REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
23-10-2012	Final Report	1-Jul-2008 - 30-Jun-2011

4. TITLE AND SUBTITLE
Matter-wave optics of diatomic molecules

5a. CONTRACT NUMBER
W911NF-08-1-0307

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Pierre Meystre

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Arizona
College of Optical Sciences
Arizona Board of Regents, University of Arizona
Tucson, AZ 85722 -3308

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
54356-PH.36

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The goal of this research was to carry out a theoretical study of the generation and control of quantum-degenerate molecular systems, including but not limited to dipolar molecules. Major directions includde (a) the controlled association of diatomic as well as more complex ultracold heteronuclear molecules, such as molecular trimers, into deeply bound states; (b) the study of the coherent dynamics and quantum
control of elementary chemical reactions such as for instance the displacement reaction A + B2 -> AB + B; the

15. SUBJECT TERMS
matter-wave optics, ultracold molecules, polar molecules, quantum optomechanics, quantum-degenerate atomic ssystems, quantum optics, coherent control

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER
UU	UU	UU	UU		Pierre Meystre / 520-621-4651

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

Report Title

Matter-wave optics of diatomic molecules

ABSTRACT

The goal of this research was to carry out a theoretical study of the generation and control of quantum-degenerate molecular systems, including but not limited to dipolar molecules. Major directions includde (a) the controlled association of diatomic as well as more complex ultracold heteronuclear molecules, such as molecular trimers, into deeply bound states; (b) the study of the coherent dynamics and quantum control of elementary chemical reactions such as for instance the displacement reaction A + B2 -> AB + B; the study of the ground state and dynamics of quantum degenerate dipolar gases, in particular dipolar condensates; and (d) the detection, manipulation and quantum control of condensates using quantum detectors such as ultracold micro- and nano-scale cantilevers, and conversely the manipulation and control of nano-scale cantilevers by ultracold atomic and molecular systems.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
10/11/2012	1.00	H. Uys, P. Meystre. Cooperative scattering of light and atoms in ultracold atomic gases, Laser Physics Letters, (07 2008): 0. doi: 10.1002/lapl.200810020
10/11/2012	2.00	P. Meystre, M. Bhattacharya. Multiple membrane cavity optomechanics, Physical Review A, (10 2008): 0. doi: 10.1103/PhysRevA.78.041801
10/11/2012	3.00	S. Singh, M. Bhattacharya, O. Dutta, P. Meystre. Coupling Nanomechanical Cantilevers to Dipolar Molecules, Physical Review Letters, (12 2008): 0. doi: 10.1103/PhysRevLett.101.263603
10/11/2012	4.00	O. Dutta, R. Kanamoto, P. Meystre. Stability of the density-wave state of a dipolar condensate in a pancake-shaped trap, Physical Review A, (10 2008): 0. doi: 10.1103/PhysRevA.78.043608
10/11/2012	5.00	Hui Jing, Yajing Jiang, Weiping Zhang, Pierre Meystre. Creation of three-species, New Journal of Physics, (12 2008): 0. doi: 10.1088/1367-2630/10/12/123005
10/11/2012	6.00	P. Meystre, W. Chen. Cavity QED characterization of many-body atomic states in double-well potentials: Role of dissipation, Physical Review A, (04 2009): 0. doi: 10.1103/PhysRevA.79.043801
10/11/2012	7.00	H. Jing, J. Cheng, P. Meystre. Coherent bimolecular reactions with quantum-degenerate matter waves, Physical Review A, (02 2009): 0. doi: 10.1103/PhysRevA.79.023622
10/11/2012	10.00	M. Bhattacharya, S. Singh, P. -L. Giscard, P. Meystre. Optomechanical control of atoms and molecules, Laser Physics, (07 2009): 0. doi: 10.1134/S1054660X09170034
10/11/2012	34.00	W. Chen, K. Zhang, D. Goldbaum, M. Bhattacharya, P. Meystre. Bistable Mott-insulator–to–superfluid phase transition in cavity optomechanics, Physical Review A, (07 2009): 11801. doi: 10.1103/PhysRevA.80.011801
10/11/2012	31.00	H. Jing, Y. Jiang, Weiping Zhang, P. Meystre. Laser-catalyzed spin-exchange process in a Bose-Einstein condensate, Physical Review A, (03 2010): 31603. doi: 10.1103/PhysRevA.81.031603
10/11/2012	30.00	K. Zhang, W. Chen, M. Bhattacharya, P. Meystre. Hamiltonian chaos in a coupled BEC–optomechanical-cavity system, Physical Review A, (01 2010): 13802. doi: 10.1103/PhysRevA.81.013802
10/11/2012	32.00	Swati Singh, Pierre Meystre. Atomic probe Wigner tomography of a nanomechanical system, Physical Review A, (04 2010): 41804. doi: 10.1103/PhysRevA.81.041804
10/11/2012	33.00	K. Zhang, W. Chen, P. Meystre. Dynamics of a bistable Mott insulator to superfluid phase transition in cavity optomechanics, Optics Communications, (03 2010): 665. doi: 10.1016/j.optcom.2009.10.047
10/11/2012	29.00	R. Kanamoto, P. Meystre. Optomechanics of a Quantum-Degenerate Fermi Gas, Physical Review Letters, (02 2010): 63601. doi: 10.1103/PhysRevLett.104.063601
10/11/2012	28.00	W. Chen, D. S. Goldbaum, M. Bhattacharya, P. Meystre. Classical dynamics of the optomechanical modes of a Bose-Einstein condensate in a ring cavity, Physical Review A, (05 2010): 53833. doi: 10.1103/PhysRevA.81.053833
10/11/2012	27.00	Rina Kanamoto, Pierre Meystre. Optomechanics of ultracold atomic gases, Physica Scripta, (09 2010): 38111. doi: 10.1088/0031-8949/82/03/038111

