MUON $g-2$, CURRENT EXPERIMENTAL STATUS AND FUTURE PROSPECTS*

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(Received April 27, 2018)

The muon gyromagnetic anomaly a_μ has been measured with a precision $\delta a_\mu / a_\mu = 540$ ppb using magic-momentum muon decays recorded up to 2001 by the E821 BNL experiment. Two projects aim at significantly improving that experimental precision: the E989 Collaboration at Fermilab plans to collect 21 times the BNL statistics and to improve by a factor four the uncertainty, the E34 Collaboration is designing a new experiment at J-PARC with a novel approach based on the production, injection and storage of ultra-cold low-energy muons. E34 aims at matching the BNL precision in a first phase, and to provide a significantly higher precision measurement in a second phase.

DOI:10.5506/APhysPolB.49.1247

1. Introduction

The muon gyromagnetic anomaly is defined from the muon gyromagnetic factor g_μ as $a_\mu = (g_\mu - 2)/2$. A sequence of experiments has measured a_μ with increasing precision over time, as shown in figure 1, achieving a remarkable sub-ppm accuracy. On the experimental side, it is a low-energy measurement whose high precision allows testing quantum loop effects either from high order Standard Model processes or from new physics processes.

The present experimental precision, $\delta a_\mu / a_\mu = 540\,\text{ppb}$, is dominated by the E821 Collaboration measurement, which uses the magic-momentum ($p = 3.094$ GeV$/c$) muon decays collected at Brookhaven in the years from 1998 to 2001. The E821 2006 final report [1] concludes a series of measurements that started in 1960. Over the last several years, Standard Model (SM)

* Presented at the Cracow Epiphany Conference on Advances in Heavy Flavour Physics, Kraków, Poland, January 9–12, 2018.

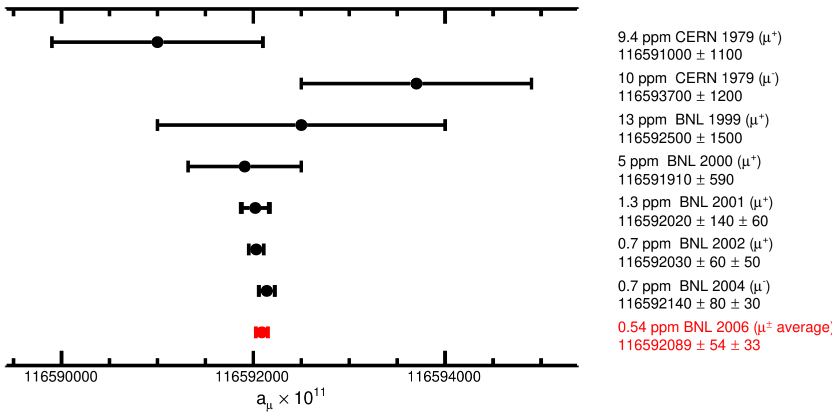

Fig. 1. Experimental measurements of a_μ since 1979.

theory predictions of a_μ have reached a precision $\delta a_\mu / a_\mu = 300\,\text{ppb}$ [2], and today the measured discrepancy between experiment and theory corresponds to about 4 standard deviations [2].

Improvements on the experimental and theoretical precision are required in order to understand if the observed discrepancy is caused by physics beyond the SM or by statistical fluctuations. Two projects aim at obtaining significant improvements of the experimental accuracy in the incoming years: the Fermilab E989 and the J-PARC E34 experiments.

