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ION TRAPPING OF UNSTABLE NUCLEI FOR HIGH PRECISION SPECTROSCOPY

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Abstract *Status of a laser-micro wave resonance experiment for unstable nuclei using an ion trap and a laser at INS is reported.*

1. Introduction

High precision atomic spectroscopy with ion traps has already quite some history. Application of this experimental technique to short lived nuclear ions, however, has remained still rather new. Mass measurements of unstable neuclei using a Penning trap have shown its powerful effectiveness[1]. There is also an interesting application of the Penning trap to unstable nuclear spectroscopy, i.e., measurements of the hyperfine anomaly or Bohr-Weisskopf (BW) effect[2] using a laser-microwave double resonance (LMDR). The measurements of the LMDR so far were carried out mostly for stable nuclei and only few long lived radioactive nuclei[3]. We have been working to build a system to apply this method to short-lived unstable nuclei produced by cyclotoron beams.[4),5)] Isotopes of $^{39, 41}$Ca were chosen as the first objects for a LMDR experiment. The element Ca has in addition another unstable odd isotopes of $^{45, 47, 49, 51}$Ca, which are good candidates aimed at the future Japanese Hadron Project (JHP). The study of the BW effects for these nuclei will provide information on the structure of the ground states of these nuclei, especially on a valence neutron. Experimentally, the availability of the laser light for the Ca II is also of importance. In order to develop the total system in a timely manner, we have been developing the instruments in two places. At INS, the scheme to trap radio-active nuclear ions in ion traps is being developed. On the other hand, at ILS, the preparation of laser system and a laser cooling experiment on Ca ions has been carried out. This paper reports the present status of our experiment.

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2. Direct ion trapping

One of the important technical problems for the present study is to develope a method to trap ions injected from outside of the ion trap. There are two candidate places for on-line laser-ion trap experiment at INS cyclotron laboratory. One is at a focal plane of a gas filled recoil mass separator (GARIS)[6] and the other is at that of a high resolution on-line isotope separator. Here we describe a scheme using the GARIS, which is schematically shown in fig.1. Unstable nuclear ions, separated by the GARIS, stop in a high pressure He gas. The ions are extracted in a flow of He gas jet and collected by a sextupole ion guide (SPIG) with a high transmission officiency. The principle and basic property of the SPIG has been described in ref.[7] (see fig.2). Recently a bunching of ion in a revised SPIG has been successfully tested. In the configuration of the revised SPIG, three ring electrodes along the SPIG axis, as shown in fig.3(a), are added. Applying independent potentials to these electrodes, we can control the trapping potentials formed along the SPIG axis. Since the trapping region is filled with He gas of 0.8 Pa in which the mean-free-path of ions for the collision with He atom is order of 1cm, ions from upstream can be accumulated by a gas cooling. The SPIG rods go through three skimmers (the last one is not shown) and the pressure distribution is from upstream, 11, 1.2, 5×10^{-3} and 1.5×10^{-4} Pa, when the gas cell is at 25 kPa. This good vacuum was realized by a three stage differential pumping system. Figure 3(b) shows the experimental observation of the bunching effect for ions in the SPIG.[8] The time sequence of the applied voltages to these rings is also shown. In the 'Thru'(through) period, all rings were grounded, a DC current of 2nA was detected. In the 'Acc'(accumulation) period, the downstream ring (Rd) was turned to 70 V and the central ring (Rc) was to -5 V to produce a potential barrier and a well, respectively. In the 'S' (storage) period, the upstream ring (Ru) was also raised to 100 V to stop the supply of ions from the upstream gas cell. In the 'Ext' (extraction) period, Rd was grounded and, Rc and Ru were raised to 80 V and 150 V, respectively, to extract the ions in the potential well as a bunch. A short pulse (the middle pulse in the figure) at the beginning of the 'Ext' is the signal of the bunched ions accumulated for 9 ms of the 'Acc' period and 0.6 ms of the 's' period. The number of ions in the pulse was estimated to be $7*10^{6}$, which corresponds to a 7% fraction of the ions supplied in the accumulation period. At the beginning of 'Acc' period, ions around in the upstream of the Rd were pushed out to the Rd by the positive pulse (the left pulse). At the end of the sequence ('Ext' →'Thru'), ions accumulated in the upstream region of the Ru for the periods of 'S' and 'Ext' (~3 ms) were extracted (the right pulse). Since the length of the upstream is much longer than the Rc, the signal was not so small.

