Active Electronic Cooling of Single Ions for Precision Mass Measurements

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We plan to exploit the subthermal capability of our electronic detector to actively cool the axial motion of a single ion in a Penning trap below the 4 Kelvin temperature of the detector to which it is coupled. A sideband cooling technique will then be used to cool both the cyclotron and magnetron modes of motion as well. A subthermal ion will help increase the precision with which atomic masses can be compared from our current relative accuaracy of 10^{-10} to better than 10^{-11}.

Mass comparisons are made by measuring the cyclotron frequency of the ion which is inversely proportional to its mass. A cyclotron frequency measurement begins by initially cooling the cyclotron mode with a sideband coupling to the damped axial mode. It is then driven to a fixed phase and amplitude with an RF drive pulse and allowed to accumulate phase at the cyclotron frequency for some time T. The accumulated phase is measured by a coherent coupling to the detected axial mode. From a series of phase measurements versus T we extract the cyclotron frequency. The finite temperature of the cyclotron motion before the initial cyclotron drive pulse limits our ability to establish a fixed phase and amplitude at $T = 0$. Clearly variations in the initial phase result in phase noise. In addition, the amplitude fluctuations produce cyclotron frequency fluctuations at the level of a few parts in 10^{11} due to both relativistic mass increase and magnetic field inhomogeneities. By cooling the ion's motion we will reduce both the phase and frequency fluctuations in our measurements of the cyclotron frequency.

We detect the image current that the ion's axial motion induces in the endcap electrodes of the trap. To do this we have developed a detector consisting of a hand-wound high Q superconducting transformer (Q$\approx 4 \times 10^4$, $f_{res} \approx 2 \times 10^5$Hz) coupled to a dc SQUID. The resonant-circuit damps the ion's axial motion with a characteristic time scale of about 1 sec. This coupling allows the ion to come to thermodynamic equilibrium with the circuit. With recent improvements (the dc SQUID has a noise floor 10× smaller than the previous rf SQUID), we are only limited by the thermal or Johnson noise of the superconducting resonant circuit. The peak ratio of Johnson to SQUID noise floor powers is greater than 100 see Fig. 1.

The Penning trap dc trapping voltage is normally chosen to make the ion's axial motion resonant with the detector circuit. By detuning the ion's axial motion from resonance, the ion damps more slowly. This corresponds to a decrease in the bandwidth of the ion's signal and yields a detection capability below 4K. Thermodynamic equilibrium ensures that when detuned

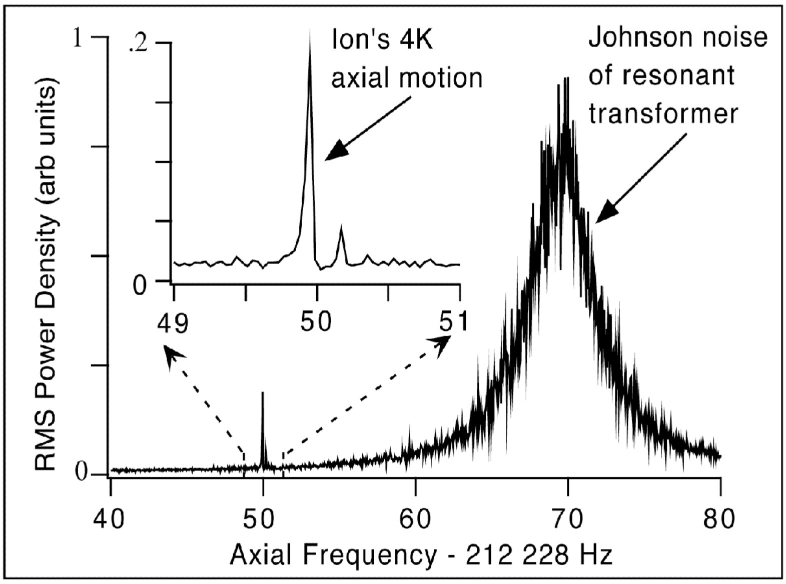

Figure 1: Average detected spectral power density of a single Ne^{++}. The broad resonance is the Johnson noise multiplied by the transfer function of the superconducting transformer. The small resonance in the wing is the detected 4K axial motion of a single Ne^{++} which displays a power signal to noise ratio ≈ 10.

from resonance, the axial motion is still at 4K. We will exploit the off-resonance subthermal measurement capability to measure this thermal motion and apply an axial feedback drive on one of the trap endcaps to reduce it. Fig. 1 is an example of the average observed 4K motion of a single Ne^{++} detuned from resonance with the detector. From the ion's perspective, applying continuous feedback is equivalent to adding a subthermal imedance in series with the resonant-circuit.

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