2. The a_μ measurement

A muon with charge q, mass m and energy described by the Lorentz factor γ in an uniform magnetic field with intensity B revolves on a circular orbit with cyclotron frequency $\vec{\omega}_{\rm c} = -q\vec{B}/m\gamma$. The muon spin precesses at frequency $\vec{\omega}_{\rm s} = -(gq\vec{B}/2m) - [(1-\gamma)q\vec{B}/\gamma m]$ [3], where the two terms describe the Larmor precession of a spin at rest, and the Thomas precession contribution related to the circular motion of the muon. The muon anomalous precession frequency is the difference between the two frequencies

$$\vec{\omega}_{\rm a} \equiv \vec{\omega}_{\rm s} - \vec{\omega}_{\rm c} = -\left(\frac{g-2}{2}\right)\frac{q\vec{B}}{m} = -a_\mu \frac{q\vec{B}}{m}\,. \tag{1}$$

The parity-violating decay $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ produces electrons whose distribution in the solid angle and in energy depends on the muon-spin direction. In the laboratory frame, the electron distribution in momentum and angle is modified by the Lorentz boost due to the muon momentum. For a polarized muon beam stored in magnetic field, detectors counting muon-decay electrons above an energy threshold record a rate that is modulated according to the angle between the muon spin and the muon momentum and, therefore, with frequency $\omega_{\rm a}$, as shown in figure 2. Fitting the detected electron rate with an exponentially decay function modulated by a cosine returns $\omega_{\rm a}$ with a precision

$$\frac{\delta\omega_{\rm a}}{\omega_{\rm a}} = \frac{1}{\omega_{\rm a}\gamma\tau_\mu}\sqrt{\frac{2}{NA^2P^2}}\,, \tag{2}$$

where γ accounts for the relativistic dilation due to the muon momentum, τ_μ is the muon lifetime, N is the number of detected muons above threshold, A is the amplitude of the muon rate modulation (which depends on the threshold) and P is the muon polarization.

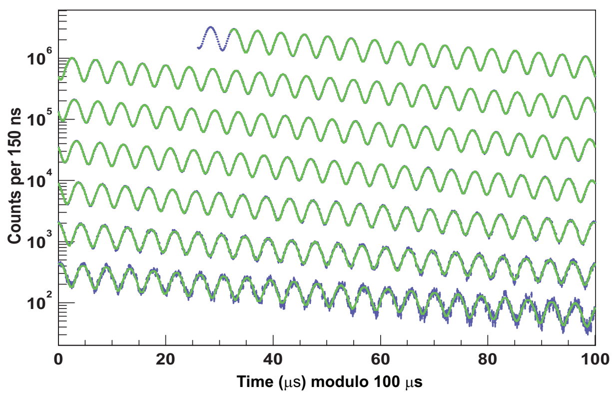

Fig. 2. Modulation of the rate of detected electron above threshold in E821. The fit is overlaid on the data. The data is wrapped around every 100 μs. Courtesy of the E821 Collaboration.

The magnetic field is measured with pulsed proton Nuclear Magnetic Resonance (NMR) probes in terms of the proton Larmor precession frequency, $\omega_{\rm p}$, and $a_\mu^{\rm exp}$ is obtained as

$$a_\mu^{\rm exp} = \frac{g_e}{2}\frac{\omega_{\rm a}}{\omega_{\rm p}}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}\,, \tag{3}$$

where g_e is the electron gyromagnetic factor, m_μ and m_e are the electron and muon masses, μ_p and μ_e are the proton and electron magnetic moments. The uncertainty on $a_\mu^{\rm exp}$ is dominated by the uncertainty on the ratio $\omega_{\rm a}/\omega_{\rm p}$. The electron g_e factor, the muon-to-electron mass ratio, and the proton-to-electron magnetic moment ratio are known with high accuracy from other independent measurements [4].

3. Muon magic momentum

The E989 project relies on the experimental arrangements that were first used for the 1975 CERN measurements of the muon anomaly and since then for the following CERN and BNL measurements. A beam of polarized muons with charge q, mass m, velocity v, $\beta = v/c$ and Lorentz factor γ is stored in a ring equipped with uniform magnetic field $\vec{B}$ and electric quadrupoles field $\vec{E}$ for vertical confinement. Due to the motion of the muons through the quadrupoles electric field, there is an additional contribution to the muon spin precession frequency, which modifies ω_{a} as follows:

$$\vec{\omega}_{\mathrm{a}} = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]. \tag{4}$$

By setting the muon momentum around the "magic" momentum $p_\mu = 3.094$ GeV$/c$, ($\gamma = 29.4$), the contribution proportional to the electric field vanishes. Small deviations and uncertainties around the magic momentum correspond to manageable systematic uncertainties on the a_μ measurement.

