REMARKS ON THE OCCASION OF RECEIVING THE 1980 ISMAR AWARD

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As the Society has graciously awarded me its 1980 prize for the co-discovery of Nuclear Quadrupole Resonance (NQR) and the precise rf spectroscopic studies on an individual localized electron in a magnetic field (Geonium) I feel it appropriate to respond with a brief reminiscence about the early days of NQR followed by a description of the work leading to Geonium and its spectra.

In 1948, in the Institute of Hans Kopfermann in Göttingen, where I had just completed my experimental diplom-arbeit under Peter Brix, it was well known that I was supporting myself and my studies by the repair and barter of pre-war radios. So when Hubert Krüger, then one of Kopfermann's assistants, wanted to launch a search for rf spectra in solids, I was a natural choice and was signed on as his doctoral student. Prompted by the work of Pound (1) on ≤100 KHz quadrupole splittings in the NMR lines of single ionic crystals, Krüger suggested to me to choose a suitable compound, grow a single crystal as large as a child's head and build a super-regenerative spectrometer (see Figure 1) as described by Roberts (2) and begin a search for the zero magnetic-

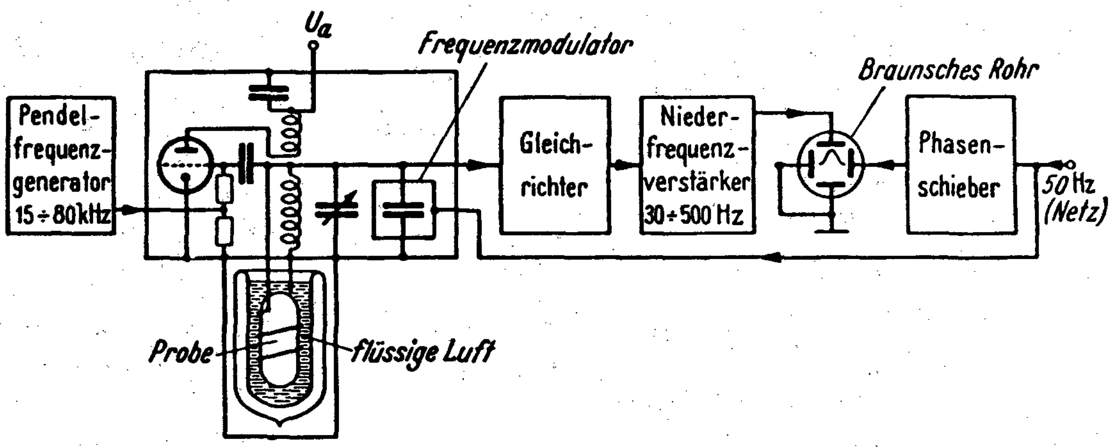


Figure 1. Simple frequency modulated super-regenerative spectrometer used in the first Nuclear Quadrupole Resonance experiments by Dehmelt and Krüger (3).

field spectrum. Realizing that polycrystalline samples would do fine and that signal/noise ratios sufficient for oscilloscopic observation and a fast search for ~ 100 MHz spectra might be available in frozen organic covalent compounds such as $Cl\text{-}CH_3$ at liquid air temperatures, I ventured along this alternate route. Noting that the vibrational frequency of N_2 changed little when going from the gaseous to the solid state, I estimated the zero field resonance frequencies in solid $Cl\text{-}CH_3$ from the rotational spectra data of Gordy et al. (4) to be 37.6 and 29.5 MHz for the ^{35}Cl, ^{37}Cl isotopes. I could not find the resonances with my super-regenerative spectrometer whose frequency I modulated with an oscillating capacitor fashioned from a relay. Blaming this (incorrectly, as it turned out later) on too much rotational freedom of the round molecule in the lattice I picked something more rectangular and interlocking but with essentially the same Cl-C bond, trans 1:2 dichloroethylene, and found two resonances, at 35.5 and 28.0 MHz, which could be quenched by bringing a bar magnet close to the sample and whose frequency ratio 1.27 agreed closely with that expected from the microwave data. Nuclear Quadrupole Resonance was found in the summer of 1949 (see Figure 2) and Kopfermann's Institute, was able to participate in the exploration of the new frontiers opened up by the pioneering work of Edward Purcell and of Felix Bloch.

After having developed NQR for several years, learned microwave techniques, and applied them to atomic phosphorus in Walter Gordy's laboratory, where I also collaborated with William Fairbank on liquid ^3He NMR, I finally obtained a faculty appointment at the University of Washington in 1955. Following an old desire to get away from the complexities of condensed matter I became intrigued by the trigger techniques developed for the rf spectroscopy of atoms, especially by the optical double resonance techniques of Alfred Kastler. Also, in my student days the orthodoxy whose purpose appears to be to invite challenge, had been that it was

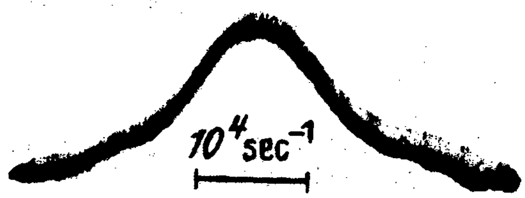


Figure 2. First Nuclear Quadrupole Resonance signal, observed on my home-made oscilloscope. Broad band display was used, from Dehmelt and Krüger (5).

impossible to measure spin and magnetic moment of a free electron. I took up the challenge, and proposed rf spectroscopy of stored ions in 1956 (6). Extending Kastler's techniques, I developed spin-exchange optical pumping, and by this means succeeded in the first spin magnetic resonance experiment on free electrons in December 1956 (7). These experiments, eventually yielded a magnetic moment value μ_s = 1.001 116(40) Bohr magnetons.

