the nuclear spin, $\frac{3}{2}$, and k_B is the Boltzmann constant. Because $f_k(\beta)\equiv 0$ for $k > 2I$, $f_4(\beta)$ and higher terms are absent from the angular distribution. Thus Eq. (1) becomes

$$W(\theta) = 1 + \tfrac{21}{25} A_1 f_1^{3/2}(\beta)P_1(\cos\theta) + \tfrac{63}{100} f_2^{3/2}(\beta)P_2(\cos\theta) + \tfrac{324}{625} A_3 f_3^{3/2}(\beta)P_3(\cos\theta). \tag{3}$$

In this experiment the $P_1(\cos\theta)$ and $P_2(\cos\theta)$ terms of the angular distribution were measured. The $P_3(\cos\theta)$ term is exceedingly small because $f_\beta^{3/2}(\beta)$ is small (going like $\beta^3 \approx 10^{-3}$) and because the parity-nonconserving A_3 is expected to be small. The results of this experiment were analyzed in terms of this expression both at high temperature where $f_k^{3/2}(\beta) = 0$ and at low temperature where $f_k^{3/2}(\beta) \neq 0$. The high-temperature (>0.2 K) work served as a measure of systematic errors in the equipment.

Data Analysis

In this experiment the applied-field direction rotates in the plane of the two counters, A and B, as shown in Fig. 2. At $t = 0$ the field points up in Fig.

2, and the counts are stored in channel $i=0$ of the two multiscalers. At $t=25$ sec the field points toward counter B and the counts are stored in channel $i=25$ of the multiscalers, and so on. It follows from Eq. (3) that the counting rate normalized to unity for high temperatures will be

$$N_i=\left[1+\tfrac{1}{4}\tfrac{63}{100}f_2^{3/2}(\beta)\mp\tfrac{21}{25}A_1f_1^{3/2}(\beta)\sin\frac{i}{100}-\tfrac{3}{4}\tfrac{63}{100}f_2^{3/2}(\beta)\cos\frac{2i}{100}\right]. \tag{4}$$

N_i is related to the experimental counting rate C_i by

$$N_i=100C_ie^{i/\tau}\Big/\sum_{j=0}^{99}C_je^{j/\tau}\,,$$

where τ is the decay constant. The $-$ sign of Eq. (4) now refers to counter A and the $+$ sign to B. The output of the multiscalers is read onto punched paper tape, and the computer calculates the following relevant quantities for each run:

$$S_1=\tfrac{2}{100}\sum_{i=0}^{99}N_i\sin\frac{i}{100}=\mp\tfrac{21}{25}A_1f_1^{3/2}(\beta)\,,$$

$$C_2=\tfrac{2}{100}\sum_{i=0}^{99}N_i\cos\frac{2i}{100}=-\tfrac{3}{4}\tfrac{63}{100}f_2^{3/2}(\beta)\,. \tag{5}$$

The results are indicated in Table I. The background counting rate per unit energy increment just above the 363-keV line was 2% of the average counting rate in our window. Multiplying the background by 0.02 and subtracting, the S_1 term becomes

$$\tfrac{1}{2}[S_1^A-S_1^B]=(2.7\pm1.8)\times10^{-4}=-\tfrac{21}{25}A_1f_1^{3/2}(\beta)\,, \tag{6}$$

and the C_2 term becomes

$$\tfrac{1}{2}[C_2^A+C_2^B]=(-7.7\pm2.1)\times10^{-4}=-\tfrac{3}{4}\tfrac{63}{100}f_2^{3/2}(\beta)\,. \tag{7}$$

Thus, $f_2^{3/2}(\beta)=(16.3\pm4.4)\times10^{-4}$, and from the definition of $f_2^{3/2}(\beta)$ for a nuclear spin in a field we calculate $|\beta|=|\mu|H/Ik_BT=0.086\pm0.012$.

TABLE I. Results of a computer analysis of all data taken. The calculated quantities, S_1 and C_2 for counters A and B, are defined in Eq. (5). The 363-keV data are for the SCA's set on the 363-keV peaks; for the background measurements the SCA's were set to accept counts of energy slightly greater than the peaks. The background is found to be 0.02 of the peak counts; hence columns two and three must be corrected by 0.02 of columns four and five, respectively. The runs are numbered in order of time sequence (except of the Mn^{54} data which were obtained several days before the low-temperature $^{159}\mathrm{Gd}$ work).

