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Challenge in Reaching 10^{-7} Precision: Magnetic Field, Counters and Hadronic Contribution

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Challenge in Reaching 10^{-7} Precision: Magnetic Field, Counters and Hadronic Contribution

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Abstract

Determining the muon magnetic moment anomaly, a_μ, to .35 PPM will open a window on physics at a mass scale which is not now accessible to high energy experiments. Measurements of magnetic field and spin precession frequency free from systematic error at the 10^{-7} level are required to attain this goal. Approaches to these problems are discussed. A novel method of precision measurement of magnetic field using the cyclotron frequency of heavy ions is outlined.

To fully utilize the great experimental precession of the planned measurement of a_μ, knowledge of the hadronic contribution to a_μ must be improved. The status of experiments leading to such an improvement is reported.

1. Introduction

In the g-2 experiment $a_\mu = (g-2)/2$ is determined as a ratio of the anomalous spin precession frequency ω_a to the magnetic field:

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

Two experimental measurements are made: the frequency ω_a determined from the $\cos(\omega_a t)$ modulation of the counting rates in the electron shower counters and the magnetic field determined by proton NMR. An alternative method using the cyclotron frequency of heavy ions circulating in the ring will be discussed later in this paper. If proton NMR is used, a_μ can be expressed in terms of a ratio of frequencies $R = \omega_a/\omega_p$ where ω_p is the proton resonance frequency

$$a_\mu = \frac{R}{(\lambda - R)} \qquad \lambda = \frac{\mu_\mu}{\mu_p}$$

The constant λ is known[1] to .36 PPM from measurement of the hyperfine structure of muonium. An improvement to the level of .1 PPM or better is anticipated in the next few years.

To attain a sensitivity of .35 PPM in a_μ, $3\ 10^{10}$ muon decays must be observed. The improvement in statistical precision over previous g-2 experiments is due to the hundred fold greater proton intensity which will be available at the AGS with the Booster.

In order to match this statistical precision, it is required that:

1) The systematic errors in the frequency measurement be kept to less than .1 PPM. This corresponds to 30 ps in the timing measurement.

2) The average magnetic field seen by the muons be known to .1 PPM.

To fully utilize the planned experimental result, the value of a_μ calculated within the standard model should be known to comparable precision. This gives rise to a third requirement.

3) The hadronic contribution to a_μ must be known to .5% of its value. This contribution to a_μ is not directly calculable, but relies on a separate experimental measurement.

These three requirements are the subject of this paper.

2. Magnetic Field

a. Requirements and Approach

The magnetic field averaged over all muon trajectories over the course of the experiment must be known to one part in 10^7. If the magnetic field is not constant over the active volume, a knowledge of the spatial distribution of the muons is required to perform the appropriate averaging. The magnetic field will be measured by proton NMR. With appropriate diamagnetic shielding corrections an absolute field measurement 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 approach to field measurement using the cyclotron frequency of heavy ions (described below) directly averages over the orbits in the ring which with care can simulate the muon distribution.

It is anticipated[3] that the field can be made uniform to one part in 10^6 through a combination of shimming and the use of current loops for the final field shaping.

Provisions for shimming are incorporated into the magnet design. Figure 1 shows a cross section of the g-2 magnet. Noteworthy are the bumps on the edges of the pole which compensate for the sextapole component of the field, and the air gap between the pole and the yoke. Shimming on the pole face will correct local variations in the field while shimming in the air gap will correct longer wavelength variations.

The requirements in both uniformity and knowledge of the magnetic field are an order of magnitude better than attained by the final CERN experiment[2]. The experiment by necessity incorporates many improvements over the

CERN design. 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 (trolley).

b. Precision Determination of Magnetic Field in the g-2 Muon Storage Ring Using the Cyclotron Frequency of Heavy Ions

In order to determine $(g-2)_\mu$ to .3 PPM it is necessary to know the magnetic field integral around the storage ring to the same absolute precision. The field integral can be determined by making a detailed field map using NMR. Another approach is to observe particles of known properties stored in the ring.