10/11/2012 26.00 G. Phelps, S. Singh, D. Goldbaum, E. Wright, P. Meystre. All-Optical Optomechanics: An Optical Spring Mirror,
Physical Review Letters, (11 2010): 213602. doi: 10.1103/PhysRevLett.105.213602

10/11/2012 25.00 Gregory Phelps, Pierre Meystre. Laser phase noise effects on the dynamics of optomechanical resonators,
Physical Review A, (06 2011): 63838. doi: 10.1103/PhysRevA.83.063838

10/11/2012 21.00 H. Jing, Y. Deng, P. Meystre. Slow-light probe of Fermi pairing through an atom-molecule dark state,
Physical Review A, (06 2011): 63605. doi: 10.1103/PhysRevA.83.063605

10/11/2012 22.00 L. Buchmann, P. Meystre, H. Jing, D. Goldbaum. Quantum Optomechanics of a Bose-Einstein Antiferromagnet,
Physical Review Letters, (06 2011): 223601. doi: 10.1103/PhysRevLett.106.223601

10/11/2012 23.00 P. Meystre, M. Tasgin. Spin squeezing with coherent light via entanglement swapping,
Physical Review A, (05 2011): 0. doi: 10.1103/PhysRevA.83.053848

10/11/2012 24.00 H. Jing, Y. Deng, P. Meystre. Spinor atom-molecule conversion via laser-induced three-body recombination,
Physical Review A, (04 2011): 43601. doi: 10.1103/PhysRevA.83.043601

10/11/2012 35.00 H. Jing, Y. Jiang, P. Meystre. Magneto-optical control of atomic spin mixing in dipolar spinor Bose-Einstein condensates,
Physical Review A, (12 2009): 63618. doi: 10.1103/PhysRevA.80.063618

TOTAL: **23**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

P. Meystre, Quantum optics of atoms and molecules, Invited talk, 2008 Latsis Symposium "Bose-Einstein condensation in dilute atomic gases and in condensed matter," Lausanne, Switzerland (2008).

P. Meystre, "Vers le zero absolu, ou, quand les atoms deviennent des ondes," public lecture, 2008 Latsis Symposium "Bose-Einstein condensation in dilute atomic gases and in condensed matter," Lausanne, Switzerland (2008).