3. Laser cooling of stored ions

Laser cooling is very important to perform the BW effect experiment for short-lived nuclear isotopes. It can cool the ion motion in momentum space as well as in physical space. After the cooling, a single cooled ion can give a comparable flourescence to that of 10^{6} ions uncooled. This is really crucial to deal with a small number of unstable nuclear ions produced by a cyclotron beam. We will begin with a general remark on the BW effect and come to our recent result of laser

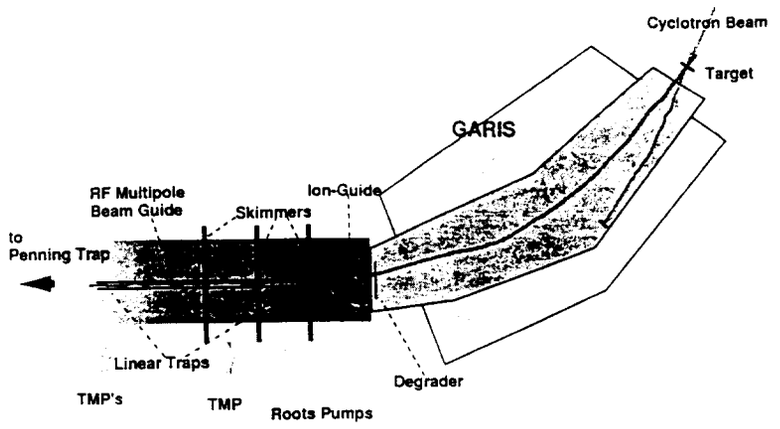


Fig. 1 Schematic lay-out of the INS on-line ion trap system[4].

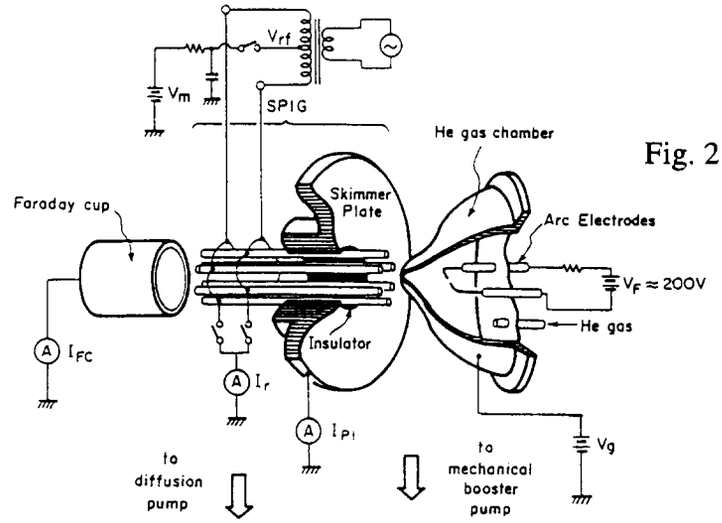
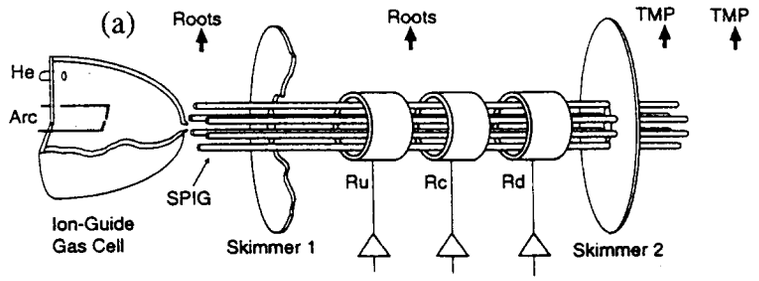


Fig. 2 Lay-out of the ion guide and SPIG system for the test experiment. The aperture of the SPIG is 2.5mm, the rf frequency is 4.7 MHz and the voltage is 60V[7].



