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The $g-2$ experiment

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Summary. — This paper briefly describes the main features of the muon $g-2$ experiment E989 at Fermilab. The experiment aims to measure the muon anomaly with a 140 ppb accuracy, improving by a factor 4 last measurement done at BNL (E821), and potentially revealing new physics beyond the Standard Model.

1. – Introduction

The muon $g-2$ experiment at Fermilab, E989, plans to measure the muon anomaly a_μ, where $\mathrm{a}_\mu = (g-2)/2$, with an uncertainty of $1.6\cdot 10^{-10}$. The 140 ppb accuracy consists of a 100 ppb statistical error and a total systematic error due to the combined uncertainties of about 70 ppb on the spin precession frequencies of muons (ω_a) and knowledge of the magnetic field through the measurement of the frequency precession of protons at rest (ω_p). In fact the experiment extracts the muon anomaly from the ratio of these two frequencies:

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}, \tag{1}$$

where μ_μ/μ_p is the ratio between muon and proton magnetic moments, known with 27 ppb from the hyperfine structure of muonium [1]. The E989 140 ppb accuracy would improve with respect of the Brookhaven E821 experiment by a factor four. It is well known that the result of the E821 experiment differs by more than 3σ from the theoretical value predicted by the Standard Model, including QED, electroweak and hadronic interactions, that is actually calculated with a 0.4 ppm uncertainty. Therefore, a fourfold improvement in the experimental precision is crucial to confirm that this discrepancy is due to physics beyond the Standard Model.

The main improvement of the new muon $g-2$ measurement comes from the Fermilab accelerator facility producing a high-intensity and pure muon beam that provides a large

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(*) `http://muon-g-2.fnal.gov/g2_collaboration.pdf` statistics for the $g-2$ experiment. In fact to achieve a statistical uncertainty of 100 ppb, the total data set must contain more than $1.6 \cdot 10^{11}$ detected positrons with energy greater than 1.8 GeV, and arrival time greater than 30 μs after injection into the storage ring. Besides the incoming muon beam, the FNAL E989 experiment introduces a large series of refinements focused on optimizing the muon storage efficiency, and improving the instrumentation used to measure both ω_a and ω_p [2].

2. – Description of the experiment

The muon production starts with a bunched beam of protons from the 8 GeV Booster impinging into a pion production target. Pions with a 3.11 GeV/c momentum are collected and sent into a large-acceptance beamline. Muons are produced in the weak pion decay together with neutrinos. In the pion decay, the direction of the muon spin is fully correlated to the direction of the muon momentum in the rest frame of the pion. Therefore, by selecting the highest-energy muons, a beam of polarized muons is obtained with a polarization greater than 90%. Pions and muons from their decay are injected into the Delivery Ring, where after several turns most of the remaining pions decay. The surviving muon beam is extracted and brought to the storage ring built for E821 at Brookhaven and relocated in a dedicated building in Fermilab. The storage ring magnet is energized by three superconducting coils. The continuous "C" magnet yoke is built from twelve 30° segments of iron, designed to eliminate the end effects and minimizing also the field gradients. The muons enter through a hole in the magnet and then the injector magnet delivers the beam to the edge of the storage region. A fast kicker pulse ($\simeq$150 ns) puts magic-momentum muons onto a stable orbit centered at the magic radius. The magic momentum $p_{magic} = m/\sqrt{a_\mu} \simeq 3.09\,\mathrm{GeV}/c$ is the momemtum for which the focusing quadrupole electric-field contribution to ω_a cancels at the first order, requiring just small corrections for momentum spread. A tracking system allows to monitor the stored muon population, improving both the corrections due to the electric field and the convolution of the stored muon population with the magnetic-field volume.

The magnetic field inside the ring is measured in different ways to achieve high precision. The magnetic-field shimming, measurement and control systems are based on pulsed Nuclear Magnetic Resonance (NMR), since it can measure magnetic fields to absolute accuracies of tens of ppb. In particular the field is measured by detecting the free induction decay (FID) signal of protons in materials containing hydrogen such as water, using almost 400 fixed probes positioned above and below the vacuum chamber around the ring. The frequencies are controlled at 1 ppb by a Rb clock and a GPS receiver. The uncertainty on the frequency is due to the signal-to-noise ratio of the FID, corresponding to about 25 ppb for a single FID. A trolley with a circular array of 17 NMR probes can be moved along the ring and measures the magnetic-field distribution over the muon storage volume when the beam is off. After an accurate shimming process, the field is very uniform, the dipole part having an RMS of 15 ppm.

The measurement of ω_a has also several improvements with respect to E821, that aim to lower the systematic error as summarized in table I. To measure ω_a the decay positrons are dectected by 24 calorimeter stations placed around the storage ring. Each calorimeter is composed of 54 lead-fluoride crystals where the positron showers produce Cherenkov light pulses read out by large-area silicon-photomultipliers (SiPM) arrays for a total of 1296 channels [3]. The SiPMs work in avalanche mode and the segmentation of the calorimeters allows to reduce pileup effects. A specially designed electronics allows not

Table I. – *Summary of the main contributions to the systematic error on* ω_a.

Uncertainty source	E989 solution	Accuracy goal (ppb)	E821 (ppb) [4]
Gain stability	Laser calibration	20	120
Lost muons	Collimation	20	80
Pileup	Calorimeter segmentation	40	90
CBO	Beamline matching	30	50
E field	Trackers and simulation	30	50
Total	Quadrature sum	70	180

only to count positrons above a given threshold but also to measure the total deposited energy as a function of time with a resolution of a few percent [5].

As shown in table I, the largest contribution to the systematic error on ω_a comes from the SiPM gain stability. After injection, the muon decay is measured by the calorimeters for about ten muon lifetimes corresponding to $700\,\mu$s. Thus, over a 1 ms time frame, the instantaneous rate at the calorimeters changes by four orders of magnitude causing fast gain variations. On a longer timescale the gain changes mainly for temperature and bias voltage variations. In order to minimize the effect of these gain variations, a laser calibration system has been assembled, providing absolute calibration, gain correction and time synchronization for all the channels of the calorimeters [6]. Six lasers distribute light to all channels through a distribution chain composed of optical elements, *e.g.*, fibers, mirrors, beamsplitters and diffusers, in a stable and uniform way. Each laser is monitored by a "source" monitor while each distribution chain to any calorimeter is monitored by a "local" monitor. The laser system is designed to monitor gain variations of the order of 10^{-4} in the $700\,\mu$s window and at the permil level on a long timescale.

3. – State of the experiment

The experiment has been taking data since March 2018. By the shutdown in July 2018 the accumulated data set approaches twice that of E821, but much of the running involved varying conditions aimed to optimize data collection and explore potential systematics. We expect a new value for a_μ in 2019, after we are certain that the analysis is complete. In the next two years a statistics higher than E821 by a factor 21 will be acquired, in order to achieve, together with the reduced systematics, the planned accuracy.

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