E821, A NEW MEASUREMENT OF THE MUON ANOMALOUS MAGNETIC MOMENT AT B.N.L.

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The muon $(g-2)$ experiment at Brookhaven completed its first run in June and July of 1997. The main components of the experiment, including the superconducting inflector, super-ferric storage ring, electrostatic quadrupoles, and lead-scintillating calorimeters were commissioned satisfactorily. Our first measurement of the ratio R of the muon spin precession frequency relative to that of a free proton, $R = (3.707220 \pm 0.000048) \times 10^{-3}$ is in good agreement with the world average. We expect to increase the knowledge of the anomalous magnetic moment to 1 ppm within a year.

1 Introduction

The anomalous magnetic moment of the muon

$$a_\mu = \frac{(g-2)_\mu}{2} \tag{1}$$

is, like that of the electron, mostly determined by contributions due to the QED corrections. However, in the muon case relative contributions due to heavy particles (hadrons) have been measured [1]. The goal of the Brookhaven experiment is to improve the knowledge of a_μ and measure the contribution due to the weak corrections, which are calculated to be 1.3 ppm [2], up to 25 %. As the current calculations of the hadronic correction have an uncertainty of 0.66 ppm, a better understanding of the hadronic corrections is needed. Our knowledge of the hadronic corrections has improved recently, and more work is underway [3,4,5,6].

To determine the weak contribution to 25 %, we need to measure a_μ to 0.35 ppm, an improvement of a factor of 20 over the previous measurement. This measurement will then also be a sensitive test for physics beyond the standard model [2,7,8,9].

In here a description of the experimental setup of the first year of running will be given, as well as the results of the 1997 run and an outlook to the 1998 and 1999 runs.

2 Experimental setup

The principle of our measurement is similar to that of the third CERN measurement [1]. Polarized muons are stored in a uniform dipole field with electrostatic focussing. The muon spin precesses relative to its momentum with frequency

$$\vec{\omega}_a = \frac{-e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma_\mu^2 - 1}\right)\right]\vec{\beta} \times \vec{E} \tag{2}$$

assuming that $E/c << B$ and $\vec{\beta} \cdot \vec{B} \simeq 0$.

If we store muons with a "magic" γ of 29.3, the second term in equation 2 becomes zero, and we can calculate a_μ as

$$a_\mu = \frac{\omega_a m_\mu}{Be} \tag{3}$$

The magnetic field is measured with NMR probes, which are calibrated with respect to a spherical water sample. Therefore, our magnetic field measurement is related to the frequency of a free proton in the magnetic field. We can then calculate a_μ relative to this frequency as

$$a_\mu = \frac{f_a/f_p}{\mu_\mu/\mu_p - f_a/f_p} \tag{4}$$

The ratio of magnetic moments is known to 0.15 ppm [10], and is expected to be improved by a recent experiment[11].

Our signal is created by the detection of decay positrons from the reaction $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$. Because of the parity violating nature of weak decay, the high-energy positrons are preferentially emitted along the muon spin direction. By making an energy cut in the detected positron spectrum, we select positrons going in the forward direction in the muon rest-frame. The muon spin precession frequency is then reflected in the expected distribution:

$$N(t) = N_0 e^{-t/\tau_\mu}\left[1 - A\cos(\omega_a t + \phi)\right] \tag{5}$$

In this equation τ_μ is the dilated muon lifetime, and A an energy dependent asymmetry parameter.

2.1 The Beam

The AGS delivered 8 proton bunches onto a nickel target every 2.6 seconds. The bunches were delivered with a 33 ms. spacing, and contained about 5×10^{12} protons each. A positive secondary beam was transported along a 116 m. beam line to the superconducting inflector. At this point the beam mainly consists of pions (about 60 %). The inflector cancels the 1.45 T magnetic field, and delivers the beam slightly further out in radius, and with a higher momentum (0.5 %) than that of the stored muons. About 25 ppm of the pions produce stored muons. Most of the beam interacts outside of the storage region, producing a huge flash seen by the detectors. The scheme described above is called the "pion injection mode".