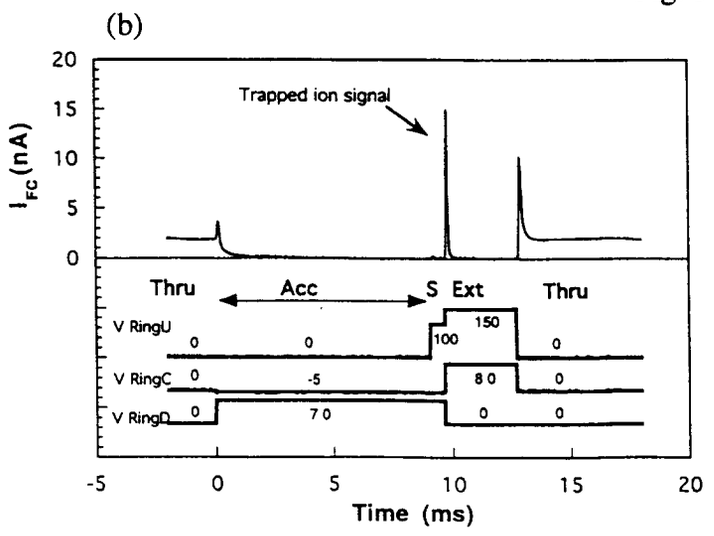


Fig. 3 (a) Revised SPIG for bunching experiment and (b) the result of bunching effect[8].
The aperture and length are 2.8mm and 30cm. The rf frequency and voltage are 6.7 MHz and $\sim 100V_{pp}$. Three ring electrodes (Ru, Rc and Rd), placed at cocentered positions along the SPIG axis, are connected to the output of fast high voltage amplifiers by which the axial trapping field is controlled. For details of fig.3(b) see text.

cooling experiment of Ca ions.

3.1 BW effect

The hyperfine structure (hfs) constant A is given as

$$A = [\ \mu_I \overline{B(o)} / IJ\ ]\ (\ 1+\varepsilon\ ) \qquad (1),$$

where μ_I is the nuclear magnetic dipole moment, $\overline{B(o)}$ is the time-averaged magnetic field at the site of the nucleus generated by the orbital electrons, I and J are the total angular momenta of the electrons and the nucleus and ε is called the BW effect correction which describes the extent of the deviation of the nuclear magnetism from that of a point nucleus. If we can measure the A constant and the μ_I very precisely and calculate B(r) accurately enough, it will be possible to determine ε, which will be compared with nuclear model predictions. There has been tremendelous progress in atomic physics since the work of BW, it is still, however, not easy to provide accurate B(r) for all atoms. So one does think of another way where B(r) does not come into play explicitly. As B(r) stays the same among the different isotopes and isomers, the hyperfine anomaly $^1\Delta^2$ defined in the following is normally used.

$$^1\Delta^2 = (A^1g^2 / A^2g^1\ ) - 1 \equiv \varepsilon_1 - \varepsilon_2 \qquad (2),$$

where g is nuclear gyromagnetic factor and suffices 1, 2 are to differentiate isotopes or isomers to be compared. The magnitude of the hyperfine anomaly is around 10^{-3} in the maximum for the case of proton odd nuclei. Therefore, to say a definite thing about $^1\Delta^2$, it is necessary to determine the A factors and the g_I factors with accuracies of better than 10^{-6}. This is the reason why we need a high precision measurement.

