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Precision determination of the magnetic field in a muon storage ring using the cyclotron frequency of heavy ions— a technique for use in a new measurement of the muon g-2 value.*

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Abstract: A new experiment will measure the muon g-2 value with 20 times better precision than it is presently known. To reach this goal, the magnetic field in the muon storage ring must be known to be a part in 10^7. This can be achieved by storing singly charged heavy ions in the ring and measuring their cyclotron frequency.

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1. Introduction

An experiment[1] to measure the anomalous magnetic moment of the muon, $a_\mu = (g-2)/2$ to .35 parts per million is being prepared at the Brookhaven National Laboratory Alternating Gradient Synchrotron. This is a factor of 20 improvement in precision over the present value[2]. In the experiment, 3.1 GeV/c muons are confined to a 1.4T superferric storage ring[3]. The magnetic field averaged over all muon trajectories over the course of the experiment must be known to a part in 10^7. This can be achieved by storing singly charged heavy ions in the ring and measuring their cyclotron frequency. The charge to mass ratio for singly ionized gold, for example, is 2000 times smaller than for the muon. Ions with the same magnetic rigidity as a 3.1 GeV/c muon will be near the nonrelativistic limit where the cyclotron frequency is proportional to the mass of the ion and almost independent of its momentum. This technique is made possible by the availability of heavy ions at the AGS complex.

The g-2 experiment is described in Section 2; the magnetic field measurement using the heavy ions is described in Section 3.

2. The g-2 Experiment

Within the standard model the magnetic moment anomaly of the muon is calculable[4,5] with no adjustable parameters. Any undiscovered particles which couple to the muon 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 magnetic moment anomaly is the most direct test for

particle substructure. The new experiment will be sensitive to muon substructure at the 4-5 TeV level. The weak interaction[5] 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 contribution involving a virtual W boson[7] is particularly interesting since it involves the W interacting directly with the magnetic field and thus is sensitive to the W magnetic moment and to W substructure. A discussion of contributions to a_μ arising from theories beyond the standard model can be found in ref. 8.

The experiment measures the spin precession of polarized muons which are confined in a magnetic storage ring. For a Dirac particle, g is equal to 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.

The experiment utilizes a constant magnetic field in the storage ring with electrostatic quadrupoles for vertical focusing. Due to a cancellation of effects, at the "magic" momentum[9] of 3.094 GeV/c, ω_a does not depend on electric field; a_μ is then determined solely by ω_a and the average magnetic field B.

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

Great care has been taken in the design of the ring[3] to ensure uniformity and stability of the magnetic field. It is anticipated that the field will be

uniform to one part in 10^6. Proton NMR will be used to stabilize and map the field. 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 directly measures the component of B normal to the particle velocity averaged over the orbits in the ring which with care can simulate the muon distribution. With NMR, the magnitude of B is obtained and independent measurements must be made to check the alignment of the magnetic field.

Magnetic Field Measurement Using the Cyclotron Frequency of Heavy Ions

For non-relativistic particles the cyclotron frequency is independent of momentum. The magnetic field can be determined from ω_c if the mass is known to sufficient precision.

The magnetic field is given by

$$B = \frac{M\gamma}{e}\,\omega_c$$

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

Since the relativistic correction is proportional to β^2, for small β a large error in the momentum can be tolerated.

The g-2 ring will store 3.1 GeV/c muons. If singly charged gold ions are to be stored at the same magnetic field they must have a kinetic energy of 23 MeV and a β of .015. A 3 10^{-4} determination of the momentum will then contribute only .1 PPM to the magnetic field error. For Au^{+2} a .75 10^{-4} determination is required to achieve the same precision.

The source of heavy ions at the AGS is the Tandem Van de Graaff generator. Its terminal voltage is 16 MeV and it is capable of producing 23 MeV Au^{+1} directly. However, 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 before introducing them into the g-2 ring. This manipulation of the charge state is made possible by the fact that equilibrium charge state of an ion is critically dependent on the composition of the material through which the ion passes[10]. For 23 MeV gold passing through carbon the most probable equilibrium charge state is +12; passing through a hydrogen gas cell the most probable equilibrium charge state is +4 with significant yields at +1 and +2. With the introduction of appropriate equipment to bunch the beam at the Tandem, yields of 10^3 to 10^5 ions in a 10 ns pulse can be anticipated. These rates are more than adequate for detection in a scintillation counter or solid state detector. The statistics are sufficient to define the leading edge of the pulse to the required accuracy.

A pulse of Au^{+1} ions in the g-2 ring will have a cyclotron frequency of 114 khz (8.8 μs period). This frequency will be known very precisely from NMR field maps. The cyclotron frequency measurement can be used to verify and improve the knowledge of the field. After the ions have been introduced into the ring and have completed a large number of revolutions, they can be deflected into a counter for a time measurement. If each bunch is allowed to circulate for 40 revolutions (.35 ms) and the time measurement is made with 1 ns resolution, the average over 1000 pulses will determine the timing to 30 ps and provide a 10^{-7} measurement of the cyclotron frequency. The low velocity of the ions facilitates a high precision frequency measurement.

