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A NEW PRECISION EXPERIMENT TO MEASURE THE MUON g-2 VALUE

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ABSTRACT

A new measurement[1] of the g-2 value of the muon with a sensitivity of .35 parts per million is being prepared at the Brookhaven National Laboratory Alternate Gradient Synchrotron (BNL AGS). The weak interaction contributes significantly to the magnetic moment anomaly at the planned level of sensitivity.

INTRODUCTION

An experiment to measure the magnetic moment anomaly of the muon[1], $a_\mu = (g-2)/2$, with a precision of .35 parts per million has recently been approved at the BNL AGS. The planned level of accuracy is a factor of 20 improvement over the present experimental value[2].

Precision experiments can complement high energy experiments in probing physics at higher mass scales. Within the standard model the muon magnetic moment anomaly is calculable[3] with no adjustable parameters. Any undiscovered particles which couple to muons or undiscovered interactions of the muon will alter a_μ. The new experiment is thus a standard model test and a search for an indication of particles and interactions beyond the standard model.

The planned level of accuracy brings the experiment into a new and interesting region. The weak interaction[4] contribution to a_μ is approximately 1.5 PPM, and thus the new experimental value will be sensitive to it while the present experimental value is not. The magnetic moment anomaly is the classic test for particle substructure. The new experiment will be sensitive to muon substructure at the 4-5 TeV level. A further discussion of contributions to a_μ arising from theories beyond the standard model can be found in ref. 5.

MASTER

EXPERIMENTAL APPROACH

The experiment measures the spin precession of polarized muons which are trapped in a magnetic storage ring. For a Dirac particle g=2 and the spin precession frequency ω_s is equal to the cyclotron frequency ω_c. The spin precession in excess of the cyclotron frequency is termed the anomalous spin precession ω_a. In a g-2 experiment ω_a is measured directly. Shower counters distributed around the inside of the storage ring (fig. 1) detect electrons from muon decay. The counting rate for high energy electrons (emitted forwards) is modulated at the frequency ω_a.

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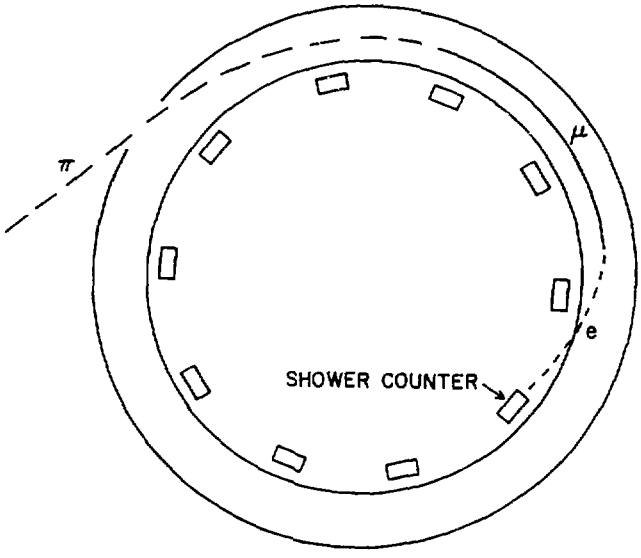

Fig. 1 Schematic view of the g-2 experiment.