For non-relativistic particles the cyclotron frequency determines the magnetic field if the mass is known to sufficient precision; the dependence on momentum is weak for slow particles.

The orbital frequency is given by

$$\omega_c = \frac{eB}{M\gamma} \qquad (1)$$

Now

$$\frac{\Delta B}{B} = \frac{\Delta\gamma}{\gamma} = (\beta)^2 \frac{\Delta P}{P} \qquad (2)$$

So for small β, a large error in the momentum can be tolerated.

This leads to the idea of using the cyclotron frequency of singly ionized heavy atoms to determine the magnetic field. The g-2 ring has a central momentum of 3 GeV/c. For singly ionized gold, this corresponds to β=.015, T=23 MeV. A 6 10^{-4} determination of the momentum will contribute only .2 PPM to the magnetic field error. For Au^{+2} a 1.5 10^{-4} determination is required to achieve the same precision.

A pulse of ions circulates in the ring and the orbital frequency is determined. The cyclotron frequency for Au^{+1} is 114 khz (8.8 μs period). If we measure time to 1 ns, then we must follow the ions for 10 ms (1200 revolutions) to determine ω to .1 PPM. The low velocity of the ions makes the frequency measurement easier and .1 PPM is reached for a single pulse of heavy ions. We can make repeated measurements to reach .1 PPM.

If we average over many pulses, a better time measurement may be obtained. For 1 ns timing and 1000 pulses, the average time may be determined to 30 ps and only 40 revolutions are required.

The time to make a single measurement may be <<1 second. Thousands of measurements can be made in a short period of time and the ring can be mapped by varying the position and momentum of the beam within the ring.

Note that with this method the average value of $\int B_z dl$ is obtained. This is exactly the quantity required. With NMR, B rather than B_z is obtained and independent measurements must be made to check the alignment of the magnetic field.

If the magnetic field is measured in terms of the cyclotron frequency of gold ions, we require the constant m_μ/M_{Au} to determine the muon magnetic moment anomaly a_μ. The mass of a gold atom is known[4] to .02 PPM (AMU) and the mass of the muon is known[5] to .15 PPM (AMU).

Spreading of the pulse of heavy ions during the measurement time is small. If the heavy ion beam has a momentum spread of $\Delta P/P = 10^{-3}$, then the cyclotron frequency will have a spread of $2.25\ 10^{-7}$ and the pulse will spread by 2 ns over the 10 ms measuring time. If the momentum distribution is asymmetric, a shift will result, so this effect must be taken into account.

The heavy ions are below the Coulomb barrier and thus activation of the ring is not a problem.

The source of heavy ions at the AGS is the Tandem Van de Graaff generator. Its accelerator voltage is 16 MeV and it is capable of producing 22 MeV Au^{+1} directly. The transfer line from the Tandem to the AGS cannot accommodate ions of such high magnetic rigidity so it is necessary to transport them in a higher charge state and reduce them to charge state +1 or +2 later on[6]. The ions would then traverse a half turn in the AGS on their way to the g-2 ring. Approaches in which the Tandem produces ions of lower energy which are then accelerated in the AGS Booster Ring can also be considered.

The vertical focussing in the g-2 ring is provided by electrostatic quadrupoles. For muons of the magic momentum[7], the electric field has no effect on the anomalous spin precision. This is due to a cancellation between the effect of the radial electric field on the cyclotron frequency and the effect of the induced magnetic field in the muon rest frame on the spin precession. The electric field must be reduced during the field measurement with heavy ions so that its effect on their cyclotron frequency is decreased. How far it can be reduced is determined by the ratio of the vertical emittance of the heavy ion beam to the vertical acceptance of the ring.

If the electric field is turned off, for 40 turns we have a vertical angular acceptance of 25 μr. The Tandem emittance is such that the full beam can fit but we must aim well. If we maintain an electric field, we must turn it down by a factor of 66 to compensate for the low velocity of the ions, and by a further factor of 500 to keep the uncertainty in the correction to ω_c less than .1 PPM (assuming that E is known to ±5%). This reduces the electric field to one volt from a normal value of 30 KV. The ring will then have a vertical acceptance of 4.5 π mm mr, five times larger than the emittance of the Tandem. It will thus be possible to map the field in vertical as well as horizontal steps.

