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

PHYSICAL REVIEW VOLUME 118, NUMBER 4 MAY 15, 1960

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

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(Received December 8, 1959)

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-

* Supported by the Joint Program of the U. S. Atomic Energy Commission and the Office of Naval Research.
† 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).
[6] J. H. Smith, E. M. Purcell, and N. F. Ramsey, Phys. Rev. **108**, 120 (1957).
[7] R. L. Garwin and L. M. Lederman, Nuovo cimento **11**, 776 (1959).
[8] D. F. Nelson, A. A. Schupp, R. W. Pidd, and H. R. Crane,

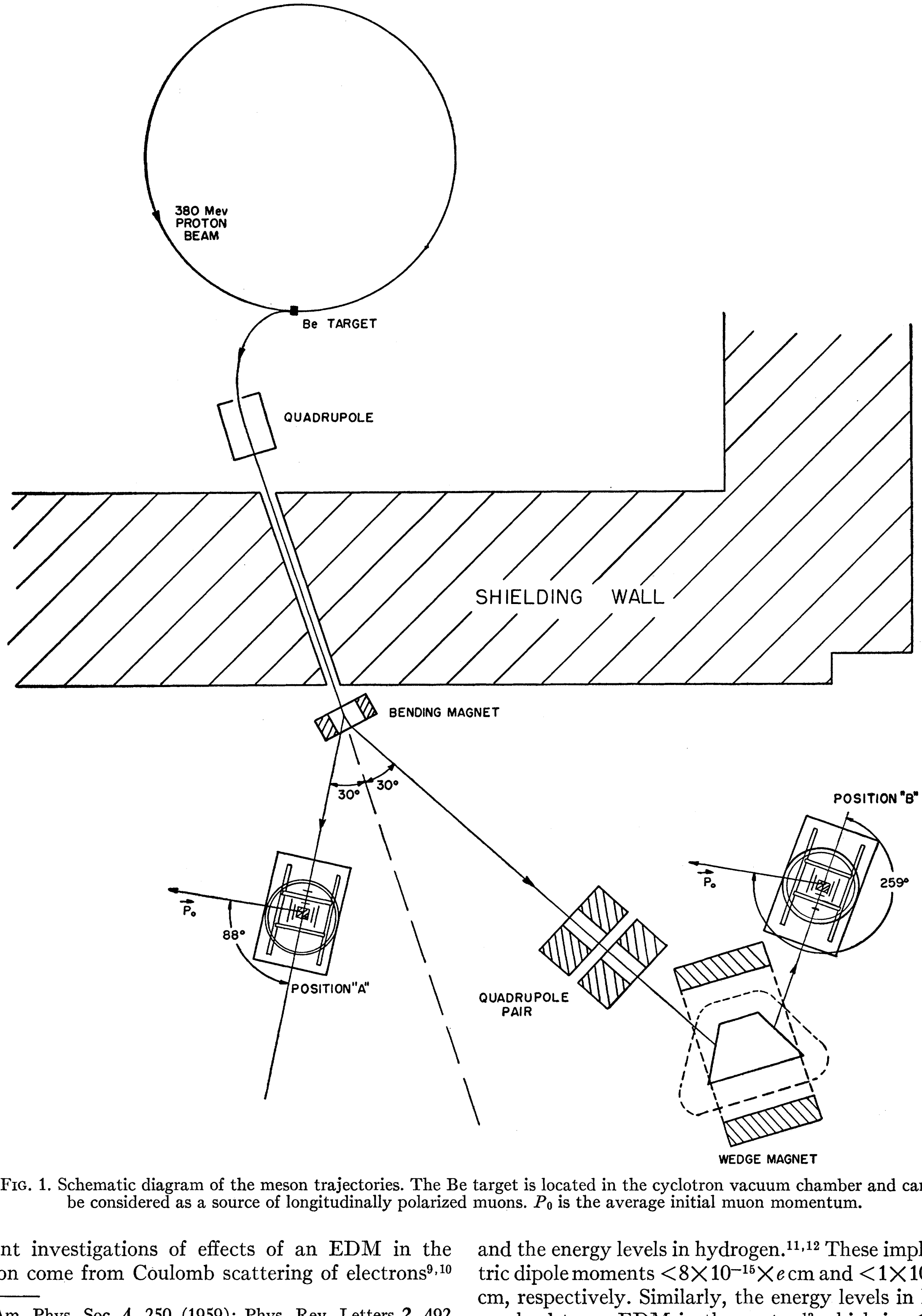

FIG. 1. Schematic diagram of the meson trajectories. The Be target is located in the cyclotron vacuum chamber and can be considered as a source of longitudinally polarized muons. P_0 is the average initial muon momentum.

