that a spin of 1− should be assigned to the ground state of Lu^{174}.

An isomeric state in Lu^{174} of 75-μsec lifetime and 133 kev above the ground state has been observed.[7] It seems possible that this is the other member of the predicted doublet.

[7] C. L. Hammer and M. G. Stewart, Phys. Rev. **106**, 1001 (1957).

ACKNOWLEDGMENTS

One of us (R.G.W.) is grateful to the National Science Foundation for the grant of a fellowship which enabled the completion of this research. Appreciation is expressed to R. P. Sullivan of the Department of Physics and Astronomy for assistance in the electronic phases of this research and to the Office of Naval Research for support in obtaining the enriched isotopes.

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Nuclear Orientation of Mn^{56}†*

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The angular distribution and circular polarization of the gamma rays emitted from 2.6-hr Mn^{56}, polarized at low temperatures in cerium magnesium nitrate, have been measured. Comparing the angular distribution results with angular correlation data it is possible to establish the spins of the 2.65- and 2.98-Mev excited states of Fe^{56} as 2 uniquely. The amplitude mixing ratios $\delta(E2/M1)$ for the 1.81- and 2.13-Mev γ-rays are shown to be $+0.11\pm0.06$ and -0.27 ± 0.03, respectively. Gamma anisotropies from aligned Mn^{56} in the same cooling salt have been studied; the results are compared with other Mn alignment experiments. From a simultaneous measurement of the angular distribution of the γ-rays from polarized Mn^{52} and Mn^{56}, the ratio of the nuclear g-values $(g_{52}/g_{56})=0.47\pm0.05$ has been determined, giving $\mu_{56}=3.35\pm0.35$ nm. The results of the circular polarization experiment determine μ_{56} to be positive.

I. INTRODUCTION

EXPERIMENTS by the nuclear cryogenics groups in Oxford and Leiden have shown that manganese isotopes incorporated in the lattice of cerium magnesium nitrate crystals can be oriented by the low-temperature method. Grace and co-workers[1] have applied both the Gorter-Rose method of nuclear polarization and the Bleaney method of alignment to the relatively long-lived Mn^{54}; Huiskamp and collaborators[2,3] have used both techniques to orient Mn^{52}. Huiskamp[2] has pointed out that there exists a discrepancy in the alignment data when comparing the results from the two Mn isotopes in the same cooling salt.

The purpose of the present work was to extend the magnetic hfs orientation methods to the investigation of the short-lived 2.6-hr isotope Mn^{56}. The spins of the levels and the multipolarity of the γ rays were determined from the study of the anisotropy of the γ rays emitted, which also yielded information about the magnitude of the magnetic dipole moment of Mn^{56}. The sign of this moment was measured by the observation of the circular polarization of the gamma rays.

II. DECAY SCHEME AND FORMALISM

The principal features of the decay scheme of Mn^{56} are well established (see, for instance, Strominger *et al.*[4]); Fig. 1(a) is based on this together with the results of the present experiment. Investigations of the γ spectrum by Cook[5] revealed additional high-energy γ rays of 2.52 and 3.39 Mev, not shown in the decay scheme.

From Coulomb excitation[6] and angular correlation and polarization correlation experiments[7] the 0.845-Mev state of Fe^{56} has a spin of 2^+. γ-γ angular correlation measurements by Metzger and Todd[8] and by Stimag *et al.*[9] show γ_2 and γ_3 to be mixed dipole-quadrupole transitions, the spin of the 2.98-Mev state being 3 or 2, and that of the 2.65-Mev state being 2.

Childs and Goodman,[10] using the atomic beam magnetic resonance technique, have measured the spin of Mn^{56} to be 3. Thus only Gamow-Teller beta transitions can take place to the excited states of Fe^{56} with

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* The research reported in this paper forms part of a Ph.D. thesis submitted by R. W. Bauer.

[1] Grace, Johnson, Kurti, Lemmer, and Robinson, Phil. Mag. **45**, 1192 (1954).

[2] Huiskamp, Steenland, Miedema, Tolhoek, and Gorter, Physica **22**, 587 (1956).

[3] Huiskamp, Diddens, Severiens, Miedema, and Steenland, Physica **23**, 605 (1957).

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[5] C. S. Cook, Nuclear Phys. **7**, 480 (1958).

[6] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).

[7] G. T. Wood and P. S. Jastram, Phys. Rev. **98**, 1187 (1955).

[8] F. R. Metzger and W. B. Todd, Phys. Rev. **92**, 904 (1953).

[9] Stimag, Skeel, and Jastram, Bull. Am. Phys. Soc. **4**, 56 (1959).

[10] W. J. Childs and L. S. Goodman, Bull. Am. Phys. Soc. **3**, 21 (1958).

