The Muon g-2 experiment at Brookhaven

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Abstract. The new muon storage ring at Brookhaven is intended to measure the anomalous magnetic moment a_μ of the muon to sub ppm accuracy. A preliminary run in 1997 gave $a_\mu = 1\ 165\ 925\ (15) \times 10^{-9}$ in agreement with previous CERN measurements. The principles of the experiment and numerous detailed improvements will be described.

INTRODUCTION

A new measurement of the g-factor of the muon is underway at Brookhaven. This experiment is intended to test the standard electro-weak theory and to look for new physics. What is new physics? It stands for any speculation that has not yet been disproved by experiment.

Why the muon? Well the muon is a structureless, apparently point particle and that is what you need for testing fundamental theory. How do we know that it is a structureless point particle? Because up to now it conforms to the theory! It

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would also be interesting to find some structure of the muon, or a new interaction which might explain the $\mu - e$ mass difference. One used to speculate that it might somehow be coupled to the nucleon but that is not evident. Now the favoured coupling is to the Higgs.

Also because the muon is more massive than the electron, its g-factor is $40,000$ times more sensitive to new physics. The anomalous moment of the electron is known to amazing accuracy, 4 parts per billion (ppb), 2000 times more accurate than the present muon data; but this can only test QED to 44 ppb, the present accuracy in the fine structure constant α. Therefore the present muon data is 200 times more sensitive to typical departures from the standard model. The new BNL experiment aims to reduce the error in a_μ by a further factor of 20.

The g-factor of the muon is $g_\mu = 2(1 + a_\mu)$ where a_μ, called the "anomalous magnetic moment", is a correction due to quantum fluctuations in the electric field around the particle. It is a small effect but fortunately a_μ can be measured directly using the so-called $(g-2)$ principle.

The orbit angular frequency of muons in flight in a magnetic field B is

$$\omega_c = \frac{eB}{mc} \tag{1}$$

while the spin precession frequency is

$$\omega_s = g\frac{e}{2mc}B \tag{2}$$

If $g = 2$ these frequencies are exactly equal, so longitudinally polarised muons will stay that way. But if $g > 2$ then the spin turns faster than the momentum vector at a relative angular frequency

$$\omega_a = \omega_s - \omega_c = a_\mu(e/mc)B \tag{3}$$

where $a_\mu = (g-2)/2$. By measuring the change in spin direction relative to the momentum vector one can measure a_μ directly.

The magnetic field is calibrated by the proton NMR frequency ω_p while e/mc is obtained from the very accurate measurements of muon precession at rest [1] and from muonium hyperfine structure [2].

$$\lambda = \omega_s/\omega_p = \mu_\mu/\mu_p \tag{4}$$

again in fields calibrated by proton NMR. One then finds

$$a_\mu = \frac{R}{\lambda - R} \tag{5}$$

where $R = \omega_a/\omega_p$ is the ratio measured in the $(g-2)$ experiment.

