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Atom interferometers have proven to be versatile tools, applicable in many different scientific and technical arenas. We have concentrated our efforts in the three major areas of precision measurements of important quantities in atomic physics, basic research into atom interferometric inertial sensors, and investigations of fundamental quantum mechanical principles.

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New Developments in Atom Interferometry

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FINAL PROGRESS REPORT

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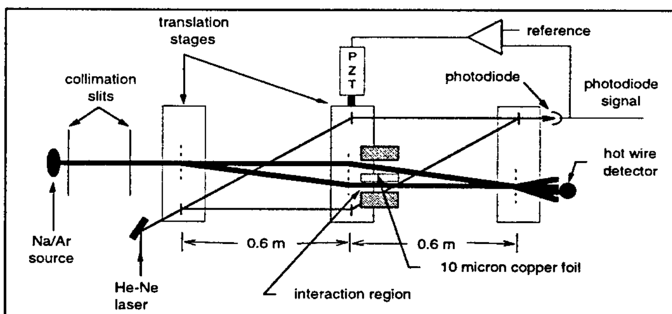
Statement of the Problem Studied

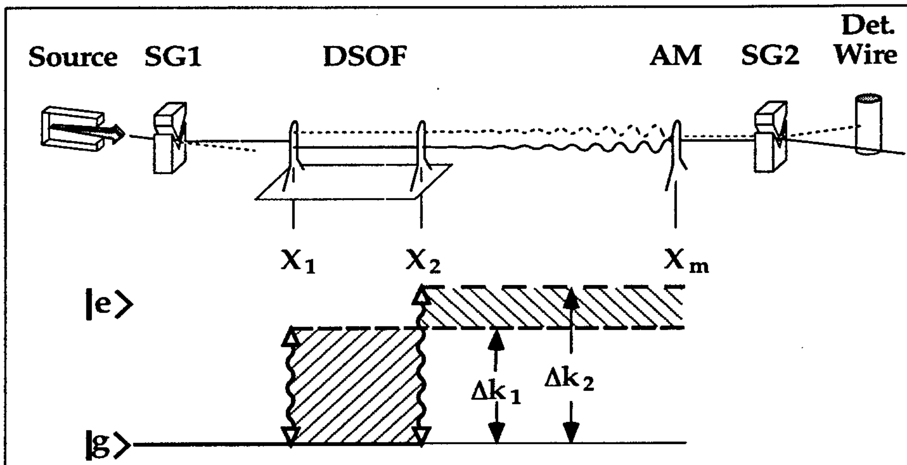
Atom interferometers have proven to be versatile tools, applicable in many different scientific and technical arenas. We have concentrated our efforts in the three major areas of precision measurements of important quantities in atomic physics, basic research into atom interferometric inertial sensors, and investigations of fundamental quantum mechanical principles.

Precision measurements are of obvious significance as we attempt to deepen our understanding of micro/nanoscopic systems such as Bose-Einstein condensates, and hone the predictive power of theoretical models describing them. As for the inertial sensing, atom interferometers have already demonstrated extreme sensitivity to inertial effects and hold future promise both in inertial navigation and eventually in the study of general relativity. Finally, atom interferometers by their nature are ideal tools with which to investigate the important, yet still-mysterious notion of quantum coherence and decoherence. Because atoms possess a rich internal structure in addition to their external motion, our separated beam interferometer provides a unique opportunity to study the differences between decoherence of internal versus external degrees of freedom, to probe the fundamental limits on the coherence of ever larger and more complicated systems, as well as to seek fresh insight into the problem of (de)coherence in general.



A schematic, not to scale, of our atom interferometer (thick lines are atom beams). The 0th and 1st diffracted orders from the first grating strike the middle grating where they are diffracted to form an interference pattern in the plane of the third grating. A thin septum is placed between the two arms of the interferometer. An optical interferometer (thin lines) measures the relative positions of the atom gratings.

