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CONTRIBUTIONS TO THE IMPLEMENTATION OF A SINGLE-ION FREQUENCY STANDARD

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Abstract: We review the advances made at Hamburg University that are relevant for the implementation of frequency standards in the micro-wave and optical domains, based on a single ion confined in an electrodynamic trap. Recent accomplishments include the double-resonance detection of Ramsey fringes with a single $^{171}Yb^{+}$ ion, a quantitative limit set to the line strength of the YbII $(S_{1/2} - F_{7/2})$ E3 line resulting from an attempt of measuring single-ion absorption by quantum amplification, and the first recording of the *emission spectrum* of single-ion resonance fluorescence. Moreover, single-ion *stimulated emission* has been observed, for the first time, by quantum amplification on the Ba II $(S_{1/2} - D_{5/2})$ E2 line. — The significance of the ion's vibrational dynamics for enhanced precision of frequency measurement and control is stressed. A novel concept of stochastic cooling is reported, along with evidence on the vibrational dynamics derived from time-dependent vibrational-side-band spectra of quantized opto-optical triple resonance on the BaII E2 line.

Frequency standards and atomic clocks on the basis of trapped ions have for a while attracted intense attention [1]. An important aspect of these devices is the small residual imprecision which may not exceed 10^{-15} with presently discussed systems. Even more remarkable is the residual inaccuracy on the order of 10^{-18} which, however, seems achievable only with a *single* ion trapped in ultra-high vacuum, in the node of the trapping field [2]. Since signals derived from a single ion are weak, their use for the frequency control of a standard is not obvious and requires detailed studies.

Such a frequency standard consists of an oscillator, i.e. a micro-wave generator or a laser, whose emitted wave is made to excite the ion on a hyperfine or optical line. Excitation is probed by sequentially exciting the fluorescence on a resonance line that shares a common level with the signal transition, or "clock line". This is the well-known double-resonance scheme, which is combined, however, for a single particle, with the concept of "quantum amplification": Present or absent fluorescence probes the upper or lower energy eigenstate of the signal line as being populated by the ion or not [3]. The fluorescence is detected, and the ensuing current signal is made to control the phase or frequency of the oscillator via a feedback loop. For this purpose the fluorescent response of the ion upon frequency scanning the oscillator wave is used as a discriminant: by

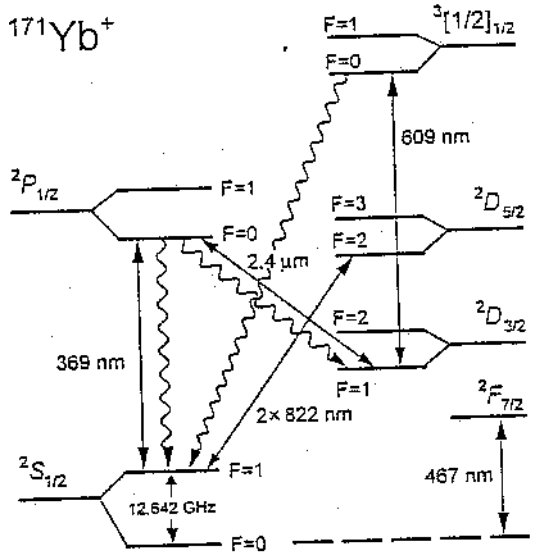

Fig. 1: Energy levels and lines of ^{171}YbII.

alternating the oscillator frequency being set at symmetric detunings on the upper and lower wing of the particular line shape of even symmetry, or by setting it to the centre of a dispersive line of odd symmetry. The alternating readout of the fluorescence detection generates a low-frequency ac signal whose modulus is used as the feedback that controls the phase or frequency setting of the oscillator. The usual way of exciting the ion by the output wave of the oscillator is with a pair of $\pi/2$ pulses separated by a time T of free evolution, which is known as the Ramsey method in the time domain [4]. Since the first $\pi/2$ pulse generates a coherent superposition of ionic energy eigenstates, i.e. a magnetic dipole or electric quadrupole, this superposition state is not compatible with the state-probing effect of the succeeding fluorescence detection. Consequently, this scheme of excitation gives rise to a stochastic distribution of results and to the corresponding "quantum projection noise" [5], that, in principle, dominates the measurement, save for the presence of major technical noise sources.

In the framework of the current "Förderungs-Schwerpunkt" of the DFG we have accomplished a series of observations and measurements on trapped Yb^+ and Ba^+ ions that are relevant to metrology. Among the small group of ion species that allow single-ion preparation and measurement by well-accessible light sources, ytterbium stands out in that it shows resonance lines not too far in the uv, and potential E2 clock lines in the blue, both of which might be excited (two-photon or frequency-doubled) by diode laser light [6] (Fig. 1). Also, there is an E3 line connecting the $S_{1/2}$ ground state with the $F_{7/2}$ level that is possibly the longest-living metastable state in the periodic system [7]. The odd isotope $^{171}Yb^+$ shows a hyperfine transition in the ground state to be excited by a micro-wave at 12.6GHz.

