EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

# NEW LIMITS ON THE ELECTRIC DIPOLE MOMENT OF POSITIVE AND NEGATIVE MUONS

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## ABSTRACT

New measurements of the electric dipole moment of muons of both charges have been made in the Muon Storage Ring at CERN. The values found are

$$D_{\mu^+} = (8.6 \pm 4.5) \times 10^{-19}\ e\cdot cm$$

$$D_{\mu^-} = (0.8 \pm 4.3) \times 10^{-19}\ e\cdot cm$$

(errors are of 1 standard deviation). We conclude, at 95% confidence level, that $|D_\mu| \leq 1.05 \times 10^{-18}$ e•cm.

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## 1. INTRODUCTION

This paper reports a new upper limit for an electric dipole moment (EDM) of the muon. As is well known, the existence of a static EDM for an elementary particle would imply violation of both parity P and time reversal T invariance (Landau, 1957). Although CP (Christenson et al., 1964) and T (Schubert et al., 1970) violation have been established in the neutral kaon system, neither has been observed in any other process*). It is not even established which of the fundamental interactions it is to be associated with or whether it is the result of a new "super-weak" interaction. Theories which place the violation in the strong, electromagnetic, weak, or super-weak interactions all make predictions as to the magnitude of effects which should be seen outside the K complex. Theories placing CP violation in the strong interaction have been discussed by Prentki and Veltman (1965), Okun (1965), and Lee and Wolfenstein (1965). Bernstein et al. (1965), Barshay (1965), Salzman and Salzman (1965), and Arbuzov and Filippov (1966) have considered CP violation in the electromagnetic interaction. Weak CP violation in the context of gauge theories is discussed by Lee (1973) and Pais and Primack (1973), while "super-weak" theory is discussed by Wolfenstein (1964) and Mohapatra et al. (1975). A good review article of early models of CP violation is that of Wolfenstein (1969), while other references to gauge theory models can be found in Mohapatra (1972). Some model-independent estimates can be made for the expected size of the electric dipole moments (Wolfenstein, 1974; Kleinknecht, 1976) but the detailed structure of the models can modify these estimates over a range of several orders of magnitude. The measurements of particle electric dipole moments thus provide increasingly significant constraints on these theoretical developments and in particular the results for the neutron (Dress et al., 1977), the proton (Harrison et al., 1969) and the electron (Weisskopf et al., 1968; Player and Sandars, 1970) have reached an impressive level. It should be emphasized, however, that all these measurements come from studies of neutral systems. Interaction of the EDM with external electric fields is, for charged particles, largely masked by the much stronger coupling of the charge itself, making it much more difficult to set precise limits on the EDM (Garwin and Lederman, 1959). This point is underlined by the eight orders of magnitude between the limits set for the free electron (Nelson et al., 1959; Rand, 1965) and those deduced from a neutral atomic system (Weisskopf et al., 1968; Player and Sandars, 1970).

## 2. EXPERIMENTAL

The present experiment was carried out at the CERN Muon Storage Ring simultaneously with the measurement of the muon g-factor anomaly, $a \equiv (g-2)/2$, which has been reported previously (Bailey et al., 1977a). The latter experiment has

*) For a recent review of CP violation and $K^0$ decays, see Kleinknecht (1976).

been discussed in several review articles*) and we recall here the principles of the method only to the extent necessary for an understanding of the present measurement.

Muons obtained from pion decay with an initial longitudinal polarization of $\geq 95\%$ travel around the 14 m diameter circle of the Muon Storage Ring. The vertical magnetic field of 1.47 T is highly homogeneous. Weak vertical focusing is provided by an electrostatic quadrupole field (Flegel and Krienen, 1973).

The precession frequency of the muon spin relative to its velocity vector $\vec{\beta}$, which is perpendicular to the magnetic and electric fields $\vec{B}$ and $\vec{E}$, is

$$\vec{\omega} = -\frac{e}{mc}\left\{a\vec{B} + \left[\frac{1}{\gamma^2 - 1} - a\right]\vec{\beta} \times \vec{E} + \frac{f}{2}\left[\vec{E} + \vec{\beta} \times \vec{B}\right]\right\} . \qquad (1)$$

Here we have included the effect of an electric dipole moment defined by $D \equiv (f/2)(e\hbar/2mc)$ in analogy with the magnetic moment.