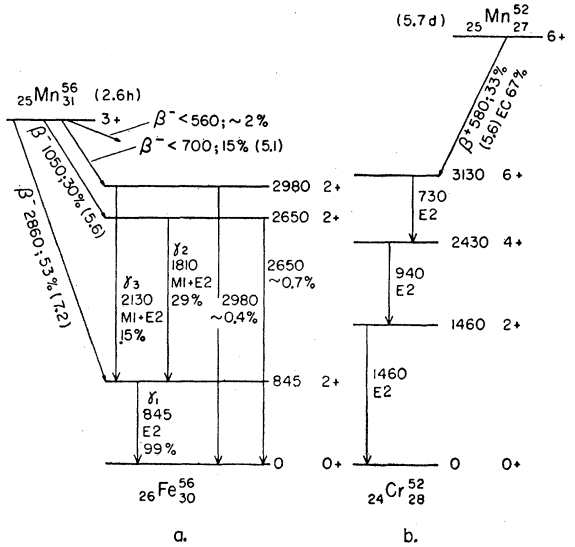

FIG. 1. Decay schemes of (a) Mn^{56} and (b) Mn^{52}. The energies are given in kev, the intensities in percent of disintegration. For the beta transitions the log ft values are indicated.

spin 2. The possibility of a GT-Fermi mixture exists only if the 2.98-Mev state has spin 3.

The spin assignments given in Fig. 1(a) for the 2.65- and 2.98-Mev excited states are those established by the results of the present experiment. Recently published results of γ-γ angular correlation and nuclear orientation experiments by Dagley *et al.*[11] show agreement with the findings from our experiment.

The expression for the angular distribution of a γ ray with respect to the axis of orientation of an oriented spin system can be written in the form:

$$W(\theta)=1+\sum_{n=2,4\cdots} B_n U_n F_n(L) P_n(\cos\theta), \qquad (1)$$

where $F_n(L)$ is a function of the angular momenta of the γ transition, U_n is a similar function for any intermediate unobserved transition, and B_n is an orientation parameter. For a definition of these quantities, see Blin-Stoyle and Grace.[12] $P_n(\cos\theta)$ is the Legendre polynomial of order n.

The γ radiation from an ensemble of oriented nuclei is in general partially polarized. Since a beam of partially polarized photons can be considered as an incoherent superposition of a beam of completely polarized photons and of a beam of unpolarized photons, we can characterize the degree of polarization by one single number P, defined by the ratio of the intensity of the polarized beam to the total intensity of the beam, where $0 \leqslant P \leqslant 1$.

Using the notation of Eq. (1), the expression for the degree of polarization P of a γ ray emitted from a system of oriented nuclei with rotational symmetry can be written in the general form:

$$P\xi = P_c \varkappa_c + P_L \varkappa_{||}, \qquad (2)$$

where the polarization vectors of the γ rays are the same as introduced by Tolhoek and Cox.[13] The degree of circular polarization P_c is

$$P_c = \frac{1}{W(\theta)} \sum_{n=1,3\cdots} B_n U_n F_n(L) P_n(\cos\theta), \qquad (3)$$

and the degree of linear polarization P_L is

$$P_L = \frac{\mp 1}{W(\theta)} \sum_{n=2,4\cdots} B_n U_n F_n(L) \frac{C(LLn,11)}{C(LLn,1-1)} \times \left[\frac{(n-2)!}{(n+2)!}\right]^{\frac{1}{2}} P_n^2(\cos\theta), \qquad (4)$$

where the minus sign is for electric, the plus sign for magnetic transitions. $C(LLn,11)$ are Clebach-Gordan coefficients, $P_n^2(\cos\theta)$ is the associated Legendre polynomial of order n. Expressions (1), (3), and (4) can easily be expanded to cover mixed γ transitions of multipole order L and $L+1$ (see, for instance, the treatment by Blin-Stoyle and Grace[12]).

III. APPARATUS AND EXPERIMENTAL PROCEDURE

In earlier experiments by Grace *et al.*[1] and Huiskamp *et al.*[2,3] the successful use of cerium magnesium nitrate $Ce_2Mg_3(NO_3)_{12}\cdot 24H_2O$ for nuclear orientation of Mn isotopes has been reported. A discussion of the orientation mechanism has been presented by these authors. The reason for selecting this cooling salt for our experiment is that by adiabatic demagnetization with the facilities available a temperature of about 0.003°K can be reached, this giving rise both to nuclear alignment in zero external magnetic field due to the splitting of the S_z states of the Mn ion (see discussion of the spin Hamiltonian for this case[1,2]) and to nuclear polarization with an external field H_p of several hundred gauss.