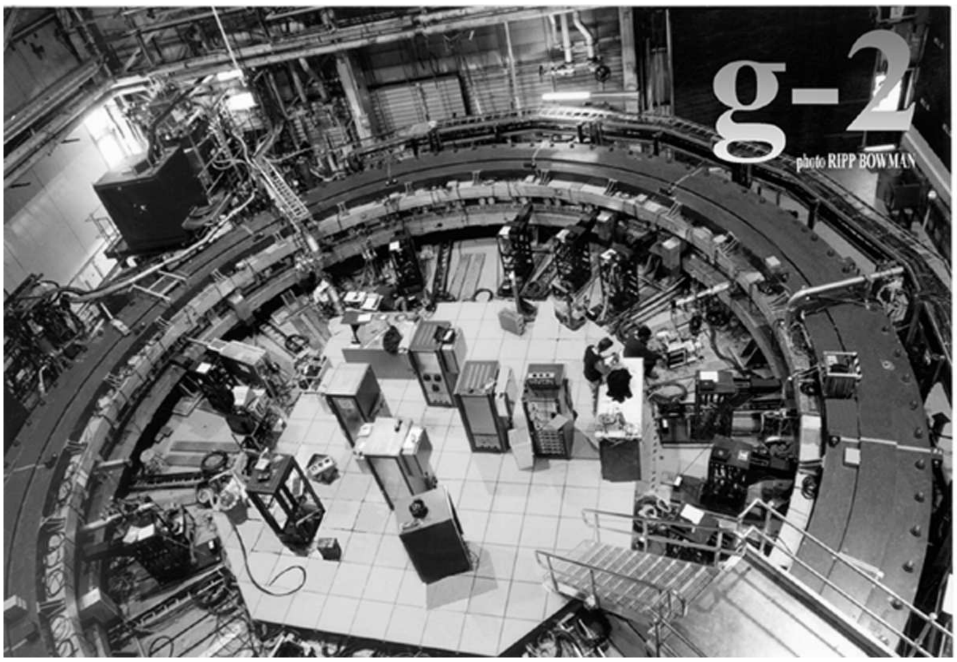

FIGURE 1. The Brookhaven Muon Storage Ring

The $(g-2)$ precession formula (3) was derived above in non-relativistic approximation, but it turns out to be correct at high energies also [3]. While the muons live longer in the laboratory, ω_a is not slowed down by time dilation . Therefore by using high energy muons one can measure more precession cycles and thus get better accuracy.

MUON STORAGE RING

So to make the measurement one ideally needs a large ring magnet, continuous in azimuth with no straight sections and a uniform magnetic field calibrated by proton NMR. A uniform field provides horizontal focusing but no vertical focusing, so the muons would soon be lost. If a weak magnetic gradient is added to focus vertically [4] then ω_a becomes a function of radius limiting the accuracy to order 100 ppm. In the last CERN experiment [5] the magnetic field was flat and the vertical focusing was provided by electric quadrupoles, all of the same sign, distributed around the ring. One can show that this combination gives weak focusing with an effective gradient $n_{eff} = 2V\rho/a^2\beta B$ where V is the voltage applied to quadrupole plates distance a from the centerline and ρ is the radius of the ring.

The vertical component of the electric field does the focusing, but is accompanied by a horizontal component , varying with radius, which in general alters the $(g-2)$ frequency so one is no better off.

$$\omega_a = (e/mc)\left[a_\mu B - (a_\mu - 1/(\gamma^2 - 1))\beta \times E\right] \qquad (6)$$

At CERN we chose $\gamma = \sqrt{1 + 1/a_\mu} = 29.3$ so the second term in (6) is zero and the electric field then has no effect on the spin precession. To satisfy this condition the stored muons must have the so-called "magic" momentum of 3.094 GeV/c.

Polarised muons were produced inside the storage volume by injecting pions of about 3.1 GeV/c. During the first turn 20% decay to muons and some of these from forward decay fall onto permantently stored orbits. About 10^4 π were needed to give one stored μ.

The electrons from muon decay in orbit have energy varying from 0 to 3.1 GeV, so they are bent more sharply by the magnetic field and emerge on the inside of the ring where they are detected in energy-sensitive calorimeters. By requiring high energy in the lab one selects forward emitted electrons in the muon rest frame, so as the spin turns the number of electrons is modulated, (figure 1), and one can read off the precession frequency. At CERN this gave a_μ to 7 ppm.

IMPROVEMENTS

In the new BNL experiment the following improvements have been introduced:

•A larger aperture ring magnet with more uniform magnetic field. Field 14.5 T, orbit radius 711 cm.

•Superconducting coils implying more stable current and less temperature effects in the iron.

•Special shimming devices including pole face windings to correct lower order multipoles.

•A storage aperture of circular cross-section, (diameter 9 cm). The average field seen by the stored muons is then much less sensitive to higher field multipoles.

•An NMR trolley which travels round the ring inside the vacuum chamber to map the field without turning the magnet on and off.

• 24 special windows to allow the decay electrons to exit with minimum showering and so give a larger amplitude $(g-2)$ modulation.

•Polarised muons are produced outside the ring in a $\pi - \mu$ decay channel and injected with the aid of a fast full-aperture kicker. This gives a factor of 10 improvement in the stored intensity and much less background.

•Higher beam intensity due to accelerator improvements at the AGS since 1970.

• 24 calorimeters with separate timing circuits to reduce signal overlap.

•Electronics to record individual electron hits for off-line processing and algorithms for dealing with overlapping signals.