Attempts to eliminate the inert buffer gas used in these early experiments led to lengthy experiments with various traps. Finally, in 1959 I began to concentrate on the high vacuum Penning trap (magnetic field plus parabolic axial electric potential, the latter well known from NQR) after I realized that the electric shift it

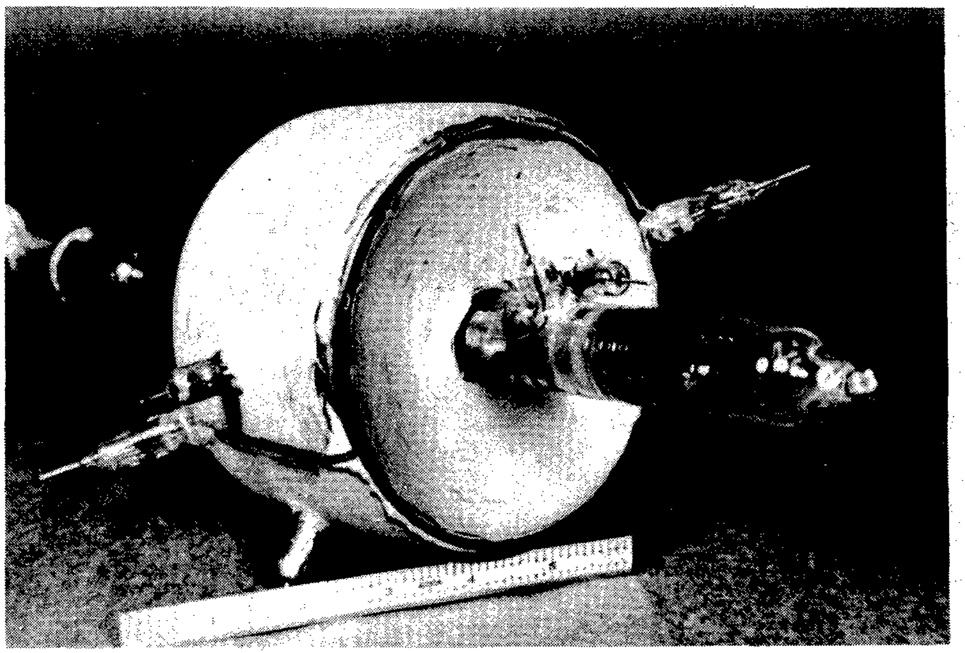


Figure 3. My 1959 anharmonicity-compensated 7-electrode low magnetic field sealed-off Penning trap tube used in axial and cyclotron resonance experiments in electron clouds (8,9).

induced in the electron cyclotron frequency would be constant throughout the trap volume. The first successful trap tube built by me in 1959 is shown in Figure 3, and an axial resonance obtained with it in Figure 4 (8,9). While developing this trap in electron cloud experiments with Walls and Stein, I also gained further experience in the successful work with Paul traps on the hfs of $^3He^+$ and H_2^+ in my laboratory. Finally, the conditions were ripe to attempt the realization of an old goal of mine that dated back to the day I saw my teacher Richard Becker draw a dot on the blackboard in his Electricity and Magnetism lecture saying: "Here is an electron . . ." The goal was the isolation, permanent confinement, and continuous observation of an individual electron (almost) at rest in space. This "mono-electron oscillator", whose feasibility I had pointed out in 1962 (see Figure 5) was demonstrated together with Wineland and Ekstrom in 1973 (see Figure 6.)

We worked out a scheme (12) to monitor the spin state of the trapped electron by means of small axial frequency shifts induced by an auxiliary shallow magnetic bottle (to communicate with the electron on the axial frequency via FM radio). My scheme was stimulated by rumors about the axial Stern-Gerlach Effect for charged particles circulating during my student days in the corridors of Kopfermann's Institute where Paul and Friedburg (13) invented the magnetic hexapole lens for atomic beams in 1951 (now used in the H-maser), and also by a 1953 proposal by Felix Bloch (14). Realization of Bloch's proposal which relies on the vanishing magnetism of electrons in

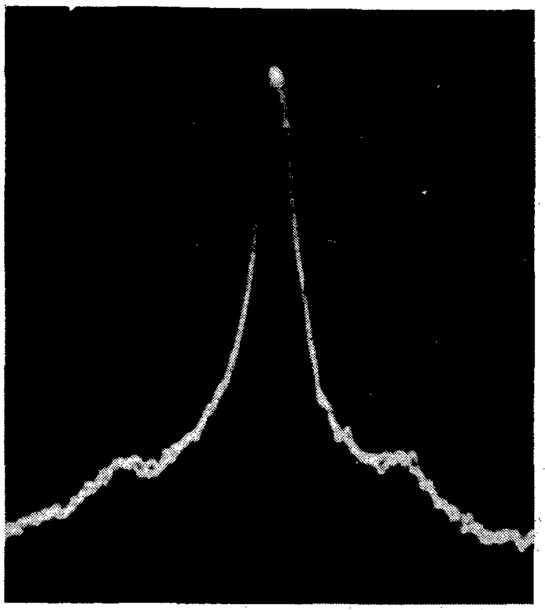


Figure 4. Axial resonance obtained in 1960 with my 1959 Penning trap tube. The central peak is at $\nu_z = 2.75$ MHz. The two satellites are at $\nu_z \pm \nu_m$ where $\nu_m = 100$ KHz denotes the magnetron or drift frequency. The cyclotron frequency was $\nu_c' = 37.9$ MHz (8,9).