Mn^{56} was produced at the M. I. T. cyclotron by neutron capture and resulting reduction of $(MnO_4)^-$ in solution to $Mn^{56}O_2$ which was separated by filtration. By this method about 5 mC of Mn^{56} in less than 1 mg of stable Mn^{55} were obtained, enough activity to allow several half-lives for source preparation, mounting in the cyrostat and cooling to about 1°K. The assembled cryostat, the polarizing magnet, and the counter geometry are shown in Fig. 2.

With 100–150 μC of Mn^{56} at the beginning of the demagnetization experiments, the angular distribution of the intense γ rays, γ_1, γ_2, and γ_3, was observed as the double nitrate crystals warmed up after each cooling process. Measurements were made both with a polar-

[11] Dagley, Grace, Gregory, and Hill, Proc. Roy. Soc. (London) **A250**, 550 (1959).

[12] R. J. Blin-Stoyle and M. A. Grace, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42, p. 555.

[13] H. A. Tolhoek and J. A. M. Cox, Physica **19**, 101 (1953).

izing field H_p of 450 gauss along the trigonal axis of the nitrate crystals, and with no external field. Two scintillation counters were used (see Fig. 2), the polar counter measuring $W(\theta=0)$ consisted of a 3-in.×3-in. NaI(Tl) crystal on a DuMont 6363 photomultiplier tube, the equatorial counter measuring $W(\theta=\pi/2)$ consisted of a 2-in.×2-in. NaI(Tl) crystal on a DuMont 6392 tube. Thus an anisotropy defined by

$$\epsilon=[W(\pi/2)-W(0)]/W(\pi/2) \qquad (5)$$

was measured for the three γ rays as a function of the warmup times. It was found that the warmup was mostly due to radioactivity heating, especially when working with an activity of 50 μC or more of Mn^{56}. The external heat-leaks were estimated to be below 10 ergs/min.

The gamma spectra from both counters at successive time intervals after demagnetization were recorded in a multichannel pulse sorter at the LNS Data Center. The pulse-height distribution of Mn^{56} from the polar

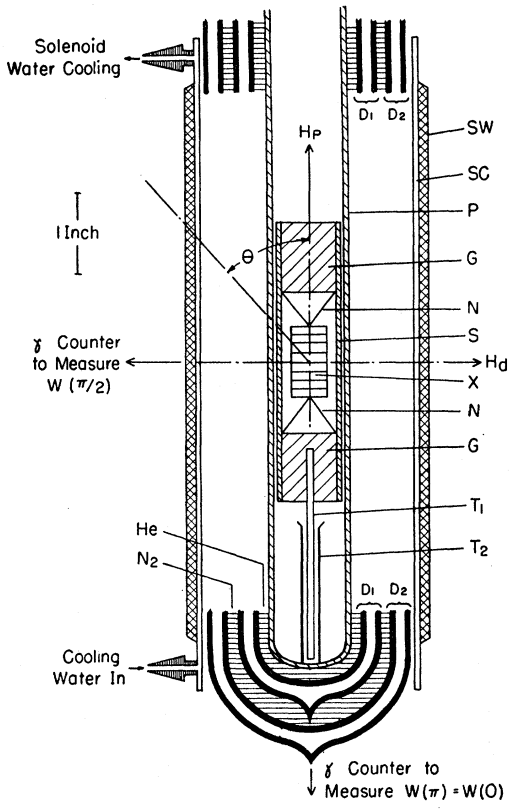

FIG. 2. Schematic diagram of the experimental arrangement for the measurement of the angular distribution of the γ rays. X are the Ce-Mg-nitrate crystals containing the Mn^{56} activity, suspended with nylon threads N from guard salts G (manganous ammonium sulfate). S indicates supports of glass rod; T_1 and T_2 are glass capillaries to support the sample in the Pyrex salt chamber P. D_1 is a He Dewar, D_2 a nitrogen Dewar. H_p is the polarizing field produced by the solenoid, SW are solenoid windings, and SC is the solenoid cooling jacket. The direction of the demagnetizing field H_d is indicated.