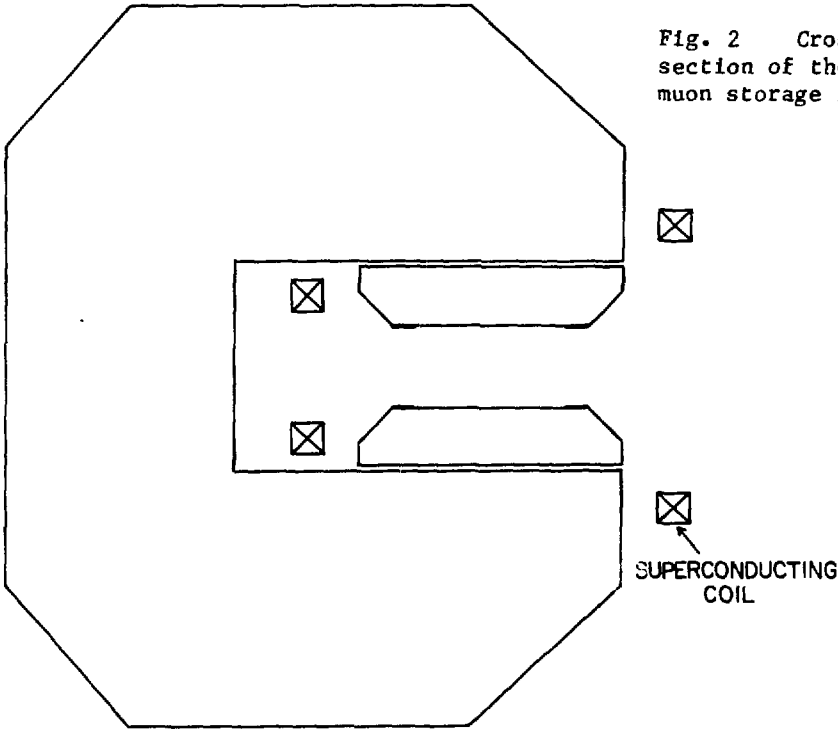

Fig. 2 Cross section of the g-2 muon storage ring.

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The new experiment is similar in concept to the 1978 CERN experiment[2] in that it uses a constant magnetic field with electrostatic quadrupoles for vertical focusing. In the presence of an electric field E the anomalous spin precision is given by[6]

$$\omega_a = e/mc \left[a_\mu B + (a_\mu - 1/(\gamma^2-1)\left|\vec{\beta} \times \vec{E}\right| \right]$$

For $\gamma = 29.3$ corresponding to muon momenta 3.094 GeV/c, the coefficient of the electric field term vanishes and a_μ is determined solely by ω_a and the constant magnetic field B.

The experiment will utilize a 14-meter diameter 1.5 Tesla storage ring. The ring is powered by superconducting coils. The ring will have azimuthal symmetry interrupted only by the field-free inflector region through which the pion beam enters. Forward decay muons are captured in stable orbits and are polarized due to the angular asymmetry of the pion decay process. The muons make 440 revolutions per lifetime and undergo 15 anomalous spin precessions per lifetime. The ring is a C magnet in cross section open on the inside where the shower counters are located. Shower counters of a lead scintillation sandwich design are planned, but other electron calorimeter designs are under study.

CONTRIBUTIONS TO $(g-2)_\mu$

In contrast to $(g-2)_e$, which even at the level of 4 parts per billion (present experimental[7] precision) involves only electrons and photons, $(g-2)_\mu$ is sensitive to the presence of other particles. For example, vacuum polarization loops involving e, μ, π, and τ are significant for $(g-2)_\mu$ (figs. 3a and b).

Within the standard model, $(g-2)_\mu$ has contributions from (1) QED involving leptons and photons only, (2) QED involving hadrons, (3) the weak interaction. At present the pure QED contribution has been calculated to about .1 PPM, the hadronic contribution to 1 PPM, and the weak contribution to .01 PPM. A factor of 4 improvement in the value for the hadronic contribution is required to match the sensitivity of the new experiment.

The calculation of the hadronic contribution requires experimental input in the form of $\sigma(e^+e^- \to \text{hadrons})$ over the range of energies from $\sqrt{s} = 2m_\pi$ up to about 1 GeV. An experiment[8] at the VEPP-2M ring at Novosibirsk using the CMD-2 detector is planned to take the relevant data. Fixed target experiments with energetic positron beams (>100 Gev) can also measure these cross sections[9].