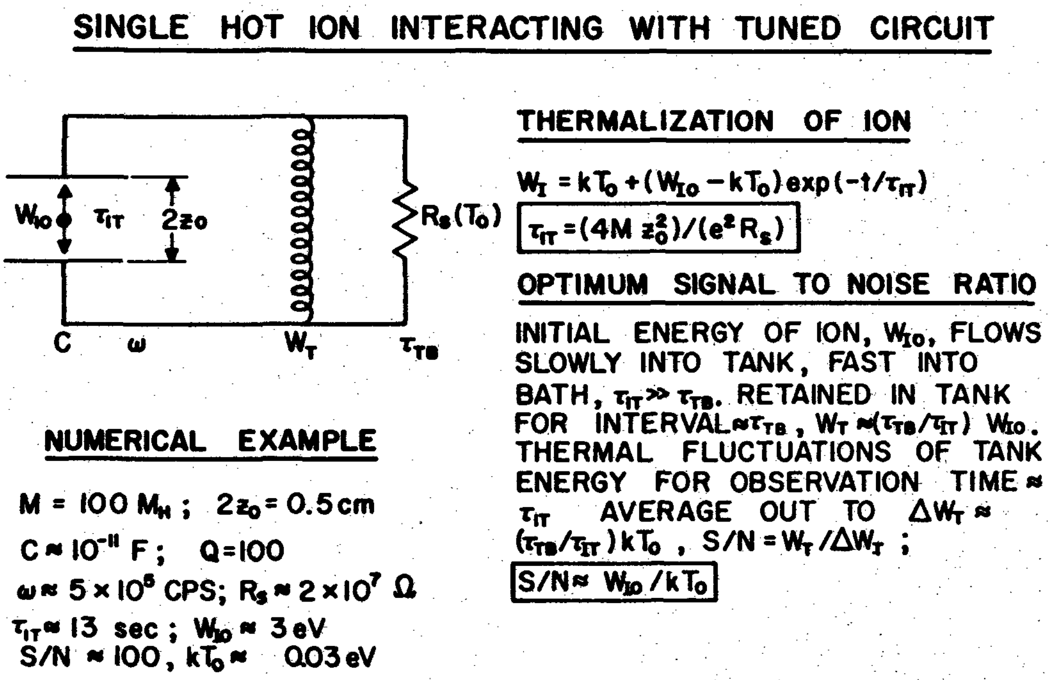


Figure 5. Early discussion of the cooling of a hot elastically bound ion through interaction with a resonant circuit, and of the signal/noise ratio available for narrow-band detection of the transient signal (10).

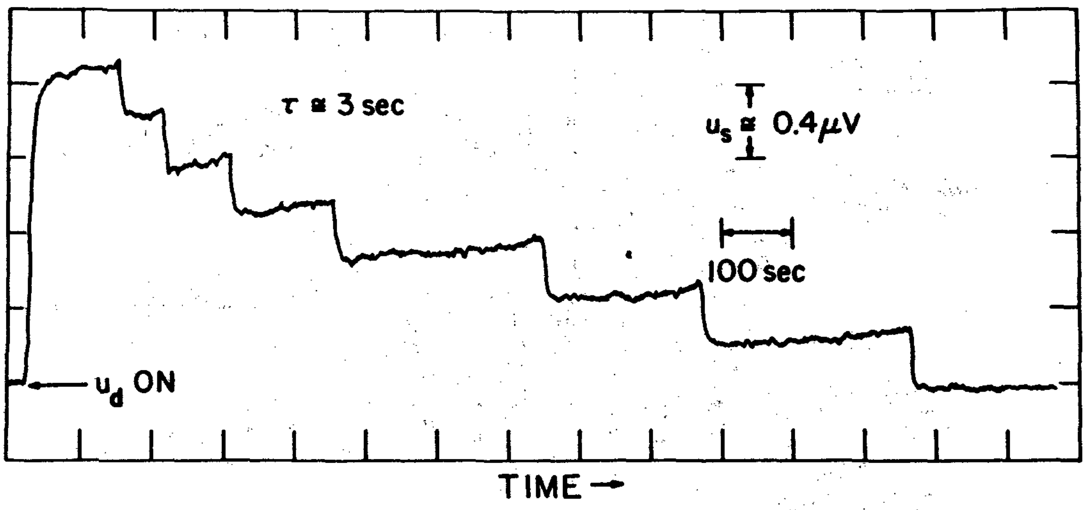


Figure 6. Recorder trace of forced oscillation signal versus time. The signal at $\nu_{z0} \approx 55.7$ MHz for an initially injected bunch of electrons decreases discontinuously as the electrons are successively boiled out of the trap by the drive at $\nu_z' \approx 54.7$ MHz. The last plateau corresponds to a single electron (11).

the $m = -\frac{1}{2}$, $n = 0$ state, is being attempted by groups at Stanford and at Mainz. However, no results have been reported so far on this continuing work (15).

Our scheme and subsequent successful experiment resurrects the axial Stern-Gerlach Effect for the free electron. This Effect was briefly discussed by Wolfgang Pauli (16) at the 1930 Solvay Congress (17), and immediately discarded on the basis of Heisenberg's uncertainty principle. Pauli was then illustrating Niels Bohr's assertion that it is impossible to measure the spin and associated magnetic moment of a free electron in experiments based on spin dependent changes in classical trajectories. Obviously, after our experiment Bohr's assertions cannot claim general validity.

The magnetic bottle (Figure 7) used in our apparatus for observation of Geonium Spectra (see Figure 8) is realized by a nickel wire wound around the ring electrode of the Penning trap which the 18 - 52 kG applied magnetic field magnetizes to saturation. The trap tube which, Ekstrom and Robert Van Dyck, built along lines suggested by me, is shown in Figure 9. In operation it is submerged in a liquid He bath. Figure 10 shows a ~ 8 Hz wide axial resonance line at $\nu_z \approx 60$ MHz obtained with our apparatus. Important contributions to the development of this apparatus were also made by Schwinberg. We observed the first spin-flip signal in 1976 (see Figure 11) with the detection circuit shown in Figure 12. This experiment marks the advent of serious mono-particle spectroscopy. The trace shows the continuously recorded axial resonance frequency of the electron, the recorder sweeping back and forth until on the third sweep (backward) a spin flip becomes apparent *indicating a frequency*

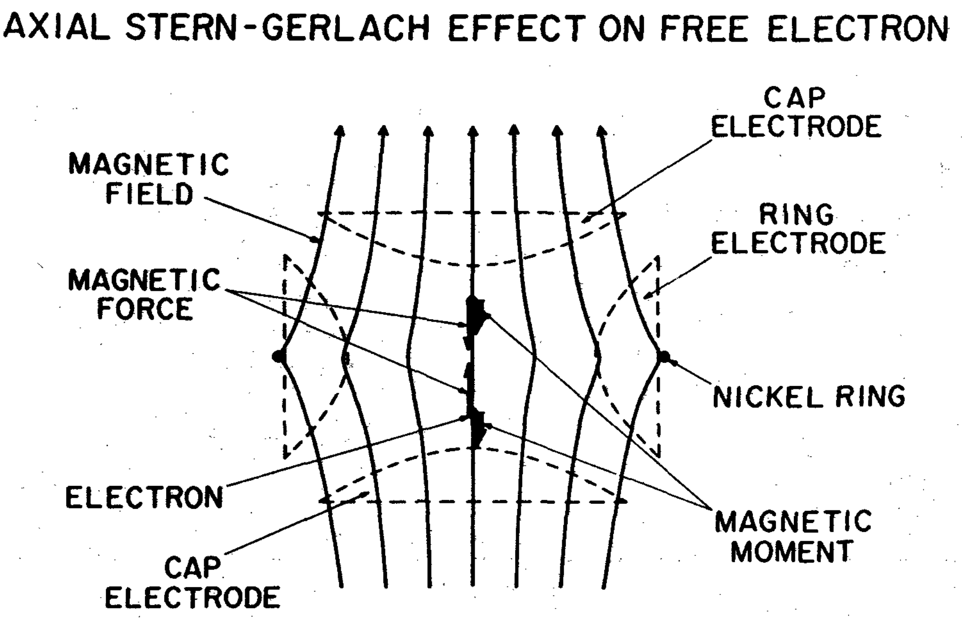


Figure 7. The axial Stern-Gerlach Effect (schematic): an electron slowly moving along a field line in an inhomogeneous magnetic field with its magnetic moment parallel/antiparallel to the field is driven towards stronger/weaker fields. We show here the minute magnetic forces which add to the strong axial electric forces in our experiment and slightly modify the parabolic trapping potential (25).