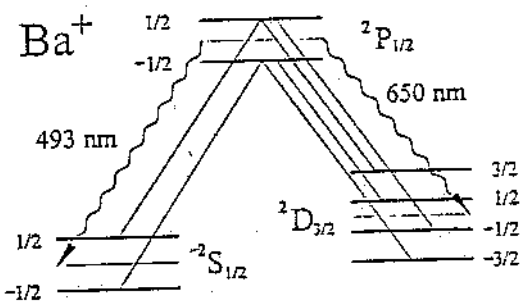

Fig. 2: Energy levels and lines of BaII.

The studied topics enclose:

– Implementation of a multi-ion micro-wave frequency standard [8].

– Single-ion microwave-optical double resonance, Rabi type [9].

- * ditto, Ramsey type [10].
- Measurements of Te_2 lines used as calibration marks for the E3 line [11].
- * Search for the ultra-narrow E3 line (467nm) [12].
- Two-photon excitation of $S_{1/2} - D_{5/2}$ (822-nm) by an diode laser (in preparation).
- Cleaning the states $D_{3/2}$ and $F_{7/2}$ by re-pumping the ion with radiation at 2.4μm, 609nm, 638nm, and 770nm [13].
- Spectral detection of the ionic micro-motion [14].

We shall report, in this communication, on the selected topics marked by an asterisk.

Another ion species most suitable for single-ion experiments is Ba^+ (Fig. 2). This is the species that was used with both the first observation of laser cooling [15] and the first preparation and visual detection of a *single* ion [16]. In the metrologic context, the following topics have been studied recently using a single $^{138}Ba^+$ ion:

- Dark resonances and "trapped" states of the ion [17].
- Light shift and Fano resonances [18].
- * The emission spectrum of resonance fluorescence [19].
- * Excitation spectroscopy of the E2 line BaII $S_{1/2} - D_{5/2}$, including
  - observation of resolved sidebands of the ionic secular motion [20],
  - modelling the motional sidebands in 3D [21],
  - first recording of excitation spectra of *stimulated emission* [22],
  - the concept of stochastic cooling [23],
  - spectroscopic recording of the ion's vibrational dynamics [24].
- Optical triple resonance and possible dispersive effects of quantum jumps [25].

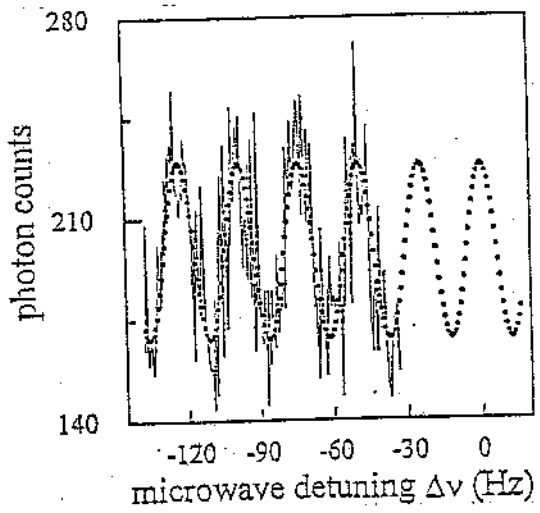

Fig. 3: Tuning spectrum of rf-optical double resonance ("Ramsey fringes") on single $^{171}Yb^+$. Dots: Numerical fit. Microwave frequency at $\Delta\nu = 0$ is 12 642 815 400 Hz(B_0 = 321μT) which is Zeeman-upshifted from zero-field resonance at 12 642 812 118 Hz.

Although Rabi-type double resonance on both an ensemble of $^{171}Yb^+$ ions in a Paul trap [8] and on such a single ion has been demonstrated [9], only recently we have achieved to record *Ramsey* fringes with quantum amplification, on a *single* $^{171}Yb^+$ ion, in double-resonance spectroscopy. A recording is shown in Fig. 3. So far the best-resolved recordings feature fringes 12Hz wide. This width is ascribed to magnetic fluctuations in the laboratory environment during the time T separating the micro-wave $\pi/2$ pulses.