The vacuum requirements are an issue because of the large atomic cross sections for interacting with residual gas. A vacuum of 10^{-10} Torr is

adequate if the ions are followed for 1000 turns. This is a better vacuum than is required by the other needs of the experiment (10^{-9} is envisioned in the g-2 proposal) but still in the range which can be achieved. (The AGS booster will have a vacuum of 10^{-11} Torr.) A vacuum of a few 10^{-9} is adequate if the ions are followed for only 40 turns.

The momentum of the heavy ion beam must be determined to $\Delta p/p \approx 10^{-4}$. This can be achieved by time-of-flight because of the low velocity of the ions. Alternatively, a measurement of the radius of the beam orbit in the g-2 ring to ±1 mm will suffice.

The cyclotron frequency may be determined by sensing the ion pulse with pickup electrodes. Alternatively, the pulse may be intercepted by a scintillator after making the required number of revolutions. The advantage of the latter method is that the intensity of the heavy ion pulse is then no longer an issue. In principle, a single ion could be used to determine the $\int B_z d\ell$ to .1 PPM.

c. Test Magnet

A test magnet (fig. 2) has been assembled at Brookhaven in order to study[8] shimming and field measuring techniques at the .1 PPM level. The test magnet is modeled to 72% scale in cross section and is 36 inches long. It differs from the g-2 magnet in several important ways: (1) It is an H magnet rather than a C magnet. (2) It is straight and finite length rather than circular. (3) It is normal rather than superconducting. In spite of these differences it should prove very useful in developing techniques applicable to the g-2 magnet.

Notice in the photograph of the test magnet (fig. 2) the features corresponding to the g-2 magnet (fig. 1): the pole profile, the field shaping bumps at the pole edge, an aluminum plate separating the pole from the yoke to simulate the air gap. The aluminum plate has machined slots, visible in the photograph, into which shims can be inserted. An NMR probe is positioned in the magnet.

The test magnet power supply has been placed in series with a filter to remove ripple. Measurements with an NMR probe and with search coils have already begun. In a short time a current transformer with an accuracy of 3 PPM will be installed to better regulate the field. Shimming studies can be carried quite far with present setup using a pair of search coils for differential measurements. These are insensitive to slow drifts when studying field shapes.

The first goal of the test magnet program is to produce a region of field, perhaps 3 inches by 6 inches, which is uniform to 10 PPM. It is expected that experimental studies within this good field region will be applicable to the g-2 magnet.

The test magnet program will include studies of the following topics:

1) Steel types. It would be especially interesting to have poles made of the low carbon steel envisioned for the g-2 magnet.
2) Surface flatness, grinding and polishing.

3) Field measuring techniques.
4) Shimming (including field shaping with current loops).
5) Calculation of required shims from a map of the field.
6) Magnetization and cycling.
7) Evaluation of alternative NMR systems
(e.g. frequency modulation vs. field modulation).
8) Properties of high precision NMR probes.
9) Calibration and comparison of NMR probes.

d. Trolley

A trolley carrying NMR probes which can be moved around the vacuum chamber while it is under vacuum is envisioned for the g-2 ring. The field will be continuously measured by the fixed NMR probes at the edge of the aperture, and periodically measured within the aperture by the trolley. The magntic field should be unaffected by whether the ring is under vacuum or not. It is time consuming to restore the vacuum once it has been broken; if frequent measurements within the aperture are desired, the trolley must operate in vacuum. Many difficulties accompany this mode of operation: Dissipation of heat, getting the power in and the NMR signals out, functioning of sliding contacts. A test trolley has been constructed at Yale by A. Disco. These problems are being studied and some imaginative solutions have been found.

3. Counters

The freedom from systematic timing error required is well within the capability of modern electronic circuits. In fact, in the previous CERN experiment completed 10 years ago, the timing errors are quoted as less than .5 PPM. Since the statistical error in that experiment was 7 PPM, further study of the magnitude of timing errors was not of interest at that time.