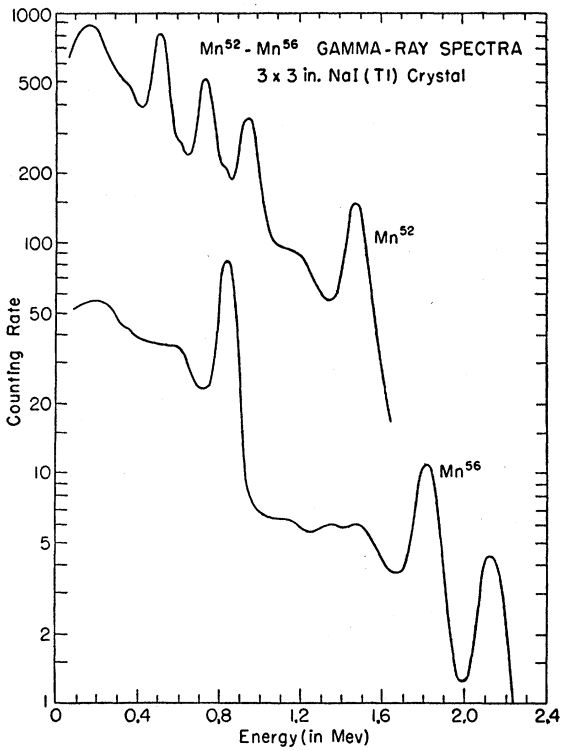

FIG. 3. Pulse-height distribution of the γ rays from Mn^{56} and Mn^{52} using a 3-in.×3-in. NaI(Tl) scintillation spectrometer.

counter is given in the lower curve of Fig. 3. The relative contributions of γ_2 and γ_3 were determined with the help of Y^{88} and Na^{24} in similar geometry.

For the measurement of the ratio of the nuclear g-values of Mn^{56} and Mn^{52}, both isotopes were grown into the same crystal. The same amounts of Mn^{56} were used as above, with the addition of about 50 μC of Mn^{52}. The latter was produced in the M. I. T. cyclotron by $(d,2n)$ on a chromium probe; a chemical separation of Mn was made, and none of the other Mn isotopes produced were abundant enough to disturb our measurements. The Mn^{52} spectrum is given in the upper curve of Fig. 3. For the comparison measurements the angular distributions of the 1.46-Mev γ ray of Mn^{52} and of γ_2 and γ_3 of Mn^{56} were studied. The method of data accumulation was the same as above.

The decay scheme of Mn^{52} with all the spin assignments is well established (see, for instance, Strominger *et al.*[4]); Fig. 1(b) is based on this. The F-GT mixture in the beta decay has been measured[14]; the magnetic moment of Mn^{52} is known to be 3.08 nm from paramagnetic resonance experiments.[15] Thus Mn^{52} is well suited as our "thermometric" isotope for the measurement of the magnitude of the magnetic dipole moment of Mn^{56}.

[14] Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **110**, 787 (1958).

[15] Abraham, Jeffries, Kedzie, and Leifson, Bull. Am. Phys. Soc. **2**, 382 (1957).

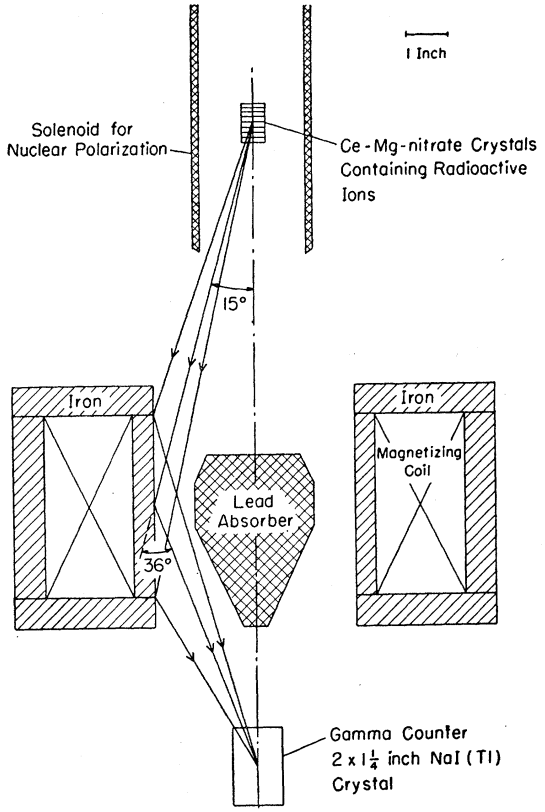

FIG. 4. Schematic diagram of experimental arrangement for the measurement of the circular polarization of the γ rays using forward Compton scattering. The source holder, salt chamber, and Dewars are not shown.

The sign of the magnetic moment of Mn^{56} was determined by the analysis of the circular polarization of the 0.845-Mev γ ray. Calculations from Eq. (3) showed that the degree of circular polarization of this γ ray is slightly reduced (by about 10%) because of depolarization in the high-energy gamma-ray transitions feeding the 0.845-Mev excited state, but still large enough for detection. The γ polarization was analyzed by forward Compton scattering of the circularly polarized γ ray with polarized electrons (in magnetically saturated iron) similar to the method introduced by the Leiden group.[16,3] Our geometry, different from that of the Leiden experiments, is shown in Fig. 4. The polar counter used in the previous experiments was replaced by the scattering magnet and a γ-ray detector. The equatorial counter measuring $W(\theta=\pi/2)$ was retained to monitor the temperature.

