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The Brookhaven Muon g-2 Experiment*

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1 Introduction

A new experiment is being mounted at BNL to measure the anomalous magnet moment of the muon to 3 parts in 10^7. In this talk I will describe the physics issues that this precision allows us to explore, the experimental method, and an interesting new device which we will use to inject muons into our muon storage ring. The device is a 1.45T non-ferrous superconducting magnet, where all fringe field is contained by a superconducting sheet.

2 Physics Issues

The gyromagnetic ratio of a particle, g, is the ratio of the magnetic field created by a revolving charge and the angular momentum of the particle from revolving mass. g-2 measures the difference between the charge distribution and the mass distribution. If the distributions are the same, whatever their size, (g-2) = 0. Also, if the particle is point-like, (g-2) = 0. For the proton, g-2 = 3.6, and the large value is due to the constituents: the proton is an extended object with charged quarks and neutral mass distributed inside. The electron and muon g-2 ≈ .002, and they are thought to be very small objects.

A precision measurement of g-2 gives us a means of seeing the average effect of quantum fluctuations of the particle. A charged particle emits and absorbs photons, fluctuating within the Uncertainty Principle, producing an electric field. When the particle travels through an external magnetic field, photons from the external field interact with the particle, which affects the spin and g-2. These interactions see the fluctuating particle, as well as the bare particle. The g-2 value is an average of the effects from the different states. For the electron, the difference between theory and experiment for g-2 is $(48 \pm 28) \times 10^{-12}$, in remarkable

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agreement for this precision, and this confirms our understanding of electromagnetism[1].

The original muon g-2 experiments were done to see if the muon charge and mass distributions might differ, since the muon is 200x more massive than the electron. Also, any new field carried by the muon, vs. the electron, would also be probed by g-2. From an experiment in 1961 at CERN[2],

$$(g-2)/2 \text{ muon} = 0.001162 \pm 5$$

compared to the electron $= 0.001160\ldots$

The muon and electron g-2 values were the same at this level of precision.

The muon, because of its mass, is more sensitive than the electron to fields carried by heavier particles. This increased sensitivity is proportional to the square of the mass, and the muon is 40,000x more sensitive than the electron to contributions from the emission and absorption of heavier particles. This is the reason it is exciting to measure the muon g-2 to great precision.

A precise measurement of muon g-2 is sensitive to the emission and absorption of the very heavy particles that carry the weak force, the W and Z bosons. Table I shows the predicted contributions to the muon g-2. The W and Z contribute at a level of 4 and -2×10^{-6} of the muon (g-2). The present theory[3] predicts the anomaly $a = (g-2)/2$ to 2×10^{-6} and the 1979 CERN measurement[4] has a precision of 7×10^{-6}. To see an effect of 2×10^{-6}, both the theory and the experiment must be improved. The present agreement between theory and experiment is $(4 \pm 9) \times 10^{-6}$ of the anomaly. Again, there is remarkable agreement at this precision, which verifies the electromagnetic contributions, and the new hadronic contribution (for the electron, this contributions is not important) where the electric field photon fluctuates to a pion pair, as shown in Table I.

The theoretical error is mainly from the estimate of the hadronic contribution. This contribution is obtained from experiment, a measurement of the cross section for e^+e^- creating $\pi^+\pi^-$. Experiment CMD2 at VEPP-2M, Novosibirsk[5] is currently measuring this, and we expect that the theoretical error in the muon anomaly will be reduced to about 0.5×10^{-6}.

The goal of the Brookhaven experiment is to improve the muon g-2 measurement by a factor of 20, or 3×10^{-7} of the anomaly. At this level of precision, and with the reduction of the theoretical error, we will be able to:

- measure the W and Z contribution
- "*see*" muon size for $\geq 3 \times 10^{-18}$ cm

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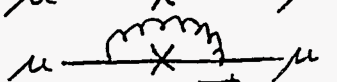
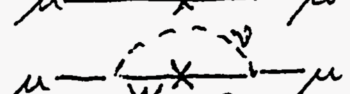
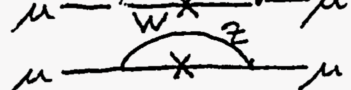
- "*see*" possible "*excited muons*" to 400x proton mass
- "*see*" W size for $\geq 8 \times 10^{-18}$ cm
- "*see*" the g-2 of the W boson for ≥ 0.04
- "*see*" speculated new particles where

$$\Delta \frac{g-2}{2} \frac{m_\mu^2}{m_x^2}, \quad m_x < 5000 \ \textit{proton} \quad \textit{masses} \ .$$

How do we get all of this from one number? The beauty of g-2 is that not only can we discover that there is something new over a broad range of possibilities, but, if that doesn't happen, we can show that there is nothing new for that same range of possibilities (> SSC domain), and we show that we understand the interactions of γ, W, Z.