The challenge will be to maintain the timing accuracy in the presence of the much higher counting rates in the new experiment. The counting rate varies over the course of the measurement, decaying with the muon lifetime.

In addition to the high counting rates due to muon decays, there is an initial burst of radiation if pion injection is used (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. K. Ishida's contribution to these proceedings describes in detail the requirements for muon injections.

The general approach to the problem of high counting rate is to use scintillators and phototubes which are as fast as possible and to use highly segmented detectors. Double counting in the detectors must be rejected to avoid timing errors. Since the pion induced background has a large neutron component, scintillators which do not contain hydrogen are advantageous if pion injection is used. J. Miller's contribution to this workshop describes in detail the status of the detector system.

4. Hadronic Contribution

Within the standard model the muon magnetic moment anomaly a_μ is calculable with no adjustable parameters. The dominant contribution to a_μ is from QED involving leptons and photons only. This has been calculated[9] to about .1 PPM using the experimentally determined value of α as input. (The value of α is now known[10] to .01 PPM.) The QED contribution involving hadronic vacuum polarization is known to 1 PPM. The calculated weak interaction contribution has an uncertainty of .01 PPM. Thus in order to compare the result of the new experiment with the standard model prediction, knowledge of the hadronic contribution must be improved by at least a factor of 4.

Calculation of the hadronic contribution requires experimental input in the form of $\sigma(e^+e^-\to\text{hadrons})$ over the range of energies from $\sqrt{s} = 2\ m_\pi$ up to about 1 GeV. This cross section can be determined in experiments with electron-positron colliding beams[11] or by experiments with energetic positron beams incident upon electrons in a fixed target[12] ($s=1.022\ E_{e^+}$ GeV where E_{e^+} is the positron energy in GeV. The value of $R = \sigma(e^+e^-\to\text{hadrons})/\sigma(e^+e^-\to\mu^+\mu^-)$ must be known to 1/2% in order to determine the hadronic contribution to the desired precision.

The VEPP-2M storage ring is the only operating storaging with center of mass energy in the region .36-1.4 GeV. A program of measurements of R is planned[13] at VEPP-2M. I will describe the outlook and schedule for these measurements as reported by members of the group at Novosibirsk.

A reconstruction of the VEPP-2M complex and implementation of a new booster storage ring to increase the luminosity will be completed in December 1988.

Installation of the new detector CMD-2 (cryogenic magnetic detector) will be completed in March 1989 at which point colliding beam experiments with the goal of measuring R to 1/2% will begin.

In the CMD-2 detector, the e^+e^- interaction point is surrounded by a drift chamber array inside a superconducting solenoid. Below $\sqrt{s}$ = 900 MeV collinear pairs of muons, pions and electrons can be distinguished by the momentum measurement alone. This is the most bias-free method of particle identification. Outside of the solenoid is a CsI calorimeter and a muon range system. Energy in the calorimeter supplies another basis for discrimination between pions, muons and electrons. R is dominated by $\pi^+\pi^-$ pairs in this mass region but $\pi^+\pi^-\pi^\circ$, $\omega\pi$, $\rho\pi\pi$, 5π, 6π final states will also be studied.

The luminosity of the upgraded storage ring will be $5\ 10^{31}\ cm^{-2}\ sec^{-1}$. With this luminosity, 15 days of running gives the required statistical precision and extensive study of systematic effects is possible.

All systematic errors are expected[14] to be considerably better than in the previous measurement[10] of R with CMD-1. The cross section for $e^+e^-\to$hadrons is normalized to that for $e^+e^-\to\mu^+\mu^-$, so that anything that affects the detection of hadrons (mainly pions) differently than the detection of muons results in a systematic error. Nuclear interaction of pions

which resulted in a 1% systematic error in CMD-1 are expected to be .1% for CMD-2 due to a decrease in the amount of material through which the pions pass before detection. Better tracking in the new drift chamber array will reduce the systematic error due to pion decay from 1% for CMD-1 to .1% for the new detector. Radiative corrections contributed a 1% systematic error in R for CMD-1. The new drift chamber system will permit a better test of collinearity. The collinearity test can identify events where a particle radiated a photon. Radiative corrections should be correspondingly improved.

