2012 WCU Project Mid-Term Evaluation (Type 2)

Part A. General Information

Type of Project	(X) Recruiting foreign scholars to existing academic programs		
Proposal No.	R32-10045		
Project Title	Fundamental studies with Bose-Einstein condensates and their applications		
Principal Investigator	Full Name	Kyungwon An	
	Affiliation(Univ.)	Seoul National University	
Research Field Classifications	Proposed Field[1)]	Breakthrough Technology	
	(X)Natural Science ( )Life Science ( )Engineering ( )Humanities & Social Sciences		
Related Sub-field[2)]	Atomic Physics	Superfluidity	Optics
Relative Importance (%)[3)]	30	30	25
Project Duration	from 12/01/2008 (mm/dd/yyyy) to 8/31/2013 (mm/dd/yyyy) (5 years)		

1) The principal investigator is required to provide a description of the proposed field (Ex: Financial engineering, Energy/Environment, NBIC fusion tech., Bio Pharmaceutics/Biomedical engineering, Etc.)
2) Refer to the field classification table provided by NRF
3) Assign percentages to the relevance of each sub-field. The percentages of all sub-fields need not total 100 percent.

A-2. Participants

1) **Principal Investigator** (please attach short vitae, not to exceed 4 pages)

✓ Briefly describe your role as a principal investigator

<table>
<tr><th>No.</th><th>Full Name</th><th>Major field of study</th></tr>
<tr><td rowspan="3">1</td><td>Kyungwon An</td><td>atomic physics/ quantum optics</td></tr>
<tr><td colspan="2">Role in the project</td></tr>
<tr><td colspan="2">Prof. An as a principal investigator (PI) will lead the group and provide various supports to the participating scholars for the success of the project. He has been a PI of several projects (Creative Research Initiative, National Research Laboratory, Pure Basic Science, etc) of similar size to the present project in the past 10 years in Korea. His expertise in the cavity-QED microlaser, single-atom traps and quantum chaos in microcavities will be useful for carrying out the proposed studies. He will work together with Dr. Shin in creating BECs and will play a major role in cavity-QED/quantum information experiments and quantum chaos experiments with BECs working closely with Prof. Jeong.</td></tr>
</table>

2) **Korean Participants** (please attach short vitae, not to exceed 4 pages per participant)

<table>
<tr><th>No.</th><th>Full Name</th><th>Major field of study</th></tr>
<tr><td rowspan="3">1</td><td>Hyunseok Jeong</td><td>quantum optics/ quantum information</td></tr>
<tr><td colspan="2">Role in the project</td></tr>
<tr><td colspan="2">Prof. Jeong will provide a theoretical support for the proposed experiments with his expertise and knowledge of quantum information theory, theoretical quantum optics, and foundations of quantum theory. His expertise on these subjects will be immediately useful for the quantum information study with BEC: generation of macroscopic quantum superposition/entanglement and quantum information processing by using BECs and optical systems.</td></tr>
</table>

3) Foreign Participants (please attach short vitae, not to exceed 4 pages per participant)

No.	Full Name	Major field of study
1	Yong-il Shin	atomic physics (BEC experiment)
	Role in the project	
	There is no BEC experiment group in Korea. Hence, the main role of Dr. Shin is to introduce and activate the BEC experiments and to educate/train graduate students at SNU to be a researcher in this field. Shin has participated in various quantum gas experiments at the Ketterle group at MIT. His major scientific achievements include first demonstration of a trapped BEC interferometer, first observation of decay of a doubly-quantized vortex in BEC, and observation of phase separation of a superfluid and a normal gas. Recently he has successfully performed a series of experiments with strongly interacting Fermi mixtures in collaboration with Wolfgang Ketterle at MIT, defining the frontier of the current Fermi gas experiments. Through the research activities in this WCU program, he will make an essential contribution to establish an active BEC community in Korea.	

Part B. Project Description

Keywords	Bose-Einstein condensate	strongly correlated material	superfluidity
	quantum information	matter wave	quantum chaos
	superconductivity	Schroedinger's cat	scar mode
Project Goal	- To realize Bose-Einstein condensates by laser trapping and cooling of neutral atoms - To understand many-body physics in strongly interacting fermion/boson systems - To realize macroscopic superposition and entanglement with BEC for quantum information applications - To realize matter-wave scar modes of ultracold atoms for quantum chaos studies		
Project Contents	Bose-Einstein condensates can be realized by cooling neutral atoms down to a nano Kelvin range with laser trapping and cooling techniques. With ultracold atoms in BEC we can study many important physical phenomena to which the conventional approaches have severe limitations. Particularly, complete control of experimental parameters and the spectroscopic precision of atomic physics make the ultracold atoms in BEC ideal for direct examination of many theoretical predictions. Related to condensed matter physics, experimental study of strongly interacting fermion/boson systems is proposed: study of Fermi-Hubbard models by using optical lattices and its application to high temperature superconductivity, and fermionic superfluidity and pair correlations in strongly interacting Fermi gases. Related to quantum optics, we propose to study macroscopic superposition and entanglement such as atomic Schrödinger cat states by using coherent interaction of BECs with a high-Q microcavity and to explore its application to quantum information. Moreover, experimental and theoretical investigation of matter-wave scar modes of ultracold atoms trapped in a light potential with asymmetric boundary is proposed as a new platform for quantum chaos studies.		
Expected Project Outputs	- To have our own, Korea's first BEC for the pride of Korea's science and technology - To advance our research capacity to the level of the leading nations in the related fields of condensed matter physics, quantum information and quantum chaos - To acquire home-grown techniques in precision measurement, atomic clock and quantum computation - To build our own BEC research community which does not exist so far		

Note: This page should match to summary of Proposal from Application Form from Selection Evaluation. Summary should *__not exceed 1 page__*

Part C. Progress Report

C.1. Research Status

C.1.1 Studies of BEC and ultracold Fermi gas

During the second phase of the WCU project, our research activities have been focused on 1) optimization the performance of the sodium BEC machine, 2) machine upgrade for Lithium-6 Fermi gas experiments, and 3) study on Skymion-like excitations in spinor BECs.

C.1.1.1 Fast production of large sodium Bose-Einstein condensates in an optically plugged magnetic quadrupole trap

We have demonstrated a fast production of large ^{23}Na Bose-Einstein condensates in an optically plugged, magnetic quadrupole trap. A magnetic quadrupole trap provides a large trap volume and tight confinement due to the linearity of the potential, which make it beneficial to efficient evaporation. Also the quadruple field can be generated from a simple pair of coaxial coils with opposite currents, allowing large optical access to a sample. However, Majorana spin-flip loss is a significant drawback in the quadrupole trap. Near the zero-field point at the trap center, nonadiabatic spin transitions to an untrappable state cause atom loss and resultant heating, eventually limiting the maximum gain in phase-space density. Among the several techniques to avoid this detrimental effect, we have used a repulsive optical plug potential to repel atoms away from the zero-field center region.

The optical plugging scheme preserves the linearity of the trapping potential, so it is advantageous for fast evaporation. The first ^{23}Na BEC of ~ 5×10^5 atoms was produced in an evaporation of 7 s. Recently, this method has been revisited and high efficiency of evaporation cooling in a plugged trap has been demonstrated by producing a large condensate of ~ 3×10^7 atoms in an evaporation of 40 s. In our new setup, we have succeeded to produce a large condensate with N~ 1.0×10^7 atoms in an evaporation of 14 s, which is comparable to the best records in terms of condensate size and production time.

