3-3 Trapping and Cooling of Ions for Quantum Information Processing

HAYASAKA Kazuhiro, UETAKE Satoshi, and IMAJO Hidetsuka

In quantum networks quantum information is processed by exchanging quantum states between physical systems. We have studied trapping and cooling of ions for quantum information processing to build a prototype of the quantum network. We have found $^{43}Ca^{+}$ as the best candidate for the qubit in the quantum network. The schemes for quantum gate operations and for quantum state transfer with the ion species are discussed. We have developed a ring ion trap and a light source consisting of violet diode lasers for realizing the schemes. We have achieved deterministic coupling of a single $^{40}Ca^{+}$ to the optical field in a cavity.

Keywords
Quantum network, Quantum state transfer, Ion trap, Violet diode laser, Cavity QED

1 Introduction

Quantum mechanics enables novel way of communications with such features as absolute security and large capacity, which cannot be realized by existing technologies. The communication system transferring quantum states between the nodes with high fidelity is essential for exploiting the novel nature of the quantum mechanics. Quantum network is such a system, which combines different physical subsystems possessing different advantages. The subsystems perform single tasks such as quantum memory, quantum gates or quantum state transmission. By transferring the quantum states between the subsystems, the whole system can transfer quantum states from a node to another with high fidelity. The quantum network consisting of atoms and photons is expected as a prototype for supplying with actual experimental setups for various schemes of quantum communication [1][2]. In this network atoms compose nodes, while photons work as channels. The atoms perform quantum computations such as error correction and routing, and their quantum states are transferred to the photons. The photons carry the quantum states to the different locations.

The ions trapped and laser-cooled to a low temperature in an ion trap were proposed as a candidate for quantum computation in 1995 [3]. Vast volumes of theoretical and experimental studies have been done related to the proposal by many groups. We have studied and developed essential technologies for realizing a prototype of the quantum network, based on the ion trap technologies developed at communications research laboratory. We have found $^{43}Ca^{+}$ as the best candidate for quantum computation and quantum state transfer. We have designed the schemes for quantum computation and quantum state transfer using $^{43}Ca^{+}$ ions. A ring trap essential for realizing the schemes has been designed and fabricated. A simple and high-performance diode laser system for generating and cooling of $^{43}Ca^{+}$ ions has been developed using commercial violet diode lasers. We have studied cavity quantum electrodynamics (Cavity

QED) as an essential physical process for exchanging quantum states between atoms and photons, in collaboration with Max-Planck Institute for Quantum Optics. Deterministic control on the coupling of a single ion and a cavity mode has been achieved. The outline of these studies is described in this paper.

2 Quantum information processing and quantum state transfer with $^{43}Ca^+$

In quantum information processing with trapped ions, two energy states of an ion are assigned to a quantum bit (qubit), and quantum gate operations such as phase gate, controlled-NOT gate are performed on the energy levels. The controlled-NOT gate is performed by coupling two ions to the common vibrational mode [3], or to the optical field in a cavity [4]. For the quantum state transfer from an ion to a photon, the ion is coupled to an optical cavity with small mode volume. This method is called cavity QED [2]. The quantum state transfer between a qubit corresponds to the transfer of a superposition of two eigenstates from the ion to the cavity field. This process can be expressed as,

$$\left(\alpha|0\rangle_{ion} + \beta|1\rangle_{ion}\right)\otimes|0\rangle_{photon} \leftrightarrow |0\rangle_{ion}\otimes\left(\alpha|1\rangle_{photon} + \beta|0\rangle_{photon}\right) \quad (1)$$

where $|0\rangle_{ion}$ and $|1\rangle_{ion}$ are eigenstates of the ion, $|0\rangle_{photon}$ and $|1\rangle_{photon}$ are number states of the optical field. The photonic states might be replaced by polarization eigenstates, for example, states with clockwise and counter-clockwise rotating polarization. Since this transfer process is free from projection, states with quantum entanglement consisting of many qubits can be transferred as well, simply by transferring the state of each qubit successively [2]. From the discussions above, an ion species having energy levels for quantum gate operations, as well as an optical transition for quantum state tranfer by Cavity QED, is suited for a qubit in the quantum network.

