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A simple method for counting the number of trapped ions in an ion trap

K. Okada[1], T. Nakamura[1], S. Ohtani[1], M. Wada[2], J. Tanaka[2], H. Kawakami[2], I. Katayama[2], D. Schnier[2,⋆], H. A. Schuessler[2 ⋆], O. Becker[3], F. Arbes[3], G. Werth[3]

[1] Institute for Laser Science(ILS), The University of Electro-Communications, 1-5-1 Chofugaoka Chofu-shi, Tokyo 182, Japan
(Fax: +81-424/85-8960, E-mail: okada@news1.ils.uec.ac.jp)
[2] Institute for Nuclear Study(INS), The University of Tokyo, 3-2-1 Midoricho, Tanashi-shi, Tokyo 188, Japan
(Fax: +81-424/68-5844, E-mail: wada@insuty.ins.u-tokyo.ac.jp)
[3] Institut für Physik, Johannes Gutenberg Universität, D-55099 Mainz, Germany (Fax: +49-6131-39-5169, E-mail: werth@vipmza.physik.Uni-Mainz.DE)

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Abstract. The number of stored Ca^+ ions in an ion trap was measured optically by utilizing the metastable states. All the ions trapped are first pumped into the metastable D states. The ions in the metastable D states are transferred to the ground S state via the P state by exciting a $D \rightarrow P$ transition. Each ion then emits one photon through a subsequent $P \rightarrow S$ spontaneous emission. Thus, the number of photons is the same as the number of trapped ions initially in the metastable states. When a fraction of all the stored ions are pumped into the metastable states, the method is still applicable if the fraction of the ions is known.

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In many ion trap experiments, it is of importance to know the number of trapped ions non-destructively. It is, however, not so easy to count the ions reliably and only a few, sometimes ambiguous, methods have been used so far. The measurements of a small current induced by the collective motion of trapped ions can be applied to the ion number measurements [1–5]. When a large number of ions are trapped in an ion trap, a rf resonance absorption method is normally used for the measurement of the number of the trapped ions. The sensitivity and the accuracy of the method, however, are not so high because it requires the measurement of a small induced current between endcap electrodes which is often masked by noise from the driving rf field and the signal height and shape depends critically on the proper tuning of the amplifier circuits.

In laser spectroscopy of trapped ions, the intensity of the laser induced fluorescence can be used to estimate the number of stored ions [6]. Actually, a small number of laser cooled ions is really countable by detecting discrete decay or stepwise cooling of the laser-cooled ions [7]. In the case of an ion cloud, one must know the mean excitation rate for the whole ensemble of stored ions to estimate the number. It is, however, not so simple to estimate the excitation rate, because one must normally assume several ambiguous parameters, such as the temperature of the ion cloud, the power and the diameter of the laser beam at the trap region and the fraction of ions irradiated. These parameters depend upon the experimental conditions.

In the present paper, we propose a new method to reliably count the number of ions in an ion trap.

1 Principle

Some ions, such as Ca^+, Ba^+ and Sr^+, have metastable D states from which P states can be accessed by E1 allowed optical transitions. For these ions, we can count the number of trapped ions by employing the one to one correspondence of emitted photons to trapped ions when we utilize metastable states. We use a UV pumping laser to excite the $S \rightarrow P$ transition and two IR lasers to excite the $D \rightarrow P$ transitions (See Fig. 1). The method works as follows. We firstly excite the $S \rightarrow P$ transition while the IR lasers are turned off for the optical pumping of all the trapped ions into the D states. Then, we turn off the UV laser and excite the $D \rightarrow P$ transitions by the IR lasers. At this moment, a prompt fluorescence yield occurs because each ion, quickly excited from the D states, emits one photon due to the spontaneous emission from the P to the S state. Since one UV photon corresponds to one ion, the total number of trapped ions, N, can be derived as

$$N = \frac{N_{\mathrm{det}}}{\epsilon}, \tag{1}$$

where N_{det} is the number of detected UV photons due to the excitation of the $D \rightarrow P$ transition and ϵ is the detection efficiency.