pendent investigations of effects of an EDM in the electron come from Coulomb scattering of electrons[9,10] and the energy levels in hydrogen.[11,12] These imply electric dipole moments $<8\times10^{-15}\times e$ cm and $<1\times10^{-13}\times e$ cm, respectively. Similarly, the energy levels in hydrogen lead to an EDM in the proton[13] which is $<e\times1.3\times10^{-13}$ cm.

Bull. Am. Phys. Soc. 4, 250 (1959); Phys. Rev. Letters 2, 492 (1959).

[9] B. Margolis, S. Rosendorff, and A. Sirlin, Phys. Rev. **114**, 1530 (1959).

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[13] R. M. Sternheimer, Phys. Rev. **113**, 828 (1959).

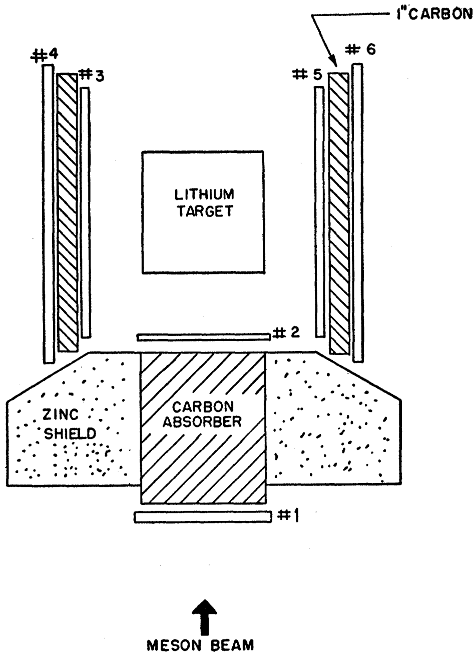

FIG. 2. Apparatus to measure transverse polarization. The beam intensity was monitored with counters 1 and 2 and the muons are brought to rest in the Li target. The magnetic fields used to precess the muons were produced with three pairs of Helmholtz coils surrounding the apparatus. A $12\bar{3}\bar{5}$ count triggered the gate, and electrons were counted in either the 34 telescope or the 5–6 telescope.

II. DESCRIPTION OF EXPERIMENT

A possible EDM in the muon can be detected by using a longitudinally polarized beam from the cyclotron and the asymmetry of the decay electrons.[14] A transverse electric field applied to an EDM would exert a torque proportional to $\boldsymbol{\sigma}\times\mathbf{E}$, and would cause the spin vector $\boldsymbol{\sigma}$ to precess away from the longitudinal direction.

In this experiment the electric field was created in the rest frame of the muon by its motion in a magnetic field $\mathbf{B}$.

$$\mathbf{E}=(\gamma/c)\mathbf{v}\times\mathbf{B}. \tag{1}$$

The presence of an electric dipole moment $fe\hbar/mc$ would cause a rotation of the spin vector out of the horizontal plane by an amount

$$\theta=2f\theta_0\beta\gamma,$$

where θ_0 is the total angle through which the trajectory is deflected by the magnetic fields and $\gamma=1/(1-\beta^2)^{\frac{1}{2}}$ (see Appendix).

Should the above precession occur, another effect which causes a second order change in the precession is produced by the ionization loss mechanism.[15] Before the polarization is analyzed, the muons are brought to rest. The longitudinal electric field produced this way generates a precession of the transverse component of spin about the momentum vector $\mathbf{p}$ through an angle

$$\phi=2(p/mc)f.$$

Thus, a particle which was longitudinally polarized at production would have the following polarization at the target: the component of polarization perpendicular to the horizontal plane is $P_1=P_0\sin\theta\cos\phi$; the component in the horizontal plane and perpendicular to the final momentum is $P_2=P_0\sin\theta\sin\phi$; finally the component of polarization in the momentum direction is $P_3=P_0\cos\theta$.

Muons are produced near a beryllium target bombarded by the proton beam and are nearly longitudinally polarized. The mesons are deflected by the cyclotron fringe field and then by an additional system of magnets. The presence of an EDM can be detected by comparing the vertical component of the beam polarization for two different total bending angles of the muon beam trajectory. In this way the geometry in the region where the muons are born remains fixed and the initial beam polarization does not influence the result.

