Improved Measurement of the Positive Muon Anomalous Magnetic Moment

Muon $(g-2)$ Collaboration
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(June 26, 2000)

A new measurement of the positive muon's anomalous magnetic moment has been made at the Brookhaven Alternating Gradient Synchrotron using the direct injection of polarized muons into the superferric storage ring. The angular frequency difference ω_a between the angular spin precession frequency ω_s and the angular orbital frequency ω_c is measured as well as the free proton NMR frequency ω_p. These determine $R = \omega_a/\omega_p = 3.707\ 201(19) \times 10^{-3}$. With $\mu_\mu/\mu_p = 3.183\ 345\ 39(10)$ this gives $a_{\mu^+} = 11\ 659\ 191(59) \times 10^{-10}$ (± 5 ppm), in good agreement with the previous CERN and BNL measurements for μ^+ and μ^-, and with the standard model prediction.
pacs 14.60.Ef

In this brief note we present a new measurement of the anomalous g-value $a_\mu = (g-2)/2$ of the positive muon from the Brookhaven Alternating Gradient Synchrotron (AGS) experiment E821. We previously reported a result based on data collected during 1997. [1] In that work, as in the CERN measurements, [2] pions were injected into the storage ring, and approximately 25 parts per million (ppm) of the daughter muons from pion decay were stored. In August 1998 a fast muon kicker was commissioned, which permitted the direct injection of muons into the storage ring.

Except for the use of muon injection, many of the experimental aspects are the same as described in reference [1]. However, important improvements were implemented. These included better stability and homogeneity of the storage ring magnetic field, improved stability of the positron detection system, and extended capacity of the data acquisition system. For the 1998 run, the AGS contained six proton bunches, each with a maximum intensity of about 7×10^{12}, with one bunch extracted every 33 ms. The 3.1 GeV/c positive muon beam was formed from decays of a secondary pion beam which was 1.7% higher in momentum, thus providing a muon polarization of about 95%. The pion decay channel consists of a 72 m long straight section of the secondary beamline. The muons were selected at a momentum slit, where the (higher energy) pions were directed into a beam dump. The beam composition entering the storage ring was measured with a threshold Cerenkov counter filled with isobutane. By stepping the pressure from zero to 1.2 atm, the threshold for Cerenkov light from e^+, then μ^+ and finally π^+ was crossed. The beam was found to consist of equal parts of positrons, muons and pions, consistent with Monte Carlo predictions. While this measurement was not sensitive to the proton content of the beam, calculations predict it to be approximately one third of the pion flux. The flux incident on the storage ring was typically 2×10^6 for each proton bunch.

The 10 mrad kick needed to put the muon beam onto a stable orbit was achieved with a peak current of 4100 A and a half period of 400 ns. Three pulse-forming networks powered three identical 1.7 m long one-loop kicker sections consisting of 95 mm high parallel plates on either side of the beam. The current pulse was formed by an under-damped LCR circuit. The kicker plate geometry and composition were chosen to minimize eddy currents. The residual eddy current effect on the total field seen by the muons was less than 0.1 ppm 20 μs after injection. The time-varying magnetic field from the eddy currents was calculated with the program OPERA [4] and was measured in a full-size straight prototype vacuum chamber with the use of the Faraday effect. [5] Since the muons circulate in 149 ns, they were kicked several times before the kicker pulse died out.

About 10^4 muons were stored in the ring per proton bunch. With muon injection, the number of detected positrons per hour was increased by an order of magnitude over the pion-injection method employed previously. Furthermore, the injection related background (flash) in the positron detectors was reduced by a factor of about 50, since most of the pions were removed from the beam before entering the storage ring.

For polarized muons moving in a uniform magnetic field $\vec{B}$ perpendicular to the muon spin direction and to the plane of the orbit and with an electric quadrupole field $\vec{E}$, which is used for vertical focusing [2], the angular frequency difference, ω_a, between the spin precession frequency ω_s and the cyclotron frequency ω_c, is given by

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

The dependence of ω_a on the electric field is eliminated by storing muons with the "magic" γ=29.3, which corresponds to a muon momentum $p = 3.09$ GeV/c. Hence measurement of ω_a and of B determines a_μ. At the magic gamma, the muon lifetime is $\gamma\tau = 64.4$ μs and the $(g-2)$ precession period is 4.37 μs. With a field of 1.45 T in our storage ring, [6] the central orbit radius is 7.11 m.

