Status of muon (g-2) experiment at BNL

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The new muon (g–2) experiment is currently in progress at Brookhaven National Laboratory. In the first "check-up" run with pion injection in 1997 all apparatus was successfully commissioned and 12 million high energy decay positrons were detected. That allowed us to measure muon (g–2) value with accuracy 13 ppm (parts per million), which is comparable with accuracy of the most recent CERN experiment. Our result is in good agreement with both CERN result and current theoretical value. Implementation of direct muon injection in August 1998 significantly increased the rate of data taking and allowed us to collect 130 million positrons in 1998 run and well above 2 billions in 1999 run, which is enough to lower statistical error below 1 ppm. A number of improvements, especially in magnetic field quality, were done and some are in progress in order to lower systematic error to the desired level of ~ 0.1 ppm.

1. Introduction

The magnetic moment of a particle is related to its intrinsic spin via the gyromagnetic ratio:

$$\vec{\mu} = g\,\frac{e\hbar}{2mc}\,\vec{S}$$

For a lepton the Dirac theory predicts g = 2. A deviation from g = 2, $a = \frac{1}{2}$(g–2) arises from radiative corrections. Pure QED calculations for the muon (g–2) value were done to very high order [1]: $a_\mu(QED) = C_1(\alpha/\pi) + C_2(\alpha/\pi)^2 + C_3(\alpha/\pi)^3 + C_4(\alpha/\pi)^4 + C_5(\alpha/\pi)^5 = 116\ 584\ 706(2)\cdot 10^{-11}$, where $C_1 = 0.5$, $C_2 = 0.765\ 857\ 381(51)$, $C_3 = 24.050\ 531(40)$, $C_4 = 126.02(42)$ and $C_5 = 930(170)$.

The leading strong interaction correction to a_μ arises from hadronic vacuum polarization $(h.v.p)$ in the order of $(\alpha/\pi)^2$. This contribution can be evaluated from a dispersion relation using $e^+e^- \longrightarrow hadrons$ and hadronic τ–decay data and from perturbative QCD calculations for higher energy. Recent analysis gives $a_\mu(h.v.p, O(\alpha/\pi)^2) = 6951(75)\cdot 10^{-11}$ [2]. The next order hadron vacuum polarization terms also can be found using experimental data, though calculations are far more elaborate. That was done in [3] with a precision much better than the anticipated precision of BNL (g–2) experiment: $a_\mu(h.v.p,\ O(\alpha/\pi)^3) = -101(6)\cdot 10^{-11}$.

Another $O(\alpha/\pi)^3$ term, hadronic light–by–light scattering diagram, has been difficult to express in terms of experimentally accessible observables, and hence potentially it is a source of a serious problem. At present the hadronic light–by–light contribution was estimated within the framework of chiral perturbation theory and the $1/N_c$ expansion [4]: $a_\mu(hadronic\ light-by-light) = -79(15)\cdot 10^{-11}$. The total hadronic contribution is $a_\mu(hadronic) = 6771(77)\cdot 10^{-11}$.

The leading one–loop electroweak contribution to the muon (g–2) was calculated in early seventies. Two–loop contribution was calculated two decade later and found to be relatively big, leading to a reduction of $a_\mu(weak)$ by a factor of $1 - 97\alpha/\pi \approx 0.77$. The current value is $a_\mu(weak) = 151(4)\times 10^{-11}$ [5] , the error is due to uncertainties in the Higgs boson mass, quark 2–loop effects and possible 3–loop (or higher) electroweak contributions. The total theoretical value in the framework of the Standard Model is a sum $a_\mu(th) + a_\mu(QED) + a_\mu(hadronic) + a_\mu(weak)$,

$$a_\mu(th) = 116\,591\,628\ (77)\cdot 10^{-11}\ (0.66\ ppm).$$

The largest error for the Standard Model prediction comes from the first order hadronic vacuum polarization, 0.66 ppm. We expect this error to be reduced significantly in ongoing $e^+e^- \longrightarrow hadrons$ and τ–decay experiments in Novosibirsk, Beijing, Frascatti and Cornell.