P. Meystre, "Quantum metrology with cold atoms and cold mirrors," International Conference on Coherence, Squeezing and Entanglement for Precision Measurements with Quantum Gases," Levico Terme (Trento) Italy (2008).

P. Meystre, "Quantum Optics," Invited Lecture, Graduate Students Symposium on Atomic and Molecular Physics, DAMOP Annual Meeting, State College, PA (2008).

"P. Meystre, "Herbert Walther, Scientist Extraordinaire," invited talk, 21st International Conference on Atomic Physics, Storrs, CT (2008).

M. Bhattacharya, O. Dutta, S. Singh and P. Meystre, "Quantum control of ultracold AMO systems by nanomechanical resonators," invited talk, Frontiers in Optics 2008/Laser Science XXIV, Rochester, NY (2008).

P. Meystre, "Cavity optomechanical probing and control of atoms and molecules," invited talk, Swiss National Center for Competence in Research "Quantum Photonics" General Assembly, Muenchenwiler, Switzerland, 2009.

P. Meystre, "Optomechanical control of ultracold atoms and molecules," invited talk, 18th International Laser Physics Workshop LPHYS'09, Barcelona, Spain (2009).

R. Kanamoto and P. Meystre, "Fermionic optomechanics," invited talk, 18th International Laser Physics Workshop LPHYS'09, Barcelona, Spain (2009).

P. Meystre, "Optomechanical control of ultracold atoms and molecules," invited talk, WE Heraeus Seminar on Quantum Optics of nano- and micromechanical systems," Bad Honnef, Germany (2009).

P. Meystre, "Cavity optomechanics," keynote lecture, Photonica 09, II International School and Conference on Photonics, Belgrade, Serbia (2009).

P. Meystre, "Control and sensing of ultracold atoms and molecules by nanomechanical cantilevers," invited talk, Laser Science XXV, APS Division of Laser Science 25th Annual Meeting, San Jose, CA (2009).

R. Kanamoto and P. Meystre, "Fermionic optomechanics," Workshop on Quantum Nonstationary Systems, Brasilia, Brazil (2009).

S. Singh, M. Bhattacharya, O. Dutta and P. Meystre, "Coupling nanomechanical cantilevers to dipolar molecules," APS DAMOP Annual Meeting, Charlottesville, VA (2009).

W. Chen, K. Zhang, M. Bhattacharya, D. S. Goldbaum and P. Meystre, "Bistable Mott insulator to superfluid phase transition in cavity optomechanics," APS DAMOP Annual Meeting, Charlottesville, VA (2009).

P. Meystre, "Bose-Einstein Condensation and Atom Optics," invited lectures series, 21st Chris Engelbrecht Summer School "Quantum Optics," Stellenbosch, South Africa (2010).

P. Meystre, "Cavity Optomechanics with Ultracold Atoms," invited talk, Gordon Research Conference on Mechanical Systems in the Quantum regime," Galveston, TX (2010).

P. Meystre, "Cavity optomechanics," invited talk, "Frontiers in Nonlinear Waves," a conference in honor of Vladimir Zakharov's 70th birthday. Tucson, AZ (2010).

P. Meystre, "Cavity optomechanics," plenary talk, RIAO-OPTILAS 2010, Lima, Peru (2010).

S. Singh and P. Meystre, "Atomic probe Wigner tomography of a nanomechanical system," contributed paper, APS DAMOP Annual Meeting, Houston, TX (2010).

□W. Chen, D. Goldbaum, M. Bhattacharya an P. Meystre, "Classical dynamics of the optomechanical modes of a Bose-Einstein condensate in a ring cavity," contributed paper, APS DAMOP Annual Meeting, Houston, TX (2010).

□D. S. Goldbaum, K. Zhang and P. Meystre, "Two-fluid model of a Bose-Einstein condensate in the cavity optomechanical regime," contributed paper, APS DAMOP Annual Meeting, Houston, TX (2010).
□
G. A. Phelps, D. S. Goldbaum and P. Meystre, "E□ffects of laser linewidth on the back-action cooling of optomechanical resonators," contributed paper, APS DAMOP Annual Meeting, Houston, TX (2010).