Any quantum computation algorithm can be reduce to combinations of single qubit rotation and controlled-NOT gate on two qubits. In quantum computation with trapped ions, the controlled-NOT gate is much more demanding than the single qubit rotation. The single qubit ration can be easily done by illuminating the qubit with a laser pulse. In fact, as long as eight years were required to realize the controlled-NOT gate using the common phonon mode as the bus bit. Ca^+ ions were used in the experiment [5]. A different controlled-NOT gate using geometrical phase has been realized almost at the same time with Be^+ [6]. In connection to the quantum state transfer, there are reports on Cavity QED with single ions by two groups. Both groups used Ca^+ to couple the ion to the optical field in the cavity [7][8]. Several ion species including Be^+, Mg^+, Ca^+, Cd^+ are used quantum information studies, but the published reports indicate the advantages of Ca^+ over other ions. The isotope of Ca^+ used in the experiments is $^{40}Ca^+$. It also has main two disadvantages. The first disadvantage is the absence of a transition free from the first order Zeeman shift. This arises from the total spin of $^{40}Ca^+$ being integer multiple of 1/2. The temporal energy shift owing to magnetic field fluctuation limits the coherence time of the qubit [5]. The second disadvantage is the absence of a microwave transition. It is still an open question, which qubit out of the optical qubit and the mirowave qubit offers a better qubit with trapped ions. However, no comparison is possible by using $^{40}Ca^+$. These two problems can be immediately settled by use of the isotope $^{43}Ca^+$ instead of $^{40}Ca^+$.

Figure 1 shows the energy levels of $^{43}Ca^+$. An optical qubit insensitive to residual magnetic fields is available by taking the $^2S_{1/2}$(F=4, m_F=0) and $^2D_{5/2}$ (F=6, m_F=0) states as a qubit. The hyperfine levels F=3, F=4 of the $^2S_{1/2}$ state can serve as a microwave qubit. The quantum state transfer can be implemented by coupling the $^2D_{5/2}$ – $^2P_{3/2}$ transition to an optical cavity. The photons at 854 nm carry quantum states of the ion. The quantum state transfer from the microwave qubit can be achieved first by mapping the microwave qubit to the optical qubit in the same ion with a π-pulse, and then

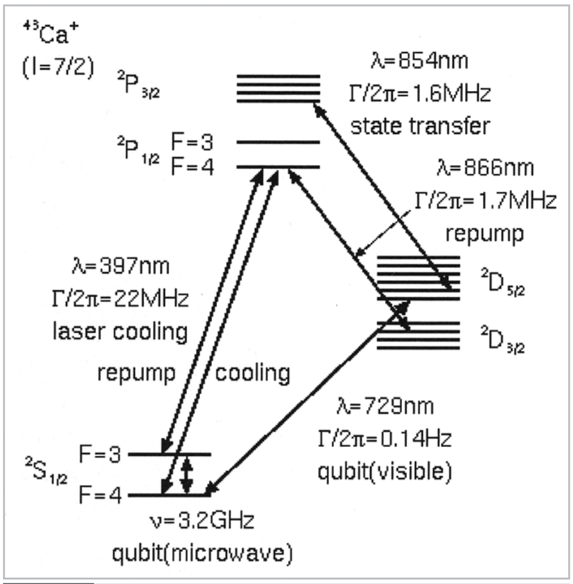

Fig. 1 *Energy diagram of $^{43}Ca^+$*

by the same procedure for the optical qubit.

No experimental study has been reported on trapping and laser cooling of single $^{43}Ca^+$ ions in spite of these advantages. This is mainly due to two problems. The first problem is extremely small ^{43}Ca natural abundance of 0.135 %. The standard method of generating the ions from natural sample by electron bombardment can yield only one $^{43}Ca^+$ while it generates as many as 1000 $^{40}Ca^+$ ions. The second problem is formation of the dark state appearing due to the hyperfine energy structure associated with the nuclear spin of 7/2 in contrast to 0 in $^{40}Ca^+$. The dark state doesn't absorb the laser light and precludes laser cooling. However, recent studies indicate the solutions of the problems. The first problem of the small abundance might be solved by resonant ionization. This method uses the lasers at 423 nm and 390 nm to generate Ca^+ ions from neutral Ca. The use of a frequency-stabilized laser at 423 nm with a sufficiently small linewidth might permit selective generation of $^{43}Ca^+$ by exploiting the difference of 600 MHz in the resonant frequency between ^{43}Ca and ^{40}Ca. This feasibility was experimentally demonstrated [9]. The second problem of the dark state might be solved by the proposed laser-cooling scheme with three lasers having different polarizations and detunings [10]. In the scheme the dark state is destabilized, because it cannot adiabatically follow the fast polarization change of the total laser field consisting of the three laser beams. It has been theoretically shown that a $^{43}Ca^+$ can be cooled to the same Doppler limit temperature as for $^{40}Ca^+$, which is free from a dark state [10].