4. Fermilab E989

As in the CERN measurements starting in 1975, E989 obtains a polarized muon beam by colliding protons on a target, producing pions and accepting muons from forward pion decays into a storage ring.

At FNAL, a flux consisting of 12 fills per seconds each containing $10^{12} \times$ 8.9 GeV protons hits a target producing a large number of secondary particles. For each fill, about 1.2×10^8 positive pions with suitable momentum close to 3.1 GeV are accepted on a beam line ending in a pion temporary storage ring with about 500 m circumference. Here, they complete a few revolutions, eventually decaying into muons and neutrinos ($\pi^+ \to \mu^+\nu_\mu$). A 95% polarized positive-muon beam is obtained by extracting the muons from the pion ring and moving them into a 14 m-diameter muon storage ring, which accepts muons within $\pm 0.5\%$ of the magic momentum.

Thanks to improvements in the beam lines with respect to E821, E989 expects a high purity muon beam with no protons and about 10^{-5} pion contamination. Muons in the storage ring decay with a dilated lifetime of about 64 μs, producing positrons that are tracked by 3 in-vacuum straw-chamber modules inside the ring and by 24 lead–fluoride electromagnetic calorimeter modules along the ring.

Each tracker module consists of 8 sub-modules made of 4 layers of 32 straws; the 4 layers are organized in 2 views at $\pm 7.5^\circ$ with respect to the vertical. Each calorimeter module consists of 54 crystals in a 6×9 matrix, equipped with silicon photomultipliers to read the crystals' Cherenkov light.

The measurement of ω_a relies on fitting the rate of positrons with energy larger than 1.86 GeV over time. To minimize muon contamination and losses related to the injection, the fit starts 30 μs after injection. About 1.6×10^4 muons per fill are stored, and about 1.0×10^4 survive after 30 μs. About 1.1×10^3 positrons above threshold are detected per fill. By recording about 21 times the E821 statistics, E989 plans to reduce the statistical error on ω_a from 458 ppb to 100 ppb.

The systematic uncertainty on ω_a is expected to improve from 180 ppm with E821 to 70 ppm with E989. The largest systematic contribution on the E821 ω_a measurement originated from uncertainties on how the calorimeter gain varies for each detector element as a consequence of the exponentially decaying hit rate within each fill. A significantly more elaborate and redundant laser calibration system will accurately measure the calorimeter gain variations with reference laser light pulses, reducing the expected systematic contribution from 120 ppb to 20 ppb. Systematics from rate-dependent hit pileup will be reduced by using a highly segmented calorimeter with very fast silicon photomultiplier readout and higher digitization sampling rate. Improvements on the storage ring collimators will reduce the systematics from the muon loss rate. Improvements in the storage ring optics will reduce systematics from coherent betatron oscillations related to the weak electric focusing field. Systematics from the quadrupole electric field and from deviations of the magnetic field direction with respect to the vertical will be reduced by improvements in tracking and simulation.