TABLE I - Muon g-2

x represents the interaction of the photon from the external magnetic field. The underlined digits refer to the error.

Diagram	**Contribution to (g-2)/2**
	0
 + all others from elect/mag. field	+ 0.001 165 846 96 ± 6
 (hadronic contrib.)	+ 0.000 000 070 27 ± 175
 (W contrib.)	+ 0.000 000 003 89
 (Z contrib.)	- 0.000 000 001 94
Total theoretical prediction for (g-2)/2 for muon[4]	= 0.001 165 919 18 ± 176
Experiment[5]	= 0.001 165 923 ± 8

Difference = $(4 \pm 9) \times 10^{-9}$

3 The Experiment

The muon spin precesses in a magnetic field slightly faster than the momentum:

$$\omega_s = \omega_c + \frac{g-2}{2} \frac{eB}{mc},$$

where ω_s is the spin precession frequency, ω_c is the frequency of the momentum, and B is the magnetic field. By storing muons in a precise magnetic field and observing the frequency of the spin rotation relative to the momentum (ω_s - ω_c), we are able to measure the small number g-2 directly.

The new muon g-2 experiment is constructing a muon storage ring, which will be one magnet driven by 14 meter diameter superconducting coils, with the magnetic field shaped by iron in a C-configuration, open side facing the center (Fig. 1). Muons, collected from π decay in a long beam line, and with their spins polarized in their direction of motion from the parity-violating $\pi \rightarrow \mu + \nu$ decay, are brought through a hole in the iron backleg into a field-free region near the storage ring. This field-free region is created by a 1.7 meter long superconducting injector magnet (Fig. 2) which fits in-between the poles of the storage ring magnet. The muons then cross the storage volume about a quarter of the way around the circumference, and are kicked onto the storage orbit by magnetic kicker. 3.1 GeV muons live an average of 64 microseconds, and decay to electrons (and two neutrinos). The electrons remember the spin direction of the parent muon: more energetic electrons are emitted when the muon spin points along its momentum. The electrons, with a lower energy than the muons, spiral to the inside of the ring where they hit electron calorimeters, which are distributed around the inside circumference of the storage ring vacuum chamber. The calorimeters register more high energy electrons when the spin of the muons point forward, so that one observes a rise and fall of counts in the calorimeter as the muon spins sweep around. Now, (g-2)/2 ≈ .001, and this is boosted by the relativistic gamma factor of 29, giving a phase advance of the spin of .034 x 360° = 12.3° per rotation in the storage ring. One turn takes 149 nanoseconds, so the frequency of the muon spins is 4.4 microseconds, which is observed in the calorimeters. This is shown in Figure 3 for the CERN experiment.

The 4.4 microsecond spin precession sits on the exponentially falling muon decay rate. The experiment must measure the spin frequency very precisely, as well as the average magnetic field seen by the muons.

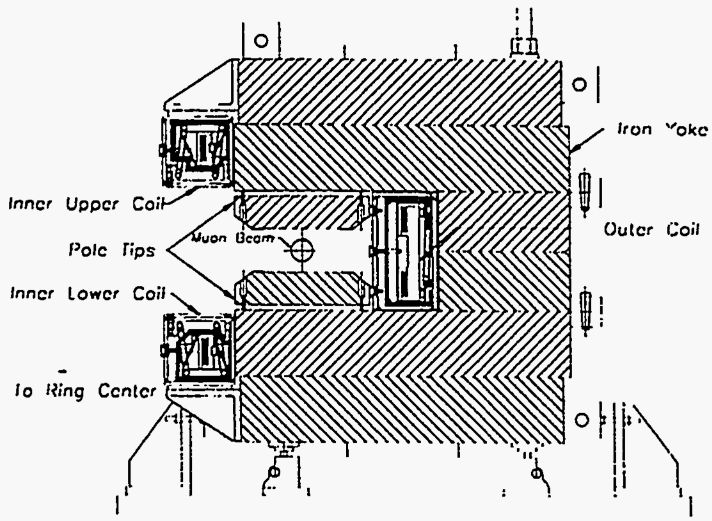


Fig. 1. A cross section view of the storage ring magnet. The muon beam will be contained in the 9 cm diameter circle shown, with the center of the storage ring 7.1 meters to the left. The coils are superconducting solenoids 13.4 and 15.1 meters in diameter.

