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6. AUTHOR(S)
Prof. David Pritchard

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

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"Atom Wave Interferometer"

Annual Office of Naval Research Progress Report

Atom Interferometry

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December 1, 1993 - November 30, 1994

Since our demonstration of an atom interferometer made with three nanofabricated atom gratings, we have devoted considerable effort to applying these instruments to the wide range of fundamental and applied scientific problems for which they are so well suited. During 1994, we performed atom interferometer experiments to test fundamental concepts of coherence in quantum interference and began an experiment to demonstrate the very high intrinsic sensitivity of atom interferometers to acceleration and rotation. This year, we have also completed and submitted several major papers, some of which are already in press. These include papers on atomic polarizability, index of refraction of matter waves, near field imaging (atomic Talbot effect), molecule optics and interferometry, and a proposed new velocity selection scheme for precision measurements.

The development of atom interferometers represents a significant advance in atomic physics. They give us the ability to measure accurately interactions that shift the phase or energy of the particles in one of the two interfering paths in the interferometer. This allows qualitatively new measurements in atomic and molecular physics and fundamental tests of quantum mechanics (especially in areas involving atom-photon interactions), and provides new ways to measure accelerations and rotations:

- Atom interferometers permit completely new precision measurements of ground state properties of atoms and molecules. Important applications include precision measurements of atomic polarizabilities to test atomic structure models, measuring both molecular polarizability tensor components, and determining long range forces that are important in cold collisions and Bose-Einstein condensation.

- Atom interferometers have important applications to fundamental measurements in quantum mechanics. These include measurements of topological and geometric phases, loss of coherence to a reservoir, quantum measurement, and investigations of multi-particle interferometry and entanglement.

- The large mass and low velocities of atoms make atom interferometers especially sensitive to inertial effects like acceleration and rotation. They are projected to have sensitivities that significantly exceed the best commercial laser gyroscopes.

- Atom interferometers may have significant applications to solid state physics, including measurements of atom-surface interactions and lithography using coherently manipulated atom fringe patterns that are directly deposited onto substrates.

The key elements in our interferometer are the nanofabricated transmission diffraction gratings with a 200 nm period that we fabricated at the National Nanofabrication Facility (NNF) at Cornell University using a process that we developed there. One of the important contributions this year has been the development of an alignment process to eliminate edge discontinuities or "stitches" between the adjacent 50 μm^2 fields within the much larger grating windows. This technique has produced our most coherent gratings to date, resulting in a measured fringe contrast of nearly 45%.

We integrated a dye laser into our apparatus to investigate photon-atom interactions in our interferometer and to polarize our atom beam by optical pumping techniques. This permitted us to investigate the loss of coherence or "decoherence" between the two spatially separated de Broglie wave components when resonant single photons are scattered in our interferometer. In our experiments, which are a realization of the classic gedanken experiments of Heisenberg and Feynman, we found that fringe contrast decreases significantly when the separation of the paths exceeds about a quarter of a wavelength of light. This is in accordance with the expectations of Bohr's complimentarity principle, since if the separations were much larger than the wavelength of light, then, in principle, one could determine from which path the atom was scattered. However, contrast at larger separations also exhibits strong revivals. This result is in excellent quantitative agreement with our theory which explicitly considers the phase differences imparted to the two paths from the scattering photons.

We extended our decoherence experiment to study the possibility of recovering some of the lost coherence by using information about the scattering angle of the photon. By using highly collimated beams and a movable narrow slit in front of the detector, we were able to select only atoms that were scattered by photons emitted at a particular scattering angle. For these atoms, we found that the fringe contrast persisted over significantly larger path separations than in our decoherence experiment and with a phase that depended upon the selected photon scattering angle. We call this a "recoherence" experiment. It explicitly shows, for the first time, that resonantly scattering a photon from an atom does not irreversibly destroy the atomic coherence and explicitly reveals the entanglement of the photon scattering angle and the phase difference imparted to the two atom de Broglie waves in the interferometer.

Phase shifts that arise from the path length differences in interfering de Broglie waves in accelerating frames have been discussed by many authors in both non-relativistic and relativistic contexts. Recently, we have obtained preliminary results in which we measured rotations of our interferometer at rotation speeds of about one earth rate (7.3×10^{-5} rads/sec). This is about three-orders of magnitude more sensitive than previous measurements of rotation using atom interferometry and shows the promise of using atom interferometers for inertial navigation systems. We expect to be able to measure rotations to less than 5×10^{-4} earth rates with one hour of integration time and demonstrate accuracies below the 1% level at higher rotation rates, close to the performance of the best commercial laser gyroscopes.

In order to improve the precision of atom and molecular interferometry measurements, we have proposed a promising high-flux velocity selection technique that will permit the application of large phase shifts without loss of fringe contrast due to the velocity dependence of the phase for most applied potentials. In this approach, which we call "velocity multiplexing," a potential is applied such that the phase shifts of atoms in the peaks of a multi-peaked velocity distribution are exact integral multiples of 2π. Thus, interference patterns from each of the velocity peaks add constructively to produce high fringe contrast at very large applied phase shifts. This technique eliminates the troublesome systematic errors normally associated with measurements of dispersive phases and appears capable of measurements with accuracies below 0.1%.

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