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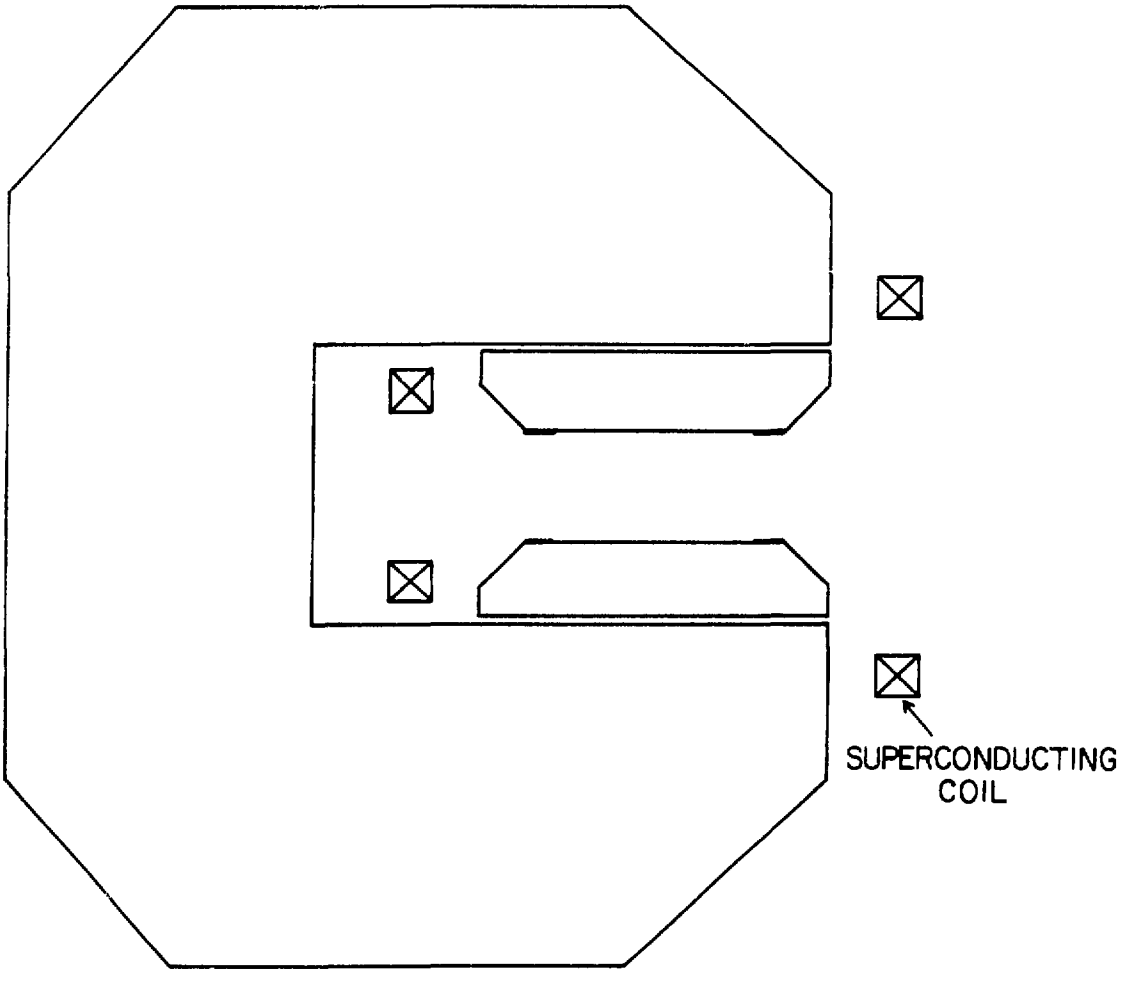
Figure Captions

Fig. 1 Cross section of the g-2 storage ring.

Fig. 2 Test magnet used for studying magnetic measurement and shimming.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