The distinct feature of our system is that the plug beam is offsetted from the magnetic zero-field point. This seems contradicting to the role of the plug, but we find that a slight misalignment less than a beam waist is favorable for BEC production because it forms a single global minimum in the combined magnetic and optical potential. The pointing stability of the plug beam was improved by using a fiber, which makes the fine adjustment of the plug position possible.

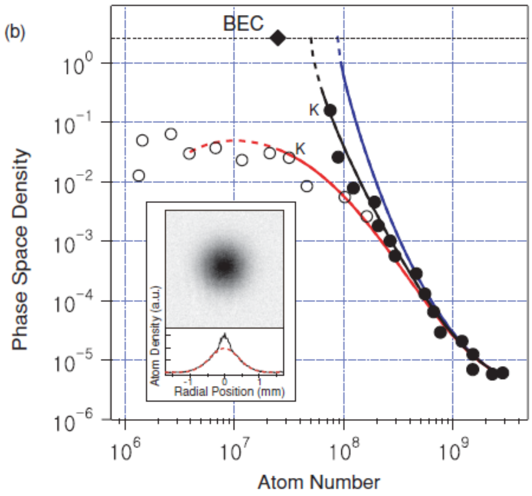

Fig. 1 Evaporation trajectory in the plane of atom number and phase space density with an optical plug (solid circles) and without the plug (open circles). The solid lines are from numerical simulation with a plug (black), no plug (red), and no loss (blue).

C.1.1.2 Machine upgrade for producing ultracold Lithium-6 Fermi gases

We have designed machine upgrade to produce ultracold Fermi gases. Our atom selection for the study of a strongly interacting Fermi gas will be ^{6}Li. Lithium atoms have broad Feshbach resonances between the three lowest hyperfine spin states, which is necessary for stable control of the scattering length of atoms. Any binary mixture out of the three lowest hyperfine states has a long life time enough to form a superfluid. A degenerate Fermi gas of ^{6}Li atoms will be prepared using laser cooling and sympathetic cooling with ^{23}Na atoms. The experimental procedure will be like the following: First, a large number of ^{6}Li and ^{23}Na atoms are collected in a double MOT and transferred into a magnetic trap; Evaporative cooling is applied only to ^{23}Na atoms, which at the same time sympathetically cool ^{6}Li atoms; A pure Fermi gas is transferred into an optical dipole trap; and finally, a variable spin mixture is prepared at high magnetic field with population transfer using rf transitions between spin states. The sympathetic cooling is very efficient due to good collisional properties between ^{6}Li and ^{23}Na. Because during the sympathetic cooling the number of lithium atoms is almost preserved, this method allows a large sample, which is important when we need to resolve the spatial structure of a sample.

We have prepared most of components for this machine upgrade, including an two-species atom oven, Feshbach coils and their current switching system, and 670 nm laser system.

Fig. 2 (left) 670 nm laser system. (right) 23Na-6Li two species oven.

C.1.1.3 Study on Skyrmion-like excitations in a spinor BEC

Skyrmions are particle-like topological solitons, first proposed to account for the existence of protons and neutrons in high energy physics and recognized to have an important role in many condensed matter systems such as liquid ^{3}He-A, quantum Hall systems, liquid crystals, and helical ferromagnets. Atomic Bose-Einstein condensates (BECs) with internal spin degrees of freedom are attractive for the study of topological objects because the rich structure of their order parameters can accommodate various topological excitations.

We investigate an experimental method for imprinting Skyrmion spin textures in a spinor Bose-Einstein condensate by rapidly moving the zero-field center of a three-dimensional quadrupole magnetic field through the condensate (Fig.3). Various excitations such as two-dimensional Skyrmions and coreless vortices were created in spin-1 sodium condensates, initially prepared in a uniform polar or ferromagnetic phase. The spin textures were characterized with the spatial distribution of the spin tilt angle, which is found to be in good quantitative agreement with the local description of single spins under the field rotation. We demonstrate the creation of a highly charged Skyrmion in a trapped condensate by applying multiple times of the imprinting process.

Stability is one of the key issues in the study of Skyrmions. 3D Skyrmions, which are not experimentally discovered yet, are anticipated to be energetically unstable against shrinking to zero size without additional stabilizing mechanisms. We have investigated the stability of the Skyrmion spin texture in a polar spinor BEC. The order parameter manifold of the polar phase is $M=(U(1)xS^2)/Z_2$, having the nontrivial second homotopy group. Thus, the spin textures realized in this work represent the first example of topologically stable 2D Skyrmions in a spinor BEC. Their nature has been confirmed by the observation that the spin textures are stable on a short time scale. They are, however, dynamically unstable to deform and eventually decay to a uniform texture. The spatial patterns of the deformed spin textures reveal that the decay dynamics involves breaking the polar phase inside the Skyrmion.

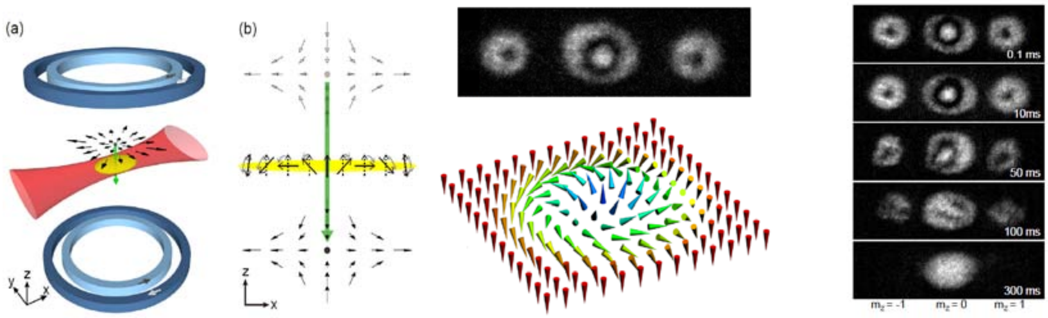

Fig. 3 (left) Imprinting of skyrmion spin textures in a spinor BEC using a magnetic quadrupole field. (middle) Example of the skyrmion spin texture. (right) Dynamic evolution of the skyrmion excitation in a polar spinor BEC.

C.1.1.4 Probing phase fluctuations in a 2D degenerate Bose gas

Phase coherence is one of the main characteristics of superfluidity and critically affected by the dimensions of the system. In low dimensional systems, large thermal and quantum phase fluctuations prohibit the establishment of long-range phase coherence which is a typical order parameter for a three-dimensional superfluid. Nevertheless, a two-dimensional (2D) interacting system can undergo a superfluid phase transition at a finite critical temperature with an algebraically decaying coherence. This transition is successfully described in the Berezinskii-Kosterlitz-Thouless (BKT) theory as a topological phase transition, where the critical point is associated with spontaneous pairing of free vortices with opposite circulations.