•Improved electron calorimeters good stability in gain and timing.

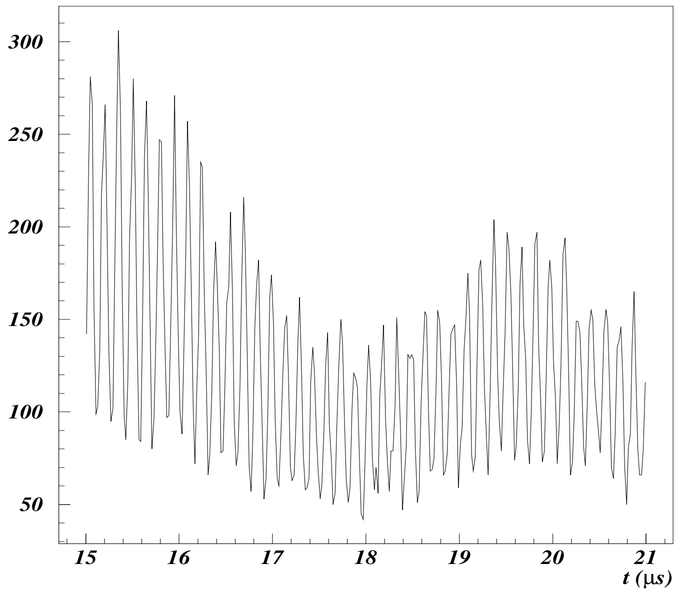

FIGURE 2. Decay electron counts at early times showing muon orbit period (149 ns) plus slow g-2 modulation

•Use of the whole AGS beam in 8 separate RF buckets at 33 ms intervals. This limits the peak counting rates; in effect the experiment is made 8 times per AGS cycle of 2.3 seconds.

•Measurement of the muon distribution inside the storage volume by

(a)trace back of the decay electron tracks using drift chambers

(b)pick up electrodes.

•Position-sensitive detectors in front of the calorimeters

•A direct current superconducting inflector [6] to cancel the magnet field along the path of the incoming beam

PRELIMINARY TESTS

A preliminary engineering run was made in early 1997 to test the system. At this stage the fast kicker for direct muon injection was not available, so we used pion injection as in CERN and experienced the anticipated severe background in the detectors. As a result the fit to the $(g-2)$ precession was not started until 80 μs after injection. Nevertheless data taken over 8 days gave a_μ to 13 ppm.

A Fourier fit to the data at early times (figure 2), when the muons are still bunched, gives the distribution of rotation frequencies shown in figure 3 compared

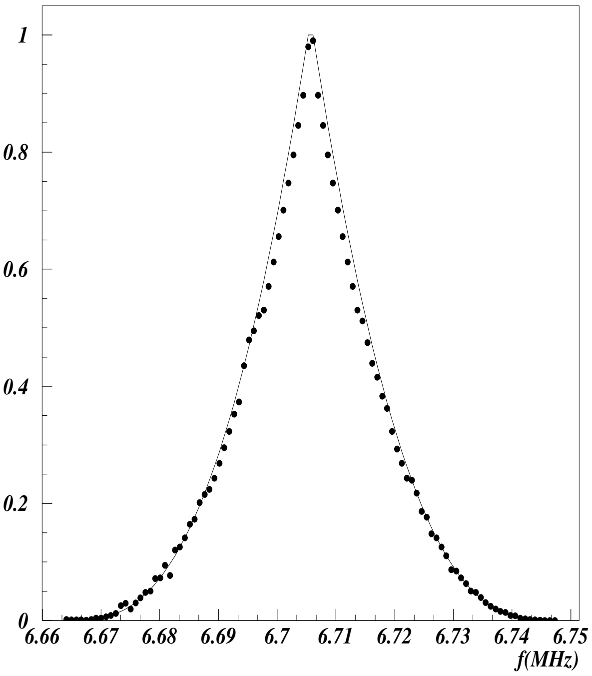

FIGURE 3. Distribution of rotation frequencies calculated from fig.2 (•), and phase space prediction for a circular aperture (solid line)

with the prediction for a uniformly populated circular aperture; with excellent agreement.