The search for the YbII E3 transition

$S_1/_2 - F_7/_2$ is a major challenge since the lifetime of the F level is not known, but certainly longer than 8d [7]. In order to achieve a detectable transition rate on this line, the spectral bandwidth of the oscillator wave (467nm) and the ionic absorption profile have to be narrowed and matched for sake of optimizing their overlap. This aim requires (*i*) the elimination of inhomogeneous motional line broadening by both laser cooling of the ion's secular motion and compensation of its micro-motion by adjusting a dc field, such as to place the ion in the node of the trapping field, and (*ii*) broadband control of the output frequency of the laser oscillator. The latter feat has been achieved by a set of control circuits operating in series [11]: 1. A first stage controlled by a focal FPI for the elimination of fluctuations with a characteristic time $\tau < 1$ms. 2. A second stage, at the site of the trap, based on a super cavity whose mirrors are spaced by a hollow cylindrical rod of glass ceramics ("Zerodur") that takes care of controlling laser fluctuations with $1\text{ms} < \tau < 1\text{s}$. 3. A third stage for long-term frequency control by a reference line of Te_2. — The second stage is the most critical one since it is to eliminate acoustic perturbations that act along the path of transfer of the light from the oscillator to the trap. It employs simultaneous electrooptic modulation of the light by a large radio frequency Ω and $f \simeq 700$kHz, where f is used for Pound-Drever locking one of the two sidebands of the high-frequency phase modulation, split into a triplet, to a resonance of the super cavity. Variation of Ω makes to scan the carrier in the range $10\text{MHz} \times 2\pi < \Omega < 1\text{GHz} \times 2\pi$. The wavelength of the light is measured by setting Ω to the FSR of the cavity (Ω_0), multiplying it with the mode order, and adding the fractional residue of the wavenumber when Ω corresponds to the actual light wavelength. In this way, a set of Te_2 lines in the neighbourhood of the Yb^+ E3 transition has been measured, which are used for locking the laser, and as a wavelength reference (Fig. 4).

The elimination of the ion's micro-motion has been achieved by spectral resolution of its sidebands of Doppler phase modulation in the excitation spectrum of 609-nm dye-laser light near resonant with the $D_3/_2 - {}^3[1/2]_1/_2$ transition. This light was used for back pumping the ion, via electronic Raman anti-Stokes processes, to the ground state. Spectra at stepwise better adjusted values of an extra dc potential show the modulation index diminishing and prove the ion approaching the ac field node. The final displacement of the ion location off the node of the trapping field was found to be less than 40nm.

The ion having been prepared, stepwise scanning the clock light over a range of 100MHz across the E3 resonance should, on resonance, result in extinguished scattering of the resonance light (369nm) over time intervals on the order of a second for each absorptive event, i.e. the appearance of "quantum jumps" into and out of the $F_7/_2$ level, with rate

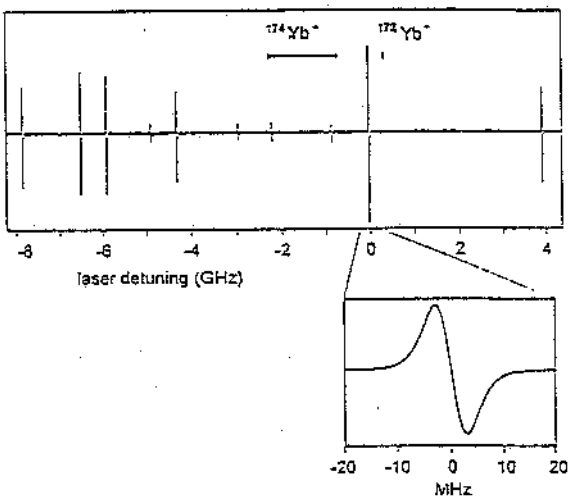

Fig. 4: Saturation spectrum of Te_2 close to the resonances of the $S_1/_2 - F_7/_2$ E3 line for $^{174}Yb^+$ and $^{172}Yb^+$.

1/sec. Quantum jumps with a rate on the order 1/min have been observed so far, however, found uncorrelated with the tuning of the light. This zero result is compatible with the $F_7/_2$ decay time exceeding 8d with 90% probability, and exceeding 100d with 50% probability. A future version of this experiment will combine some 20 ions in a linear trap with a focal enhancement cavity for the light enclosing the ion position. We expect more than 1000 times improvement of sensitivity for absorption on the E3 line, and a detectable quantum-amplified signal on resonance.

With the Ba^+ ion, two kinds of narrow lines of metrological significance have been studied: The line $S_1/_2 - D_3/_2$, two-photon excited by visible light close to 493nm and 650nm, and the E2 line $S_1/_2 - D_5/_2$. The former line shows up dark resonances when one of the two light fields is scanned, and the condition of equal detuning of the light frequencies from the respective one-photon resonances is met [17]. The latter E2 line has been excited by the light of a colour-centre laser at 1.76μm, alternated with irradiation by the green visible probe light field that excites resonance scattering. Zero scattering signals excitation on the E2 line, and the rate of zero-scattering events peaks at the line centre. Spectra of the Zeeman-split E2 line have been recorded in this way, where four components are observable, out of ten, with the linear polarization of the light being parallel with the magnetic field, as it is set in the observations. One component is shown in Fig. 5. Its line width is mainly due to saturation broadening, with about 16kHz resulting from the residual bandwidth of the ir light, due to spurious acoustic modulation of the reference