S. M. Pompea, L. W. Fine and P. Meystre, "Photonics education for a green future: connecting the dots of the Arizona STEM education experiment, " SPIE Eco-Photonics 2011: Sustainable Design, Manufacturing, and Engineering Workforce Education for a Green Future, Strasbourg, France, 2011.

□P. Meystre, "Cavity optomechanics," Invited Tutorial, CLEO:2011, Baltimore (2011).

□P. Meystre, "Cavity optomechanics - beyond the ground state," Invited paper, DAMOP Annual Meeting, Atlanta, GA (2011).

□P. Meystre, "Recent progress in cavity optomechanics," invited paper, International conference NLWO11: Nonlinear Waves in Optics, Rouen, France (2011).

□P. Meystre, "Cavity optomechanics - beyond the ground state," Invited paper, Quantum Optics of Micro- and Nanomechanical Systems, Monte Verita, Ascona, Switzerland (2011).

□P. Meystre, "Cold atoms and quantum degenerate gases," invited talk, NSF Workshop on Theoretical Atomic, Molecular and Optical Physics: Recent Developments and a Vision for the Future, Washington, DC (2011).

R. Kanamoto and P. Meystre, "Optomechanics of a quantum degenerate Fermi gas, " contributed paper, ERATO Macroscopic Quantum Copntrol Conference on Ultracold Atoms and Molecules, Tokyo 2011.

□S. Steinke, S. Singh, M. Tasgin, P. Meystre, K. Schwab, and M. Vengalattore, "Sensitive position magnetometry and quantum state control in a hybrid BEC-membrane system," contributed paper, DAMOP Annual Meeting, Atlanta, GA (2011).

□D. Goldbaum and P. Meystre, "Optical generation of vibrational entanglement in a membrane," contributed paper, DAMOP Annual Meeting, Atlanta, GA (2011).

□G. Phelps and P. Meystre, "Laser phase noise e□ects on the dynamics of optomechanical resonators," contributed paper, DAMOP Annual Meeting, Atlanta, GA (2011).

Number of Presentations: 33.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Visiting Professor, Institut d'Optique Th¶eorique et Appliqu¶ee, Universit¶e de Paris-Sud, Paris (June 2008).

Awarded the Humboldt Foundation Senior US Scientist Prize (2009)

Elected General Councilor of the American Physical Society (2010)

Selected as American Physical Society Outstanding Referee (2010)

Selected as Optical Society of America Traveling Lecturer (2010)

Appointed representative for Section B (Physics), American Association for the Advancement Science (AAAS) Council, (2011)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Pierre-Louis Giscard	0.47	
Wenzhou Chen	0.28	
HyoJun Seok	0.78	
FTE Equivalent:	**1.53**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Mishkat Bhattacharya	0.43
Daniel Goldbaum	0.39
Hui Jing	0.25
FTE Equivalent:	**1.07**
Total Number:	**3**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Pierre Meystre	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Greg Phelps	0.78	Physic (BS)
FTE Equivalent:	**0.78**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	1.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	1.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	1.00

Names of Personnel receiving masters degrees

NAME
Pierre-Louis Giscard

Total Number: 1

Names of personnel receiving PHDs

NAME
Wenzhou Chen (0.3)
Omjyoti Dutta (0)

Total Number: 2

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Scientific accomplishments

PROPOSAL NUMBER: 54356
PROPOSAL TITLE: Matter-Wave Optics of Diatomic Molecules
CONTRACT NUMBER: W911NF0810307

This proposal was a continuation of proposal 48298, contract number W911NF0510222, and it concentrated likewise on two major topics: coherent superchemistry and cavity optomechanics. The major new aspect has been to merge more closely these two components, in a direction that is now more generally described as “hybrid optomechanics.” Broadly speaking, the rapid progress witnessed by quantum optomechanics makes it increasingly realistic to consider the use of mechanical systems operating in the quantum regime to make precise and accurate measurements of feeble forces and fields. In that context the remarkable potential for functionalization of opto-- and electromechanical devices is particularly attractive. Their motional degree(s) of freedom can be coupled to a broad range of other physical systems, including photons via radiation pressure from a reflecting surface, spin(s) via coupling to a magnetic material, electric charges via the interaction with a conducting surface, etc. In that way, the mechanical element can serve as a universal transducer or intermediary that enables the coupling between otherwise incompatible systems. This potential for functionalization also suggests that quantum optomechanical systems have the potential to play an important role in classical and quantum information processing, where transduction between different information carrying physical systems is crucial.

The following summarizes some of our main results. They are grouped into 3 categories: superchemistry in quantum degenerate atomic systems; general aspects of quantum optomechanics; and hybrid optomechanical systems. This highlights the evolution of our research program from the study of relatively simple ultracold atomic and molecular systems to manybody physics aspects and to exploiting the promise of functionalized hybrid systems involving ultracold atomic and molecular systems optomechanically coupled to macroscopic mechanical elements.

1. Superchemistry in quantum degenerate atomic and molecular systems

Our work on superchemistry was done largely in collaboration with Dr. Hui Jing, a visiting professor from China. We have worked out a number of examples that illustrate the importance of quantum coherent effects in controlling chemical reactions between ultracold atoms and molecules. For example, in one project we demonstrated theoretically that the abstraction reaction can be driven coherently and efficiently with quantum-degenerate bosonic or fermionic matter waves. We showed that the initial stages of the reaction are dominated by quantum fluctuations, resulting in the appearance of macroscopic nonclassical correlations in the final atomic and molecular fields. We also studied the creation of heteronuclear triatomic molecules, and showed that a constructive triple-path quantum interference effect can lead to an almost ideal conversion rate, in comparison with the single- or double-path cases. The important effect of the initial population imbalance on the atom–molecule dark state is also investigated.

A third example considered the two-color photoassociation of a quantum degenerate atomic gas into ground-state diatomic molecules via a molecular dark state. This process can be described in terms of a level scheme that is formally analogous to the situation in electromagnetically induced transparency in atomic systems and therefore can result in slow-light propagation. We showed that the group velocity of the light field depends explicitly on whether the atoms are bosons or fermions, as well as on the existence or absence of a pairing gap in the case of fermions, so that the measurement of the group velocity realizes a nondestructive diagnosis of the atomic state and the pairing gap.

We also showed theoretically that it is possible to optically control collective spin-exchange processes in spinor Bose condensates through virtual photoassociation. The interplay between optically induced spin exchange and spin-dependent collisions was shown to provide a flexible tool for the control of atomic spin dynamics, including enhanced or inhibited quantum spin oscillations, the optically induced ferromagnetic-to-antiferromagnetic transition, and coherent matter-wave spin conversion.

2. General issues in optomechanics

While considerable progress has been achieved in quantum optomechanics, both on the experimental and theoretical front, sa number of questions still remain to be addressed. On the practical side, technical noise remains a major issue, be it laser noise, clamping noise or thermal noise. With this in mind, we I have worked with an undergraduate student (Greg Phelps) to investigate theoretically the influence of laser phase noise on the cooling and heating of a generic cavity optomechanical system. We derivedthe back-action damping and heating rates and the mechanical frequency shift of the radiation-pressure-driven oscillating mirror, and derived the minimum phonon occupation number for small laser linewidths. We also explored the regime of parametric amplification where coherent oscillations of the mirror are realizable and found that heating from laser phase noise is of significance and can cause the onset of instabilities in that situation.

As just mentioned, a dominant hurdle to the operation of optomechanical systems in the quantum regime is the coupling of the vibrating element to a thermal reservoir via mechanical supports and the associated clamping noise. To address this issue we proposed a scheme that uses an optical spring to replace the mechanical support. We show within a simplified model that the resolved-sideband regime of cooling can be reached in a configuration using a high-reflectivity disk mirror held by an optical tweezer as one of the end mirrors of a Fabry-Perot cavity. However, we now believe that this approach suffers from a number of practical limitations that may best be addressed by alternative approaches that combine the use of optical trapping with mechanical tethering, as proposed e.g. by Kimble and coworkers. For this reason, we have now largely abandoned further work on an all-optical approach.