Figure 4 shows the time distribution of the decay electrons at later times with the $(g-2)$ modulation. Figure 5 gives the result of our measurement with the CERN results for comparision. Agreement is good. Combining these numbers for μ^+ and μ^- and using $\lambda = 3.18334547(47)$ [7], the current weighted mean value for the anomalous moment is

$$a_\mu = 1\ 165\ 923.4\ (7.2) \times 10^{-9}\ \ (6.2\, ppm) \tag{7}$$

COMPARISON WITH THEORY

According to the Standard Model

$$a_\mu(theory) = a_\mu(QED) + a_\mu(weak) + a_\mu(hadron) \tag{8}$$

The QED contribution consists of a series expansion in (α/π) which has been evaluated over a period of 40 years with ever increasing accuracy [8]. At present

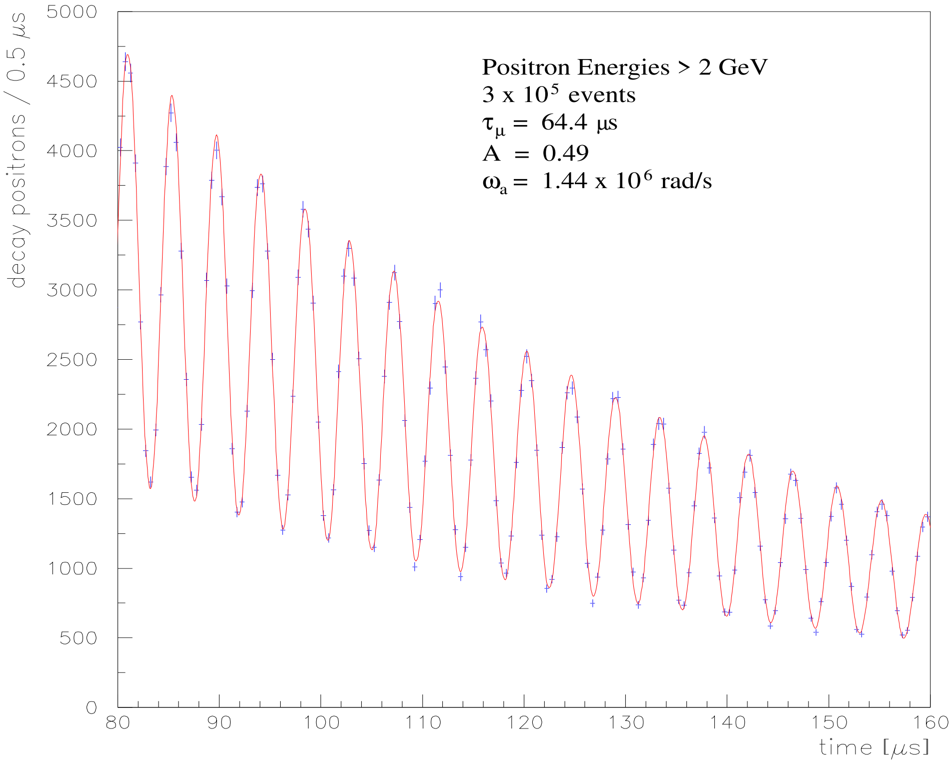

FIGURE 4. Decay electron distribution at late times showing g-2 modulation. A fit to this data gives a_μ

$$a_\mu(QED) = 116\ 584\ 706\ (2) \times 10^{-11} \quad (16\ ppb) \tag{9}$$

The weak effect comes from two first order diagrams (figure 5) [9] plus second order loops

$$a_\mu(W) = \frac{G_F m_\mu^2}{8\pi^2\sqrt{2}}\left(\frac{10}{3}\right) = 389 \times 10^{-11} \tag{10}$$

$$a_\mu(Z) = \frac{G_F m_\mu^2}{8\pi^2\sqrt{2}}\left(\frac{1}{3}\right)\left[(3 - 4\cos^2\theta_W)^2 - 5\right] = -194 \times 10^{-11} \tag{11}$$

giving first order weak $= a_\mu(W) + a_\mu(Z) = 195 \times 10^{-11}$ $(1.6\ ppm)$ But the second order weak contribution is [10] -44×10^{-11} giving in total

$$a_\mu(weak) = 151 \times 10^{-11} \quad (1.3\ ppm) \tag{12}$$

The theorists are very interested to have an experimental check on $a_\mu(weak)$ because this would be the first test of loop diagrams involving Z and W.