If there is a relaxation of the D states to the ground state due to gas collisions, the method should be modified. In this case, complete optical pumping of the stored ions to the D states is not attained. We need, therefore, to know the

⋆ On leave from the Department of Physics, Texas A&M University, College Station, Texas 77843, USA.

population ρ_D of ions pumped into the D states to estimate the number of ions, then

$$N = \frac{N_{\rm det}}{\rho_D \epsilon}. \tag{2}$$

To explain the modified method, we take the three level system, in which the population ρ_D is given as

$$\rho_D = \frac{A_{PD}\Gamma_{SP}}{A_{PD}(\Gamma_{SP}+\gamma_{DS})+\gamma_{DS}(A_{PS}+2\Gamma_{SP})}, \tag{3}$$

where $A_{\rm if}$, $\Gamma_{\rm if}$ and $\gamma_{\rm if}$ are the spontaneous emission rate, the excitation rate and the relaxation rate, respectively with the subscripts i and f which denote the initial- and final-state, respectively. ρ_D can be estimated experimentally as follows. We measure fluorescence intensities at two different equilibrium conditions; $I_{\rm a}$ when all the lasers are turned on and $I_{\rm b}$ when the IR laser is turned off. The stationary intensities $I_{\rm a}$ and $I_{\rm b}$ are given as

$$\begin{aligned} I_{\rm a} = {} & \epsilon N A_{PS}\Gamma_{SP}(\Gamma_{DP}+\gamma_{DS})/ \\ & (A_{PS}\Gamma_{DP}+\Gamma_{SP}(A_{PD}+3\Gamma_{DP})+ \\ & \gamma_{DS}(A_{PS}+A_{PD}+2\Gamma_{SP}+\Gamma_{DP})), \end{aligned} \tag{4}$$

$$I_{\rm b} = \frac{\epsilon N A_{PS}\Gamma_{SP}\gamma_{DS}}{A_{PD}\Gamma_{SP}+\gamma_{DS}(A_{PS}+A_{PD}+2\Gamma_{SP})}. \tag{5}$$

The approximate value η of the population ρ_D is given as a ratio of the measured fluorescence intensities.

$$\begin{aligned} \eta &= (I_{\rm a}-I_{\rm b})/I_{\rm a} \\ &= \frac{\Gamma_{DP}(A_{PD}-\gamma_{DS})(\Gamma_{SP}+\gamma_{DS})}{(\Gamma_{DP}+\gamma_{DS})\{A_{PD}\Gamma_{SP}+\gamma_{DS}(A_{PS}+A_{PD}+2\Gamma_{SP})\}} \\ &= (1+\delta)\rho_D. \end{aligned} \tag{6}$$

If the excitation rate Γ_{DP} is much higher than the relaxation rate γ_{DS}, the correction factor δ is derived from the above equations as

$$\delta \cong \frac{\gamma_{DS}}{\Gamma_{SP}}, \tag{7}$$

then η becomes accurate when the excitation rate of the $S\rightarrow P$ transition is high. This correction factor δ is obtained experimentally through the measurements of the decay rate of the fluorescence after turning the IR laser off.

The decay curve of the fluorescence is described as

$$I \propto C_1 \exp(-\lambda_+ t) + C_2 \exp(-\lambda_- t) + \frac{c}{b}, \tag{8}$$

and the two decay rates λ_+(fast) and λ_-(slow) are given as

$$\lambda_\pm = \frac{a}{2} \pm \frac{1}{2}\sqrt{a^2-4b}, \tag{9}$$

where $C_{1,2}$ are constants determined by the initial conditions, $a = A_{PS}+A_{PD}+\Gamma_{SP}+\gamma_{DS}$, $b = A_{PD}\Gamma_{SP}+\gamma_{DS}(A_{PS}+A_{PD}+\Gamma_{SP})$ and $c = \gamma_{DS}\Gamma_{SP}$. The fast component λ_+ almost equals to the spontaneous decay rate of the P state. $\lambda_\pm$ can be simplified as follows under our experimental condition.

$$\lambda_+ \cong A_{PS}+A_{PD}. \tag{10}$$

$$\lambda_- \cong A_{PD}\Gamma_{SP}/(A_{PS}+A_{PD})+\gamma_{DS}. \tag{11}$$

From (8) and (11), we obtain two equations for Γ_{SP} and γ_{DS} with the measured stationary fluorescence intensities $I_{\rm a}$, $I_{\rm b}$ and the decay rate λ_-, so that δ is estimated by using known transition probabilities [10]. Consequently, the number of trapped ions can be estimated even in cases where not all ions are pumped into the metastable state.