Precision measurement of a_μ probes short–distance structure of the theory and hence provides stringent test of the Standard Model or, alternatively, search for New Physics beyond. Previous measurement of a_μ at CERN [6] confirms

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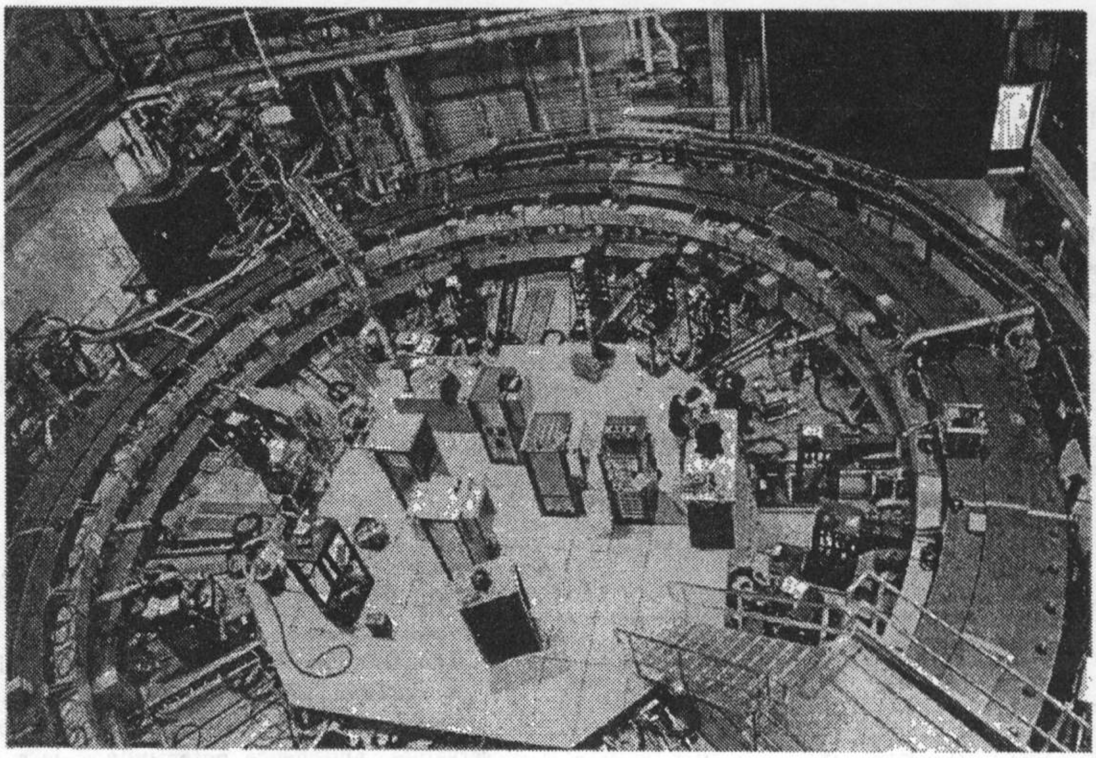

Figure 1. Muon storage ring at Brookhaven National Laboratory

theoretically predicted contributions from QED and strong interactions with experimental precision of 7.2 ppm. The goal of current BNL muon (g–2) experiment [7] is to lower experimental error to 0.35 ppm (a factor of ~20 improvement), which would allow us to see week interactions contribution at the level of 3–4 sigma.

The principle of the BNL experiment is based on the spin motion of polarized muons in a storage ring and is the same as that for the most recent CERN experiment [6]. In a uniform magnetic field B the spin precesses with an angular frequency ω_s which is greater than the orbital cyclotron frequency ω_c by ω_a, which is the (g–2) precession frequency:

$$\begin{aligned} \omega_a &= \omega_s - \omega_c = \\ &= \left[g\frac{eB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \right] - \frac{eB}{\gamma mc} = a_\mu \frac{eB}{mc}. \end{aligned}$$

In order to retain muons in the storage ring vertical focusing is provided by electrostatic quadrupoles. With both magnetic and electric fields present, the expression for ω_a becomes

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

For a special value of muon energy $E_\mu = 3.096$ GeV and $\gamma = 29.3$. the electric field does not contribute to $\vec{\omega}_a$. Choosing this "magic energy" allows us to separate the functions of the fields: the homogeneous magnetic field B determines the muon spin precession and electrostatic quadrupoles provide vertical focusing of the muon beam.