Three technologies are considered to be essential for building the prototype of the quantum network with $^{43}Ca^+$ based on the above discussions. The first technology is the ion trap for selective generation and laser cooling of $^{43}Ca^+$. It is demanding to obtain a pure sample of $^{43}Ca^+$ ions even by resonant ionization due to the too small natural abundance of about 1/1000. However, it is possible to distinguish individual $^{43}Ca^+$ and $^{40}Ca^+$ aligned in a trap with a high-sensitivity camera by shining them with lasers having different frequencies. A specially designed trap might select only $^{43}Ca^+$ and prepare pure array of the qubits. Such an ion trap should be developed. The second technology is the light sources for generating and cooling $^{43}Ca^+$ ions. Simple and stable light sources to realize the experiments demanding simultaneous operation of several wavelengths should be developed. A system consisting only of diode lasers might be an ideal solution. The third technology is Cavity QED. The proposed scheme for the quantum state transfer demands that the coupling of the single ion to the optical cavity have to be controlled with a spatial resolution smaller than optical wavelengths [2]. The recent results of our studies on these three technologies are described in the following chapters.

3 Ion trap for quantum information processing with $^{43}Ca^+$

The ion trap is a device for storing charged particles in space by electromagnetic field. The linear trap is assumed to be suitable for quantum information studies [3]. This trap consists of four rods driven by alternative electric field. When the ions in a linear trap are laser-cooled to a very low temperature, the

Coulomb force becomes dominant over thermal motion, and the ions form a linear array along the trap axis. The ground state and the first excited state of the quantized motion of the ions can serve as a qubit, when the ions are cooled to this ground state. Cirac and Zoller assumed this qubit as a bus bit for the two-qubit controlled-NOT gate in their original proposal in 1995 for scalable quantum computation with trapped ions [3]. This controlled-NOT gate has been realized with two $^{40}Ca^{+}$ ions by a group in Innsbruck in 2003 [5]. Another controlled-NOT gate using geometric phase has been demonstrated with two Be^{+} ions almost at the same time [6]. Any quantum computation algorithm can be reduced to combinations of phase rotation gate on one qubit and two-qubit controlled-NOT gate [3]. The realization of the controlled-NOT gate has been the biggest problem in quantum computation with trapped ions. Its realization has made the scalable quantum computation with trapped ions in the original proposal [3] approached to the reality.

The original proposal assumes the use of a simple linear trap. However, the linear trap was initially designed for applications such as mass spectroscopy and high-precision spectroscopy, and, therefore, it is not optimized for quantum information processing. Recently, the studies are in progress in several groups to design ion traps suitable for quantum information purposes, such as quantum gate operation and quantum memory [11]. In these traps, the electrodes are divided into regions for specific quantum operations. The total quantum information processing is achieved by shuttling the ions successively though these regions. The ring trap has an advantage of making the ions rotate along its axis. We have studied the ring trap, considering this advantage is fitted for quantum information processing.

We have designed a ring trap depicted in Fig.2. The trap is divided into two regions. The first region is Generation region for generation ions from neutral atomic beam. The second region is Gate operation region for observing the ions and for manipulating quantum states of the ions. The DC-electrodes located along the trap center control the ions' motion, and also shuttle them between the regions. It is reported that the neutral atoms sticking to the trap electrodes disturb the ions' motion and even their quantum states by giving rise to contact potential [12]. This could be avoided by separating the Gate operation region from the Generation region. The generated $^{43}Ca^{+}$ ions can easily change into ^{43}Ca atom and can be lost by charge exchange with ^{40}Ca [9]. This loss might be avoided by transporting the generated $^{43}Ca^{+}$ ions quickly from the Generation region. Therefore, the separation of the regions is assumed to be an advantage for obtaining a pure array of qubits.

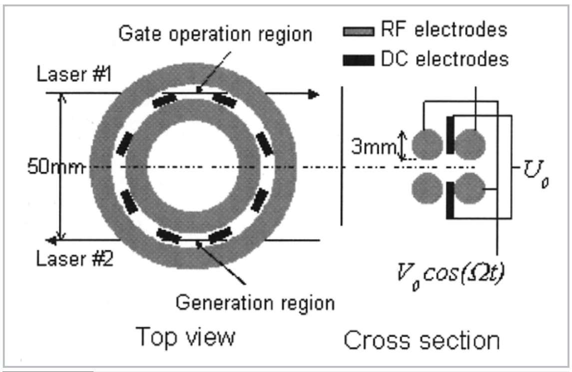

Fig.2 *Ring trap designed for the $^{43}Ca^{+}$ experiment*

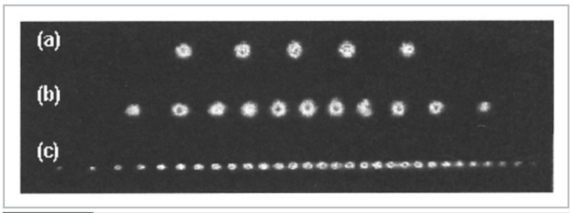

Fig.3 *Magnesium ions aligned in a row in the ring trap*

The experiment with Mg^{+} ions has been performed for confirming the effective control on the ions' motion by the DC-electrodes. The Mg^{+} ions are first generated in the Generation region by electron bombardment on an atomic beam. The generated Mg^{+} ions were observed by the fluorescence excited by 280-nm coherent light. The light was generated by frequency doubling of a dye laser. By successively changing the voltages applied to the

DC-electrodes, the ions were successfully shuttled to the Gate operation region. The images of the ions aligned in a row in the Gate operation region were taken with an image-intensified CCD camera, and are shown in Fig. 3. The image (a)-(c) corresponds to 5, 11, more than 29 ions respectively. Because one ion serves as one qubit, more than 29 qubits are prepared in Fig. 3(c). The trap was operated with a radio frequency voltage of V_0 = 150V, DC-electrode voltage of U_0 = 200V. Detailed characterization of the trap is in progress to optimize the electrode structure, in order to obtain a better efficiency and a shorter time of the ion shuttling.

The control of ions' motion was successfully demonstrated in the ring trap combined with DC-electrodes. This novel structure might be applicable to quantum gate operation and Cavity QED, when the interaction of the moving ions with laser beams, or a cavity, could be controlled by DC voltages. Such high degree of control might be feasible by programmed operation of a classical computer. It is also of great interest to rotate the ions as fast as possible in the ring trap without degrading the quantum coherence of the ions. This is relevant to the number of gate operations done with qubits before they lose coherence. Many steps of operation are essential for the large scale quantum computing.

4 Diode-laser-based light sources for $^{43}Ca^+$

Table 1 *Light sources needed for phase gate on $^{43}Ca^+$*

Wavelength(number)	Purpose
390nm(1), 423nm(1)	Resonant ionization
397nm(3)	Laser cooling
405nm(1)	Frequency reference for the violet diode lasers
866nm(1)	Repump
895nm(1)	Frequency reference for the infrared diode lasers
729nm(1)	Qubit manipulation

Although $^{43}Ca^+$ offers an ideal qubit for the nodes in the quantum network, actual experiments demands several frequency-stabilized lasers. The lasers used in an experimental setup for single qubit rotation in $^{43}Ca^+$ are list in Table 1. Even the most fundamental gate operation demands this number of lasers. It is far from reality to generate these wavelengths simultaneously by using popular large-scale lasers, such as dye laser, Ti:S laser. In fact, the use of this number of lasers is unavoidable with any alkaline-metal-like ion species with a hyperfine structure as in $^{43}Ca^+$. The practical advantage of $^{43}Ca^+$ is that all the necessary lasers can be constructed from diode lasers (LD). The infrared lasers in 800-nm range and the 729-nm laser in table 1 can be assembled from commercial extended-cavity diode lasers (ECDLs). In general, the violet light sources between 390 nm and 423 nm are fabricated by frequency doubling of high-power infrared LDs. If it is possible to construct these light sources from recently released commercial GaN violet diode lasers, one can realize an even simpler light source system. However, there has been no report on a high quality violet light source for laser cooling and quantum state manipulation based on the GaN LD. Therefore, we have studied frequency control on the violet diode lasers, and have developed technologies to operate multiple violet diode lasers simultaneously.

The first step was to fabricate a violet ECDL in longitudinal and transverse single mode based on a multi mode GaN LD. Then the spectrum of the ECDL was narrowed by resonant optical feedback with a confocal cavity. For long-term frequency stabilization we have performed Doppler-free spectroscopy of K atom having a narrow transition with a linewidth of about 200 kHz at 405 nm. This transition was used to stabilize a reference laser. A simple way to stabilize multiple violet diode lasers on the reference laser was developed using a repeatedly scanned cavity and a computer. The frequency fluctuations of the violet diode lasers were reduced to less than 1 MHz for an hour. The details are described in the following.

Single-mode operation of a LD is relatively easily obtained by fabricating an ECDL. In an ECDL, the first order diffracted beam is used to chose a wavelength. This method is widely used to red and infrared LDs. We have applied this to a violet LD and obtained a violet ECDL with a power of 3 mW and a linewidth less than 2 MHz at 397 nm [13]. This ECDL was successfully used to laser-cool $^{40}Ca^{+}$ ions in an ion trap with a radius of 5 mm. About 30 ions were cooled to a temperature to form a crystallized state [13]. This was the first evidence to show the performance of the violet LD for laser cooling. A linewith and frequency fluctuation smaller than 1 MHz is desired for stable and reproducible experiments with $^{43}Ca^{+}$ having a natural linewidth of about 22 MHz. However, detailed observation of the violet ECDL spectrum revealed frequency jitters of about 5 MHz for one second. Further control on the spectrum was necessary.

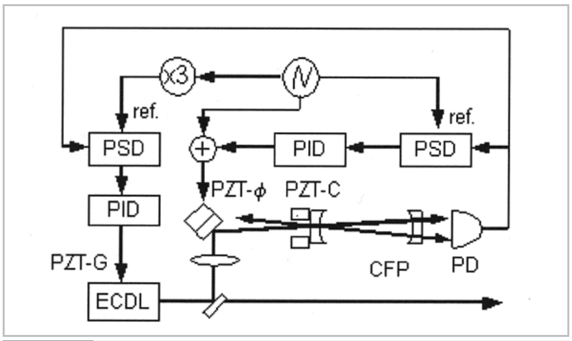

Fig.4 *Scheme for reducing the violet diode laser linewidth by optical feedback*

Resonant optical feedback was employed to reduce the violet ECDL linewidth to less than 1 MHz. Optical feedback was known to be effective for solitary LDs in red and infrared region. Only small number of attempt for an ECDL was reported. The main problem of the optical feedback in an ECDL was small locking range coming from the laser cavity finesse larger than that of a solitary LD. The locking periods and frequency scanning range became intolerably small due to this. We have applied optical feedback to a violet ECDL for the first time. The problem of the small locking range was evaded by our own method of using two supplemental slow electric feedback loops. This method enables hours of locking periods and scanning ranges of several GHz [14]. This feedback scheme is depicted in Fig. 4. The frequency fluctuations were reduced to less than 300 kHz for one second, and the linewidth was narrowed to less than the upper limit of 270 kHz determined by the resolution of the spectrum analyzer [14].

The frequency of the optically locked violet ECDL fluctuates according to the confocal cavity. An absolute frequency reference is required for long-term frequency stabilization. In infrared region, atomic absorption lines such as Cs lines (D1 895 nm, D2 852 nm) and Rb lines (D1 795 nm, D2 780 nm) are often used as the reference. An advantage of alkaline atoms is high vapor pressure enabling simple use of a gas cell for frequency reference. No atomic line was known for violet LDs. We have found the K absorption line with a linewidth of about 200 kHz at 405 nm. Doppler-free spectroscopy was performed with an optically stabilized violet ECDL. An absorption line profile with a full width at half maximum of 3.6 MHz and a signal to noise ration of about 17 was successfully observed [15]. Frequency stabilization more than four hours was achieved by locking the violet ECDL to the K line. The frequency fluctuation was estimated to be less than 200 kHz.

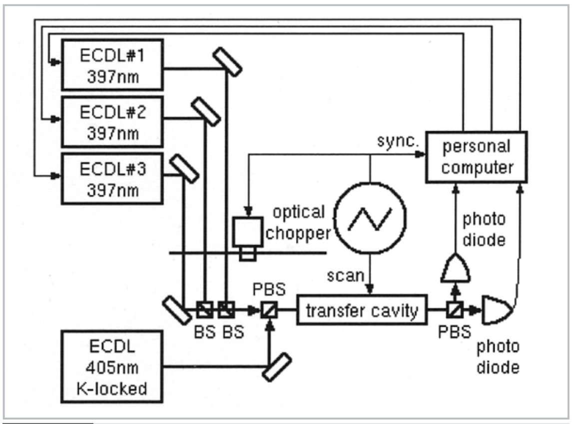

Fig.5 *Frequency stabilization of multiple violet diode lasers by means of a transfer cavity*

As is shown in table 1, one laser at 390 nm and 423 nm, and three lasers at 397 nm have to be frequency-stabilized on the 405 nm violet ECDL simultaneously. A simple method using a repeatedly scanned cavity and computer has been developed. The stabilization scheme is shown in Fig. 5. The figure corresponds to stabilization of three lasers at 397 nm, but it is directly extended by adding two input ports, so that the lasers at 390 nm and 423 nm are stabilized simultaneously. The transfer cavity is repeatedly scanned with a saw tooth signal, and works as a scanning Fabry-Perot spectrum analyzer. The reference ECDL at 405 nm and one 397 nm ECDL selected by the optical chopper are coupled to the transfer cavity. The peaks of the fringes of two ECDLs are measured simultaneously. The frequency of the 397 nm ECDL is controlled by computer so that its peak should be located at a fixed distance from the peak of the 405 nm ECDL. By selecting one from the three 397 nm ECDLs with the optical chopper successively, all the ECDLs are frequency-stabilized. After optimizing the feedback scheme theoretically, actual system was implemented. Three ECDLs at 397 nm were successfully frequency-stabilized for more than one hour simultaneously. An emulator operating in the same stabilization scheme was built for estimating the frequency stability, because no evaluation system for 397 nm was available. The emulator consists of a commercial frequency-stabilized He-Ne laser and an ECDL at 866 nm. The 866-nm ECLD is stabilized to the He-Ne laser by means of a transfer cavity. The frequency of the 866-nm ECLD was directly measured with an optical frequency comb based on a femto-second Ti:S laser having a stability of 10^{-13}. The stability of the emulator was 100 kHz for 1000 seconds. The upper limit of the frequency fluctuation of the 397-nm ECDLs was estimated by error signal and the measured stability of the emulator. The estimation gives 250 kHz for 1000 seconds. This stability is assumed to be small enough for laser cooling of $^{43}Ca^{+}$.

Up to here the frequency stabilization of the violet LDs was described. The fabricated system is assumed to have sufficient performance for laser cooling and quantum state measurement of $^{43}Ca^{+}$. In addition to this system, other lasers listed in table 1 are also necessary for repumping at 866 nm as well as for qubit manipulation at 729 nm. The 866-nm ECDL was frequency stabilized in the same method as for the violet ECDL except the reference laser locked to Cs D1 line at 895 nm. The 729-nm ECDL is more demanding than other ECDLs, because the corresponding atomic line in $^{43}Ca^{+}$ has a linewidth smaller than 1 Hz. Single-mode operation and optical feedback were confirmed with a laboratory-made ECDL at 729 nm. Locking of its frequency to a super cavity placed in a vacuum chamber should give sufficient frequency stability. Actual experiments with prototypes of the quantum network could be realized by setting up more than two stable nodes with a small cost. Our simple way of fabricating the light source system based on diode laser has an advantage in building stable nodes with a small cost.

5 Cavity QED for quantum state transfer

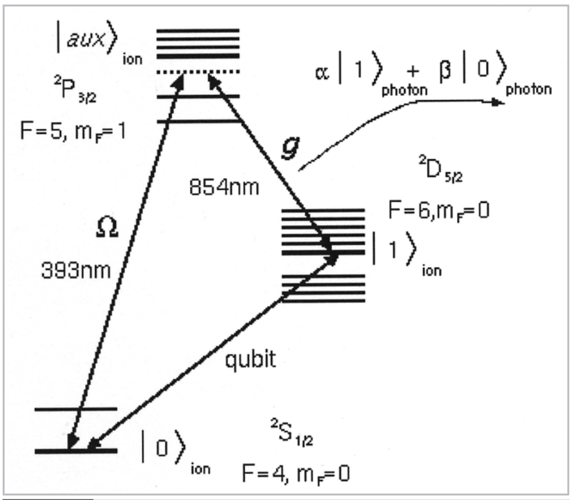

Fig.6 Scheme for the quantum state transfer in $^{43}Ca^{+}$ by Cavity QED

The quantum states transfer between an atomic system and a photonic system might be implemented either by cavity QED [2] or by electromagnetically induced transparency (EIT) [16]. In the atomic system consisting of ions, the density of the atomic particle cannot be made large due to Coulomb repulsion. Therefore, cavity QED is suited for trapped ions. The scheme for the quantum state transfer in a $^{43}Ca^+$ is depicted in Fig. 6. The ion with a Λ-shaped three-level system is first coupled to a high-finesse cavity with the coupling constant g, and then the quantum state of the ion is transferred to the cavity field by illuminating the ion with laser pulse having a Rabi frequency of $\Omega(t)$. The quantum state transfer described by formula (1) with high fidelity is realized, when the coupling constant g is sufficiently large compared to the decay rate Γ from $|aux\rangle_{ion}$ to $|1\rangle_{ion}$. In addition, the cavity loss has to be much smaller than g. Photon-to-ion state transfer is also possible, when the time sequence of this ion-to-photon state transfer is reversed.

The most important parameter in cavity QED is the coupling constant g. This gives the frequency of photon exchange between the cavity field and the ion. The coupling constant g is explicitly expressed as,

$$g = \sqrt{\frac{\mu^2 \omega}{2\hbar\varepsilon_0 V_m}}\psi(\mathbf{r}) \tag{2}$$

where μ, ω, ε_0 are dipole matrix element of the ion's transition, its transition frequency, and the vacuum permittivity, respectively [17]. $V_m = \int |\psi(\mathbf{r})|^2 d\mathbf{r}$ gives the mode volume of the cavity mode expressed as $\psi(\mathbf{r})$ at the ion's location $\mathbf{r}$. In formula (2), the values of μ and ω cannot be altered, once the ion is specified. Therefore, a large value of g can be obtained by having a small value of V_m and a large value of $\psi(\mathbf{r})$. This demands the ion be fixed inside the cavity mode. The mode in the cavity with a spot size w_0 is expressed as

$$\psi(\mathbf{r}) = \cos\left(\frac{2\pi z}{\lambda}\right)\exp\left(-\frac{x^2+y^2}{w_0^2}\right) \tag{3}$$

when the cavity axis is taken as z direction. The maximum value of $\psi(\mathbf{r})$ can be obtained only when the ion is confined at the anti-node of the standing wave (3) having a spatial period of 1/2 λ. This situation would be realized for $^{43}Ca^+$ when the ion's position is controlled with a precision of a few 10 nm, since the wavelength of the ion-cavity coupling is 854 nm. The technology of controlling on the position of an atomic particle with this resolution is not established yet.

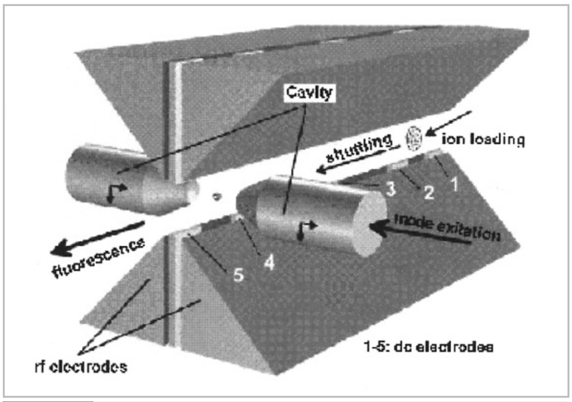

Fig.7 Linear trap combined with a cavity for Cavity QED

We have performed an experiment for establishing the technology of locating an ion in an optical cavity with a spatial resolution smaller than optical wavelengths. The experiment was done using $^{40}Ca^+$ ions, in collaboration with Prof. Walther's group of Max-Planck Institute for Quantum Optics. The use of a short wavelength is advantageous for testing the ability to control the ions' position with a high spatial precision in a cavity. Therefore, the $^2P_{1/2}$- $^2S_{1/2}$ transition at 397 nm was coupled to a cavity, and the coupling constant g was controlled through the overlap of the ions' position and the cavity mode [7][18][19]. A cavity was attached to a linear trap as shown in Fig. 7. The cavity consists of two mirrors with a diameter of 3 mm in 7-mm length. The top of the mirrors is tapered down to a diameter of 1 mm. The distance of the mirror surfaces is 6 mm. The ions are generated in the area of the trap separated 25-mm away from the cavity. This is important in avoiding contamination of the mirrors with neutral calcium emitted from the atomic oven. The generated ions are shuttled into the cavity by applying voltages to the dc-electrodes successively. Then the ions in the cavity are laser-cooled to the Doppler-limit temperature by laser beams at 397 nm. Discrete steps in the fluorescence from the ions arising when the ions are excited to the metastable $^2D_{5/2}$ state are used to identify the number of ions in the cavity [18]. By controlling the generation period of the ions, only one ion can be captured with a high probability. After having a single ion in the cavity, the cavity mode is excited by weak laser beam at 397 nm, and the fluorescence from the ion was measured. Because the fluorescence intensity is proportional to $\psi(\mathbf{r})$ in formula (3), $\psi(\mathbf{r})$ is deduced from the fluorescence intensity. The relative position of the ion to the cavity was scanned by voltages applied to the dc-electrodes and by piezoelectric transducer supporting the cavity. The observed three-dimensional distribution of the fluorescence intensity showed that the ion could be localized at any position in the longitudinal and transverse mode of the cavity. The longitudinal mode profile obtained by the scan is shown in Fig. 8. The mode is a standing wave at 397 nm and has a period of 198.5 nm. The ion's position is controlled with a smaller spatial resolution compared to this. The ion is not completely at rest, but is vibrating due to small energy determined by Doppler-limit temperature. The size of ion's motion is estimated to be 42 nm full width at maximum from the visibility of the standing wave pattern. The ion's position in the cavity was thus successfully controlled to a spatial size sufficiently smaller than the optical wavelength.

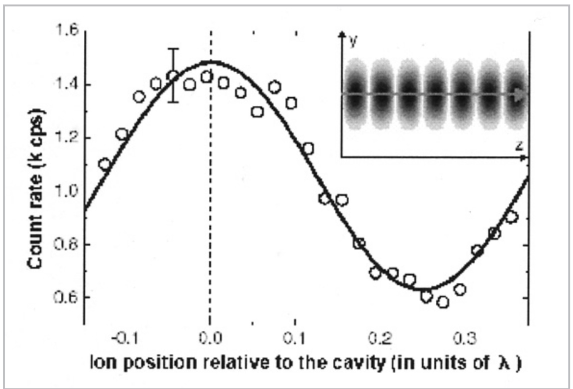

Fig.8 Mode pattern of the standing wave at 397nm probed with a $^{40}Ca^+$

We have realized the control on the coupling of a single ion and an optical cavity. This control was assumed to be one of the barriers for the quantum state transfer. The most basic quantum state transfer is the case with $\alpha=1$, $\beta=0$, corresponding to the generation of a single photon form a single ion. Deterministic generation of single photons is essential for applications like quantum cryptography, quantum computation with linear optics [17]. The experiment for the deterministic generation of single photons is in progress, and we have successfully observed generated photons with an efficiency of a few percent. The improvement in the efficiency to more than 50% is theoretically expected by optimizing the experimental parameters [18][19]. Therefore, the deterministic single photon source is also an important application of our cavity QED system. The experiments have been done so far with $^{40}Ca^+$ ions requiring a relatively simple experimental setup. The control on the ion-cavity coupling by cavity QED can be applied also to $^{43}Ca^+$ by combining the ring trap and the violet diode laser system developed for $^{43}Ca^+$.