2.2 The Magnet

The continuous super-ferric C-shaped storage ring magnet [12], shown in figure 1, is excited by three 14 m diameter superconducting coils carrying a current of 5177 A. This produces a uniform field of 1.45 T across the storage region. The short time stability of the field was found to be better than 0.1 ppm. The long term instability of up to 100 ppm was mainly due to thermal effects in the magnet yoke. The magnetic field has been measured using several methods. Before the run, hall probes were used to map the inflector area of the storage region. During the run, 366 fixed NMR probes were read out, and in between runs an NMR trolly carried 17 probes around the ring in the storage region, mapping the field every centimeter. Furthermore, at fixed positions plunging probes were used to map the field. This resulted in a very accurate field map across the storage region. The map averaged along the beam-direction is shown in figure 2.

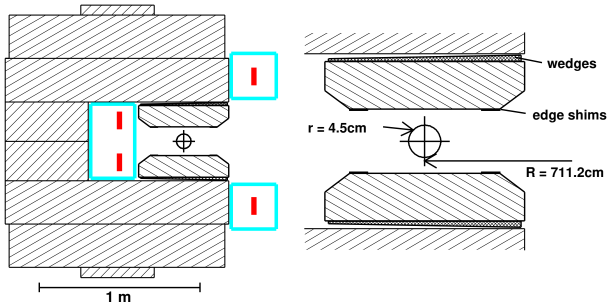

Figure 1: Storage ring magnet cross section.

2.3 The Muon Distribution

The B-value to be used in formula 3 is the average B-field as seen by muons in the storage ring. Therefore, we need a good measurement of the position of the muon beam as well as the magnetic field.

We have foreseen several methods to infer the muon distribution. In front of one of the calorimeter stations a set of four planes of wire chambers can be used to get direction information from the decay electrons. This can then be used to trace back to the point were the muon decay took place. During injection, a fiber harp can be used to obtain the position of the injected beam.

At early times after injection, the muon beam is still bunched. By looking at muon decays at these early times, we obtain a distribution of rotation frequencies of the muon beam, thus giving the radial distribution.

For the 1997 run it was found that this so-called "fast rotation" method combined with the accurate field measurements gave us the best beam-position information. Both the wire chambers and the fiber harp will be used for the upcoming runs.

2.4 Positron energy detection and timing

The lead-scintillating-fiber calorimeters [13] are read out by custom 400 MHz waveform digitizers (WFDs) which provide timing and energy information for the positrons. Both the WFD and the NMR clocks were phase locked to the same LORAN-C frequency signal. A LED and a laser system were used to measure gain and timing drifts over the data collection period. It was found that the gain shifts were less than 1 %, and early-to-late timing shifts were on average less than 20 ps.