The magnetic field in Eq. 1 is the average over the muon distribution. We obtained the equilibrium radius distribution by determining the distribution of rotation frequencies in the ring from the time spectra of decay positrons. [1] The distribution, reproduced with a tracking code, was found to be 3 mm toward the outside of the central storage region. This offset was caused by the mode of operating the kicker. The calculated and measured radial distributions are shown in Fig. 1.

The magnetic field seen by the muon distribution was calculated by tracking a sample of muons in software through the field map measured by NMR, and by averaging the field values. The resulting average corresponds within 0.02 ppm to the field value taken at the beam center and averaged over azimuth. We used the latter to account for variations with time, and to obtain the present result.

Positrons from the in-flight decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ were detected with 24 Pb-scintillating fiber calorimeters [7] placed symmetrically around the inside of the storage ring. Twenty-one of these detectors were used in the present analysis. The observed positron time spectrum shown in Fig. 2 was adequately represented by [2,3]

$$N_0(E)e^{-t/\gamma\tau}[1 + A(E)cos(\omega_a t + \phi(E))]. \qquad (2)$$

The normalization constant N_0 depends on the energy threshold, E, placed upon the positrons. The (integral) asymmetry A depends on E and on the beam polarization. The fractional statistical error on ω_a is proportional to $A^{-1}N_e^{-1/2}$, where N_e is the number of decay positrons detected above threshold. For an energy threshold of 1.8 GeV where N_eA^2 is maximum, A was found to be 0.34 on average.

As in Ref. [1], the photomultiplier tubes were gated off before injection. With the reduced flash associated with muon injection, it was possible to begin counting as soon as 5 μs after injection in the region of the ring 270° around from the injection point, and 35 μs in the injection region. Data from the detectors gated on at 5 μs were used in the rotation frequency analysis mentioned above. The fit to Eq. 2 was begun after scraping [1] was completed and when the photomultiplier outputs from the 21 detectors used in this analysis were stable, 25-40 μs after injection. Time histograms were formed for each detector. These data were analyzed separately and the resulting values for ω_a were in good agreement ($\chi^2/\nu = 17.2/20$).

Values for ω_a and ω_p, the free proton NMR angular frequency in the storage-ring magnetic field, were determined separately and independently. Thereafter the frequency ratio $R = \omega_a/\omega_p$ was determined. A correction of +0.9 ppm was added to R to account for the effects [3] of the electric field and the muon vertical betatron oscillations on ω_a. We obtain $R = 3.707\ 201(19)\times 10^{-3}$, where the 5 ppm error includes a 1 ppm systematic error discussed below.

Since the 1997 run, a substantial reduction in the overall systematic error has been achieved. As regards ω_p, the stability of the magnetic field has been improved by thermal insulation of the magnet and by NMR feedback control to the main magnet power supply. The field homogeneity has been improved by additional shimming with iron shims near the intersections of pole pieces, and the surface coils around the ring on the pole faces have been used to compensate on average for the higher multipoles in the magnet. Additional shimming was also done using the iron wedges placed in the air gap separating the high quality low carbon pole piece steel from the yoke steel. This shimming produced a field which, when averaged over the azimuth, was uniform to within ± 4 ppm, as is shown in Fig. 3. The knowledge of the muon distribution in the ring obtained as indicated above allows us to determine the average field $< B >$ seen by the muons. The uncertainty in $< B >$ is ± 0.5 ppm.

The other systematic errors are associated with the determination of ω_a from the positron data. These arise principally from pile-up, and from AGS "flashlets". A pile-up error occurs when two pulses overlap within the time resolution of about 5 ns and are incorrectly identified as one, which then gives incorrect times and energies for the positrons. Pile-up is estimated to produce an effect on ω_a of less than 0.6 ppm, which we conservatively take as an error estimate. Occasionally under unstable conditions, the AGS was observed to extract beam during our data collection period of 600 μs which caused a background in our calorimeters ("flashlets"). We conservatively estimate that this effect on ω_a in the 1998 data sample is less than 0.5 ppm. Smaller errors arise from the details of the fitting procedure, rate dependent timing shifts, gain changes in the photomultipliers, uncertainties about the radial electric field and the vertical betatron motion, and from muon losses.

