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New Comparison of the Positron and Electron g Factors

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A new double Penning trap structure has been built which permits one to trap a positron in a well-compensated experiment trap where measurements have yielded the geonium positron g-factor anomaly, $g(e^+)/2-1 \equiv a(e^+) = (1\,159\,652\,222 \pm 50) \times 10^{-12}$. The uncertainty is based on the resonance linewidths and an estimate of the remaining systematic error associated with extrapolating to zero spin-flip power. By comparison to the electron-spin anomaly, a positron/electron g-factor ratio of $1+(22\pm 64)\times 10^{-12}$ is obtained.

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Recent success measuring the electron g-factor anomaly, $a(e^-)$, in a well-compensated Penning trap[1] points out the obvious potential of that device for measuring the positron anomaly, $a(e^+)$, to the same precision. Previously, $a(e^+)$ had been measured directly by Gilleland and Rich[2] to an accuracy of 1000 ppm and indirectly by us to 10 ppm. In the first experiment, the anomaly is measured in a magnetic mirror machine by directly observing the difference between the precessing polarization of the spin of the positron and its cyclotron rotation and then calibrating the magnetic field with use of an NMR probe. However, the crucial problem with that experiment was the need for an intense polarized-positron source and an efficient positron polarimeter which did not exist at that time.[3] The other previous experimental result was obtained indirectly by combining our previous mass ratio,[4] $m(e^+)/m(e^-) = 1 \pm 1.3 \times 10^{-7}$, and our much more precise value of the electron anomaly[1] with the ratio of the positron and electron anomalous magnetic moments, $\mu'(e^+)/\mu'(e^-) = 1 \pm 10^{-5}$, measured by Seredynakov *et al.*[5] in a positron/electron storage ring.

In comparison, using well-compensated Penning traps, our resonance techniques should attain accuracies of a few parts in 10^8 for the single-positron anomaly, with the magnetic field calibrated directly *in situ* with the positron's cyclotron frequency. In addition, the ratio of the positron and electron g factors should be measurable to even greater accuracy since small systematic errors should be identical to first order. Thus, a very sensitive test of matter-antimatter symmetry should be possible. Any violation of that symmetry will be a violation of CPT invariance.[6]

The method of continuously loading positrons into a Penning trap has been described previously by us[7] and involves using the double Penning trap arrangement shown schematically in Fig. 1. Positrons, which are initially loaded off axis in the storage trap, must be centered by applying an rf drive at $\nu_z + \nu_m$ to an asymmetrically placed probe (SBE probe in Fig. 1) where ν_z and ν_m are, respectively, the axial oscillation and magnetron rotation frequencies. The positron loading process is also very sensitive to collisions with background gas during the energy-damping phase

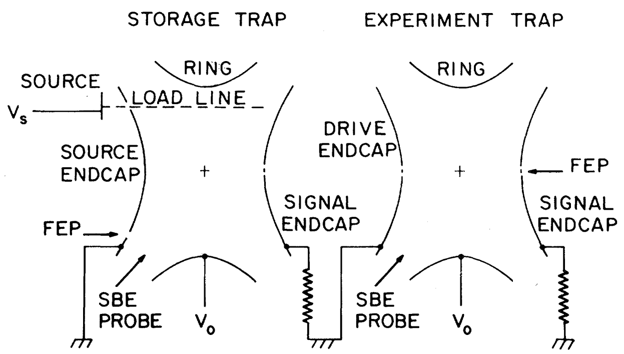

FIG. 1. Schematic of double trap configuration. The sideband excitation (SBE) probes are used in the radial centering process for off-axis–loaded positrons and position stabilizing in the experiment trap. Signal end caps are tuned to the axial frequency via an external inductor in order to observe the axial motion driven by an rf signal applied to the opposite end cap. The dc potential, V_0, is 8.3 and 10.3 V, respectively, for the storage and experiment traps.

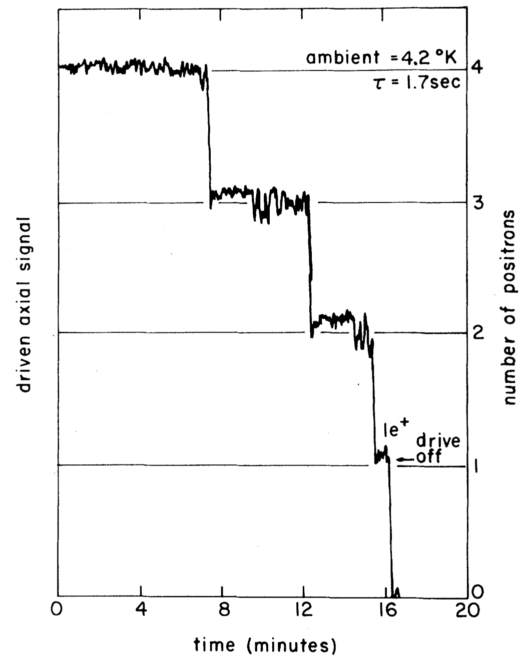

FIG. 2. Positron ejection record. An intense rf pulse at $\nu_z + \nu_m$ is applied to the SBE probe and the continuously monitored drive axial signal registers the loss of single positrons after numerous (>10) consecutive pulses.

