π^+ photoproduction. If this resonant behavior is to be assigned to a definite state of isotopic spin, then the fact that the peak is more prominent in π^+ than π^0 production indicates a $T = \frac{1}{2}$ resonance as suggested by Wilson.[7] However, no very simple explanation of the pion-nucleon interaction in this energy region appears likely in view of the rather different behavior observed in the three related reactions: π^+ photoproduction, π^0 photoproduction, and pion-nucleon scattering.

*Supported in part by the U. S. Atomic Energy Commission.

[1] P. L. Donoho and R. L. Walker, Phys. Rev. 107, 1198 (1957).

[2] R. R. Wilson, Nuclear Instr. 1, 101 (1957).

[3] Walker, Teasdale, Peterson, and Vette, Phys. Rev. 99, 210 (1955).

[4] Tollestrup, Keck, and Worlock, Phys. Rev. 99, 220 (1955).

[5] Woodward, Heinberg, Wilson, and Zipoy, Bull. Am. Phys. Soc. Ser. II, 3, 32 (1958).

[6] Heinberg, McClelland, Turkot, Woodward, Wilson, and Zipoy, Phys. Rev. 110, 1211 (1958).

[7] R. R. Wilson, Phys. Rev. 110, 1212 (1958).

ELECTRIC DIPOLE MOMENT OF THE MUON *

D. Berley, R.L. Garwin,† G. Gidal, and L. M. Lederman

Columbia University, New York, New York

(Received July 18, 1958)

The problem of the muon rest mass and its possible origin in an unknown interaction demands very close examination of the properties of this particle. For example, the magnetic moment should be measured with high precision[1]; some progress in this direction has recently been made.[2] The present note describes a search for an electric dipole moment in the muon with a sensitivity of the order of 1% of a "natural" moment: e times the muon Compton wavelength (1.85×10^{-13}cm).

The detection of an electric dipole moment for any elementary particle would constitute proof that time-reversal invariance is violated.[3] Smith *et al.*[4] have set a limit of $\lesssim e \times 10^{-20}$cm for the electric dipole moment of the neutron. The sensitivity achieved by the neutron measurement cannot, in any simple way, be applied to a charged particle due to the well-known difficulty of establishing a known electric field at the position of the particle in matter. Thus the only available information on charged particles comes from the energy levels in hydrogen where the observations and theory of the Lamb shift limit the contribution of electron and proton electric dipole moments to of the order $e \times 10^{-13}$cm.[5] The existence of longitudinally polarized beams of mu mesons and the availability of muon decay as a polarization analyzer suggest a convenient method by means of which one may search for a muon electric dipole moment.

We note that a transverse electric field will exert a torque proportional to $\vec{\sigma} \times \vec{E}$ which will cause the spin vector $\vec{\sigma}$ to precess away from the longitudinal direction.

In the present experiment the electric field was that created in the rest system of the muon moving in a magnetic field B, and equal to $(1/c) \times \vec{v} \times \vec{B}$. As shown in Fig. 1, the particles are first deflected in the magnetic field of the cyclotron and, after emerging from the shielding wall, further deflected by an additional magnet. The presence of an electric moment $fe\hbar/mc$ will cause a rotation of the spin vector out of the

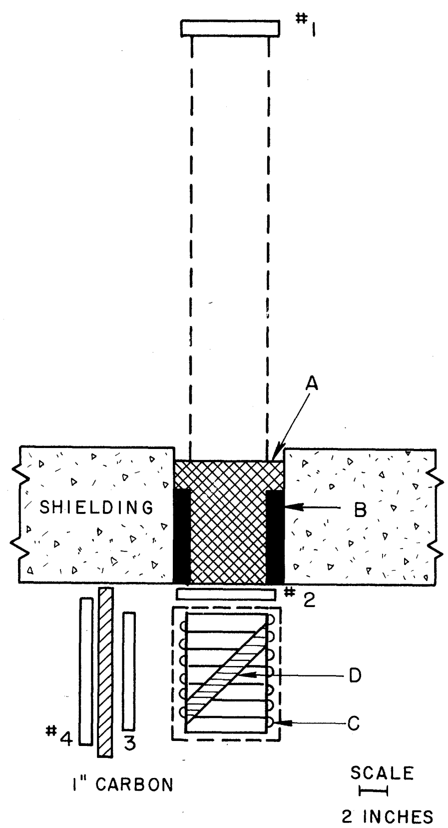

FIG. 1. Schematic diagram of the meson trajectories. The Be target is located in the cyclotron vacuum chamber and can be considered as a source of longitudinally polarized μ mesons.

horizontal plane by an amount $\theta=2\theta_0(v/c)f$, where θ_0 is the angle through which the trajectory is bent in the magnetic field.

Should the above precession occur there is an additional effect which produces a second-order change in the measured precession angle. Before the polarization of the muons can finally be analyzed the mesons must be stopped in a target. The ionization loss mechanism effectively produces a longitudinal electric field in the rest system of the particle. When a mu meson of momentum p is brought to rest, the transverse component of the electric dipole moment produces a rotation of the spin about the momentum vector.[6] The angle of rotation is $\phi=2(p/mc)f$. For a particle whose polarization was initially longitudinal, its polarization after passing through the magnet system and absorber is summarized as follows: the component of polarization perpendicular to the horizontal plane is $P_1=P_0\sin\theta\times\cos\phi$; the component of polarization 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 direction of the momentum is $P_3=P_0\cos\theta$.

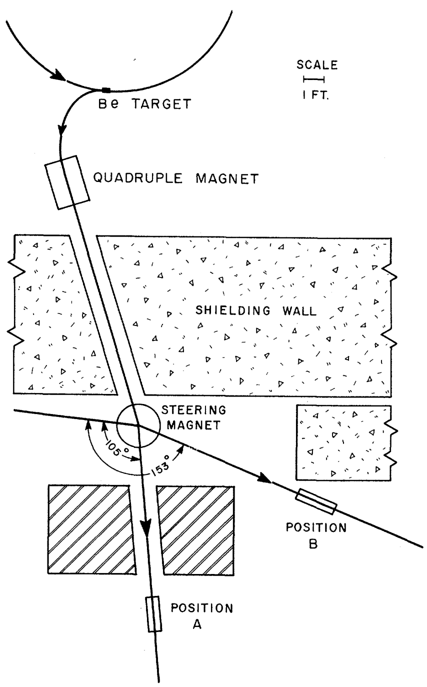

FIG. 2. Apparatus to measure transverse polarization. The meson beam is monitored with counters 1 and 2 and is stopped in the carbon target B. A is the precessing coil, containing 300 turns. It is shown in a position appropriate for rotating a transverse spin component in the vertical plane toward (+90°) or away (-90°) from the electron telescope (No. 3 and No. 4). The coil can be rotated 90° to cause the spin to precess in the horizontal plane. Geometric alignment is accomplished by adjusting counters 1, 2, and the 8-in. long coil as a rigid unit.

The polarization analyzer was the mu-decay electron asymmetry. The apparatus was similar to that described by Garwin, Lederman, and Weinrich[7] and is shown in Fig. 2. The decay-electron counting rate is assumed to have an angular anisotropy of the form $R=1+a\vec{e}\cdot\vec{e}_{max}$. Here $\vec{e}$ is a unit vector in the electron direction and $\vec{e}_{max}$ is a unit vector in the direction of maximum counting rate. The electron anisotropies were measured when the mu mesons were caused by an applied magnetic field to precess through angles of ± 90°, 0°, and 180° in the vertical plane and through ± 90° in the horizontal plane. The angle θ was found from these measurements. First, a trajectory bending angle of 105° was used—position A shown in Fig. 1. The experiment was then repeated with a more favorable bending angle of 153°. The results of these two runs are

$$\theta=+0.64\pm0.024 \text{ radians } (105^\circ \text{ run}),$$
$$\theta=+0.017\pm0.028 \text{ radians } (153^\circ \text{ run}).$$

An accurate measurement of ϕ was not made for two reasons. It is noted that the transverse component of polarization is small and hence the component of polarization P_2, in the cyclotron plane, depends on a small electric dipole moment to second order. Secondly, it is conceivable that at the mu meson source, the initial polarization has small transverse components in the horizontal plane. Such a bias could be due to an anisotropic distribution of the decaying pi mesons in the horizontal plane. This effect would influence angle ϕ. The complete up-down symmetry of the apparatus excludes such a bias in the vertical direction and hence in the angle θ.

We have investigated effects which could simulate an electric dipole moment by inducing a vertical component of polarization. One of these is the presence of a stray transverse component of magnetic field when the longitudinal precession field is being used. This was reduced by (1) Helmholtz coils which cancelled the cyclotron fringing field and (2) providing an iron return path to keep the field inside the precession coil parallel to the axis of the coil. For the run at position A, an absolute upper limit to the uncertainty in θ from this source is 0.032 radian while at position B the field was measured with greater precision and this uncertainty was reduced to 0.013 radian. Uncertainties in the alignment of the polarization analyzer were less than 0.01 radian.

Combining the two runs, the value of the electric dipole moment of the muon is found to be (in units of $e\hbar/mc$)

$$f = 0.006 \pm 0.005.$$

This corresponds to a unit charge multiplied by a distance of $(1.1\pm0.9)\times10^{-15}$cm. The result is consistent with a vanishing dipole moment expected on the basis of time-reversal invariance.

We acknowledge with thanks the discussions with N.M. Kroll and G. Feinberg on this subject.

---

*This work is supported by the U. S. Atomic Energy Commission and the Office of Naval Research.

†Also at International Business Machines Watson Laboratory, Columbia University, New York, New York.

[1] See, for example, R. Feynman, Proceedings of the Eighth Annual High-Energy Conference, Geneva, 1958 (unpublished).

[2] Coffin, Garwin, Penman, Lederman, and Sachs, Phys. Rev. 109, 973 (1958); Lundy, Sens, Swanson, Telegdi, and Yovanovitch, Phys. Rev. Lett. 1, 38 (1958).

[3] L. Landau, Nuclear Phys. 3, 127 (1957); T. D. Lee and C. N. Yang, Brookhaven National Laboratory Report BNL-443, 1957 (unpublished).

[4] Smith, Purcell, and Ramsey, Phys. Rev. 108, 120 (1957).

[5] Gerald Feinberg (private communication).

[6] T. D. Lee and G. Feinberg (private Communication).

[7] Garwin, Lederman, and Weinrich, Phys. Rev. 105, 1415 (1957).

π^- SCATTERING AND DISPERSION RELATIONS*

H-Y. Chiu
Laboratory of Nuclear Studies,
Cornell University, Ithaca, New York

and

J. Hamilton†
Laboratory of Nuclear Studies,
Cornell University, Ithaca, New York
and
Brookhaven National Laboratory, Upton, New York
(Received July 23, 1958)

In a recent paper[1] by one of us, the discrepancy in the π^--p dispersion relation was discussed. Although the disagreement between experiment and theory is much smaller than Puppi and Stanghellini[2] believed, there was still evidence of some disagreement with at least one of the apparently accurate experimental results. We now report further work which very much weakens the evidence for disagreement.

In deducing the forward scattering amplitude from their results, Korenchenko and Zinov[3] used a least-squares fit of the form $A + B\cos\theta + C\cos^2\theta$ for the elastic scattering differential cross section; this gives the results at 307 and 333 Mev shown in Figs. 2 and 3 of reference 1. At these energies d waves could be important and we should fit with the form $A+B\cos\theta+C\cos^2\theta+D\cos^3\theta+E\cos^4\theta$. As the least center-of-mass angle measured is about 40°, this d-wave fit could give a forward scattering intensity $|f(0)|^2$ which differs appreciably from that given by the p-wave fit (i.e., $D=E=0$). Also, the error in $|f(0)|^2$ as deduced from the d-wave fit will in general be appreciably larger than the error in $|f(0)|^2$ deduced by the p-wave fit. This is because the errors in the observed $|f(\theta)|^2$ for the vew smallest values of θ are much more important in the d-wave fit than in the p-wave fit.

The d-wave fit (as given in reference 3) for 333 Mev gives the real part of the forward scattering amplitude $D_-^b = 0.08_{-0.08}^{+0.07}$ (nuclear units). The mean value lies close to the theoretical curve for coupling constant $f_1^2=0.08$ (Fig. 3 of reference 1); the experimental error is large. At 307 Mev the usual precedure gives $D_-^b = (-0.014\pm0.014)^{\frac{1}{2}}$ (nuclear units). This imaginary value, which occurs because the d-wave analysis gives a much reduced $|f(0)|^2$, is a warning about the accuracy of the experiment. We conclude that the 307- and 333-Mev results now do not show disagreement with the dispersion relation for $f_1^2 = 0.08$.

We have reexamined the elastic differential cross sections of Ashkin *et al.*[4] at 150, 170, 220 Mev to find the effect of a d-wave fit of the form $A+B\cos\theta+C\cos^2\theta+D\cos^3\theta$. (At these energies we do not expect the d-wave phase shifts to be so large that $E\neq0$ is justified.) The least center-of-mass angles are around 37°. The results in nuclear units ($\hbar = c = \mu = 1$) are shown in Table I.

These changes in the experimental values of D_-^b are of the same order of magnitude as we would expect from the d-wave phase shifts given by Chew *et al.*[5] An important aspect of the new values of D_-^b at 150 and 170 Mev is their large errors. We suggest that the errors in the d-wave fit coefficient D should not be greater than the