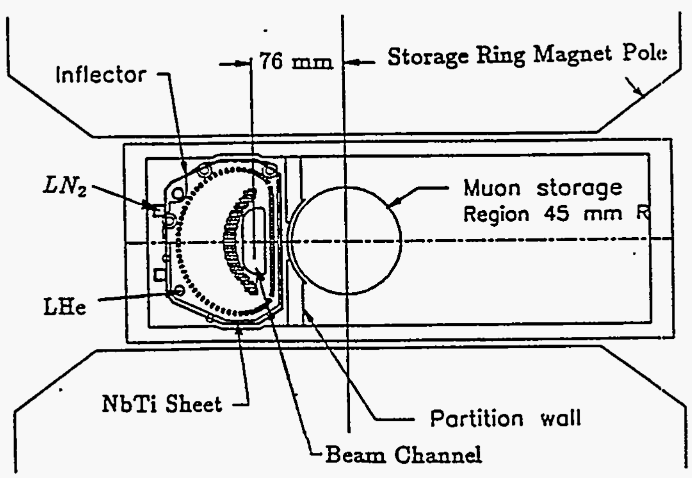


Fig. 2. Inflector and storage ring cross section at the downstream end of the inflector. The entering beam is 76mm from the center of the storage ring at this point. The inflector is a 1.5T superconducting magnet with no escaping fringe field.

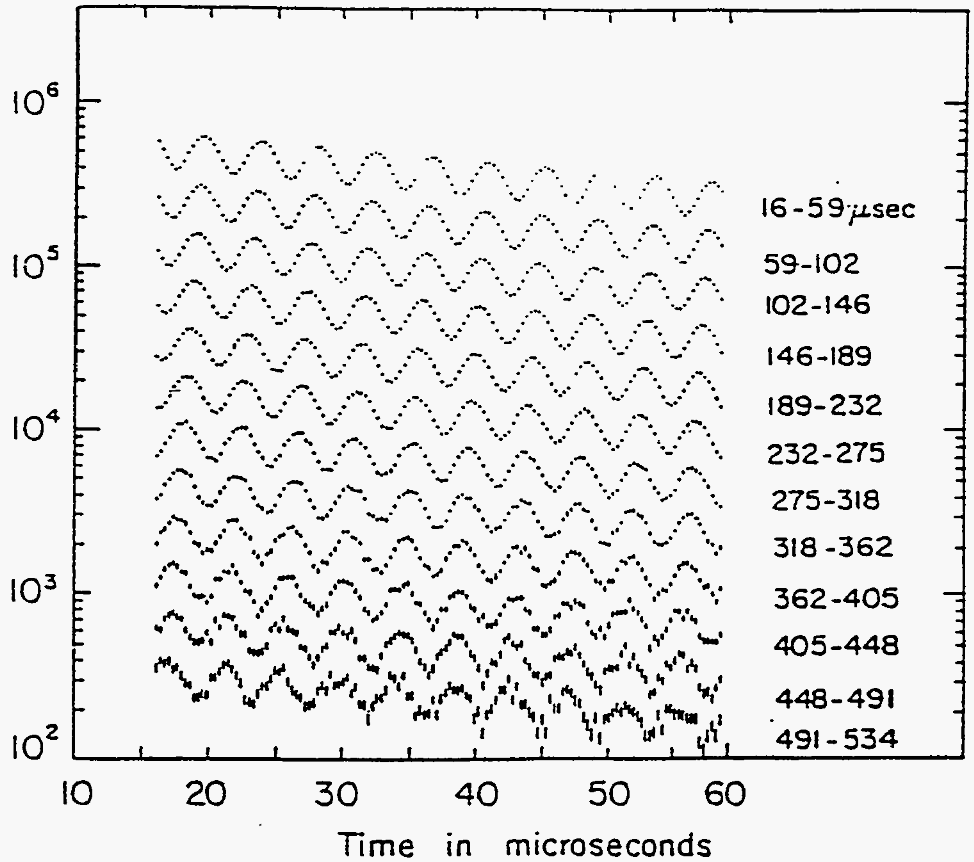


Fig. 3. Number of high energy electrons observed by the CERN III experiment[4] vs. storage time. In order to show 8 muon lifetimes of data, the plot reuses the time axis every 43 μsec.

4 Experimental Challenges

There has been considerable effort at developing tools to obtain a flat magnetic field, to 10^{-6}, and to measure the field to 10^{-7} using a trolley to carry NMR probes inside the storage ring vacuum.

A lead-scintillating fiber calorimeter system has been developed to be flat in response over the huge dynamic range--from 5 MHz at the beginning of the store to KHz later. We have developed blanking circuits for the injection time, studied the PMs and the wave form digitizer read-out for rate issues, and developed a very stable binning procedure to systematically assign times for the events.

