STATUS OF THE BNL MUON $(g-2)$ EXPERIMENT

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The muon $(g-2)$ experiment at Brookhaven is completing a 3-month run for checkout and initial data-taking. The main components of the experiment, which include the pion beam line, the superconducting inflector, the superferric storage ring with its pulsed electric quadrupoles and magnetic field measurement system, and the detector system based on lead-scintillating fiber electron calorimeters, have been satisfactorily commissioned. The muon $(g-2)$ precession frequency is clearly seen as a large signal. At present over $\sim 20 \times 10^6$ decay positrons with energies greater than 1.3 GeV have been detected. Considerable additional data are expected before the end of our beam time this July.

1 Introduction

For the electron the anomalous g factor

$$a_e = \frac{(g-2)_e}{2} \qquad (1)$$

arises entirely from virtual photons and electron-positron pairs at the presently measurable level of 4 ppb.[1] The agreement between experimental and theoretical values of a_e, which is limited by the accuracy of about 25 ppb with which the fine structure constant α is known, provides one of the most decisive tests of pure QED.[2]

For the muon, the relative contributions to a_μ of heavier particles or new contact interactions are much larger than for the electron because they usually scale as $(m_\mu/m_e)^2 \simeq 4 \times 10^4$. Hence the most recent CERN measurement [3] of a_μ with a precision of 7 ppm observed the contribution from virtual hadrons of $a_\mu^{had} \simeq 60$ ppm.

The goal of the new BNL muon $g-2$ experiment is to measure a_μ to 0.35 ppm, a factor 20 improvement over the CERN experiment. With this precision the electroweak contribution[4] of 1.3 ppm, which arises from virtual processes involving the Z and W vector bosons, should be observed. In addition, a sensitive and powerful test for contributions beyond the standard model will be provided, especially for μ and W substructure or anomalous couplings, but also for supersymme-

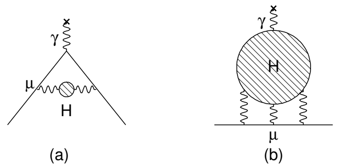

Figure 1: (a) The lowest order hadronic contribution to a_μ. (b) The hadronic light-by-light contribution.

try and leptoquarks, or indeed for almost any proposed modification of the standard model.[4,5,6,7,8]

2 Hadronic and Weak Contributions

The hadronic contribution to a_μ cannot in present practice be calculated from first principles of QCD. However, using dispersion theory the lowest order term in a_μ^{had}, which is shown in Fig. 1a, and also the next order term except for Fig. 1b, can be expressed in terms of $R(s) = (\sigma_{tot}(e^+e^- \rightarrow hadrons))/(\sigma_{tot}(e^+e^- \rightarrow \mu^+\mu^-))$. Present experimental knowledge of R ,[9,10] including recent data from τ decay,[11] determine that $a_\mu^{had}(tot) = 6\ 828(98) \times 10^{-11}$ or (59.0 ± 0.84) ppm of a_μ. The higher order hadronic contributions [12] (excluding the contribution from Fig. 1b) is $-101(6) \times 10^{-11}$. The contribution of the light-by-light scattering diagram of Fig. 1b has recently been estimated to be $a_\mu^{had} = -92(32) \times 10^{-11}$ or (0.79 ± 0.27) ppm of a_μ.[4,13] The uncertainty on this contribution should be reduced when additional calculations have been completed.[14] Further measurements of R are expected from the CMD2 detector in the e^+e^- collider at Novosibirsk with $E_{cm}(max) = 1.4$ GeV, from the ϕ factory at Frascati, and from the Beijing e^+e^- collider in the energy region above and below the J/ψ energy.

The electroweak contribution to a_μ arises in lowest order from the diagrams shown in Figs. 2a and 2b, and was calculated in the early 1970's. Higher order contributions involving electroweak radiative corrections are shown in Figs. 2c, 2d and 2e. The first order weak contribution of $195(4) \times 10^{-11}$ is reduced to $151(4) \times 10^{-11}$ (1.3 ppm of a_μ) when the second order terms are included.[15,16,17]

The full theoretical value from the standard model is :

$$a_\mu = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak} \tag{2}$$

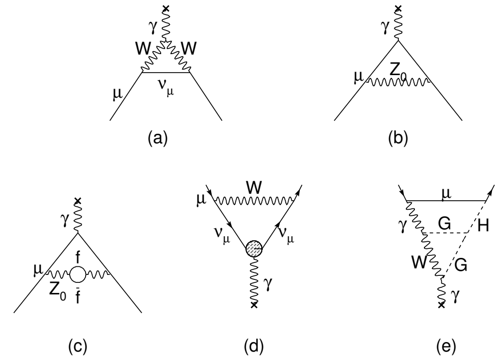

Figure 2: Weak contributions to the muon anomalous g factor. Single-loop contributions from (a) virtual W and (b) virtual Z gauge bosons. These two contributions enter with opposite sign, and there is a partial cancellation. The two-loop contributions fall into three categories. An example of each category is given. (c) Fermionic loops which involve the coupling of the gauge bosons to quarks; (d) Bosonic loops which appear as corrections to the one-loop diagrams; and (e) A new class of diagrams where G is the longitudinal component of the gauge bosons.