Our transverse atom/molecule interferometer realizes a Mach-Zehnder geometry using three nanofabricated transmission gratings, and generates a "white-fringe" (i.e. insensitive to momentum spread in the beam) interference pattern. Its most unique feature—unduplicated by any of the other atom interferometers demonstrated—is a spatial separation of the two interfering beam paths which permits the application of an interaction to only one of the two paths. We have also constructed an interferometer in which the two interfering paths are separated in longitudinal momentum and internal state space, rather then position space. This 'longitudinal' interferometer is ideally suited to the study of interactions that change the kinetic or potential energy of an atom, leading to time-dependent superpositions of states with different total energies.

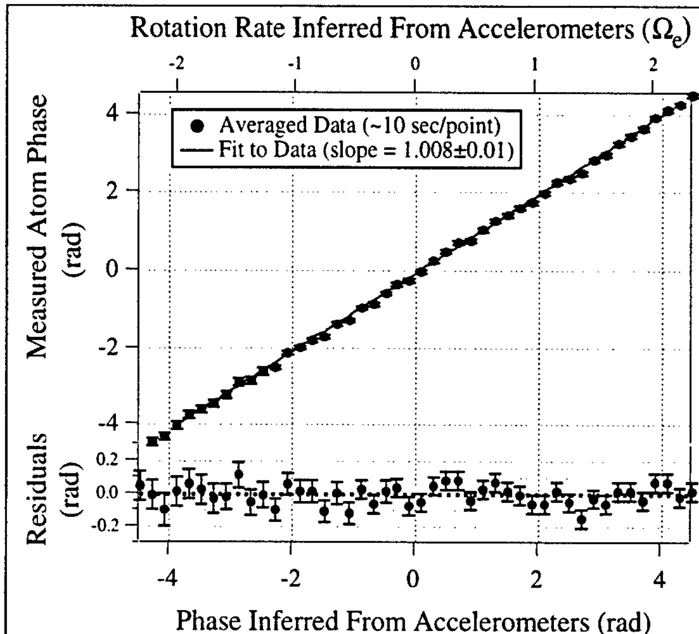


Longitudinal interferometer: the interfering paths are separated in momentum and internal state space, rather than position space. Atoms incident in the ground state are excited either in the first or second of two "DSOF" (for Differentially Detuned Separated Oscillatory Fields) coils. As the atoms are excited, they also receive a momentum kick proportional to the detuning of the field coil from resonance. Beyond the second region, the two paths overlap to produce an interference pattern.

Summary of Important Results

Inertial Effects

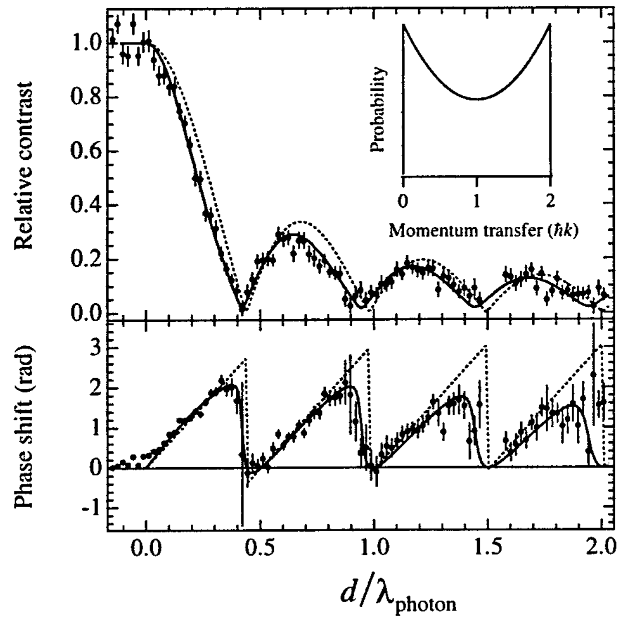
The extreme sensitivity of atom interferometers to rotations was demonstrated by our pioneering, shot noise limited measurement of the atomic Sagnac Effect [SCD93] . By suspending our interferometer and subjecting it to a slow sinusoidal rotational oscillation, we observed rotation rate sensitivity better than one arc-second per second with a one second averaging time. This sensitivity approaches that of commercial laser gyroscopes. Furthermore, we have shown that the phase response of our device is within 1% of prediction, the first precision measurement of this effect. The more recent work by Kasevich [GBK97] shows that an interferometer designed specifically for rotation sensing can perform better than the best laboratory laser gyroscope. This suggests future applications of atom interferometers to precision inertial navigation and geophysics, and ultimately to tests of general relativity.



