FINAL REPORT: Strategic Applications of Ultracold Atoms

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13. ABSTRACT (Maximum 200 words)

This consortium has initiated a focused collaborative program to advance matter wave sensors. We seek to combine atom interferometry with atom lasers and atom waveguides with the prospect of improving the sensitivity of such sensors by orders of magnitude as compared with existing state-of-the-art sensors. We will identify, explore and exploit fundamental scientific possibilities surrounding the production, manipulation and detection of ultra-cold atoms for a variety of sensing applications. Such sensors include gravimeters, gravity gradiometers, gyroscopes, magnetometers and frequency standards and have applications in science and technology and within the DoD.

Sensitive and accurate inertial force sensors can be used in covert/passive navigation, precision guidance, underground structure detection, gravitational mapping, *etc.* They are non-emanating and capable of operating in a jammed-GPS environment.

We seek to build awareness of DoD needs critical to national defense at the graduate training level, and to establish a dialogue between DoD and industrial researchers/managers and PhD trainees. The institutions identified in the proposed consortium attract talented students who are likely to become future leaders in science and technology.

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FINAL REPORT: Strategic Applications of Ultracold Atoms
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Statement of Problem Studied

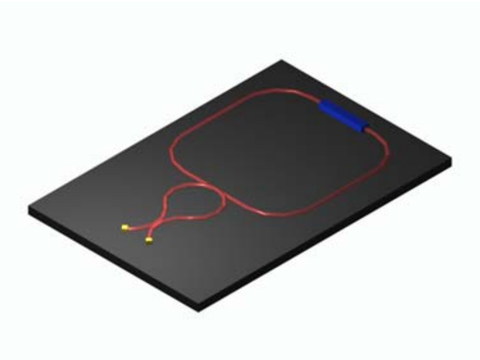

Fig. 1. Atom laser gyro (ALG). An active atom laser gain element (blue) injects coherent de Broglie waves into 10 cm x 10 cm microfabricated ring resonator (red) and a planar substrate (black). Atom detection (yellow) is at the Heisenberg limit using quantum state manipulation techniques.

This consortium proposes a focused collaborative program to advance matter wave sensors. We want to combine atom interferometry with atom lasers and atom waveguides with the prospect of improving the sensitivity of such sensors by orders of magnitude as compared with existing state-of-the-art sensors. We will identify, explore and exploit fundamental scientific possibilities surrounding the production, manipulation and detection of ultra-cold atoms for a variety of sensing applications. Such sensors include gravimeters, gravity gradiometers, gyroscopes, magnetometers and frequency standards and have applications in science and technology and within the DoD.

Sensitive and accurate inertial force sensors can be used in covert/passive navigation, precision guidance, underground structure detection, gravitational mapping, *etc.* They are non-emanating and capable of operating in a jammed-GPS environment.

The recent demonstration of atom lasers and the recent progress in atom optics/interferometry raise the tantalizing prospect of a new class of ultra-sensitive sensors drawing on advances in both areas (Figs. 1 and 2). Compact, field-ready versions of these sensors could be orders of magnitude more sensitive than current state-of-the-art sensors.

As a concrete example of how developments in the atom laser and atom optics/interferometry fields will impact sensor technology, we consider the impact of advances in atom source, atom optics and atom readout on precision rotation sensing. Fig. 1 illustrates our vision of a prototype Sagnac effect rotation sensor, an atom-laser gyroscope. We want to emphasize that *all* components described below have already been demonstrated or are under development in at least one of the collaborating groups. The device operating principles are as follows: Single mode atom waveguides are used to guide atoms in a ring resonator configuration (analogous to the resonator of a ring laser gyroscope). An active atom gain element is inserted in the ring to inject de Broglie waves into the ring. Atoms are outcoupled at a waveguide beamsplitter and mixed on an atom-heterodyne detector. Squeezed state detection techniques are used to detect rotation shifts below the shot-noise limit. Spurious interferometer phase shifts, due to atom-atom interactions, are suppressed by tuning the atom-atom interaction strength to zero using Feshbach resonances. Intracavity loss from three-body collisions and output coupling of atoms is compensated for by the active gain element. To estimate the possible performance of this device, we assume that 10^6 atoms/sec can be coherently coupled into the ring through the active gain element and then detected at the Heisenberg-limit, that the ring has an area of 100 cm^2 (for a 10 cm x 10 cm device), and that an atom transits the loop an average of 10 times before being outcoupled. In this case, the device can resolve rotations of $2x10^{-15}$ rad/sec after 1 second. This is a factor of 10^6 improvement over the current state-of-the-art.

Minor modifications in the waveguide topologies allow for the realization of compact acceleration sensors such as gravimeters and gravity gradiometers, with similar gains in sensitivity expected. Assumptions similar to those of the previous paragraph lead to estimated accelerometer sensitivities of 10^{-14} g in 1 second and sensitivities to gravity gradients of 10^{-3} E (1 E = 10^{-9} sec^{-2}) after 1 second.

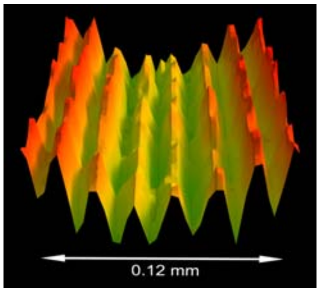

Fig 2. Interference fringes of two overlapping Bose-Einstein condensates [**Error! Bookmark not defined.**]. A major goal of the consortium is to develop this first demonstration into high-precision matter-wave sensors. This will be done by combining state-of-the art atom interferometry, BEC atom sources and atom wave guides.

Summary of most important results

Major program accomplishments in the three year performance interval include: 1) development of methods to create and detect entangled quantum states relevant to sub-shot noise interferometer read-out; 2) demonstration of Bose-condensate atom transport in waveguides; 3) demonstration of Bose-Einstein condensation on a micro-fabricated chip; 4) demonstration of novel waveguide structures for cold-atoms; 5) demonstration of a Bragg grating atom interferometer; 6) demonstration of a CW atom laser and 7) study of atom-surface interactions relevant to microfabricated waveguide devices. These experimental accomplishments, which have significantly advanced understanding of basic physical principles relevant to next generation atom interference sensors, have been supported by substantial advances in the understanding of degenerate atomic systems by the theory collaboration.

Accomplishments (organized by consortium performer):

Cold-atom guides (Prentiss; Harvard): Waveguide atom interferometers offer great potential for creating small, compact, robust rotation and acceleration sensors for guidance applications. Right now, magnetic field guiding is the leading candidate for realizing such guided interferometers. The Harvard group has developed waveguides based on ferromagnetic material, that allow very tight confinement to be obtained far above the physical surface of the magnetic structure, greatly reducing the heating of the atoms and even destruction of the atom sample that has resulted in experiments using atom waveguides based on current flowing through microfabricated wires. These structures have been used to produce atom clouds longer that 2 cm with more than 10^9 trapped atoms. A ferromagnetic ring waveguide has been designed and built, and cold atoms have been loaded atoms into it.

BEC Interferometery (Prichard/Ketterle; MIT):

Progress in the field of atom optics depends on developing improved sources of matter waves and advances in their coherent manipulation. Miniaturizing the current carrying structures used to confine Bose-Einstein condensates offer prospects for finer control over the clouds. The MIT group has demonstrated that a gaseous Bose-Einstein condensate transported with optical tweezers can be transferred into a magnetic trap microfabricated on a silicon substrate. This has opened up a front on which further techniques for coherent condensate transport and manipulation can be explored. In their experiments, a condensate was released from the magnetic microtrap into a single-wire magnetic waveguide and it propagation characteristics were. Condensates were observed to propagate 12 mm before exiting the field-of-view of the imaging system. A single-mode (excitation-less) condensate propagation along homogeneous segments of the waveguide was observed. Transverse excitations were created in condensates propagating through perturbations in the guiding potential. These perturbations resulted from geometric deformations of the current carrying wires on the substrate. Finer imperfections were observed when trapped condensates were brought closer to the microchip as evidenced by the longitudinal fragmentation of the cloud. Such imperfections have to be controlled in order to use atom chips for precision atom interferometry.

Unlike other macroscopic quantum systems such as superfluid ^{4}He and optical lasers, dilute gas Bose-Einstein Condensates have so far been only produced in a pulsed mode. The MIT group has realized a continuous BEC source by periodically replenishing a condensate held in an optical dipole trap with new condensates. A moving optical tweezers for Bose-Einstein condensates was used to transport condensates from where they were produced into a reservoir optical trap. The freshly produced condensates periodically replenished the condensate in the reservoir trap, thereby continuously maintaining a condensate of more than 10^6 atoms. The crucial step in realizing a continuous BEC source was to make sure that the new cooling cycle did not destroy the condensate held in the reservoir trap. This involved shielding it from light during laser cooling, keeping it far away from the incoming hot atoms, and to hold it in an optical trap which made it immune against stray magnetic fields which were created during the evaporative cooling phase.