Positive muons were deflected by the magnet system shown in Fig. 1. First they were deflected through 30 degrees by a dipole magnet with vertical focussing. For the run at position B they were then focussed by a quadrupole pair for injection into a large wedge shaped magnet. The particle trajectories in this magnet had previously been determined by wire measurements and represented a deflection of 111 degrees. Upon emergence, the muons were stopped in a lithium metal target 71 inches from the exit of the magnet. For the run at position A, the target was placed 108 inches from the dipole bending magnet.

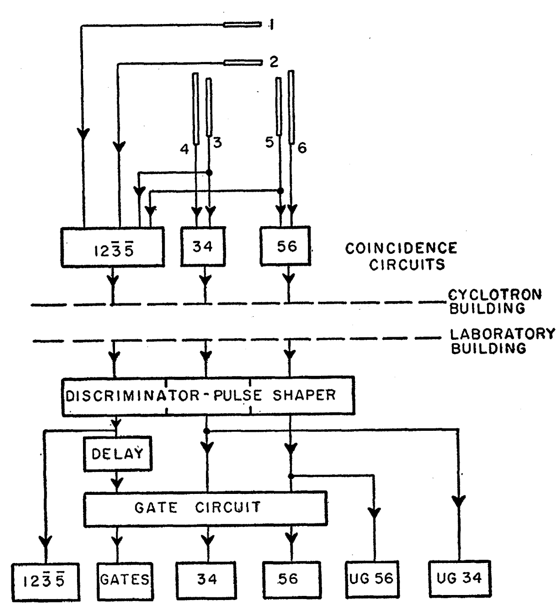

FIG. 3. Block diagram of the electronics.

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[15] T. D. Lee and G. Feinberg (private communication).

The polarization direction of the beam was determined by precessing the muons with a fixed magnetic field and measuring the electron asymmetry in two counter telescopes. A diagram of the apparatus is shown in Fig. 2. An incident muon ($12\overline{3}\overline{5}$) initiated a 1.6-microsecond gate delayed 0.7 microsecond and decay electrons (34 and 56) were counted during the time the gate was open. A block diagram of the electronics is shown in Fig. 3. The precession field was provided by a set of Helmholtz coils and was uniform to 1% over the region of the target.

The electron asymmetry is assumed to have the form

$$R=1+aP_0\hat{e}\cdot\hat{e}_{\max},$$

where aP_0 is the asymmetry parameter and $\hat{e}$ and $\hat{e}_{\max}$ are unit vectors in the direction defined by the electron telescope and the direction of maximum counting rate, respectively. The direction of the polarization vector with respect to the momentum can then be determined from three measurements: The ratio of the electron counting rates after the muon spin has precessed (1) +90 degrees and −90 degrees about a magnetic field along the muon momentum **p**, (2) 0 degrees and 180 degrees about a magnetic field along the momentum **p**, and (3) +90 degrees and −90 degrees about an axis perpendicular to **p** in the vertical plane. If these ratios are x_1, x_2, and x_3 respectively, then

$$(x_1-1)/(x_1+1)=aP_0\sin\theta\cos\phi,$$
$$(x_2-1)/(x_2+1)=aP_0\sin\theta\sin\phi,$$
$$(x_3-1)/(x_3+1)=aP_0\cos\theta.$$

To deduce the beam polarization from x_3, the asymmetry parameter must be corrected for gate width and solid angle, and integrated over the electron energy spread accepted by the counters. In addition, the measured asymmetry parameter contains a dilution due to background and accidental coincidences. Including these effects the measured x_3 is consistent with complete longitudinal polarization of the muons. Note that we need never use these corrections since we measured x_3 at each running position. The muon energy was determined from a differential range curve to be 112±6 Mev at position B and corresponds to $\beta\gamma=1.83$.