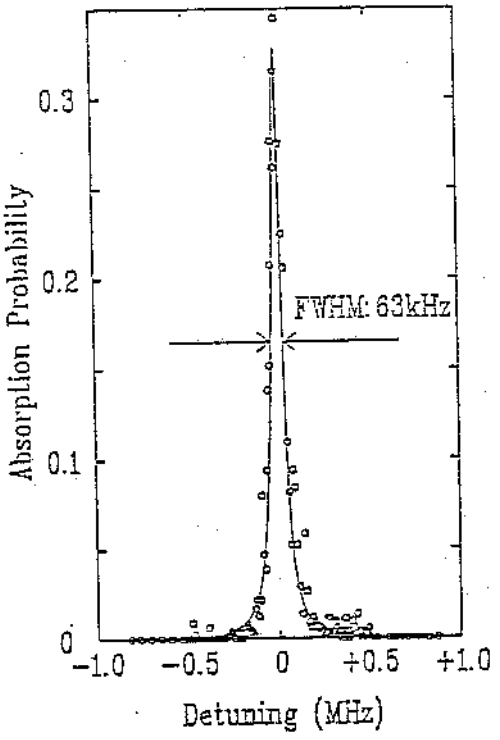

Fig. 5: Optical triple-resonance spectrum of a component $m_S = +1/2$, $m_D = +3/2$ of BaII ($S_1/_2 - D_5/_2$) E2 line recorded as the rate of "no fluorescence" events *vs.* detuning of the 1.76-μm laser light.

cavity controlling the ir laser. We feel that a factor-ten improvement is feasible with existing equipment. An even narrower line, however, would require more sophisticated shock damping of the reference cavities [26].

The technical noise being substantially reduced, and with the means of almost quenching it at hand, the limiting residual imprecision, due to quantum effects, of the outlined double-resonance measurement comes in sight. The source of the corresponding noise is quantum incompatibility of "preparation" by the clock light and "read-out" by light scattering. A magnetic dipole or electric quadrupole, i.e. a coherent *superposition*, is generated by the $\pi/2$ pulse of the wave (ω) on the clock transition, whereas the observed fluorescence monitors the ion in an *eigenstate* of its internal energy. Consequently, the measurement is incompatible with the preparation, and its results are distributed over a finite range of values, around the expectation value. The number of ions N_- found in state $|-\rangle$, by exciting their fluorescence, out of $N = N_+ + N_-$ uncorrelated ions, is a binomial distribution [5], and its variance is

$$\langle(\Delta N_-)^2\rangle = N p_-(1 - p_-) , \tag{1}$$

where $p_-(\omega)$ is the probability of finding an ion in state $|-\rangle$ that depends on the frequency ω of the clock wave. With the excitation of a perfect superposition state, p_- is $1/2$, and the variance is maximum. The corresponding uncertainty of the measured frequency is

$$|\Delta\omega| = \langle\Delta N_-\rangle \Big/ \frac{\partial\,\langle\Delta N_-\rangle}{\partial\omega} = 1/T\sqrt{N} \quad , \tag{2}$$

which is *independent* of frequency. In contrast, with N correlated ions, e.g. in a linear electrodynamic trap, the uncertainty obeys the condition [27]

$$|\Delta\omega_c| \geq 1/TN \quad , \tag{3}$$

such that a properly defined squeezing parameter is

$$\xi_R \equiv \Delta\omega_c/\Delta\omega = 1/\sqrt{N} \tag{4}$$

for optimum ion correlation. An example of a correlated state is, for $N = 2$,

(5) $$\psi(t=0) = (|+\rangle_1 |+\rangle_2 + |-\rangle_1 |-\rangle_2)/\sqrt{2} \quad .$$

General correlated states of this type are known as "spin-squeezed" states [28] in view of the isomorphism of spins and two-level systems. A remarkable way of generating these states has been recently suggested by D.J. Wineland et al. [29]. Correlations of the centre-of-mass harmonic-oscillator motion of the individual ions in a linear trap are made to be mapped, by vibrational-radiative coupling of Jaynes-Cummings type [30], into correlations of the N individual two-level systems that simultaneously interact with the clock wave. The proposed way of implementing this scheme is using stimulated electronic Raman excitation for the transfer [29]. In any event, studies of the *vibrational* dynamics and its coupling to the internal dynamics of the ions are of utmost importance for future attempts of increasing the precision of a frequency standard beyond the quantum limit. Here, we report on two recent experiments on a single trapped Ba^+ ion some of whose results may contribute to the diagnostics or preparation of vibrational states of the ion related to its secular motion.

Although excitation spectra of the resonance fluorescence of a *single* trapped ion have been recorded many years ago [31], *emission* spectra have not been reported so far. We have recently achieved the recording of these spectra of resonant light scattering off a Ba^+ ion showing up to five partially resolved spectral components. The set-up, shown in Fig. 6, entails a confocal cavity as a filter for spectral selection of the scattered light.

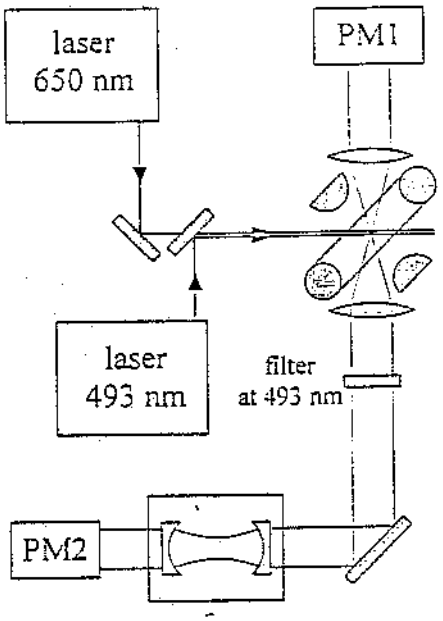

Fig. 6: Set-up for recording emission spectra of single-ion resonance fluorescence.