Inertial Sensing Results: Although out interferometer was not optimized for rotational sensitivity measurements, the agreement between the predicted accelerations and accelerations as determined by accelerometers is within the 0.8% experimental uncertainty.

Fundamental Physics

The power of atom interferometers to explore fundamental issues in quantum mechanics is illustrated by our extension of a *gedankenexperiment* proposed by Feynman [CHL95]. In this work, we studied the relationship between "which path" information and atomic coherence by scattering a single resonant photon from each atom that passes through our interferometer. As the separation between the arms of our interferometer at the point of scattering increased, the contrast of our atomic interference fringes vanished. In addition, we recovered the lost coherence by measuring interference fringes due to only atoms scattering photons into a small range of final directions.



Demonstration of coherence loss in our atom interferometer due to scattering a single photon. The interfering contrast and phase shift are plotted as a function of the separation of the two interfering paths at the point of scattering. The inset shows the angular distribution of spontaneously emitted photons projected onto the x axis. The dashed curve corresponds to purely single photon scattering, and the solid curve is a best fit that includes contributions from atoms that scattered 0 photons (4%) and 2 photons (14%). In future experiments, we will further explore the multiple-photon scattering regime.

Atomic & Molecular Properties

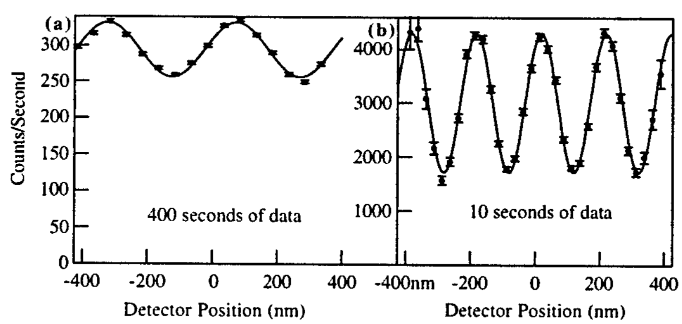
Our atom interferometric measurements of atomic polarizability are an order of magnitude more accurate than previous methods [ESC95]. Our work on determining the index of refraction of various gases for atom and molecular de Broglie waves has no precedent in atomic physics [SCE95, HCL97]. These experiments provide information about the long range form of atom-atom scattering potentials by measuring the *phase* accumulated by the atom during a scattering event, a quantity which has never before been experimentally accessible.

Nanofabricated Gratings and Precision Septum Technology

Our recent advances in nanofabrication have provided both improved atom optical elements and innovative techniques for creating thin freestanding membranes (septa).

Atom diffraction gratings have now been manufactured with periods smaller than ever before using both traditional electron beam lithography and a new optical interferometric lithographic technique developed at MIT. Microfabrication technology has been applied to the design of new interaction regions for our separated beam interferometer as well, opening up new experimental possibilities.

In the past we have manufactured gratings at the Cornell Nanofabrication Facility using electron-beam lithography. The quality and size of these gratings was previously limited by thermal drift in the electron beam optics. In an important contribution to the field of electron beam lithography, we solved this problem by introducing alignment marks and a procedure to reference them in order to periodically compensate for the drift during the e-beam writing process [RTC95a, RTC95b] . The subsequent error reduction made possible the construction of smaller (140nm) gratings, and resulted in 200nm gratings which doubled our atomic interference contrast.



(a) Interference fringes from the original interferometer with 400nm period gratings, demonstrated in Feb. 1991. The scan required 400 seconds of data, the contrast is 12.9%, and the signal/noise ratio is 2.2. (b) Interference fringes acquired with greatly improved 200nm gratings and an improved beam. The scan was acquired in 10 seconds. The contrast is 43.1% and the resultant S/N is now 23.6. (The data are shown on the same horizontal scale, but note the different vertical axes.)

The push to create smaller period gratings led to the development of interferometric lithography by Prof. Henry Smith's group at MIT's Nanostructures Laboratory. Their technique uses interference of diffracted UV laser light through 200nm "parent" gratings to write a 100nm period grating. This method has the benefit of short exposure times and large scale grating coherence as opposed to electron beam methods, which write serially in a process that takes minutes per grating.