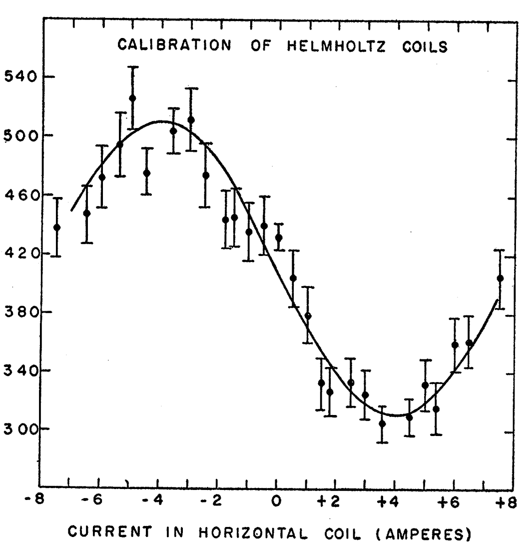

FIG. 4. Calibration curve for the coils which produced the magnetic field along the momentum direction. This provides the current settings required to precess the muons through a given angle.

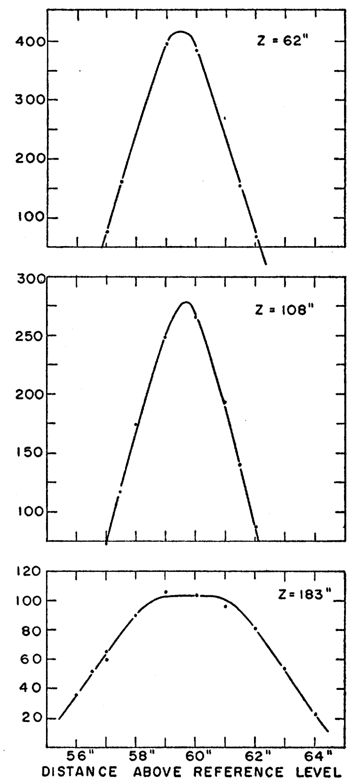

FIG. 5. Vertical distributions of the beam at position A. The line of centers is taken as the beam direction. Z is measured from the exit of the bending magnet along the beam direction.

The Helmholtz coils which provided the magnetic fields were calibrated by repeating the classical muon precession experiment.[12] Figure 4 is the calibration curve for the coils which produced the magnetic field along the momentum direction, H_3.

Note that for a beam that is initially longitudinally polarized, the angle ϕ depends on a small electric dipole moment to second order and for this reason was not accurately measured. It was, however, checked that $\phi\lesssim 0.1$ radian, thus taking ϕ equal to zero represents negligible error in θ.

Care was taken to eliminate two sources of a stray transverse component of magnetic field, which would simulate an electric dipole moment. First, the cyclotron fringe field was cancelled over the region of the target with a set of Helmholtz coils. This was done with a flip coil galvanometer arrangement. The vertical component of field, H_1, was cancelled at the center of the target. This was possible since the gradient of the cyclotron field was uniform and the results of both pairs ofelectron

TABLE I. Summary of data.

Position	x_3	aP_3	x_1	aP_1	$\theta = aP_1/aP_3$ radians	f
A (88° run)	1.45±0.03	0.18±0.01	1.004±0.003	0.002±0.0015	0.011±0.008	0.002±0.002
B (259° run)	1.55±0.04	0.22±0.01	0.995±0.005	−0.0025±0.0025	−0.011±0.011	−0.0007±0.0008

counters were averaged. A small residual vertical component δH_1 would simulate $\theta = \delta H_1/H_3$: δH_1 was made less than 0.06 gauss and $H_3 = 12$ gauss for 90° precession, so that the contribution to the error in θ from this source is $\lesssim 0.005$ radian. The currents in those coils which nulled the transverse components of field were regulated by a transistor regulator recently described by Garwin.[16]

Secondly, the precessing field was aligned with the muon momentum with special attention to the vertical component. The direction of the momentum was determined by taking vertical distributions of the beam at three positions along the trajectory. These are shown in Figs. 5 and 6. The locus of the centers of these distributions is taken as the beam direction, and can be determined to ±0.002 radian. The alignment was made by sighting along this direction with a line accurately perpendicular to the axis of a small solenoid connected to a galvanometer. The Helmholtz coil was then rotated in the vertical plane until reversing its magnetic field gave a zero deflection of the galvanometer. The error in this alignment is estimated at ±0.004 radian. Thus the total contribution to the error in the measured angle θ from the precessing field alignment is $\delta\theta = \pm 0.005$ radian.