The (g–2) frequency ω_a appears as a modulation of the muon decay electron spectrum. Electrons from muon decay are detected with calorimeters and their times of arrival are accurately measured. An accurate determination of a_μ requires an accurate measurement of ω_a and of B.

The increased precision in our experiment is possible principally because of the high proton beam intensity of the AGS, which is about 200 times that available at CERN, where the dominant error was statistical. Our secondary beam line will provide either π or μ beams for injection into the storage ring. With π injection a fraction of the muons from π decays are captured in the storage ring; with μ injection a fast kicker is required to capture muons and a higher intensity of stored muons is expected.

The BNL (g–2) storage ring is shown in Fig. 1. Twenty four detector stations [8] detect decay electrons on the inside of the ring. They handle high rates and provide precise time measurements with systematic errors less than 20 ps. Each sta-

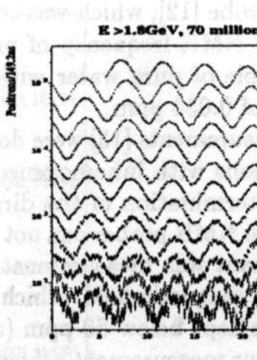

Figure 2. Time distribution of a sample of 70 million high energy decay positrons

tion consists of an electromagnetic calorimeter and a horizontal array of five scintillator paddles on the front face of the calorimeter. The calorimeters are made of scintillator fibers embedded in lead. The radiation length of the calorimeter is about 1 cm, energy resolution is $10-13\%/\sqrt{E(\mathrm{GeV})}$. Scintillator paddles provide additional time measurement and rough information about the vertical coordinate of the entrance point of the electron into the calorimeter and can be used to veto multi-electron events (pileup rejection).

With the pion injection most of pions collide with the vacuum chamber, which produces an intense flash in the detectors. Special PMT base was designed to turn off the PMT during the flash and then turn it on in several μsec after injection. Data are collected for a time interval of about 600 μsec. Fig. 2 shows typical time distribution of decay positrons.

3. Magnetic field shimming, measurement and control

The principal equipment for the experiment is the superferric storage ring. To achieve the desired precision we must know B averaged over the muon storage volume at the 0.1 ppm level. Hence the requirements on the field homogeneity and stability are very stringent.

The BNL (g–2) magnet provides a magnetic field of about 1.45 Tesla over the muon storage region, which is of toroidal shape with the radius of the central orbit being 711.2 cm (280 inches) and cross sectional diameter being 9 cm. The cross section of the muon storage ring is shown in Fig. 3. The magnet has a C-shape to allow decay electrons to be observed inside the ring. The field in the storage region is determined dominantly by the iron, i.e. its geometry, construction tolerances, temperature control, etc. The air gap between the pole pieces and the yoke serves to decouple the magnetic field in the storage region from that in the yoke.

The magnet is excited by four ring-shaped superconducting coils. That provides thermal stability, low power consumption, low resistance R and hence use of a low voltage well regulated (to 0.3%) power supply, high L/R and hence low ripple currents, thermal independence of the coils and the iron.

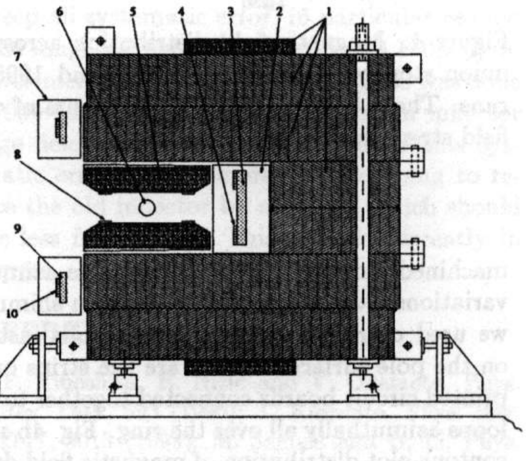

Figure 3. BNL (g–2) magnet: 1 – yoke plates, 2 – outer cryostat, 3 – outer mandrel, 4 – outer lower coil, 5 – pole, 6 – muon storage region, 7 – inner upper cryostat, 8 – Rose (edge) shim, 9 – inner lower mandrel, 10 – inner lower coil.