We demonstrate a new quantitative probe for phase fluctuations in a 2D degenerate Bose gas using the density correlations in a freely expanding sample. Irregular density modulations gradually develop in the coherent part of the sample during expansion (Fig. 4 left). We observe that the power spectrum of the density distribution has an oscillatory shape and find that the peak positions are independent of temperature and show scaling behavior in the course of expansion. The relative intensity of phase fluctuations is estimated from the spectral peak strength normalized with the central density of the coherent part and we show that it decreases at lower temperature in thermal equilibrium. This confirms the thermal nature of phase fluctuations in the 2D system (Fig. 4 right). In addition, we investigate the relaxation dynamics of nonequilibrium states by measuring the time evolution of the relative intensity of phase fluctuations. Interestingly, ring-shaped density ripples stochastically appear in a perturbed sample after a long relaxation time, which we identify with free vortices having a long lifetime in a 2D sample. This work (arXiv:1206.2232) is accepted for publication in Physical Review Letters.

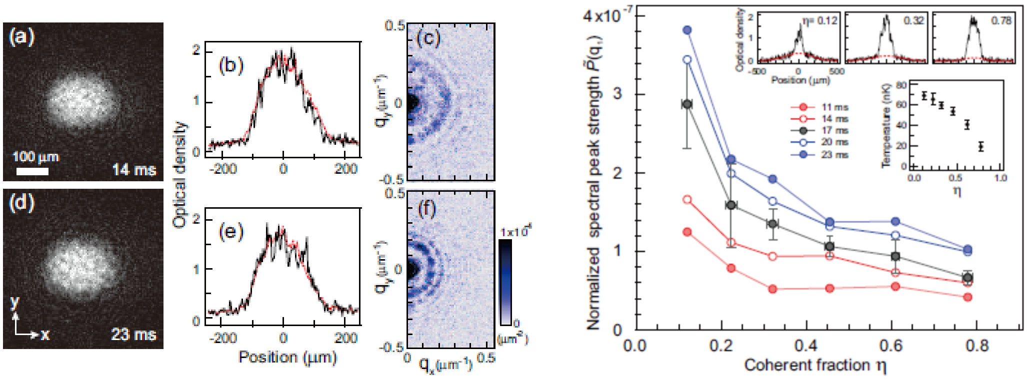

Fig. 4 (left) Development of density modulations in an freely expanding 2D Bose gas. The power spectrum of the density modulation has been measured to estimate the strength of the phase fluctuations in the 2D sample. (right) Power spectral strength vs temperature.

C.1.2 Experimental studies of quantum information using BEC

C.1.2.1 Development of the technology for studying BEC- optical lattice interactions

The tunneling of trapped atoms inside an optical lattice plays an important role in the Bose-Hubbard model which describes the interaction between an optical lattice and a BEC. Recently, the phase transition between superfluid and Mott insulator depending on the tunneling has been extensively studied. In the present study, one of our goals is to transport a BEC into a resonator using an 1D optical lattice conveyor belt. In this respect, detailed understanding on the dynamics of the atom inside the lattice as well as the lattice itself is essential for our study.

In year 3, we focused on studying the details about the tunneling rate inside an optical lattice potential. In other groups, a real-time imaging technique was used to observe tunneling, but this method is difficult to apply if the lattice constant is much smaller than the resolution length of the imaging system or if the tunneling is too rapid to directly monitor. We, therefore, measured the resonance fluorescence spectrum emitted from the atom in order to study the tunneling in a more comprehensive manner. To accurately observe the tunneling, we trapped a single atom in a 3D optical lattice potential. Since we used a phase stabilized configuration for the laser beam, the phase fluctuation of the trap laser is compensated and a stable trap system for a single atom emitting photons during a relatively very long time has been realized.

To measure the spectrum of trapped single atom, we used a high-sensitive second-order correlation spectroscopy technique based on photon counting. From measured spectrum, we obtained a narrowed linewidth of the spectrum, called the Lamb-Dicke effect, without Doppler broadening since the atom is localized tightly in a micropotential. We observed the tunneling of the atom with controlling the height of potential barrier, and verified that the experimental results are well agreed with theoretical analysis based on band structure calculation. This result was published in Nano Letters in 2011 [W. Kim *et al.*, Nano Letters **11**, 729 (2011)].

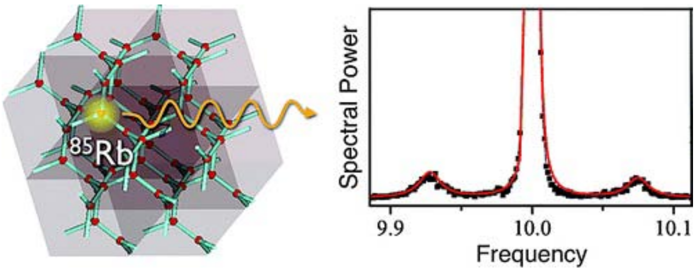

Fig. 5 A single atom trapped in an optical lattice potential (left) and the resonance fluorescence spectrum from the atom (right). Since each lattice potential minimum acts as a 3D harmonic oscillator approximately, one can observe Stokes and anti-Stokes sidebands besides the central Rayleigh peak.

In the 4th year, we focused on the dynamics of atoms when the optical lattice is moving at a constant speed. To make the lattice move, we shifted one of the counter propagating trap beams to a different frequency. Then the velocity of the optical lattice is proportional to the frequency difference. We probed the dynamics of atoms in terms of the spectrum of the near-resonance fluorescence which necessarily occurs in a MOT system. The spectrum measurement is non-destructive since it does not require an additional probe laser or destruction of the trap. Therefore, we can continuously measure the dynamics of atoms in a steady state. So far we have measured the fluorescent spectrum in a moving optical lattice as a function of the lattice speed. When the optical lattice moves slowly compared to the oscillation frequency of the optical lattice potential, most of the atoms are localized at the lattice potential minima and the spectrum is narrowed by the Lamb-Dicke effect. On the other hand, when the optical lattice moves fast, some atoms are no longer localized and thus a Doppler-broadened spectrum appears. We measured the change of the spectral shape with varying the lattice speed (Fig. 6). We are now modeling the observed spectral change in terms of the transition between vibrational energy levels of the lattice potential while the transition is induced by the small acceleration that the lattice experience due to the harmonic potential shape of the MOT.

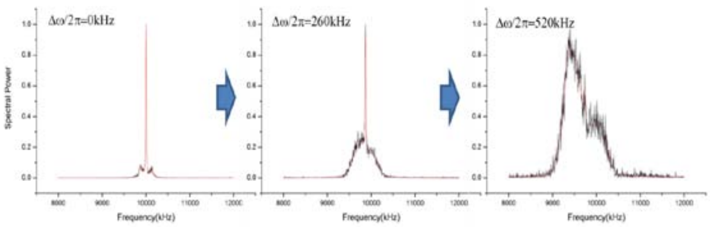

Fig. 6 The change of spectral shape according to the frequency difference between counter propagating trap beams. The speed of the optical lattice is proportional to the frequency difference. The oscillation frequency of the optical lattice micropotential was 120 kHz.

C.1.2.2 Developing cavity-QED technology for BEC-cavity interactions: Quantum information with a single atom in a cavity

Realization and investigation of a BEC-cavity system is one of our goals. As an intermediate step, we have constructed a cavity-QED system and studied its properties and explored its applications. Especially, a deterministic single photon generator has been demonstrated, which is one of the key issues in quantum information and quantum communication.