The scattering magnet was similar in construction to those described by Schopper.[17] The detector consisted of a 2-in. high$\times 1\frac{1}{4}$-in. diam NaI(Tl) crystal, a 6-in. logarithmic spiral Lucite light pipe, mounted on a RCA 6655 photomultiplier tube.

[16] Wheatley, Huiskamp, Diddens, Steenland, and Tolhoek, Physica **21**, 841 (1955).
[17] H. Schopper, Nuclear Instr. **3**, 158 (1958).

The method of data accumulation was similar to the one described above using the multichannel analyzer. Thus gain shifts of the photomultiplier and the associated electronic equipment could easily be observed and corrected for. A typical pulse-height distribution of the scattered radiation of Mn^{56} in the geometry of Fig. 4 is given in Fig. 5. The scattered peak of γ_1 appears at about 0.62 Mev, while γ_2 and γ_3 are not observed in peaks.

For the analysis of the circular polarization, we observe the effect E defined by

$$E=\frac{N_a-N_p}{\frac{1}{2}(N_a+N_p)}=\frac{2fP_c(d\sigma_c/d\sigma_0)}{1+P_L(d\sigma_L/d\sigma_0)}, \tag{6}$$

where N_a is the number of scattered photons when the polarizing field H_p of the solenoid used for the nuclear polarization experiment and the analyzing field H_a in the iron scatterer are antiparallel; N_p is the number of scattered photons when the two fields are parallel. $d\sigma_c$, $d\sigma_L$, and $d\sigma_0$ are the circular-polarization-dependent, linear-polarization-dependent, and polarization-independent parts of the Compton cross section, respectively, which are discussed in a recent review by Schopper.[17] The degrees of polarization are given in Eqs. (3) and (4). The fraction f of the polarized electrons is a property of the magnet; for our experiment it was measured to be 0.071.

For an incident γ ray of 0.845 Mev, the ratios of the cross sections averaged over the angles in our present

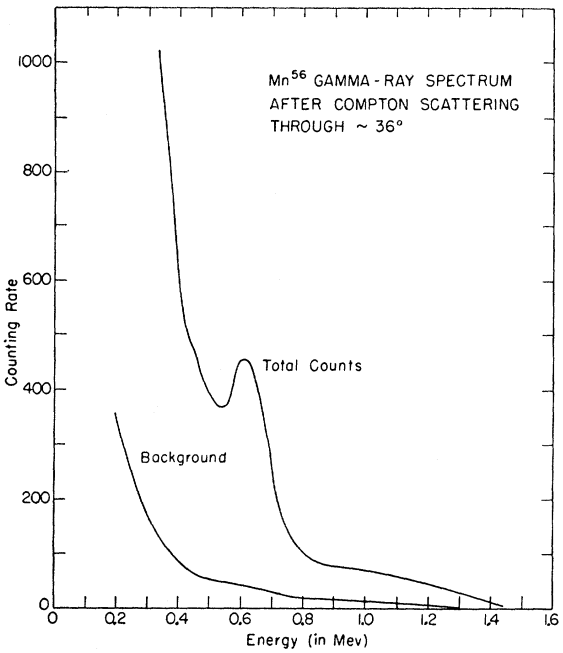

FIG. 5. Pulse-height distribution of the γ rays from Mn^{56} after being scattered by the magnet used for the analysis of circular polarization. Note that the incident 0.845-Mev γ rays gave a scattered peak at 0.62 Mev.

geometry are $\langle d\sigma_c/d\sigma_0\rangle_{Av}=+0.35$ and $\langle d\sigma_L/d\sigma_0\rangle_{Av}=-0.21$, giving in Eq. (6)

$$E=\frac{N_a-N_p}{\frac{1}{2}(N_a+N_p)}=\frac{0.050P_c}{1-0.21P_L}. \quad (7)$$

In our geometry P_L is less than 4% of the anisotropy ϵ defined in Eq. (5); thus we can neglect the P_L term in the denominator.

During one warmup period, the polarizing field H_p was kept in the same direction; reversing the analyzing field H_a between counting intervals, the effect E was calculated by taking successive differences between the counting rates per interval. During a cycle of four demagnetizations the two field directions with respect to each other were changed systematically. The circular polarization apparatus was tested on polarized Co^{60}. The experimentally observed effect agreed with the calculated values of the efficiency.

