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Preliminary Proton/Electron Mass Ratio using a Compensated Quadring Penning Trap

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A new type of compensated Penning trap with the ring electrode split into equal quadrants allows intense unshifted ion cyclotron resonances to be synchronously detected with very small relative linewidths ($< 2\times10^{-9}$). By measuring the cyclotron frequencies of both protons and electrons in the same magnetic field (5 T) and the same trapping volume ($<10^{-7}$ cm^3), a preliminary value of the mass ratio $m_p/m_e = 1836.153\,00(25)$ is obtained with an accuracy that is more than four times greater than any previous direct measurement.

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The proton/electron mass ratio is a fundamental constant which appears often in specific theories of atomic or elementary-particle physics in the form of a reduced mass effect or an isotope shift. An illustration of the need for precision in this mass ratio can be found in the recent comparison of theory with a precision measurement of the Lyman-α resonances of atomic hydrogen and deuterium.[1] Also, a 0.01-ppm determination of m_p/m_e will allow an unambiguous consistency check to be made upon many other precisely measured fundamental constants such as the Faraday, the as-maintained ampere to absolute ampere, the atomic mass unit to kilgram conversion factor, the proton gyromagnetic ratio, and the Avogadro number. Previously, the most precise value of m_p/m_e was 1836.151 65(68), indirectly determined from other precision constants.[2] This can be compared with direct measurements of 1836.1502(53) made by Gärtner and Klempt[3] and 1836.1527(11) obtained by Gräff, Kalinowsky, and Trant[4] with use of a time-of-flight technique to detect resonant cyclotron excitation in a Penning trap. The only precise theoretical value is a speculation by Wyler[5] that suggests that $m_p/m_e = 6\pi^5 = 1836.118\,11$, which is many standard deviations away from several experimentally obtained values of m_p/m_e.[6]

The compensated Penning trap[7] is a device which requires both electric and magnetic fields in order to confine charged particles. However, our use of this device is specifically characterized by nondestructive detection of the charge's motion by using resonance techniques. The use of such methods in this trap have made precision measurements of the electron g factor[8] possible and therefore suggested that these methods would also work to measure ion cyclotron frequencies directly.[9,10]

The simple result of comparing respective cyclotron resonances should directly yield the mass ratio (assuming identical charges). However, the motion of a charged particle in a Penning trap slightly modifies this simple picture.[8] The charge oscillates axially in the electric potential well with a frequency ν_z while rotating in a radial plane at the observed cyclotron frequency ν_c'. In addition, the crossed electric and magnetic fields produce a slow unbounded, but metastable, rotation of the center of the cyclotron orbit at the magnetron frequency ν_m. From the equations of motion for one ion of mass m and charge e isolated within a Penning trap, we have

$$\nu_c = \nu_c' + \nu_m = eB_0/2\pi mc,$$

where $\nu_m = \nu_z^2/2\nu_c'$ and B_0 is the applied magnetic field. The magnetron frequency which is used to correct the observed cyclotron frequency can be measured with use of a motional sideband[11] such as $\nu_z + \nu_m$ or $\nu_c' + \nu_m$. Such cooling or centering resonances for the magnetron motion have been observed by us and described previously.[8] For a single electron in a recent trap, the measured and computed values of ν_m have agreed to within a few ppm. Such agreement is crucial in order to justify the use of this type of resonance method.

The experimental apparatus, shown in Fig. 1, consists of a trap tube supported at the center of a 30 cm long, very stable (<2 ppb/h), and reasonably uniform (<3 ppm over a 1-cm sphere) superconducting solenoid. The "quadring" Penning trap, shown schematically with hyperbolic endcap and ring electrodes, is characterized by dimensions $R_0 = 0.159$ cm and $Z_0 = 0.112$ cm. In addition, the trap has two guard electrodes[7] (not shown) which compensate for the truncations and cuts in the main electrodes and a hyperbolic ring electrode split into four equal quadrants.[10] This quadring design allows excitation to occur on two opposite quadrants and detection to take place on the other pair which in effect form the plates of a capacitor externally tuned to the ion cyclotron frequency. The two axial frequencies, $\nu_z(e^-)$ and $\nu_z(p^+)$, are also detected with use of a tuned circuit resonant at the appropriate frequency and attached to one or the other endcap. Also shown is the Schottky multiplier diode which generates the microwave field required to excite the electron cyclotron resonance at $\nu_c'(e^-)$. Finally, the entire apparatus, consisting of trap tube, microwave diode, and tuned preamplifiers, is constructed to operate in a liquid-helium environment in order to yield the required signal-to-noise ratio and high resolution.