The single photon generator was made of a single 85 rubidium atom and a high-finesse Fabry-Perot cavity. The atom-cavity was designed for high efficiency and rapid repetition rate in the generation of single photons. Our experimental setup is shown in Fig. 7. Cold rubidium atoms are trapped in a magneto-optical trap (MOT) just above the cavity mode, and released in the direction of gravity by turning off the trap. When an atom passes through the cavity mode, the atom is excited by a pump laser pulse and a single photon is generated by the coherent interaction of the atom and the cavity mode. We have demonstrated a repetition rate of 10 MHz and an efficiency of 17% in single photon generation by optimizing the parameters of the cavity and the pulse laser. Also, the single photon nature of generated photons is observed by the intensity correlation measurement and the probability of two or more photon state was observed to be less than 10%. The number of deterministically generated single photons was 1.7×10^6 per second, which is about 30 times larger than the previous experiment [J. Bochmann *et al.*, Phys. Rev. Lett. **101**, 223601 (2008)] in an atom-cavity system. This research result was published in Optics Express in 2011[S. Kang *et al.*, Optics Express **19**, 2440 (2011)].

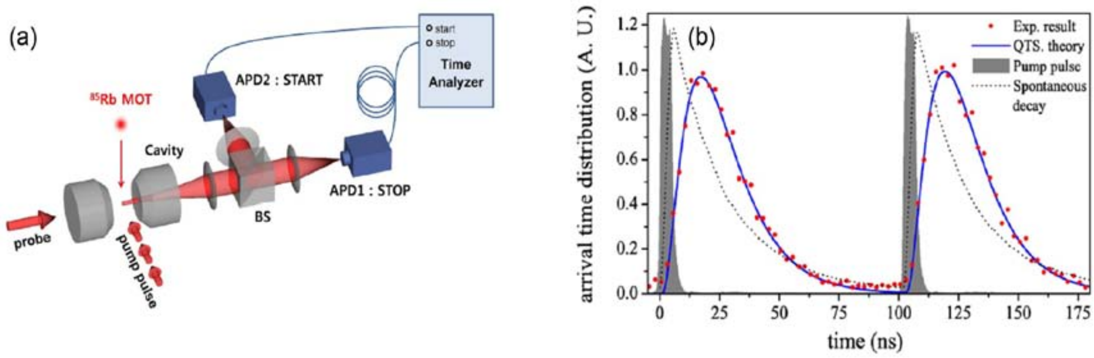

Fig. 7 (a) Experimental schematic for our controlled generation of single photons in a cavity-QED system. (b) Arrival-time distribution of generated single photons and it's theoretical fit. Repetition rate was about 10 MHz.

In the 4th year, we investigated trapping of a single rubidium atom in the cavity mode in order to achieve a higher efficiency and a longer interaction time in the single photon generation. For this, we installed a dipole trap beam along the cavity axis. The dipole-trap laser is red-detuned from the atomic level to form a standing-wave trap potential with a maximum trap depth of 0.68mK in temperature. The cavity is tuned to the ac-Stark shifted (blue shifted) atomic transition by the dipole-trap laser, so is a weak cavity probe laser. When an atom dropped from the MOT arrives at the cavity mode, or more precisely when the cavity transmission drops to a low level by the atom-cavity interaction, the probe laser is turned off. Interestingly, we have found the atom is cooled by the probe laser during this process by the so-called cavity cooling mechanism. In this mechanism, the energy of the transmitted photons is larger than that of the incident probe photons due to the atom-cavity interaction, and therefore, the atom interacting with the cavity must loose its kinetic energy and thereby becomes trapped by the dipole trap, which is a conservative-force trap. We observed the atom remains in the cavity mode for up to 0.5 second. Interestingly, the observed survival probability of the atom in the dipole trap showed an initial fast decay (ms time scale) followed by a slow decay as shown in Fig. 8. We suspect the initial fast decay may come from a sudden shutoff of the probe laser once the atom is optimally coupled to the cavity. We are currently investigating the origin of this fast decay and hope to remove it in order to make the survival probability even larger.

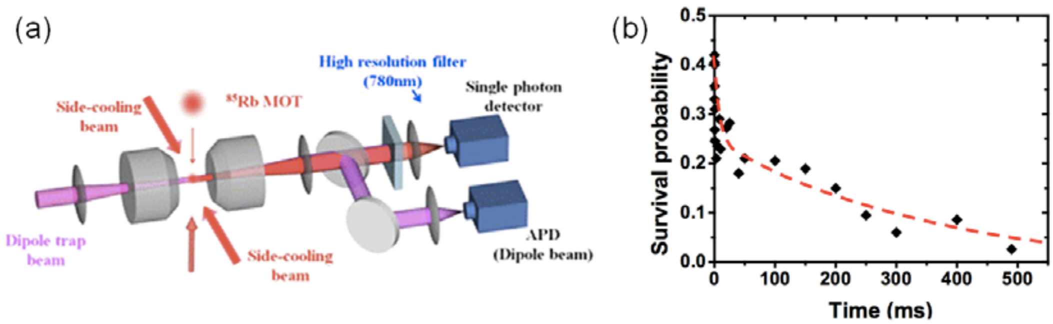

Fig. 8 (a) Experimental scheme for trapping a single atom in a cavity with a dipole trap beam along with the cavity cooling mechanism. (b) Survival probability for the trapped atom.

C.1.2.3 Developing measurement technique for particle noise in BEC

The measurement of the pair-correlation in a system of strongly-interacting Fermionic atoms is an important issue in the condensed matter physics with BEC and also one of the main purposes in our research project. This measurement can be done by probing the relative ratio between the unpaired free states and the paired correlated states. We plan to investigate of the noise difference between the images of the paired and unpaired atomic gas densities. As a preceding experiment of this research, we survey the photon statistics of the cavity-QED microlaser, which is an appropriate light source to test our noise-detection scheme because of its diversity of photon statistics.

We measured the second order correlation function and thus the photon statistics of the microlaser, and observed the transition from photon bunching to photon antibunching depending on the pumping parameter.

We also made an effort to improve the accuracy of the high-order correlation function, which is affected by recording precision of photon arrival times. Our old time-to-digital converter (TDC) showed some distortion at high intensity of photons. To solve this problem, we introduced a field programmable gate array (FPGA), which has programmable logic circuits and first-in first-out (FIFO) memories in it. We succeeded in obtaining 10-ns resolution in the photon waiting time distribution with the FPGA clock derived from 40 MHz with 5/2-ratio amplifying. We confirmed that the distortion appeared in the old photon-counting system has disappeared in the waiting time distribution of 10 MHz pulses on the new TDC.

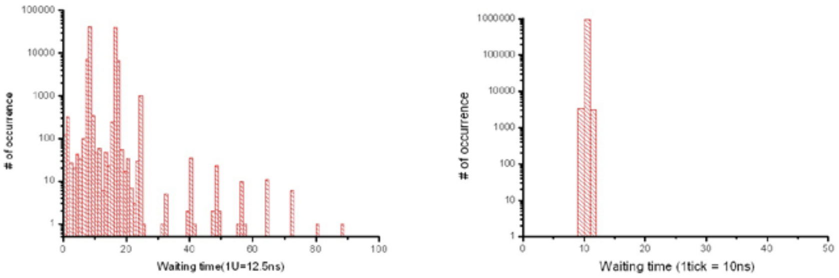

Fig. 9 Waiting time distribution measured with old TDC (left) and new TDC (right). The new TDC method shows no distortion and exact waiting time.

