Recent Results on the Muon Anomalous Magnetic Moment from BNL E821

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Abstract. The new muon $(g-2)$ experiment at BNL aims at a final precision of 0.35 ppm on the muon anomaly. The experiment has completed four runs beginning in 1997 and has sub-ppm data on tape. Analyzed data include a published 13 ppm result from our initial commissioning run and a recently completed 5 ppm result from our 1998 initial muon injection run. We are actively working on the remainder of the data analysis and on systematic studies.

INTRODUCTION

The quest for phenomena that cannot be explained by the Standard Model (SM) of fundamental interactions is the focal point of present day particle physics. Although the SM is consistent with all available experimental data, there is increasingly strong theoretical reason and also circumstantial evidence that points to the existence of new physics below the TeV scale [1] (*e.g.* the indication of neutrino oscillations at Super-Kamiokande, the solar neutrino problem, the apparent

TABLE 1. Standard Model predictions for a_μ [5].

Variable	Value ($\times 10^{11}$)	relative contribution (ppm)
a_μ(SM)	116 591 628(77)	± 0.66
a_μ(QED)	116 584 705.7(1.8)	± 0.015
a_μ(had)	6771(77)	57.79 ± 0.66
a_μ(weak)	151(4)	1.30 ± 0.03

non-unitarity of the Cabibbo-Kobayashi-Maskawa matrix and the consequences of atomic parity non-conservation). Precision experiments at low energy can probe for deviations from the SM predictions and provide complementary constraints to those obtained in high-energy collision experiments. The uncertainty principle mandates that even heavy particles make small contributions to low-energy observables, such as the magnetic moment of the muon.

THEORY

The magnetic moment of a particle is related to its spin, $\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$. According to Dirac's theory, the proportionality constant g, or gyromagnetic ratio, is equal to 2 for pointlike, *i.e.* structureless, particles. The discovery that $g_e \neq 2$ for electrons [2] and the calculation by Schwinger [3] predicting that (to first order in α) the radiative correction to g_e is α/π, were the first steps towards the very complex present day calculations.

The muon magnetic moment expressed as [4]

$$\mu_\mu = (1 + a_\mu)\frac{e\hbar}{2m_\mu} \qquad \text{where} \qquad a_\mu = \frac{(g-2)}{2}. \tag{1}$$

The SM prediction for the anomaly a_μ is traditionally split in three parts, $a_\mu(\text{SM}) = a_\mu(\text{QED}) + a_\mu(\text{hadronic}) + a_\mu(\text{weak})$. Any contribution from "new" physics will be reflected in a measured value which does not agree with this prediction. The presently most accurate predictions for each of these contributions are given in table 1. The uncertainty is dominated by that in a_μ(hadronic), which cannot be calculated directly, but must be determined from data.

EXPERIMENT

For polarized muons moving in a uniform magnetic field $\vec{B}$ which is perpendicular to the muon spin direction and to the plane of the orbit, and with an electric quadrupole field $\vec{E}$ for vertical focusing, the difference angular frequency, ω_a, between the spin precession frequency ω_s and the cyclotron frequency ω_c, is given by [6]

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

The dependence of ω_a on the electric field is eliminated by storing muons with the "magic" γ_μ=29.3, which corresponds to a muon momentum $p_\mu = 3.09$ GeV/c. Hence measurement of B and of ω_a determines a_μ.

The magnetic field strength is measured using proton NMR, whereas ω_a is extracted from the modulation of the positron rate of in-flight decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$. For an energy threshold E, this rate is [6,7]

$$N(t) = N(E)e^{-t/\gamma\tau}\left[1 + A(E)\cos\left(\omega_a t + \phi(E)\right)\right], \tag{3}$$

with $N(E)$ a normalization constant and $A(E)$ the parity violating asymmetry parameter. Maximum statistical power is obtained for $E = 1.8$ GeV.

RESULTS

Our experiment measures the frequency ratio $R = \omega_a/\omega_p$, where ω_p is the free proton NMR frequency in our magnetic field. Including the pitch and electric field corrections, we obtain $R = 3.707\ 201(19) \times 10^{-3}$, where the 5 ppm error includes a 1 ppm systematic error estimate. We obtain a_{μ^+} from $a_{\mu^+} = R/(\lambda - R)$ $= 116\ 591\ 91(59) \times 10^{-10}$ in which $\lambda = \mu_\mu/\mu_p = 3.183\ 345\ 39(10)$. [4,8] This new result is in good agreement with the mean of the CERN measurements for a_{μ^+} and a_{μ^-}, [4] and our previous measurement of a_{μ^+}, [9].

Assuming CPT symmetry, the weighted mean of the four measurements gives a new world average of $a_\mu = 116\ 592\ 10(46) \times 10^{-10}$ (± 3.9 ppm), which agrees with the standard model to within one standard deviation.

REFERENCES

1. P. Herczeg, in: *Precision Tests of the Standard Electroweak Model*, Advanced Series on Directions in High-Energy Physics, Vol. 14, edited by P. Langacker, Singapore: World Scientific, 1995, pp. 786.
2. J.E. Nafe, et al., Phys. Rev. **71**, 914 (1947), D.E. Nagl, et al., Phys. Rev. **72**, 971 (1947) P. Kusch and H.M. Foley, Phys. Rev. **74**, 250 (1948).
3. J. Schwinger, Phys. Rev. **73**, 416 (1948) and Phys. Rev. **75**, 898 (1949).
4. Particle Data Group, Eur. Phys. J. C **3**, 1 (1998).
5. V.W. Hughes and T. Kinoshita, Rev. Mod. Phys. **71**, S133 (1999).
6. J. Bailey, et al., Nucl. Phys. B **150**, 1 (1979).
7. F.J.M. Farley and E. Picasso in *Quantum Electrodynamics*, ed. T. Kinoshita, (World Scientific, Singapore, 1990), p. 479.
8. W. Liu, et al., Phys. Rev. Lett. **82**, 711 (1999).
9. R.M. Carey et al., Phys. Rev. Lett. **82**, 1632 (1999).