If the mean excitation rate Γ_{SP} is estimated in the above way, the number of trapped ions is also obtained from the stationary fluorescence intensity $I_{\rm a}$ as follows. If we take the usual experimental condition of $\Gamma_{DP} \gg \Gamma_{SP}$, the first term in the denominator of (4) is much larger than the other terms, then we obtain the stationary intensity $I_{\rm a}$ as

$$I_{\rm a} = \epsilon \Gamma_{SP} N. \tag{12}$$

This gives an alternative way to estimate the number of trapped ions when Γ_{SP} is obtained reliably.

In the four level system where ions are pumped into the D states via the $S_{1/2}\rightarrow P_{3/2}$ transition, we can also use the above results in the following way: 1) When we pump ions into one of the D states, the population of the pumped D state becomes smaller due to the collisional fine structure mixing. However, (7) can be used to estimate the correction factor. 2) When ions are pumped into both D states, we can treat the D states as one state. The mean relaxation rate of both states substitutes for the γ_{DS} in the estimate of the correction factor. As long as the assumption of $\Gamma_{DP} \gg \gamma_{DS}, \Gamma_{SP}$ is valid, we can deduce the population ρ_D by using (6) and (7). In the measurement of the ratio η, we should be careful of the coherent effect in the four level or three level system, the so called dark resonance which can reduce the fluorescence intensity [8, 9]. It can be avoided by making a slight misalignment and a proper detuning of the lasers.

2 Experimental apparatus

The experimental setup is as follows. A linear rf trap, which consists of three sections, each made from four separated cylindrical rods each with a diameter of 6 mm, was used to store Ca^+ ions. The closest distance $2r_o$ between diagonal electrodes was 5.22 mm. The rf frequency was 8 MHz and the amplitude was 204 V. We also applied a DC voltage of 7-15 V to the two end sections. The Ca^+ ions were produced by focusing a Nd:YAG pulsed laser beam on a metallic calcium target placed at one side of the trap. The peak power of the beam on the target was estimated to be more than 10^9 W/cm^2, which enabled us to easily prepare a laser ablated plasma consisting of Ca^+ ions in the trap.

To excite the $S_{1/2}\rightarrow P_{3/2}$ transition of Ca^+ ions, we used 393 nm UV laser light which was generated by intracavity second harmonic generation using an angle tuned $LiIO_3$ crystal in a Ti-Sapphire ring laser (Coherent 899-21) pumped by an Ar^+ ion laser (Coherent Innova 300, 10 W). The linewidth of the UV laser is less than 1 MHz and the maximum power is about 2 mW. To excite the $D\rightarrow P$ transitions, we used two laser diodes (LD, Spectra Diode Lab., SDL-5400). The power of LD's with a linewidth of about 30 MHz is 10 mW. The beam diameters of the UV and the IR lasers at the trap center are estimated as about 0.3 mm and 1 mm respectively from the measurements of the fluorescence distribution. By using two mechanical shutters, we can generate a laser beam pulse with a variable width and provide the necessary pulse sequence for the measurements. All the laser beams were