E989 uses the BNL E821 14 m-diameter storage ring, which has been transported from BNL to FNAL and reassembled. The 1.45 T magnetic field is accurately mapped and measured along the muon path in the storage ring with a total of 400 pulsed proton NMR probes located above and below the muon storage volume, as shown in figure 3. Interpolation of the measured field between these probes is cross-checked with measurements by 17 NMR probes in a trolley that is periodically moved on a rail along the whole storage ring to measure the field exactly in the muon storage region. The muon distribution along the storage ring is measured by tracking their decay electrons. The muon distribution is folded with the magnetic field map to obtain the average effective proton precession frequency ω_p for the a_μ measurement. By means of a large number of improvements on several sources of systematics, E989 expects to estimate a 70 ppb systematic uncertainty on ω_p, significantly improving the 170 ppb systematic uncertainty quoted by E821. One source of systematics is the uniformity of the field within the 4.5 cm radial acceptance of the storage ring. The magnetic field uniformity is carefully optimized with corrective coils and a shimming procedure based on positioning a large number of magnetic elements along the ring to remove any measured field inhomogeneity. With respect to E821,

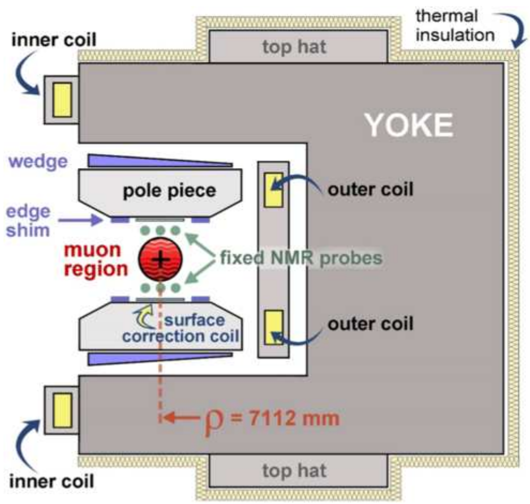

Fig. 3. Cross section of E989 magnet.

local field inhomogeneities are now reduced from 100 ppm to 50 ppm. Like E821, E989 expects to obtain an azimuthally averaged magnetic field uniformity of 1 ppm across the radial acceptance.

E989 plans to get measurements with 1–2 times the BNL statistics in 2018, 5–10 times in 2019 and 21 times in 2020. Combining in quadrature the expected statistical and systematic uncertainties on $\omega_{\rm a}$ with the expected entirely systematic uncertainty on $\omega_{\rm p}$, E989 ultimately aims to obtain a 140 ppb precision on the a_μ measurement.

5. J-PARC E34

The J-PARC E34 Collaboration has proposed a novel scheme to measure a_μ, based on "ultra-cold" muons stored at low momentum in a small magnet, where they can remain confined without focusing quadrupole electric field. In more detail, E34 relies on a 3 GeV/c proton beam, which produces pions at rest on a graphite target. The pions decay producing 29 MeV/c surface muons, which are stopped on a silica aerogel target equipped with micro-channels obtained with laser ablation [5]. Here, positive muons bind with electrons to form muonium atoms. By firing lasers with $\lambda = 122$ nm and $\lambda = 355$ nm, the muonium atoms are first excited and then ionized, producing 50% polarized thermal muons with RMS(p) $\sim$ 3 keV/c. Laboratory tests show that J-PARC can assemble a muon source with a rate of about $2 \times 10^5 \mu$/s [5]. These ultra-cold muons are accelerated to a momentum of 300 MeV/c with a LINAC and stored is a conventional magnetic resonance imaging (MRI) magnet, operated at 3 T. Containment is obtained with a very weak radial magnetic field, whose intensity does not affect the a_μ measurement. There will be no electric field. The experimental set-up, illustrated in figure 4, is remarkably compact when compared to the CERN, BNL and FNAL storage rings. The storage radius is just 33 cm, the cyclotron period is only 7.4 ns, and the muon lifetime is ten times shorter that at the magic momentum. Positrons from muon decays are detected by a high granularity double-sided silicon microstrip detector, composed of radially-arranged vertical planes with radial strips on one side and axial strips on the other side.