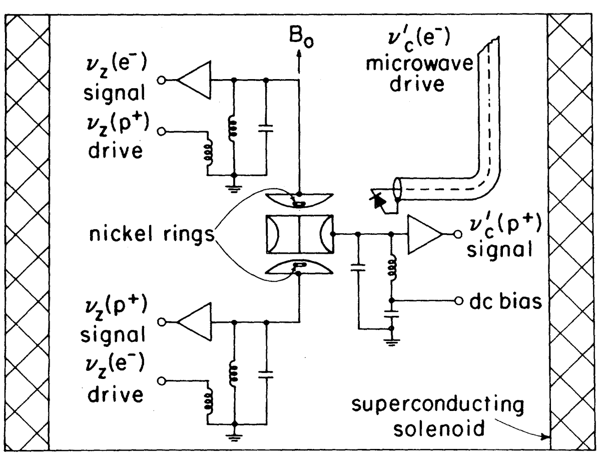

FIG. 1. Schematic of experiment. Both endcaps and the quadring have tuned preamplifiers attached to measure either ν_z or ν_c'. rf axial drives are applied to the endcap opposite the detector and microwave excitation for $\nu_c(e^-)$ radiates from a Schottky multiplier diode.

Included in each endcap are a small nickel ring and a source of either electrons or hydrogen. The electron source is a sharpened tungsten needle which can be biased to field emit a primary electron beam through the trap and generate within the trapping volume both secondary electrons and ions from either background gas or hydrogen liberated from a hydrated titanium filament in the opposite endcap. The nickel rings produce a very weak magnetic bottle which generates a change in the uniform magnetic field given by $B_2(z^2 - r^2/2)$, where B_2 depends on geometry and material.[8,12] The net effect of this bottle is to weakly couple the magnetic moment of the charge to the axial resonance in the form of a small frequency shift (~25-ppb shift per quantum level for electrons). However, this coupling is useful only for detecting the electron's cyclotron frequency [$\nu_c(e^-) \sim 140$ GHz] and, at the present level of accuracy, does not provide a significant perturbation to the proton cyclotron resonance.

Preliminary trapping of electrons presently indicates that the chosen well depth is too shallow to fully compensate the trapping field and to allow narrow single-electron resonances to be observed. The large volume of space sampled in the shallow well obviously produces a large anharmonic contribution to the potential. Nevertheless, the compensation is adequate to observe cyclotron resonances for the ten electrons as shown in Fig. 2. These signals are proportional to axial frequency shifts and are produced by locking the axial resonance to a stable drive oscillator. As typical of past electron traps with magnetic bottles,[8,10] the resonances show a clear low-frequency edge, corresponding to $Z_{\rm rms} = 0$, and a high-frequency exponential tail. Typical repeatability of these edges is better than 0.1 ppm for low applied microwave power.

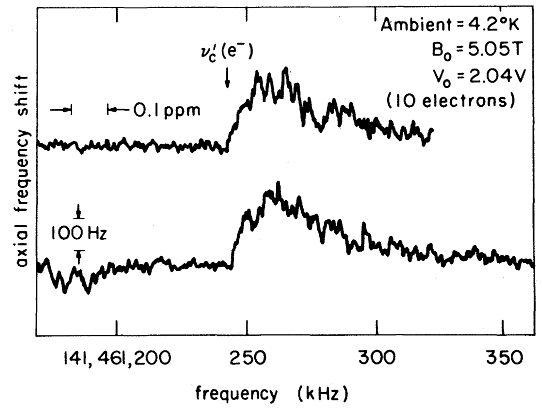

FIG. 2. Electron cyclotron resonance. Two separate traces show the repeatability of the low-frequency edges ($Z_{\rm rms} = 0$). As usual, the high-frequency tail is due to the thermal axial states.

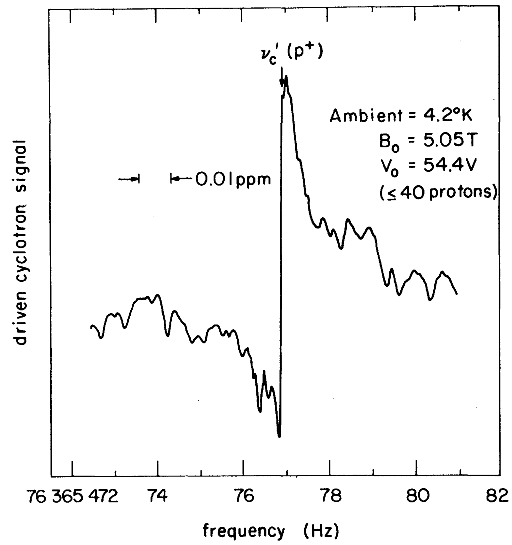

FIG. 3. Proton cyclotron resonance. The drive phase has been adjusted to approximately produce a dispersion curve during synchronous detection. The linewidth is limited primarily by observation time.

