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Rb atomic absorption line reference for single Sr^+ laser cooling systems

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Abstract. The near coincidence of the ^{85}Rb, $5s\,^2S_{1/2}(F''=2) \rightarrow 6p\,^2P_{1/2}(F'=2,3)$ absorption resonance with the $^{88}Sr^+$, $5s\,^2S_{1/2} \rightarrow 5p\,^2P_{1/2}$ transition is exploited to provide a simple, effective frequency reference for a laser cooling/fluorescence excitation source applied to single Sr^+ ions. A modulation-free frequency stabilization system has been designed which uses the differential signal from two frequency-displaced beams traversing a Rb cell and which probe the Doppler-broadened Rb *S*–*P* lineshape at microwatt power levels. The method is applied to frequency lock a 422-nm frequency-doubled diode laser system that is used for excitation of a single $^{88}Sr^+$ ion. Stable, long-term laser cooling and fluorescence are achieved using the frequency-stabilized 422-nm source resulting in observed ion confinement times without adjustment of over 8 h, together with an improvement in single-ion loading efficiency.

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Trapped, single ions have been an important and useful spectroscopic sample which have allowed advances in such fields as laser cooling, single-atom physics, high-resolution spectroscopy, and optical frequency standards [1–3]. The promise of examining a contained, single atomic particle, isolated from the external perturbing environment has been a driving force toward the proposal of such systems as nearly ideal frequency references for stable laser systems. In some ways, rapid progress in these studies has been hampered by the necessary multiplicity of laser sources which are required for fluorescence excitation, optical pumping, and probing. Recently, a number of groups have developed compact, solid-state laser systems for single-ion work which have allowed study into a variety of ion types and have simplified such experiments [4–11]. The single Sr^+ ion system has shown a particularly good match of the relevant transitions for detection, laser cooling, and probing to the available solid-state laser technology [7–11]. Advances in the absolute frequency measurement of a diode laser source stabilized on the $^{88}Sr^+$ 445-THz electric quadrupole reference transition [9–11] have resulted in this single-ion transition being very recently adopted as a recommended radiation for realizing the metre.

One important issue in further improving the ease and reliability of single-ion work is the implementation of absolute frequency references for the principal laser cooling source. For a laser-cooled single ion, the linewidth of the cooling/excitation resonance is near its natural width which is typically on the MHz level. These linewidths are typically narrower than the free-running frequency drifts of most laser sources. Since the incident cooling radiation has a profound effect on the ion kinetic temperature and fluorescence as a function of detuning, absolute stabilization of such a source is crucial. Indeed, if the frequency drifts of the cooling radiation source bring the detuning above the peak transition frequency, rapid laser heating can ensue, resulting in the loss of the ion. It is clear that accurate and stable control of the laser cooling source is a strong prerequisite for successful single-ion experiments.

In neutral atom laser cooling experiments for alkali atoms [12], saturation dip stabilization can be achieved by using a gas cell absorber of the same species. Unfortunately, the single-ion experiments do not have access to such simple references. A number of groups have employed opto-galvanic signals detected from excitation within hollow cathode discharges [8, 13]. These Doppler-broadened reference lines are typically quite wide (> 2 GHz) and suffer from low signal to noise. The signals obtained from such sources are characteristically employed to locate the necessary ion resonance but are not used for actual stabilization. Some groups have reported stabilization of their laser source by stabilizing one of the laser sources used in harmonic sum mixing to an iodine-saturated absorption resonance [14] and more recently, dye-laser-based cooling sources stabilized to saturation absorption lines in Te_2 [15, 16] have been mentioned. Hence atom/molecular absorbers can be an important route to providing reliable frequency control for single-ion spectroscopy.

In order to improve further the practicality of the $^{88}Sr^{+}$ optical standard, a search was undertaken for a reliable atomic/molecular reference which would be in close proximity to the $5s\,^2S_{1/2} \rightarrow 5p\,^2P_{1/2}$ cooling/fluorescence excitation transition at 422 nm. Although Te_2 absorption lines lie in this region, the nearest line is 1.9 GHz away [17]. Moreover, our present 422-nm laser cooling source is based upon a frequency-doubled diode laser system which produces $\approx 130\,\mu$W. This power level is more than sufficient for single-ion requirements but is below the powers needed for saturation absorption. A search of atomic data for a coincidence between the Sr^{+} S–P transition and a possible atomic absorber indicated that the Rb, $5s\,^2S_{1/2} \rightarrow 6p\,^2P_{1/2}$ transition existed within 1 GHz of the single-ion frequency [18]. This low-lying transition in Rb is strongly allowed and has a calculated absorption of $10^2\,\mathrm{m^{-1}Pa^{-1}}$. Also, the relatively low melting point of rubidium means that sufficient vapour pressures, on the order of 0.1 Pa, can be achieved at temperatures around 100 °C. The strong, stable, Doppler-broadened absorption profile obtained from such a setup can be used as a reliable large-bandwidth discriminator to servo the cooling laser frequency.