5 The Superconducting Inflector and Shield

We have inherited the name "*inflector*" from the CERN g-2 experiment. The inflector (or injector) cancels the magnetic field near the storage ring without affecting the main storage ring field at a level of 10^{-6}. CERN's precision was less, and they used a pulsed 1.5T magnet. We were concerned with the effects of the pulsing circuit on our electronics, with remnant fields, and we needed to be able to inject each of the twelve AGS bunches at short intervals (33 msec between stores). Our solution was to construct a DC inflector and capture the return magnetic field with a cosine θ bucking coil so that the main magnetic field would not be affected. The device must fit within the 18 cm gap of the storage ring.

The device that was developed uses a double cosine θ winding (Fig. 2)[6]. A short model of the correct cross section was built, and the design works well[7]. However, there is significant field leakage at the end near the storage region and from the granularity of the conductors. A field of roughly 200 gauss was measured at the position of the center of the storage ring near the inflector. After studying shimming approaches we have adopted and tested an approach of shielding the stray field with a superconducting sheet[8].

The superconducting shield is a remarkable device. If the shield were superconducting when the main magnetic field was turned on, it would exclude this field from the inside of the inflector, and also cause very large perturbations in the storage ring field. The proposal was to only activate the shield <u>after</u> the main field is on. The shield then locks in the main field, not affecting it at at least 0.2 x 10^{-6} level (as measured). When the inflector magnet is then turned on, it correctly bucks out the field seen by the entering muons, and its stray field is trapped by the shield, so the field seen by the stored muons is not affected. This is described in Ref. 8 and one test of this approach is shown in Figure 4.

6 Summary

Many innovations have not been mentioned. We use the large proton flux provided by the AGS/Booster complex; we are building a beam line capable of both pion injection (used by the CERN experiment: the pion decay in the storage ring provided the kick that stores the muons) and muon injection; we will have devices to measure the muon distribution in the ring to weight the average magnetic field seen by the muons; we are building a precision NMR system with absolute calibration to better than 10^{-7}; a new electrostatic quadrupole system has been developed with a current lead configuration that dumps charge that builds up due to E x B containment; in addition to the calorimeters, we will have scintillator hodoscopes which give the muon position, reduce confusion from overlap, and provide an independent time measurement; we plan a new analysis of the calorimeter data which measures charge and is not sensitive to overlapping pulses.

The experiment requires 3×10^{10} muons to reach the statistical level of 3×10^{-7}, for the standard analysis. These data can be obtained in two weeks. Therefore, the ultimate sensitivity of the new experiment will depend on our control of systematic errors.

The magnet shimming will begin in early 1995, and the first run with beam will be January 1996.

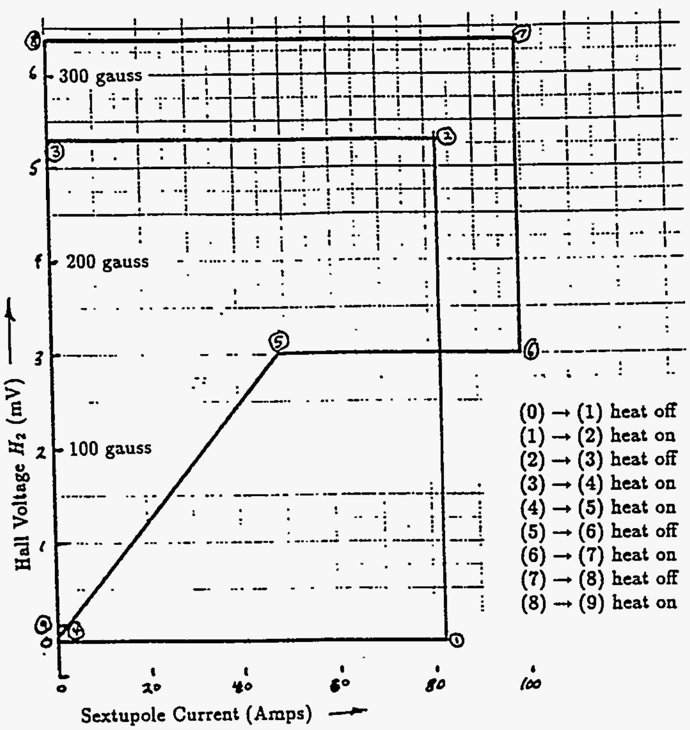


Fig. 4. An SSC sextupole was wrapped with a superconducting shield, and its field was measured outside the device. A heater was used to change the shield from superconducting (heat off) to normal (heat on) . Several cycles are shown[8].

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