The photon antibunching is characterized by a negative mandel Q. In the previous works Mandel Q was bigger than -0.2 even though the theory predicts that it should be less than -0.5. However, with the new measurement system, we could obtain Q=-0.48, which corresponds to 4 times larger reduction of shot noise than before.

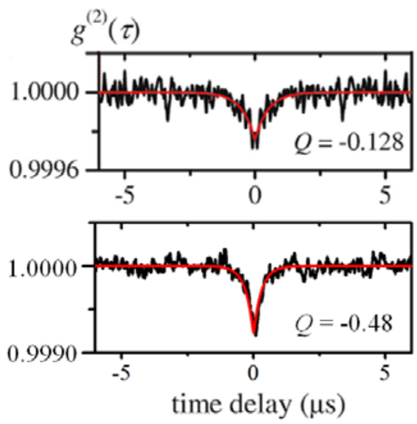

Fig. 10 The second-order correlation function obtained with the old measurement system (up), and the recent result with the new measurement system (down). The new record of Q=-48 which is close to the theoretically expected value of Q~-0.6, shows the largest reduction (28%) of quantum noise while the last record of Q=-0.128 indicates only 6% noise reduction.

C.1.1.4 3D imaging of vacuum fluctuations in a cavity for BEC-cavity interaction

As a prerequisite for the coupling of a BEC and a cavity, we performed experimental observation of vacuum fluctuations in a high-Q cavity. While the modes of electromagnetic field in a cavity are determined by the Maxwell equation satisfying the cavity boundary condition, there exist intrinsic quantum vacuum fluctuations in each mode, predicted by the quantum electrodynamics (QED) theory. To image the 3D structure of vacuum fluctuations in a cavity, we used single Ba^{138} atoms as a nanoscopic detector. In order to localize the atomic position in nanometer precision we used a home-made atomic beam mask with an array of 200nm-diameter nano holes in front of the cavity. To minimize the divergence of the atomic beam through the nano holes, we employed a home-made L-shape cavity to reduce the distance between the atomic mask and a cavity mode down to 400μm. The excited atoms, pumped just in front of the cavity, emit photons into the cavity mode driven by the vacuum fluctuations while their emission rate is proportional to the average intensity of the vacuum fluctuations during the transit. By measuring the emitted photons at various positions of the atomic mask, we could reconstruct the 3D structure of vacuum fluctuations in the cavity mode.

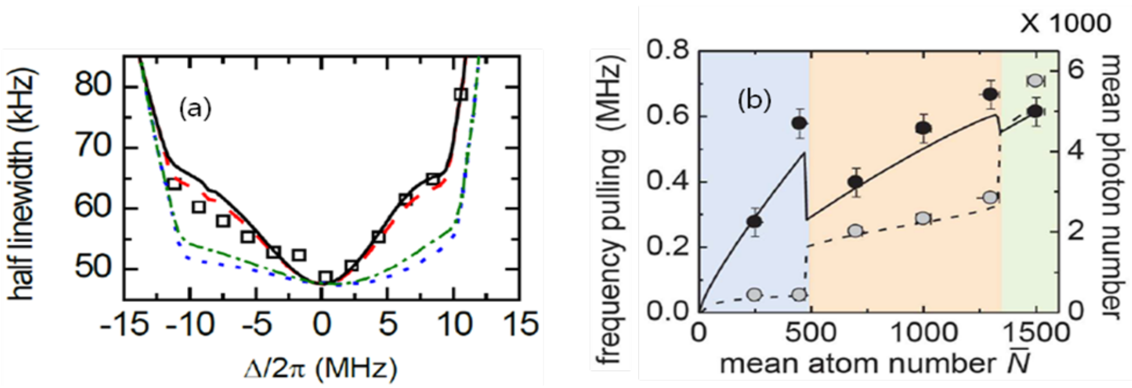

Fig. 11 (a) The linewidth of the microlaser as the atom-cavity detuning Δ varied. Theoretical curves are obtained by nondispersive effect only (blue dotted), including the differential pulling induced by photon number distribution Δn (green dashed-dot), including the differential pulling induced by atom number distribution ΔN (red dashed) and including the effect of both Δn and ΔN (black solid). (b) The magnitude of the pulling (black circles: experiment, solid curve: theory) and the mean photon number (grey circles: experiment, dashed curve: theory) at Δ=3.3 MHz. Oscillatory behavior of the frequency pulling is noted in accordance to the stepwise variation of the mean photon number.

C.1.2.6 Observation of the spectrum of the cavity-QED microlaser

Frequency pulling in lasers comes from the change in the optical path caused by the dispersion of the gain medium under non-resonant condition. Due to the frequency pulling, the oscillation frequency of a laser differs from the resonant frequency of the cavity and the amount of the pulling is constant determined by the bandwidths of the gain medium and the resonator. In the cavity-QED microlaser operating under non-resonant condition, the coherent interaction between atoms and the cavity is expected to bring about unconventional frequency pulling. In this study, we first extended the theory of the resonant microlaser spectrum into the non-resonant regime to introduce the quantum distribution of the frequency pulling, and then we performed its experimental verification. As opposed to the independence of the frequency pulling on the pumping parameter in the conventional laser, the average of the frequency pulling in the microlaser is sensitive to the pumping parameter and shows an oscillatory behavior reflecting the coherent Rabi oscillation. In addition, we proved that the quantum distribution determines not only to the center frequency but also to the linewidth of the cavity-QED microlaser.

C.1.3 BEC-Quantum chaos

C.1.3.1 Developing arbitrary-shaped Time-averaged Potential Barrier (TAPB) system

BEC as an ultracold atomic matter wave can be an ideal model system for studying quantum chaotic behaviors under nonintegrable-shape potential boundaries. Moreover, the existence of nonlinear interactions in BEC provides an opportunity to study its role in the quantum chaos that could not be covered in the previous microcavity experiments. To this end, we have developed an arbitrary-shaped time-averaged potential barrier (TAPB) system.

Our TAPB system is basically based on the dipole interaction between the BEC and a blue detuned laser beam (532nm). As shown in Fig. 12(a), a blue-detuned TAPB beam (532nm) is superimposed on a Na BEC, which is trapped in a 2D optical dipole trap(1064nm). With a 2D acousto-optic deflector (AOD), we deflect the direction of the TAPB beam arbitrarily along the horizontal and the vertical directions relative to the beam propagation. The deflection angles can be controlled by adjusting the rf-frequencies of the 2D AOD. Accordingly, we can draw arbitrary patterns on a plane perpendicular to the beam propagation. Fig. 12(b) shows some examples of the generated patterns at the image plane P_1. The arbitrary patterns drawn in the image plane (P_1) are directly mapped onto the BEC plane (P_2) with a 4f system of a magnification of 0.6, formed by two lenses L2 and L3. All the parameters related to the TAPB are controlled by a computer combined with an analog voltage output board (NI-DAQ usb-6353). The frame rate of pattern drawing also can be controlled up to 1000 frames per second (fps). Because the typical oscillation frequency of the BEC is about 10Hz, we set the frame rate of the patterns at 100fps. Optimized pattern generating algorithm and pattern-control program have also been developed.

After loading BEC in a 2D dipole trap, we adiabatically turned on the TAPB during 10ms. Then we suddenly turned off the TAPB, and took an absorption image with a resonant probe laser. Figure 13 shows the results. Figure 13(a) shows a typical 2D Na BEC without TAPB while Figs. 13(b)~(d) show the results of various TAPB patterns mapped onto the 2D BEC. With these results, we plan to demonstrate the existence of whispering gallery mode (WGM) of BEC as a first step of quantum chaos study with BEC. Towad this end, we are now improving the beam quality of TAPB beam after the 2D AOD.

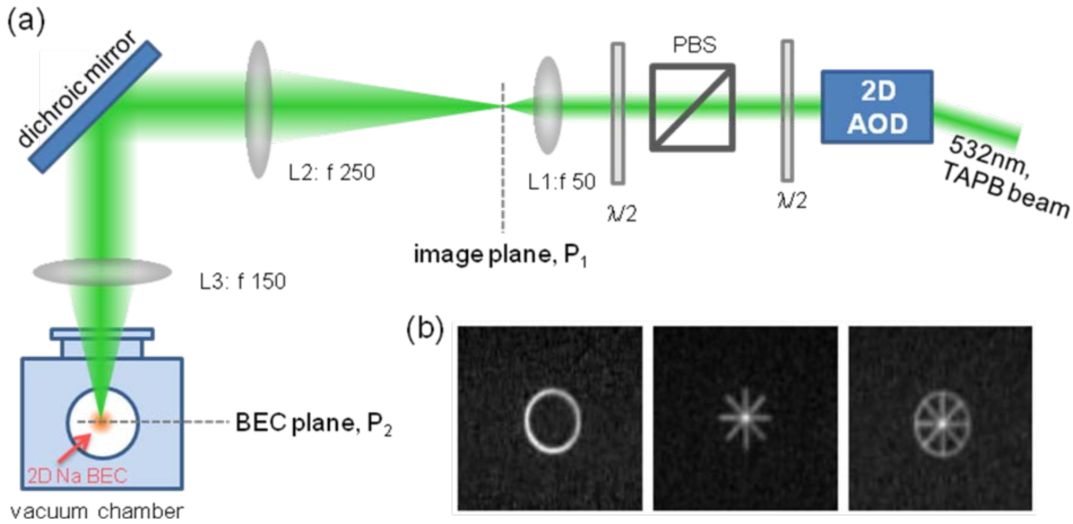

Fig. 12 (a) Optical system for generating arbitrary-shaped TAPB. A 532nm TAPB beam is superimposed on the BEC plane after passing through a 2D AOD and a 4f system. Patterns generated on the plane P_1 is mapped onto the BEC plane P_2. (b) Some examples of arbitrary pattern generation. These patterns are imaged by a CCD at the image plane P_1.

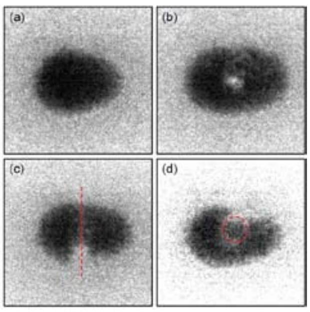

Fig. 13 (a) Absorption image of the Na BEC trapped in a 2D dipole trap. (b)~(d) A various patterns of TAPB superimposed on the BEC. (b) single point. (c) vertical line. (d) circle.

C.1.3.2 Dynamical Tunneling

Emergence of interactions among unperturbed-basis quantum states is a prominent feature in a nonintegrable system. This feature has attracted a lot of interests both theoretically and experimentally in the field of quantum chaos. However, relatively little attention has been paid to the underlying physics of these interactions. To complement the study of mode-mode interactions in asymmetric microcavities, which are representative examples of optical nonintegrable systems, we have adapted the resonance-assisted tunneling (RAT) theory to the microcavity systems. For this purpose, interactions among unperturbed-basis states are categorized according to their coupling strengths (strong and weak interactions) and the husimi functions of quasi-resonance modes are examined near the interaction regions. We found that the husimi functions of quasi-resonance modes undergoing a strong interaction are localized on a resonance chain structure (along the stable and unstable periodic orbits) in the phase space. Moreover, in this case the angular mode indices of interacting modes are equal to an integer multiple of the number of the chain islands for the interaction. This result is consistent with the prediction of the RAT theory.

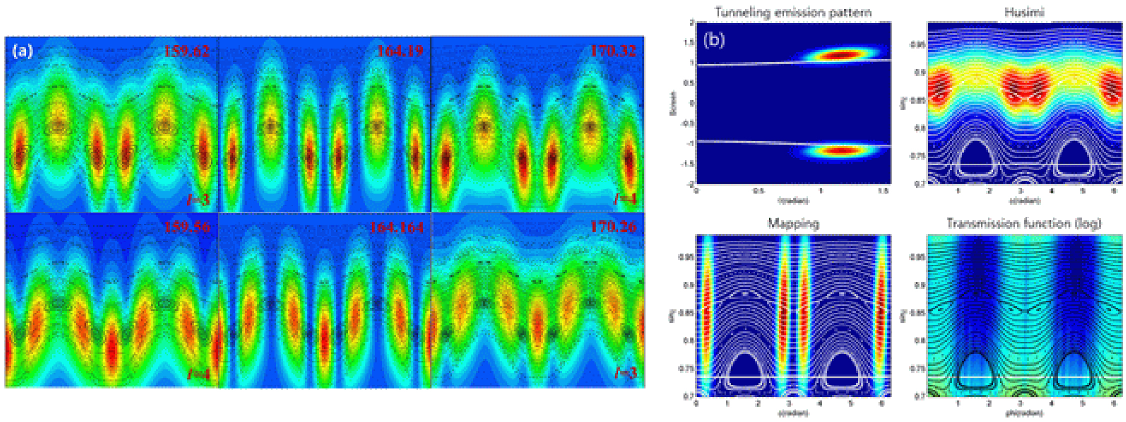

Fig. 14 (a) Husimi functions near the interaction region of unperturbed-basis modes of radial-mode index *l*=3 and 4 in the quadru-octapolar microcavity at deformation of 8%. (b) Tunneling emission pattern and the husimi distribution (*nkr*=210.61). When the husimi function is located just above the chained islands, the dynamical tunneling rate is enhanced. Consequently, the tunneling light appears to originate from the phase-space positions below the high-density regions of the husimi function.

In order to understand the dynamical processes in nonintegrable systems, we have also studied the tunneling emission in a quadru-octapolar deformed microcavity. We introduced a transmission function in the phase space which is expected to contain the information on the outgoing light from the cavity. The transmission function is numerically obtained by dividing the husimi function by the phase space distribution that is mapped from the tunneling distribution by the relation of local angular momentum conservation.

We found that the transmission function is influenced by the structures in Poincare surface of section (PSOS) as follows. In a slightly deformed case, in which tori structure is preserved, the transmission function is nearly a constant, corresponding to a very slow exponential decay, so that the tunneling emission occurs directly from the original mode distribution in the phase space. As the deformation increases, however, island-chain structures emerge. In this regime, the transmission function is observed to have dependence on the relative positions of the husimi function and the island chain: the tunneling emission occurs at different positions from those of the high-density regions of the husimi function. This is a clear demonstration that the PSOS structure strongly affects the dynamical tunneling rate.