Dye laser light, at 493nm, excites the $S_1/_2 - P_1/_2$ resonance line, and induces resonance scattering, and a second laser, at 650nm, excites the $D_3/_2 - P_1/_2$ line for evading optical pumping into the metastable $D_3/_2$ state. The green light is slightly down-tuned from its resonance in order to laser-cool the ion, which is confined in the radio-frequency trap of 1-mm ring diameter. A 0.6-mT dc magnetic field removes the spatial degeneracy and prevents optical pumping among the Zeeman levels. The fluorescence is detected along the magnetic field and at right angles with both the linear polarization and the direction of propagation of the laser light in two opposite directions by two photomultipliers whose signals are read-out by a photon counter. In channel 1, the green fluorescence rate is detected, its

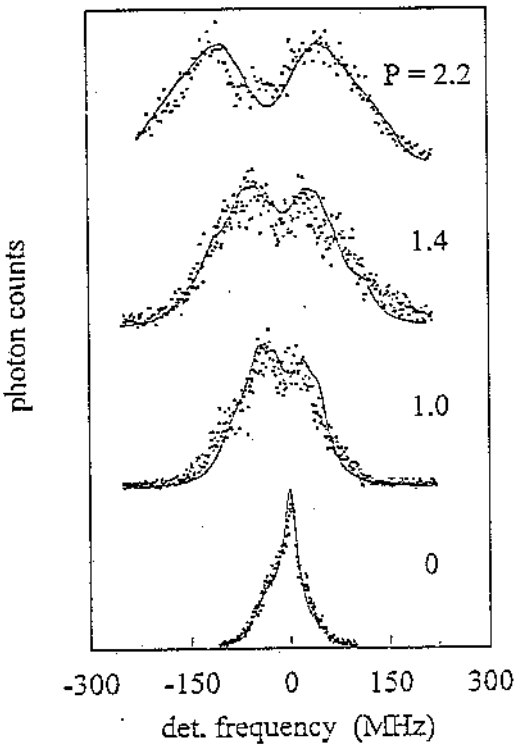

Fig. 7: Spectra of single-ion green resonance fluorescence, with the amplitude of micro-motion stepwise reduced (P: index of Doppler phase modulation).

maximum being 10^4 counts/s, in order to record excitation spectra whose fits to calculated ones provide us with values of the light intensities at the ion site, light detuning, and dc magnetic field. From these data, emission spectra of the fluorescence are calculated. Channel 2 contains a green glass and the piezo-tunable confocal filter resonator (finesse 45, free spectral range 750MHz). The photon-counting signal (maximum rate $200s^{-1}$) is recorded *vs* the filter scan and yields spectra of the ion's green fluorescence. Each data point corresponds to 1s integration of the counting rate.

Particular care has to be taken as to eliminate residual micro-motion of the ion that is caused by the driving field of the trap, if the ion location misses the node of the quadrupolar radio-frequency trapping field as a result of spurious surface charges on the electrodes. This micro-motion shows up as phase modulation of the ion's dielectric polarization, and consequently as sidebands in the spectra of the fluorescence. Fig. 7 shows such sideband spectra at various values of the modulation index P that characterizes the amplitude of the micro-motion. This motion is completely cancelled (P = 0) when the ion has been shifted to the very position of the radio-frequency node. The full lines show calculated spectra that take into account the 15MHz transmission band of the filter resonator, and a Bessel-distributed sideband spectrum. Note that carefully eliminating the micro-motion is indispensable in order not to confuse the recorded spectra.

With the ion at rest in the trap centre, spectra of its green resonance fluorescence have been recorded at various detunings of the lasers. Such a spectrum is shown in Fig. 8, where the green-light excitation is strong and the red-light excitation is weak, and both lasers are substantially detuned from their resonances (–36MHz and –61MHz, respectively). A calculated spectrum is shown that here results from a direct numerical fit to the observed data points. Fig. 8b shows this spectrum generated from a corresponding spectrum with the red laser being resonant. The variations of the