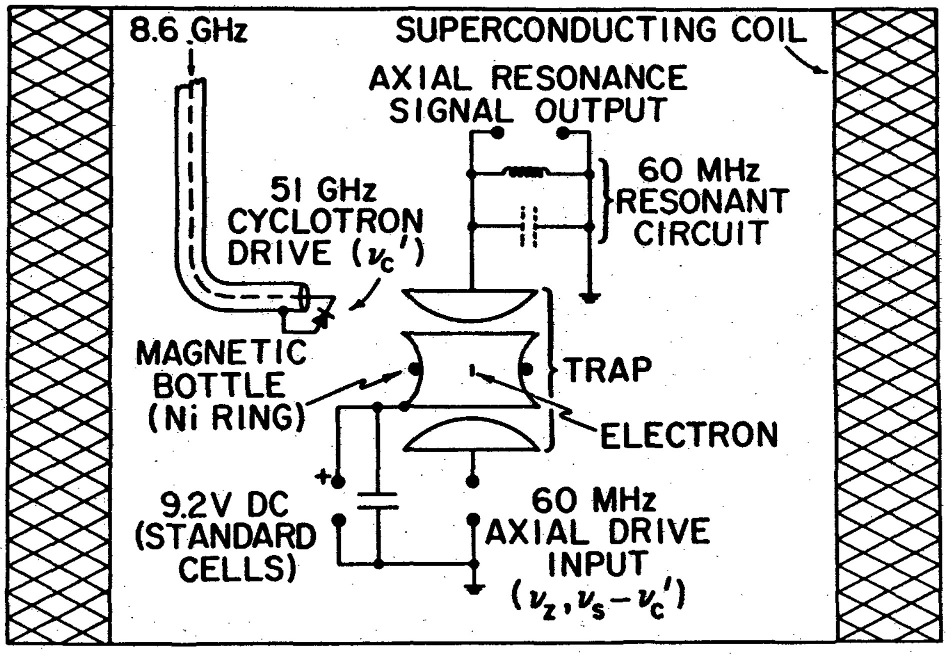


Figure 8. Geonium spectroscopy experiment (schematic). This apparatus allows the measurement of the cyclotron frequency, ν_c', and the spin-cyclotron-beat (or anomaly) frequency, $\nu_a' = \nu_s - \nu_c'$, on a single electron stored in a Penning trap at $\simeq 4^\circ$K ambient. Detection is via Rabi-Landau level-dependent shifts in the continuously monitored axial resonance frequency, ν_z, induced by a weak magnetic bottle (18).

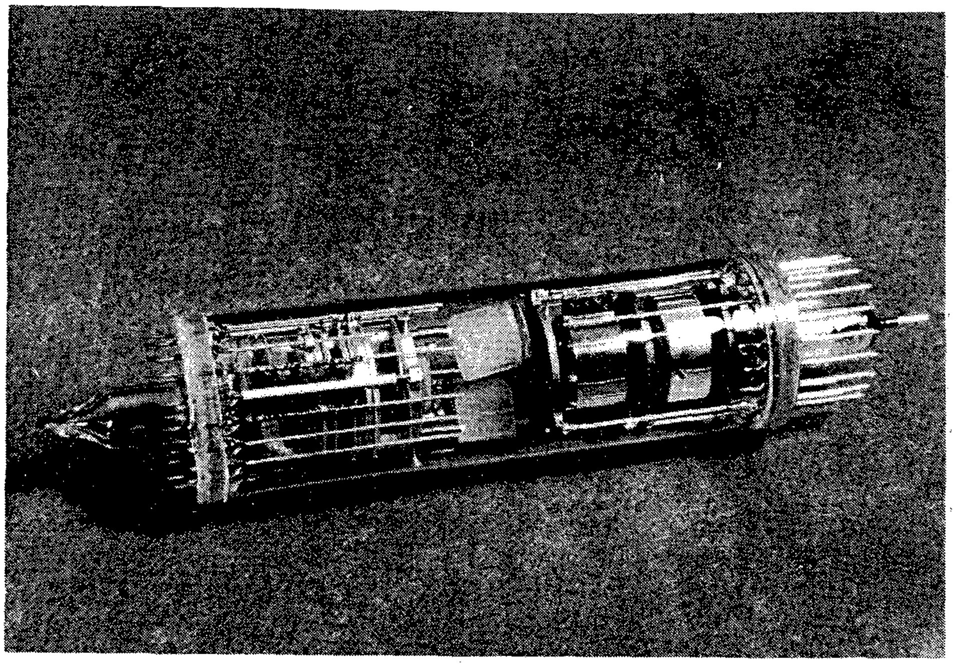


Figure 9. Photograph of 6-electrode 1974 tube. The left half houses the trap, the right ion-getter and cryosorption pumps capable of < 10^{-14} torr vacuum (19).