3.2 A laser-microwave double resonance for $^{43}Ca^+$ ions

We have taken ^{43}Ca, which is the unique odd nucleis in the stable Ca isotopes, as a test object. There has been already a precise measurement of A for ^{43}Ca [9]. Figures 4(a) and 4(b) show the magnetic sublevels of a $^{43}Ca^+$ ion in a weak magnetic field and a strong magnetic field. There are two metastable D states which are a nuisance for laser excitation of the ground state $S_{1/2}$ to the state $P_{3/2}$ repeatedly. In order to solve the problem, we use two diode lasers of 854nm and 850nm to excite the atoms in D states back to P state. A UV laser light at λ = 393nm with σ- polarization is used to excite atoms from the $^2S_{1/2}$, F=4, m_F=-4 to the $^2P_{3/2}$, F=5, m_F=-5. The laser frequency is slightly shifted to a lower value from the center so that the laser cooling is effected. Ions stored in an ion trap at first are at the temperature of several thousand degree Kelvin, which is described later. This causes a large Doppler broadening of the fluorescence spectrum. The broadening, however, enables the ions which have a distribution over different m-sublevels of the F=4 state to be also excited to the $P_{3/2}$ states. Due to the selection rule for σ- light, the Δm_F=-1 transition is only allowed from $S_{1/2}$ to $P_{3/2}$ states. As a consequence of continuous laser excitation, the population of the lower m_F states in the F=4 increases and finally we have optical pumping of the F=4, m_F=-4 state. Now we can observe the fluorenscence due to recycling between S and P states. It should be also emphasized that the ^{43}Ca nuclei are now polarized. As a next step, we will

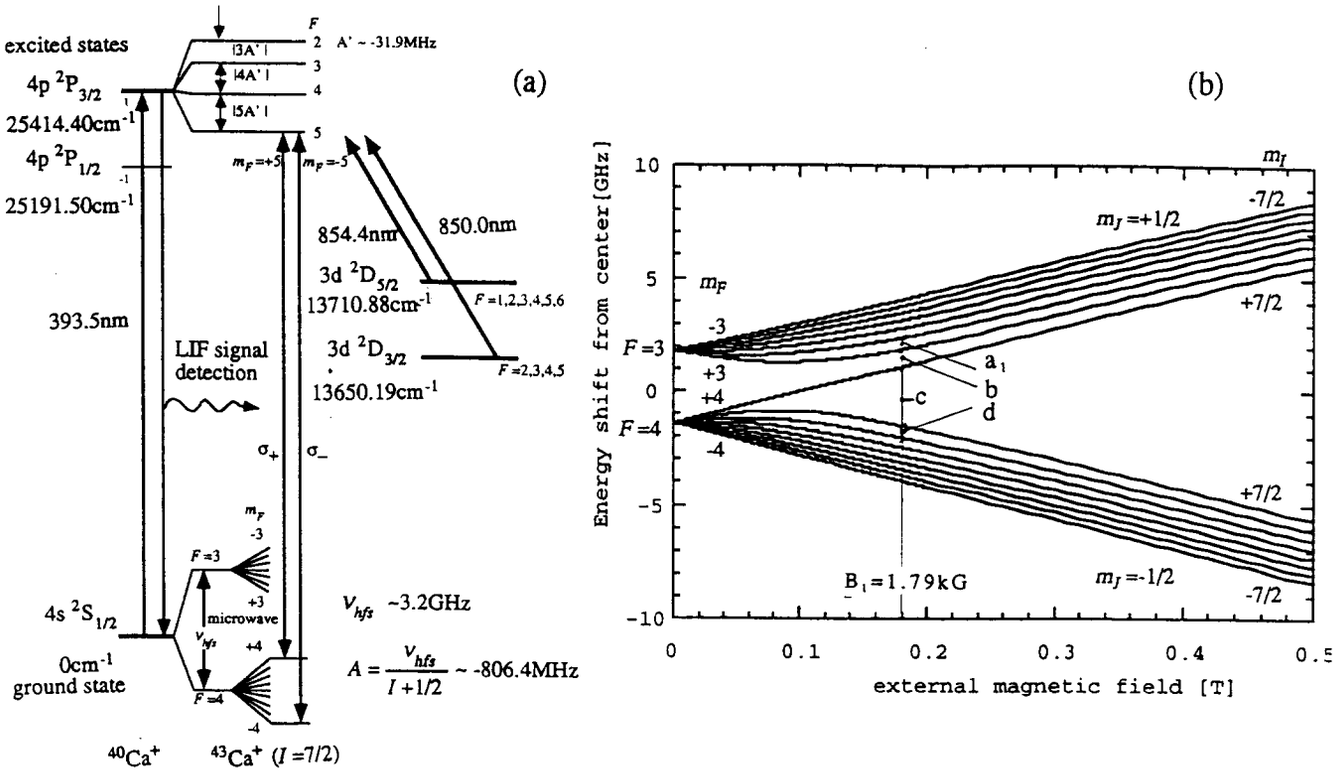


Fig. 4 (a) Hyperfine structure of $^{43}Ca^+$ ion in a weak magnetic field and (b) its ground state in a strong magnetic field.

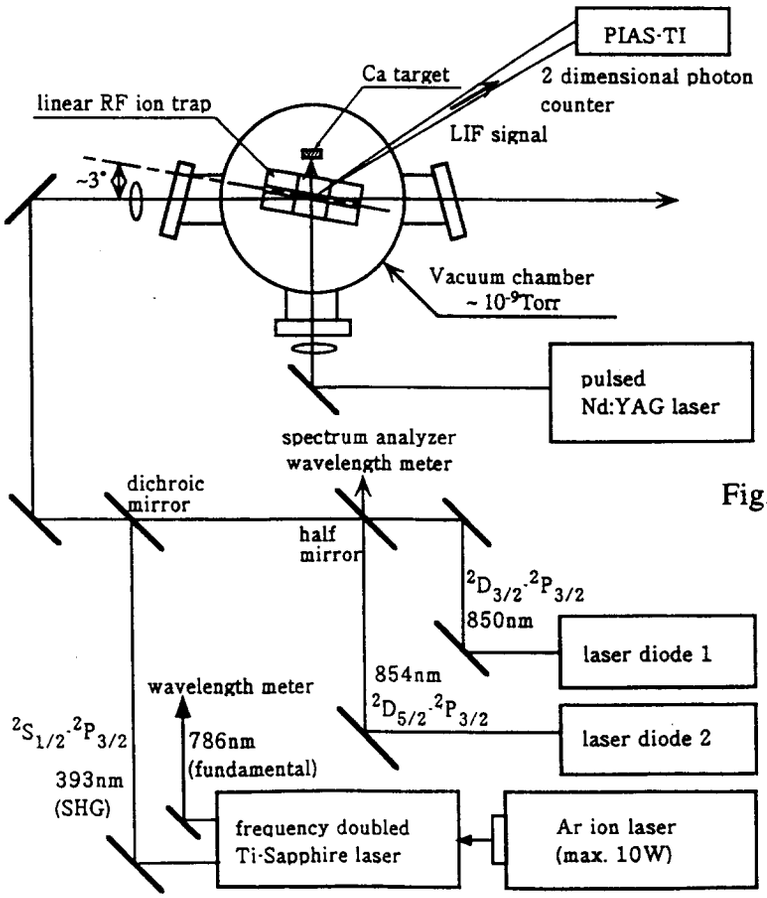


Fig. 5 Experimental set-up of a laser system and a linear RF trap.

proceed to alpply a micro-wave to excite the state $^2S_{1/2}$, F=4, m_F=-4 to $^2S_{1/2}$, F=3, m_F=-3. The resonance is observed as a decrease in the laser fluorescence. If a single ion is stored in the trap, we will see a disappearance of the fluorescence, which is a quantum jump effect. The way to observe the resonance mentioned above is called a shelving method. We can also excite the state $^2S_{1/2}$, F=4, m_F=4 to $P_{3/2}$, F=5, m_F=5 with σ^+ polarized laser light. The $^{43}Ca^+$ ions after laser-cooling are sent into a Penning trap. The ions are in either one of the states (m_I, m_F) = (7/2, 1/2) or (-7/2, -1/2), which are selected by the polarization of the laser light. For the precise measurement of the g_I factors, we will use the so-called clock transition. Namely at a certain magnetic field strength, the frequency of the transition becomes insensitive to a small change in the magnetic field. It is also important that the transition frequency should depend strongly on the g_I factor. With these two factors in mind, one candidate of the clock transition a (~520MHz) at field strength B_1 (1.79kG) is chosen, which is shown in fig.4(b). Knowing the precise magnetic field strength B_1 and additional frequencies of the transitions b (~780MHz), c(~2.5GHz) and d(~521MHz) shown in the figure, we can determine the A factor and g_I /g_J ratio accurately, where g_J is electron magnetic g factor.

