6431200

# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
12/19/00

**3. REPORT TYPE AND DATES COVERED**
Annual Technical 12/1/99 - 11/30/00

**4. TITLE AND SUBTITLE**
Atom Wave Interferometers

**5. FUNDING NUMBERS**
N00014-96-1-0432

**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**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
99PR01097-00

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

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

**Long-term research objective:**
Matter wave interferometers, in which de Broglie waves are coherently split and then recombined to produce interference fringes, have opened exciting new possibilities for precision and fundamental measurements with complex particles. The aim of our research program is to extend the ideas and techniques of atom optics and atom interferometry which underlie atom interferometers, to use these devices to make qualitatively new and/or more precise measurements in atomic physics, and to perform fundamental experiments in quantum mechanics based on our ability to measure interactions that displace the de Broglie wave phase or change the quantum coherence of the beams (reducing the amplitude of the interference pattern).



20001222 111

**14. SUBJECT TERMS**

**15. NUMBER OF PAGES**

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

Fiscal Year 2000 Annual Report: N000149610432
Last Modified: 9/19/00 4:56:19 PM

Principal Investigator


| | | | |
|---|---|---|---|
| Name: | David Pritchard | Address: | Department of Physics/Research Laboratory of Electronics<br>77 Massachussetts Ave |
| Organization: | MIT | City/State/Country: | Cambridge, MA USA |
| Title: | Professor | Zip Code: | 02139 |
| Phone: | (617)253-6812 | Fax: | (617)253-4876 |
| Email: | dpritch@mit.edu | Website: | http://web.mit.edu/physics/people/david_pritchard.htm |


Contract Information

| | | | |
|---|---|---|---|
| Contract/Grant Number: | N000149610432 | Contract/Grant Title: | Atom Wave Interferometers |

Program Officer: Narducci

CO-PI Information - Number of Co-PIs = 0

Technical Section (Including Objective, Approach, and Progress)

Long-term research objective:

Matter wave interferometers, in which de Broglie waves are coherently split and then recombined to produce interference fringes, have opened exciting new possibilities for precision and fundamental measurements with complex particles. The aim of our research program is to extend the ideas and techniques of atom optics and atom interferometry which underlie atom interferometers, to use these devices to make qualitatively new and/or more precise measurements in atomic physics, and to perform fundamental experiments in quantum mechanics based on our ability to measure interactions that displace the de Broglie wave phase or change the quantum coherence of the beams (reducing the amplitude of the interference pattern).

Science and Technology objective:

To develop the techniques of atom optics and atom interferometers, and to find new applications in many scientific and technical arenas. We have pioneered applications in three major areas: precision measurements in atomic physics, atom interferometric inertial sensors, and investigations of fundamental quantum mechanical principles.

Approach:

Our transverse Mach-Zehnder interferometer for atoms and molecules uses three nanofabricated transmission gratings, and generates a "white-fringe" (i.e. insensitive to momentum spread in the beam) interference pattern. Its most unique feature is a spatial separation and isolation of the two interfering beam paths, permitting the application of an interaction to only one of the two paths. Also, we have recently constructed a novel interferometer in which the two interfering paths are separated in longitudinal momentum space. It 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.

We have also started atom interferometry experiments using a Bose-Einstein condensate in collaboration with Wolfgang Ketterle. Using BEC and lasers we have developed a means of amplifying a matter wave which can enhance the contrast of atom interference fringes.

Progress:

This past year we built an improved Mach Zehnder interferometer for atoms and applied it to studying decoherence. The process of decoherence in quantum systems has been described as the collapse of the wave function, and causes a transition from from quantum mechanical to classical behavior. We have studied this emergence of classical behavior in three different experiments.

By scattering a controlled number of photons from each atom within the interferometer we have demonstrated a calculatable and universal form of decoherence which is relevant to quantum computation, quantum error correction, and quantum communication. In two other experiments we have broadened the pedagogical framework of decoherence by studying the effect of a deterministic momentum transfer to each atom, and also studying the role of each atom's internal state.

Technology Transfer

Our demonstration of the inertial sensing capabilities of atom interferometers continues to garner

*The* RESEARCH LABORATORY *of* ELECTRONICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 MASSACHUSETTS AVENUE
CAMBRIDGE, MASSACHUSETTS 02139-4307

December 19, 2000

Dr. Peter J. Reynolds
Program Officer, ONR 331
Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

In accordance with the terms of the Office of Naval Research Grant No. N00014-96-1-0432, I am sending you the following material:

| | |
|---|---|
| Type of Material: | Annual Technical Reports |
| Title: | Atom Wave Interferometry |
| Submitted by: | Prof. David E. Pritchard |
| Period Covered: | December 1, 1998 - November 30, 1999<br>December 1, 1999 - November 30, 2000 |
| Number of Copies: | Three plus Form 298 |
| Distribution: | Navy Distribution List (3) |

Thank you. Please contact me if you have any questions or comments.

Mary S. Greene
RLE Financial Assistant, Room 36-437

cc: Prof. Pritchard (1)
A.F. Favaloro, E19-702
File (1)

OSP 6431200

Enclosures

Room 36-437 ♦ Telephone: (617) 253-8139 ♦ Facsimile: (617) 253-1301 ♦ Electronic Mail: mgreene@rle.mit.edu

widespread interest both within the scientific community where it is hoped such devices will eventually lead to tests of general relativity, and in the military where atom interferometers may one day replace laser gyroscopes in some inertial navigation systems. Our grating fabrication efforts in collaboration with Prof. Henry Smith at MITs Microsystems Technology Laboratory are helping to test the large scale reproducibility and feature-size limits of UV lithography.

Our most recent demonstration of a calculatable and universal form of decoherence is relevant to qunatum computation, quantum error correction and quantum communication. Because quantum interference is essential for these quantum information processing applications, the process of decoherence needs to be understood. The kind of decoherence we studied, which results from an environment where multiple scattering events each cause a small amount of decoherence, is one of the major problems faces by current efforts on quantum computation.

It is too early to predict the ultimate destiny of atom amplification, but is seems likely that it will result in improved signal-to-noise in future matter wave devices.

ONR Database Statistics

| | | | |
|---|---|---|---|
| 1 | Papers Published in Refereed Journals Citing ONR Support | 1 | Papers in Press in Refereed Journals Citing ONR Support |
| 0 | Books or Chapters Published Citing ONR Support | 0 | Books or Chapters in Press Citing ONR Support |
| 1 | Technical Reports & Non-Refereed Papers | 0 | Invention Disclosures Citing ONR Support |
| 0 | Patents Granted Citing ONR Support | 0 | Patents Pending Citing ONR Support |
| 3 | Presentations | 0 | Degrees Granted |
| 0 (total); 0 (women); 0 (minority) | PICOPI | 2 (total); 0 (women); 0 (minority) | Grad Students |
| 1 (total); 0 (women); 0 (minority) | Post Docs | | |

Refereed Journal Articles

1. Physical Review Letters, Sept 20, 1999,
Volume 83, Issue 12, pp. 2285-2288
Measurement of the Density Matrix of a Longitudinally Modulated Atomic Beam
Richard A. Rubenstein, David A. Kokorowski, Al-Amin Dhirani, Tony D. Roberts, Subhadeep Gupta, Jana Lehner, Winthrop W. Smith, Edward T. Smith, Herbert J. Bernstein, and David E. Pritchard

Books and Chapters

Technical Reports

1. Atom Interferometry, RLE Progress Report No. 142
Section 10, 1999

Presentations

1. "Atom Optics", Two lectures presented at:
Euroschool Bose-Einstein Condensates and Atom Lasers 17-25 July 2000
Institut d'Etudes Scientifiques de Cargese
Corsica, France
by David E. Pritchard

2. "Two Routes to Gaussian Decoherence"
Poster presented at
Euroconference on Atom Optics and Interferometry
Institut d'Etudes Scientifiques de Cargese
Corsica, France.
by Alexander D. Cronin

3. "Decoherence from two separated environments"
poseter presented at:
Euroconference on Atom Optics and Interferometry
Institut d'Etudes Scientifiques de Cargese
Corsica, France.
by Alexander D. Cronin

4. "From Single to Multiple Photon Decoherence"
poster presented at DAMOP meeting
June 14 - 17, 2000
University of Connecticut Storrs, Connecticut
by: Alexander D. Cronin, David A. Kokorowski, Tony D. Roberts

Patents

Honors/Awards/Prizes

None entered.

Other Sponsored Work

Army Research Office contract DAAG55-98-1-0429
New Developments in Atom Interferometry
$240,000 start:8/1/98 end:7/31/01

Army Research Office contract DAA55-97-1-0236
Matter Wave Interferometry with Separated Beams - AASERT
$99,000 start:6/1/97 end: 5/31/00

National Science Foundation grant PHY-9877041.
Ionic, Atomic and Molecular Physics
$781,000 start: 10/1/98 end 9/30/00
(split between two different projects)

OFFICE OF NAVAL RESEARCH
END-OF-THE-YEAR REPORT - Part III
Viewgraph Explanations

NOTE: We have provided more than the required three viewgraphs. A minimal presentation might include the introductory viewgraph plus the "Inertial Sensing Technologies" slides.

Atom Interferometery (intro.)

Interferometers are extremely sensitive to changes in the relative phase between the interfering waves (e.g. via different interactions they may experience). Since atoms are capable of a wide range of interactions stemming from the varied properties that they exhibit (e.g. magnetic moments, polarizabilities, absorption frequencies), atom interferometers with separated beam paths offer an opportunity for a rich variety of precision and fundamental studies.

Our group has developed two types of atom interferometer, one based on nanofabricated diffraction gratings arranged in a Mach-Zehnder geometry (typical interference pattern shown on the upper right), and one based on Ramsey's celebrated "Separated Oscillatory Fields" technique (typical interference pattern shown on the lower right).

Recent accomplishments achieved using these two unique devices include a demonstration of an atomic interferometer's applicability as an inertial sensor, groundbreaking studies in the field of longitudinal atom optics and a quantitative study of quantum decoherence caused by different mechanisms. Along the way we have developed a cadre of atom optical elements that will be useful in future experiments both in our laboratory and elsewhere.

Transverse Interferometer:

A schematic of the atom interferometer is shown. In this design, which is based on the Mach-Zehnder geometry, a supersonic beam of atoms is coherently split, recombined and the resulting fringe pattern is imaged using three transmission diffraction gratings. A unique feature of this interferometer is the physical separation of interfering beam paths. Since the paths may be subjected to different potentials, the observable phase and amplitude changes of the interference pattern provide a new window to atomic interactions. Examples of experiments that take advantage of this feature include measurements of the complex index of refraction of sodium matter waves traveling through various gases and a measurement of the polarizabiltity of sodium.

## Inertial Sensitivity

Atom interferometers are much more sensitive to rotations and accelerations than interferometers based on light, typically by $\sim 10^{10}$ which is the ratio of an atom's rest energy to a photon's energy. Thus, atom interferometers hold great promise as ultra sensitive rotation sensors. In this shown the results of an experiment in which the interferometer was suspended and driven with a sinusoidal force. Although the interferometer itself 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.

## Inertial Sensing Technologies

In this graph, we plot sensitivity (the reproducibility with 1 s integration time) and resolution ( phase shift /angular velocity). The performance of the atom interferometer is comparable to those of commercial laser gyroscopes and, if optimized, is expected to be at least an order of magnitude more sensitive than the best laser gyroscope.

## Quantum Decoherence Rate

The contrast of our atom-beam interference fringes is a direct measure of quantum coherence. And because progress in fields such as quantum computation relies on understanding and correcting for mechanisms which destroy such coherence, we have studied the effects of different decoherence environments on our atom interferometer.

We measure the decoherence of our spatially separated atomic superposition due to spontaneous photon scattering. We observe a qualitative change in decoherence versus separation as the number of scattered photons increases and verify quantitatively the decoherence rate constant in the many photon limit. Our results illustrate an evolution of decoherence consistent with general models developed for a broad class of decoherence phenomenon.

# ATOM INTERFEROMETRY

Prof. David E. Pritchard, MIT

## OBJECTIVES

- Perform qualitatively new/more precise measurements in atomic physics
- