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Decay of 45-Day Fe^{59}†

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The gamma rays following the decay of 45-day Fe^{59} have been studied using the techniques of gamma-ray scintillation spectrometry, including γ-γ coincidence and γ-γ directional correlation measurements. In addition to the previously reported 0.192-, 1.10-, and 1.29-Mev gamma rays, two additional gamma rays having energies of 0.145 and 0.337 Mev were observed. These latter two arise from a state at 1.43 Mev in Co^{59}. All gamma rays were observed to decay with a half-life of 45±5 days. Directional correlation measurements on the 0.14–1.29 Mev and 0.19–1.10 Mev cascades were performed. The results of these measurements, together with the gamma-ray relative intensities, suggest an assignment of $\frac{1}{2}-$ to the 1.43-Mev state in Co^{59}.

I. INTRODUCTION

THE decay of Fe^{59} has been studied by many authors. The most detailed of this work is that of Metzger[1] and of Schiff and Metzger.[2] Their investigations included beta-ray and conversion electron spectra, β-γ and γ-γ coincidence measurements, and γ-γ directional correlation studies. Three gamma rays, with energies of 0.19, 1.09, and 1.29 Mev, were observed. From these results a level scheme for Co^{59} was constructed which was consistent with the observed data. This scheme was simple, with levels at 1.1 Mev and 1.29 Mev. The 0.19- and 1.09-Mev gamma rays were found to be in cascade, with the 1.29-Mev gamma ray crossing over to the ground state.

Recently the Co^{59} energy level structure has been investigated by Mazuri, Sperduto, and Buechner[3] in a (p,p') scattering experiment. The results of these measurements indicated levels at 1.097, 1.189, 1.289, 1.432, 1.458, and 1.479 Mev. These results, together with data obtained at this laboratory[4] which indicated the presence of additional low-energy gamma rays in the decay of Fe^{59}, prompted further study of this nuclide. A more complete decay scheme is proposed, based upon coincidence spectrometry and γ-γ directional correlation measurements.

II. SOURCE PREPARATION

To reduce the possibility of contamination, considerable care was taken in the preparation of source material for these studies. Sources were made from material produced by thermal neutron activation of enriched Fe^{58} by the Isotopes Division of the Oak Ridge National Laboratory. This material was further purified by repeated solvent extraction of Fe in ether.

III. GAMMA-RAY MEASUREMENTS

The gamma radiation emitted in the decay of Fe^{59} was observed with 3-in.×3-in. cylindrical NaI(Tl) detectors. Sources were prepared on rubber hydrochloride films (10 mg/cm^2) and counted at 10 cm on the vertical axis of the detector, using 400 mg/cm^2 polystyrene beta-ray absorbers. All measurements were made in a detector shield with inside dimensions of 32 in.×32 in.×32 in. to reduce the effect of scattering from material surrounding the detector. If smaller detector shields are used, the magnitude of the back-scatter peak is sufficient to prevent the observation of weak gamma rays in the energy region from 100 to 400 kev. Energy calibration of the spectrometers was achieved by using sources of Ce^{141}, Cs^{137}, and Zn^{65}. The method of internal comparison was applied to reduce the effect of rate-dependent gain fluctuations in the photomultipliers.

A typical pulse-height spectrum obtained from Fe^{59} is shown in Fig. 1. Gamma rays were observed at the following energies: 0.145, 0.192, 0.337, 1.10, and 1.29 Mev. The decay of a source was followed for a period of two half-lives with an indication that all gamma rays decayed with a half-life of 45±5 days. The decay of the low-energy region of the gamma-ray spectrum is shown in Fig. 2.

Relative intensities of the gamma rays were obtained by successive subtraction of pulse-height distributions representing the response of the detector to monoergic radiation for the particular geometrical arrangement used in these measurements. This method is discussed in some detail in the report by Heath.[5] Relative emission rates were then obtained using calculated detector efficiencies and experimentally determined photopeak efficiencies.[5] The results of the gamma-ray analyses are given in Table I. In the case of the weak low-energy transitions, the accuracy of the method is somewhat limited by the large contribution from the Compton-electron distributions of the two high-energy gamma rays. As a check on these results, relative intensities were also obtained directly from γ-γ coincidence measurements.

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[1] F. R. Metzger, Phys. Rev. 88, 1360 (1952).

[2] D. Schiff and F. R. Metzger, Phys. Rev. 90, 849 (1953).

[3] M. Mazuri, A. Sperduto, and W. W. Buechner, Massachusetts Institute of Technology, Laboratory for Nuclear Science Annual Progress Report, May, 1957 (unpublished), p. 134.

[4] R. L. Heath, D. G. Proctor, and C. W. Reich, Bull. Am. Phys. Soc. 4, 278 (1959).

[5] R. L. Heath, Atomic Energy Commission Report IDO-16408, 1957 (unpublished).

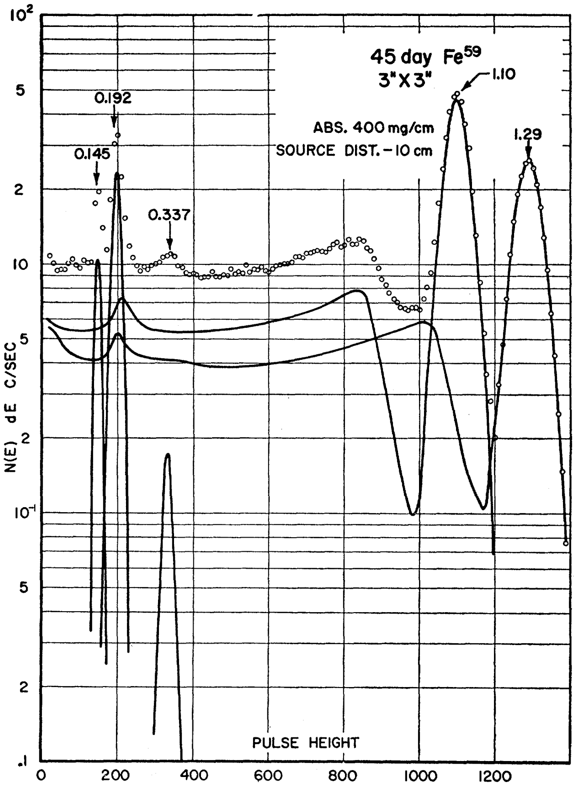

FIG. 1. Gamma-ray spectrum of 45-day Fe^{59}.

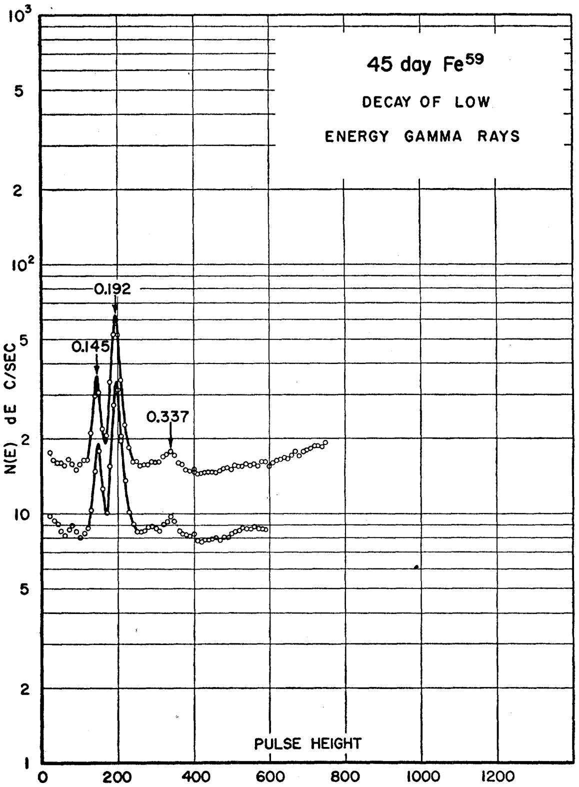

FIG. 2. Decay of the low-energy region of the Fe^{59} gamma-ray spectrum. The lower curve shows the spectrum taken 43 days later than the upper spectrum.

IV. COINCIDENCE MEASUREMENTS

From an examination of the information obtained from the singles gamma-ray spectrum, the intensities and energies of the two previously unreported gamma rays at 0.145 and 0.337 Mev suggested a new level at 1.43 Mev. This level would de-excite to the 1.29-Mev level by the 0.145-Mev gamma ray and to the 1.10-Mev level by the 0.337-Mev gamma ray.

To verify this proposed level, γ-γ coincidence measurements were made using a pair of 3-in.×3-in. NaI detectors. The detectors were mounted 6 cm apart with their axes in a horizontal line. A graded back-scatter shield was used to reduce false-coincidence effects from scattering between the two detectors. Polystyrene absorbers were used to stop the beta radiation.

The coincidence circuitry was of the "fast-slow" type with a fast resolution of 6×10^{-7} sec. The coincidence spectrometer consisted of an automatic sliding-window single-channel analyzer operated in coincidence with a 100-channel discriminator type pulse-height analyzer.

TABLE I. Energies and intensities of Fe^{59} gamma rays.

Gamma-ray energy (Mev)	Intensity (percent of β transitions) from analysis of singles spectrum	Intensity from coincidence experiments
0.145 ± 0.005	0.8	0.7
0.192 ± 0.005	2.5	2.6
0.337 ± 0.01	0.3	0.3
$1.10\ \pm0.01$	55.6	
$1.29\ \pm0.01$	44.1	

Two experiments were sufficient to establish the 1.43-Mev level as the origin of the two gamma rays in question. The single-channel analyzer was set in turn to span the photoelectric peaks of the 1.29- and 1.10-Mev gamma rays. The results of these measurements are shown in Figs. 3 and 4. From the first measurement, only the 0.145-Mev gamma ray is found to be in coincidence with the 1.29-Mev gamma ray. The 1.10-Mev gamma ray was observed to be coincident with the 0.145-, 0.192-, and 0.337-Mev gamma rays. These coincidence relationships together with relative intensities and energies are considered to be reasonable confirmation of the existence of the 1.43-Mev level.

V. DIRECTIONAL CORRELATION MEASUREMENTS

Directional correlation measurements of the 0.19–1.10 Mev and 0.14–1.29 Mev cascades were also performed. These cascades provided a situation containing most of the difficulties inherent in such measurements. Thus, it was felt that this case could provide a reasonable test of the techniques under adverse conditions. Both cascades presented two difficulties: low intensity of the low-energy gamma ray, and the large factor by which the

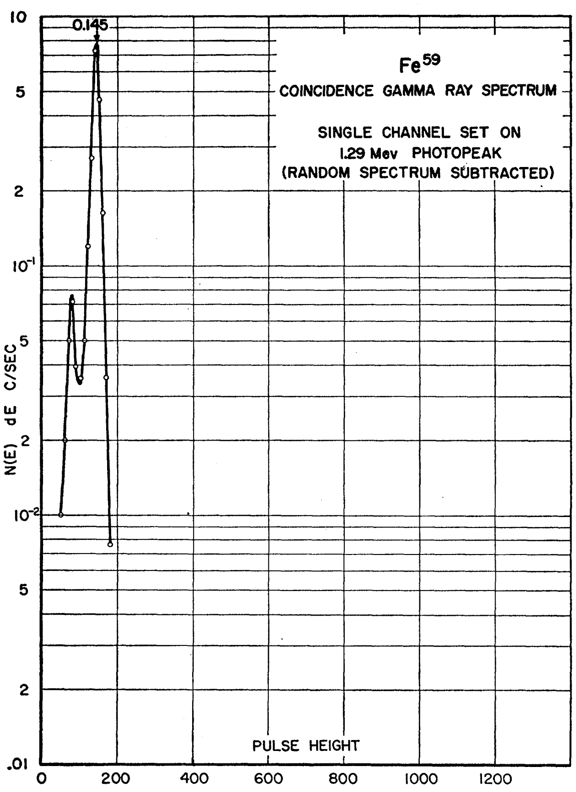

FIG. 3. Gamma-ray spectrum of radiation coincident with the 1.29-Mev gamma ray in the decay of Fe^{59}.

energies of the two gamma rays in the cascade differ. This latter feature put rather stringent requirements on the timing relationships in the coincidence circuitry. A detailed description of the apparatus and techniques involved in the directional correlation measurements is planned for a subsequent paper and will not be included here.

As set up for the correlation measurements, the coincidence circuit had a measured resolving time of ~60 mμsec and a low-energy cutoff of ~80 kev. The gamma-ray detectors were 3-in.×3-in. NaI(Tl) crystals mounted on Dumont-6363 photomultiplier tubes. The Fe^{59} source, in HCl solution, was contained in a thin-walled Lucite holder ($\frac{1}{16}$ inch i.d.). The source-detector distance was 10 cm. In the experiment, a coincidence was required between the fast outputs of the fixed and the movable detectors and the slow output of the fixed detector, which was set to detect only the photopeak of the higher energy gamma ray. When this requirement was met, the coincidence circuit gated on a conventional 20-channel analyzer, which examined the spectrum in coincidence with the high-energy gamma ray. Thus, at each angle, a coincidence spectrum of the low-energy radiation was obtained, from which the number of coincidence counts in the photopeak could be obtained by the usual means.[5] The use of a multi-channel analyzer with one of the detectors provides several advantages over a second single-channel analyzer. First, the necessity for correcting the coincidence data for gain shifts in the movable detector circuitry is eliminated. In view of the nature of the low-energy gamma-ray spectrum in this case, such corrections would have been very difficult to make. Second, the presence of scattering and other extraneous effects may be detected by their appearance in the spectrum. Their contribution can then be removed by graphical analysis. Data were taken in increments of 9°, from 90° through 180°. Several runs were taken at each angle, each run being taken for a predetermined time. Several times during the course of an experiment, the random coincidence rate was measured. This rate was about 1% of the gross coincidence rate.

The 0.19–1.10 Mev Cascade

A complication, due to Compton scattering, arose in the measurement of the correlation for the 0.19–1.10 Mev cascade. The photopeak of the 1.10-Mev gamma ray essentially coincides with the Compton end-point for the 1.29-Mev gamma ray. Thus, in the correlation measurement, one obtains an appreciable number of true but unwanted coincidences involving the Compton-scattered 1.29-Mev gamma ray. For 180° scattering, the energy of this scattered photon is ~0.21 Mev. This effect was minimized by placing a $\frac{1}{4}$ inch thickness of

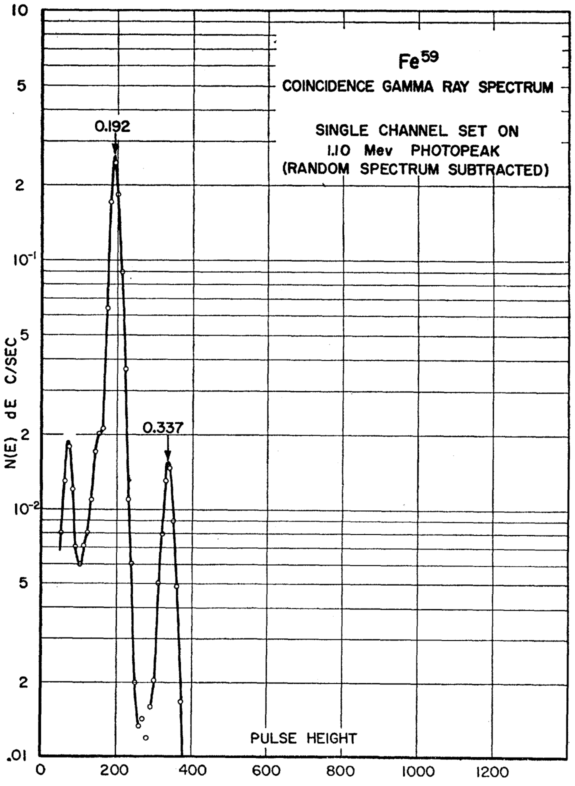

FIG. 4. Gamma-ray spectrum of radiation coincident with the 1.10-Mev gamma ray in the decay of Fe^{59}.

lead over the crystal of the fixed detector and by placing a graded scatter shield at 45° with respect to the fixed detector. With this configuration any Compton-scattered radiation had to traverse a considerable thickness of lead in order to reach the movable detector. This, plus the analysis of the spectrum of low-energy radiation, eliminated the effects of scattered radiation.

The measured directional correlation function for this cascade is shown in Fig. 5. The measured value of A_2 [in the expansion $W(\theta)=1+A_2P_2(\cos\theta)$] is $+(0.024\pm0.005)$. The quoted error is the standard deviation of the mean, calculated in the usual manner.[6] For an assumed cascade of 3/2 (1) 5/2 (1) 7/2, the theoretical value of A_2, after correction for the finite solid angle of the detectors, is $+0.043$.

The 0.14–1.29 Mev Cascade

Two measurements of the directional correlation function of the 0.14–1.29 Mev cascade were made. One of these measurements is shown in Fig. 6. These yielded an average value for A_2 of $-(0.069\pm0.005)$. For a 1/2 (1) 3/2 (2) 7/2 cascade, the theoretical coefficient, corrected for solid angle, is -0.061.