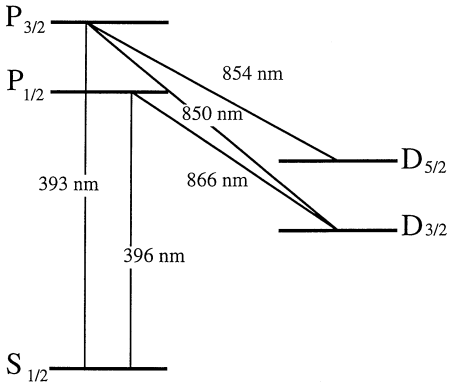

Fig. 1. Energy diagram of $^{40}Ca^{+}$ ion

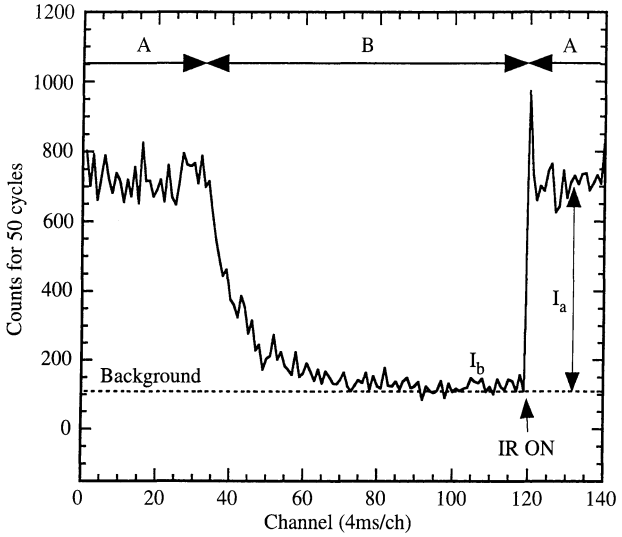

Fig. 2. Fluorescence intensity as a function of time showing the present method in the case of a weak UV laser (1 μW). The fluorescence spike at the moment when the IR lasers are turned on indicates the number of ions in the trap (For details, see text.)

merged by a half mirror and a dichroic mirror and were sent into the trap chamber through a glass window. The chamber was evacuated to less than 10^{-7} Pa by a turbo molecular pump backed by a rotary pump. For buffer gas cooling of trapped ions, we introduced helium gas to the vacuum chamber from the fore vacuum side of the turbo molecular pump in order to reduce impurities. The fluorescence from the ions, focused by two lenses which were mounted inside the chamber and a camera lens (Nikon 28 mm f/2.8), was detected by a position sensitive photon counting system (Hamamatsu PIAS-TI). The dead-time of the detector was 10μs and it was used to correct the data. An interference filter with 33% transmittance at 393 nm was inserted in front of the camera lens to detect only 393 nm UV photons. We also inserted a neutral density (ND) filter for decreasing the detection efficiency in order to avoid a pile-up effect in the detector. The detection efficiency of the optical system was estimated to be 3×10^{-4} by using the data of the geometry of the detection system, transmittance of the optical elements and the quantum efficiency of the detector.

3 Experimental results

The method of counting trapped ions has been tested in the case of Ca^{+} ions. The Ca^{+} ion has the excited $P_J(J = 1/2, 3/2)$ states and the metastable $D_J(J = 3/2, 5/2)$ states near the ground $S_{1/2}$ state as illustrated in Fig. 1. The D states have long lifetimes of about 1 second [11–13]. Figure 2 shows the time spectrum of the fluorescence. In this measurement, the power of the IR and the UV lasers were 6 mW and 1μW, respectively. The measured buffer gas pressure by the ionization gauge was 4×10^{-6} Pa.

In the period A, the UV pumping laser (393 nm) and two IR (850, 854 nm) lasers were turned on and the stationary intensity of UV fluorescence $I_{\rm a}$ was observed. In the period B, the IR lasers were turned off by the mechanical shutter. Then, a fraction of ions was pumped into the metastable D_J states. As a result, the fluorescence intensity decreased to $I_{\rm b}$. At the end of the period B, the IR lasers were turned on again, then, a prompt increase of the fluorescence intensity was observed as a spike peak due to the $D_J \rightarrow P_{3/2}$ excitation of ions in the D states. The number of emitted UV photons $N_{\rm det}$ due to the $D_J \rightarrow P_{3/2}$ excitation is the same as the number of ions in the D_J states. Since the prompt increase should be occured for a much shorter period than the channel-advance time of the data acquisition system (a multi-channel scaler), $N_{\rm det}$ was obtained by subtracting the $I_{\rm a}$ from the counts at the spike peak.

The number of detected photons in the prompt increase accumulated for 50 cycles of measurements was 358$\pm$82, after a correction of the dead-time of the detector. The two stationary intensity $I_{\rm a}, I_{\rm b}$ and the decay rate λ_- were obtained as 614$\pm$67 counts, 20$\pm$39 counts and 23.7$\pm$1.8 Hz, respectively. Then, the intensity ratio η was 97$\pm$4% and Γ_{SP} and γ_{DS} was obtained to be 426$\pm$33 Hz and 0.8$\pm$1.3 Hz through (8)–(11). The correction factor δ derived was less than 1%, which allowed to take $\rho_D = \eta$. Consequently, the total number of trapped ions was obtained as N =(7.4$\pm$1.3)/ϵ, where ϵ is the detection efficiency. The absolute number was obtained to be 2.5×10^4 with $\epsilon = 3 \times 10^{-4}$. For a consistency check, we estimated the number of ions from the above obtained mean excitation rate Γ_{SP} using (12). The result, N' =(7.2$\pm$0.6)/ϵ, agreed with the result obtained by our new method. The accuracy of N' seems to be high in comparison with N, however, the estimate of Γ_{SP} is not a straight way and it is not always possible to obtain the time constant λ_- accurately.

We also performed an second measurement in which a very high signal-to-noise ratio was attained. The time sequence of the method is shown in Fig. 3. The key point of the measurement is to stop the UV laser when we observe the prompt increase of the fluorescence. Origins of the noise in the previous experiment were stray photons from the UV laser, fluorescence from ions in the ground state and dark count of the detector. The first two, which are in fact the dominant ones, can be suppressed completely by blocking the UV laser at the moment of turning the IR lasers on. The result is shown in Fig. 4. The experimental condition was the same as the previous experiment in Fig.2 except for the power of the IR lasers(0.9 mW). The channel-advance time of the data acquisition system was also shortened to resolve

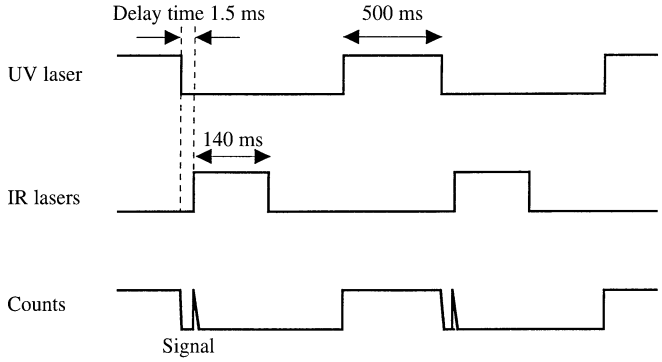

Fig. 3. Time sequence of the experiments shown in Fig. 4. The periods given in the figure are typical values