This paper describes the implementation and demonstration of an absolute frequency stabilization system for the Sr^{+} laser cooling/fluorescence transition using a ^{85}Rb reference line. A low-power portion (1 μW) of the 422-nm beam is passed through an acousto-optic modulator and the resulting beams are used to probe the Doppler-broadened Rb absorption profile at two frequencies. By detecting the differential transmitted power in the two beams, a correction signal is derived, which stabilizes the source laser frequency. The method is similar to that employed in polarization-stabilized HeNe lasers where two operating cavity modes have output power proportional to their position on the gain profile of the HeNe laser transition and are stabilized at absolute frequencies located symmetrically on either side of the gain maximum [19, 20]. Similar to such systems [20], we are able to obtain frequency stabilities over several hours on the level of 10^{-9}. Application of this stabilized laser system has been demonstrated through the reliable loading and laser cooling of single trapped ions of $^{88}Sr^{+}$ using the NRC trap system. Results from such work are also presented.

1 Considerations concerning the stabilization method

Consider a beam of frequency ν_0 and power P_0 which is input into an acousto-optic modulator operating at a downshift frequency f_S with an efficiency η into the first-order shifted beam. For this analysis, the power shifted into higher orders is included as a loss in the transmission of the device. The efficiency of transmission for the unshifted beam is proportional to $(1-\eta)$. The two emerging beams at ν_0 and $\nu_0 - f_S$ are made parallel to each other and pass through a cell whose transmission follows a Doppler-broadened absorption profile with line centre ν_{ref}, full width half maximum $\Delta\nu_D$, and peak absorption fraction α (see Fig. 1a). After exiting the cell, the transmitted powers are individually monitored and a voltage proportional to the difference of the beam powers is obtained.

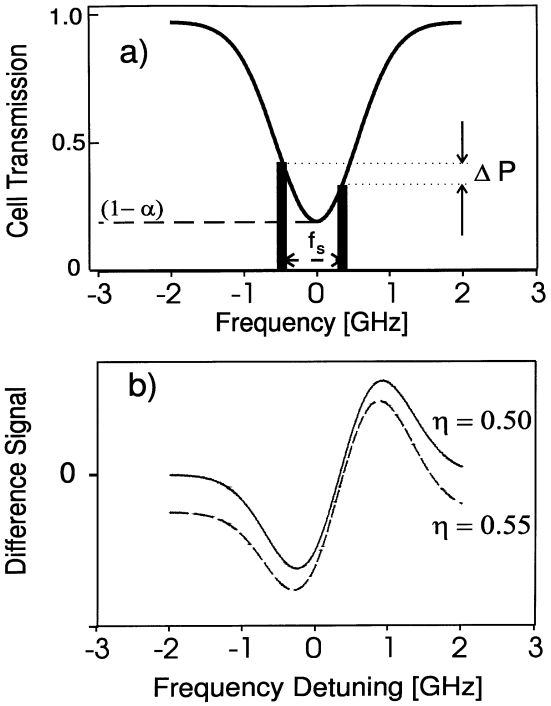

Fig. 1a,b. Illustration of the frequency stabilization method based on two beams of frequency spacing f_s, showing in **a** the relative transmission of the beams through an absorption cell with peak absorption α resulting in an output transmitted power difference of ΔP. In **b** the calculated difference signal is obtained for a relative efficiency into the frequency shifted beam of $\eta = 0.5$ (*solid curve*) and $\eta = 0.55$ (*dashed curve*). Calculations are based on parameters of $\alpha = 0.78$, $\Delta\nu_D = 1.3$ GHz, and $f_s = 0.65$ GHz