$$\begin{aligned} &= 116\ 584\ 705.7(1.9)\times 10^{-11}\,(\pm 0.016 \text{ ppm}) \\ &\quad +6\ 828(98)\times 10^{-11}\,(\pm 0.84 \text{ ppm}) \\ &\quad + \quad 151(4)\times 10^{-11}\,(\pm 0.03 \text{ ppm}) \\ &= (116\ 591\ 685 \pm 97)\times 10^{-11}\,(\pm 0.84 \text{ ppm}). \end{aligned}$$

The theoretical error of ± 0.84 ppm is due dominantly to the uncertainty of a_μ^{had}. This uncertainty will be reduced substantially when the new data from Novosibirsk are analyzed. New data from Frascati and from Beijing will further reduce the uncertainty.

3 The Brookhaven Experiment

A new experiment to measure the anomalous g factor of the muon more precisely has been constructed at Brookhaven National Laboratory. First exploratory data were taken in June and July 1997.

The principle of the measurement is the same as the third CERN experiment.[3] Polarized muons are stored in a uniform dipole magnetic field with electrostatic quadrupoles providing weak vertical focussing. The muon spin precesses relative to the momentum vector with the frequency

$$\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma_\mu^2 - 1}\right)\vec{\beta}\times\vec{E}\right], \quad (3)$$

assuming that the electric dipole moment of the muon is zero. The dependence of ω_a on the electric field can be eliminated by storing muons with the "magic" γ_μ=29.3, corresponding to a muon momentum $p_\mu = 3.094$ GeV/c. In this ideal case $a_\mu - 1/(\gamma_\mu^2 - 1) = 0$, and the focussing electric field does not affect the spin precession frequency which then depends only on the average magnetic field seen by the muons. In practice there is a small electric field correction to ω_a at the $\leq$1 ppm level since not all muons are precisely at the magic momentum, and a pitch correction at a similar level is introduced because of oscillations of the muon orbits induced by the vertical focussing. The dimensionless a_μ is extracted from ω_a through

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p} \quad (4)$$

where ω_p is the free proton precession frequency in the same magnetic field seen by the muons. The ratio of muon to proton magnetic moments, μ_μ/μ_p, is currently known to 0.30 ppm from the Zeeman effect in muonium and μSR, and to 0.15 ppm from the hyperfine structure interval in muonium,[18,19] and will be improved by a recent experiment.[20]

The source of the stored muons is the AGS proton beam, which delivers eight bunches with a total of $\approx 40\times 10^{12}$ protons at 24 GeV/c onto a nickel production target. The cycle of eight bunches is repeated every 2.6 s, with the individual bunches having a $\sigma = 27$ ns and spaced apart by 33 ms.

From each bunch roughly 4×10^7 pions at $\approx$ 3.1 GeV/c are transported from the production target along a 116 m beam line, then through a hole in the back of the storage ring magnet yoke. After passing through a superconducting inflector magnet [21] the pion beam enters the toroidal storage region which has a radius of 7.112 m and a 9 cm diameter cross section.

From the pion decay, $\pi^+ \rightarrow \mu^+\nu_\mu$, a small fraction of muons are launched onto a stable orbit and are stored after pulsed electric quadrupoles and a set of collimators are used to scrape the muon beam to fit well inside the storage region and thus reduce losses at later times. The fast rotation structure of the muon beam at the cyclotron period of 149 ns has been observed.

The storage ring is a continuous superferric 'C' magnet with the open side facing inward, see Fig. 3. The storage ring field is excited by three superconducting coils which carry 5177 A current to reach the 1.4513 T central field. During this run, the field strength and changes in homogeneity are monitored by 366 NMR probes [22] spaced around the ring outside of the storage volume. In addition, the field inside the storage region is mapped several times every week using a trolley containing a matrix of 17 NMR probes which operates in vacuum inside the storage region. When integrated over azimuth the field in the storage region is uniform to about 25 ppm. The dipole field is stable to a few ppm/hour, with the field changes caused primarily by the thermal expansion and contraction of the iron yoke, which affects the magnet gap. In future years with direct muon injection, the requirements on the magnetic field homogeneity are more stringent, and shimming will resume after this run to achieve the design goal of 1 ppm homogeneity in the $\int \mathbf{B}\cdot d\mathbf{l}$.

