A NEW MEASUREMENT OF THE MUON MAGNETIC ANOMALY

K. Jungmann, H. N. Brown, G. Bunce, R. M. Carey, P. Cushman, G. T. Danby, P. T. Debevec, H. Deng, W. Denninger, S. K. Dhawan, V. P. Druzhinin, L. Duong, W. Earle, E. Efstatiadis, F. J. M. Farley, G. V. Fedotovich, S. Giron, F. Gray, M. Grosse-Perdekamp, A. Grossmann, U. Haeberlen, E. S. Hazen, D. W. Hertzog, V. W. Hughes, M. Iwasaki, D. Kawall, M. Kawamura, B. I. Khazin, J. Kindem, F. Krienen, I. Kronkvist, R. Larsen, Y. Y. Lee, I. Logashenko, R. McNabb, W. Meng, J.-L. Mi, J. P. Miller, W. M. Morse, D. Nikas, C. Onderwater, Y. Orlov, C. Ozben, C. Pai, J. Paley, C. Polly, J. Pretz, R. Prigl, G. zu Putlitz, S. I. Redin, O. Rind, B. L. Roberts, N. M. Ryskulov, S. Sedykh, Y. K. Semertzidis, Y. Shatunov, E. Solodov, M. Sossong, A. Steinmetz, L. R. Sulak, C. Timmermans, A. Trofimov, D. Urner, P. V. Walter, D. Warburton, D. Winn, A. Yamamoto, D. Zimmerman

Boston University; Brookhaven National Laboratory; Budker Institute of Nuclear Physics, Novosibirsk; Cornell University; Fairfield University; University of Heidelberg; MPI f. Med. Forsch., Heidelberg; University of Illinois; KEK; University of Minnesota; Tokyo Institute of Technology; Yale University

ABSTRACT

The muon magnetic anomaly may contain contributions from physics beyond the standard model. At the Brookhaven National Laboratory (BNL) a precision experiment aims for a measurement of the muon magnetic anomaly \( a_\mu \) to 0.35 ppm, where conclusions about various theoretical approaches beyond standard theory can be expected. The difference between the spin precession and cyclotron frequencies is measured in a magnetic storage ring with highly homogeneous field. Data taking is in progress and part of all recorded data has been analyzed. Combining all experimental results to date yields preliminarily \( a_\mu (expt) = 1 165 921(5) \cdot 10^{-9} \) (4 ppm) in agreement with standard theory.

1 Physics Motivation

The magnetic anomaly of fermions \( a = \frac{1}{2} \cdot (g - 2) \) describes the deviation of their magnetic g-factor from the value 2 predicted in the Dirac theory. This
quantity has been measured for single electrons and positrons in Penning traps by Dehmelt and his coworkers to 10 ppb \(1\). Accurate calculations for \(\alpha\) of these two particles are possible to this level, which involve exclusively the "pure" Quantum Electrodynamics (QED) of electron, positron and photon fields. The presently most accurate value for the fine structure constant \(\alpha\) \(2\) can be obtained from a comparison between experiment and theory, where it appears as an expansion coefficient. The high accuracy, to which QED calculations can be performed, is demonstrated by the compatibility of this value of \(\alpha\) and the ones obtained in measurements based on the quantum Hall effect \(3\) or the number extracted from the precisely known Rydberg constant using an accurate determination of the neutron de Broglie wavelength and relevant mass ratios. Moreover, the agreement of \(\alpha\) values determined from the electron magnetic anomaly and from the hyperfine splitting in the muonium atom \(4\) may be interpreted as the most precise reassurance of the internal consistency of QED, because the first case involves the theory of free particles whereas in the second case distinctively different bound state approaches need to be applied \(5\).

The anomalous magnetic moment of the muon \(a_\mu\) is more sensitive by a factor of \((m_\mu/m_e)^2 \approx 4 \cdot 10^4\) to heavier particles, which appear virtually in loop graphs, and other than electromagnetic interactions. Such effects can be studied in a precise determination of \(a_\mu\), because very high confidence in the validity of calculations of the dominating QED contribution arises from the excellent description of the electron magnetic anomaly and electromagnetic transitions in fundamental systems like, e.g. hydrogen and muonium atoms \(6\).