The obtained voltage difference can be expressed as:

$$\Delta V = \kappa P_0 \left\{ (1-\eta)\left(1 - \alpha \exp\left[\frac{-\Delta^2}{d^2}\right]\right) - \eta\left(1 - \alpha \exp\left[\frac{-\Delta^2}{d^2}\right] \exp\left[\frac{f_S(2\Delta - f_S)}{d^2}\right]\right)\right\}, \quad (1)$$

where $\Delta = \nu_0 - \nu_{\mathrm{ref}}$, $d = \Delta\nu_D/(4\ln(2))^{1/2}$, and κ is a constant incorporating the transmission efficiency through the modulator, relay optics, and conversion from light power to a voltage signal. For the special case of equal beam intensity emerging from the modulator ($\eta = 1/2$), one has the discriminator profile as shown in the solid curve in Fig. 1b that is symmetric about the $\Delta V = 0$ lock point. It can be seen that a smooth profile is obtained whose width is comparable to the Doppler width of the absorption profile. Solving (1) for the frequency value of ν_0 at the $\Delta V = 0$ stabilization point with $\eta = 1/2$, one can see that:

$$\frac{f_S(2\Delta - f_S)}{d^2} = 0\,. \quad (2)$$

Hence $\Delta = f_S/2$ and $\nu_0 = \nu_{\mathrm{ref}} + f_S/2$ at the frequency lock point. It can be seen that for this particular setting of $\eta = 1/2$, the stabilization point is insensitive to changes in the reference cell peak absorption α or width $\Delta\nu_D$. The lock point for the laser frequency can be adjusted by changing f_S. For values of η displaced from the $\eta = 1/2$ condition, the system can be sensitive to cell parameters (notably α). As shown in the dashed curve of Fig. 1b, the overall effect of changing η is

to shift the discriminator curve with the lock point ($\Delta V = 0$) being placed away from the central symmetry point. Changes in the depth and width of the absorption profile can now manifest themselves in changes of the stabilization point. Numerical calculations for the present experimental arrangement show that deviations of η within a range of $\pm 10\%$ maintain the insensitivity of the lock position to below 2 MHz for a 1% change of peak absorption. Hence for small variations near $\eta = 1/2$, the power balance method can be used with minimal degradation in the lock stability.

2 Experimental setup

A schematic diagram for the 422-nm source and Rb cell stabilization system is shown in Fig. 2. A commercial external cavity diode laser (New Focus Model 6226) provides 14 mW of power at 843 nm. After passing through crossed 100-mm and 300-mm focal length cylindrical lenses, the circularized beam is mode matched with a $f = 125$ mm lens into a resonant, frequency-doubling cavity. An optical isolator (Optics for Research OI-5-NIR), of -34 dB reverse isolation, is placed between the laser and the doubling cavity to prevent unwanted perturbation of the laser frequency by optical feedback. In addition, a $\lambda/2$ waveplate is used to control the polarization incident on the doubling cavity. The desired source radiation at 422 nm is produced by second-harmonic generation in temperature-tuned, non-critically phasematched $KNbO_3$. Enhancement of the fundamental 843-nm radiation is provided by a triangular resonator cavity consisting of an equilateral arrangement of plane high-reflection mirrors (spaced by 15 cm) and a pair of anti-reflection coated lenses of $f = 5$ cm located symmetrically about the doubling crystal to produce the desired beam waist within the non-linear medium [8]. A cavity free spectral range of 660 MHz with a finesse of 85