IV. RESULTS

Three experiments were performed with sources containing Mn^{56} alone, during which the anisotropies ϵ of the three intense γ rays were observed. Both the measurements with a polarizing field (450 gauss) and no polarizing field are given in Fig. 6. It is seen that the anisotropy is positive for all three γ rays. The curves are those calculated on the basis of $I=3$ for Mn^{56}, using the anisotropy of γ_1 (pure $E2$) as reference for the degree of orientation having corrected for the disorientation due to the preceding γ rays, and using the amplitude mixing ratios $\delta(E2/M1)$ for γ_2 and γ_3 with the respective alternative spin assignments as given in Table I.

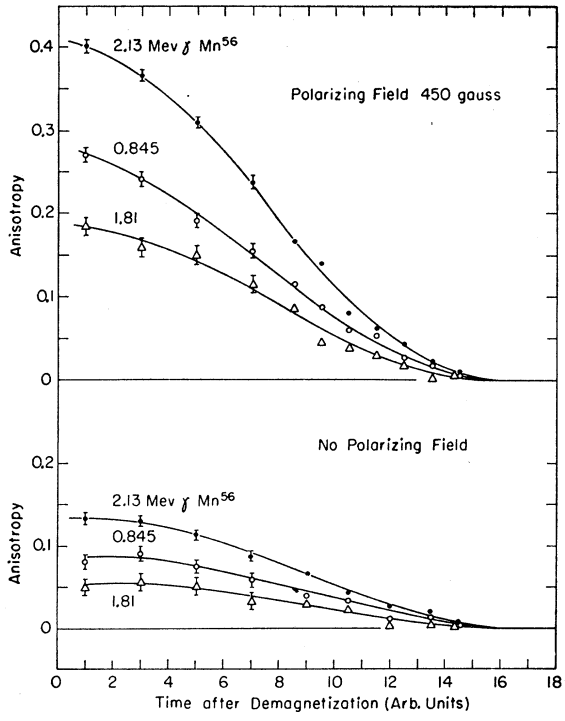

FIG. 6. The observed anisotropy ϵ of the γ rays from Mn^{56} with and without polarizing field is plotted against warmup time (arbitrary units). The curves are those calculated on the basis of certain spin assignments and mixing ratios (see text). Statistical errors are shown.

TABLE I. Alternative values of $\delta(E2/M1)$ deduced from the nuclear polarization experiment of Mn^{56}. The signs are appropriate for the first member of a γ-γ cascade. $L_\beta=0$ corresponds to a Fermi transition, $L_\beta=1$ to a Gamow-Teller transition in the preceding beta branch.

Cascade	(2-2-0)	(3-2-0) if $L_\beta=0$	(3-2-0) if $L_\beta=1$
γ_2	$+0.11\pm0.06$ or (-3.0 ± 0.6)	(-0.35 ± 0.04) or (-10_{-3}^{+4})	(-0.40 ± 0.06) or (-6_{-6}^{+2})
γ_3	-0.27 ± 0.03 or (-1.2 ± 0.2)	(-0.65 ± 0.04) or (-2.5 ± 0.5)	(-1.0 ± 0.1) or (-1.9 ± 0.2)

From the alternative values of the mixing ratios in Table I, we can eliminate the bracketed values by comparison with Table II where we have listed the mixing ratios as obtained from published γ-γ angular correlation experiments. It is to be observed that the sign of δ has to be reversed if one is to compare values of δ obtained from the nuclear orientation experiment where γ_2 and γ_3 are in effect the lower members of a cascade, with values of δ obtained from angular correlation experiments where the mixtures are the upper member of the cascade (see, for instance, addendum to the paper by Linqvist and Heer[18]). This change of sign has been made on the values of δ given in Table I.

Thus, by this comparison, our experiment uniquely determines the spin of the 2.98-Mev state in Fe^{56} to be 2^+, the mixing ratios of the 1.81- and 2.13-Mev γ rays to be $+0.11\pm0.06$ and -0.27 ± 0.03, respectively. These results have also been derived in a recently published nuclear orientation experiment by Dagley *et al.*,[11] who aligned Mn^{56} in nickel fluosilicate containing

TABLE II. Values of $\delta(E2/M1)$ deduced from published γ-γ angular correlation experiments of Mn^{56} for the possible spin sequences.

Author	γ_2(2-2-0)	γ_3(2-2-0)	γ_3(3-2-0)
Metzger and Todd[a]	$+0.15\pm0.08$ or $+1.55\pm0.08$	-0.29 ± 0.06 or $+6.3\pm0.06$	-0.18 ± 0.06 or ...[d]
Stimag *et al.*[b]	$+0.06\pm0.02$ or $+2.0\pm0.02$	-0.27 ± 0.02 or $+5.9\pm0.02$	-0.018 ± 0.02 or ...
Dagley *et al.*[c]	$+0.19\pm0.02$ or $+1.42\pm0.02$	-0.28 ± 0.02 or $+6.1\pm0.02$	-0.18 ± 0.02 or ...

