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

B.L. ROBERTS[a], D.H. BROWN[a], R.M. CAREY[a], W. EARLE[a], E. EFSTATHIADIS[a], E.S. HAZEN[a], B.J. HUGHES[a], F. KRIENEN[a], J.P. MILLER[a], J. OUYANG[a], O. RIND[a], L.R. SULAK[a], W.A. WORSTELL[a], J. BENANTE[b], H.N. BROWN[b], G. BUNCE[b], J. CULLEN[b], G.T. DANBY[b], C. GARDNER[b], J. GELLER[b], H. HSEUH[b], J.W. JACKSON[b], L. JIA[b], R. LARSEN[b], Y.Y. LEE[b], M. MAPES[b], W. MENG[b], .M. MORSE[b], C. PAI[b], I. POLK[b], R. PRIGL[b], S. RANKOWITZ[b], J. SANDBERG[b], Y.K. SEMERTZIDIS[b], R. SHUTT[b], L. SNYDSTRUP[b], A. SOUKAS[b], A. STILLMAN[b], T. TALLERICO[b], F. TOLDO[b], K. WOODLE[b], T. KINOSHITA[c], Y. ORLOV[c], D. WINN[d], J. GERHAEUSER[e], A. GROSSMANN[e], K. JUNGMANN[e], G. zu PUTLITZ[e], P. von WALTER[e], U. HAEBERLEN[f] P.T. DEBEVEC[g], W. DENINGER[g], D.W. HERTZOG[g], S. SEDYKH[g], D. URNER[g], P. CUSHMAN[h], S. GIRON[h], J. KINDEM[h], D. MAXAM[h], D. MILLER[h], C. TIMMERMANS[h], D. ZIMMERMAN[h], L.M. BARKOV[i], A. CHERTOVSKIKH[i], V.P. DRUZHININ[i], G.V. FEDOTOVICH[i], V.B. GOLUBEV[i], D.N. GRIGOREV[i], B.I. KHAZIN[i], E.A. KURAEV[i], Yu. MERZLIAKOV[i], N. RYSKULOV[i], S. SEREDNYAKOV[i], Yu.M. SHATUNOV[i], E. SOLODOV[i], K. ENDO[j], H. HIRABAYASHI[j], S. ICHII[j], S. KUROKAWA[j], Y. MIZUMACHI[j], T. SATO[j], A. YAMAMOTO[j], K. ISHIDA[k], S.K. DHAWAN[m], F.J.M. FARLEY[m], V.W. HUGHES[m], D. KAWALL[m], M. GROSSE-PERDEKAMP[m], S.I. REDIN[m]

[a] *Department of Physics, Boston University, Boston, MA 02215, USA,* [b] *Brookhaven National Laboratory, Upton, NY 11973, USA,* [c] *Newman Laboratory, Cornell University, Ithaca NY 14853, USA,* [d] *Fairfield University, Fairfield, CT 06430, USA,* [e] *Physicalisches Institut der Universität Heidelberg, 69120 Heidelberg, Germany,* [f] *MPI für Med. Forschung, D69120 Heidelberg, Germany,* [g] *Department of Physics, University of Illinois, Urbana, IL 61820, USA,* [h] *Department of Physics, University of Minnesota, Minneapolis, MN 55455, USA,* [i] *Budker Institute of Nuclear Physics, Novosibirsk, Russia,* [j] *KEK, Japan,* [k] *Riken, Japan,* [m] *Department of Physics, Yale University, New Haven, CT 06511, USA.*

The new muon $(g-2)$ experiment at Brookhaven will finish construction soon, and muons will be stored in the storage ring in early 1997. This experiment will measure the anomalous magnetic moment of the muon to a fractional precision of 0.35×10^{-6}, which will provide the first measurement of the contribution to $(g-2)$ by virtual W and Z gauge bosons, as well as placing new constraints on physics beyond the standard model. The physics motivation, the technique and the status of this experiment are reviewed.