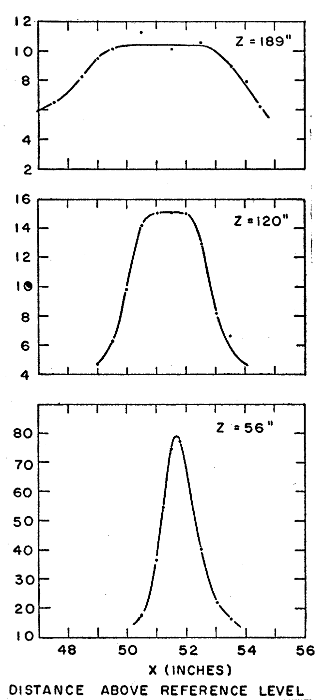

FIG. 6. Vertical distributions of the beam at position B. Z is measured from the exit of the wedge magnet along the beam direction.

Magnetic field effects on the counters were negligible since the phototubes were outside the region of precessing field and were magnetically well shielded. As a check, π mesons were stopped in the target and no electron asymmetry was found. ($x = 1.004 \pm 0.009$.)

III. RESULTS

The most significant data were taken with the beam deflected as shown in Fig. 1 and are summarized in Table I. In addition, data at two other positions have already been reported.[4] The angle the polarization made with the horizontal plane was found to be (including all sources of error)

$$\theta = 0.011 \pm 0.011 \text{ radian (position } A\text{, 88° run)},$$

$$\theta = -0.011 \pm 0.013 \text{ radian (position } B\text{, 259° run)}.$$

The possible precession due to an EDM is then the difference between these angles and leads to the result,

$$f = 0.0020 \pm 0.0015.$$

Because of the complete up-down symmetry of the production process, it is unlikely that the muons have an initial component of polarization out of the horizontal plane. The use of the total bending angle is therefore justified[17] and combining the results of positions A and B, one obtains

$$f = -0.0004 \pm 0.0007.$$

This corresponds to an EDM$\lesssim e \times 2 \times 10^{-16}$ cm. We note that (f) is approximately an upper limit for the probability amplitude for both parity and time reversal mixing.

IV. ACKNOWLEDGMENTS

We wish to thank Professor Leon M. Lederman for suggesting this topic and for his continued guidance and encouragement. We wish to thank Dr. Richard L.

[16] R. L. Garwin, Rev. Sci. Instr. 29, 223 (1958); Erratum Rev. Sci. Instr. 29, 900 (1958).

[17] *Note added in proof.* Recent measurements at CERN [Charpak, Lederman, Sens, and Zichichi (to be published)] yield $f = (2.7 \pm 2.8) \times 10^{-4}$. Stimulated by comments of the CERN group (R. L. Garwin and F. Farley), we have reexamined in more detail the kinematics of the muon production process and the effect of any vertical bias in the geometrical acceptance function (of the Quad-magnet, shielding wall, etc.) on the initial beam polarization (G. Gidal, thesis, Columbia University, February 1960; Nevis Rept. No. 83, Appendix II).

The results are that the possible geometrical errors in alignment permit of a maximum transverse vertical polarization of the muons (produced above the median plane and accepted by the detector) which is less than the quoted uncertainty, but depends on a (quote plausible) assumption as to the effective muon source size.

Garwin for helpful conversations and Dr. S. Rosendorff for his cooperation on the appendix. Lastly, we wish to thank the staff of the Nevis cyclotron laboratory for their cooperation.

APPENDIX

Following Foldy's[18] treatment of the magnetic moments, the most general way to introduce an electric dipole moment into the covariant, gauge invariant Hamiltonian for a spin $\frac{1}{2}$ particle interacting with a static electromagnetic field is by the addition of a term $-(ief\hbar/2mc)\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$.

This term leaves the Hamiltonian invariant under charge conjugation but not under parity or time reversal. It can be written as $+(fe\hbar/mc)\bar{\psi}\{\boldsymbol{\sigma}\cdot\mathbf{E}+i\boldsymbol{\alpha}\cdot\mathbf{B}\}\psi$ so that the Hamiltonian for a muon with an EDM in a constant external magnetic field, $\mathbf{B}$, becomes

$$H=c\boldsymbol{\alpha}\cdot\boldsymbol{\pi}+\beta mc^2+(ife\hbar/mc)\beta\boldsymbol{\alpha}\cdot\mathbf{B}$$
$$=\rho_1 c\boldsymbol{\sigma}\cdot\boldsymbol{\pi}+\rho_3 mc^2-(fe\hbar/mc)\rho_2\boldsymbol{\sigma}\cdot\mathbf{B}.$$