Run numbers	1, 2, 14, 16, 17, 18, 19	3,[a] 5, 6, 8, 9, 10, 11	15	4, 7, 12,[b] 13	$^{54}\mathrm{Mn}$
Temp (K)	0.2 – 4	0.028 – 0.034	0.3	0.028	300
γ Ray	363	363	back.	back.	854
$10^4\times S_1^A$	-2.4 ± 2.5 $\chi^2=0.5$[c]	0.3 ± 2.3 $\chi^2=0.2$	-18 ± 67	31 ± 25 $\chi^2=0.8$	3.0 ± 2.9
$10^4\times S_1^B$	-1.7 ± 2.7 $\chi^2=1.6$	-5.3 ± 2.5 $\chi^2=0.8$	22 ± 63	17 ± 24 $\chi^2=1.2$	2.6 ± 2.9
$10^4\times\frac{1}{2}\left[S_1^A-S_1^B\right]$[d]	-0.3 ± 1.9 $\chi^2=2.0$	$\underline{2.8}\pm\underline{1.7}$ $\chi^2=0.7$	-20 ± 46	8 ± 17 $\chi^2=0.3$	0.2 ± 2.0
$10^4\times C_2^A$	1.3 ± 2.6 $\chi^2=1.3$	-9.0 ± 2.7 $\chi^2=0.9$	47 ± 67	25 ± 25 $\chi^2=0.3$	-3.1 ± 2.9
$10^4\times C_2^B$	-1.8 ± 2.7 $\chi^2=0.4$	-5.1 ± 2.8 $\chi^2=0.3$	32 ± 63	19 ± 23 $\chi^2=3.4$	-2.4 ± 3.0
$10^4\times\frac{1}{2}\left[C_2^A+C_2^B\right]$[d]	-0.3 ± 1.8 $\chi^2=1.0$	$\underline{-7.1}\pm\underline{2.0}$ $\chi^2=0.6$	40 ± 46	23 ± 17 $\chi^2=2.5$	-2.8 ± 2.0

[a] Run 3, at 0.034 K, was not included in $\frac{1}{2}\left[C_2^A+C_2^B\right]\times10^4$, because its relatively high temperature would result in a misleading average because of the stronger temperature dependence of C_2 on T. If run 3 were included, however, this quantity would be -5.4 ± 1.7 and χ^2 would be 1.0.

[b] In run 12 the window was set at about 1000 keV rather than 400 keV.

[c] The statistical quantity, χ^2, is $\sum_{i=1}^{N}(A_1-\langle A\rangle)^2/(\delta A_i)^2\,(N-1)$ for N values A_i, of weighted average $\langle A\rangle$. δA_i is the statistical uncertainty of each measurement.

[d] The quantities $\frac{1}{2}\,[C_1^A-C_1^B]$ and $\frac{1}{2}\,[S_2^A+S_2^B]$ were found to be $(2.5\pm1.7)\times10^{-4}$ and $(2.6\pm2.0)\times10^{-4}$ with χ^2's of 0.9 and 1.7, respectively. These quantities are defined by analogy with Eq. (5).

If we assume $T = 0.028 \pm 0.005$, $H = 453$ kOe, $I = \frac{3}{2}$, and the ferromagnet is fully saturated, then $|\mu| = (0.22 \pm 0.05)\mu_N$. To determine the sign of μ, and hence β, we note that the $\frac{3}{2}^-$ level of ^{161}Dy (^{159}Gd plus two protons) and the $\frac{3}{2}^-$ level of ^{157}Gd (^{159}Gd minus two neutrons) have moments of -0.40[17] and -0.37,[18] respectively. Therefore, we take μ for ^{159}Gd to be $-(0.22 \pm 0.05)\mu_N$ and deduce that $\beta = -0.086 \pm 0.012$.

By knowing β, we can calculate $f_1^{3/2}(\beta) = -0.071 \pm 0.010$, and thus $A_1 = +(4.5 \pm 3.0) \times 10^{-3}$. Of course, if the sign of μ is wrong, then the sign of A_1 must be changed. It is important to note that the magnitude of A_1 depends only on two measured quantities, S_1 and C_2. C_2 determines the nuclear polarization, and the polarization together with S_1 determines A_1.