3.3 Laser and ion-trap system

Figure 5 shows the present experimental set-up of the laser system for Ca^+ ions. For the laser cooling of Ca^+ ions, a piece of natural Ca metal is laser-ablated using a YAG laser. For the $^{43}Ca^+$ experiment, a thin plate of Be in which $^{43}Ca^+$ ions were implanted is to be used. The UV light of 393nm is generated by a non-linear crystal of $LiIO_3$ placed inside the cavity of a Ti-Saphire laser (Intra-cavity doubling). We have obtained nearly 2mW of power at 393nm. Two infra-red (IR) diode lasers are also required to excite and pump out the ions from the two metastable D states. The wave lengths of the three lasers are adjusted by measuring the absorption or opto-galvano effect in Ca discharge tube. The fluorescence is detected by a position sensitive photon counting device (PIAS, Hamamatsu product). The optical lens system for the fluorescent light has a magnification of five and has a interference filter to only detect 393 nm.

Figure 6 shows the configuration of the linear trap. The trap comprises three sections, each made from 4 separated cylindrical rods with a diameter of 3 mm. A distance between diagonal electrodes was 5.22 mm. The RF frequency was 8 MHz and the amplitude was 24 V. We also applied a dc voltage of 7-15 V to the two end sections.

3.4 Laser cooling of Ca ions.

Figure 7 is a time spectrum of the fluorescence, which shows a laser cooling of Ca ions. The Ca ions which are produced by a laser ablation has a temperature of more 10^3 K. The laser cooling for the ions using the laser described before does take more than 3 sec as shown in the figure. The flat part in the figure just corresponds to the equilibrium between the laser cooling and rf and/or collision heating. Figure 8 is an image of a crystal consisiting of three $^{40}Ca^+$ ions after laser cooling. The intensity of fluorescence from a single ion was about 200 cps at an UV laser

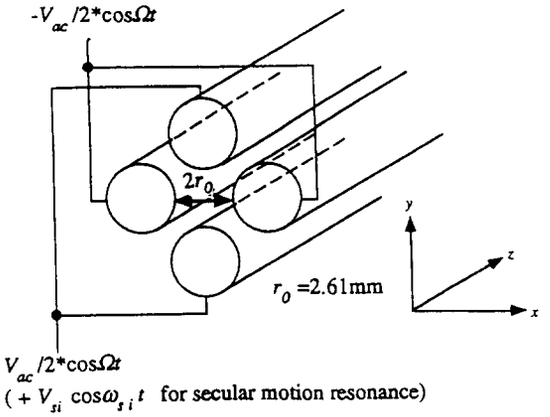
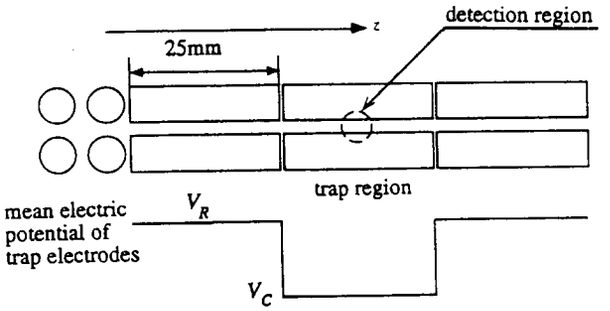


Fig. 6 The configuration of the present linear trap.