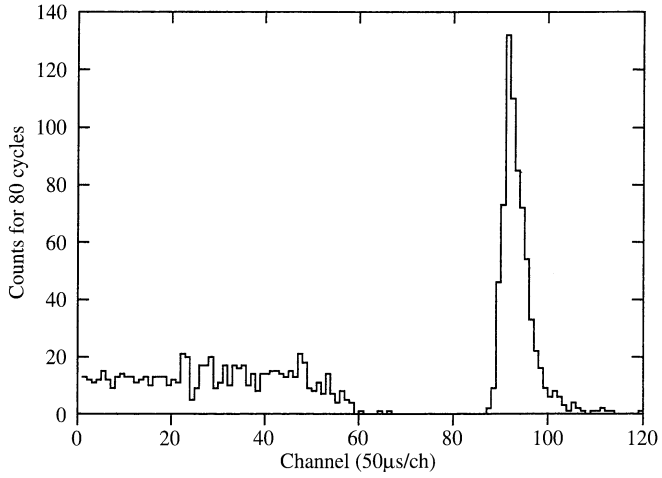

Fig. 4. Typical result for the improved measurement accumulated for 80 cycles

the structure of the spike peak. Since the background counting rate due to the noise became zero, we could increase the UV laser power to about 180 μW in order to pump all the trapped ions into both D states (ρ_D = 1). Consequently, the observed time spectrum of the spike peak was not prompt but exponentially decayed. The round rising edge indicated a slow response of the mechanical shutter. We also take into account the relaxation of pumped ions in the metastable D states to the ground state due to gas collisions [11, 12, 14] during delay-time of 1.5 ms time interval between turning the UV laser off and IR lasers on, which was necessary to avoid overlapping of the noise to the spike peaks. The loss of ions in the D states during the delay period of 1.5 ms was less than 3.5% even if we take the upper limit value of the relaxation rate, which should be λ_- according to (11). The sum of the detected UV photons was 920$\pm$30 counts after 80 cycles of measurements. The total number of ions was N = (11.5$\pm$0.4)/ϵ, then the absolute number of ions was estimated to be $N = 3.8\times10^4$. The precision of the relative number ϵN can be improved by increasing the statistics of the measurements, however, the accuracy of the absolute ion number N is restricted by the uncertainty of the detection efficiency ϵ, which may be as large as 30 %.

In some particular cases, we should be careful with the fine structure mixing effect due to buffer gas collisions [11, 12, 14, 15]. It may become serious when we pump into

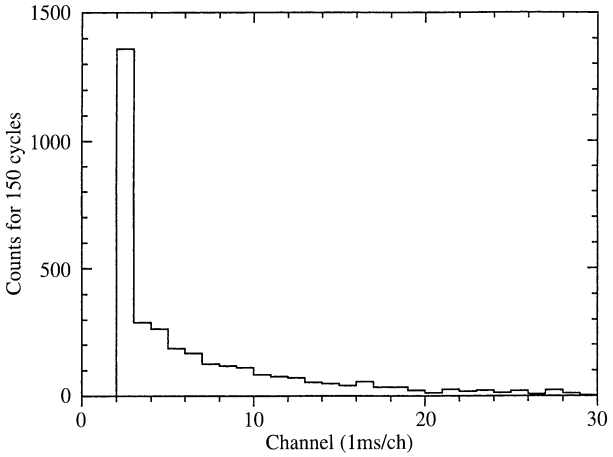

Fig. 5. Mixing effect between the fine structure doublet. The slow decay time constant of 6.6 $\pm$ 0.3 ms mainly depends on the mixing rate from the $D_{3/2}$ to the $D_{5/2}$ state

only one metastable state ($D_{3/2}$) using UV excitation of the $S_{1/2}\rightarrow P_{1/2}$ transition instead of the $S_{1/2}\rightarrow P_{3/2}$. In order to show this effect, we performed an experiment as shown in Fig. 5. In this measurement, the experimental condition was the same as previously but only one IR laser (854 nm, $D_{5/2}\rightarrow P_{3/2}$) was used. Firstly, we pump all of ions into both D states, then we excite the $D_{5/2}\rightarrow P_{3/2}$ transition only. The time spectrum shows a slow decay component as well as a prompt one. The prompt peak was the contribution of ions initially in the $D_{5/2}$ state. The slow part was due to a feed from the another metastable state, $D_{3/2}$, to the $D_{5/2}$ state. The time constant of 6.6$\pm$0.3 ms mainly depends on the mixing rate. The same effect was observed when we used the other IR laser (850 nm) only to excite the $D_{3/2}\rightarrow P_{3/2}$. If one uses the $S_{1/2}\rightarrow P_{1/2}$ transition to pump into the $D_{3/2}$ state and detect the fluorescence due to the excitation of the $D_{3/2}\rightarrow P_{1/2}$, one might miss a fractional amount of the ions, which are populated in the $D_{5/2}$ state by the mixing effect, in the estimate of the total number of ions. One should use two IR lasers by which both $D_{5/2}$ and $D_{3/2}$ states can be excited even though one uses the $S_{1/2}\rightarrow P_{1/2}$ excitation for the pumping.

4 Conclusion

We have developed and demonstrated a new, simple and reliable method to count the total number of trapped ions having an appropriate energy level scheme. If the detection efficiency is sufficient high to obtain a required statistics, in principle, the method can be applied to all range of the number of trapped ions. Since the ambiguity comes only from the estimate of the detection efficiency, this method is very reliable particularly for the estimate of the relative number of ions in the same setup as long as the efficiency is constant. This assumption is true except for the case that the view of the detector does not cover the whole area where ions are distributed. It is also possible to measure the detection efficiency accurately by counting fluorescence from a saturated single ion which can be cooled by a single laser radiation, such as Be^+ or Mg^+.

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