AFRL-AFOSR-VA-TR-2020-0167

Cavity-Mediated Interactions in a Quantum Mechanical Array

Dan Stamper-Kurn
REGENTS OF THE UNIVERSITY OF CALIFORNIA

05/22/2020
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 04-09-2020	**2. REPORT TYPE** Final Performance	**3. DATES COVERED** *(From - To)* 01 Aug 2014 to 31 Jul 2019

4. TITLE AND SUBTITLE Cavity-Mediated Interactions in a Quantum Mechanical Array	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER FA9550-14-1-0257
	5c. PROGRAM ELEMENT NUMBER 61102F
6. AUTHOR(S) Dan Stamper-Kurn	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) REGENTS OF THE UNIVERSITY OF CALIFORNIA 2150 SHATTUCK AVE RM 313 BERKELEY, CA 94704-5940 US	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AF Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/AFOSR RTB1
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-VA-TR-2020-0167

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The grant FA9550-14-1-0257 supported experimental and theoretical investigations on quantum measurement, quantum optics, quantum dynamics of multimode systems, and quantum information science. The main focus of this work was on quantum systems of varying complexity that are made to interact strongly with optical fields by being placed in high-finesse optical resonators. Investigations spanned four main directions: cavity optomechanics, cavity spin-optodyanmics, quantum mechanical arrays evolving under light-induced interactions, and the development of a new experimental platform for the study of open many-body quantum systems.

15. SUBJECT TERMS
cavity optomechanics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			METCALFE, GRACE
Unclassified	Unclassified	Unclassified	UU		**19b. TELEPHONE NUMBER** *(Include area code)* 703-696-9740

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final report

Contract/Grant Title: Cavity-Mediated Interactions in a Quantum Mechanical Array

Contract/Grant #: FA9550-14-1-0257

Reporting Period: 2014 – 2019

Abstract

The grant FA9550-14-1-0257 supported experimental and theoretical investigations on quantum measurement, quantum optics, quantum dynamics of multimode systems, and quantum information science. The main focus of this work was on quantum systems of varying complexity that are made to interact strongly with optical fields by being placed in high-finesse optical resonators. Investigations spanned four main directions: cavity optomechanics, cavity spin-optodyanmics, quantum mechanical arrays evolving under light-induced interactions, and the development of a new experimental platform for the study of open many-body quantum systems.

Report

Grant FA9550-14-1-0257, spanning a five-year granting period from July 2014 to June 2019, supported experimental and theoretical research on the quantum mechanical nature of metrology, optics, dynamics and information. Specifically, this work was conducted using experimental platforms in which a gas of ultracold rubidium atoms is trapped within the mode-volume of a high-finesse optical resonator. The use and further development of two different experimental setups was supported by this grant: a fully operational setup, established largely through previous AFOSR support, in which a microfabricated “atom chip” is used to trap and transfer atoms into the mode-volume of a 250-micron-long Fabry Perot optical resonator (“E3” in our group parlance); and a second experiment that we began developing during the present granting period (“E6”), features of which are described below.

The research work over the past five years has evolved into four different main directions.

1) Cavity optomechanics

First, our group entered the present granting period having established a new path for studying **cavity optomechanics** with ultracold atoms. In the period 2014-2019, we had two significant contributions in this research area. The first was the achievement of force-detection at levels approaching the standard quantum limit [1]. This was work already well developed in the previous AFOSR grant period. The 2014-2019 grant supported the publication of our work. The publication of this work was accompanied by a fair bit of science-media coverage.

A second finding in the area of cavity optomechanics, a theoretical result relevant to quantum optics more generally, of a new type of quantum squeezing, which we dubbed “complex squeezing.” Squeezed states of light have been explored theoretically and experimentally for decades. Yet, remarkably, our understanding of squeezing has been constrained implicitly by the assumption that optical squeezing should always be detected using a homodyne receiver. This assumption makes sense when one talks about squeezing a single mode of light (or of any bosonic field). However, in treating optical squeezing in a continuous quantum field, such as in a propagating beam of light, a richer definition of squeezing is required to accommodate the inherent multi-mode nature of the field.

We found that the reliance on homodyne detection of light leads one to neglect other forms of squeezing that occur naturally in systems that produce inhomogeneous squeezing spectra. The new form of squeezing introduced in this work arises from unequal-time correlations between amplitude and phase fluctuations of the optical field. The correlation between the Fourier components of the amplitude and phase fluctuations at a given signal frequency are then complex valued, leading us to name these correlations as “complex squeezing.”