In addition to developing novel grating fabrication methods, we have also developed new techniques for manufacturing narrow freestanding membranes, or septa, which we use to physically isolate the atom waves traversing the two arms of our separated beam atom interferometer. We now construct a septum by anodically bonding a thin (~10μm) silicon wafer to a borosilicate glass substrate which possesses a matching coefficient of thermal expansion. A cavity cut into the glass permits passage of the atom beam and also serves as a gas cell for the index of refraction experiments described above. The measured thickness of the shadow of our septum in the atomic beam was 16μm, half that of the stretched foil septum we employed previously.

New Vacuum Chamber and Vibrational Isolation

Approximately one and a half years ago, we embarked on a program of substantial improvements to our apparatus. These upgrades will add tremendously to both the overall performance and the flexibility of our apparatus. A new atomic beam source and improvements in our atom detection electronics have provided a significantly greater atom count rate (we now detect an intensity of 10^{22} atoms/sec•sr•cm^2). These advances, combined with improvements in the quality of our matter gratings and in the vibration isolation of our apparatus, have allowed us to increase the signal/noise ratio of our transverse atom interference fringes by more than an order of magnitude.

We have constructed a new vacuum chamber, consisting of five identical six-way crosses, each ~50cm long, which increases the overall length of our beam machine to ~3.5m and will allow greater separation between the arms of our transverse interferometer. The greatly increased number of flange ports, together with the mounting of critical components on an optical breadboard results in flexibility and modularity sufficient to operate two experiments simultaneously. We expect that the external and internal (for the optical breadboard) vibration isolation will decrease phase zero drift and reduce vibrations to below 10nm rms, resulting in the ability to achieve high contrast interference with the 100nm gratings described above.

Longitudinal Atom Optics

Past work in particle beam optics and interferometry has focused overwhelmingly on transverse momentum coherences [BER97] ; the study and application of entanglements and coherences involving the longitudinal momentum of neutral particles is just beginning.

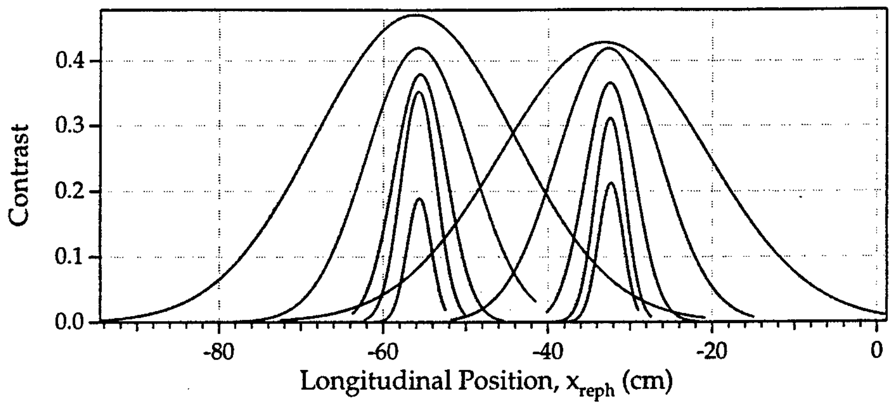
Longitudinal atom optics provides a new set of tools for the manipulation and control of the quantum state of matter wave beams. In particular, they provide a method of probing the coherence structure of atomic beams, may shed new light on the correct quantum description of these systems [BEL87] , and may resolve outstanding controversies [COM83, KOH83]. The techniques of longitudinal atom optics may also have applications in experiments requiring the use of short pulses of atoms. Finally, the extension of longitudinal atom optics into the slow atom regime holds out the possibility of producing useful atom optical devices such as an atomic Fabry-Perot cavity.

Over the last two years, we have developed powerful theoretical tools for understanding longitudinal atom optics. We have shown that conventional radiofrequency resonance regions constitute longitudinal atom optical elements (beamsplitters), which transform an incident matter wave with a single momentum into a coherent superposition of components with two different momenta. We have also shown that both amplitude and phase modulation of matter wave beams can act as longitudinal beamsplitters.