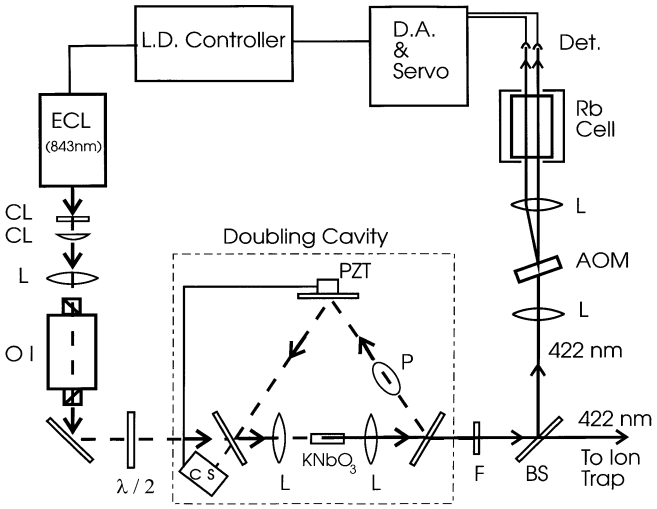

Fig. 2. Schematic diagram of the experimental arrangement for the 422-nm source and the stabilization to the Rb absorption resonance. ECL = extended cavity laser, CL = cylindrical lens, L = spherical lens, OI = optical isolator, $\lambda/2$ = half-wave plate, CS = enhancement cavity detectors and servo, PZT = piezoelectric translator, $KNbO_3$ = frequency doubling crystal, P = Brewster angle polarizing plate, F = 844 nm absorbing filter, BS = beam splitter, AOM = acousto-optic modulator, Det. = phototransistor detectors, D.A. = differential amplifier, L.D. Controller = controller electronics for the 843-nm diode laser system

is obtained. With a transmission of the input coupling mirror of $T_c = 0.03$, the calculated power enhancement factor for the present losses is 20. The $KNbO_3$ crystal is 1 cm long and maintained at the optimum phasematching temperature of approximately $-17\,^{\circ}$C via thermoelectric cooling. The enhancement cavity is stabilized to the incident laser frequency by the modulation-free method first demonstrated by Hänsch and Couillaud [21]. This cavity stabilization method observes the polarization ellipticity of the 843-nm beam reflected from the input mirror of the enhancement cavity and uses this signal to stabilize the cavity into resonance with the input radiation. With an incident power of $P = 12$ mW at 843 nm on the input mirror, 130 μW of 422-nm power is produced with the enhancement cavity remaining locked indefinitely. Unwanted 843-nm radiation is then filtered via a BG14 red-absorbing, blue-violet glass filter and the transmitted 422-nm light is sent to the ion trap optics and Rb cell stabilization system. Most of the optical power is directed to the ion trap with 60 μW passing through the ion trap with a beam waist of $\omega = 16\,\mu$m. A 2-μW portion of the 422-nm beam is sent to the Rb stabilization system where it is initially focused by a $f = 150$ mm lens into a high-frequency, acousto-optic modulator [AOM] (Brimrose, model TEF 680-200-422). With ~ 26 dBm applied input rf power, the AOM produces unshifted and frequency-downshifted beams of comparable output power. In order to maintain a constant relative fraction of power in the two beams emerging from the AOM, a rf power-stabilized, AOM driver consisting of a phase-locked oscillator followed by an amplitude-stabilized power amplifier are employed . The driver stability is better than 0.1 dB at the output of 26 dBm and could be smoothly varied to produce output powers from 20 to 30 dBm. By adjusting the power ratio of the two beams about the $\eta = 1/2$ position, smooth tuning of the stabilized laser frequency is obtained. The two beams are made parallel to one another (5 mm separation) by a $f = 45$ mm lens located a focal length away from the AOM. They then traverse a 75-mm-long, temperature-stabilized Rb absorption cell maintained at a temperature of $T = 120\,^{\circ}$C. The vapour pressure within the cell is estimated to be 0.1 Pa, producing a peak small-signal absorption fraction of $\alpha = 0.78$ for the $5s\,^2S_{1/2}$ $(F'' = 2) \rightarrow 6p\,^2P_{1/2}(F' = 2, 3)$ Doppler-broadened absorption profile. A matched pair of phototransistors (Motorola MRD 300) are then used to measure the light power transmitted through the cell. The two signal amplitudes are fed into a differential amplifier followed by a servo lag/integrator which is used to control the piezo-translator in the 843-nm external cavity laser (tuning response was 7 GHz/V). An open loop servo gain decreasing by 17 dB/decade to a unity loop gain at 80 Hz is employed. The choice of this cut-off frequency is due to the limited frequency response of the resonant cavity frequency doubler servo.

3 Results

For the natural mixture of ^{85}Rb and ^{87}Rb present in the cell, the observed small signal absorption for the $5s\,^2S_{1/2} \rightarrow 6p\,^2P_{1/2}$ transition centred at 710.9623 THz consisted of three groups of lines as shown in Fig. 3. The central Doppler profile was the closest to the centre of the $^{88}Sr^+$ single-ion $5s\,^2S_{1/2} \rightarrow 5p\,^2P_{1/2}$ resonance transition and consisted of the