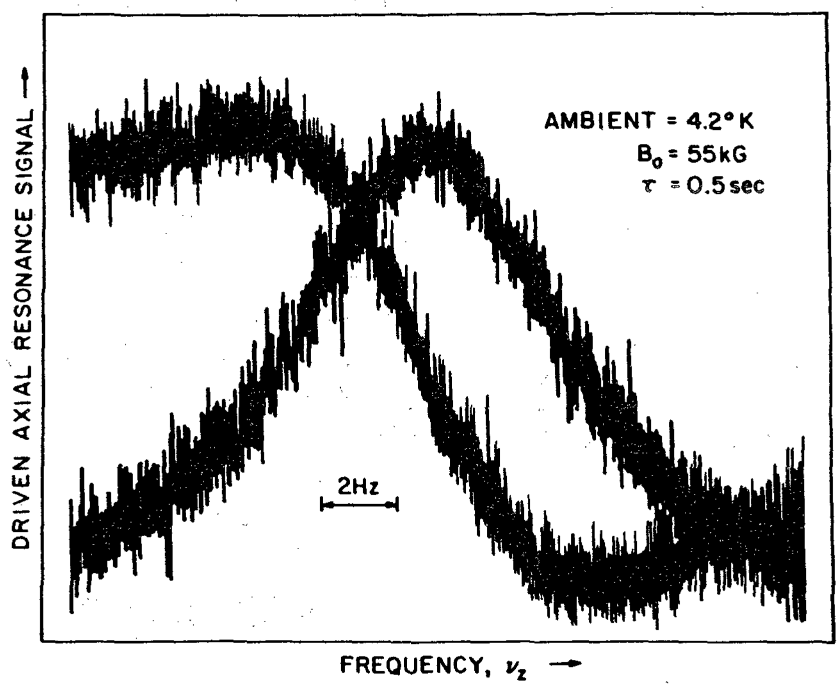


Figure 10. Axial resonance signals at ≈ 60 MHz; note 8 Hz width. Absorption and dispersion modes are shown (18).

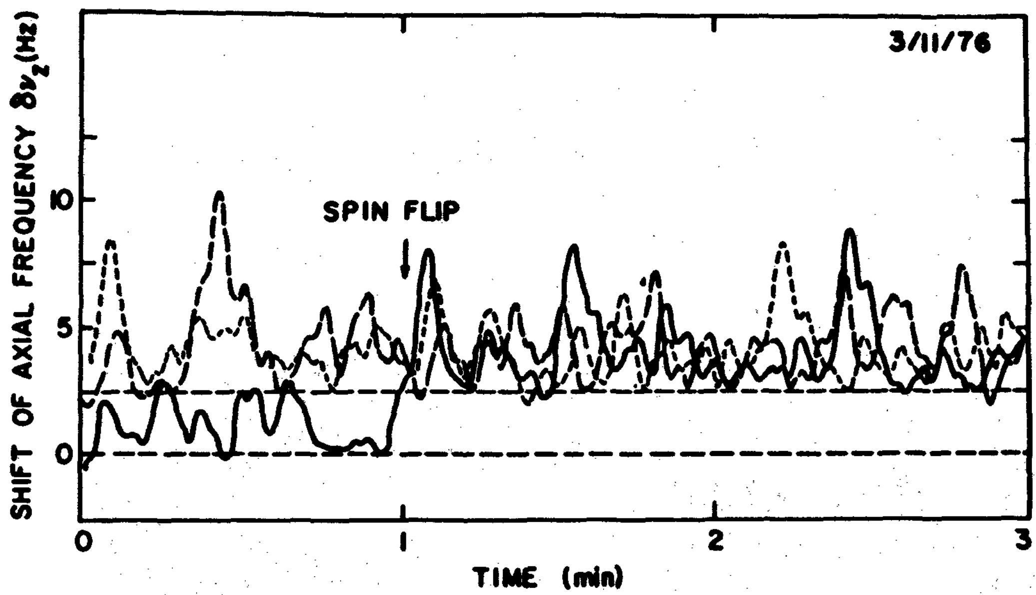
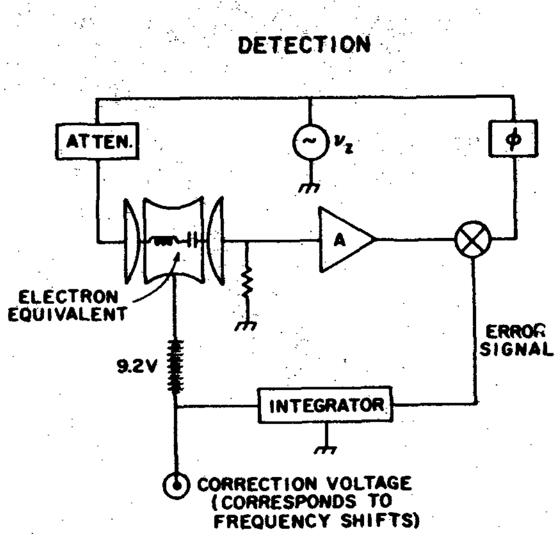


Figure 11. First spin flip seen in monoelectron oscillator (GEONIUM). Due to the random fluctuations in the thermally excited cyclotron motion the axial frequency shift $\delta\nu_z$ associated with the magnetic bottle shows a corresponding unsymmetric fluctuation always staying above a fixed floor for a given spin direction. However, this floor suddenly changes by 2.5 Hz when the spin is flipped, which occurs occasionally for the near-resonance $\nu_z - \nu_a \simeq 2$ KHz obtaining here. Only the ν_z (detection) drive was used (19).

Figure 12. Detection circuit for the axial resonance at ν_z. The electron acts effectively like an LC series resonant circuit connecting the cap electrodes. The circuit also locks the electron frequency to that of the very stable generator. (18).



difference of 2.5 Hz between $m = +\frac{1}{2}$ and $m = -\frac{1}{2}$. Already this constitutes a crude measurement of the magnetic moment. The prominent upwards random fluctuations reflect the dependence of the bottle induced frequency shift $\delta\nu_z = (m + n + \frac{1}{2})$ 2.5 Hz on the thermally excited (4°K) cyclotron motion (quantum number n). The spin flip is an "assisted" Majorana "flop" (20) caused by the driven axial motion, at $\nu_z \simeq \nu_s - \nu_c$, and the thermal cyclotron motion at ν_c, through the inhomogeneous field of the magnetic bottle. The bottle here serves a distinct, different, second function (see Figure 13).