Errors

The principal source of error in this work is felt to be the statistical error. There was no evidence of any type of systematic error in the γ-ray data. No $P_1(\cos\theta)$ or $P_2(\cos\theta)$ terms were seen at high temperatures (see the table, column two), and thus there is no significant source motion due to the rotating field. Any contribution from bremsstrahlung asymmetry is corrected by the background terms measured (the table, columns four and five). Errors could arise if our detector efficiency were sensitive to the circular polarization of the γ rays. Our previous experience, however, with ^{60}Co polarized in an Fe foil showed no evidence of a large circular-polarization sensitivity. While no such sensitivity is expected, this type of error cannot be excluded at present.

Our temperature is not known very precisely. The fringes of the field may have warmed the resistor giving too high a temperature, but the field and activity may have warmed the sample even more, giving us too low a temperature reading. 5 mK seems like a reasonable error limit. The temperature error, however, does not affect A_1.

There are other possible problems, such as faulty GdFe$_2$ metallurgy, incomplete magnetic saturation, and so on, which would yield too small a value for $|\mu|$. These errors, though, would only cause second-order errors in A_1.

CONCLUSIONS

Evidence is seen for parity impurities in the nuclear levels of ^{159}Tb through the tendency for γ rays to be emitted in the direction of the $\frac{5}{2}^-$ level polarization. The measured asymmetry is $+(4.5 \pm 3.0) \times 10^{-3} P_1(\cos\Theta)$, where Θ is the angle between the Tb spin and the detector. Since control experiments have shown no evidence of systematic error, the statistics are reliable. Thus, the probability of a null or negative $P_1(\cos\Theta)$ coefficient is 7%. The sign of this term is based on an assumed negative moment of the ^{159}Gd parent. A subsidiary conclusion is the nuclear moment of ^{159}Gd, measured to have a magnitude of $0.22 \pm 0.05\mu_N$.

A significant outgrowth of this work is the demonstration of the usefulness of modern low-temperature technology to nuclear research, principally through the ability to maintain nuclear polarization for extended periods of time. The only real time limit is the lifetime of the radioactive source. Future work may lead not only to accurate parity-violation measurements, but also to sensitive time-reversal checks through circular-polarization measurements on γ rays emitted by polarized nuclei.

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†Present address: Physics Department, Michigan State University, East Lansing, Michigan 48823.

‡Present address: Brookhaven National Laboratory, Upton, New York 11973.

[1] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

[2] R. J. Blin-Stoyle, Phys. Rev. 118, 1605 (1960); F. C. Michel, Phys. Rev. 133, B329 (1964).

[3] For recent surveys of the theoretical and experimental situation, see W. D. Hamilton, Progr. Nucl. Phys. 10, 1 (1969); E. M. Henley, Ann. Rev. Nucl. Sci. 19, 367 (1969).

[4] D. P. Boyd, P. F. Donovan, B. Marsh, D. E. Alburger, D. H. Wilkinson, P. Assimakopoulus, and E. Beardsworth, Bull. Am. Phys. Soc. 13, 1424 (1968).

[5] V. M. Lobashov, V. A. Nazarenko, L. F. Saenko, L. M. Smotritskii, and G. I. Kharkevitch, Zh. Eksperim. i Teor. Fiz. – Pis'ma Redakt. 5, 73 (1966) [transl.: JETP Letters 5, 59 (1967)]. and Phys. Letters 25B, 104 (1967); V. M. Lobashov, N. A. Lozovay, V. A. Nazarenko, L. M. Smotrizky, and G. I. Kharkevitch, Phys. Letters

30B, 39 (1969).

[6] J. C. Vanderleeden and F. Boehm, to be published; E. Bodenstedt, L. Ley, H. O. Schlenz, and U. Wehman, Phys. Letters 29B, 165 (1969); D. W. Cruse and W. D. Hamilton, Nucl. Phys. A125, 241 (1969); F. Boehm and E. Kankeleit, Nucl. Phys. A109, 457 (1968); V. M. Lobashov, V. L. Nazarenko, L. F. Saenko, L. M. Smotritskii, and G. I. Kharkevitch, Zh. Eksperim. i Teor. Fiz. – Pis'ma Redakt. 3, 268 (1966) [transl.: JETP Letters 3, 173 (1966)]; B. Jenschke and P. Bock, Phys. Letters 31B, 65 (1970).

