PHYSICAL REVIEW A VOLUME 36, NUMBER 7 OCTOBER 1, 1987

Microwave-cavity modes directly observed in a Penning trap

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(Received 27 April 1987)

The microwave-cavity mode pattern has been directly observed in an old-style compensated Penning trap by a simple bolometric technique which monitors changes in the temperature of the axial center-of-mass motion for a cloud of electrons. The method allows one to easily determine the position of individual modes to a precision better than 0.01%. Presently, over 60 modes have been observed for fields between 17 and 60 kG and an upper limit estimate of 2300 has been made for the cavity Q.

The proton-electron mass ratio[1] can be determined with statistical accuracies of a few parts in 10^9, and g-factor measurements[2] on single electrons and positrons have statistical uncertainties on the order of 1 part in 10^{12}. Potential accuracies are anticipated to approach 0.1 parts per 10^9 for such mass ratios and 1 part in 10^{13} for g-factor measurements when an ac variable-bottle technique[3] can be demonstrated to work. At these levels of precision, there is concern that the high-Q microwave cavity formed by the electrodes of the compensated Penning trap[4] will shift the free-space electron cyclotron frequency used to calibrate the magnetic field. This concern arose from the observation that various cyclotron damping-time constants were measured[5] to be significantly different from their free-space values. These initial measurements have stimulated theoretical interest, with predictions being made for mode patterns, damping times, and frequency shifts in cylindrical traps.[6] Now, for the first time, the entire mode pattern has become experimentally visible in an old Penning trap that was used for very early g-2 measurements.[7] The absolute positions of the mode frequencies can easily be determined to better than 0.01% and we anticipate that 10% measurements of the resonant strength of the individual modes may be possible in the future.

The recently proposed[8] procedure for observing these modes is based on well-established bolometric methods, used previously to determine electron-cloud damping characteristics for various heat inputs.[9] Typically, a cloud of $\approx 1000e^-$ is loaded into the trap and then its axial noise temperature is monitored by means of the noise currents induced in a resonant circuit (tuned to the electron's axial frequency, ν_z). To raise the cloud's temperature above ambient, a $2\nu_z$ drive is applied to an end cap, thus exciting one of the dominant, non-center-of-mass modes of the cloud's motion. Due to fast internal collision coupling, all the internal modes are heated, thus causing a corresponding rise in temperature of the coherent axial center-of-mass motion. This axial temperature is observed via a square-law detector whose signal is thus proportional to the increase in temperature of the internal modes.

The existence of the cavity modes is made visible by sweeping the magnetic field. When the cyclotron frequency coincides with a mode of the cold cavity, the cyclotron motion, which is strongly coupled to the internal modes via collisions, is strongly cooled. The equilibrium temperature of the internal modes of the cloud is thus reduced, thereby reducing the detected axial temperature. Figure 1 is a plot of the axial temperature versus magnetic field (converted into an equivalent cyclotron frequency) for a particular mode near 162 GHz whose full width at half maximum of 70 MHz yields a line $Q \approx 2300$. Of the more than 60 modes observed in the range from 48–167 GHz (17–60 kG magnetic fields), this one appeared to be the narrowest, and therefore its Q represents an upper limit on the cavity Q.

This method of determining cavity mode locations will allow us to obtain regions of magnetic field for each Penning trap which will minimize the strong mode-frequency pulling effects that have been predicted. More importantly, it will be possible to measure the cavity modes near 141.339 GHz which was the cyclotron frequency for single electrons and positrons stored in a recent g-2 trap.[2,10] The data obtained from that trap form the basis of our recent g-factor measurements.[2] In that

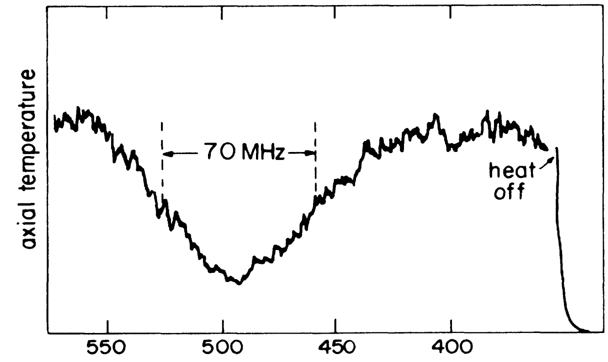

FIG. 1. Axial temperature vs magnetic field (converted to equivalent cyclotron frequency) for a single cavity mode near 162 GHz. The point where heat is turned off indicates the detection response time and corresponding base line. FWHM (full width at half maximum) yields relative line Q of ≈ 2300.

work, we estimate a "most probable cavity shift" of $\approx 4\times 10^{-12}$ in the g factor, but it may now be possible to refine that estimate. [*Note added in proof:* A lower than expected line Q (less than 500) was recently observed in this g-2 trap, indicating that cavity shift estimate (based on $Q=1000$) is quite reasonable.]

One approach for future g-2 research will involve using a much lower cavity Q (which can now be experimentally verified) than previous traps; when combined with the knowledge of exact cavity mode positions, data can be generated with much reduced uncertainty due to this possible systematic effect. The method is simple enough to work even at 77 K (since cavity Q and size will be almost the same as those at 4 K). This suggests that future traps, which will include variable magnetic bottles[11] (when superconducting at 4 K), can be tested for mode patterns without the interaction of the magnetic bottle with the swept magnetic field.

This work is supported by the U. S. National Science Foundation under the "Single Elementary Particle at Rest in Free Space" and " Mono-Ion Research" projects.

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[10] The microwave cavity Q for this recent trap is believed to be lower than that found in the old-style Penning trap, due to larger openings between electrodes and slots in the ring surface.

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