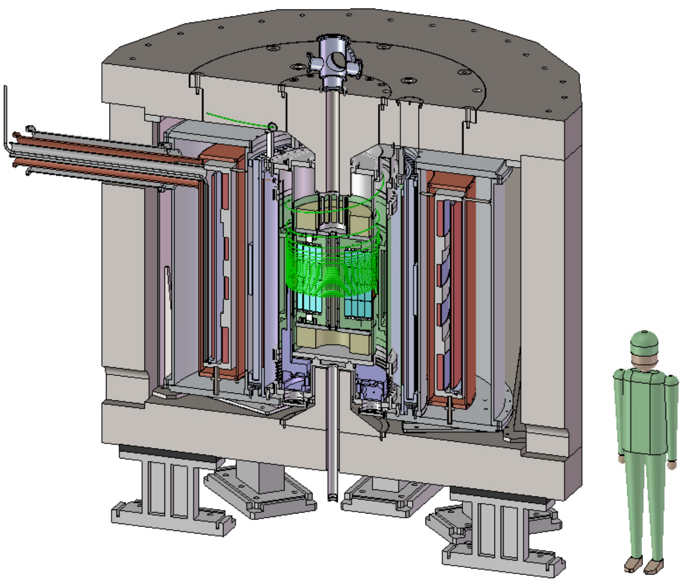

Fig. 4. (Colour on-line) The proposed set-up for the J-PARC $g-2$ Experiment. Muons enter at the top left (green trajectory) and spiral into the highly uniform magnetic field region. Their decay positrons curl inward to an array of silicon tracking detectors. Courtesy of T. Mibe.

Having a small magnet facilitates the attainment of a very uniform magnetic field. The detector has high and uniform efficiency, and is also well-suited for the detection of the muon electric dipole moment (EDM) effects, which modulate the muon spin vertical angle and, as a consequence, the positron rate distribution in the vertical angle. The E34 set-up will have to compensate its smaller muon polarization and shorter measurement time with a larger muon statistics. On the other hand, its muon production scheme is very efficient and the highly segmented silicon detector is expected to be very resilient to pileup effects.

The novel approach of E34 requires a large amount of research and development activity, which is expected to be complete in 2018. So far, the Collaboration has measured the yield and properties of thermal muonium production, has built and operated a ionization laser system at 10% of the design power, has demonstrated the feasibility of electro-static acceleration of thermal muons, has obtained a magnetic field uniformity at the 1 ppm level, and has built a full size silicon detector complete with custom frontend electronics.

A first phase of the E34 experiment is approved, and the Collaboration is going to start data taking in 2020, with the goal to measure a_μ with a statistical uncertainty of 370 ppb. The systematic uncertainties are substantially different from the ones estimated for the BNL and FNAL experiments and there are not yet estimates. The Collaboration expects to be able to obtain a 100 ppb statistical precision in a second phase of operations, which is not yet approved. Table I summarizes the comparison of E34 with E989.

TABLE I

Comparison between E34 and E989, reproduced from [6]. The events in the final fit for E34 correspond to the goal for the second phase of operations.

Parameter	FNAL E989	J-PARC E34
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in the final fit	1.5×10^{11}	8.1×10^{11}

6. Summary

In the next years, the muon anomaly experimental precision will improve significantly with the operation of two very different experiments. The first one, E989, improves the "magic momentum" scheme used at CERN since 1975 and later remarkably exploited in BNL. The second one relies on a novel scheme based on thermal muons accelerated to a low momentum and stored in a small magnet with no electric field focusing. The two experiments will have different and mostly independent systematic uncertainties. Table II summarizes the existing uncertainties on the muon anomaly and the expected improvements with the two new forthcoming experiments.

TABLE II

Reported and expected uncertainties on the muon anomaly measurements.

	E821 [ppb]	E989 [ppb]	E34-1 [ppb]	E34-2 [ppb]
$\delta\omega_{\rm a}$ statistical	458	100	370	100
$\delta\omega_{\rm a}$ systematic	180	70		
$\delta\omega_{\rm p}$ systematic	170	70		
δa_μ	540	140		

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