Using the example of the ponderomotive squeezing of light, we showed that such complex squeezing is generated by cavity optomechanical systems. Moreover, we described a detection scheme, called synodyne detection, in which the complex squeezing is detected by mixing the squeezed light field with a two-tone local oscillator matched to the correlations in the complex squeezed beam. Beyond pointing out a new resource in quantum optics, we showed further that such complex squeezing allows one to perform phase-sensitive force detection beyond the standard quantum limit. The performance of such a force sensor is similar to that achieved in back-action evasion schemes. However, in our scheme, which might be dubbed “back-action accounting,” the beyond-SQL performance is attained without driving the system parametrically (avoiding the subsequent dynamical instability) and is also achieved in the unresolved sideband regime [2].

2) Cavity spin optodynamics and cavity opto-magnonics

Second, our group pioneered a new line of research called **cavity spin-optodynamics**, or perhaps **cavity opto-magnonics**, which examines the quantum-level interactions between light and the collective spin of an atomic ensemble. This research direction was foreseen in our previous work [3], where we noted the analogy between cavity spin-optodynamics and cavity optomechanics, allowing us to make predictions about a host of novel quantum mechanical phenomena that could be observed in the new setting. In the present granting period, we realized several of these predictions experimentally.

In our first major work in this area, we studied the dynamics of the collective spin of an atomic ensemble that is trapped within a driven optical resonator, while it is also subject to a magnetic field oriented transverse to the cavity axis. While undergoing Larmor precession under this applied field, the ensemble is also subject to torques generated by light with the optical cavity. These torques have two effects. First, the incoherent back-action of the measurement of the atomic spin causes the spin to be perturbed, just as required by the Heisenberg uncertainty relation. This disturbance sets a limit on how precisely the spin state can be determined through measurement, and also sets a limit on how precisely that measurement information can be used to control the subsequent spin dynamics. Second, because the light that measures the atomic spin remains for a time within the optical cavity, it acts back upon the spin in a coherent manner. That is, the atomic spin state affects the optical field, and, in turn, the optical field affects the atomic spin state, but with a temporal delay. This “loop delay” conditions a feedback mechanism, mediated by cavity light, which directs the atomic spin toward a fixed point in its phase space, and which also suppresses the accumulating disturbance from measurement back action.

We demonstrated that this autonomous feedback mechanism will drive the atomic spin deterministically toward either its high-energy or low-energy fixed point, depending on whether the cavity is driven with light whose frequency is above or below the cavity's resonance frequency. The autonomous feedback also affects the spin dynamics by shifting the Larmor resonance frequency, a phenomenon analogous to the optical spring effect of cavity optomechanics. The gain of the feedback mechanism was measured and compared to theory we had developed to describe our system.

Our experiment also demonstrated quantum aspects of this feedback system. By driving the cavity with a separate, weak probe beam at the cavity's resonance, we could detect Stokes and anti-Stokes sidebands induced by the evolving atomic spin onto the light field. The asymmetry in the intensity of these sidebands reported the effective spin temperature reached under steady-state feedback. We observed the spin temperature to be achieved as the balance between feedback-induced damping and quantum back-action heating. We demonstrated that autonomous feedback brought the spin ensemble to an effective temperature determined by the cavity half-linewidth (once converted to temperature units), and that, at this temperature, the spin ensemble was stabilized with high-fidelity into a pure quantum state when driven in the resolved sideband regime, where the Larmor frequency greatly exceeds the cavity linewidth. Our report on this work [4], published in Physical Review Letters, along with our previous theoretical work [3], now form the basis for a new research area, termed *cavity optomagnonics* or *spin cavitronics*, that is spreading into laboratories worldwide.

A second research effort, which is still underway in our laboratory, expands upon this first work and asks whether cavity-induced dynamics could be used for autonomous feedback stabilization of a collective spin, and, in particular, whether that stabilization can drive the spin system to a non-equilibrium steady state. The informal answer is "yes," as described below, while we work to clean up a few remaining questions before making a more formal contribution through a publication. Details will be provided in future reports.

3) Light-induced interactions in a quantum mechanical array

The third area of investigation, which was stated in fact as the major research target for our grant, is the study of **many-body quantum systems coupled through light-induced interactions**. Here, we built on the fact that atoms trapped within an optical resonator can be made to represent several distinct quantum mechanical degrees of freedom simultaneously. For example, for one set of experiments, we divided our atomic gas so that it was trapped in several spatially separated traps. The motion of atoms in each of these traps represented a distinct mechanical degree of freedom. In prior work, we showed how the motion of each of these mechanical elements could be detected by studying the light emitted by a driven cavity to which they were each optomechanically coupled [5]. In the present work, we studied how two such mechanical objects become coupled to one another by the common interaction they have with the cavity field. In other words, we showed how the exchange of cavity photons between one object and another leads to real forces and real interactions between the objects. A highlight of our work was the observation and characterization of quantum noise in that light-induced coupling [6].

