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Geonium Without a Magnetic Bottle—A New Generation*

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Work is now underway to improve the accuracy of the electron magnetic moment measurements by 10 to 100; that is, to an accuracy of 1 part per trillion. At this level of accuracy, the magnetic bottle so crucial to previous measurements must be removed. In fact, intrinsic bottles due to the paramagnetism of the trap electrodes must be carefully canceled. A promising replacement for the magnetic bottle is the relativistic mass increase which acts like a magnetic bottle 20 times smaller than the one previously used but with no distortion of the magnetic field. The relativisitic mass increase has been observed for 0.5 eV electrons. We have also trapped electrons in a new style, compensated Penning trap (described here) which is simpler to construct, promises to be more reliable when cycled to liquid helium temperatures, and can be easily disassembled.

Key words: compensated Penning trap; geonium; intrinsic magnetic bottle; magnetic bottle; Penning trap; relativistic mass increase.

1. Introduction

The advent of single particle spectroscopy at the University of Washington began a string of very accurate measurements of properties of elementary particles. The magnetic moment anomaly of the electron has been measured to an accuracy of 34 parts per billion [1]. Elsewhere in these proceedings are reports of a comparison of the electron and positron magnetic moment anomaly to an accuracy of 64 parts per billion [2], and a measurement of the ratio of the proton to electron mass to 136 parts per billion with further increases in accuracy expected soon [3].

We judge there is a reasonable prospect of improving the measurements of electron and positron magnetic moments by a factor of 10 to 100. This paper is a progress report on the efforts in the past year and one half to realize this improvement. As in nuclear magnetic resonance spectroscopy (where resolutions of 10^{-10} have been achieved), we expect that geonium spectroscopy will have similar wide application if we can approach the NMR resolution. There is also considerable theoretical interest in the magnetic moments of the electron and positron. Calculations of the $(\alpha/\pi)^4$ corrections according to QED are presently underway (see these proceedings). If an independent, more accurate value for the fine structure constant also becomes available (some proposals are contained in these proceedings), then our measurement will provide a test of the QED calculations. Conversely, if one chooses to believe the calculation and the appropriateness of QED, then our measurement will provide the fine structure constant. To our knowledge, no other techniques can get within orders of magnitude of the accuracies we believe are realizable.

The new feature of the next generation geonium experiments is that we hope to rely on the relativistic mass shift rather than using the magnetic bottle which was crucial to previous experiments. The magnetic bottle is undesirable at this level of accuracy because it makes the magnetic field inhomogeneous.

We divide our program into three phases: the first is completed, the second is mostly completed, and the third is about to begin. First, we have demonstrated that we can observe the relativistic mass increase of an electron of energy 0.5 eV [4]. Second, we have constructed a simpler version of the compensated Penning trap which is demountable and promises to be more reliable as well. We have trapped electrons in it (24 hours before leaving for this conference) but much testing remains to be done including a demonstration that intrinsic magnetic bottles have been removed [5]. Third, we shall measure the electron's magnetic moment anomaly.

2. Observation of the Increase in the Relativistic Mass, γm_0, of a 0.5 eV Electron (γ = 1.000 001)

A slightly modified, compensated Penning trap made of OFHC copper was assembled using electron tube construction techniques which have been discussed elsewhere [6]. For our purposes we need not review the monoelectron oscillator formed except to observe that the electron's harmonic oscillation along the magnetic field lines has a frequency ν_z ($\approx$60 MHz) which is inversely proportional to the square root of the electron mass. The observed cyclotron oscillation around the magnetic field lines has frequency ν'_c ($\approx$21 GHz) which is inversely proportional to the electron mass.

The energy in the cyclotron motion is increased by sweeping a microwave drive through the cyclotron frequency. Both ν_z and ν'_c thus decrease because the electron's mass, γm_0, (where m_0 is the rest mass) increases. The harmonic and cyclotron oscillation frequencies decrease by 60 Hz and 42 kHz, respectively, for a 1 eV excitation.