In a series of three experiments at CERN \(7\) \(a_\mu\) could be measured to 7.2 ppm. This has verified the muons nature as a heavy leptonic particle and the proper description of its electromagnetic interactions to very high accuracy by QED. In the last of these measurements contributions arising from strong interactions, which amount to 57.8(7) ppm \(8\), could be verified. At BNL a new dedicated experiment has been designed to determine the muon magnetic anomaly \(a_\mu\) with 0.35 ppm relative accuracy, meaning a 20 fold improvement over the previous approaches. At this level exists particular sensitivity to contributions arising from weak interaction through loop diagrams with W and Z bosons (1.3 ppm) \(9\). The experiment promises here a clean test of renormalization in weak interaction. The muon magnetic anomaly may also contain contributions from new physics \(10\). A variety of speculative theories can be
tested which have been invented to extend the present standard model in or-
der to explain some of the features which are described but not fundamentally
understood yet. The spectrum of such theoretical models includes physics con-
cepts like muon substructure, new gauge bosons, supersymmetry, an anomalous
magnetic moment of the W boson, leptoquarks and violation of Lorentz and
CPT invariance. Here a precise measurement of $a_\mu$ can be complementary to
searches in high energy experiments and the sensitivity may even be higher.

2 The Brookhaven Muon g-2 Experiment

In the new experiment at the alternating gradient synchrotron (AGS) of BNL
polarized muons are stored in a magnetic storage ring with highly homogeneous
field $B$ and with weak electrostatic focussing. The difference $\omega_a$ of the spin
precession and the cyclotron frequencies,

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{e}{m_\mu c} B,$$

(1)
is measured, with $m_\mu$ the muon mass and $c$ the speed of light. Positrons
(electrons) from the weak decays $\mu^{\pm} \rightarrow e^{\pm} + 2\nu$ are observed. For relativistic
muons the influence of a static electric field vanishes \cite{11}, if $a_\mu = 1/(\gamma_\mu^2 - 1)$
which corresponds to $\gamma_\mu = 29.3$ and a muon momentum of $p = 3.09$ GeV/c,
where $\gamma_\mu = 1/\sqrt{1-(v_\mu/c)^2}$ and $v_\mu$ is the muon velocity. For sufficient accuracy
of the electric field correction the average muon momentum $p$ needs to be within
a few parts in $10^4$ of magic momentum.

For a homogeneous field the magnet must have iron flux return and shield-
ing. Because of the particular momentum requirement and in order to avoid
strong magnetic saturation effects of the iron a device of 7 m radius was built.
It has a C-shaped iron yoke cross section with the open side facing towards the
center of the ring. It provides 1.4513 T field in a 18 cm gap. The magnet is
energized by 4 superconducting coils carrying 5177 A current.

The magnetic field is determined by a newly developed narrow band mag-
netometer system which is based on pulsed nuclear magnetic resonance (NMR)
of protons in water and vaseline. It has a capability for an absolute mea-
surement to $\approx 50$ ppb. \cite{12}. The field and its homogeneity are continuously
monitored by 380 NMR probes. They are distributed around the ring and they
are embedded near the magnet poles in the walls of the Al vacuum tank. For
mapping the field inside the storage volume a trolley carrying 17 NMR probes is run in regular intervals, typically twice a week. This device contains a fully computerized magnetometer built entirely from nonferromagnetic components. The field accuracy is derived from and related to a precision measurement of the proton gyromagnetic ratio in a spherical water sample \( [13] \). On average the field around the ring is homogeneous to 1 ppm (Fig.1). This has been achieved using mechanical shimming methods which include movable iron wedges in an air gap between the low carbon steel pole pieces and the magnet yoke as well as iron strips of adjusted width fixed to the neighbourhood of junctions between poles. A set of 60 electrical coils, which run on the surface of the pole pieces around the ring and which can be driven at individually different currents, allows the compensation of other than dipole components of the field. The absolute value of the field integral in the storage region is known at present.
E >1.8GeV, 70 million positrons (1999 Run)

Figure 2: A sample of the recorded data. Positrons with an energy exceeding 1.8GeV as counted in the detector stations as a function of time after injection. Several regions in time have been folded onto one graph with the boundaries (in µs) mentioned to the right in each case. Time dilatation results in a 64.4 µs lifetime. No evidence for significant background is visible after 8 lifetimes.

to better than 0.5 ppm. There is a potential for a significant improvement in this figure. Field drifts are compensated using a set of 36 selected fixed NMR probes. Their average is kept within 0.1 ppm of the nominal value by regulating the main magnet power supply. To avoid large short term thermal effects, the magnet yoke has been dressed with passive thermal insulation material.

The weak muon focussing is provided by electrostatic quadrupole electrodes with 10 cm separation between opposite plates. They cover 43 % of the ring circumference. The electric field is applied by pulsing ±24.5 kV voltage for 1.4ms duration to minimize electron trapping and avoid electrical breakdown. The storage volume diameter is defined by circular apertures to 9 cm.