The muon momentum (3.094 GeV/c) was chosen such that the second term inside the curly brackets of Eq. (1) vanishes $\{\gamma = [1 + (1/a)]^{1/2} = 29.3\}$. The third term displays the effect of the EDM on the spin motion and, since the laboratory electric field is negligible compared with the magnetic field ($|\vec{E}| < 10^{-3} \cdot |\vec{B}|$), this term reduces to a precession frequency $\vec{\omega}_{edm} = -(e/mc)(f/2)\vec{\beta} \times \vec{B}$ about an axis radial to the orbit. The origin of this motion is the torque acting on the EDM from the apparent electric field in the muon rest frame. Equation (1) is therefore simply the vector sum of $\vec{\omega}_{edm}$ with the normal (g-2) frequency $\vec{\omega}_a$:

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm} = -\frac{e}{mc}\left(a\vec{B} + \frac{f}{2}\vec{\beta} \times \vec{B}\right) . \qquad (2)$$

The effect of an EDM is illustrated in Fig. 1. The plane of the spin precession is tilted such that its normal is at an angle $\delta = \omega_{edm}/\omega_a = f\beta/2a$ to the magnetic field. This leads to a vertically oscillating component of the muon polarization with the same frequency as the precession of the horizontal polarization. The observation of this vertical component constitutes the basis of the direct measurement of an EDM. In addition, the (g-2) frequency $\omega_a$ is increased to $\omega = \omega_a(1 + \delta^2)^{1/2}$, making an EDM a possible candidate for a discrepancy between the measurement of the anomaly a and the theoretical prediction.

The evolution of the muon polarization as a function of storage time is observed through the asymmetry in the angular distribution of the decay electrons with respect to the direction of the muon spin. This is achieved by selecting high-energy decay electrons (forward-going in the muon rest frame) in the shower

*) Farley (1975); Combley and Picasso (1974); Bailey and Picasso (1970); Field (1976); Combley (1975).

detectors. To be sensitive to the vertical component of the polarization, one has to record whether a decay electron is upward- or downward-going. The numbers of decay electrons in these two categories are given by

$$\begin{aligned} N_{up} &= \frac{N}{2} e^{-t/\tau} \{1 - A_\mu \cos(\omega t + \psi) + A_e \sin(\omega t + \psi)\} \\ N_{down} &= \frac{N}{2} e^{-t/\tau} \{1 - A_\mu \cos(\omega t + \psi) - A_e \sin(\omega t + \psi)\} . \end{aligned} \tag{3}$$

The asymmetry $A_e$ is proportional to the magnitude of the EDM and is a function of the energy threshold of the detectors. For a decay electron energy threshold of 800 MeV, analytical and Monte Carlo calculations show that $A_e = 0.22\ \delta$.

In the experiment, pairs of scintillation counters were placed in front of five of the shower detectors and by this means decay electrons were labelled as above or below the median plane. These two categories are not equivalent to upward- and downward-going, since the muon decays do not all occur in the median plane. The resulting dilution of sensitivity was found to be 0.75 from a Monte Carlo simulation, leading to the relation $A_e = (0.164 \pm 0.019)\delta$ for the split counter system.

## 3. DATA ANALYSIS AND SYSTEMATIC ERRORS

As can be seen from Eqs. (3), an EDM introduces a phase shift between the two time spectra $N_{up}$ and $N_{down}$. Assuming $A_e/A_\mu << 1$, this phase difference is $\Delta\phi = 2A_e/A_\mu = 2 \times 0.164 \times \delta/A_\mu$. In the second equality we have used the Monte Carlo result for a threshold of 800 MeV, for which the asymmetry $A_\mu$ is about 15%. To measure $\Delta\phi$, the two sets of data were separately fitted by the maximum likelihood method to the function

$$N(t) = N_0 \left[L(t)\ e^{-t/\tau} \{1 - A \cos(\omega t + \phi)\} + B\right] . \tag{4}$$

The muon time-dilated lifetime $\tau$, the asymmetry A, the phase $\phi$ of the modulation, the constant background B and the two parameters $A_L$ and $\tau_L$ of the subsidiary function $L(t) = 1 + A_L \exp(-t/\tau_L)$ were allowed to vary. The latter function allows for small distortions of the data from muon losses and electronic gain changes (Bailey et al., 1977b). As the frequency $\omega$ is accurately known from the (g-2) experiment, it is held fixed in the fit. The consistency of the two data sets was checked by comparing the parameters obtained from the fits. Both lifetime and background for the separate data were the same within statistical errors and are in any case only very weakly correlated with the phase. This is also true for the subsidiary function L(t).

In order to detect tilt angles of a few mrad equivalent to phase differences of the same order the apparatus has to be checked for systematic bias. In principle, any breaking of the symmetry between "up" and "down" counters can give a spurious phase difference simulating an EDM. Four possible sources of error are considered in detail below.