[a] See reference 8.
[b] See reference 9.
[c] See reference 11.
[d] For γ_3(3-2-0) only the small value of δ has been listed. The large value, which is -2.9, turns out to be compatible with the nuclear orientation experiment (Table I), but leads to an angular correlation function which is inconsistent with the experimental points of the angular correlations measured by the authors quoted above.

[18] T. Lindqvist and E. Heer, Nuclear Phys. 2, 680 (1957).

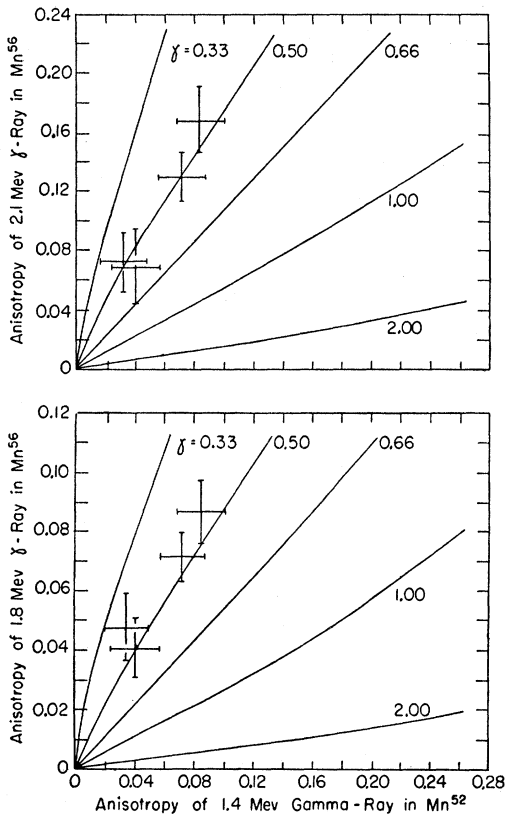

FIG. 7. The simultaneously observed anisotropies of the γ rays from Mn^{56} and Mn^{52}. The curves are those calculated for given ratios γ of the nuclear g-value of Mn^{52} to that of Mn^{56}. Statistical errors are shown.

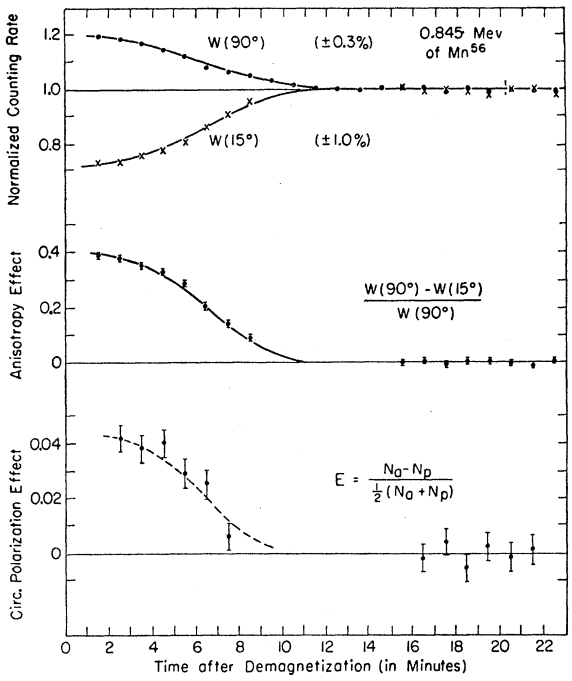

FIG. 8. The angular distribution $W(90°)$ and $W(15°)$, the anisotropy effect, and the polarization effect E, observed on the 0.845-Mev γ ray emitted from Mn^{56}, as a function of the warmup time (in minutes). Statistical errors are shown.

about 1% Mn which was activated after the crystal was grown from inactive solution.

The results of the anisotropy measurements in zero external field (alignment), given in Fig. 6, show that the values of ϵ are appreciably lower than the values obtained with polarized nuclei. The relative decrease of the initial anisotropy as a function of the warmup is less in the case of aligned nuclei; thus our results show general agreement with the findings of Huiskamp *et al.*[2,3] in the case of Mn^{52}. We did not find a considerable *increase* in the anisotropy as the temperature increased, as was reported by Grace *et al.*[1] to be the case in Mn^{54} (about 30% increase during the warmup from 0.003 to 0.010°K).

The smaller initial anisotropy in the case of aligned Mn^{56} is thought to be caused by the internal fields due to the cerium ions which in these crystals are very close to the divalent ions. Thus there exists the possibility that not all nuclear spins have the same preferred axis of alignment, since it is known that there are two different magnetic complexes of Mn ions in these crystals (see, for instance, Trenam[19]) for which the magnetic properties have been measured only in dilute salts. This coupling mechanism, however, might easily be broken in the polarization experiment where larger anisotropies are observed.