It is instructive and illustrates one aspect of the significance of the term "Geonium" which I coined for the closed system (electron, trap-magnet-earth) to look at the time development of the system due to resonance of the axial motion at ν_z with the spin-cyclotron beat frequency ν_a, (see Figure 14). Assuming the initial state mnkq = $\frac{1}{2}$000 and 0°K ambient temperature, energy and angular moment conservation considerations show that due to the magnetic bottle a transition to the state $-\frac{1}{2}$110 may occur. In this transition, the spin looses an amount of angular momentum $\hbar$, the cyclotron motion gains the kinetic angular momentum $2\hbar$, the earth looses $\hbar$ and the energy excess in the spin state energy over the cyclotron energy is absorbed by the axial motion (quantum number k). The magnetron motion quantum number q remains unchanged. Observation in our experiment of the two different values for the floors of the cyclotron noise patterns corresponding to n = 0 confirms the spin value $\frac{1}{2}$. In its first function the magnetic bottle serves even better in the detection of cyclotron excitation (see Figure 14) as larger shifts $\delta\nu_z$ are easily produced.

The most recently obtained cyclotron resonance (21,22) is shown in Figure 15. The characteristic vertical rise-exponential decay shape of the line is due to the thermal axial motion at about 20°K through the magnetic bottle. The nearly vertical edge allows determination of the cyclotron frequency to ~ 500 Hz or 3 parts per billion. A similarly shaped resonance at the spin-cyclotron beat frequency $\nu_a \equiv \nu_s - \nu_c$ is shown in Figure 16. Actually, both anomaly frequency and cyclotron frequency as measured in our apparatus, now designated ν_a', ν_c', are shifted by the radial electric field in the trap by an amount δ_e with respect to the zero electric field values ν_a, ν_c so that $\nu_c = \nu_c' + \delta_e$ and $\nu_a = \nu_d' - \delta_e$. For an ideal trap one has $\delta_e = \nu_m$, where ν_m denotes the magnetron or drift frequency in the trap which also may be measured to milli-Hz by our magnetic bottle technique, (see Figure 17). The presence of the magnetic bottle makes

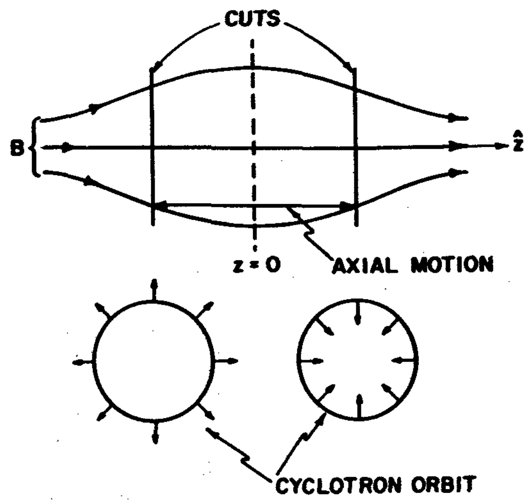


Figure 13. Mechanism for inducing spin flips by the electron's axial motion in the magnetic bottle. From the electron's frame of reference, a magnetic field is seen rotating at ν_c', but modulated by the auxiliary axial motion at ν_a', yielding sidebands at $\nu_c' \pm \nu_a'$ with $\nu_s = \nu_c' + \nu_a'$. (18).

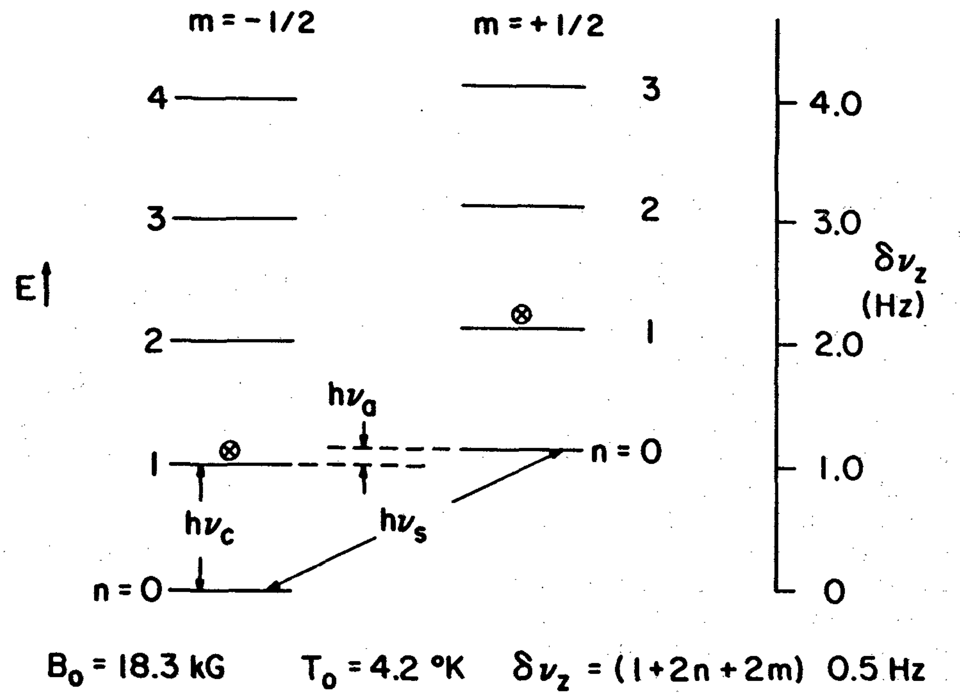


Figure 14. Electron Rabi-Landau levels and associated magnetic bottle shifts $\delta\nu_z$. (18).

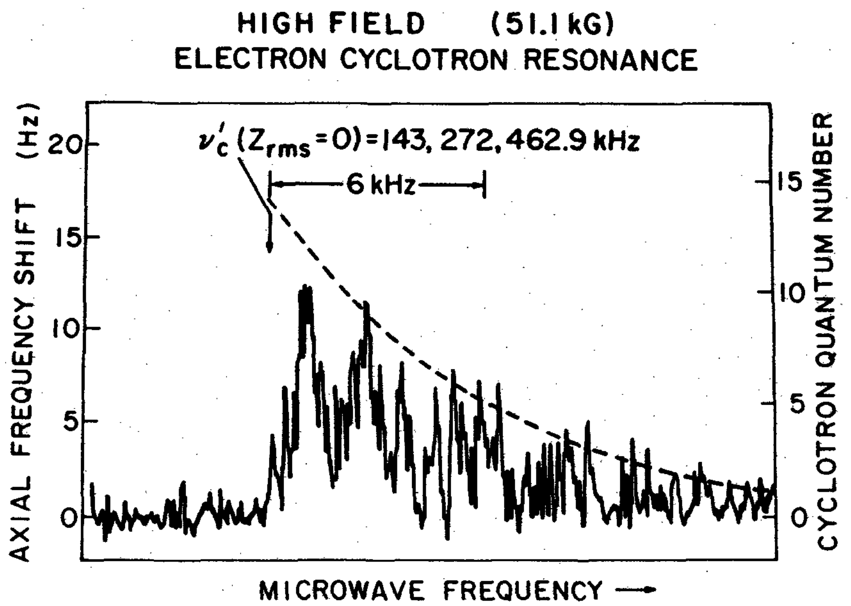


Figure 15. Geonium cyclotron resonance. The vertical rise-exponential decay line shape exhibiting a signal strength decline to 1/e for a 6 kHz displacement reflects the proportionality of the average magnetic bottle field seen by the electron to the instantaneous thermally excited axial energy. At an axial temperature 16°K the nearly vertical edge allows determination of ν_c' when the electron is at the bottom of the magnetic well (z = 0) to ~ 500 Hz (21,22).

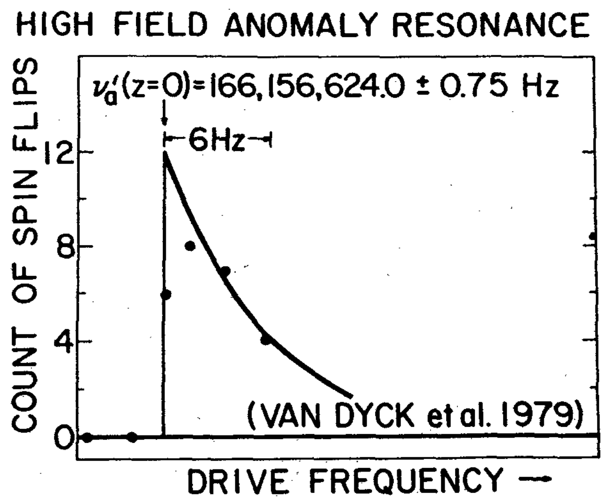


Figure 16. Geonium anomaly resonance. The line shape is similar to that of Figure 15 and the characteristic ~ 6 Hz displacement is also that expected for $T_z \simeq 16°K$ (21).

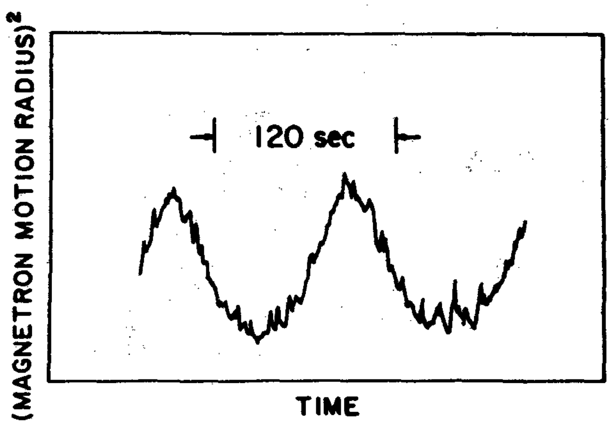


Figure 17. Beat between free and driven magnetron motions at 35,052.628 and 35,052.620 Hz. Driving the completely undamped magnetron motion only ≃ 10mHz away from the resonance creates a slow beat from which the resonance frequency may be determined to ≃ 1 mHz (18).

it clearly desirable to always localize the electron, whose orbit z is shown in Figure 18, as close as possible to the bottle center. This may indeed be achieved by a new technique developed by us, (see Figure 19). Table 1 shows data from an earlier phase of the experiment, performed at 18 kG. The anomaly a, the g-factor and the frequencies ν_s, ν_c are related by

$$g/2 \equiv \nu_s/\nu_c = 1 + a \ .$$

Comparing ν_m, and δ_e calculated from the measured ν_c', ν_z values provides a sensitive check of the axial symmetry of the trap. In the meantime, in about 40 additional runs at 18.6, 32.0, and 51.1 kG, we have collected more precise data and are now quoting (21)

$$\nu_s/\nu_c \equiv g/2 = 1.001\ 159\ 652\ 200\ (40).$$

This also equals the electron spin

Table 1

SAMPLE DATA AND RESULTS (18)

<u>MEASURE</u> (<u>1</u> <u>RUN</u>)

ν_z = 59 336 170.14 ± .10 Hz
ν_m = 34 471.9 ± .1 Hz
ν_c' = 51 072 915 ± 10 KHz
ν_a' = 59 261 337.5 ± 4.5 Hz

<u>CALCULATE</u>
<u>FROM</u> $2\delta_e\nu_c' = \nu_z^2$
δ_e = 34 468.18 ± .1 Hz

<u>MEASURE</u> <u>TRAP</u> <u>INPERFECTIONS</u>
$\nu_m - \delta_e$ = 3.7 Hz , $(\nu_m - \delta_e)/\delta_e \simeq 10^{-4}$
(CORRECTION TO δ_e) << 3.7 Hz

<u>OBTAIN</u> (<u>8</u> <u>RUNS</u>)
<u>WITH</u> $\nu_c = \nu_c' + \delta_e$, $\nu_s - \nu_c = \nu_a' - \delta_e$,
$a \equiv (\nu_s - \nu_c)/\nu_c$