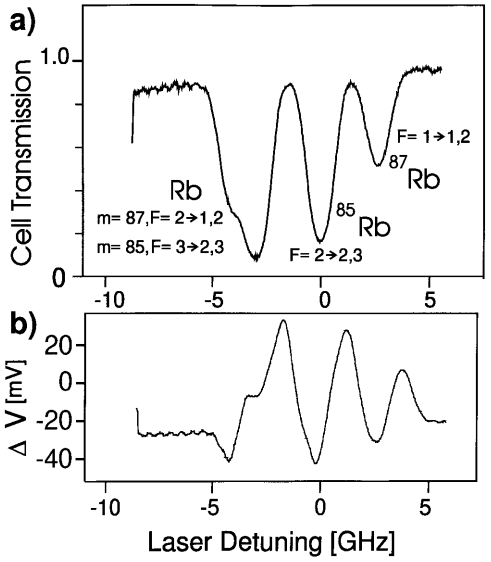

Fig. 3. a Measured cell absorption spectrum for a natural isotopic mixture of Rb on the $5s\,^2S_{1/2} \rightarrow 6p\,^2P_{1/2}$ transition showing the groups of hyperfine transitions within resolved Doppler broadened lineshapes. **b** Measured difference signal as laser was scanned across spectrum

unresolved $5s\,^2S_{1/2}$ $(F'' = 2) \rightarrow 6p\,^2P_{1/2}(F' = 2, 3)$ transitions of ^{85}Rb. Since the hyperfine splitting of the upper $^2P_{1/2}$ state is small (< 150 MHz), the observed profile is dominated by the kinetic Doppler profile of width $\Delta\nu_D = 1.3$ GHz (FWHM). The measured frequency offset of the peak absorption of the unresolved Doppler profile from the line centre of the $^{88}Sr^+$ S–P transition was $\Delta\nu = 540 \pm 50$ MHz.

Figure 4 shows the absorption profile of the unshifted beam traveling through the Rb cell together with the observed discriminator trace of the frequency stabilization system. As can be seen, the lock point of the servo is located to the high-frequency side of the centre of the Rb profile at an offset of approximately 500 MHz which was found to be optimal for laser cooling of the $^{88}Sr^+$ ion. A discriminator width of

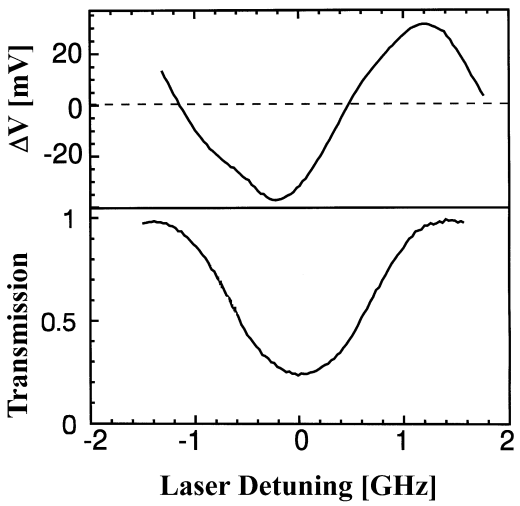

Fig. 4. Measured absorption profile (*bottom*) and difference signal (*upper curve*) for the central $5s\,^2S_{1/2}(F = 2) \rightarrow 6p\,^2P_{1/2}(F = 2, 3)$ spectral feature used in the laser stabilization of the 422 nm source for Sr^+ single-ion cooling

1.2 GHz is obtained. With the servo loop closed, the 422-nm laser remained in lock for periods as long as the longest experimental periods employed (> 12 h). From the servo correction signal, it could be seen that cancellation of long-term (> 5 s) frequency drifts of > 100 MHz over an hour were occurring. It is believed that the majority of the frequency drifts arise from thermal drifts of the 843-nm laser external cavity. Technical data of the commercial 843-nm laser give a thermal sensitivity at 843 nm of approximately 250 MHz/°C. The observed free-running drifts observed are consistent with the measured laboratory temperature fluctuations. Studies of the linewidth of the 422-nm radiation stabilized with the Rb reference cell were performed by using a sealed, temperature-stabilized etalon whose side of fringe transmission signal served as a frequency discriminator. The measured short-term ($t < 0.1$ s) rms fluctuations for the 422-nm source were 0.7 MHz. No change in the short-term linewidth was observed with or without the Rb cell servo. This result indicates that most of the 422-nm source-width originates from the rapid frequency fluctuations associated with the 843-nm diode laser.