Small numbers of protons have also been trapped and synchronously detected in order to yield the cyclotron resonance shown in Fig. 3. By means of the compensation process, narrow linewidths ≤ 0.2 Hz have been obtained for $\nu_c'(p^+)$ at 76.4 MHz (resolution ~1 ppb). In such a highly corrected trap, a center-of-mass resonance for N charges moving in the external field has a linewidth proportional to N. In this case, the external damping in the quadring tuned circuit would predict that the single-proton cyclotron linewidth is 0.005 Hz. Thus, the observed 0.2-Hz cyclotron resonance is produced by a cloud containing at most forty protons; in particular, observation time makes up ~80% of the present linewidth. Axial proton resonances have also been synchronously detected, but with 100 times less resolution; fortunately, axial instability affects the observed cyclotron resonance only at the ppb level via the magnetron (correction) frequency.

It is commonly known that an imperfect trap can exhibit a shift in its ion cyclotron resonance proportional to the number of trapped ions.[3,4,13] However, this dependence does not result from space-charge fields unless the cloud contains dissimilar ions, because internal interactions between like ions in a cloud whose extent is small compared with the wavelength of the exciting rf field cannot shift or further broaden the cyclotron or axial resonances.[14] Selection of negative ring potential prevents negative ions from being trapped and, as a precaution, intense rf drives are applied at the axial frequencies of the other possible positive ions (H_2^+, H_3^+, and He^+). These drives have sufficient strength to sweep the dissimilar ions from the trap since their axial motion is undamped.

Figure 4 shows the mass ratio m_p/m_e plotted versus number N. This dependence follows entirely from the variation of $\nu_c(p^+)$ on N since no number dependence has been observed for $\nu_c(e^-)$ within the available resolution. A linear least-squares fit of the data yielded a slope $= -0.22 \times 10^{-6}$/ion. An earlier version of this split-ring design was found to have little compensation and also yielded a number dependence 100 times as great as the present trap and with opposite sign.

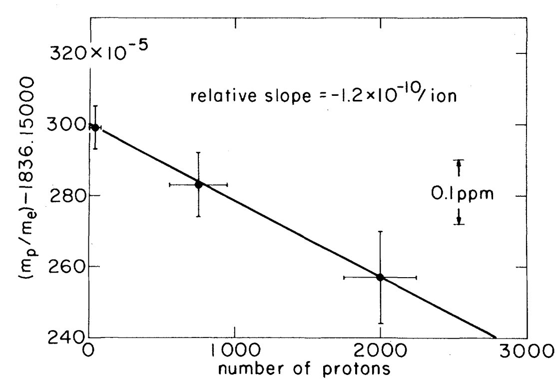

FIG. 4. Mass ratio vs proton number. This dependence is due entirely to the sensitivity of $\nu_c(p^+)$ to proton number and appears to depend on the compensation of the trap.

This suggests that the number dependence can be eliminated experimentally by properly compensating the trap.

The intercept of the linear fit in Fig. 4 corresponds to the preliminary mass ratio $m_p/m_e = 1836.153\,00(7)$. However, an analysis of bottle-related position dependence of the magnetic field suggests that a systematic error as large as 0.1 ppm may exist if the two charge types do not have the same average position in space. Thus, a preliminary mass ratio of

$$m_p/m_e = 1836.153\,00(25)$$

reflects the uncertainty in magnetic field location. Future tests will specifically search for the magnetic saddle point[10] and vary the magnetic-bottle strength to eliminate this problem. Also, a deeper potential well will be used to trap and detect a single electron in order to yield increased $\nu_c(e^-)$ resolution which is typically parts in 10^9 for previous electron traps. This preliminary result agrees with values measured by Gräff, Kalinowsky, and Trant[4] and Gärtner and Klempt[3] within their experimental errors and with the indirect determination within two standard deviations of that result. However, we expect that our techniques will ultimately produce a mass ratio with a precision that exceeds 0.01 ppm. Other possible improvements include using double traps[15] and a variable magnetic bottle.[16]

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