Based on our theoretical framework, we have developed an extension of Ramsey's classic separated oscillatory field (SOF) resonance method in which two different excitation frequencies are applied in the two oscillatory field regions. We have demonstrated a phenomenon analogous to a spin echo, which this configuration can exploit to rephase and to measure coherent amplitude modulation that has been washed out by velocity inhomogeneities in our atomic beam.

Longitudinal Interferometry

In the last year we have begun a series of atom optical experiments using our new longitudinal interferometer. We constructed small hairpin (~150μm wide) radiofrequency coils with correspondingly wide (3 MHz) resonance profiles and drove them with a system of three coherently phase-locked frequency synthesizers tuned to excite both hyperfine and Zeeman transitions in our sodium beam. We implemented an amplitude modulator by sinusoidally varying the power to a RF coil tuned to a Zeeman resonance and deflecting the excited atoms out of the atomic beam. The remaining (modulated) atoms passed through a pair of differentially detuned SOF ("DSOF") coils whose difference frequency was adjusted to exactly match the modulation frequency.



Contrast of rephased Ramsey fringes plotted as a function of x_{reph}. When x_{reph} (a parameter determined by the weighted average of the frequencies in the two DSOF coils) is equal to the position of applied amplitude modulation, the rephased contrast is a maximum. The data above were taken for two different amplitude modulator positions (32.8 and 56.1 cm upstream). At each modulator position, data were recorded for modulation frequencies of 50,100,200,300 and 400 kHz—50 and 400 kHz are the broadest and narrowest curves, respectively.

The extra degree of freedom—the average of the DSOF frequencies—was scanned continuously over a range of ~300KHz. When the position weighted detuning,

$$x_{reph} = \frac{\delta_2 x_2 - \delta_1 x_1}{\delta_2 - \delta_1},$$

where $x_{1,2}$ and $\delta_{1,2}$ are the positions and detunings from resonance (respectively) of the two coils, was equal to the upstream position of the amplitude modulator, we observed high contrast rephased fringes. The envelopes of these fringes, plotted against x_{reph}, allow us to determine both the frequency and the position of the applied modulation.

Source Search and Density Matrix Deconvolution

The DSOF interferometer was next used to investigate the coherence properties of our supersonic atomic beam source, addressing questions [COM83, KOH83, BEL87] about the correct quantum description of such a system. We have searched for amplitude modulation (wave packets) in the beam, which is associated with off-diagonal density matrix elements in the momentum representation. A preliminary analysis of the data shows no evidence of momentum coherences in the region of the density matrix over which we were able to search.

We went on to generate a density matrix with complex coherent structure which we then measured using a novel double Fourier transform method we recently proposed [DKR97]. This experiment constitutes the first reconstruction of the longitudinal quantum state of a matter wave beam, and a paper describing it will be published in upcoming months.

Publications and Technical Reports

Note: List includes only publications in refereed journals.

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Coherence and Structural Design of Free-Standing Gratings for Atom-Wave Optics, Michael J. Rooks, Richard C. Tiberio, Michael Chapman, Troy Hammond, Edward Smith, Alan Lenef, Richard Rubenstein, David Pritchard, Scott Adams, Juan Ferrera, James M. Carter and Henry I. Smith, Jpn. J. Appl. Phys. 34 (1995) pp. 6935-6939.

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Multiplex Velocity Selection for Precision Matter Wave Interferometry, T.D. Hammond, D.E. Pritchard, M.S. Chapman, A. Lenef, and J. Schmiedmayer, Appl. Phys. B **60**, 193 (1995).

Index of Refraction of Various Gases for Sodium Matter Waves, Jorg Schmiedmayer, Michael S. Chapman, Christopher R. Ekstrom, Troy D. Hammond, Stefan Wehinger and David E. Pritchard, Phys. Rev. Lett. 74, 1043 (1995).

Near Field Imaging of Atom Diffraction Gratings: the Atomic Talbot Effect, M.S. Chapman, C.R. Ekstrom, T.D. Hammond, J. Schmiedmayer, B.E. Tannian, S. Wehinger and D.E. Pritchard, Phys. Rev. A 51, R14 (1995).

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