Due to parity violation in the weak muon decay process the positrons
(electrons) are emitted preferentially along (opposite) to the muon spin direction. This causes a time dependent variation of the spatial distribution of decay particles in the muon eigensystem which translates into a time dependent variation of the energy distribution in this experiment. Inside the ring the positrons(electrons) are observed in 24 shower detectors consisting of scintillating fibers embedded in lead. They have 13 radiation lengths thickness and an average resolution of $\sigma/E = 6.8\%$ at the nominal energy cut of $E = 1.8$ GeV which is applied in the analysis leading to the positron distribution shown in Fig. 2. All positron events are digitized individually in a custom waveform digitizer at 400 MHz rate and stored for analysis. The time standard of the detectors and the field measurement system is a single LORAN C receiver with better than $10^{-11}$ long term stability.

The technical improvements over previous experiments at CERN include an azimuthally symmetric iron construction for the magnet with superconducting coils, a larger gap and higher homogeneity of the field, segmented positron (electron) detectors covering a larger solid angle and improved electronics. A major advantage is the two orders of magnitude higher primary proton intensity available at the AGS Booster at BNL. Further conceptually novel features are the NMR trolley, a superconducting static inflector magnet and direct muon injection onto storage orbits by means of a magnetic kicker. Previously pions had been introduced into the ring some of which decayed into stored muons. The electrostatic quadrupoles at BNL have twice the field gradient compared to the CERN experiment and in addition the vacuum requirements are more relaxed due to a new design which minimizes electron trapping. The vacuum chamber is scalloped to avoid preshowering.

3 Present Status of results

By now data taking has been carried out for $\mu^+$ in two extended periods. In the startup phase of the experiment in 1997 pion injection was used. The efficiency of this process was below the theoretical expectation, which is $25 \cdot 10^{-6}$, resulting in $\approx 10^3$ stored muons per injection pulse (with $5 \cdot 10^{12}$ protons from the AGS on target). This method is accompanied by a significant flash in the detectors caused by hadronic interactions of unused pions. The impact of this effect was minimized by gated photomultiplier operation. The data were useful only after 22-75 $\mu$s, depending on the detector position. The
first result obtained in this way was $a_{\mu^+} = 1 \, 165 \, 925(15) \cdot 10^{-9} (13 \text{ ppm})$. 

Muon injection, which is employed regularly since 1998 with an efficiency of order 5%, gives about an order of magnitude more muons per injection pulse and largely reduces flash background. In addition, major improvements in the magnetic field homogeneity and stability were made and the detector efficiency was increased. A part of the new data ($\approx 4\%$) have already been completely analyzed and provides the preliminary value of $a_{\mu^+} = 1 \, 165 \, 919(6) \cdot 10^{-9} (5 \text{ ppm})$ where the uncertainty is dominated by statistics. Among the systematic errors the dominating contributions arise from positron pileup in the detectors, flashlets, i.e. the additional delivery of small bunches of protons after the AGS main pulse, and the field calibration. Combining all the measured values from CERN and BNL (Fig.3) yields $a_{\mu}(\text{expt}) = 1 \, 165 \, 921(5) \cdot 10^{-9} (4 \text{ ppm})$. This agrees with the latest theoretical value $a_{\mu}(\text{theor}) = 1\,165\,916\,287(77) \cdot 10^{-11} (0.66 \text{ ppm})$. The dominating error here arises from the knowledge of the hadronic part, which has been calculated using electron positron annihilation into hadrons and hadronic $\tau$-decays.

4 Perspectives

The data recorded up to now cover more than $2 \cdot 10^9$ decay positrons. This leads to an expected statistical uncertainty at the 1 ppm level. Further data taking is in progress, now with typically $40 \cdot 10^{12}$ protons per AGS cycle which provides 10 pulses. The systematic errors are expected to sum up to a few 0.1 ppm. In order for the new muon g-2 experiment to reach its 0.35 ppm design accuracy, besides $\omega_\alpha$ and the field also the muon mass respectively its magnetic moment needs to be known to 0.1 ppm or better (see eq.(1)). This has been achieved very recently by microwave spectroscopy of the Zeeman effect in the muonium atom ($\mu^+ e^-$) ground state hyperfine structure, resulting in a measurement of the ratio of the muon magnetic moment to the proton magnetic moment $\mu_\mu / \mu_p$ to 120 ppb. (A comparison of the simultaneously obtained muonium ground hyperfine interval with QED theory may be interpreted in terms of an even more precise value of this quantity at 30 ppb.)

In minimal supersymmetric models, as a particular example of relevant speculative models, a contribution to $a_\mu$ of

$$\Delta a_\mu(SUSY)/a_\mu \approx 1.25 \text{ ppm} \left( \frac{100 \text{ GeV/c}^2}{m} \right)^2 \cdot \tan \beta,$$

(2)
is expected, where \( \tilde{m} \) is the mass of the lightest supersymmetric particle and \( \tan \beta \) is the ratio of the vacuum expectation values for the two involved Higgs fields. At the projected accuracy for g-2, there is a sensitivity to large values of the latter parameter.