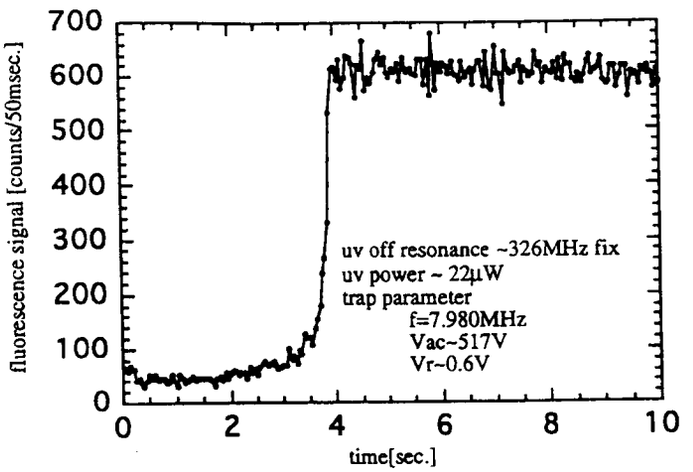


Fig. 7 Flourescence from the trapped Ca ions as a function of time. The UV laser was detuned by 200MHz from the resonance center.

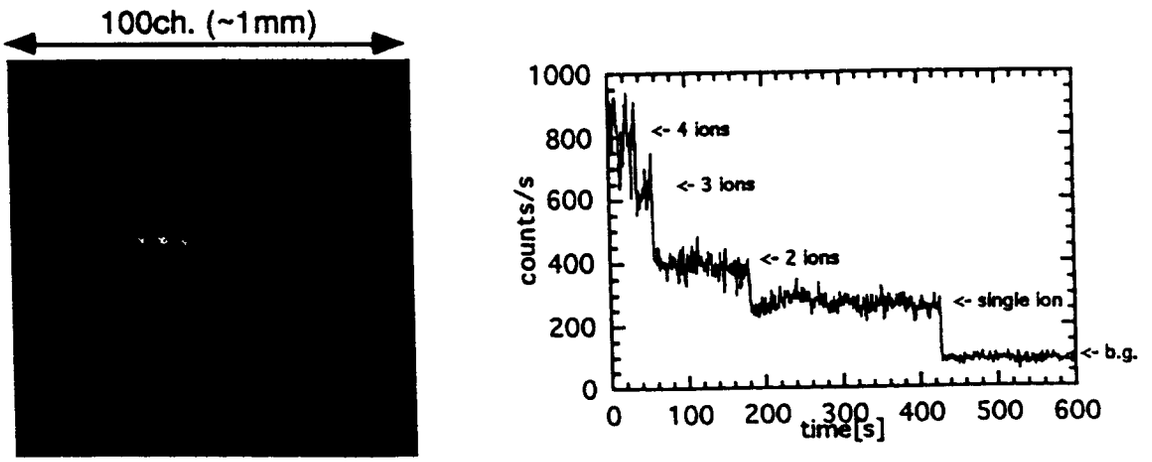


Fig. 8 Image of three $^{40}Ca^{+}$ ions aligned in a linear trap and a time spectrum showing a discrete decay of the fluorescence intensity corresponding to a decrease of the number of ions.

power of 300μW. The single ion repeated the cycle of absorption and emission with a frequency of as high as 4 MHz which was estimated by using a detection efficiency of 5×10^{-5}. The counting rate is sufficient to perform a high precision spectroscopy experiment. We soon proceed to perform a laser-microwave resonance for $^{43}Ca^{+}$ ions. We are also working to build a Penning trap using a super conducting magnet.

4. Conclusion

The status of the laser-microwave resonance experiment for Ca isotopes is reported. The experiment is intended to develope a system to measure the Bohr-Weisskopf effect for a wide range of unstable nuclei. The lasers and ion trap will be first tested for the stable isotope ^{43}Ca. A new trapping scheme for unstable Ca ions has been also developed. In near future we will start the LMDR experiment for the unstable ^{39}Ca and ^{41}Ca isotopes.

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