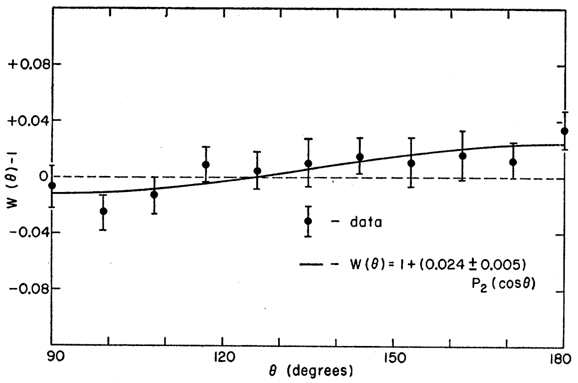

FIG. 5. The measured directional correlation function for the 0.19–1.10 Mev cascade in Co^{59}. Each point represents a total of ~3000 counts, collected during three 30 minute runs. The quoted errors represent statistical errors only and were calculated as in reference 6. No statistically significant $P_4(\cos\theta)$ term was found. The solid curve gives the least squares fit assuming a function of the form $W(\theta)=1+A_2P_2(\cos\theta)$.

In neither of the two cascades was any significant $P_4(\cos\theta)$ term detected. If the spin sequences are as stated (see also Sec. VI), then no $P_4(\cos\theta)$ terms would be expected to occur. The measured coefficients are observed to differ somewhat from the values expected for pure transitions. While these measurements tend to support the level scheme proposed in Sec. VI, in view of the experimental difficulties involved, they are not believed to be sufficiently sensitive to prove definitely the existence of quadrupole admixtures in the dipole transitions.

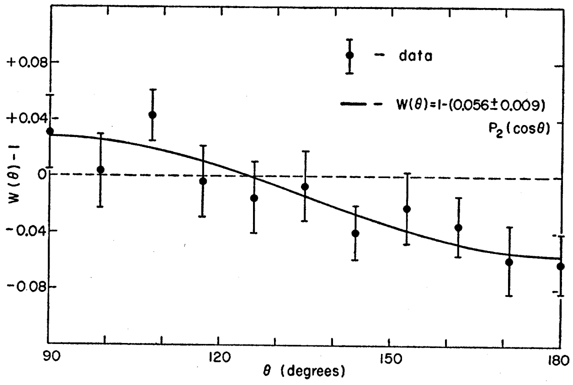

FIG. 6. One of the measurements of the directional correlation function for the 0.14–1.29 Mev cascade in Co^{59}. Each point represents a total of ~2000 counts, collected during three 45-minute runs. No statistically significant $P_4(\cos\theta)$ term was found. The solid curve gives the least squares fit assuming a function of the form $W(\theta)=1+A_2P_2(\cos\theta)$.

VI. DISCUSSION

From the experimental evidence discussed above, the decay scheme shown in Fig. 7 is proposed for the decay of 45-day Fe^{59}. The beta-ray branching ratios are derived from gamma-ray intensities, assuming the existence of the 1.56-Mev ground-state beta-ray transition reported by Metzger.[1]

Of the Co^{59} levels reported by Mazuri et al.,[3] only three appear to be populated to any extent in the decay of Fe^{59}. Since Co^{59} has 27 protons and 32 neutrons, the

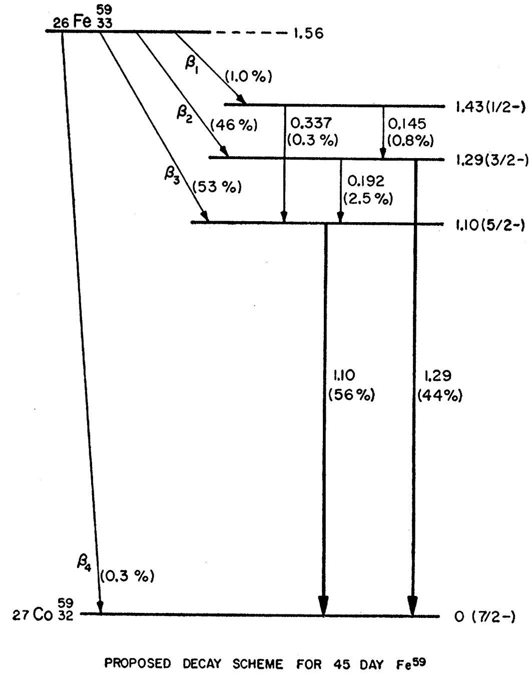

FIG. 7. Proposed decay scheme for 45-day Fe^{59}.