### 3.1 Energy response of the shower detectors

The phase of the (g-2) precession is a function of the electron energy threshold, known from the analysis of the data in five pulse-height bands. Therefore, a difference in the energy response of the upper and lower half of the counters would give a spurious EDM signal.

The magnitude of this effect can be estimated by measuring the asymmetry $A_\mu$ as a function of pulse height, separately for the "up" and "down" data. $A_\mu$ is a rapid function of electron energy. The agreement between the asymmetries indicated that this systematic error in $\Delta\phi$ was less than 0.1 mrad, which is negligible compared with the statistical error.

### 3.2 Efficiencies of "up" and "down" scintillators

By repeatedly inverting each scintillation counter pair during the runs, their efficiency ratio was found to be unity to better than 1%. As a result, we also obtained an unbiased ratio of stops recorded above and below the counter split.

### 3.3 The position of the horizontal split

This should correspond to the centre of the stored muon population which is not necessarily half way between the pole pieces; small radial components of magnetic field can displace the median plane.

The sensitivity of the fitted phase difference $\Delta\phi$ to vertical misalignments was determined experimentally with the results shown in Fig. 2. A straight-line fit to the data gave $\Delta\phi = (7.6 \pm 1.0)$ mrad/mm, equivalent to a simulated EDM of $(3.9 \pm 0.5) \times 10^{-19}$ e·cm per mm displacement. This effect derives from the fact that the decay electron trajectories are curved inwards by the magnetic field. Thus an electron initially emitted outwards travels further before hitting the shower counter than one emitted inwards. The resulting different vertical spread of electrons at the detector means that the average phase of the recorded "up" or "down" events depends upon the vertical position of the counter split. The size of the effect observed agrees with a Monte Carlo simulation.

The position of the split between a pair of counters was adjusted such that the numbers of "up" and "down" counts were equal. The uncertainty of ±0.5 mm assigned to this positioning reflects the long term instability of the median plane of the storage ring. The location of the median plane found in this way was in good accord with that calculated from measurements of the radial component of the magnetic field.

### 3.4 Timing errors

The timing signal for both "up" and "down" events was taken from the shower counter, common to both, so no phase error could arise from the electronics.

## 4. RESULTS

The results of seven periods of data taking are summarized in Table 1. One standard deviation statistical errors are quoted. Adding in quadrature the error due to ±0.5 mm uncertainty in the vertical alignment of the counters gives the following results:

$$D_{\mu^+} = (8.6 \pm 4.5) \times 10^{-19}\ \mathrm{e \cdot cm}$$

$$D_{\mu^-} = (0.8 \pm 4.3) \times 10^{-19}\ \mathrm{e \cdot cm}\ .$$

Assuming the CPT theorem they can be combined to give for the muon

$$D_{\mu} = (3.7 \pm 3.4) \times 10^{-19}\ \mathrm{e \cdot cm}\ .$$

In all three cases, one standard deviation errors are quoted.

## 5. DISCUSSION

We conclude that at 95% confidence $|D_\mu| \leq 1.05 \times 10^{-18}$ e•cm. This limit represents a factor of 27 improvement in the upper limit for a muon electric dipole moment over the previous best direct measurement (Charpak et al., 1961).

Although this limit on the EDM of the muon is less stringent than those on the electron (Weisskopf et al., 1968; Player and Sandars, 1970) and neutron (Dress et al., 1977), the new measurement contributes to the constraints on theory, since the relative sizes of the moments for different particles depend very much on the structure of the model and, in particular, whether CP violation is placed in the hadron, lepton, or boson sector. For example, a model studied by Lee (1973), in which CP violation is associated with the Higgs boson sector, predicts electric dipole moments of the following orders:

$$D_n \lesssim 10^{-23}\ \mathrm{e \cdot cm}, \quad D_\mu \lesssim 10^{-25}\ \mathrm{e \cdot cm}, \quad D_e \lesssim 10^{-32}\ \mathrm{e \cdot cm}\ ,$$

while one of the models examined by Pais and Primack (1973), which incorporates CP violation in the leptonic weak current, yields

$$D_n \lesssim 10^{-24}\ \mathrm{e \cdot cm}, \quad D_\mu \lesssim 10^{-20}\ \mathrm{e \cdot cm}, \quad D_e \lesssim 10^{-24}\ \mathrm{e \cdot cm}\ .$$