of the trapping process; therefore, the entire apparatus is usually immersed in liquid helium to obtain pressures much less than 10^{-11} Torr within the trapping volume.

The second trap shown in Fig. 1 has been carefully designed and compensated to make precision measurements possible. This trap is similar in detail to the loading trap (but without a positron source and with field-emission point located on axis). It is virtually identical to past precision compensated Penning traps.[1] This double-trap combination was constructed because it was initially thought (and later demonstrated) that the holes required for positron trapping and centering would make it nearly impossible to compensate the storage trap enough to allow precision measurements to be made. By use of this second trap, it then became necessary to transfer the positrons from storage into the second trap through a channel drilled between the two adjacent end-cap electrodes of the double trap combination.

The transfer is accomplished by pulsing the two adjacent end caps to the approximately common ring potential for a few microseconds. Pulses much longer than 10 μs tend to have an efficiency much less than the 25%–50% observed efficiency since radial drifting can occur during the passage between traps (for instance via collisions with background gas). An accumulated drift more than 0.025 cm will cause the positron to hit the drive end cap of the experiment trap (see Fig. 1) since the hole in that electrode will be the smallest one encountered.

Once the positrons have been transferred, they can be detected by using a large off-resonance axial drive, similar to that which is normally used when electrons are loaded into the trap, one at a time. In addition, if sideband cooling is utilized, this signal can be reliably calibrated to determine the number of transferred positrons. Subsequently, the excess beyond one are systematically ejected by use of *intense* rf pulses also at the sideband cooling frequency. Figure 2 shows an example of this process for a case where four positrons were transferred into the trap and three are ejected. The rf amplitude in the pulse is carefully adjusted such that at least ten consecutive pulses are required in order to eject one positron from the cloud (i.e., less than 10% chance of driving one out per pulse). Once a single positron is isolated, the drive signal can be reduced in order to observe the narrow (4 Hz) axial resonance typical of a well-compensated trap.

Not shown in Fig. 1 are four symmetrically placed nickel screws, located in the central plane of the ring electrode within the experiment trap.

This magnetic material will produce a very weak magnetic bottle which effectively couples the magnetic moment of the charge to the axial resonance in the form of a 1.3-Hz shift per unit change in the magnetic quantum level via the axial Stern-Gerlach effect.[1] By locking of this axial frequency to a frequency synthesizer, the changes in the magnetic state are reflected in the lock-loop correction voltage, making it possible to measure both the cyclotron frequency, ν_c', and the spin anomaly frequency, ν_a'.

Figure 3 shows a typical positron cyclotron resonance obtained with this coupling scheme. As typical of past electron traps with magnetic bottles,[1] the resonance shows a clear low-frequency edge, corresponding to $Z_{\rm rms}=0$, and a high-frequency exponential tail, indicative of the Boltzmann distribution of axial states. The dotted curve represents an exponential decay with a 24-kHz linewidth, which is four times greater than the narrowest electron cyclotron resonance obtained in previous traps.[1,8] However, the nearly vertical edge is resolvable to ≈ 0.01 ppm.

In order to flip the spin, the magnetic bottle is again used, but now to create a precessing magnetic field in the radial plane at the spin frequency $\nu_s=\nu_c'+\nu_a'$. This process has been described previously[1] and involves applying the anomaly drive to the end caps yielding a weakly driven axial motion at ν_a'. From the positron's frame of reference rotating at the cyclotron frequency ν_c', the axial modulation will yield sidebands with ν_s as the desirable upper sideband. Figure 4 shows the corresponding anomaly resonance taken by alternation of detection and excitation in order to yield the best resolution. The solid line represents an exponential decay with a 12.5-Hz linewidth. Again, the edge is nearly resolvable to 0.01 ppm.

By measurement of corresponding edge frequencies, the g factor and its anomaly can be determined from the following relation:

$$a(e^\pm)=g(e^\pm)/2-1$$
$$=[\nu_a'-\nu_z^2/2\nu_c']/[\nu_c'+\nu_z^2/2\nu_c'].$$

This equation has been investigated and found to be highly accurate as long as ν_a', ν_c', and ν_z are the actual observed frequencies of motion in the Penning trap.[9] At present, four separate runs have been made with a single positron transferred into the highly compensated Penning trap. Time studies of the cyclotron resonances indicate an effective magnetic field jitter on the order of 0.05 ppm. This was probably due to collisions with some residual background gas which causes the radial position of the particle to vary in time within the magnetic bottle field. Future work will eliminate small leaks found in the trap-tube envelope.