This experimental work inspired two important theoretical contributions. In one, we outlined a thorough theoretical treatment of light-induced coupling between two mechanical oscillators. We aimed to show under what conditions that coupling would lead either to phonon exchange between the two oscillators or to photon-pair generation and two-mode mechanical squeezing, and, also, to what extent that coupling would allow for the generation of quantum entanglement [7]. A second work explored the broader question of whether light-induced coupling should be considered as a quantum mechanical or a classical type of interaction. The distinction between the two was highlighted in recent papers exploring the gravitational force [8, 9]. We showed that cavity optomechanics allowed for this question to be probed in a controlled way, by operating the cavity-optomechanical system so that the cavity photons that mediate interactions serve, to varying degrees, as either force carriers or information carriers [10].

Photon mediated interactions are not limited only to mechanical degrees of freedom. As discussed above, our experimental system permits us to work not only with the mechanical motion but also with the internal spin dynamics of atoms trapped within the cavity. This feature allowed us to investigate how cavity-photon-mediated interactions could also be used to couple dissimilar quantum mechanical objects. Specifically, we investigated how the coupling of both spin and mechanical degrees of freedom to the same optical cavity could lead to interactions between these degrees of freedom. In the parlance of condensed-matter physics, such interaction is a form of spin-orbit coupling. Thus, our experiments can be described as exploring the effects of light-induced spin-orbit coupling in an atomic gas.

The novel phenomenon accessible through such coupling is the coupling between a positive-mass and a negative-mass oscillator. The positive-mass oscillator is the one familiar to us, e.g. a mechanical harmonic oscillator. A negative-mass oscillator is one for which the signs of both the kinetic and potential energy terms in the harmonic-oscillator Hamiltonian are negative. As we demonstrated, the coupling of a positive-mass to a negative-mass oscillator leads to a dynamical instability, and to the generation of strongly correlated fluctuations between these two oscillators through resonant pair production, where, here, a phonon and a magnon are produced simultaneously. In our work, the optical cavity was used not only to mediate interactions, but also to measure the state of the two-mode spin-orbit system undergoing dynamics. We observed the predicted correlated excitations of the mechanical and spin degrees of freedom of a trapped atomic gas [11].

The task of measuring the correlated motion of two objects within the same cavity – both in the case of mechanical-mechanical [2] and of spin-mechanical [11] cavity-mediated interactions – led us to the interesting and more general question of quantum state retrodiction. Many experiments on quantum systems involve state estimation from continuous measurements. For example, in our experiment on quantum-limited force detection, we performed continuous measurements of the motion of a mechanical object placed inside an optical cavity, and then interpreted that continuous measurement signal to detect forces that may have been applied to the object [1]. This measurement task is one of real-time estimation or filtering, in which the measurement signal gathered in the past is used to make a continuous real-time estimate of the state of the system at present. A different task can be considered, where our goal is to determine the quantum state of the system at an initial time by gathering continuous measurement data from the system at all later times. For this task, we must find a way to process late time to data to propagate our estimate backwards in time and to retrodict (rather than predict) the state.

In recent theoretical work, we showed how such quantum state retrodiction should be performed in measuring the state of a single- or multimode quantum system. We derived a rigorous statistical analysis that defines the filters that should be applied to data to achieve such retrodiction. Main findings are that standard quantum limits to measurement are attained at high measurement cooperativity, and also that such limits can be achieved in measuring simultaneously the state of several quantum oscillators so long as their resonances are well resolved [12].

4) A new platform for the study of open many-body quantum systems

The fourth effort supported by the grant in question is the development of a new experimental platform. The design of the new apparatus targets several future scientific goals.

The first is to characterize quantum optical correlations produced by quantum matter inside a driven optical cavity. Our current experimental system already allowed us to start in this direction, with experiments that were the first to observe the ponderomotive squeezing of light [13]. However, our ability to detect such quantum correlations was badly limited by losses in our optical system, particularly within the mirror coatings of the optical cavity. Thus, we sought to build a new apparatus with an optical cavity that would be much more efficient at directing cavity photons out of a single cavity mirror and onto a photodetector.

A second goal is to explore the topic of quantum feedback on many-body quantum systems. Again, we area already gaining a foothold in this area with the current studies on autonomous feedback stabilization of a collective atomic spin. But additional possibilities will open up with a cavity system that is, as discussed above, more efficient optically. This higher efficiency allows our photodetection to capture a greater fraction of the information that is being emitted by the many-body quantum system within the optical cavity. This information can then be used in an active measurement-based scheme for feeding back to the dynamics of that quantum system. With this greater capability to apply feedback, we can ask the following very broad question: How does a many-body quantum system behave under continuous feedback? Does it undergo novel dynamical/transport processes? Does it undergo phase transitions?