The experiment is planned for both \( \mu^+ \) and \( \mu^- \) as a test of CPT invariance. There is actual interest in view of the suggestion to compare tests of CPT invariance in different systems on a common basis, i.e. by using the energies of the states involved. For fermion magnetic anomalies particles with spin down in an external field need to be compared to their antiparticles with spin up. The nature of g-2 experiments is such that they provide a figure of merit \( r = |a^- - a^+| \cdot \frac{\hbar \omega}{m c^2} \) for a CPT test, where \( a^- \) and \( a^+ \) are respective...
magnetic anomalies, and \( m \) is the particle mass. For the past electron and positron measurements one has \( r_e \leq 1.2 \cdot 10^{-21} \) which is a much tighter bound than from the neutral kaon system, were the mass differences between \( K^0 \) and \( \bar{K}^0 \) yield \( r_K \leq 1 \cdot 10^{-18} \). An even more stringent CPT test arises therefore already from the past muon magnetic anomaly measurements were \( r_\mu \leq 3.5 \cdot 10^{-24} \). Hence, this may be viewed as the presently best known CPT test based on system energies. The BNL g-2 experiment allows to look forward to a 20 times more precise test of this fundamental symmetry.

According to the standard theory an elementary particle is not allowed to have a finite permanent electric dipole moment (edm) as this would violate CP and T symmetries, if CPT is assumed to be conserved. An edm of the muon would manifest itself in the g-2 experiment in a time dependent up down asymmetry of decay positrons which can be searched for along with the muon g-2 measurements. The BNL experiment is expected to provide one order of magnitude improvement over the present limit at \( 1.05 \cdot 10^{-18} \) cm. This is possible through proper segmentation of the detector packages. A further highly promising approach has been suggested as a dedicated follow on experiment. It is expected that based on the g-2 setup an experiment can be tailored to allow 5-6 orders of magnitude increase in sensitivity. It should be noted that a non standard model value of \( a_\mu \) would call for a muon edm search, as both quantities are intimately linked in many theories, where their sizes are connected through a CP violating phase \( \lambda \). Another possibility is using the magnet as spectrometer in which pion decays are observed for restricting the muon neutrino mass by a further factor of 20.

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References

1. R. Van Dyck, Jr., in *Quantum Electrodynamics*, ed. T. Kinoshita World Scientific, p. 322 (1990)
2. V.W. Hughes and T. Kinoshita, Rev. Mod. Phys. **71**, S133 (1999).

3. M. E. Cage et al., IEEE Trans. Instrum. Meas. **38**, 284 (1989); Th. Udem et al., Phys. Rev. Lett. **79**, 2646 (1997); E. Krüger et al., Metrologia **32**, 117 (1995); IEEE Trans. Instrum. Meas. **46**, 101 (1997); C. Caso et al, The European Physical Journal C3, 1 (1998)

4. W. Liu et al., Phys. Rev. Lett. **82**, 711 (1999)

5. T. Kinoshita and D.R. Yennie, in loc.cit. [1], p. 1 (1990)

6. M.G.Boshier et al., Comm. At. Mol. Phys. **33**, 17 (1996)

7. J. Bailey et al., Nucl. Phys. B**150**, 1 (1979); F.J.M. Farley and E. Piccasso, in *Quantum Electrodynamics*, ed. T. Kinoshita, World Scientific, Singapore p. 479 (1990)

8. M. Davier and A. Hoecker, Phys. Lett. **419**,419 (1998)

9. A. Czarnecki et al., Phys.Rev.Lett. **76**, 3267 (1996)

10. P. Mery et al., Z.Phys. C **46**, 229 (1990); J. Lopez et al., Phys.Rev. D **49**, 366 (1994); G. Couture and H. Konig, Phys. Rev D **53**, 555 (1996); U. Chattopathayay and P. Nath, Phys. Rev. D **53**, 1648 (1996); T. Moroi Phys. Rev. D **53**, 6565 (1996); F.M. Renard et al., Phys.Lett.B **409**, 398 (1997); W. Marciao, talk at HISMUS Workshop, Tsukuba (1999)

11. V. Bargmann, L. Michel and V. Telegdi, Phys.Rev.Lett. **2** 435 (1959)

12. R. Prigl et al., Nucl.Instr.Meth. A **304**, 349 (1996)

13. W.D. Phillips et al., Metrologia **13**, 81 (1977); X. Fei et al, Nucl.Instr.Meth. A **394**, 349 (1997)

14. R.M. Carey et al, Phys. Rev. Lett. 82 (1999) 1632

15. H. Dehmelt et al., **83**, 4694 (1999); Bluhm et al. Phys.Rev.D **57**, 3932 (1998)

16. Y. Semertzidis, in: Frontier Tests of QED and Physics of the Vacuum, E. ed. Zavattini et al., Y. Semertzidis et al., Letter of Intent to BNL-AGS (1997)