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STATUS OF THE NEW MUON $(g-2)$ EXPERIMENT[a]

MUON $(g-2)$ COLLABORATION[bc]
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The new muon $(g-2)$ experiment is now fully operational. The goal of the experiment is to obtain a relative error on $(g-2)$ of ±0.35 ppm to measure the electroweak contribution for the first time, and to observe, or place stringent limits on physics beyond the standard model which can contribute to $(g-2)$. A brief status report is presented.

1 Introduction

The anomalous magnetic moment of the muon, which was measured at CERN over twenty years ago,[1] has long served as a testing ground for standard model physics, and has also placed severe constraints on physics beyond the standard model.[2] A new experiment to measure the muon anomaly a factor of twenty more precisely than the CERN measurements has been underway at the Brookhaven AGS for over ten years.[3] A new 700 ton super-ferric storage ring provides a uniform magnetic field for muon storage and spin precession, and muon were stored in it for the first time in May 1997. Subsequent runs in 8/98 and 1-3/99 employed direct muon injection into the ring, which permitted a substantial improvement on the number of stored muons over the CERN technique of using pion decay inside the storage ring to store muons.

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2 The General Technique

The Brookhaven experiment uses the same technique used in the third CERN experiment, i.e. a storage ring operating at the "magic" γ. For polarized μ moving in a uniform magnetic field perpendicular to the muon spin direction and to the plane of the orbit, and with an electric quadrupole field $\vec{E}$ for vertical focusing,[4] the angular frequency difference, ω_a, between the spin precession frequency ω_s and the cyclotron frequency ω_c, is given by

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]. \tag{1}$$

The dependence of ω_a on the electric field is eliminated by storing muons with the "magic" γ_m=29.3, which corresponds to a muon momentum $p = 3.09$ GeV/c. Hence measurement of ω_a and of B determines a_μ. With γ_m and $B_0 =$ 1.45 T, the muon lifetime in the storage ring is 64.4 μs, the $(g-2)$ precession period is 4.37 μs, the central orbit radius is 7.112 m and the cyclotron period is 149 ns. Since only the central orbit in the storage ring is at the magic γ, it is necessary to make a small correction for the presence of the electric field.[1,4]

Experimentally one measures ω_a and B, and thereby obtains a_μ . Since we wish to limit systematics to $\simeq 0.1$ ppm it is necessary to know the field in the storage ring to this precision. Only NMR can provide a field measurement at this level, so the experiment includes a rather extensive NMR system. The field was monitored by 366 fixed NMR probes placed above and below the beam vacuum chamber.[5] In the first run, the field was allowed to drift, but in the second and third run, the average field measured by 50 of the probes was used to stabilize the magnet power supply. Periodically the field in the storage region was mapped in 1 cm steps by an NMR trolley, with 17 NMR probes, which operates in vacuum inside the beam vacuum chamber.

Once muons are stored, decay electrons above a minimum energy are detected with lead-scintillating fiber calorimeters.[6] Parity violation in the decay means that the highest energy decay positrons are preferentially emitted in the direction of the muon spin. As the spin precesses from forward to backward the number of high energy decay positrons oscillates with the frequency ω_a. The resulting positron time spectrum is an exponential decay modulated by the $(g-2)$ frequency. We aim for an overall accuracy of ± 0.35 ppm with the systematic errors at the level of ~ 0.1 ppm.

The AGS accelerates 6 proton bunches to 24 GeV/c and each bunch is kicked separately out of the AGS and onto a pion production target. The intensity is limited by target shock considerations to $\sim 7 \times 10^{12}$ protons per bunch.

Two methods of injection into the ring have been used. At CERN, and in our first run, a beam of π^+ of momentum 0.5% above the magic momentum were injected into the storage ring. As they cross the storage region, some small fraction ($\sim 25 \times 10^{-6}$) decay by $\pi^+ \to \mu^+ + \nu_\mu$ and launch the daughter muon onto a stable orbit. The rest of the beam strikes material in the ring and produces background (commonly called "the flash") which is seen by the electron calorimeters.

We have developed a fast muon kicker which permits direct injection of a muon beam into the storage ring. The beamline downstream of the pion production target is set to 1.7% above the magic momentum, and at the end of a 72 m straight section a muon beam of the magic momentum is selected. The undecayed pion beam is dumped well upstream of the storage ring, and a low intensity (4×10^5) μ^+ beam is brought into the storage ring.

The kicker consists of three identical 1.7 m long pairs of parallel plates inside the vacuum chamber through which a current pulse (peak = 4200 A) is passed. The 10 mrad kick needed is produced by currents (rather than by ferrite, etc.), and the design is such that eddy currents from the initial current pulse contribute less that 0.1 ppm to $\int \vec{B} \cdot d\vec{l}$ after 20 μs. Since the beam takes this long to de-bunch, analysis for $(g-2)$ does not begin until after the effects of the kicker field on the spin precession are negligible. Direct muon injection permits about an order of magnitude increase in muons stored per fill of the storage ring, with a flash reduction by a factor of ~ 100.

