Fluorescence spectroscopy on single trapped ^{171}Yb and ^{172}Yb ions using optical heterodyne detection

V. Bühner, Chr. Tamm

Physikalisch-Technische Bundesanstalt
Bundesallee 100, D-38116, Braunschweig, Germany
Tel +49-531-592-4415, Fax +49-531-592-4479

For weak monochromatic excitation the fluorescence emission of a single two-level atom at rest is dominated by elastic scattering [1]. Recently the corresponding extremely narrow component in the fluorescence spectrum of a confined atomic system was observed in an experiment where the fluorescence spectrum of a single trapped Mg^+ ion was analyzed by means of optical heterodyne detection [2].

We report on the observation of additional narrow structures in the fluorescence spectra of trapped $^{171}Yb^+$ and $^{172}Yb^+$ ions. Single ions are trapped in a Paul trap and laser cooled by excitation of the Yb+ resonance transition at 369 nm. Using optical heterodyne detection, the emitted resonance fluorescence is spectrally analyzed with a minimum frequency resolution bandwidth of less than 1 Hz.

The fluorescence emission of a single ^{171} Yb ion exhibits macroscopic dark periods due to quantum jumps to a metastable hyperfine sublevel. The average duration of the dark periods can be varied by changing the intensity of a repumping laser field [3]. Theoretical investigations [4] predict an additional narrow component in the fluorescence spectrum of an atom whose fluorescence emission is interrupted by quantum jumps. Specifically the additional spectral component is a Lorentzian pedestal of the elastic scattering peak whose width is determined by the dark-time statistics. We investigate the fluorescence spectrum and the dark time statistics of a single ^{171}Yb ion and find quantitative agreement with the theoretical predictions for various average dark time durations.

The fluorescence emission of a trapped ^{172}Yb ion is continuous since this isotope has no hyperfine structure. Under the realized experimental conditions the residual motion of the laser cooled ^{172}Yb ion in the harmonic trap potential leads to a phase modulation of the scattered light so that the elastic scattering peak in the fluorescence spectrum exhibits motional sidebands. In previous observations of motional sidebands in the fluorescence spectrum of atoms in an optical lattice, the sideband linewidth was essentially determined by the trap potential anharmonicity [6]. In our case, one expects that the relative strength and the linewidth of the motional sidebands are determined by the average residual motional energy and the motional damping rate constant, respectively, under conditions of continuous laser cooling [5].

In our experiment we observe the motional sidebands in the fluorescence spectrum of a trapped ^{172}Yb ion that is laser cooled to the range of the Doppler limit. A corresponding spectrum is shown in Fig.1. The observation of motional sideband linewidths in the kilohertz range is consistent with previous observations on the fluorescence spectrum of a trapped ion where

secular motion was driven by resonant electrical excitation [7]. As shown in Fig.1(b) and (c), the observed dependence of relative sideband strengths and linewidths on the cooling laser detuning is in good agreement with calculations based on Ref.[5]. Fig.1(c) indicates that the observed sideband linewidths exceed the calculated linewidths by approximately 380 Hz independent of laser detuning. This discrepancy appears to be caused by the finite resolution bandwidth of the spectrum analyzer and by an additional motional decoherence contribution due to fluctuations of the secular frequency. This work is supported by the Deutsche Forschungsgemeinschaft within Sonderforschungsbereich 407.

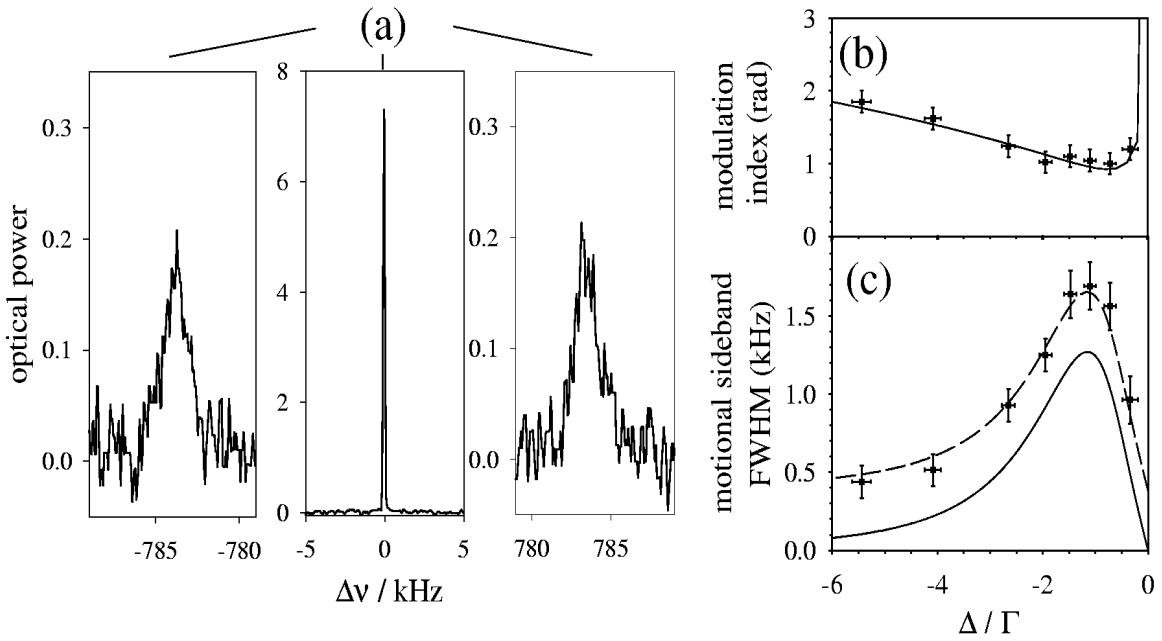

Figure 1: (a): Carrier (center) and motional sidebands in the fluorescence spectrum of a single ^{172}Yb ion. A noise floor caused by photodetection shot noise was removed. The frequency scale indicates the detuning between optical excitation and detection frequency. The spectrum was recorded using a resolution bandwidth of 124 Hz and an averaging time of 48 s. (b,c): Modulation index quantifying observed relative sideband strengths (b), and sideband linewidths (c) as a function of normalized laser detuning relative to the line center of the ^{172}Yb$^+$ cooling transition. The full lines show the theoretically expected dependence (see text). The dashed line in (b) is offset by 380 Hz relative to the full line.

[1] R.B. Mollow, Phys. Rev. **188**, 1969 (1969)
[2] J.T. Höffges et al., Opt. Comm. **133**, 170, (1997)
[3] D. Engelke et al., Europhys. Lett. **33**, 347 (1996), Chr. Tamm et al. Phys. Rev. A in press
[4] G.C.Hegerfeldt et al., Phys.Rev.A **52**,3333 (1995), B.Garraway et al., Opt.Comm. **17**,560 (1995)
[5] M. Lindberg, Phys. Rev. A **34**, 3178 (1986), J.I. Cirac et al., Phys. Rev. A **48**, 2169 (1993)
[6] P.S. Jessen et al., Phys. Rev. Lett. **69**, 49 (1992), M. Gatzke et al., Phys. Rev. A **55**, R3987 (1997), W.D. Phillips et al., Phys. Rev. Lett. **78** 2676 (1997)
[7] C. Raab et al. in Proc. 14th ICOLS, p358, World Scientific, Singapore (1999)