Chapter 1.
Introduction

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This report describes the design and construction of a unique, high precision superconducting storage ring for 3 GeV/c muons, along with the beamline, detectors, and data acquisition system which are to be used in a new precision measurement of the muon $(g-2)$ value at the Brookhaven National Laboratory.

The goal of AGS E821 is a precision measurement of the muon $(g-2)$ value, or equivalently the anomalous magnetic dipole moment $a_\mu = \frac{1}{2}(g-2)$, to 0.35 ppm which would be an improvement by a factor of 20 compared to the present experimental accuracy of 7.3 ppm from the last CERN experiment. [1,2] The ultrahigh precision aimed for in the BNL experiment presents unusual challenges in physics and in technology.

1.1. General Motivation and Scope

A measurement of a_μ with a precision of 0.35 ppm will provide one of the most sensitive and crucial tests of the standard theory. With the planned and expected improvement by a factor of 3 to 4 in the experimental determination of the hadronic contribution $a_\mu(had)$ to a_μ, the theoretical value of a_μ will be known with a precision of about 0.3 ppm. Hence a comparison of theory and experiment will provide the following:

- A very high precision test of the theoretical value of a_μ which is based on the standard theory and has its dominant contribution from virtual quantum electrodynamic processes. The standard theory incorporates the viewpoint that the muon is a heavy point-like lepton and the precision of the comparison will correspond to processes with four-momentum transfer $Q^2 = 10^3(GeV/c)^2$.
- A measurement for the first time, with an accuracy of 23%, of the weak interaction contributions to a_μ which arise from single loop diagrams with virtual W and Z bosons. This measurement will provide a crucial test of the renormalizability of the unified electroweak theory.

  In addition, the following results will be obtained:

- Comparison of a_μ^- and a_μ^+ as a test of CPT invariance.

- Measurement of the lifetimes of μ^+ and μ^- in the laboratory frame of reference as a test of special relativity and of CPT invariance.
- An improvement on the limit on the electric dipole moment of the muon as a test of T invariance.

Beyond the standard model the muon $(g-2)$ value provides a sensitive and general test for:

- Compositeness or substructure of leptons and gauge bosons.
- Extensions of the standard model with additional particle groups such as gauge bosons or supersymmetric particles.

The physics involved in muon $(g-2)$ is discussed in Chapter 2. A brief summary of the AGS experiment including its parameters and various features is given in Chapter 3.

1.2. Overview of the AGS Experiment

The principle of the experiment is based on the spin motion of polarized muons in a storage ring and is the same as that of the third CERN measurement of a_μ. [1] In a magnetic field B in a storage ring the spin precesses with an angular frequency ω_s which is greater than the orbital cyclotron angular frequency ω_c by ω_a, the $(g-2)$ precession frequency:

$$\omega_a = \omega_s - \omega_c = \frac{e}{mc} a_\mu B. \tag{1.2.1}$$

This equation applies for all values of the momentum. For a special value of the relativistic variable γ, an electric field does not contribute to the spin precession, and the vertical focussing in the storage ring can be provided by electric quadrupoles, with no effect on the spin precession of a central momentum muon. This "magic momentum" is p_μ is 3.09 GeV/c or equivalently the "magic γ" is $\gamma = 29.3$. The use of electrostatic quadrupoles for vertical focussing permits the magnetic field to be as pure a dipole field as it is possible to make.

An accurate determination of a_μ requires an accurate measurement of **B** and of ω_a together with knowledge of the constant $\frac{e}{mc}$. Our experiment aims at a determination of a_μ to 0.35 ppm, a factor of 20 improvement over the latest CERN measurement.

Longitudinally polarized muons of 3 GeV/c are stored in the ring, either by pion injection into the storage ring which is followed by $\pi \to \mu$ decay which provides the kick to place muons onto stable stored orbits, or by direct muon injection together with a fast kicker. The storage efficiency for muons stored per incident pion is ~ 26 *ppm*, whereas with direct muon injection it is 7%. The physics of muon storage is discussed in Chapter 4.