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[6] M. E. Rose, Phys. Rev. **91**, 610 (1953), Eq. (30). We are grateful to Dr. F. K. McGowan of Oak Ridge National Laboratory for making available to us an IBM-650 program used for the least squares analysis, and to Mr. E. B. Carter, Jr., for discussions concerning its use.

levels should be characteristic of a single proton "hole". From single-particle considerations,[7] the expected levels should be $f_{7/2}$, $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$, although not necessarily in that sequence. The ground state of Co^{59} has been reported to be $\frac{7}{2}$ by Mack.[8] The assignment of spins $\frac{5}{2}-$ and $\frac{3}{2}-$ to the 1.10- and 1.29-Mev levels was proposed by Schiff and Metzger[2] on the basis of γ-γ directional correlation measurements on the 0.19–1.10 Mev cascade. The assignment of spin $\frac{1}{2}-$ to the 1.43-Mev level is based largely on a comparison of radiation from this level with radiation from the 1.29-Mev level. The ratio of the energies of the 0.192- and the 1.29-Mev gamma rays is about the same as that of the 0.145- and a 1.43-Mev gamma ray. If one assumes spin $\frac{3}{2}-$ for the 1.43-Mev level, a strong ground-state transition would be expected. This is not observed. The relative intensities of the 0.145- and 0.337-Mev gamma rays are consistent with the assignment of $\frac{1}{2}-$ to the 1.43-Mev level. The directional correlation measurements also confirm this assignment.

After the publication of a preliminary report of this work,[4] J. M. Ferguson of the U. S. Naval Radiological Defense Laboratory kindly furnished us with a preprint of his work on this nuclide. The results of gamma-ray scintillation spectrometry and γ-γ coincidence measurements reported in this preprint are in agreement with our findings.

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[7] M. G. Mayer and J. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, Inc., New York, 1955).

[8] J. E. Mack, Revs. Modern Phys. **22**, 64 (1950).

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Search for an Electric Dipole Moment Structure of the Muon*†

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A search was made for an electric dipole moment in the muon with a sensitivity of 0.1% of a muon Compton wavelength times the electronic charge. The motivation for this investigation is provided by the interest in finding some property of the muon which would indicate a structure different from that of the electron, even though such a structure would violate both parity conservation and time reversal invariance. The muons pass through the fringe field of the cyclotron and an additional system of magnets producing an electric field in their rest frame. Any electric dipole moment would precess about this field producing a vertical plane component of spin transverse to the momentum. This is detected by measuring the electron asymmetry in the plane perpendicular to the momentum. The absence of such a component within the stated sensitivity gives an upper limit to the electric dipole moment of the muon as 2×10^{-16} cm$\times$the charge of the electron.

I. INTRODUCTION

THE violation of parity and charge conjugation symmetry principles in weak interactions naturally leads one to experiments which test time reversal invariance. The existence of an electric dipole moment in an elementary particle would constitute proof[1,2] that time reversal invariance is violated, provided there is no unknown symmetry to produce an additional degeneracy.[3,4] These questions are of particular interest in the study of the μ meson because of the present difficulty in explaining the muon-electron mass difference. The present experiment is designed to detect a possible electric dipole moment in the muon with a sensitivity of 0.1% of a natural moment,[5] i.e., the electronic charge multiplied by the muon Compton wavelength (1.85×10^{-13} cm).

The lowest upper limit for the electric dipole moment (EDM) of a particle has been established for the neutron[6] as $e\times5\times10^{-20}$ cm. The difficulty in producing an electric field at the position of a charged particle has limited the sensitivity with which an electric dipole moment in the electron or proton can be detected. In fact, the best upper limit to the EDM of the electron was found using the precession technique of the experiment reported here[7,8] ($e\times3\times10^{-15}$ cm). Other inde-

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† A preliminary report of this research was presented at the Ninth Annual International Conference on High-Energy Physics, Kiev, 1959 (unpublished).

‡ Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Faculty of Pure Science, Columbia University.

[1] T. D. Lee, Harvard lectures, Nevis Report No. 50 (unpublished). T. D. Lee and C. N. Yang, Brookhaven National Laboratory Report BNL-443, T-91, 1957 (unpublished).

[2] L. Landau, Zhur. Eksp. i. Teoret. Fiz. **32**, 405 (1957) [translation: Soviet Phys. JETP **5**, 336 (1957)]; Nuclear Phys. **3**, 405 (1957).

[3] N. F. Ramsey, Phys. Rev. **109**, 225 (1958).

[4] The effectiveness of the Pauli principle rules out such a degeneracy for electrons, neutrons and protons. However, no such experimental evidence exists for the muon.

[5] In a previous communication, we have reported a preliminary result giving an upper limit of 1% of the natural moment. Phys. Rev. Letters **1**, 144 (1958).

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