C.1.4 Theoretical quantum information using BEC

C.1.4.1 Quantification of quantum superpositions

In the third year, we have made a major breakthrough in developing a tool to quantify macroscopic quantum superpositions in phase space [Phys. Rev. Lett. 106, 220401 (2011)]. Our newly-proposed measure simultaneously quantifies two different kinds of essential information for a given quantum state: the degree of quantum coherence and the effective size of the physical system that involves the superposition. We have shown that it is the most general and inclusive measure ever proposed, and it can be applied to any types of multipartite states and mixed states represented in phase space. Remarkably, our measure enables one to compare different types of quantum superpositions by a single measure. For example, Fig. 15(a) corresponds to a superposition of two coherent states with a relatively small effective size but large coherence, while Fig. 15(b) to the opposite. Our measure gives the same value for the two cases.

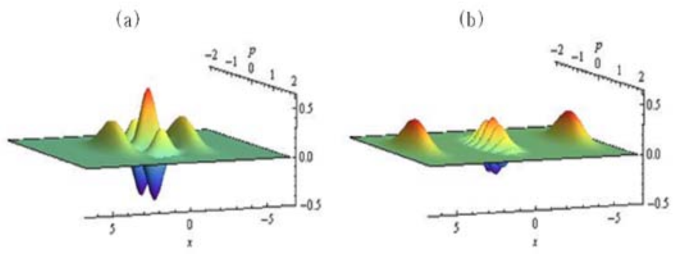

Fig. 15 (a) Pure macroscopic superposition with size factor ~2.3. (b) Partially decohered macroscopic superposition with size factor ~5. These two cases give the same value (~5.29) of our proposed quantity.

C.1.4.2 Quantum nonlocality using atom-field entanglement

We have also studied Bell inequality tests with entanglement between coherent-state fields in a cavity and atomic systems [Phys. Rev. A 85, 022120 (2012), Fig. 2]. Such entanglement can be generated using a strong dispersive interaction, and we show that Bell inequality tests can be effectively performed using ancillary atoms as depicted in Fig. 16.

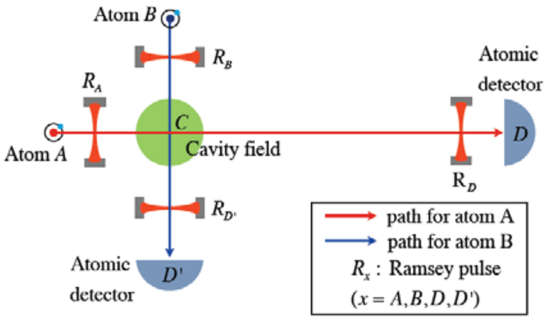

Fig. 16 Bell inequality test using atom-field entanglement. The horizontal arrow is to describe entanglement generation while the vertical arrow depicts the indirect measurement of the cavity field using ancillary atom B.

C.1.4.3 Exploring quantum entanglement and quantum nonlocality within multipartite, multidimensional and mixed systems

Quantum Entanglement and nolocality are crucial resources for quantum information processing. As most of physical systems are in mixed and multi-dimensional systems, it is important to investigate such systems in view of both fundamental aspects and practical applications. It is commonly believed that initial quantum states with high purities are required to generate quantum entanglement. We, however, showed that quantum entanglement can be generated even between high-temperature thermal states via a direct interaction between them [Phys. Rev. A 85, 044301 (2012)]. This result is in contrast with a prior research that purity of the atom is important to generate entanglement [Phys. Rev. Lett. 87, 050401 (2001)]. Besides, we have been able to propose a method to test Bell's inequality in complex high-dimensional systems [Phys. Rev. A 83, 022103 (2011)], and a scheme to test nonlocal realism based on Leggett's inequality using macroscopic and mesoscopic quantum entanglement [Phys. Rev. A 83, 022102 (2011)].

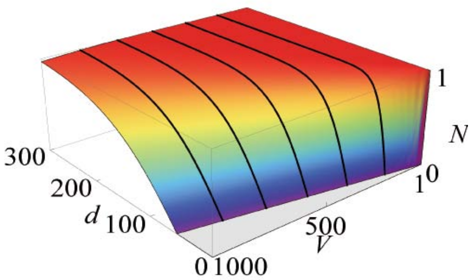

Fig. 17 *V* is the variable of the thermal state related to its temperature. Quantum entanglement (*N*) is always generated even when *V* has an arbitrarily large value as far as the displacement (*d*) of the thermal state from the origin of phase space is sufficiently large. The displacement operation does not change the initial purity of quantum states.

C.1.4.4 Quantum computation based on hybrid systems

There are a number of different qubit-encoding methods for the implementation of quantum computation with their own advantages and disadvantages. One method is to encode a qubit to a single particle such as an atom or photon and another is to encode a qubit using different states of fields such as coherent states. The former is known as the particle-like encoding while the latter as the field-like encoding. In the case of the particle-like encoding based on optical implementations, single-qubit gates are relatively easy to realize while the realization of two-qubit gates are difficult. In general, it is the opposite for the case of the field-like encoding. We have developed a universal quantum computation scheme based on a hybrid system using both the approaches in a combined ay [arXiv:1112.0825]. We showed that quantum teleportation can be performed in a deterministic way (Fig. 18), and performance of quantum computing may be significantly enhanced using the hybrid approach.

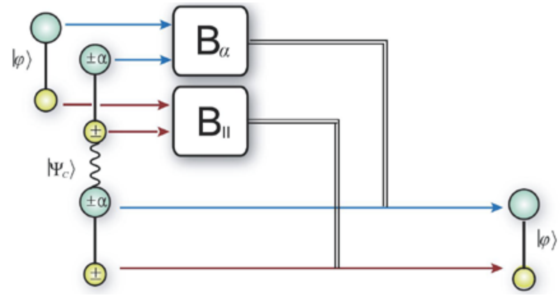

Fig. 18 Quantum teleportation using a hybrid system. The particle-like part (±α) and the field-like part (±) form a logical qubit. A hybrid qubit is teleported via an entangled channel (ψC) to the other part of the channel in an efficient way.

C.2. Expected Impact

C.2.1 BEC production technology

In the previous research phase, we have succeeded to build a sodium BEC machine which is now actively employed to develop experimental techniques for BEC application research. Especially, the newly developed techniques such as quisi-two-dimensional optical traps and high-resolution imaging are providing important tools for the study of quantum chaos and quantum information with BECs. Currently, the BEC machine is being upgraded for producing strongly interacting, ultracold Fermi gases.

C.2.2 Skyrmion imprinting technique

Using the magnetic field rotation method, Skyrmion spin textures can be deterministically imprinted in spin-1 Bose-Einstein condensates. Since the sample is kept in the optical trap after the spin texture imprinting process, our current experiment setup provides immediate opportunities to study the dynamic stabilities of the 2D Skyrmions and the coreless vortices. Recent theoretical study showed that the Anderson-Toulouse and Mermin-Ho coreless vortices are dynamically unstable toward vortex splitting and phase separation. We expect that this technique can be extended to engineer 3D topological excitations with timely control of the magnetic field. It has been proposed that knots or Dirac monopole structures can be generated by placing the zero-field point of a quadrupole field in a 3D condensate.