Electrons from muon decay are detected with calorimeters and their times of arrival are accurately measured. Because of the parity violating correlation between muon spin direction and electron emission direction, the $(g-2)$ frequency ω_a appears as a modulation of the muon decay electron spectrum. The magnetic field $\mathbf{B}$ will be measured by proton NMR. We plan to measure ω_a to about 0.3 ppm, limited principally by statistics, and $\mathbf{B}$ to about 0.1 ppm.

The principal equipment to be built is the superferric storage ring with $\mathbf{B} = 1.45$ T and a diameter of 14.22 m. Since we must know $\mathbf{B}$ averaged over the muon storage volume with cross sectional diameter 9 cm to 0.1 ppm, the requirements on the field homogeneity and stability are unusually stringent. Our design of the storage ring including the requirement of high precision is discussed in Chapters 8 and 14.

A new beam line is under construction. The beam starts with a fast kicker for proton ejection at H10 in the AGS, followed by a and a new secondary production target station. The secondary beamline will provide either π or μ beams at 3 GeV/c for injection into the storage ring. The storage ring and the $(g-2)$ experiment will be located in the old $80''$ bubble chamber building. The beamline, the inflector and the electric quadrupoles are discussed in Chapters 6, 10 and 11 respectively. The muon kicker is covered in Chapter 12, and the vacuum system is discussed in Chapter 13.

The electron detectors, which are to be located on the inside of the ring, must handle high rates and provide precise time interval measurements with systematic effects less than 20 ps. The detectors and electronics are discussed in Chapter 16, the data acquisition and on-line system are discussed in Chapter 17. Slow control is covered in Chapter 18, and off-line and simulation is covered in Chapter 19.

Although the principle of our AGS experiment is the same as that of the third CERN experiment, [1] we aim to achieve a 20 fold greater precision. This increased precision will be possible principally due to a proton beam intensity with the AGS Booster some 100 times that at CERN where the dominant error was statistical. The principal systematic error of about 1.5 ppm at CERN was due to limited knowledge of the magnetic field. Our experiment is designed to improve our knowledge of the field to 0.1 ppm. Great care must be paid to maintaining all the systematic errors at the level of 0.1 ppm or less. These questions of errors are discussed in Chapter 5.

Table 1.3.1: DOE Construction Cost Estimate (2/94)

WBS	Item	$E\&C(K\$)$	To go$(K\$)$	Total$(K\$)$
1.1	Storage Ring Magnet	4459	772	5231
1.2	Beam Monitoring	0	0	0
1.3	Magnetic Shims	276	135	411
1.4	Vacuum Chamber/Quad	243	703	946
1.5	Detectors	0	444	444
1.6	Beam/Exp. Hall	1803	1656	3459
1.7	Field Measurement	0	60	60
1.8	Muon Kicker	0	790	790
1.9	DAQ & Control	0	175	175
1.13	Direct Labor	3532	180	3712
Total	E821	10313	4915	15228

1.3. Budget and Schedule Summary

A detailed analysis of the costs and schedules has been carried out. The total construction cost of the AGS Muon $(g-2)$ experiment to DOE is estimated to be $15 M. A breakdown of the costs by major components is given in Table 1.3.1. We note that the costs shown in the above table are U.S. D.O.E. costs only.

The construction funding is distributed among four sources: U.S. Department of Energy (DOE), U.S. National Science Foundation (NSF), Japan (US-Japan Program in High Energy Physics [KEK, University of Tokyo]) and Germany (University of Heidelberg). The present six-year construction schedule covers the period FY89-FY95, with the muon kicker being built in FY96 in parallel with the first data collection run using pion injection. Details of personnel and management are given in Chapter 24, budget and schedule are discussed in Chapter 25.

1.4. References

1. J. Bailey et al., Nucl. Phys. B150, 1 (1979).

2. F. J. M. Farley and E. Picasso, *Quantum Electrodynamics* ed. by T. Kinoshita (World Scientific, Singapore, 1990), p.479.