A typical measurement is summarized in Fig. 1. We monitored changes in the harmonic oscillation frequency (the ordinates of Fig. 1). The sensitivity was calibrated as in Fig. 1(a) by changing by 50 Hz the frequency of the synthesizer to which the electron's harmonic oscillation frequency was locked. This was done repeatedly to get an indication of uncertainty.

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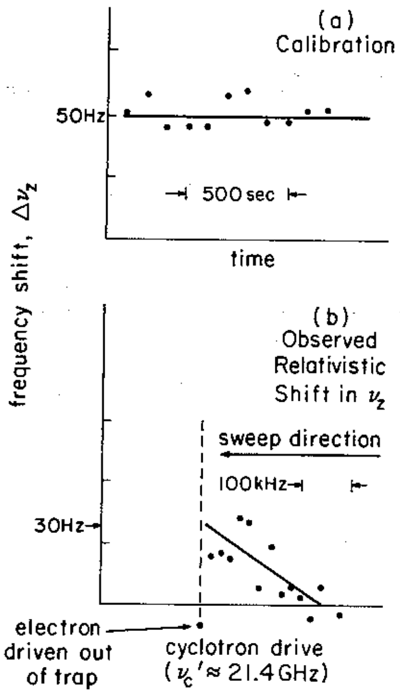

FIGURE 1. *(a) Calibration of sensitivity to changes in ν_z; (b) observation of relativistic mass increase of 0.5 eV electron.*

Sensitivity was never better than 20 Hz out of 60 MHz with 400 second signal averaging. This sensitivity was rather poor compared to the 1 Hz resolution reported for earlier geonium measurements with a one second time constant [7]. However, we were awaiting delivery of a superconducting NMR magnet with a liquid helium Dewar in its bore and thus were forced to use an old Varian electromagnet and immerse the Penning trap in liquid nitrogen rather than liquid helium. The new apparatus (discussed in the next section) will doubtlessly have much better sensitivity.

A typical mass shift measurement is plotted in Fig. 1(b). The ordinate is identical to Fig. 1(a). The cyclotron drive was swept down through resonance (right to left). Like the anharmonic oscillator, the cyclotron frequency is pulled along as the excitation proceeds. The strength of the microwave drive is very critical. A slightly stronger drive knocks the electron out of the trap, presumably via collisions.

A further complication accounts for the restricted frequency range and the abrupt loss of the electron at the left of Fig. 1(b). The cyclotron motion of an electron in a Penning trap is actually superimposed on a slow drift orbit (magnetron motion) of frequency $\nu_m \simeq 90$ kHz for our trap. As has been observed elsewhere [7], the electron can also absorb energy at $\nu_c' + \nu_m$ or $\nu_c' - \nu_m$, the former shrinking the magnetron radius, the latter increasing it. We thus sweep down in frequency. When we hit the $\nu_c' - \nu_m$ sideband our strong drive pushes the electron out of the trap radially.

2.1 New Demountable Penning Trap

We have successfully trapped electrons in a new style, compensated Penning trap which differs substantially from earlier traps. Previous Penning traps [6, 7] were constructed like glass vacuum tubes. A change in the trap, however slight, required that the whole trap be disassembled, reassembled on a new pin base, sealed by a glass blower and baked to 400 °C. When cycled between room temperature and liquid helium temperature, the glass-to-metal seals proved to be unreliable vacuum seals. An internal ion pump was thus added to partially compensate. Finally, each trap consisted of five separately machined metal electrodes separated by four tubular glass spacers each of which was precision ground. Much precision mill work was required so that construction and assembly times were measured in man-years.

We felt that the rigors of a parts per billion measurement would be greatly facilitated by a Penning trap which was simpler, more rugged, and easily accessible for modification. The glass vacuum tube technology was accordingly abandoned in favor of a tubular copper envelope, sealed to copper flanges with demountable indium seals. We dispensed with the ion pump entirely since it seems clear that cryopumping alone will easily keep the vacuum inside the trap to better than 10^{-15} Torr [8]. Porous glass cryopump cells were mounted on the upper copper flange to greatly increase the cryopumping surface area. The whole system was baked briefly to 100 °C to drive off water vapor from the electron surfaces and then a copper pump-out tube was pinched off at a vacuum of 5×10^{-8} Torr.