1 Introduction

The measurement of g factors began in 1922 with the experiments of Stern and Gerlach. In the subsequent years we have learned much about the structure of particles, and the forces which affect them, from more refined measurements of their magnetic moments. The measurement of the electron anomalous moment,

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

to a precision of a few parts per billion[1] represents a technical tour de force, and the good agreement with the QED calculation[2] represents one of the most spectacular examples of agreement between theory and experiment in all of physics. To a measurable level, the anomalous moment of the electron arises entirely from virtual electrons and photons.

For the muon, the relative contribution of heavier objects to its anomalous moment scales as $(m_\mu/m_e)^2$, and the accuracy of the most recent CERN experiment[3] was adequate to observe contributions from virtual hadrons.

Since October of 1988, a new experiment to measure the muon anomaly at least a factor of 20 more precisely, and thereby observe the contributions of virtual W and Z gauge bosons, has been under construction at Brookhaven National Laboratory. A 14m diameter superferric storage ring has been constructed to store muons and precess their spins. The ring is a continuous "C" magnet with the open side facing inward. The continuous magnet yoke is made up of 30° sectors. We were

Table 1: Some Properties of the $(g-2)$ Storage Ring

Parameter	Value	Comments
(g-2) Frequency	$f_a \sim 0.23 \times 10^6/s$	$\omega_a = 2\pi f_a$ $\tau_a = 1/f_a = 4.37\mu s$
Muon Lifetime	$\gamma\tau = 64.4\mu s$	
Muon kinematics	$p_\mu = 3.094 Gev/c$ $\gamma_\mu = 29.3$	The Central Momentum = The Magic Momentum
Cyclotron Period	$\tau_{cyc} = 149ns$	
Central Radius	$\rho = 7112mm$	(280″)
Magnetic Field	$B = 1.4513$ T	
Storage Aperture	9.0*cm* circle	
Stored μ/fill ($6.3 \times 10^{12} pot$)	2,445 26,040	π^+ injection μ^+ injection
Initial Rate in One Detector	$\sim 0.45 \times 10^6$ $\sim 5.6 \times 10^6$	π injection μ injection
In one lifetime:	432 revolutions around ring 14.7 *(g-2)* periods	

able to keep the space between sectors to less than 0.5 mm, and to even less than that between the pole pieces, each of which covers 10°. The field is excited by three superconducting coils. The outer coil ($\rho = 7.412$m) has 48 turns. The superconductor is NiTi with ultra-pure aluminum as stabilizer (Topaz conductor) and carries 5,200 A current to reach the 1.45 T central field. Some properties of our storage ring are given in Table 1.

A pion or muon beam is injected into the storage ring through a hole in the backleg of the magnet yoke. It then enters a superconducting, iron-free, truncated double-cosine theta inflector magnet[4] which permits the beam to arrive at the edge of the storage region.

Two injection schemes will be employed in the experiment. Initially we will inject a pion beam and use the $\pi \rightarrow \mu\nu$ decay to provide the kick needed to place the muons on stable orbits. This has an injection efficiency of 26×10^{-6} per injected pion. After some initial running we will commission a fast muon kicker, which is anticipated to have an injection efficiency of 7% per injected muon. As is shown in Table 1, the number of muons stored is an order of magnitude greater with direct muon injection. The kicker field, and its associated eddy currents will be measured by the Faraday effect, and the field from the eddy currents is expected to be less than 0.1 ppm at 20 μs after the kicker fires.

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

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

With the appropriate choice of γ, the electric field does not change the relative orientation between the muon's spin and its momentum, hence the name "magic gamma". Thus the magnetic field can be a uniform dipole field, and the spin-precession frequency ω_a depends only on the average magnetic field (over the muon distribution) and the anomalous moment. In practice there is a small electric field correction since only muons with the central momentum are at the magic gamma.