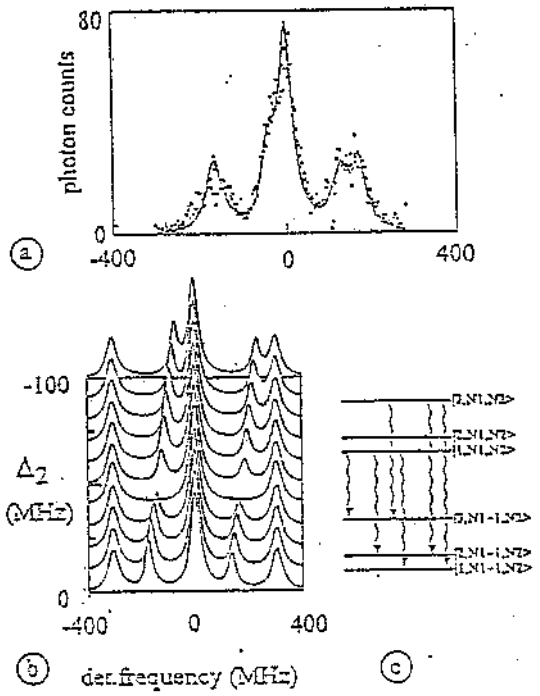

Fig. 8: (a): Spectrum of single-ion green resonance fluorescence, at strong green and weak red excitation, both detuned from resonance, and calculated spectrum (fit), Rabi freqeuncy $\Omega_1 = 168\text{MHz} \times 2\pi$, $\Omega_2 = 4\text{MHz} \times 2\pi$, detuning $\Delta_1 = -36\text{MHz}$, $\Delta_2 = -61\text{MHz}$. (b): Generation of five-line spectrum, from general seven-line spectrum, by stepwise down-tuning Δ_2, at reduced Ω_2. (c): Three-level manifolds of dressed levels, with 1 and 3 up-shifted, as they pertain to the top spectra in "b".

spectrum mirror shifts of the energy eigenstates of the ion plus light ("dressed levels", Fig. 8c). Upon down-tuning the red laser from resonance, the levels 2 are down-shifted, and the peaks marking the resonances $1 \longrightarrow 2$ and $3 \longrightarrow 2$ look up-shifted. Note that the red-laser detuning $\Delta_2 = -40\text{MHz}$ meets the two-photon resonance and "trapped state" condition ($\Delta_2 = \Delta_1$) such that fluorescence on *these* resonances is quenched for the vanishing probability of the decay of state 2. Quenching of the *total* fluorescence is concealed by the normalization of the spectra.

When further down-tuning the red laser, one shifts levels 2 close to levels 1 (Fig. 8c), and the spectra approach the observed one (8a). Thus, the five observed resonances may be identified, in the sequence of increasing frequency, as $1 \longrightarrow 3$, $1 \longrightarrow 2$, $i \longrightarrow i$, $3 \longrightarrow 2$, and $3 \longrightarrow 1$, where $i = 1,2,3$. These results demonstrate that emission spectroscopy on a single ion can provide information supplementing data derived from excitation spectra.

Vibrational distributions and dynamics of an ion in the trap may be studied by excitation spectroscopy on a narrow clock line, as the E2 line $S_1/_2 - D_5/_2$ of Ba^+. The frequencies ω_{xy}, ω_z of the ion's vibration in the trap exceed the width Γ of this clock line. With the bandwidth of the laser light small enough, motional sidebands are resolved in the spectra, that result when the signal light is scanned across this line, and the events of absorption (or stimulated emission) are recorded. Excitation on the first lower sideband, followed by spontaneous emission, gives rise to cooling to the residual kinetic energy which is Γ/ω_v times smaller than the $\hbar\Gamma/2$ Doppler limit that applies with unresolved sidebands [15]. When spontaneous emission on the narrow transition is so rare as to remain unlikely during an interval of irradiation, sideband cooling is very inefficient. One may detect, however, light-induced modifications of the vibrational state by sequentially probing the fluorescence on a resonance line after the interaction with the signal light.

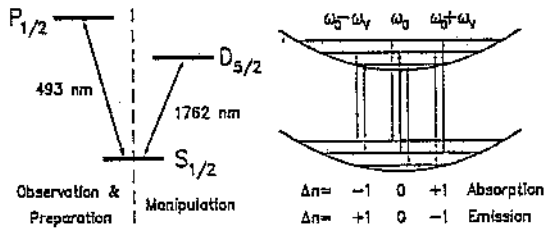

Fig. 9: Relevant levels of BaII (left). Laser excitation on the two lines alternates. A repumping laser inhibits the decay $P_{1/2} - D_{3/2}$. On the $S_{1/2} - D_{5/2}$ signal line ($\Gamma/2\pi = 6$mHz), sidebands from the ion's secular vibration in the trap (right) are resolved.

In this experiment, the ion is made irradiated by 1.76-μm clock light that alternates with fluorescence-generating green (and red) light used for monitoring the ground state (Fig. 9). The observed number of data pairs with resonance fluorescence "on" followed by "off" *vs* the tuning of the signal laser yields a spectrum of the absorption probability. In contrast, "off-on" pairs yield a *reemission* spectrum (Fig. 10). Since the matrix elements that link the vibrational levels $|n\rangle$ and $|n\pm1\rangle$ increase with n [32], the size of the sidebands depends on the ion's distribution over the vibrational levels and allows one to measure the ion's kinetic energy [33]. For the same reason, the vibrational distribution is modified towards increased $\langle n\rangle$ by each absorptive event on *both* sidebands. Thus, the size of the reemission sidebands in Fig. 10 is twice that for absorption [22].