The flash, described in section 2.1, required that

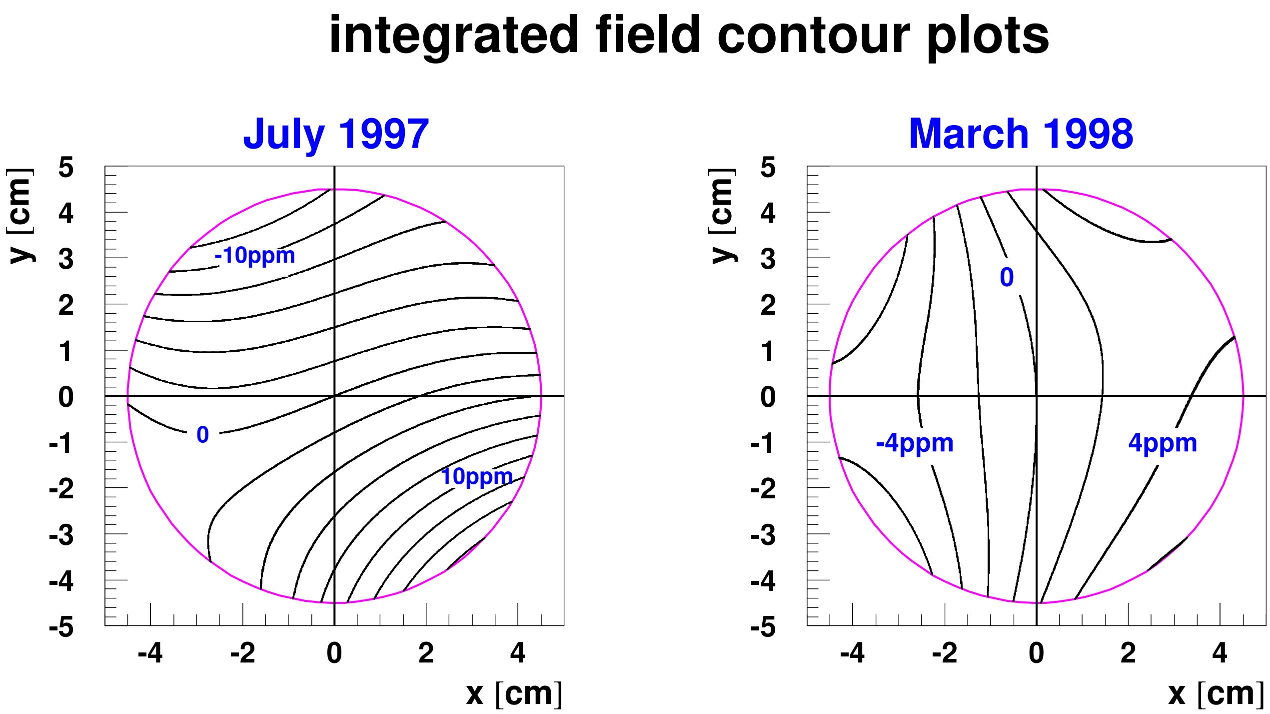

Figure 2: Field map for the 1997 run (a), and improvements for 1998 (b).

we gate off the phototubes of the calorimeters at early times. The gate-off period depends on the position of the calorimeter station around the ring. Even after the phototubes were back on, we encountered a background level which was falling with time. It was also discovered that we had a background of narrow pulses from a number of sources. To avoid the sampling of these, the pulse-height threshold of the WFDs was raised. However, other settings, like the minimum time over threshold, were not touched. Combined with the fact that our background was higher at early times, this resulted in a time dependent digitizing efficiency. We have to correct for this by using an eight parameter functional fit:

$$N(t) = N_0 e^{-t/\tau_\mu} \frac{1}{(t-t_0)^\alpha} \left[1 + (A_1 t + A_2)\cos(\omega_a t + \phi)\right] + B \tag{6}$$

Where $t_0 = 5\mu s$ after injection. The power law was found to best describe the time dependent background.

3 Results of the 1997 Run

As stated before, the experiment measures the ratio ω_a/ω_p. Including corrections (1ppm) from the electric quadrupole field for vertical focussing, we obtain

$$R = 3.707220(47)(11) \times 10^{-3} \tag{7}$$

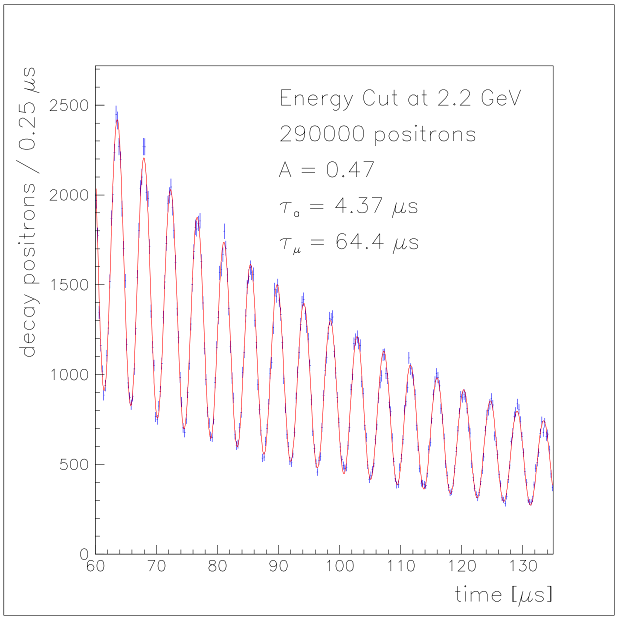

Figure 3: Analysis of part of our data. The solid line represents a fit through the data.