Diagrams of the weak interaction contributions to $(g-2)_\mu$ are shown in figs. 3c and d. The contribution involving a virtual W boson is particularly interesting since it involves the W interacting directly with the magnetic field and thus is sensitive to the W magnetic moment. In the standard model the magnetic moment of the W is equal to e/M_W. A deviation from this value would imply W substructure[9].

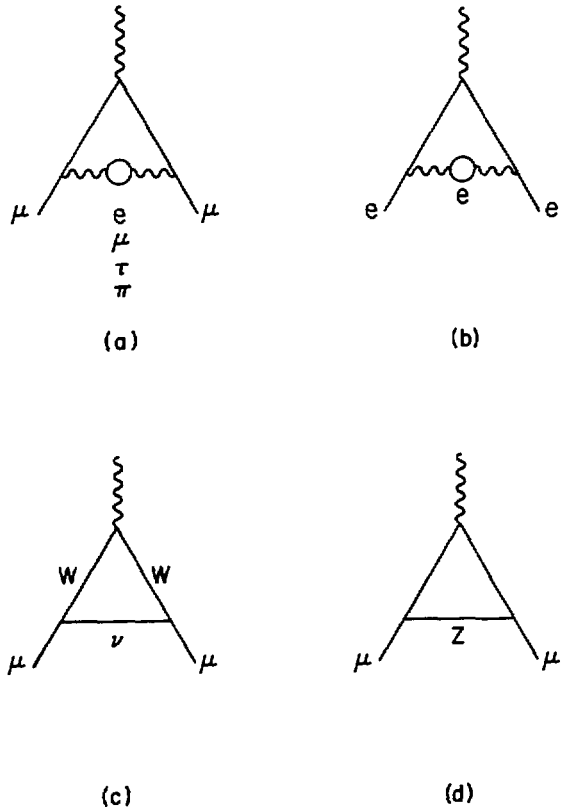

Fig. 3
(a) Vacuum polarization contribution to $(g-2)_\mu$ includes, e, μ, τ, and π loops. Lowest-order diagram is shown.
(b) Vacuum polarization contribution to $(g-2)_e$ includes only electron loops.
(c) and (d) Weak interaction contribution to $(g-2)_\mu$.

EXPERIMENTAL CHALLENGES

In the g-2 experiment the magnetic moment anomaly is determined as a ratio of the anomalous spin precession frequency to the magnetic field.

$$a_\mu = \frac{mc}{e}\frac{\omega_a}{B}$$

To attain a sensitivity of .35 PPM, 3 10^{10} muon decays must be observed with systematic timing errors less than 30 ps. The average magnetic field seen by the muons must be known to .1 PPM. Since the magnetic field is measured by proton NMR, knowledge of the constant μ_μ/μ_p is required[10].

The improvement in statistical precision over the previous $(g-2)_\mu$ experiment is due to the hundredfold greater proton intensity available at the AGS. The freedom from systematic timing error required for the frequency measurement is well within the capability of modern electronic circuits. The challenge will be to

maintain timing accuracy in the presence of high counting rates which vary over the course of the measurement.

In addition to the high counting rates due to muon decays, there is an initial burst of radiation in the pion injection approach described above (the pion beam is lost after less than one turn in the ring). Studies in a high-intensity pion beam indicate that this initial flash is manageable. However, the beam line to the experiment is long enough to accommodate a muon beam, and it may be preferable to avoid the flash problem through muon injection.

The magnetic field will be measured by proton NMR. With appropriate diamagnetic shielding corrections an absolute field measure to .1 PPM will be achieved. The challenge in this experiment is the large volume over which the field must be known--a ring 14 m in diameter with a 9 cm diameter storage region. The use of superconducting coils has advantages in current regulation, thermal stability and cost. The magnet will be continuously powered during the course of measurement to avoid problems of hysteresis. An elaborate system of measurement and control of the field is planned with 176 fixed NMR probes positioned around the ring above and below the vacuum chamber and a matrix of 25 probes which can be moved around the inside of the vacuum vessel.

The experiment will begin taking data in four years under the present construction schedule.

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