Magnetic field measured at the first powering of the magnet in 1996 varied peak-to-peak by up to 1400 ppm (0.14%) at different azimuthal locations in the ring and up to 300 ppm across the muon storage region. Several techniques [9] were used to shim the magnet to acceptable level of homogeneity of magnetic field. One of the most powerful technique was Rose (edge) shims. These are iron strips 5 cm wide on the edges of the poles surfaces. They are 10° long in azimuth, their thickness can be machined to correct the field. For the 1997 run the Rose shims were machined to the optimal value (with some margin), uniformly all over the ring. This allowed us to lower peak-to-peak variations of the field across the muon storage region (averaged azimuthally over the ring) to ∼ 25 ppm level, see Fig. 4a.

Number of further improvements were made after the 1997 run: the iron yoke was thermally insulated (wrapped) for better temperature stability of the magnetic field. Rose shims were

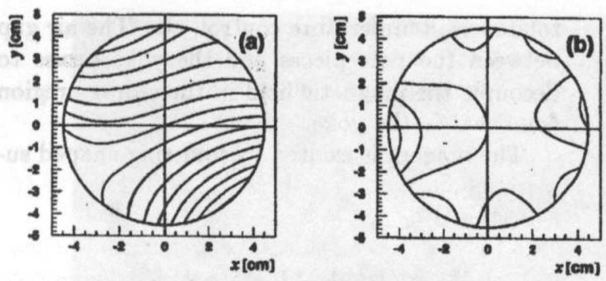

Figure 4. Magnetic field distribution across the muon storage region for 1997 (a) and 1998 (b) runs. The interval between the contours of equal field strength is 2 ppm.

machined individually to reduce large azimuthal variations, etc. Along with static iron shimming, we used current in the correction coils installed on the pole surfaces. These are the strips on the printed circuit boards connected together to form loops azimuthally all over the ring. Fig. 4b shows contour plot distribution of magnetic field during the 1998 run. The peak-to-peak variations were lowered to 5 ppm level.

To measure and control the magnetic field with 0.1 ppm accuracy, a pulsed NMR system has been developed [10]. The major part of the system is 17 NMR probes mounted on a beam tube trolley [11] and used for the magnetic field mapping during the data taking runs. The trolley is a vacuum–tight vessel with cylindrical shape and a length of 0.5 m, curved with the same radius as the storage ring. The trolley drive mechanism pulls the trolley along the ring with an electrical cable. The same cable is used for communication between the trolley and computer in the control room. The trolley rides on rails which help to form the desired electrical quadrupole field. During data taking the trolley is parked in its garage, located radially inward from the muon storage region. Both trolley drive and trolley garage are parts of the muon vacuum chamber, so field measurement with the beam tube trolley can be done without breaking the vacuum.

During the run the measurements with the beam tube trolley were taken every 24 to 72 hours. Each field map consists of about 6000 readings for each of the 17 NMR probes. Between these measurements the drift of magnetic field was monitored by the 366 fixed NMR probes embedded in the walls of the vacuum chamber in 72 azimuthal locations. Fixed probes are calibrated by beam tube trolley probes during each field mapping. At the end of the run the 17 trolley NMR probes were calibrated against a single calibration probe [10]. It was, in turn, calibrated with a standard NMR probe [12], which was constructed to measure the NMR frequency of protons in a spherical sample of pure water with a systematic uncertainty of 0.034 ppm.

A number of field measurements [13] were done with Hall probes in regions with inhomogeneous magnetic field or for determination of the direction of the field, i.e. when NMR probes can not be used. The most important was measurement of the radial component of magnetic field, which in this experiment must be kept below 50 ppm (averaged over the ring). Our measurement achieved an accuracy of 5–10 ppm, which was adequate for shimming and control of the radial field and which is one of the most precise measurements ever done with Hall probes.

4. Data taking runs

The first data taking run was done in 1997 with positive muons and pion injection. Started in late April, we had ~ 5 weeks in pulse–on–demand mode, primarily to check–up all systems, and then 6 weeks of dedicated run. The most severe problem we met at very beginning was the pion injection flash and related problems, particularly background from the secondary neutrons contamination. That costed us lost of statistics up to ~ 100 μsec after injection, additional load for the data acquisition system, distortion of the time distribution of decay positrons and as a result, the biggest contribution to systematic error.