Altogether, the systematic errors on ω_a and ω_p added in quadrature are less than 1 ppm.

The anomalous magnetic moment is obtained from the frequency ratio R by

$$a_{\mu^+} = \frac{R}{\lambda - R} = 11\ 659\ 191(59) \times 10^{-10} \qquad (3)$$

in which $\lambda = \mu_\mu/\mu_p = 3.183\ 345\ 39(10)$ [8,9]. This new result is in good agreement with the mean of the CERN measurements for a_{μ^+} and a_{μ^-} [3,8], and our previous measurement of a_{μ^+} [1]. Assuming CPT symmetry, the weighted mean of the four measurements gives a new world average of

$$a_\mu = 11\ 659\ 205(46) \times 10^{-10} \qquad (\pm 4\ \text{ppm}), \qquad (4)$$

$(\chi^2/\nu = 2.7/3)$.

The theoretical value of a_μ in the standard model has its dominant contribution from quantum electrodynamics but the strong and weak interactions contribute as well. The standard model value is $a_\mu(\text{SM}) = 11\,659\,163(8)\times 10^{-10}$ (± 0.7 ppm), where the error is dominated by the uncertainty in the lowest order hadronic vacuum polarization. [10]

In Fig. 4 the four precise measurements of a_μ and their average are shown, along with the standard model prediction. The weighted mean of the experimental results agrees with the standard model, with

$$a_\mu(\text{Expt.}) - a_\mu(\text{Theory}) = (42 \pm 47) \times 10^{-10} \qquad (5)$$

or equivalently (3.6 ± 4.0) ppm. This agreement of theory and experiment further constrains new physics beyond the standard model. [11,12]

Data collected in early 1999 should give a statistical error of about 1 ppm, with a systematic error below 1 ppm. There is substantial activity at the e^+e^- colliders of Novosibirsk [13] and Beijing, [14] to measure $\sigma(e^+e^- \to \text{hadrons})$, and these new data will further improve our knowledge of the hadronic contribution and thereby the standard model value of a_μ.

We thank D.I. Lowenstein, P. Pile and the staff of the BNL AGS for the strong support they have given this experiment. We also thank C. Coulsey, G. De Santi and J. Sinacore, for their contributions to the preparation and running of the experiment. This work was 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. A. Steinmetz acknowledges support by the Alexander von Humboldt Foundation.

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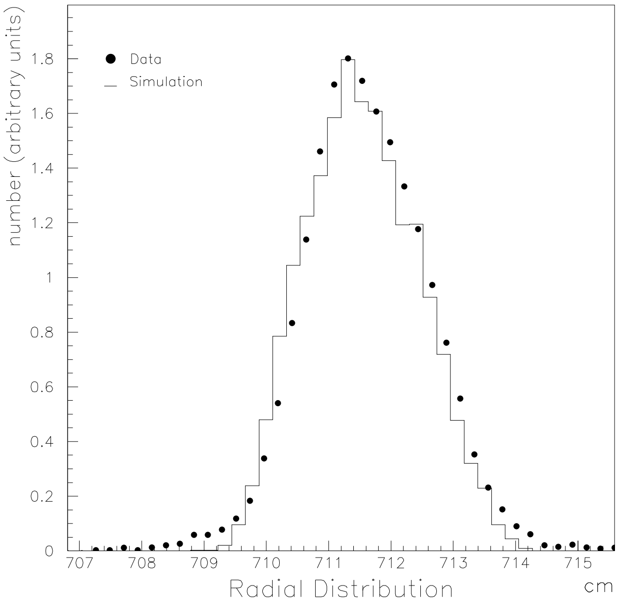

FIG. 1. The equilibrium radius distribution calculated using the tracking code (histogram) and obtained from an analysis of the beam debunching at early times (points).