[7] Yu. G. Abov, P. A. Krupchitsky, M. I. Bulgakov, O. N. Yermakov, and I. L. Karpikhin, Phys. Letters 27B, 16 (1968); E. Warming, F. Stecher-Rasmussen, W. Ratynski, and J. Kopecký, Phys. Letters 25B, 200 (1967).

[8] Taken from C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

[9] R. E. Gegenwarth, J. I. Budnick, S. Skalski, and J. H. Wernick, Phys. Rev. Letters 18, 9 (1967).

[10] Model No. 440K, Opamp Laboratories, 172 S. Alta Vista Blvd., Los Angeles, California 90036.

[11] Furane Plastics, 5121 San Fernando Road West, Los Angeles, California 90039.

[12] See, for instance, R. D. Evans, *The Atomic Nucleus* (McGraw Hill Book Company, New York, 1955), p. 214.

[13] Here [$Nn_z\Lambda\uparrow$] is the usual notation for a single particle and a deformed core. N is the number of nodes in the single-particle wave function, n_z is its number of nodes along the z axis, and Λ is the projection of the single-particle angular momentum along the symmetry axis of the deformed core. $\uparrow$ or $\downarrow$ indicates that the single-particle intrinsic spin is parallel or antiparallel, respectively, to Λ.

[14] These assignments are from R. M. Diamond, B. Elbek, and F. S. Stephens, Nucl. Phys. 43, 560 (1963).

[15] See Table III of F. C. Michel, Phys. Rev. 133, B329 (1964). This early paper discusses many of the concepts necessary in the selection of appropriate transitions for study. These ideas are also discussed by S. Wahlborn, Phys. Rev. 138, B530 (1965).

[16] S. R. DeGroot, H. A. Tolhoek, and W. J. Huiskamp, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, The Netherlands, 1965), Vol. II, p. 1199.

[17] W. Henning, D. Huenemann, W. Weber, P. Kienle, and H. H. Korner, in *Hyperfine Structure and Nuclear Radiations*, edited by E. Matthias and D. A. Shirley (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968), p. 178.

[18] J. P. Hurrell, Brit. J. Apl. Phys. 16, 755 (1965).

PHYSICAL REVIEW C VOLUME 2, NUMBER 4 OCTOBER 1970

Nuclear Resonance Fluorescence in Xe^{131}[†]

M. Berman[*] and G. B. Beard
Department of Physics, Wayne State University, Detroit, Michigan 48202

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The 637- and 723-keV states in Xe^{131} have been investigated by employing the technique of nuclear resonance fluorecence. The angular distribution of the resonantly scattered radiation from the 637-keV level is consistent with the assignment of either spin and parity $\frac{5}{2}^+$, decaying to the ground state predominantly by an $M1$ transition, or a spin and parity of $\frac{7}{2}^+$ with the decay to the ground state being pure $E2$. Considering the results of other investigators, a $\frac{7}{2}^+$ assignment appears to be the correct choice. Assuming a spin of $\frac{7}{2}$, the mean life of the 637-keV level is found to be 1.8 ± 0.8 psec. The fact that resonant scattering from the 723-keV level was observed with a source of gaseous II^{131} is attributed to Coulomb fragmentation of the (IXe^{131})$^+$ molecular ion formed following the β decay of I^{131}. The angular distribution of the resonantly scattered 723-keV γ rays is consistent with a spin and parity assignment of $\frac{5}{2}^+$ to this level, and a pure $M1$ decay to the ground state. Our results indicate that the mean life of the 723-keV level is greater than 1.5 psec.

I. INTRODUCTION

Much effort has been devoted to both experimental and theoretical investigations[1,2] of the excited states in Xe^{131} populated by the β decay of I^{131}. The properties of various levels, however, are still not well understood. In particular, the spin and lifetime of the 637-keV level, as well as the multipolarity of its transition to the ground state, were still in question at the inception of the work described here. A spin and parity assignment of $\frac{5}{2}^+$, and a pure $E2$ transition to the ground state were indicated by the results of an electric hfs alignment experiment on oriented iodine nuclei.[3] The results of internal-conversion measurements[4] were consistent with a $\frac{7}{2}^+$ assignment and a pure $E2$ ground-state transition or a $\frac{5}{2}^+$ assignment decaying 98% $E2$ ($\delta = 7.4$) to the ground state. Other authors[5,6] have proposed a $\frac{7}{2}^+$ assignment coupled with an $E2$ transition to the ground state.

The lifetime of the 637-keV level has been previously measured by means of nuclear-resonance-