Another background found later, was a leakage of particles from AGS (flashlets) due to wrong timing of AGS extraction magnet. Since AGS flashlets were practically indistinguishable from the decay positron events, we had to drop all data collected until when the extraction timing was fixed. As a result, only data collected in last two weeks of the run were used for further analysis.

Result of the 1997 run was published in [14]. In two week of running with pion injection we have collected 12 million decay positrons, which set statistical error in a_{μ^+} at 12.7 ppm, comparable with accuracy of CERN [6] experiment. Systematic error was 2.9 ppm and came mostly from issues related to the pion flash and magnetic field. Our result

$$a_{\mu^+}(BNL) = 116\,592\,500(1520) \times 10^{-11} \ (13.0\ ppm)$$

is in good agreement with both CERN measurement and theoretical value, see Fig. 5.

The next, August 1998 run was dedicated to commissioning of the muon kicker and implementation of the direct muon injection. The muon injection allowed us to increase significantly rate of decay positrons and to avoid injection flash and

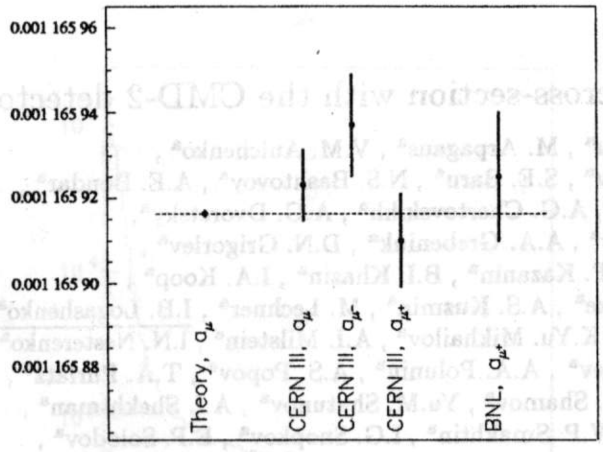

Figure 5. Muon $a_\mu = \frac{1}{2}(g-2)_\mu$ value, current status

related problems. In one week of useful data taking we have collected 130 million decay positrons, which is sufficient to get statistical accuracy at the level of 3–4 ppm. Analysis of the data is currently in progress. The main problem so far seems to be pulse overlapping due to high rate of events.

The full–scale run with muon injection was done in January–March 1999. Partially due to much tuning done in August 1998, this run was very smooth and successful. We had ~ 6 week of practically uninterrupted data taking and collected more than 2 billion positrons, which is sufficient to have statistical error below 1 ppm. In addition to regular magnetic field mapping during the run, special NMR trolley measurements were done at the end of the run in the region of the superconducting inflector [15], where field is not well uniform and regular measurements have missing points. That we believe will lower systematic error below 0.5 ppm.

At the end of the 1999 run extensive studies were done to double number of proton bunches in AGS from 6 to 12. The 12 bunch scheme allows to increase number of protons on the target per AGS cycle (and hence increase data rate) and same time decrease number of protons per bunch (and hence lower pulse overlap). A good progress was done in 1999 and we look forward to get 12 bunch scheme implemented by the next run.

5. Outlook

The BNL muon (g–2) experiment is in a very good shape. We have collected and currently are analyzing data, which are expected to provide measurement of a_μ with statistical error below 1 ppm and systematic error of order 0.5 ppm. We need another 4 month of running time in 2000 for positive muons and 6 month in 2001 for negative muons to complete this experiment. We believe this running time is sufficient for measurement a_{μ^+} and a_{μ^-} with accuracy 0.5 ppm each and combined a_μ (assuming CPT invariance) with accuracy 0.35 ppm, which is the final goal of our experiment.

In order to reach accuracy of 0.35 ppm, we have to keep all systematic error, in particular related to the magnetic field, at the level of 0.1–0.2 ppm. As was mentioned before, good progress was done in 1999 to lower systematic error from inflector fringe field to < 0.5 ppm. To reduce this systematic error further more, we are going to replace the old inflector by new one, which should have less fringe field. This work is currently in progress.

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