“Bottom-up” approaches to quantum optomechanics typically use ultracold atoms in high-Q optical resonators as mechanical elements. This is an approach that has been pursued principally by the experimental groups of D. Stamper-Kurn at Berkeley and T. Esslinger at ETH Zurich. In a new development along this general line we have investigated the cavity optomechanical properties of an antiferromagnetic Bose-Einstein condensate, where the role of the mechanical element is played by spin-wave excitations. That system can be described by a single rotor, and can in principle be prepared deep in the quantum regime under realizable conditions. This provides a bottom-up realization of dispersive rotational optomechanics, and opens the door to the direct observation of quantum spin fluctuations.

Another important issue in quantum optomechanics is the characterization of the quantum state of the mechanics. The problem here is that there are no phonon counters that work at the single quantum level, due in particular to issues with thermal noise at the relatively low frequencies at which they operate. To address this problem we have proposed a scheme to measure the quantum state of a nanomechanical oscillator that is an extension of the nonlinear atomic homodyning technique scheme first developed to measure the intracavity field in a micromaser. This is a hybrid optomechanical system that involves the use of a detector atom that is simultaneously coupled to the mechanics via a magnetic interaction and to (classical) optical fields via a Raman transition. We showed that the probability for the atom to be found in the ground state is a direct measure of the Wigner characteristic function of the nanomechanical oscillator. We also investigated the back-action effect of this destructive measurement on the state of the resonator.

3. Hybrid systems

This work on state characterization is clear evidence of the importance and power of functionalized hybrid systems, and leads naturally to our additional work on these systems, where we have considered both the coupling of mechanical elements to single atoms or molecules and also to quantum-degenerate atomic systems.

In a first study we investigated the coupling of a nanomechanical oscillator in the quantum regime with molecular (electric) dipoles. We found theoretically that the cantilever can produce single-mode squeezing of the center-of-mass motion of an isolated trapped molecule and two-mode squeezing of the phonons of an array of molecules. This work opens up the possibility of manipulating dipolar crystals, which have been recently proposed as quantum memories, and more generally, is indicative of the promise of nanoscale cantilevers for the quantum detection and control of atomic and molecular systems.

We then turned to quantum degenerate atomic systems, and carried out a theoretical study of a hybrid optomechanical system consisting of a Bose-Einstein condensate (BEC) trapped inside a single-mode optical cavity with a moving end mirror. In this arrangement the intracavity light field has a dual role: it excites a momentum side mode of the condensate, and acts as a nonlinear spring that couples the vibrating mirror to that collective density excitation. Of particular interest is the situation where the optical cavity is engineered so that a single input beam can result in two radically different stable ground states for the intracavity gas: superfluid and Mott insulator. Furthermore that system can be used as an adjustable template for investigating the coupling between cavity fields, nanomechanical systems operating in the quantum regime, and ultracold atomic gases. In a regime where the intracavity optical field, the mirror, and the side-mode excitation all display bistable behavior. In this regime we find that the dynamics of the system exhibits Hamiltonian chaos for appropriate initial conditions.

We then extended this work to the situation of ring resonators. In contrast to the more familiar case of a high-Q Fabry-Perot cavity we found that both symmetric and antisymmetric collective density side modes of the BEC can be mechanically excited. In the semiclassical, mean-field limit where the light field and the zero-momentum mode of the condensate are treated classically the system is found to exhibit a rich multistable behavior, including the appearance of isolated branches of solutions (isolas).

Moving on from bosons to fermions we explored theoretically the optomechanical interaction between a light field and a mechanical mode of ultracold fermionic atoms inside a Fabry-Perot. We found that the low-lying phonon mode of the fermionic ensemble is a collective density oscillation associated with particle-hole excitations, and is mathematically analogous to the momentum side-mode excitations of a bosonic condensate. The mechanical motion of the fermionic particle-hole system behaves hence likewise as a ‘‘moving mirror.’’ We derived an effective system Hamiltonian that has the form of generic optomechanical systems. We also discuss the experimental consequences the optomechanical coupling in optical bistability and in the noise spectrum of the system.

Technology Transfer