Since "off" detection reduces the ion to the metastable level and to the respective vibrational distribution, an "off-off" pair of data also modifies the motional state if deexcitation is attempted on a sideband [21–23,34]. The reemission spectrum accordingly depends on the history the of detection process: Each reduction during a sequence of "off" detections takes the ion to a vibrational distribution bunched closer to $|n=0\rangle$. Fig. 11 shows $\langle n\rangle$ decrease with the number q of consecutive "off" events. This "cooling" is stochastic since a sequence of q "off" events occurs with probability U(q) which decreases with q, e.g. $U(q=9) \approx 0.5$ in Fig. 11. Attempts to deexcite the ion on the lower sideband finally result in certain deexcitation, i.e. $U(q\gg1) = 0$, but if the initial occupation probability (at q=1) of the vibrational ground state is nonzero, the ion may be *trapped* in $|n=0\rangle$, i.e. $U(q\gg1) > 0$, if the upper sideband is used instead. With the outlined procedure, cooling the ion may be completed in a fraction of the lifetime of the metastable level. In the example of Fig. 11 less than 1s is required for a sequence of recordings to occur that takes the ion to a state with $\langle n\rangle < 1$.

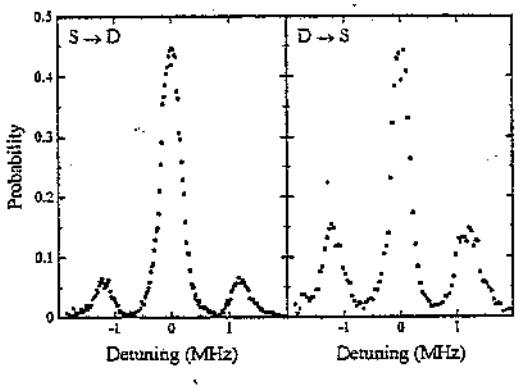

Fig.10: Probability of absorption (left) and emission (right) *vs.* detuning of the 1.76-μm laser, measured by recording the rates of fluorescence "on-off", and "on-off-on", respectively. Parameter values: Rabi frequency 10kHz, laser bandwidth 25kHz, duration of signal pulses 3ms, of probe pulses 2ms.

A set of sideband spectra with increasing q is shown in Fig. 12, where q encodes the time the ion spends in the dark state unaffected by the light. Here the first-order sidebands of both the degenerate vibrations in x-y direction and the non-degenerate vibration in z direction are resolved. The lower sidebands seem to decay faster than the upper sidebands, which would demonstrate stochastic cooling. The insert shows a 2D section of the data along the q direction – the time axis – at the upper x-y sideband, m = +1. The oscillation of the sidebands indicates Rabi flopping that involves the vibrational levels n and n+1 in the ground ($|-\rangle$) and excited "dark" ($|+\rangle$) electronic states, respectively. The transition probability includes, as factors, the squared matrix elements of the electronic and vibrational transitions [35]. Thus, the detected signal is the conditional probability of finding the ion in the dark state after q signal and probing cycles *and* having changed n by one. This probability is

$$p_+(q) = U(q) \sum_{n=0} P_n \cos^2(\Omega_{n,n+1} q\tau/2) \exp(-\gamma_n q\tau/2) , \tag{6}$$

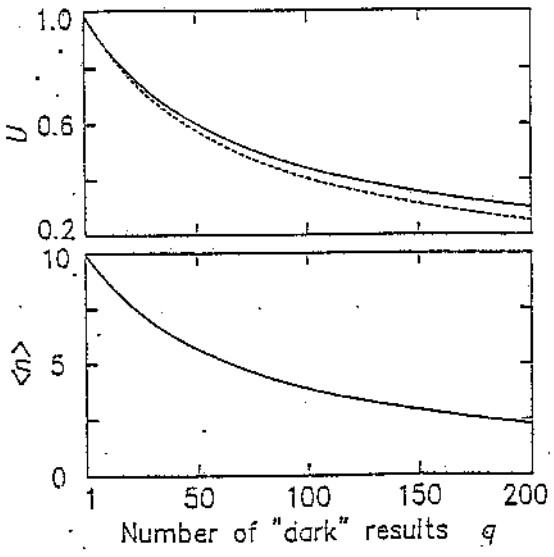

Fig.11: Probability U for the ion still residing in the excited electronic "dark" state $|1\rangle$, and mean oscillator quantum $\langle n\rangle$, *vs.* number q of successive projections to the dark state by missing detection of light scattering on the resonance line. At q = 1, the distribution is assumed thermal. Parameters: $\Gamma_1 = 0$, laser bandwidth 30kHz, vibrational frequency $\omega_x/2\pi = 1$MHz, duration of signal light irradiation $\tau = 10$ms, $(kx_0)^2 = 5 \times 10^{-4}$, Rabi frequency of signal 1.6kHz. U approaches 1/11 for $q \longrightarrow \infty$, when the ion is found in a "trapped" vibrational Fock state. Modification by spontaneous decay of state $|1\rangle$ is shown by the dashed curve.