The water is clouded however by $a_\mu(hadron)$ which arises from virtual photons producing virtual hadron loops (figure 7). The contribution to a_μ can be related

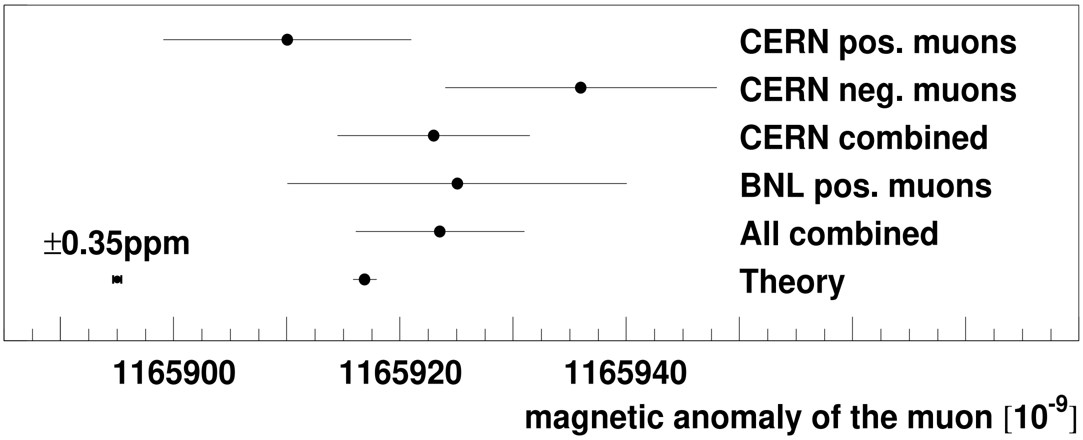

FIGURE 5. Results for $a_\mu \times 10^9$ compared with theory.

via a dispersion relation to the total cross-section for hadron production in e^+e^--collisions

$$a_\mu(had1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_0^\infty K(s)R(s)ds \tag{13}$$

where $K(s)$ is an algebraic expression in s and

$$R(s) = \frac{\sigma_{tot}(e^+e^- \Longrightarrow hadrons)}{\sigma_{tot}(e^+e^- \Longrightarrow \mu^+\mu^-)} \tag{14}$$

A long program of careful experiments at CMD2 and VEPP [11] is devoted to the measurement of $R(s)$.

One obtains another handle on $R(s)$ from hadronic τ-decay via a virtual $W^\pm$. Through conserved vector current the virtual W and the virtual photon are related [12] (figure 8). In addition one must include second order hadronic diagrams [13], -0.86 *ppm*, and hadronic light by light scattering [14],-0.68 *ppm*. The overall current value is

$$a_\mu(hadron) = 6771\ (77) \times 10^{-11} \ \ (58.6 \pm 0.82\, ppm) \tag{15}$$

Thus the error in $a_\mu(hadron)$ is about half the total weak effect which we hope to see. Further work still in progress will gradually improve the situation.

Adding all these terms together the current theoretical prediction is

$$a_\mu(theory) = 116\ 591\ 628\ (77) \times 10^{-11} \tag{16}$$

Therefore

$$a_\mu(experiment) - a_\mu(theory) = 6.1 \pm 6.2\, ppm \tag{17}$$

So there is an offset of about one standard deviation which may mean nothing. The next run at BNL with muon injection, just starting, should push the error down to about 1 ppm, with further improvements expected to follow.

If there turns out to be a difference the most likely explanation with "new physics" comes from Supersymmetry

$$a_\mu(SUSY) = 1.2\, ppm \times \tan\beta \left(\frac{100\ GeV}{\tilde{m}}\right)^2 \tag{18}$$

where $\tilde{m}$ is the typical supersymmetric mass (perhaps $100 - 200$ GeV) and the favored values of $\tan\beta$ are either about 1.5 or in the region of 40. So $a_\mu(SUSY)$ could be large and easily detectable.

Stay tuned to find whether the standard model is confirmed, or if on the other hand there are indications in favour of supersymmetry or possibly some structure of the muon.

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