By colliding two Bose-Einstein condensates the MIT group has observed strong bosonic stimulation of the elastic scattering process. When a weak input beam (third wave) was applied as a seed, it was amplified by a factor of 20, and an initially unpopulated conjugate wave was created. This large gain atomic four-wave mixing resulted in the generation of two macroscopically occupied pair-correlated atomic beams. Since each collision process adds one atom each to the seed and conjugate waves, fluctuations in the relative atom number are suppressed (squeezed). For the observed gain of twenty, the number fluctuations should be below the shot noise by a factor of $40^{1/2}$. Limitations for using collisions to create twin beams have been identified. These include loss by subsequent collisions and competition between other modes with similar gain.

Finally, the MIT group has demonstrated a new atom interferometer scheme, which shows promise for a high precision measurement of the recoil energy of an atom. A precise measurement of the recoil frequency will lead to a more precise determination of h/m and of the fine structure constant α. The interferometer extends previous schemes used at Stanford and NYU, and combines their advantages. Optical standing wave pulses were used to create a symmetric three-path interferometer. This configuration encodes the photon recoil phase in the contrast of the interference fringes, rather than in their phase. Because it is insensitive to the fringe phase, the method is not sensitive to vibrations, accelerations, or rotations. The symmetry also suppresses errors from magnetic field gradients, and our use of only one internal state suppresses errors arising from differences in the ac Stark shifts between different internal states. A crucial aspect of this new interferometer is the use of atomic samples with sub-recoil momentum distribution, in this case a BEC. This allows the contrast oscillations to persist for many cycles, permitting precise determination of the recoil phase in a single "shot."

Waveguide BEC (Chu, Vuletic; Stanford): Bose-Einstein condensation has recently been achieved in a novel microchip topology. The experimental method to obtain BEC is robust and simple; it uses only a single vacuum chamber and a magnetic microtrap which is directly loaded from a standard magneto-optical trap. The short evaporation time of 3s is limited only by the axial trap vibration frequency, and it is estimatee that the evaporation time can be shortened to 1s at a MOT loading time of 500ms. The condensates containing a few thousand rubidium atoms are produced at a distance of 60μm from the silicon substrate, and are stable to distances down to 15μm. An atom number shot noise-limited imaging system for the condensate has been set-up to study the condensate. In the near future, we will try to demonstrate sub-shot noise fluctuations ("squeezing") in the relative atom number contained in different spatial regions of the condensate. This is equivalent to a determination of the average condensate position with sub-shot noise accuracy, and may be of use in simple interferometric schemes with condensates.

Squeezing and quantum state control in optical lattice (Kasevich; Yale/Stanford): The Yale/Stanford group demonstrated that the optical lattice system can be used to produce squeezed atomic states. The basic idea of this work is to exploit mean-field interactions to produce non-trivial many-body states of weakly connected ensembles of Bose condensates. Experimentally, arrays of condensates are confined in corrugated potentials in which atoms may resonantly tunnel between adjacent wells. This opens up the possibility of producing non-trivial many-body states. In particular, the ground state of the system can no longer be described by a factorizable quantum wavefunction (ie. as the simple product of identical single-particle wavefunctions). The two-well version of this problem is exactly solvable. In the limit where the mean-field interaction dominates tunneling, the total energy of the system is minimized by suppressing number fluctuations at each trapping site – that is by squeezing the on-site number distribution. The corresponding phase spread, via the number-phase uncertainty principle, increases. On the other hand, when tunneling dominates, the ground state approaches that many-body state associated with a non-interacting gas. In this case, the number fluctuations at a given site approach those of a coherent state. These effects have been demonstrated experimentally by analyzing the phase coherence of atoms in the lattice array. This work has recently been extended to study the Mott-insulating regime, both interferometrically and by transport measurements. This work has also identified several new paths to the creation of sub-shot noise interferometers.

Theory (Meystre, Glauber, Wright; Tuscon/Harvard): The theory collaboration has significantly advanced the state-of-knowledge for the quantum field theory of degenerate bosonic and fermionic systems, with particular emphasis to sensors applications. Most recently, the focus on fermionic systems may identify mitigation strategies to overcome some of the technology hurdles identified in the study of guided atom systems.