Both these models use the gauge formalism and fall within the broad category of the "milliweak" type with CP violation included in the effective weak Hamiltonian. It is clearly important to reduce the experimental limits on the EDM of as many particles as possible. The most recent measurement of the neutron (Dress et al., 1977) is already close to excluding those models with a CP violating part in the electromagnetic interaction (Kleinknecht, 1976; Wolfenstein, 1974). In addition to the restriction of models of CP violation, the present result for the muon also curtails other domains of theoretical speculation, such as the contribution of the muon EDM to the $e^+e^-$ total cross-section at very high energies (Budny et al., 1977). Finally, as indicated above, an EDM for the muon would shift the observed (g-2) frequency. The present result limits this effect to $\Delta\omega_a/\omega_a \leq 4.6 \times 10^{-5}$ at 95% confidence level. Assigning the entire difference a(experiment) - a(theory), as given in Bailey et al. (1977a), to the effect of an electric dipole moment leads to a limit of $|D_\mu| \leq 0.74 \times 10^{-18}$ e·cm (95% confidence level), a number comparable to the directly measured limit given in this paper.

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Table 1

Summary of runs

| Run | Sign | No. of stops (million) | $\Delta\phi = \phi_{up} - \phi_{down}$ (mrad) | Dipole moment a) (e·cm) × $10^{19}$ |
|---|---|---|---|---|
| 1975 A | $\mu^+$ | 1.1 | -14.9 (17.1) | 7.7 (8.8) b) |
| B | $\mu^-$ | 1.9 | -2.6 (13.2) | -1.3 (6.8) |
| 1976 A | $\mu^+$ | 2.1 | -27.0 (11.5) | 14.9 (6.3) |
| B | $\mu^-$ | 0.8 | +1.6 (18.8) | 0.9 (10.3) |
| C | $\mu^-$ | 1.5 | +1.9 (13.6) | 1.0 (7.4) |
| D | $\mu^+$ | 2.2 | -6.3 (11.8) | 3.3 (6.1) |
| E | $\mu^-$ | 1.8 | +5.5 (13.4) | 2.8 (6.9) |
| Weighted averages | $\mu^+$ | 5.4 | -16.5 (7.4) | 8.6 (4.0) |
| | $\mu^-$ | 6.0 | +1.6 (7.2) | 0.8 (3.8) |
| | $(\mu^+ + \mu^-)$ over-all | 11.4 | -7.2 (5.2) | 3.7 (2.7) c) |

a) The definition of phase difference is such that a negative value implies a positive value for f. Since $D \equiv (f/2)(e\hbar/2mc)$, the dipole moment has the same sign as f for positive muons and the opposite for negative ones.

b) Errors quoted are 1 standard deviation statistical only.

c) The consistency $\chi^2$ of this value with the values found for the individual runs is 4.9 for 6 degrees of freedom.

Figure captions

Fig. 1 : The plane of the precession of the spin $\vec{s}$ relative to the velocity $\vec{\beta}$ is tilted out of the horizontal plane by an angle $\delta$, by combining the precession vector due to the anomalous magnetic moment, $\vec{\omega}_a$, with that due to the electric dipole moment, $\vec{\omega}_{edm}$.

Fig. 2 : The systematic phase shift $\Delta\phi$ as a function of the displacement $\Delta z$ of the scintillation counter pairs relative to the vertical centre of gravity of the stored muon population. × and ○ refer to measurements with positive and negative muons, respectively. □ represents the combined EDM measurement with zero displacement. The straight line is a least squares fit to all data shown.