6 Conclusion

We have found $^{43}Ca^+$ as the best ion species for building a prototype of the quantum network consisting of atoms and photons. The schemes for quantum information processing and quantum state transfer have been designed for the ion species. We have fabricated and characterized a ring trap and a violet diode laser system for the actual implementation of the prototype. We have realized the control of ion-cavity coupling with a spatial precision smaller than optical wavelengths in collaboration with Max-Planck Institute for Quantum Optics. The control plays an essential role in cavity QED for the quantum state transfer. In the near future the combination of these technologies would realize the quantum information processing with $^{43}Ca^+$ as qubits generated by selective ionization and aligned in space by laser cooling, as well as the quantum state transfer from the ions to the photons. These are the fundamental processes of the quantum network.

Acknowledgement

The authors are grateful to the members of atomic frequency standards group, for their help in the frequency stability measurement of the diode laser. Collaboration of Prof. H. Walther, Dr. W. Lange, Dr. M. Keller, and Dr. B. Lange of Max-Planck Institute for Quantum Optics in the Cavity QED experiments with $^{40}Ca^+$ is gratefully acknowledged.

References

1 C. Monroe, Nature 416, 238, 2003.

2 J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, Phys. Rev. Lett. 78, 3221, 1997.

3 I. Cirac and P. Zoller, Phys. Rev. Lett. 74, 4091, 1995.

4 J. Pachos and H. Walther, Phys. Rev. Lett. 89, 187903, 2002.

5 F. Schmidt-Kaler, H. Häffner, M. Riebe, S. Gulde, G. P. T. Lancaster, T. Deuschle, C. Becher, C. F. Roos, J. Eschner, and R. Blatt, Nature 422, 408, 2003.

6 D. Leibfried, B. DeMarco, V. Meyer, D. Lucas, M. Barrett, J. Britton, W. M. Itano, B. Jelenkovic, C. Langer, T. Rosenband, and D. J. Wineland, Nature 422, 412, 2003.

7 G. Guthörlein, M. Keller, K. Hayasaka, W. Lange, and H. Walther, Nature 414, 49, 2001.

8 A. B. Mundt, A. Kreuter, C. Becher, D. Leibfried, J. Eschner, F. Schmidt-Kaler, and R. Blatt, Phys. Rev. Lett. 89, 103001, 2002.

9 D. M. Lucas, A. Ramos, J. Home, M. McDonnell, S. Nakayama, J. Stacey, S. Webster, D. Stacey, and A. Steane, Phys. Rev. A 69, 012711, 2004.

10 M. Kajita, K. Matsubara, Y. Li, K. Hayasaka, and M. Hosokawa, to be puslished in Jpn. Jour. Appl. Phys.

11 D. Kielpinski, C.R. Monroe, and D.J. Wineland, Nature 417, 709, 2002.

12 Q.A. Turchette, D. Kielpinski, B.E. King, D. Leibfried, D.M. Meekhof, C.J. Myatt, M.A. Rowe, C.A. Sackett, C.S. Wood, W.M. Itano, C. Monroe, and D.J. Wineland, Phys. Rev. A 61, 063418, 2000.

13 K. Hayasaka, S. Urabe, and M. Watanabe, Jpn. J. Appl. Phys. 39, L687, 2000.

14 K. Hayasaka, Opt. Commun. 206, 401, 2002.

15 S. Uetake, K. Hayasaka, and M. Watanabe, Jpn. J. Appl. Phys. 42, L332, 2003.

16 M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. 84, 5094, 2000.

17 K. Hayasaka, Laser Engineering 31, 586, 2003. (in Japanese)

18 M. Keller, B. Lange, K. Hayasaka, W. Lange, and H. Walther, J. Phys. B, 36, 613, 2003.

19 M. Keller, B. Lange, K. Hayasaka, W. Lange, and H. Walther, Appl. Phys. B 76, 125, 2003.

HAYASAKA Kazuhiro

Senior Researcher, Quantum Information Technology Group, Basic and Advanced Research Department

Quantum Optics

***UETAKE Satoshi**, Ph. D.*

Expert Researcher, Quantum Information Technology Group, Basic and Advanced Research Department

Atomic Physics

***IMAJO Hidetsuka**, Dr. Eng.*

Senior Researcher, Quantum Information Technology Group, Basic and Advanced Research Department

Laser Spectroscopy