The ring functions as a weak-focussing storage ring with a field index of 0.135. The magnetic field after full shimming will be uniform to 1×10^{-6} when integrated over azimuth. We will strive to make the absolute uniformity as close to the ppm level as possible, but the weak focussing nature of the ring makes us primarily sensitive to the integral, rather than the differential nonuniformities. The field is monitored by 300 fixed NMR probes, and each pole piece has a dipole correction coil behind it, which can be used to adjust the local dipole field in a feedback manner.

Iron wedges 10 cm wide in azimuth are placed in the air gap behind the pole pieces. The angle of the wedge compensates for the inherent quadrupole in a "C" magnet, and the dipole field can be adjusted over a modest range (±90 ppm) by moving the wedge radially. Pole face bumps (sometimes called Rose shims) adjust the higher multipoles. Finally, the average value of the higher multipoles will be adjusted with current windings on the pole pieces which go the full 360° around the ring with a 2.5 mm radial separation. The field can be mapped when desired by an NMR trolley containing a matrix of 25 probes, which travels through the vacuum chamber (in vacuum). During data collection, it is parked out of the way of the beam in a garage. Plunging NMR probes are used to cross calibrate with the trolley probes, as well as to make quick measurements of the field at a few points inside of the storage region.

Pb-scintillating-fiber calorimeters are placed symmetrically at 24 positions around the inside of the storage ring to detect the decay electrons from $\mu \rightarrow e\nu_\mu\bar{\nu}_e$. Because of the weak decay, the highest energy electrons are preferentially along the muon spin direction, and the integral asymmetry for an energy threshold of 1.8 GeV is ~ 0.4. Both the pulse-height (energy) and the arrival time of the decay electron are recorded for later analysis. In the time spectrum of the decay electrons, one observes the expected exponential muon decay, modulated by the $(g-2)$ frequency.

To control the systematic error from rate dependent effects during a single fill of the ring, the photomultiplier tubes, bases, and readout electronics have been developed to withstand a large dynamic range of rates, and to exhibit rate dependent shifts less than 10 ps. for rates from 5 MHz to 0 MHz.

2 Theory of a_μ

Recently there has been substantial theoretical interest in the muon anomalous moment. Within the framework of the standard model are effects such as second order weak corrections with fermionic loops,[8,10] second order weak bosonic corrections[9] and the hadronic light-on-light contribution.[15,16] Non-standard model calculations include such theories as supersymmetry[5] or leptoquarks,[7] and there are two non-standard model papers at this conference, presented by Krawczyk[11] (two Higgs doublet models) and Nath[12] (supergravity).

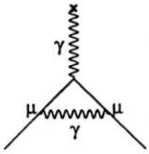

Figure 1: The Lowest Order Radiative Contribution to a_μ. The × indicates the virtual photon from the magnetic field.

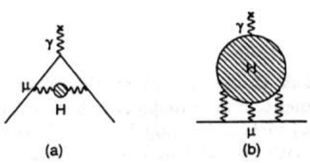

Figure 2: (a)The Lowest Order Hadronic Contribution to a_μ. (b) The Hadronic Light-on-Light Contribution. The × indicates the virtual photon from the magnetic field.

Pointlike fermions have g factors different from 2 because of virtual radiative corrections. The lowest order contribution to the anomalous moment is illustrated in Figure 1, and is equal to $\frac{\alpha}{2\pi}$. These calculations have now been extended to tenth order by Kinoshita.[2]

The large mass of the muon makes it possible for virtual hadrons to contribute through vacuum polarization at a measurable level to the muon anomaly. The lowest order hadronic contribution is shown in Figure 2(a). This hadronic contribution cannot be calculated from first principles but can be calculated using dispersion theory and data from $e^+e^- \rightarrow$ hadrons ("R" measurements). The total hadronic contribution is $a_\mu^{Had} = 6882(154) \times 10^{-11}$ (~ 60 ppm of a_μ), where the uncertainty comes from the errors on the experimental data which go into the dispersion integral. The two recent evaluations[13,14] agree that the current error from this contribution is ~ ±1.3 ppm. The latter authors estimate that this error can be reduced to (~ $\pm 59 \times 10^{-11}$) or ~ ±0.5 ppm after CMD2, the new Novosibirsk experiment, has fin-