C.2.3 Ultra-sensitive real-time spectroscopy

With our ultrasensitive real-time spectroscopy technique developed in this project, one can even measure the spectrum of a single atom. It should be a useful tool in applications requiring high-sensitive spectroscopic techniques such as spectral analysis of ultra-weak signal, spectroscopic detection of a small amount of hazardous materials in the atmosphere, in-vivo spectral analysis of fluorescent organic materials, and moreover, detection of radioactive material in atomic level near a nuclear power plant.

C.2.4 Controllable single-photon generator

Controlled generation of single photons at a fast repetition rate and at a high efficiency has a great importance in quantum communication. In addition, our single photon generator is the only one in Korea in terms of controllability and thus collaboration with domestic theory groups on quantum information would be possible. With a longer atom-cavity interaction time which we are working on now, more advanced quantum optics and quantum information studies can be conducted.

C.2.5 Technology for photon noise measurement

We showed that quantum noise can be measured with our optical method and have demonstrated necessary experimental tools for observing the pair correlation in BEC. This method is highly effective so as to be useful for an extremely weak signal. We found that the measured photon statistics of a nonclassical light source could be distorted during the detection process if the output intensity is not so small that the pulse counting board is unable to keep up with it. With the new TDC implemented, the accuracy of the second order correlation function has been greatly improved, and we thus expect to observe the ultimate Mandel Q that the quantum theory predicts and to measure the spectrum of the microlaser more precisely.

C.2.6 Nano-hole lattice technique

In the experiment of 3D imaging of vacuum fluctuations in a cavity, the nano-hole lattice was the core technique to localize and control atomic beam in the nanometer precision. This technique can be applied to more advanced studies such as a coherently pumped cavity-QED microlaser, generation of a mesoscopic superposition state of field (Schrödinger cat), etc.

C.2.7 Quantification of quantum entanglement and quantum superposition

Our result for the size measure of the quantum superposition is directly applicable to experimental results in various systems including optical systems and Bose-Einstein condensates. It may be used to study characteristics and usefulness of macroscopic quantum superpositions in various systems, and is expected to produce subsequent researches and have significant impact. The research on quantum computation based on the hybrid approach is expected to bring about a breakthrough for the implementation of quantum information processing using atoms and photons. The practical realization of quantum computation has been considered extremely challenging due to flaws of each physical system considered for qubit encoding. Our hybrid approach may provide a promising future research direction.

C.3. Next-Year Plan

C.3.1 Research on BECs and strongly interacting Fermi gases

The research activities in this phase have been focused on development of experimental techniques for BEC applications and machine upgrade for producing strongly interacting Fermi gases, In particular, the newly developed 2D optical trap has been successfully employed in Skyrmion imprinting experiments, 2D Bose gas experiments, and to study quantum chaos with BECs. Furthermore, we have developed a new quantitative method to probe phase fluctuations in a 2D Bose gas, confirming for the first time their thermal nature in the 2D system. In the following research, we will further investigate these phase fluctuations to distinguish the contribution of free or paired vortices from phonon excitations. Also, using the newly developed power spectrum method, we will investigate the nonequilibirum dyanamics in 2D Bose gases such as dynamic BKT transitions.

C.3.2 Cavity cooling and the improvement of the deterministic single-photon source

One of our ultimate goals is to combine a high-finesse cavity and a BEC in order to maximize the interaction between a quantum material and a photon. For this purpose, we will further investigate the dipole trap in a cavity combined with the cavity cooling mechanism, in which a quantum matter is cooled by the interaction between the matter and the cavity mode. The cavity cooling can be applied to a BEC in a cavity. It also allows a single photon source with a higher efficiency and a longer generation time.

C.3.3 Coherently pumped cavity-QED microlaser

Atomic localization technique by using the nano-hole lattice make it possible to coherently control the phase between the cavity field and the atom. By pumping the cavity field with atomic dipoles with a well-defined atomic phase, we can realize a coherently pumped cavity-QED microlaser, which is expected to have unique properties such as well-defined pump-output phase relation, i.e., phase imprinting, and thus would have an application in quantum information science. It can also be applied to generation of a macroscopic superposition of the cavity field, namely a Schrödinger-cat state.

C.3.4 Realization of BEC-WGM and quantum chaos study

With the generation of arbitrary-shaped time-averaged potential barrier (TAPB) developed in the previous year, we will demonstrate the existence of the whispering gallery mode (WGM) of BEC. Specifically, we first initialize the wave function of a BEC as a WGM inside a circular TAPB with additional optical potential patterns, which also can be generated by the TAPB system. We then turn off the additional potential and observe the time evolution of the BEC wave function with and without the circular TAPB. Because the initial WGM-like wave function can be an eigenmode of the circular TAPB, the time evolution of the BEC should have different behaviors for these two cases. In addition, the influence of the BEC interaction on these behaviors can be studied by varying the strength of the interaction with an additional magnetic field. For the next step, by changing the shape of the TAPB as a nonintegrable form such as a quadrupole, stadium, etc., the chaotic behaviors of the BEC inside the TAPB also can be investigated.

C.3.5 Quantum information theory

In the final year, we will further carry on our research on the hybrid scheme including BEC systems. In particular, we will investigate the generation of quantum entanglement using BECs as an intermediate tool and its possible applications. We expect to offer prospects of practical quantum information processing using hybrid systems.

Part D. Representative Papers of the Research Team

No.	Name	Publication year	Title	Role(check)		Acknowledgement (Check)	Journal Name
				First Author	Corresponding Author		
1	Yong-il Shin	2012	Observation of Topologically Stable 2D Skyrmions in an Antiferromagnetic Spinor Bose-Einstein Condensate		O	O	Physical Review Letters
2	Hyun seok Jeong	2011	Quantification of Macroscopic Quantum Superpositions within Phase Space		O	O	Physical Review Letters
3	Kyung won An	2011	Tunneling-induced spectral broadening of a single atom in a three-dimensional optical lattice		O	O	Nano Letters

Note: Fill in required information for 2 ~ 3 representative papers and attach full papers

Part E. Budget

E.1. Third Year Budget

Cumulative (UNIT: USD)
($1 = 1200 Won)

Category	Item	3rd Year (Planned)	3rd Year (Executed)	4th Year (Planned)	4th Year (Executed)
Personnel Expense	Foreign Scholar Salary	67,000	35,868	12,376	11,863
	Foreign Scholar Support HR	18,333	14,667	16,000	16,000
	Research Assistant HR	70,800	82,523	79,167	89,167
	Sub Total(A)	156,133	133,057	107,543	117,029
Direct Expense	Research Equipment / Material	90,833	64,608	113,333	79,899
	Research Activity	38,617	44,318	31,624	35,322
	Research Incentive	9,416	9,417	15,833	15,833
	Lab Construction	136,667	136,453	125,000	132,486
	Sub Total(B)	275,533	254,797	285,791	263,540
Sub Total(A+B)		431,666	387,853	348,333	380,569
Indirect Expense(C)		84,167	84,167	74,167	74,167
Total(A+B+C)		515,833	472,020	467,500	454,736