<u>a = 1 159 652 410 (200) x 10^{-12}</u>

200 x 10^{-12} IN a → 10 Hz IN ν_a

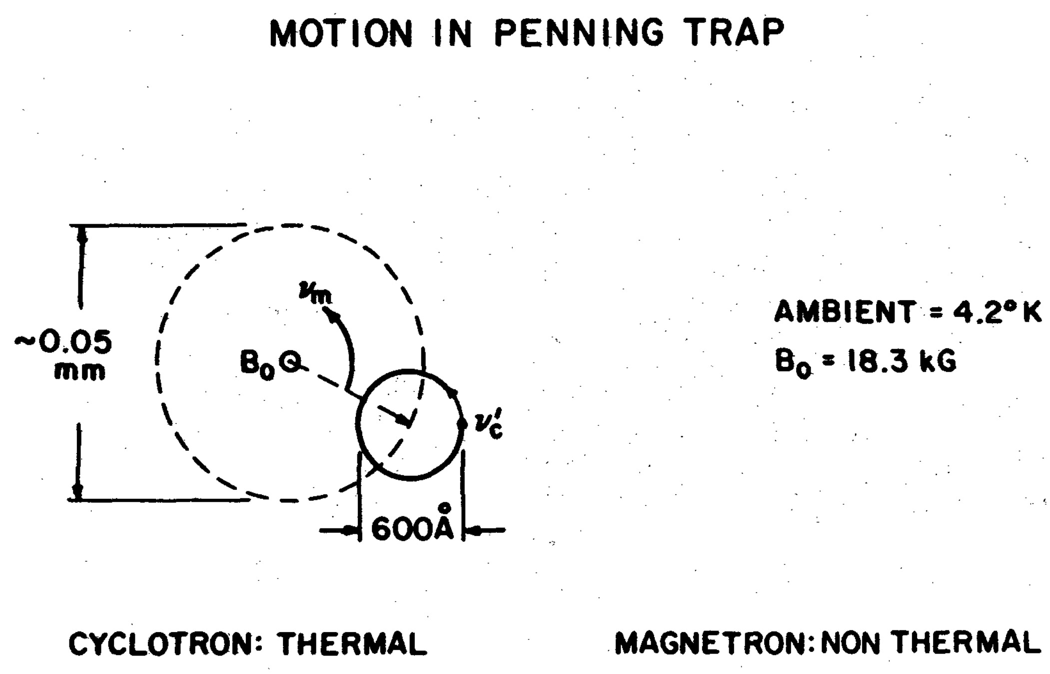


Figure 18. Geonium orbits under thermal excitation at ≃ 4°K (18).

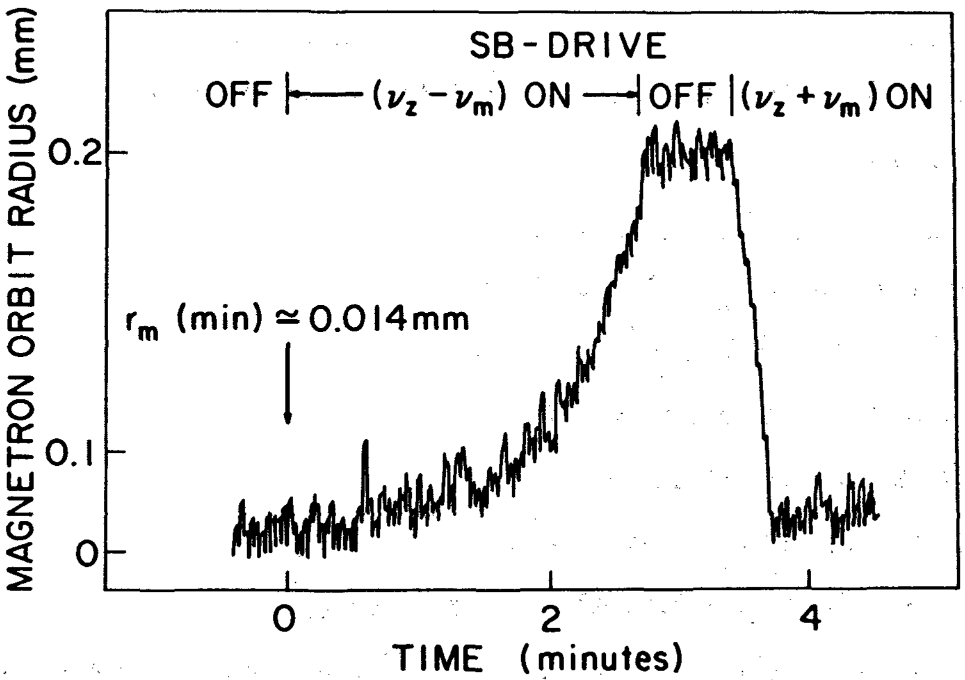


Figure 19. Expanding and shrinking of magnetron orbit radius (side band cooling). By driving the axial motion on the side bands $\nu_z \pm \nu_m$ it is possible to force the magnetron motion at ν_m to absorb/provide the energy balance $h\nu_m$ and thereby shrink/expand the magnetron orbit (18).

magnetic moment value in Bohr magnetons and is currently the most accurately determined parameter of an elementary particle.

Kinoshita (23) has compared our result in the form $a_e^{exp} = g/2 - 1$ with a theoretical a-value calculated by him and also obtained the most accurate α-value to date from it (see Table 2). In view of the many steps which enter into the determination of the non-QED value of α based on the e/h value from the Josephson Effect, one may feel that the agreement is remarkably good. A detailed account of our work will be published in Physical Review. An updated survey (25) has been published, and a recent review of lepton magnetic moments and their significance has been given by Field et al. (26). Also, Ekstrom and Wineland (27) have published a popular article on Geonium physics.

I should like to thank my theoretical colleagues at the University of Washington, especially L. S. Brown and P. C. Peters for many critical and clarifying discussions. Extensive discussions with I. I. Rabi, N. F. Ramsey, R. W. Williams, and W. H. Wing, are acknowledged. My colleagues and collaborators, Robert S. Van Dyck, Jr., Paul B. Schwinberg, and Gerald Gabrielse, read the manuscript and offered valuable comments.

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Table 2. Recent Experimental and Theoretical Anomaly Data Compiled by Kinoshita

New experimental value of a_e by Van Dyck et al. (21):

$$a_e^{exp} = 1\ 159\ 652\ 200(40)\times 10^{-12}.$$

New value of α by Williams and Olsen (24):

$$\alpha^{-1} = 137.035\ 963(15)\ (0.11\ \text{ppm}).$$

Best theoretical value of a_e to order α^3:

$$a_e^{th} = 0.5(\frac{\alpha}{\pi}) - 0.328\ 478\ 445(\frac{\alpha}{\pi})^2 + 1.183\ 5(61)(\frac{\alpha}{\pi})^3,$$

where the last term includes the new value of light-by-light contribution

$$0.370\ 986(20)(\frac{\alpha}{\pi})^3$$

obtained by Levine and Engelmann.

From (2) and (3) we obtain, Kinoshita (23),

$$a_e^{th} = 1\ 159\ 652\ 569(150)\times 10^{-12}\ .$$

Alternatively, combining (1) and (3), we find

$$\alpha_{g-2}^{-1} = 137.036\ 006(11)\quad (0.08\ \text{ppm}).$$

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