Two experiments were carried out with sources containing both Mn^{56} and Mn^{52}, during which the anisotropies of γ_2 and γ_3 of Mn^{56} and of the 1.46-Mev gamma ray of Mn^{52} were measured. These runs were carried out with polarized nuclei only. The experimental results are given in Fig. 7. The families of curves represent the calculated anisotropies ϵ on the basis of the spin assignments given in Fig. 1 and the mixing ratios determined above. The parameter γ is the ratio of the nuclear g-values of Mn^{52} to that of Mn^{56}. The experimental points scatter around the theoretical curves of $\gamma=0.47\pm0.04$. The quoted error, larger than that arising from statistics, includes an estimate of systematic errors arising from experimental uncertainties. With a $g=0.514$ for Mn^{52} and a spin of 3 for Mn^{56}, the nuclear magnetic dipole moment for Mn^{52} is calculated to be 3.35 ± 0.35 nm. This method of measurement is independent of temperature, but it depends to a large degree on the assumption that no disturbances and reorientations of the relative populations of the magnetic substates of the intermediate levels take place. The magnetic moment of Mn^{56} was recently measured, using the atomic beam magnetic resonance technique,[20] to be 3.53 ± 0.01 nm.

[19] R. S. Trenam, Proc. Phys. Soc. (London) **A66**, 118 (1953).

[20] Childs, Goodman, and Kieffer, Phys. Rev. Letters **1**, 296 (1958).

Two scattering experiments were carried out where the circular polarization of the 0.845-Mev γ ray was investigated. The results of these experiments are given in Fig. 8. The counting rate of the temperature monitor counter $W(\theta=90°)$ is given together with the counting rate in the Compton-scattering peak (energy range 0.54–0.72 Mev, see Fig. 5) from the incident γ ray, giving $W(\theta=15°)$. The effect E, defined in Eq. (6), is given in the lowest curve of Fig. 8. We find that the effect as defined above is $E=+(0.040\pm0.005)$ at the lowest temperatures; thus the counting rates in the scattering counter are larger, when the polarizing field H_p and the analyzing field H_a are opposite in direction, than in the case of the fields in the same direction. From the analysis of the angular momenta in the decay of Mn^{56}, the sign of the hyperfine coupling constant of the Mn ions (see, for instance, Trenam[19]), and the sign of the circular-polarization-dependent part of the Compton scattering cross section, we get a positive magnetic moment for Mn^{56}.

It is found that the circular polarization effect in Mn^{56} drops faster than the anisotropy of the angular distribution of the γ rays. This is thought to be due to the magnetic hfs level sequence of Mn in cerium magnesium nitrate, where nuclear magnetic substates m_I of opposite sign (from different fine-structure groups m_S) have a level spacing of the same order of magnitude as the magnetic substates m_I within one level group m_S.

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Alpha-Alpha Scattering in the Energy Range 5 to 9 Mev*

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The scattering of alpha particles from helium has been experimentally studied in the energy range 5 to 9 Mev by the measurement of three excitation functions at the center-of-mass angles 30° 33′, 54° 44′, and 70° 7′. A phase-shift analysis has been performed which indicates that only the S- and D-wave phase shifts are necessary to fit the data in this energy region. Only the well-known D state at approximately 2.9 Mev in Be^8 was observed. The D state has been compared to the single-level dispersion theory and level parameters have been extracted which are compatible with the alpha-particle model of Be^8.

INTRODUCTION

THE scattering of alpha particles by helium has been studied for many years. The first alpha-alpha scattering experiment was reported by Rutherford and Chadwick in 1927,[1] and their work was repeated and extended by other investigators. This early work was summarized in 1941, by Wheeler.[2] Unfortunately, the accuracy of these early experiments was limited by the necessity of using natural alpha-particle sources. The most recent, and precise alpha-alpha scattering experiments have been performed by Heydenburg and Temmer[3] at the Carnegie Institution in the energy range of 0.15 to 3 Mev; by Russell, Phillips, and Reich[4] at the Rice Institute in the energy range 2.5 to 5.5 Mev; by Nilson, Jentschke, Briggs, Kerman, and Snyder[5,6] at the Univeristy of Illinois in the energy range 12 to 23 Mev; and by Burcham *et al.*[7] at the University of Birmingham in the energy range 23 to 38.4 Mev.

Phase-shift analyses have been performed on all of these recent data and it is found that the only nonzero phase shifts needed to fit the data to a laboratory energy of 35 Mev are those corresponding to $l=0$, 2, 4, 6, and 8. Furthermore, only three states are observed

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