where $\Omega_{n,n+1}$ is the Rabi frequency, and τ is a signal-probe cycle (see also Ref. 36). The distribution over the vibrational states is $P_n^f = P_n\delta(n,n_0)$ for the vibrational Fock state n_0, $P_n^{th} = N[\langle n\rangle/(1+\langle n\rangle)]^n$ with a thermal state of the ion, where N is a normalization factor, and $\langle n\rangle$ is the mean vibrational quantum number, and it is the Poissonian distribution $P_n^c = \langle n\rangle^n \exp(-\langle n\rangle)/n!$, for a coherent state. Whereas with a distribution corresponding to a vibrational Fock state the oscillation is expected to damp by the small rate γ_n of the ion's vibrational decoherence, a coherent state of the ionic vibration would show quantum interference from the excitation of different vibrational quantum states n. This interference may be observed as "collaps" and "revival" in the probability $p_+(q)$. In the data of Fig. 12 the oscillation seems to extend up to q = 25, and is quenched beyond. Whether or not this dynamics indicates "collaps" remains to be seen.

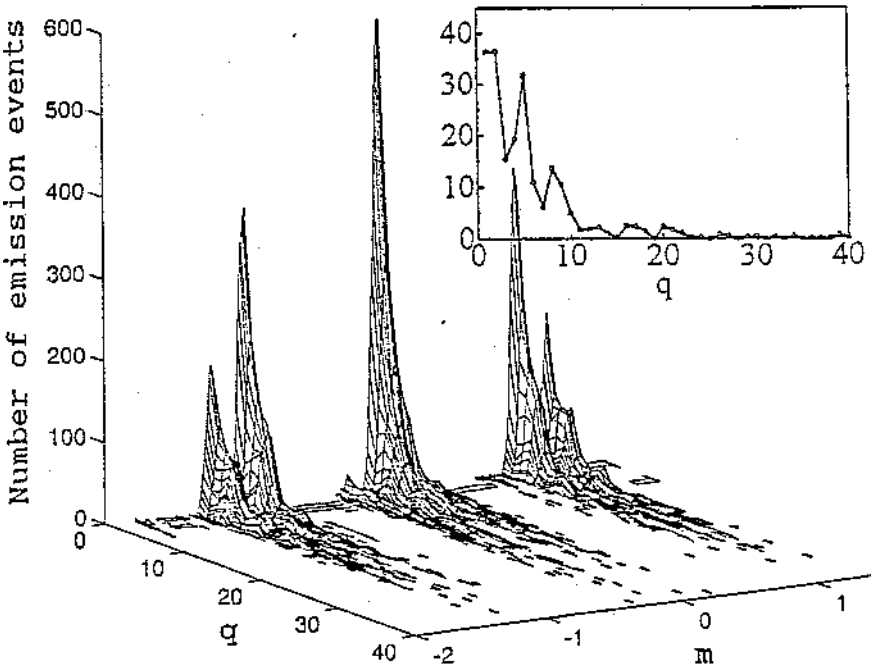

Fig.12: Vibrational sideband spectra of opto-optical triple-resonance on Zeeman component of BaII ($S_1/_2 - D_5/_2$) E2 line, recorded as rate of "fluorescence on-q×off-on" events, *vs.* detuning of the 1.76-μm light, in units of the x-y vibrational frequency $\nu_{xy} = 1$MHz and *vs.* q. Insert: Cut along the ridge of the upper x-y sideband (m = +1) *vs.* q.

In summary, various observations and measurements on single Yb^+ and Ba^+ ions have been accomplished that are relevant to the demonstration of a frequency standard based on a single trapped and laser-cooled ion. They include hyperfine transitions measured by the detection of Ramsey fringes, and dipole-forbidden optical lines, including the E3 line connecting the ground state of Yb^+ with the almost stable $F_7/_2$ level. Narrow optical resonances in a Ba^+ ion, relevant to frequency controlling, include the E2 line $S_1/_2 - D_5/_2$ which has been recorded, by detecting the tuning-dependent rate of quantum jumps, with 16kHz width of instrumental resolution, determined by the residual bandwidth of the signal laser.

Studies of laser-cooling and of the vibrational dynamics of the ion are motivated by (*i*) possible improvements of the control of the ion's motion and, consequently, of its residual Doppler effects, and (*ii*) generating spin-squeezed states, for more precise frequency measurements, by the formation of squeezed states of the ion's centre-of-mass motion and subsequent transfer the squeezing to the internal excitation of the ion on the clock line. Spectroscopy and manipulation of an individual ion in a Paul trap is reasonably advanced, and of several correlated ones may follow soon. Together with the availability of superstable cryogenic optical reference cavities for short-term and medium-term control of laser oscillators [37], these schemes improve the prospects for a frequency standard that exploits the superior long-term stability and accuracy of the internal resonances of a single ion, or correlated ions, placed in the electric field node of a trap.