Measurement of ultra-low heating rates of a single antiproton in a cryogenic Penning trap


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We report on the first detailed study of motional heating in a cryogenic Penning trap using a single antiproton. Employing the continuous Stern-Gerlach effect we observe cyclotron quantum transition rates of $6(1)$ quanta/h and an electric field noise spectral density below $7.5(3.4) \times 10^{-20} \text{V}^2 \text{m}^{-2} \text{Hz}^{-1}$, which corresponds to a scaled noise spectral density below $8.8(4.0) \times 10^{-12} \text{V}^2 \text{m}^{-2}$, results which are more than two orders of magnitude smaller than those reported by other ion trap experiments.

Quantum control techniques applied to trapped charged particles, well-isolated from environmental influences, have very versatile applications in metrology and quantum information processing. For example, elegant experiments on co-trapped laser cooled ions in Paul traps have provided highly precise state-of-the-art quantum logic clocks [1], enabled the development of exquisite atomic precision sensors [2] and the implementation of quantum information algorithms applied with highly entangled ion-crystals [3]. Decoherence effects from noise driven quantum transitions, commonly referred to as anomalous heating [4, 5], affect the scalability of multi-ion systems, which would enable even more powerful algorithms. Trapped particles are also highly sensitive probes to test fundamental symmetries, and to search for physics beyond the standard model [6, 7]. The measurements are conducted in the cryogenic Penning trap using a single antiproton. Employing the continuous Stern-Gerlach effect we observe cyclotron quantum transition rates of $6(1)$ quanta/h and an electric field noise spectral density below $7.5(3.4) \times 10^{-20} \text{V}^2 \text{m}^{-2} \text{Hz}^{-1}$, which corresponds to a scaled noise spectral density below $8.8(4.0) \times 10^{-12} \text{V}^2 \text{m}^{-2}$, results which are more than two orders of magnitude smaller than those reported by other ion trap experiments.
state analysis trap of the BASE apparatus at CERN [24], which is shown in Fig. 1. The Penning trap is realized using a superconducting magnet at 1.945 T combined with a quadrupolar electrostatic potential provided from a set of five carefully designed cylindrical electrodes with an inner diameter of 3.6 mm [22]. The central ring electrode is made out of a Co/Fe alloy, which distorts the nearly homogeneous axial magnetic field to \( B_z = B_0 + B_2 \left( z^2 - \rho^2/2 \right) \), deliberately generating a magnetic inhomogeneity of \( B_2 = 272 \text{ kTm}^{-1} \). The trajectory of a single antiproton stored in a Penning trap is composed of three harmonic oscillator modes. The modified cyclotron motion at \( \nu_z \) and the magnetron motion at \( \nu_\perp \) are perpendicular to the magnetic field, while the particle oscillates along the magnetic field lines with axial frequency \( \nu_z \). For the BASE analysis trap, \( \nu_z \approx 17.845 \text{ MHz}, \nu_\perp \approx 10 \text{ kHz} \) and \( \nu_z \approx 675 \text{ kHz} \). The gold-plated OFHC electrodes are placed inside an indium-sealed vacuum chamber which is cooled to \( T \approx 6 \text{ K} \). Cryo-pumping provides an ultra-high vacuum with pressures \(< 3 \times 10^{-18} \text{ mbar} \) which enables storage times \( > 10^6 \text{ s} \) [23]. Radio frequency (rf) lines equipped with high order low-pass and band-pass filters as well as high-insulation switches are used for particle manipulation (Fig. 1b). The axial oscillation frequency \( \nu_z \) is measured by an image current detection system [24]. The detector’s time transient is processed with a Fast Fourier Transform (FFT) spectrum analyzer. Once cooled to thermal equilibrium, the particle signature appears as a dip in the resulting frequency spectrum [25] (see Fig. 1b). A least-squares fit of the recorded spectra yields the axial frequency \( \nu_z \). In the measurements reported here, we apply active electronic feedback cooling (see Fig. 1a) [26, 27], which enables measurements at low axial temperature \( (T_\perp \approx 1.92(10) \text{ K}) \) and high axial frequency stability [19].

For explicit measurements of modified cyclotron transition rates we utilize the continuous Stern-Gerlach effect [20]. Here, the interaction of the particle’s magnetic moment \( \mu_z = \mu_+ + \mu_- + \mu_s \) with the strong magnetic inhomogeneity \( B_2 \) results in a magnetostatic axial energy \( E_{B,z} = -\mu_z \times B_2(z) \), where \( \mu_+ \) and \( \mu_- \) are the angular magnetic moments associated with the modified cyclotron and the magnetron mode, while \( \mu_s \) is the spin magnetic moment. As a result, the antiproton’s axial frequency \( \nu_z = \nu_{z,0} + \Delta \nu_z \) becomes a function of the radial quantum states:

\[
\Delta \nu_z(n_+, n_-, m_s) = \frac{\hbar \nu_+ B_z}{4\pi^2 m_\rho \nu_z} \left[ n_+ + \frac{1}{2} + \frac{\nu_z}{\nu_+} \left( n_- + \frac{1}{2} + \frac{g_pm_s}{2} \right) \right].
\]

Transitions in the corresponding states \((m_s, n_+, n_-)\) to axial frequency shifts of \( \Delta \nu_{z,s} = 172(10) \text{ mHz} \), \( \Delta \nu_{z,+} = 62(4) \text{ mHz} \) and \( \Delta \nu_{z,-} = 40(3) \text{ mHz} \), respectively.

To determine the transition rate \( \zeta_\perp \) of the cyclotron motion we first prepare a particle at low radial energy with \( n_+ < 200 \) [28]. Then, we record sequences of axial frequency measurements \( \nu_{z,k} \) with an averaging time \( \tau_0 = 50 \text{ s} \). Subsequently, we evaluate the standard deviation \( \sigma_{\nu_z}(\tau) = \sigma \left( \langle \nu_{z,j+1} \rangle(\tau) - \langle \nu_{z,j} \rangle(\tau) \right) \), where \( \langle \nu_{z,j} \rangle(\tau) \)
represents the mean values of a sub-series of axial frequency measurements with an averaging time \( \tau = 1 \times \tau_0 \). A result of such an overlapping differential Allan deviation \( \sigma_{\nu_e}(\tau) \) is shown in Fig. 2 as blue filled circles. Various measured and simulated contributions to \( \sigma_{\nu_e}(\tau) \) are also plotted in Fig. 2. The contribution from voltage fluctuations \( \sigma_v(\tau) \) (dark red triangles) is extracted from simultaneous measurement of the voltage supply stability, as shown in Fig. 1. The contribution from white frequency measurement noise, \( \sigma_{\nu_{\text{FFT}}}(\tau) \propto \delta \nu_{\text{dip}}^{1/2} \text{SNR}^{-1/4} \) (dark red squares) is calculated \[14\], \( \delta \nu_{\text{dip}} \) being the linewidth of the axial frequency dip and SNR the signal-to-noise ratio (see Fig 1 b). At small averaging times \( (\tau < 100 \text{s}) \), these two contributions dominate. Meanwhile, with long averaging times \( (\tau > 250 \text{s}) \), \( \sigma_{\nu_e}(\tau) \) is dominated by transition rates \( \zeta_+ \) in the modified cyclotron mode,

\[
\sigma_{\nu_e}(\tau) \propto \sqrt{\sigma_v(\tau)^2 + \sigma_{\text{FFT}}(\tau)^2 + \tau (\Delta \nu_{\text{dip}}^2 + \zeta_+)}.
\]

(2)