The trap itself is mounted on a copper pin base flange as shown in Fig. 2. Alignment is provided by a ring of tungsten pins brazed to the copper base. These pins align

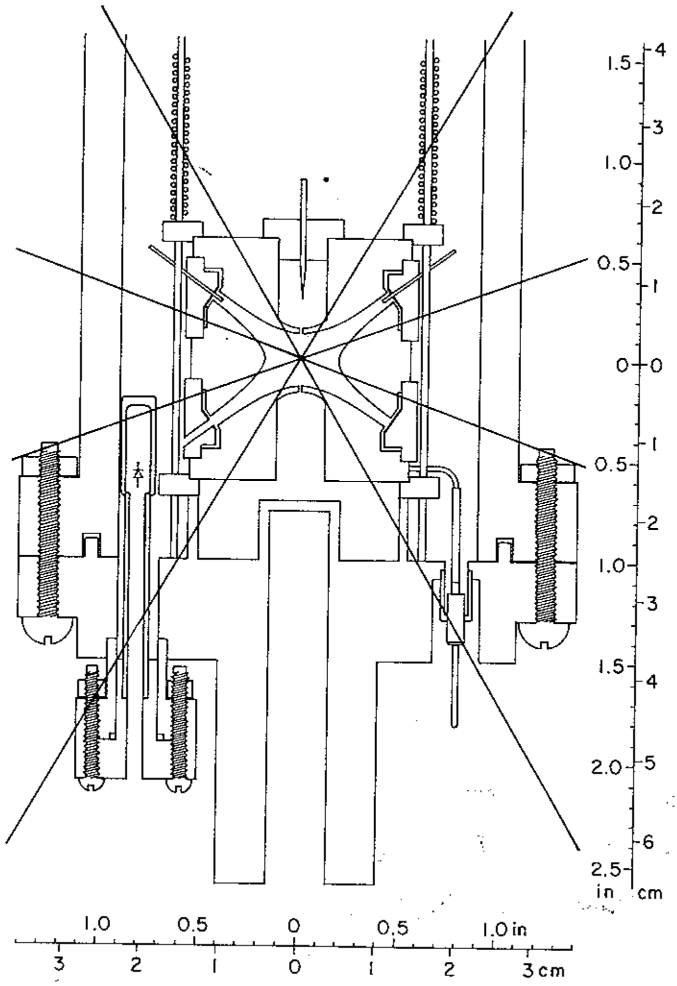

FIGURE 2. *Demountable Penning trap; θ = 30° and θ = 70° superimposed on Penning trap outline to indicate placement of magnetic compensation material.*

the trap elements by way of thin machinable glass ceramic (MACOR) rings on the outside of the endcaps and by springs. The two endcaps and the ring are made of molybdenum in this first version. These electrodes are simpler to construct than earlier traps in that no precision mill work is needed. The four ground glass spacers and the two metal compensation rings of previous traps have all been replaced by two spacers constructed from MACOR. Anharmonicity compensation is provided by a "thick-film" of silver metalized to the MACOR. Each thick film compensation ring is split to make a 1 turn coil which will be used to drive spin flip transitions (at ≈180 MHz). Holes through the spacers admit microwave drives and small probes are used to apply radio-frequency driving signals for cooling. MACOR can be machined using conventional metal working techniques and the thick film compensation electrodes can be added in several hours. Replacing six parts by two makes more precise alignment possible and also simplifies the machining.

Two demountable ports, also vacuum sealed by indium O-rings, are provided for admitting microwaves into the trap. In this first version microwaves will be generated by multiplying X-band up to 168 GHz in a multiplication diode inserted from outside the trap into a glass tube sealed to a copper stem. The electrical feed-throughs brazed into the copper base are commercially available. They are made from Constantan which is copper brazed to ceramic. The copper base has a hole on the trap axis which will allow inserting a ^{3}He NMR probe within 1.5 inches of the trap center. This probe will be used if necessary to stabilize the 60 kG magnetic field.