3.1 Demonstration of the laser stabilization system for loading and laser cooling of single Sr^+ *ions*

The Rb-stabilized, 422-nm source was utilized in continuing experiments dealing with the single $^{88}Sr^+$ ion. Detailed descriptions of the ion trap and other necessary laser sources have been given in previous work [7, 9, 11, 22]. Briefly, a single $^{88}Sr^+$ ion is trapped under ultrahigh vacuum conditions ($< 10^{-8}$ Pa) using a miniature radio-frequency, Paul-type trap having a characteristic endcap spacing of $2z_0 = 1$ mm and trap voltage amplitude and frequency of $V_0 = 260$ V and $f = 12.0$ MHz. Typical secular motion frequencies for the ion in the trap are $f_r = 870$ kHz and $f_z = 1750$ kHz in the radial and axial directions, respectively. In addition to the laser source operating on the S–P transition at 422 nm, a diode-pumped 1092-nm fiber laser [4] is used. Since the ion can relax from the $5p\,^2P_{1/2}$ into the lower $4d\,^2D_{3/2}$ metastable level with 1:13 branching, excitation at 1092 nm serves to excite the $4d\,^2D_{3/2} \rightarrow 5p\,^2P_{1/2}$ transition and ensure continuous cycling of the S–P cooling/fluorescence transition. Fluorescence photons at 422 nm are used to detect the presence of the ion by imaging the fluorescence emitted in a direction perpendicular to the incident laser beam onto a photon counting photomultiplier system. Typical detected count rates of 1×10^4 s^{-1} are observed for single-ion samples with background scattered light levels of 800 s^{-1}. Confirmation that the observed fluorescence originates from a single ion is made by exciting the ion using 445-THz radiation from a sub-kHz probe laser source [9] which is resonant to the $5s\,^2S_{1/2} \rightarrow 4d\,^2D_{5/2}$ transition. When a single ion is excited into the $4d\,^2D_{5/2}$ metastable level, fluorescence at 422 nm ceases and quantum jumps in the single-ion fluorescence from the normal 10^4 s^{-1} signal down to background are observed.

Figure 5 shows the observed single-ion fluorescence, with quantum jumps, from the single ion using the Rb stabilization system. Reliable, steady fluorescence is observed for a detuning of the 422-nm source 500 MHz above the centre of the Rb absorption. Excellent contrast between the fluorescing and metastable shelved states is obtained, allowing unambiguous

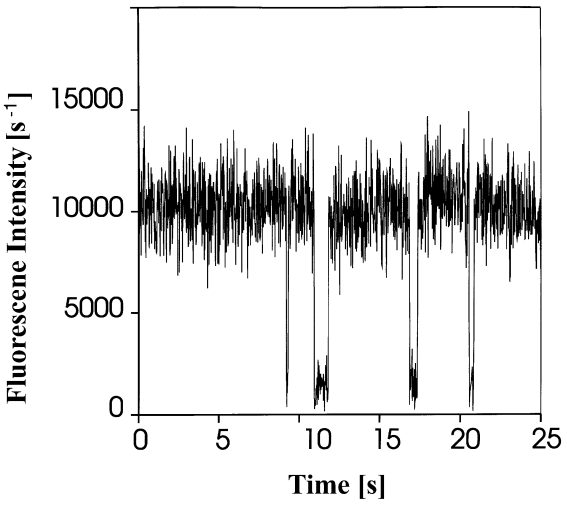

Fig. 5. Observed single Sr^+ quantum jumps in 422-nm fluorescence. The 422 nm source was stabilized to the Rb absorption line

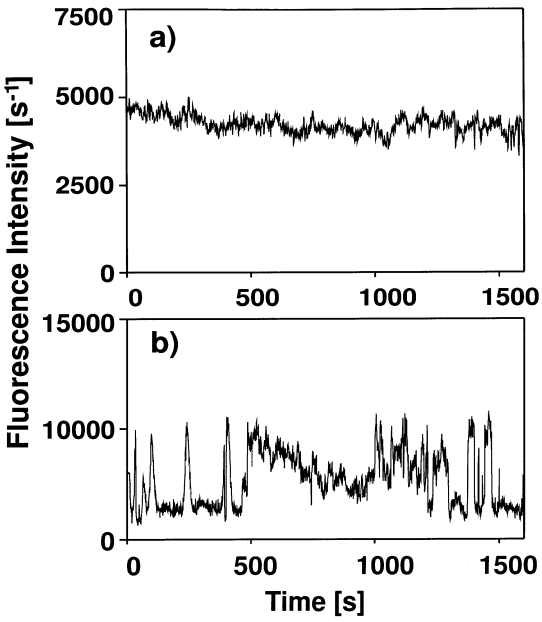

Fig. 6a,b. Long-period comparison of single-ion 422-nm fluorescence without *S–D* excitation. **a** Observed fluorescence from the ion stabilized at the Sr^+ *S–P* lower frequency half intensity point using the Rb cell-based frequency lock. **b** Observed fluorescence for a constant applied voltage on the tuning PZT of 843 nm laser