By analyzing such data and comparing the Allan deviation to Monte-Carlo simulated noise-driven random walks, we extract an absolute cyclotron transition rate of \( \zeta_+ = 6(1) \text{ h}^{-1} \), see Fig. 2. Note that \( \zeta_+ \) describes a nearly undirected random walk. The observed transition rates can be related to the noise spectral density of the radial electric field \( S_E(\omega_+) \) at the modified cyclotron frequency. Considering first order transitions in a noise-driven quantum mechanical oscillator \[30\], cyclotron transitions rates are given by

\[
\zeta_+ = \frac{q^2 n_+}{2 \mu B \hbar \omega_+} S_E(\omega_+),
\]

(3)

where \( S_E(\omega_+) \) is the spectral density of electric field noise acting on the particle’s cyclotron motion. The average increase of \( n_+ \) is given by the heating rate \( d \bar{n}_+/dt = \zeta_+ \times 1/(2n_+) \) for \( n_+ \gg 1 \). Together with the determination of a lower limit for \( n_+ \) based on the continuous Stern-Gerlach effect \[31\] we obtain an upper limit for the electric field spectral density of \( S_E(\omega_+) \leq 7.5^{+3.4}_{-2}\times 10^{-20} \text{V}^2\text{m}^{-2}\text{Hz}^{-1} \). The absolute resolution of our axial frequency measurements is limited by environmental variations of temperature, cryo-liquid levels, and pressure, which impose uncertainties on the determination of both the cyclotron quantum number \( n_+ \) as well as the transition rate \( \zeta_+ \). Nevertheless, our upper limit for \( S_E(\omega_+) \) is far below the results reported by cryogenic Paul trap \[32,33\] and room temperature Penning-trap experiments \[21,39,40\]. The current best limits extracted from those experiments are \( S_E(\omega) = 2.4 \times 10^{-15} \text{V}^2\text{m}^{-2}\text{Hz}^{-1} \) \[5\] and \( S_E(\omega) = 8 \times 10^{-16} \text{V}^2\text{m}^{-2}\text{Hz}^{-1} \) \[21,40\], respectively. Fig. 3 a) displays the commonly used scaled electric field noise \( \omega S_E(\omega) \) which accounts for the \( 1/\omega \)-dependence of the heating rate \[41,5\]. Our result \( \omega S_E(\omega) \leq 8.8^{+0.9}_{-0.7}\times 10^{-12} \text{V}^2\text{m}^{-2} \) sets an upper limit which is a factor of 1800 \[39\] lower than the best reported Paul trap heating rates and a factor of 230 lower than the best Penning trap \[21\]. Fig. 3 b) plots the heating rate \( d \bar{n}_+/dt \) for various experiments, which is in our case below 0.1 h\(^{-1}\). The corresponding energy increase \( dE/dt \), plotted in Fig. 3 c), is on the order of peV/s, demonstrating to our knowledge the highest energy stability of a particle in any ion trap experiment.

To further investigate the residual drive mechanism, we
measure transition rates $\zeta_+ (\rho_-)$ as a function of the particle’s magnetron radius $\rho_-$, thereby changing the trapping field at the particle position. We excite the magnetron mode and record series of axial frequency sequences $\Omega_k (\nu_+, \rho_-)$ for in total 7 different magnetron radii, thereby tracing a radial range of $6 \, \mu m \leq \rho_- \leq 65 \, \mu m$. The results of these measurements are displayed in Fig. 4. In Fig. 4 (a) we show the measured axial frequency fluctuation $\sigma_{\nu_+} (\nu_-, \rho_- = 250 \, s)$. For the data points displayed in Fig. 4 (b), we analyze the transition rate $\zeta_+ (\rho_-)$ of each dataset $\Omega_k (\nu_+, \rho_-)$ and determine the spectral density $S_V (\omega_+)$ of an equivalent effective voltage noise source present on each trap electrode:

$$S_V (\omega_+) = \Lambda^2 (\rho, z) S_V (\omega_+), \quad (4)$$

where $\Lambda (\rho, z)$ describes the relation between the electric field at the particle position $\vec{x} = (\rho, z)$ and the potential $V_n$ created by the $n$-th electrode:

$$\Lambda^2 (\rho, z) = \sum_{n=1}^{5} \left( \frac{\partial V_n}{\partial \rho} \right)^2 \propto \rho^2, \quad (5)$$

for low cyclotron energies, $\rho \approx \rho_-$. The linear increase of $\sigma_{\nu_+} (\tau) \propto \rho_-$ observed in Fig. 4 (a) reflects a quadratic increase of transition rates $\zeta_+ \propto \rho_-^2$. (Eq. 2). This is expected from Eq. 4, assuming electrode voltage noise $S_V$ as the dominant source of electric field fluctuations. We obtain $S_V = 225(54) \, pV \, Hz^{-1/2}$. Anomalous heating reported from Paul traps [4] scales with $d^{-4}$, $d$ denoting the electrode-ion-distance. Since the variation of $d$ is small ($\Delta d/d = 1/60$) for the considered magnetron radii, anomalous heating would result in a nearly constant electric field noise spectral density. Since a clear increase is observed in $\zeta_+$, anomalous heating is ruled out as the dominant heating mechanism. Its effect is constrained to be below $S_E (\omega_+) \leq 7.5(3.4) \times 10^{-20} \, V^2 \, m^{-2} \, Hz^{-1}$.

In order to investigate contributions to $S_V$ we consider the experimental setup depicted in Fig. 4. The effective parallel resistance of the axial detection system at the cyclotron frequency contributes about $1.5 \, pV \, Hz^{-1/2}$. The Johnson noise of the electrode RC-filters is below $1 \, pV \, Hz^{-1/2}$, the electrode Johnson noise is on the order of $10^{-3} \, pV \, Hz^{-1/2}$. None of these mechanisms can explain the observed voltage fluctuations. Field fluctuations arising from blackbody radiation are estimated to be $\omega_+ \times S_{E}^{(BB)} \approx 6 \times 10^{-14} \, V^2 \, m^{-2}$ [3] [11], which is two orders of magnitude lower than our limit of $\omega S_E (\omega) \leq 8.8 \pm 4.9 \times 10^{-12} \, V^2 \, m^{-2}$. A trapped ion polarizes neutral background gas atoms and thereby induces collisions described by the Langevin rate $\gamma$, which is proportional to the background gas density [35] [12]. From our antiproton lifetime measurement [28] we derived upper limits for the partial pressure of hydrogen $p_{\text{upper},H} < 1.2 \times 10^{-18}$ mbar and helium $p_{\text{upper},He} < 2.7 \times 10^{-18}$ mbar leading to $\zeta_+ < 4 \times 10^{-9} \, s^{-1}$. Voltage supply (UM1-14) noise at $\nu_+$ is ruled out by independent measurements. Therefore we assume parasitic coupling of stray EMI noise onto the trap electrodes to be the dominant source of electric field fluctuations in our trap. A further improvement to achieve even lower heating rates which will enhance the sensitivity of our experiment will be subject of future experimental studies.

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed $S_V$</td>
<td>$225(54) , pV , Hz^{-1/2}$</td>
</tr>
<tr>
<td>Axial detection system</td>
<td>$1.5 , pV , Hz^{-1/2}$</td>
</tr>
<tr>
<td>RC filter stages</td>
<td>$&lt; 1 , pV , Hz^{-1/2}$</td>
</tr>
<tr>
<td>Electrode Johnson noise</td>
<td>$\sim 3 \times 10^{-3} , pV , Hz^{-1/2}$</td>
</tr>
<tr>
<td>Blackbody radiation</td>
<td>$\omega_+ \times S_E (\omega_+) \approx 6 \times 10^{-14} , V^2 , m^{-2}$</td>
</tr>
<tr>
<td>Background pressure</td>
<td>$\zeta_+ &lt; 4 \times 10^{-9} , s^{-1}$</td>
</tr>
</tbody>
</table>

TABLE I. Parasitic voltage fluctuation and heating rate contributions.