The decay positrons from $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$, which constitute our signal, are detected with Pb-scintillating fiber calorimeters placed symmetrically at 24 positions around the inside of the storage ring. Because of the parity violating nature of the weak decay, the highest energy positrons are preferentially emitted along the muon spin direction. The muon spin precession is reflected in the decay positron spectrum, N(t), where we expect :

$$N(t) = N_0 e^{-t/\tau_\mu}\left[1 + A\cos\left(\omega_a t + \phi\right)\right]. \quad (5)$$

The asymmetry parameter, A, is energy dependent, and for a positron energy threshold of 1.8 GeV is ~ 0.4. The latter leads to a factor of $\sim \sqrt{2}$ improvement over CERN and is attributed to having improved energy resolution in the electromagnetic calorimeters and improved vacuum chamber design which results in less degradation of the positron energy from showering in the chamber walls.

The arrival times of the positrons are recorded in multi-hit TDCs, and the calorimeter pulses are also sampled by a custom 400 MHz waveform digitizer. An important experimental consideration is the necessity of reducing systematic early to late

Figure 3: A view of the $(g-2)$ storage ring and its detectors.

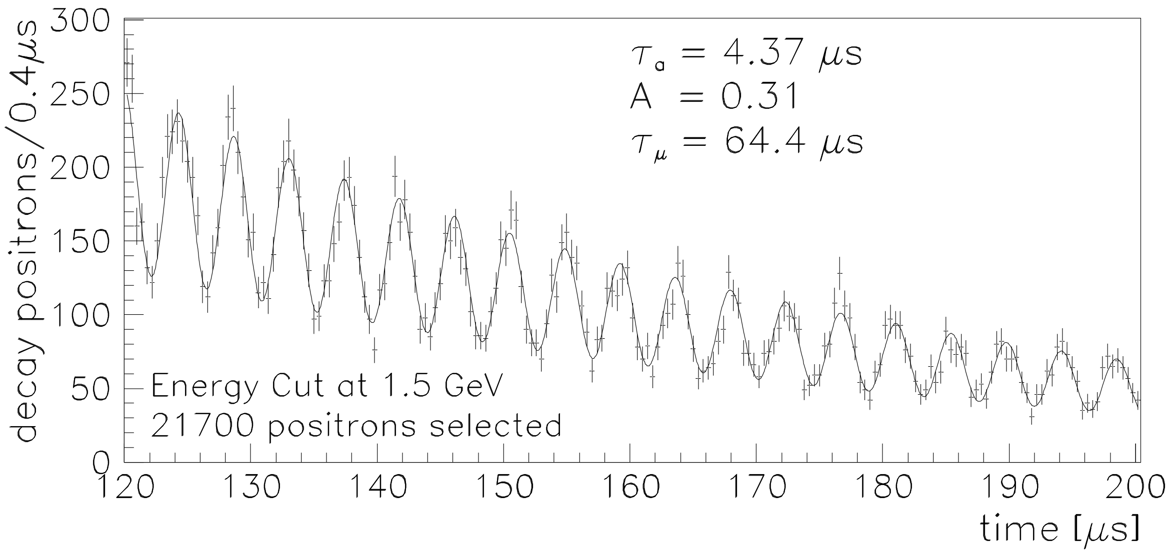

Figure 4: Time spectrum of the decay positrons from a typical run. The exponential muon decay is clearly modulated at the $(g-2)$ precession period, τ_a. The solid line represents a fit to the data.

shifts of the event times to the level of 20 ps over a period of 200 μs (muon decays are recorded for 640 μs). A laser and LED system are used to monitor such potential time shifts, as well as gain shifts. The principal difficulty is overcoming the effects of the 'flash' seen after pion injection. The calorimeter photomultiplier tubes must be gated off during this intense burst of light, and the recovery of the tubes involves possible changes in gain and pulse times (since the pulses sit on top of a residual, decaying DC light level).

In addition to the calorimeters, several detector stations are outfitted with an array of 20×32 small scintillating paddles connected to a multi-anode phototube, which will provide position sensitive information on the muon decay positrons. Additional spatial and temporal event information is derived from five stations each equipped with five scintillator paddles oriented horizontally. Finally, a sophisticated traceback chamber is in operation which allows the trajectories of the decay positrons to be traced back to their origin in the storage ring, with the objective of providing information on the stored muon phase space. The latter will be convoluted with the magnetic field to determine the average field seen by the muons.

After more than a decade in preparation, the collaboration is pleased to see for the first time at BNL the exponential muon decay, modulated by the $(g-2)$ precession which is shown in Figure 4. At present more than $\sim 20 \times 10^6$ positrons with energies greater than 1.3 GeV have been detected, corresponding to a statistical precision of $\sim 10^{-5}$ on a_μ. Systematic effects remain to be studied.

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