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VIEW & PERSPECTIVE

Muon spinning its way to new physics

The first results from the Fermilab Muon g–2 Experiment shed lights on the mystery surrounding the magnetic anomaly of the muon. This could become a window into a new era of particle physics.

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When the muon was discovered almost 80 years ago [1], it turned the particle physics world upside-down. Until today, nobody knows "who ordered it?" as questioned by I. I. Rabi and what role this second generation elementary particle played in the formation of the known universe. More mysteries about the muon came one after another. About 20 years ago, precise measurement of muon magnetic properties, the magnetic anomaly a_μ, by the Muon g–2 Collaboration at Brookhaven National Laboratory (BNL) indicated a 2.2–2.7σ deviation with the Standard Model prediction at that time [2]. In 2020, while experimentalists were busy with the muon g–2 experiment at the Fermi National Laboratory (FNAL, a.k.a. Fermilab), a group of about 70 theorists have formed a consortium called the "theory initiative" and published an improved and up-to-date calculation of the magnetic anomaly [3]. With this recommended value of a_μ, the discrepancy has increased to 3.7σ. Recently the new and upgraded muon g–2 experiment at Fermilab [4] has confirmed the discrepancy and strengthens the significance to 4.2σ [5], using only 6% of the total expected data.

This longstanding and recently enhanced discrepancy between the experimental observations and the Standard Model (SM) predictions of the $(g\text{–}2)_\mu$ motivates many new physics explanations [6]. For example, a light neutral scalar S or gauge boson can enter into the triangle one-loop diagram of $(g\text{–}2)_\mu$ [7–11]. The new physics may also come from high scale physics models, such as supersymmetry models [12, 13], or vector-like fermions [14, 15] and two-Higgs doublet models [7, 16, 17]. Hadronic vacuum polarization contributions as simulated in Ref. [18] may possibly eliminate the new physics explanation, though this would conflict with the electroweak precision test [19, 20], which requires further independent high precision lattice QCD calculation.

The magnetic moment of an elementary particle associated with its intrinsic angular momentum (spin) is given by

$$\boldsymbol{\mu}_{\text{spin}} = g\frac{q}{2m}\boldsymbol{S}, \tag{1}$$

where g is the gyromagnetic ratio or simply g-factor and q and m are the charge and mass of the particle. $g = 2$ according to Dirac's prediction in 1928 [21] for an elementary "point-like" particle such as the electron. However, since the vacuum is filled with virtual particles that are constantly appearing and disappearing, the g-factor is modified by this quantum fluctuation. The magnetic anomaly a_μ is defined as the fraction deviation from Dirac's prediction of $g = 2$:

$$a_\mu = \frac{g_\mu - 2}{2}\,. \tag{2}$$

The first order correction from Quantum electrodynamics (QED) was performed by Schwinger in 1948 to be $\alpha/(2\pi)$ [22], which was followed shortly by the experimental confirmation from Kusch and Foley in the same year [23]. Higher order QED corrections up to tenth-order [3, 24] and contributions from electroweak [3, 25] and Quantum chromodynamics (QCD) hadronic interactions [3, 26, 27] were all calculated to high precision.

The first measurement of the muon g-factor was performed by the Columbia Nevis group in the 1950s to investigate the parity violation of weak muon decay [28]. After an improved experiment several years later, a novel storage ring approach was employed by CERN in the 1970s resulting in a big improvement in the measurement precision [29]. This approach was inherited by the BNL's muon g–2 experiment [2].

The muon g–2 experiment at Fermilab adapts the storage ring technique deployed at CERN and BNL, which involves injecting and storing a spin-polarized muon beam into a magnetic storage ring with weak focusing. The a_μ measurement is made by observing the spin precession frequency $\boldsymbol{\omega}_s$ relative to the cyclotron frequency $\boldsymbol{\omega}_c$ for muons orbiting in a super-conducting magnetic storage ring with a highly uniform magnetic field $\boldsymbol{B}$,

$$\boldsymbol{\omega}_a = \boldsymbol{\omega}_s - \boldsymbol{\omega}_c = -a_\mu\frac{q\boldsymbol{B}}{m_\mu}. \tag{3}$$