At present, only one systematic effect in the

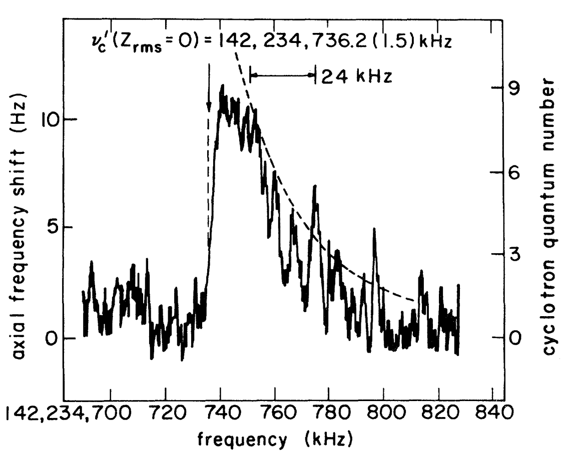

FIG. 3. Positron cyclotron resonance. The resonance is observed in the correction signals of the axial lock loop. The high-frequency tail has an exponential decay linewidth of 24 kHz (see dotted curve) which is significantly larger than expected. However, the nearly vertical low-frequency edge ($Z_{\rm rms}=0$) is resolvable to $\lesssim 1.5$ kHz (or $\lesssim 10$ ppb).

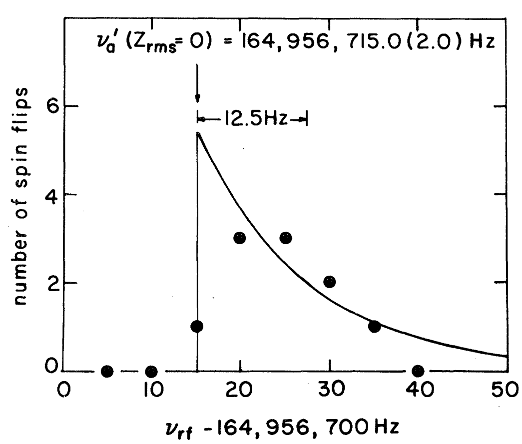

FIG. 4. Positron anomaly resonance. By alternation of detection and excitation, the number of spin flips (out of a fixed number of attempts) is plotted vs frequency. The solid curve represents an exponential decay linewidth of 12.5 Hz. However, the low-frequency edge ($Z_{\rm rms}=0$) is resolvable to ± 2.0 Hz, which corresponds essentially to the same resolution found for the cyclotron resonance.

anomaly (for both electrons and positrons) has been observed: The anomaly decreases with increasing applied anomaly drive. This may be due either to a change in the magnetron radius (change of 2-3 times the minimum radius observed) or to an uncorrected positive shift in the axial frequency associated with the added rf trapping potential produced by the strong anomaly drive. The effect was typically −0.03 ppm for the largest anomaly drive used in the older electron geonium experiments. Thus, from the four initial positron runs, a preliminary positron spin anomaly,

$$a(e^+) = (1\,159\,652\,222 \pm 50) \times 10^{-12},$$

is obtained from a weighted least-squares extrapolation with use of the systematic power dependence observed for the electron. Field jitter is incorporated in the individual anomaly errors, used to produce the weights in the least-squares adjustment. However, the error (0.043 ppm) represents primarily the uncertainty associated with the power extrapolation for the positron and only secondarily the error associated with the least-squares adjustment. This result agrees well with our previous measurements on single electrons[10] and is in reasonable agreement with the theoretical values announced at the recent Precision Measurements of Fundamental Constants–II conference,[11]

$$a_e(\text{Theor}) = (1\,159\,652\,411 \pm 166) \times 10^{-12},$$

where much of the uncertainty arises from the best e/h determination of the fine structure constant.[12] By combining the measured electron and positron anomalies, we obtain a preliminary matter-antimatter comparison of

$$g(e^+)/g(e^-) = 1 + (22 \pm 64) \times 10^{-12}.$$

The resolution of this g-factor comparison will significantly improve when measurements of both positron and electron spin anomalies in the same apparatus are completed, without the pressure effects smearing out the magnetic field edge.

We wish to thank Don Russell for his excellent machine work on the traps and glassblower Bob Morley for his superb work. In addition, we thank the National Science Foundation for its support of this research.

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