For example, it is only recently that it has been convincingly argued that atomic four-wave mixing is possible with fermions. However, the theory so as been limited to an incident beam consisting of a single test particle. It also neglected the dynamics of the density grating. These limitations have now been removed by taking into account both a multi-particle beam and the back-action of the incident beam on the fermionic density grating. Using this formalism, it has been shown that when the number of atoms in the incident beam becomes a sizable fraction of the number of atoms forming the density grating, it no longer decays away due to the dephasing resulting from the slightly different energies of the fermions forming the incident beam. Instead, it exhibits large nonlinear amplitude oscillations that are coupled to the Bragg oscillations of the beam. This leads to the efficient generation of the fourth scattered wave, even for times much longer than the grating dephasing time. It is well known that four-wave mixing with bosons can lead to the generation of squeezed states. Therefore a central feature of future work will examine the statistical properties of the scattered beam generated in fermionic four-wave mixing to see if it is possible to generate novel fermionic states. Phase conjugation should also be possible if one uses a superfluid Fermi gas due to the presence of anomalous moments resulting from the formation of Cooper pairs.

In related work, the phase resolution limit of a Mach-Zehnder atom interferometer whose input consists of degenerate quantum gases of either bosons or fermions has been analyzed. For degenerate gases, the number of atoms within one de Broglie wavelength is larger than unity, so that atom-atom interactions and quantum statistics are no longer negligible. It has been shown that for equal atom numbers, the phase resolution achievable with fermions can be noticeably better than for interacting bosons. This is a strong argument for a further extensive study of fermionic atom optics.

The recent experimental success in creating quantum-degenerate atomic Fermi gases is opening up fascinating new opportunities to explore the quantum statistics of ultracold atoms. Fermionic behavior is strongly constrained by the Pauli Exclusion Principle. This limits the variety of possible nonlinear atom optics effects, but also offers the potential for novel applications without analogs in optics. These include, for example, low-noise inertial and rotation sensors, and quantum information processing. In a new development of the theory research program, the new situation where a gas of bosons serves as a nonlinear medium for fermionic atoms has been explored. In particular, interatomic interaction between a Bose-Einstein condensate and a fermionic beam can be employed to manipulate the quantum state of the beam. As a first step, and drawing on an analogy to nonlinear optics, the interaction can be described in terms of an effective attractive Kerr nonlinearity, and show that a two-fermion bound state can result with a unique signature in a nonlinear atom optical experiment. Future study of this coupled Bose-Fermi systems may be of particular relevance for the manipulation of the quantum statistical properties of fermionic atomic beams, e.g. changes from antibunched and bunched beams, dynamic Cooper pairing, and the formation of quantum solitons in ultracold fermionic atomic beams.

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Collective enhancement and suppression in Bose-Einstein condensates.
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Amplification of Atoms and Light in Bose-Einstein condensates.
plenary talk, APS April Meeting, Washington, D.C., 4/28 – 5/1, 2001

Experiments with a Bose-Einstein Condensate in an Optical Trap.
DAMOP 2001, London, Ontario, Canada, 5/16 – 5/19, 2001.
(Talk by T. Gustavson)

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(Talk by Chandra Raman)

Optical trapping and manipulation of Bose-Einstein condensates.
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plenary talk, Eight Rochester Conference on Coherence and Quantum Optics,

Rochester, June 13 -16.

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Atomic Physics Gordon conference, Williamstown, MA, June 17 – 22.

Bose-Einstein condensation – quantum mechanics near zero temperature.
plenary talk, Conference on statistical physics STATPHYS 21, Cancún, Mexico, July 18.

Recent BEC experiments at MIT – BEC in large-volume optical traps and interference of vortices. International Workshop "Quantum Gases", Insel Reichenau, Germany, July 19 –July 21, 2001.

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(Talk by Shin Inouye)

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Kasevich, University of Maryland, Physics Dept. Colloquium, Oct. 2001.

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Kasevich, ICOLS, Utah, June 2001.

Kasevich, PMOSSP Seminar (Navy), Mitchel Field, May 2001.

Kasevich, ONR Nav. Tech. Review, Washington D.C., May 2001.

Kasevich, NTAG-2001, BIPM, Paris, Feb. 2001 (talk given by G. Foster)

Kasevich, Laser Cooling and Applications, Japan, Jan. 2001 (talk given by Jeff McGuirk).

"Atom optics," Lecture Series (10 hours), Troisième Cycle Romand de Physique, Swiss Federal Institute of Technology, Lausanne, Switzerland (2003).

“Fermionic atom optics --- a tutorial,” invited talk, TAMU-ONR-DARPA Workshop on Quantum Optics, Grand Targhee, Wyoming (2003).

“Cavity de Broglie optics --- a molecular micromaser,” invited talk, QUEST 2003 Symposium, Santa Fe, New Mexico (2003).

”Four-wave mixing of fermionic matter waves,” invited talk, 12th International Laser Physics Workshop LPHYS'03, Hamburg, Germany (2003).

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Steven Chu
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Report of Inventions

None