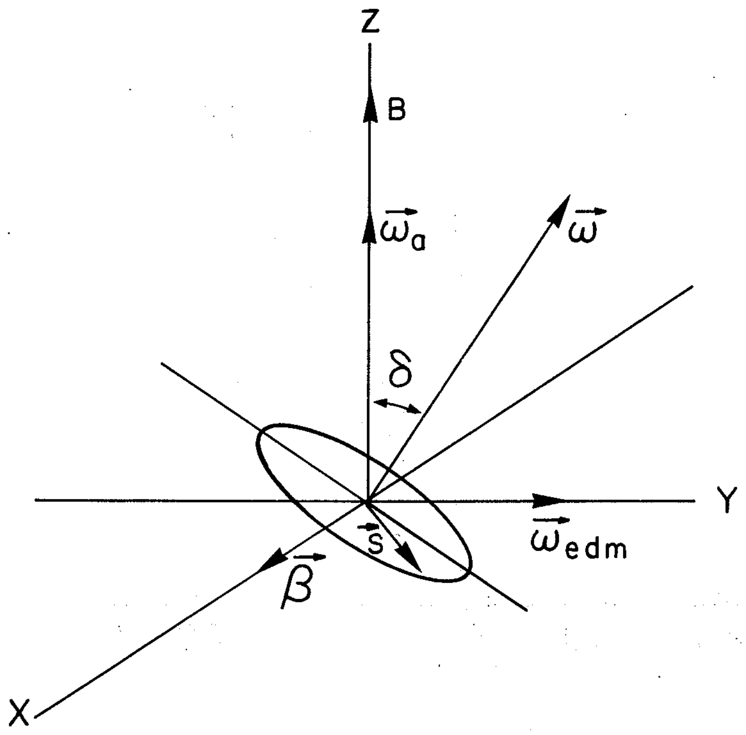


Fig. 1

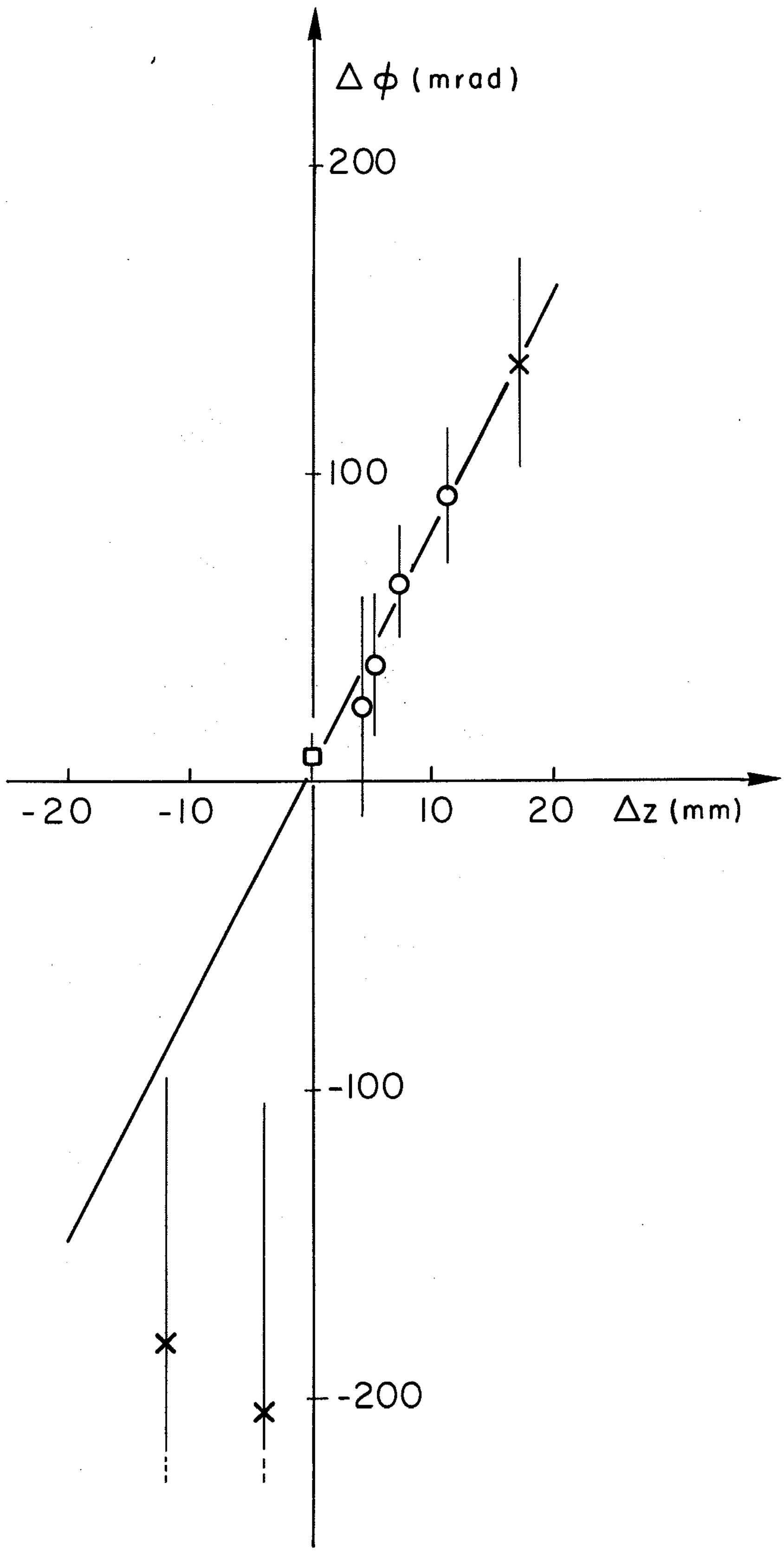


Fig. 2