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Therefore, precise measurement of a_μ requires high-precision knowledge of the ω_a frequency and magnetic field $\boldsymbol{B}$. The ω_a frequency is encoded in the time and energy distribution of decay positrons (or electrons) due to the parity violation of the weak decay of muons. The energy and time spectra of decay products is measured by 24 calorimeters, which are positioned evenly around the inner radius of the storage ring. Each calorimeter station is tucked into a notch of the scalloped vacuum chamber system. The magnetic field is measured by the nuclear magnetic resonance (NMR) technique where hundreds of NMR probes are placed around the storage ring and in a trolley inside the ring to monitor and map the field in and around the storage region. All probes have been cross-calibrated and a dedicated probe is used for the absolute calibration. The muon beam distribution in the storage ring is measured using in-vacuum straw trackers by extrapolating tracks of decayed particles. The measured magnetic field and muon beam distribution are then convolved to produce the magnetic field experienced by the muon during the measurement period.

The Fermilab experiment was fully commissioned in Summer 2017 and the first physics run (Run 1) was completed in Summer 2018. Analyses of Run 1 were completed in Feburary 2021 followed by the “unblinding procedure” to unravel the value of a_μ. The Run 1 result [5] has a 3.3σ deviation with Theory Initiative’s published value [3]. The discrepancy increases to 4.2σ after combining with the previous BNL result. The next round of analysis is currently ongoing with the data from both Run 2 and Run 3, which amounts to about 3 times of Run 1 data. Together with other improvements, the total uncertainty is expected to shrink by half. The improved results are expected to be published in Summer 2022. Also Run 4 data taking is well underway and Run 5 is on schedule to begin in Fall 2021. The overall muon g–2 experiment at Fermilab is expected to have a statistical uncertainty of about 100 ppb and a total uncertainty of about 140 ppb. If the central values of the experimental measurement and theoretical prediction remain the same, the significance of the discrepancy will reach 5σ.

Besides the Muon g–2 Experiment at Fermilab, J-PARC E34 Experiment [30] in Japan also plans to provide an independent measurement of a_μ with a new approach in terms of muon beam line, storage ring condition and positron detection. Instead of using the typical 3.094 GeV/c (“magic momentum”) muon, J-PARC experiment utilizes a low-emittance 300 MeV/c anti-muon beam, produced by re-acceleration of thermal surface anti-muons from the laser resonant ionization of muonium atoms emitted from a silica aerogel. The anti-muon beam can be stored in a 3.0 T magnetic storage ring 20 times smaller than the Fermilab storage ring. The energy or momentum of the decay positrons can then be reconstructed using 40 radially arranged silicon strip sensors. Phase-I of the J-PARC Experiment is expected to begin in 2025 and have a precision goal of about 0.5 ppm, similar to the BNL experiment results.

In addition to the magnetic anomaly measurement, the Fermilab experiment will also search for the muon electric dipole moment (EDM) [31] by measuring the tilt of the muon g–2 precession plane. The current limit on the muon EDM is $|d_\mu| < 1.8 \times 10^{-19} e$ cm (95% C.L.) set by the previous BNL measurement [32]. The sensitivity of the new measurement is expected to increase by 100 times to be in the order of $10^{-21} e$ cm. This measurement will give a unqiue opportunity to look for new anomalies in the muon sector and provide complementary information searching for new physics. Other physics topics that can be studied are the Lorentz-symmetry test and CPT-symmetry test [33, 34]. The CPT-symmetry test can be performed by comparing the a_μ for μ^+ and μ^-, and the latter involved switching the polarity of magnets and electric quadrupoles along the beamline and storage ring currently tuned for μ^+ runs. The Lorentz symmetry can be tested by searching for a sidereal variation in the anomalous precession frequency of both μ^+ and μ^-.

To conclude, the first result from the Fermilab muon g–2 experiment has strengthen the evidence of BSM physics. Together with other flavor anomalies in meson decays, we could be on the verge of a ground-breaking discovery which will turn particle physics world upside-down for the second time within a century.

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