MOTIONAL EFFECTS IN THE FLUORESCENCE SPECTRUM OF A SINGLE BA^+ ION

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We measure the spectrum of resonance fluorescence of a single Ba^+ ion in a Paul trap, using a heterodyne detection setup. The width of the coherent "carrier" peak is bandwidth limited to below 0.1 Hz. With the same resolution we detect sidebands of the micromotion of the ion, induced by the rf trapping field. Through weak electronic excitation near the frequency of the free "macro"-motion of the ion in the trapping potential, we also observe the corresponding sidebands even in the Lamb-Dicke regime of excitation. From the width of these sidebands we determine the cooling rate of the ion. This is the first online measurement of the cooling rate of a trapped particle.

The spectrum of resonance fluorescence of a single particle, for the case of weak excitation, is dominated by Rayleigh scattering which is coherent with the exciting laser. If the atom is trapped, sidebands at the frequencies of the motion in the trap appear in the fluorescence spectrum[1]. In a Paul trap these frequencies are that of the micromotion, induced by the rf driving field of the trap, and the three frequencies of the free macromotion in the (quasi-) potential of the trap.

We investigate the resonance fluorescence of a single Ba^+ ion in a miniature (1 mm diameter) Paul trap by superimposing the collimated fluorescence at 493 nm and a fraction of the exciting laser[2] light on a beam splitter[3] and analyzing their interference with a double-balanced heterodyne detector, see Fig. 1. With the FFT analyzer set to the difference frequency of the two AOMs we observe a bandwidth-limited 61 mHz wide Rayleigh peak, see Fig. 2. With the same resolution we observe the sidebands caused by the micromotion of the ion, when the FFT analyzer frequency is shifted by the rf frequency of the Paul trap, 18 MHz, see Fig. 3.

We also observe sidebands due to the macromotion of the ion, by weak electric excitation of the ion's motion around one of the macromotion frequencies, and by shifting the FFT analyzer to that frequency. Fig. 4 shows the carrier and sideband heterodyne signal corresponding to one of the macromotion resonances. The signals are described by $|A_n J_n(\mu/(1+(2\Delta f/\delta f)^2))|^2$, $n = 0$ (1) for the carrier (sideband), with Bessel functions J_n, their amplitudes A_n, maximum modulation index μ, detuning Δf of the drive from the macromotion resonance and resonance width δf. The broadening of the macromotion resonance is caused by the laser cooling that goes along with the $S_{1/2}$ to $P_{1/2}$ optical excitation. From the fit in Fig. 4 we find a cooling rate of about 1 kHz. Since the carrier signal does not reach the

first zero of J_0 we conclude that the ion remains in the Lamb-Dicke regime, i.e. its oscillation amplitude is always much smaller than the laser wavelength. In this case the determined cooling rate is equal to the one without external excitation of the motion. Measurement of cooling rates is interesting, e.g., for the use of trapped ions in quantum information.

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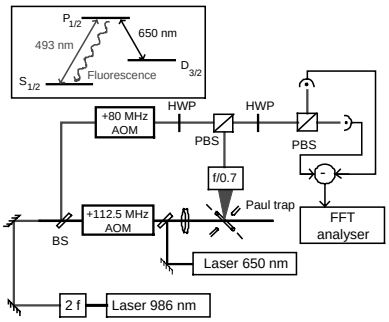

Figure 1. Heterodyne setup. The inset shows the relevant levels of Ba^+. Continuous excitation at 493 nm and 650 nm is required to generate fluorescence.

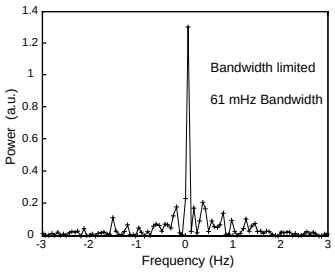

Figure 2. Rayleigh peak of elastic scattering recorded at the maximum resolution of 61 mHz. The signal consists of a single data point 15 dB above the noise.

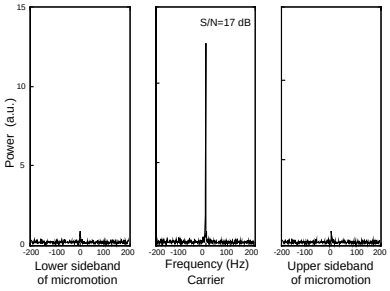

Figure 3. Rayleigh peak and micromotion sidebands at ±18 MHz away from the carrier.

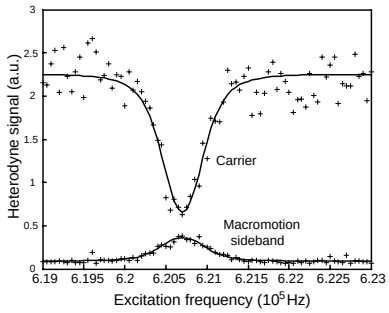

Figure 4. Carrier and sideband signal corresponding to weakly driven macromotion. Each data point corresponds to one FFT spectrum (see Fig. 2) and the drive frequency is scanned over one of the macromotion resonances. The solid line is a fit, see text.

References

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[2] C. Raab et al., Appl. Phys. B **67**, 683 (1998).
[3] J.T. Höffges et al., Advances in Quantum Chemistry **30**, 65 (1998).