A third goal is to gain further control over the cold atoms trapped within the optical cavity by bringing them to the regime of quantum degeneracy. There are two targets to consider here. First, we may look to new dynamics that arise when light-induced interactions are added onto a quantum degenerate superfluid gas. Initial forays in this direction are already being reported by the Esslinger and Lev groups. With our group's expertise in quantum fluids, and in particular spinor Bose gases, we believe there are many new directions to explore. In particular, we believe that many of those other works ignore the essential role of quantum optical and measurement-backaction fluctuations on the intracavity system. Second, starting from the superfluid state, we can imagine driving the atomic gas through the Mott insulator transition within an optical lattice. This transition would generate a perfect atomic array with exactly one atom per site. We are interested in studying how a high-finesse optical resonator can be used to generate interactions within this quantum array, and also to perform highly sensitive, selective, and potentially non-destructive measurements on this array. The path from these topics to the question of using atomic arrays within optical cavities as a quantum computer is not long.

Thus, for this third goal, we have sought to make our system capable of producing quantum degenerate atomic gases (still of rubidium atoms), and to allow for the application of light beams to produce an optical lattice within the cavity.

Our fourth goal is to allow individual elements within the array to be driven selectively by light. In our present work, we typically drive the optical cavity through its input mirrors, and thereby excite all objects trapped within the cavity with the same driving field. Alternately, as in the new apparatus, we can consider driving the cavity system not through the cavity mirrors but though the atoms within the cavity. That is, we consider directing light into the cavity, transverse to the cavity mode, directly onto atoms trapped within the cavity. This direct excitation "activates" specific atoms (or ensembles of atoms) while leaving the remaining atoms "inactive." This capability should permit us to operate the atoms-cavity system as a fully programmable quantum simulator, one where interactions are induced at will between any subset of atoms in a trapped array, and where measurements of similar selectivity can also be applied.

The present state of our new apparatus is quite advanced. More details on the apparatus will be presented in reports and publications for our future work. But here, let us just summarize a few specific advanced: We have constructed a new experimental platform in which quantum degenerate rubidium gases are produced by a combination of a two-dimensional magneto-optical trap, a three-dimensional magneto-optical trap, magnetic trapping and evaporative cooling, and optical trapping and evaporative cooling. The apparatus allows us to produce such quantum degenerate gases rapidly, with cycle times of 10 seconds or less. We have developed a system that transports these ultracold rubidium atoms from one portion of the chamber to another. We have built a high-finesse near-concentric optical cavity and installed it in vacuum where it can be loaded with ultracold atomic gases through optical transport. We have constructed a high numerical-aperture imaging system to allow atoms to be excited by light transverse to the cavity axis. Additionally, we have developed the laser systems needed to trap atoms within the cavity and to probe the cavity with light near the atomic resonance frequencies.

1. Schreppler, S., et al., *Optically measuring force near the standard quantum limit.* Science, 2014. **344**(6191): p. 1486-1489.
2. Buchmann, L.F., et al., *Complex Squeezing and Force Measurement Beyond the Standard Quantum Limit.* Physical Review Letters, 2016. **117**(3): p. 030801.
3. Brahms, N. and D.M. Stamper-Kurn, *Spin optodynamics analog of cavity optomechanics.* Physical Review A (Atomic, Molecular, and Optical Physics), 2010. **82**: p. 041804(R).
4. Kohler, J., et al., *Cavity-Assisted Measurement and Coherent Control of Collective Atomic Spin Oscillators.* Physical Review Letters, 2017. **118**(6): p. 063604.
5. Botter, T., et al., *Optical Readout of the Quantum Collective Motion of an Array of Atomic Ensembles.* Physical Review Letters, 2013. **110**(15): p. 153001.
6. Spethmann, N., et al., *Cavity-mediated coupling of mechanical oscillators limited by quantum back-action.* Nat Phys, 2016. **12**(1): p. 27-31.
7. Buchmann, L.F. and D.M. Stamper-Kurn, *Nondegenerate multimode optomechanics.* Physical Review A, 2015. **92**(1): p. 013851.
8. Kafri, D. and J.M. Taylor, *A noise inequality for classical forces*. 2013.

9. Kafri, D., J.M. Taylor, and G.J. Milburn, *A classical channel model for gravitational decoherence.* New Journal of Physics, 2014. **16**(6): p. 065020.
10. Buchmann, L.F. and D.M. Stamper-Kurn, *The quantum/classical transition in mediated interactions.* Annalen Der Physik, 2014: p. n/a-n/a.
11. Kohler, J., et al., *Negative-Mass Instability of the Spin and Motion of an Atomic Gas Driven by Optical Cavity Backaction.* Physical Review Letters, 2018. **120**(1): p. 013601.
12. Kohler, J., et al., *Simultaneous retrodiction of multi-mode optomechanical systems using matched filters*. 2019.
13. Brooks, D.W.C., et al., *Non-classical light generated by quantum-noise-driven cavity optomechanics.* Nature, 2012. **488**(7412): p. 476.