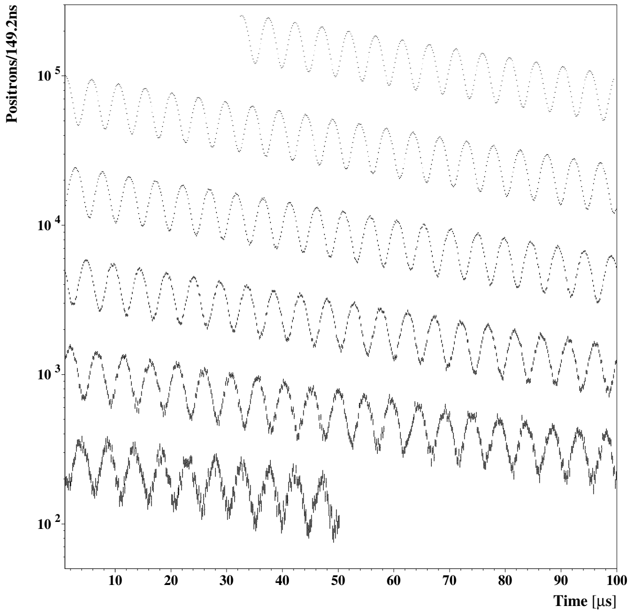

FIG. 2. The positron time spectrum obtained with muon injection for $E > 1.8$ GeV. These data represent 84 million positrons.

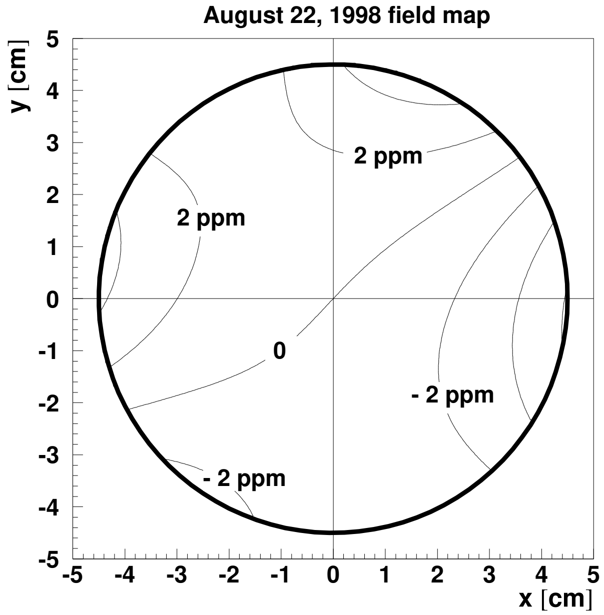

FIG. 3. A magnetic field profile averaged over azimuth. The circle encloses the muon storage region of 4.5 cm radius. The contours represent 2 ppm changes in the field.

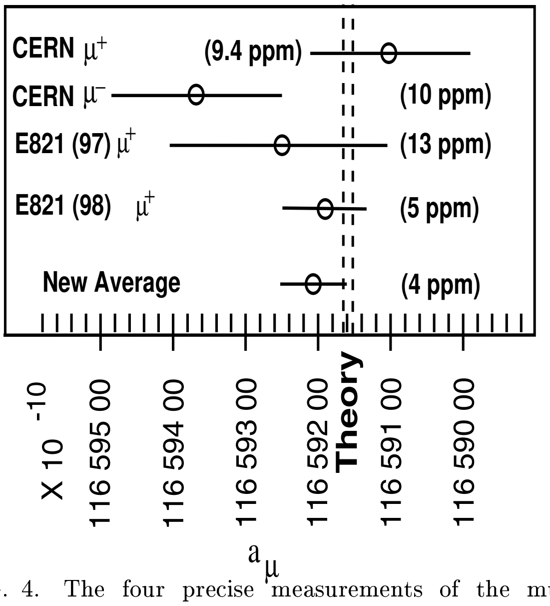

FIG. 4. The four precise measurements of the muon anomalous magnetic moment and their weighted average. The 1σ region allowed by the standard model (see text) is indicated by the dashed lines.