3 Results and Outlook

The results from our first run with pion injection, where we detected 11.3×10^6 positrons above 1.8 GeV, have recently been published.[3] The standard model value for a_μ is dominated by QED, but the strong interaction contributes at the level of about 60 ppm of a_μ, and the electroweak contribution is 1.3 ppm. The uncertainty on the hadronic contribution, which must be calculated using data from $e^+e^- \to$ hadrons and a dispersion relation, dominates the theoretical error.

The result reported recently was $a_{\mu^+} = 1\ 165\ 925(15) \times 10^{-9}$ which has a fractional uncertainty of ± 13 ppm;[3] comparable to the CERN measurements of a_μ for μ^+ and μ^-, which had errors of 10 and 11 ppm respectively. The new world average for a_μ is $a_\mu = 1\ 165\ 923.5(7.3) \times 10^{-9}$ (± 6.3 ppm). and

$$\text{Experiment} - \text{Theory} = (7.2 \pm 7.3) \times 10^{-9} \qquad (2)$$

We have now obtained substantially more data using direct muon injection. In a 3 week test run in August '98 we recorded 1.3×10^8 positrons, which implies a statistical error of ∼ ±4 ppm. In the 1999 production run we detected 2.8×10^9 positrons, which should give a statistical error $\leq \pm 1$ ppm. Figure 1 shows a sample of the data from 1999.

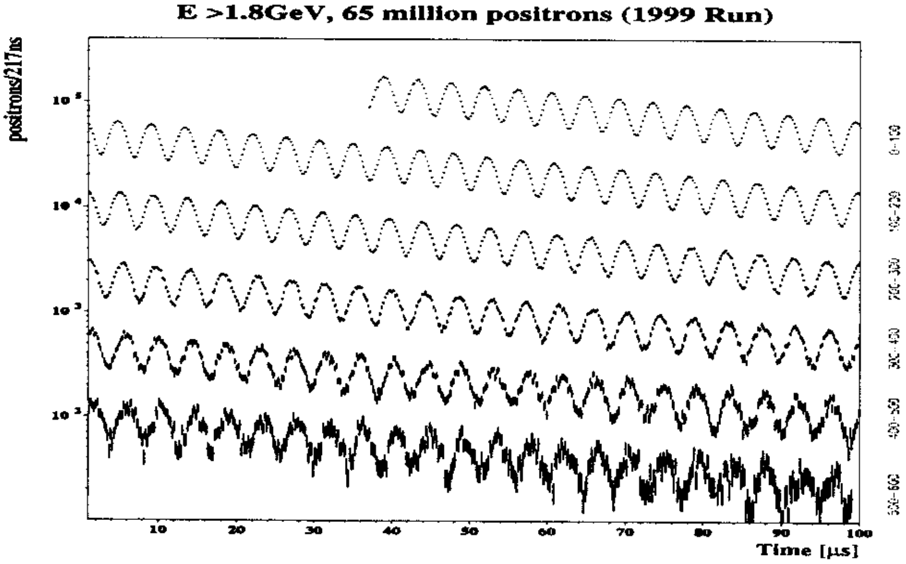

Figure 1: A sample of the 1999 data containing 65 M positrons. The numbers on the right give the time range after injection.

The largest systematic error comes from uncertainties in the average magnetic field seen by the muons, $< B >$. We expect that the total error from this uncertainty can be reduced to between 0.1 and 0.2 ppm. The shimming of the magnetic field continued up to the 1999 run, and the field uniformity over the storage region when integrated over azimuth is on the order of $\pm 2 ppm$. The uncertainty in our knowledge of $< B >$ in the 98-99 running should be on the order of ≤ 0.5 ppm. The uniform field makes the extracted value of a_μ less sensitive to our knowledge of the muon distribution when calculating $< B >$. At present, uncertainties in the knowledge of $< B >$ are dominated by the fringe field of the superconducting inflector magnet,[7] which is necessary to (almost) cancel the main field and to bring the beam to the edge of the storage region nearly undeflected. In spring 1999 we will replace the original inflector with an improved model which will permit us to reach our goal of ∼ 0.1 ppm knowledge of the field.

In addition to the measurement of a_μ, we will improve on the limit on the electric dipole moment of the muon by an order of magnitude, and also we will make an improved measurement of time dilation in the storage ring.

The active programs of $e^+e^- \to$ hadrons measurements underway at the Budker Institute in Novosibirsk and at Beijing should reduce the uncertainty on the hadronic contribution from its current uncertainty of ±0.8 ppm. When all the e^+e^- data and the hadronic τ-decay data from CLEO are available, the theoretical uncertainty should be reduced to around 0.4 ppm.

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