The momentum of the heavy ion beam must be determined to a part in 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.

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 70 ps over the .35 ms measuring time. If the momentum distribution is asymmetric, a shift will result, so this effect must be taken into account.

The vacuum requirements are an issue because of the large atomic cross sections for interacting with residual gas. A vacuum of 10^{-9} Torr is adequate if the ions are followed for 40 turns.

If the magnetic field is measured in terms of the cyclotron frequency of gold ions, the constant m_μ/M_{Au} is required to determine the muon magnetic moment anomaly a_μ. The mass of a gold atom is known[11] to .02 PPM (AMU) and the mass of the muon is known[12] to .15 PPM (AMU).

The electrostatic field which provides vertical focusing in the g-2 ring during normal operation must be reduced during the magnetic field measurement with heavy ions so that its effect on their cyclotron frequency is reduced.

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 be accepted in the ring, but accurate aiming of the beam is required. 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. 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 new g-2 experiment will complement high energy experiments in exploring physics at a multi-TeV mass scale. It is anticipated that construction of the experiment will be completed in four years. A direct determination of the appropriately averaged magnetic field using heavy ions can give added confidence to the results of this fundamental measurement.

I wish to thank Francis Farley[13] and Peter Thieberger for many fruitful discussions.

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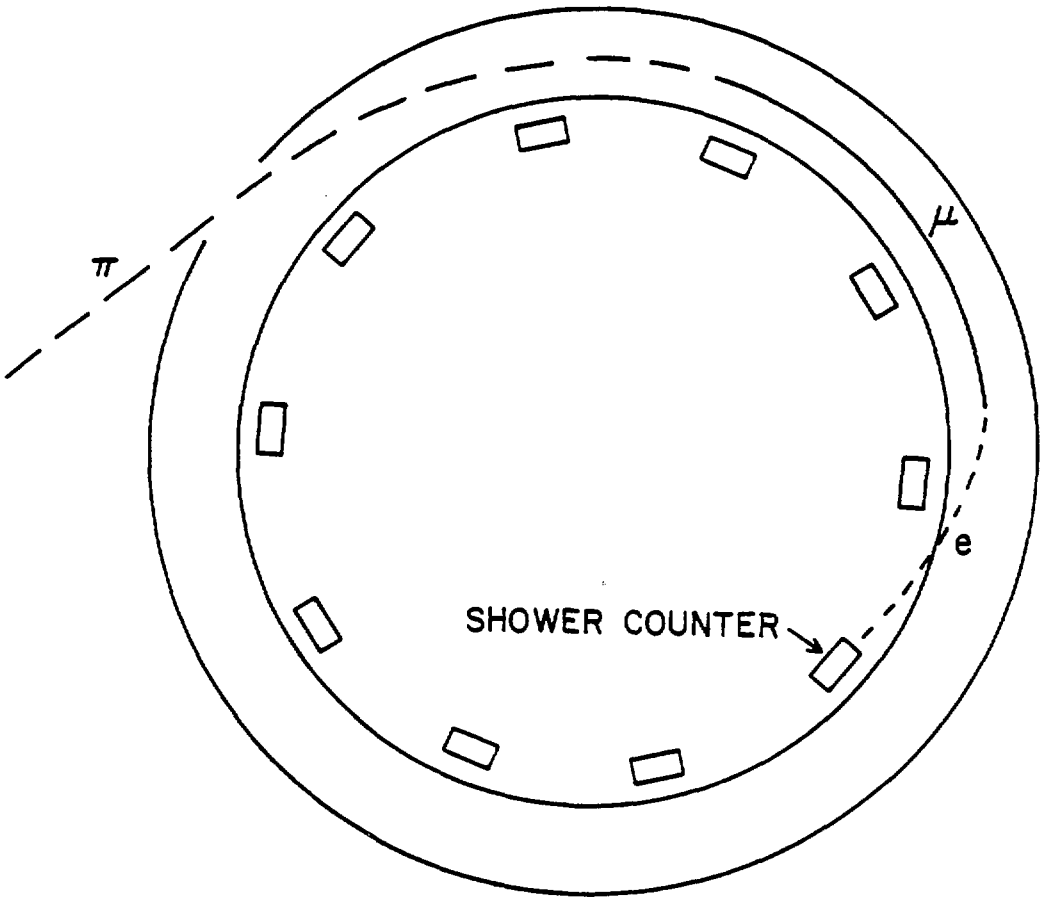
Figure Caption

Fig. 1 A schematic view of the g-2 experiment. Pions enter the 14 meter diameter storage ring. Forward decay muons are polarized and are captured in stable orbits. After many revolutions the muons decay into electrons which are detected in shower counters. The direction of the highest energy decay electrons reflects the muon spin direction. Thus the counting rate is modulated at the anomalous spin precession frequency.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