Performing a Foldy-Wouthuysen transformation[19,20] gives

$$H'=e^{-i\rho_2\phi/2}He^{i\rho_2\phi/2},$$

where $\tan\phi=-c\boldsymbol{\sigma}\cdot\boldsymbol{\pi}/mc^2$. Dropping terms which connect positive and negative energy states we find for the positive energy part

$$H'=\epsilon_\pi-\left(\frac{e\hbar}{2\epsilon_\pi/c}\right)\boldsymbol{\sigma}\cdot\mathbf{B}+\frac{fe\hbar}{m\epsilon_\pi}\boldsymbol{\sigma}\cdot(\boldsymbol{\pi}\times\mathbf{B}),$$

where $\epsilon_\pi=(m^2c^4+c^2\pi^2)^{\frac{1}{2}}$ and define $\mu_0=e\hbar/mc$. Replacing ϵ_π by its eigenvalue γmc^2 and noting that $\mathbf{v}=\boldsymbol{\pi}/\gamma m$ gives

$$H'=\epsilon_\pi-(\mu_0/2\gamma)\boldsymbol{\sigma}\cdot\mathbf{B}+f\mu_0\boldsymbol{\sigma}\cdot(\mathbf{v}/c\times\mathbf{B}),$$
$$d\boldsymbol{\sigma}/dt=(i/\hbar)[H',\boldsymbol{\sigma}]=(-\mu_0/\hbar\gamma)\boldsymbol{\sigma}\times\mathbf{B}+(2f\mu_0/\hbar)\boldsymbol{\sigma}\times(1/c)(\mathbf{v}\times\mathbf{B}),$$
$$=\sigma(d\theta/dt)\hat{n}.$$

But $\omega_0\equiv(\mu_0/\gamma\hbar)B$. So

$$d\theta/dt=2f(v/c)\gamma\omega_0,$$

and

$$\theta=2f\theta_0\beta\gamma. \qquad (2)$$

[18] L. I. Foldy, Phys. Rev. **87**, 688 (1952).
[19] L. L. Foldy and S. A. Wouthuysen, Phys. Rev. **78**, 29 (1950).
[20] H. Mendlowitz and K. M. Case, Phys. Rev. **97**, 33 (1955): The transformation used here is identical with that used in this paper for the anomalous magnetic moment. It is interesting that the result is similar, i.e., the EDM as well as the anomalous part of the magnetic moment precesses with a frequency γ times that of the normal moment. The same result is obtained classically [see V. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Letters **2**, 435 (1959)]. Note that the anomalous magnetic moment term has been omitted from H since it gives rise to a precession orthogonal to the EDM precession and is unobservable within the precision of this experiment.

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Charge Independence in the Reactions $p+d\rightarrow\pi^0+He^3$ and $p+d\rightarrow\pi^++H^3$ at 450 Mev*

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(Received December 30, 1959)

An experiment has been performed to measure the branching ratio in the production of He^3 and H^3 in p-d collisions at 450 Mev at 140° in the c.m. system. The result is 2.13 ± 0.15 which is in agreement with the prediction of a ratio 2 on the basis of charge independence alone. The production cross sections were found to be $(d\sigma/d\Omega)_{He^3}=5.41\pm0.29$ μb/sr and $(d\sigma/d\Omega)_{H^3}=11.55\pm0.49$ μb/sr.

INTRODUCTION

SEVERAL workers[1–4] have tested the validity of the hypothesis of charge independence for reactions involving pion production. Only one of these experiments[4] has been performed to an accuracy greater than 10%.

Among suitable reactions[5,6] for this test are

$$p+d\rightarrow H^3+\pi^+,$$

and

$$p+d\rightarrow He^3+\pi^0.$$

The branching ratio for these two reactions is predicted to be 2.

* Research supported by a joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† Also at Argonne National Laboratory, Lemont, Illinois, and the Department of Physics, The University of Chicago, Chicago, Illinois.
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[1] C. S. Godfrey, Phys. Rev. **96**, 1621 (1954); R. A. Schluter, Phys. Rev. **96**, 734 (1954); V. B. Fliagin et al., J. Exptl. Theoret. Phys. U. S. S. R. **35**, 854 (1959) [translation: Soviet Phys.—JETP **35**(8), 592 (1959)]; R. H. Hildebrand, Phys. Rev. **89**, 1090 (1953).
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[5] A. M. L. Messiah, Phys. Rev. **86**, 430 (1952).
[6] J. M. Luttinger, Phys. Rev. **86**, 571 (1952).