3. Bottleless Geonium

The small nickel ring, deliberately introduced into previous Penning traps, must be removed to improve our resolution of the anomaly beyond 10^{-8}. In addition, however, magnetic field inhomogeneities introduced by the paramagnetism of the trap electrodes must be removed as well [5]. A ring about the $\hat{z}$ axis with magnetism M and small cross sectional area A produces a magnetic field near the origin at (r, θ) and (ρ, z)

$$\mathbf{B} = \sum_0^\infty A_k\, r^k [P_k(\cos\theta)\hat{z} - (k + 1)^{-1} P_{k+1}(\cos\theta)\hat{\rho}]$$

where P_{km} is an associated Legendre polynomial. In cgs units

$$A_k = 2\pi MA\,(k + 1)(k + 2)\rho\, r^{-k-3} P_{k+2}(\cos\theta)\,,$$

where now the coordinates locate the ring. A symmetrical Penning trap like this one, with $\rho_o = \sqrt{2}\, z_o$, thus has a magnetic bottle with $A_2 \simeq 30\ M$. For a molybdenum trap at 4.2 K and 60 kG this suggests an intrinsic bottle about 20% of that previously introduced deliberately.

The next trap will no doubt be made of copper as a result (i.e., ten times less susceptibility). In the meantime, compensation rings made of iron will be placed between $\theta = 31°$ and $\theta = 70°$ where P_4 is negative to severely reduce the size of the intrinsic bottle. Figure 2 indicates these angles superimposed on the trap surfaces. Final cancellation will be achieved using the second order shims of the superconducting magnet.

4. g − 2 in Cooled Relativistic Geonium

We have considered many schemes for measuring g − 2 in bottleless geonium. As might be expected for an attempted measurement accurate to better than a part per billion, none of these promises to be easy. In the next few months the new trap will be used to evaluate the feasibility of these schemes.

The most promising approaches make use of the relativistic perturbation to the cyclotron levels [9, 10], as diagrammed in Fig. 3. The quantum numbers n and m pertain to cyclotron and spin levels. At 4.2 K the electron spends roughly 90% of its time in $n = 0$ and 10% in $n = 1$. The g − 2 transition, between ($n = 1$, $m = -1/2$) and ($n = 0$, $m = 1/2$), will be driven via single-turn bucking coils made from the compensation electrodes. We hope to determine if $m = -1/2$ or $m = 1/2$ and thus whether or not the spin has flipped by ascertaining whether the first cyclotron absorption occurs at $(1 - R)\nu_c$ or $(1 - 3R)\nu_c$. As a first attempt the cyclotron drive will be swept towards lower frequencies, starting between $(1 - R)\nu_c$ and $(1 - 3R)\nu_c$. This starting point must of course be determined experimentally. The successful observation of the relativistic mass increase (Section 1) suggests that there will be no major problem in driving the electron's cyclotron energy high enough to observe it via the relativistic shift of the harmonic frequency, once the classical region of $n = 10$ or higher has been reached. Obtaining substantial excitation probability to $n = 10$ promises to be more difficult since the 0.1 sec lifetime will make it difficult initially to maintain both the excitation and the frequency resolution. Experiments to establish a feasible detection scheme begin as soon as this conference ends.

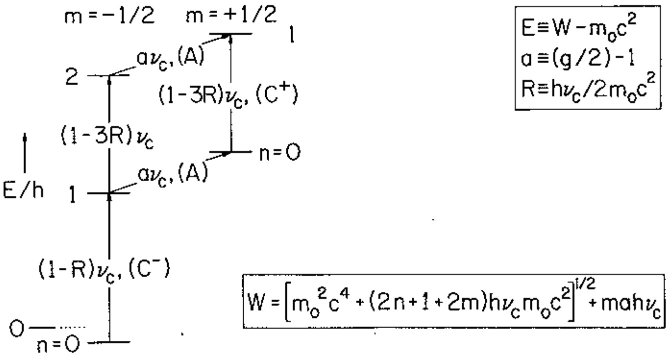

FIGURE 3. *Lowest cyclotron and spin energy levels for geonium.*

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