Table 1: Systematic errors in ppm.

Systematic Effect	$\epsilon(ppm)$
Magnetic Field B	1.0
Muon Distribution and $< B >$	0.9
WFD Energy Threshold	1.5
Gain and Pedestal Shift	0.6
Muon Losses	0.2
Timing Shifts	0.1
Radial E-field, Pitch Correction	0.05
Fitting Start Time	2.0
Binning Effects	0.2
Total Systematic Error	2.9

where the first error is statistical, and the second systematic. Adding the errors in quadrature gives a 13 ppm relative error. The contributions to the systematic error are listed in table 1. From this table it is clear that the largest errors are due to the start time of the fit and the WFD energy threshold setting. Both effects are due to the combination of a time dependent background and the misstaken electronics settings.

The anomaly is given by:

$$a_\mu = \frac{R}{\lambda - R} = 1165925(15) \times 10^{-9} \tag{8}$$

In good agreement with the CERN results as can be seen from figure 4. Assuming CPT invariance, our measurement can be combined with the CERN measurement to give a new world average of $a_\mu = 1165923.4(7.2) \times 10^{-9}$

4 Outlook to the 1998 and 1999 runs

For the next runs we will have an improved injection scheme. In stead of injecting a pion beam into our storage ring, a muon beam will be kicked into it. This increases the number of stored muons and reduces the "flash" significantly.

The magnet shimming has resumed after the run, resulting in a more uniform field, as can be seen from figure 2b, which is only a preliminary result. The fieldmap taken just before the start of the 1998 run does not show any contour lines on the scale of figure 2. The magnet will also be thermally insulated to reduce the long term instabilities.

The muon trajectory measurement will be much improved. By reducing the "flash" we are able to start taking data earlier, thus increasing the data volume that can be used for the fast rotation analysis. Furthermore, the wire chambers are much better understood and will play a significant role in the determination of the muon trajectory.

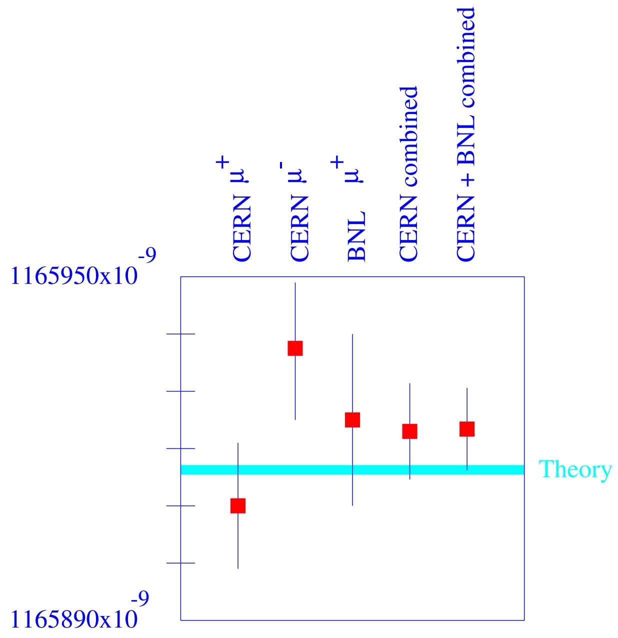

Figure 4: Comparison to CERN results.

We are confident that the improvements described above will allow us to do a measurement with a precision of about 0.6 to 1 ppm in the 1998 and 1999 runs. Additional beamtime would allow us to achieve our goal of a 0.35 ppm measurement.

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