identification of the quantum jump events. As an indication of the 422-nm system's efficiency in laser cooling, studies of the *S–D* transition at high resolution provided information on the ion kinetic temperature via the observation of the relative amplitudes of spectral features associated with motional sidebands [23]. Motional sidebands at the radial secular frequency of $f_r, = 870$ kHz were observed and the observed intensity ratio of the principal carrier line to its first-order sideband was $\sigma(0)/\sigma(1) = 3.8 \pm 0.6$. Higher-order sidebands were observed to be substantially smaller. The results confirm that the ion kinetic motion was in the Lamb–Dicke regime [24] for probing the 674 nm *S–D* transition. Using this ratio, the calculated parameters of our trap potential well, and the relations developed by Wineland and Itano [23], an ion kinetic temperature of 5 mK to 10 mK was determined for typical experimental laser detunings. Similar results were obtained for different scans indicating that the 422-nm source was providing a consistent rate of laser cooling.

Figure 6a shows the observed single-ion fluorescence from the ion without excitation on the *S–D* transition over a time period of 1500 s. Steady 422-nm fluorescence from the ion is observed with variations less than 25%. The gradual decrease in ion fluorescence over time is due to the slow power drift in the 1092-nm fiber laser source. Longer studies of the ion fluorescence showed that the 1092-nm laser behaviour dominates any changes in fluorescence. In fact, the 422-nm source with Rb cell stabilization was employed for periods exceeding 8 h without any need for adjustment. The stability of this source was instrumental in the success of recent Cs-based optical frequency measurements of the $^{88}Sr^+$ 445 THz optical frequency standard transition on a reliable day-to-day basis [11]. In contrast, Fig. 6b shows the fluorescence without the Rb stabilization and the 843-nm laser PZT bias supplied by a stable dc voltage source. It can be seen that the frequency drifts dominate the fluorescence as the source frequency moves up and down the lineshape. At the end of trace (b), the ion was heated out of the trap as the unstabilized laser moved to frequencies above the *S–P* line centre.

Another significant improvement afforded by the described stabilization method was the increased ease in obtaining reliable single-ion loading into the trap. The system provided much greater accuracy in the initial placement of the laser cooling frequency in contrast to the previously employed method based on wavemeter readings. A standard approach to ion loading has been to operate a nearby source of atoms until a detectable level of fluorescence is obtained above background. It had been previously observed that the detuning for maximum fluorescence from multiple ions was notably broader and located several tens of MHz below the optimal single-ion *S–P* detuning. The origin for this effect is presumably due to the strong Coulomb coupling of multi-ion systems and the strongly driven micromotion of the ion displaced from the trap field node [25]. Therefore if the detuning was not controlled, there was a good chance that the loading process was not halted when a single ion was in the trap. With the Rb stabilization method, initial *S–P* laser tuning near the optimal frequency for single-ion fluorescence is consistently obtained, notably decreasing the start-up time for single-ion experiments.

4 Summary and conclusions

We have demonstrated a simple and reliable method for stabilizing a low-power solid-state laser source operating on the *S–P* transition of the single strontium ion using a strong Rb absorption resonance. It is believed that this system simplifies single-ion manipulation and spectroscopy. The locking technique can be extended to any system where minimal laser power is available and a low-noise absorption profile at a nearby frequency can be obtained. It is clear that the accuracy and stability of such a method will be ultimately inferior to that obtained by saturation resonances (if they can be observed) just as polarization-stabilized HeNe lasers possess inferior stability and accuracy characteristics relative to I_2-stabilized HeNe lasers. However, when the needed accuracies

and stabilities are on the 10^{-8}–10^{-9} level, as frequently required by laser cooling experiments, the method as described here may be a helpful solution with its associated simplicity and ease of operation.

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