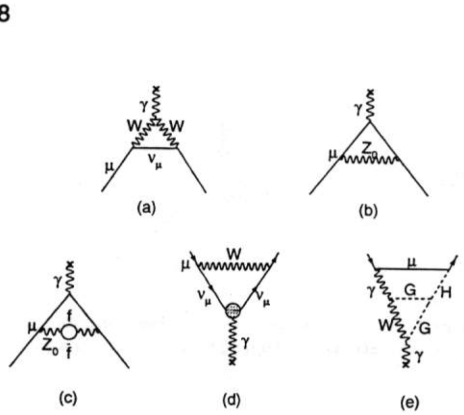

Figure 3: Weak Contributions to the Muon Anomalous Magnetic Moment. Single-loop contributions from (a) virtual W and (b) virtual Z gauge bosons. These two contributions enter with opposite sign, and there is a partial cancellation. The two-loop contributions fall into three categories. An example of 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. See Czarnecki, et al.[9] for details. The × indicates the virtual photon from the magnetic field.

ished the analysis of their data. For comparison, the goal of an error of ±0.35 ppm in a_μ translates to $\pm 40 \times 10^{-11}$.

Data collection for CMD2 should be completed in the next year, and the analysis of these data should become available over the next three years. At least a portion of these measurements will be repeated at the phi factory at Frascati. We learned at this conference[18] that the Beijing collaboration plans to carry out new measurements of R in the J/Ψ region, both above and below, going as low as $\sqrt{s} = 2.6$ GeV.

The theoretical limit seems to be set by the contribution from hadronic "light on light" (lol) scattering,[15] illustrated in Figure 2(b), a_μ^{Had}(lol) $= -52$ (18) $\times 10^{-11}$, which contributes an uncertainty of ±0.15 ppm to a_μ. This contribution cannot be estimated from data, but might be improved by a lattice QCD calculation.[17]

While calculations of the contribution to a_μ from single W and Z loops have been available for some time, (see Figure 3(a-b)) higher order calculations which include both fermionic[8,10](see Figure 3(c)) and bosonic[9] two-loop contributions,(see Figure 3(d-e)) obtain a higher order correction which turns out to be surprisingly large. 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. Since the ability to calculate loop diagrams is intimately tied to the renormalizability of the theory, this measurement will provide an important test of the renormalization prescription.

The total theoretical prediction is $a_\mu^{Theory} =$ 116 591 739 (154) $\times 10^{-11}$ where the theoretical error of ±1.3 ppm is dominated by the current uncertainty on the hadronic vacuum polarization. As mentioned above, this uncertainty will improve substantially when the new data from CMD2 are analyzed, and should improve further with the anticipated data from Beijing.

A number of nonstandard model contributions to $(g-2)$ are possible. The muon anomalous moment is very sensitive to W and μ substructure,[6] leptoquarks,[7] as well as supersymmetry,[5] especially those models with large $\tan\beta$. Muon substructure and W boson substructure are two non-standard model effects for which this experiment is most sensitive.[19,20] For example, for muon substructure $\Delta a_\mu \approx m_\mu^2/\Lambda^2$, where Λ is the length scale for substructure. The projected error on a_μ of $\sigma_{a_\mu} = \pm 40 \times 10^{-11}$, gives $\Lambda \approx 5$ TeV.

If the final result agrees with the standard model, it will place significant new limits on physics beyond the standard model.

We will measure both the μ^+ and μ^- magnetic moments which will provide a test of CPT (the CERN experiment[3] obtained values for these two which differed by over one σ.) We will also look for an up-down time variation in the decay electron spectrum, which would be the signal of an electric dipole moment contribution to the spin motion. We expect to improve the limit on the edm by an order of magnitude.

3 Progress on the Experiment

In 1996 many milestones were reached on the experiment. The primary proton line and the secondary pion/muon line were commissioned in spring 1996. The storage ring has reached full field and the first round of magnetic-field shimming will be completed in November 1996. The inflector magnet has been tested at full field and is being installed in the storage ring. The vacuum chamber installation will begin in November or early December, and the kicker assembly and installation will come next year. The detectors are built and many have been calibrated in the BNL test beam. The electronics are ready and have been shown to meet the stringent rate shift requirements listed above. The response of the detectors to beam injected into the storage ring was studied in May 1996.

We will store muons for the first time in March 1997, and will have a dedicated time for data collection in the late spring.

Acknowledgments

This work is supported in part by the U.S. Department of Energy, the U.S. National Science Foundation, the German Bundesminister für Bildung und Forschung, The Russian Ministry of Science and the US-Japan Agreement in High Energy Physics.

References

1. R. van Dyke et al. *Phys. Rev. Lett.* **59**, 26 (1987).
2. T. Kinoshita, *Phys. Rev. Lett.* **75**, 4728 (1995). A review of these calculations is given in T. Kinoshita, *Quantum Electrodynamics* (Directions in High Energy Physics, Vol. 7), ed. T. Kinoshita, (World Scientific, Singapore, 1990), p 218. These calculations are constantly being extended.
3. J. Bailey et al, *Nucl. Phys.* B **B150**, 1 (1979).
4. F. Krienen, D. Loomba and W. Meng, *Nucl. Instrum. Methods* A **283**, 5 (1989).
5. see for example J. Lopez, D. Nanopoulos, and X. Wang, *Phys. Rev.* D **49**, 366 (1994); U. Chattopadhyay and P. Nath, *Phys. Rev.* D **53**, 1648 (1996); T. Moroi PRD **53**, 6565 (1996).
6. S. Brodsky and S. Drell, *Phys. Rev.* D **22**, 2236 (1980).
7. G. Couture and H. Konig, *Phys. Rev.* D **53**, 555 (1996).
8. S. Peris, M. Perrottet, and E. de Rafael, *Phys. Lett.* B **355**, 523 (1995).
9. A. Czarnecki, B. Krause and W. Marciano, *Phys. Rev. Lett.* **76**, 3267 (1996).
10. A. Czarnecki, B. Krause and W.J. Marciano, *Phys. Rev.* D **52**, R2619 (1995).
11. Maria Krawczyk at this conference discussed two Higgs doublet models and their contributions to $(g-2)$.
12. Pran Nath at this conference discussed supergravity theories and their contribution to $(g-2)$.
13. S. Eidelman and F. Jegerlehner, *Z. Phys.* C **67**, 585 (1995);
14. D.H. Brown and W.A. Worstell *Phys. Rev.* D **54**, 3237 (1996).
15. M. Hayakawa, T. Kinoshita, and A. Sanda, *Phys. Rev. Lett.* **75**, 790 (1995); M. Hayakawa, T. Kinoshita, and A. Sanda, *Phys. Rev.* D **54**, 3137 (1996).
16. J. Bijnens, E. Pallante and J. Prades, *Phys. Rev. Lett.* **75**, 1447 (1995) and *Phys. Rev. Lett.* **75**, 3781 (1995).
17. T. Kinoshita, private communication.
18. J. Izen, private communication, and public comment in the Plenary session.
19. An overview of non-standard model physics is given by T. Kinoshita and W.J. Marciano in *Quantum Electrodynamics* (Directions in High Energy Physics, Vol. 7), ed. T. Kinoshita, (World Scientific, Singapore, 1990), p. 419.
20. P. Méry, S.E. Moubarik, M. Perrottet, F.M Renard, *Z. Phys.* C **46**, 229 (1990).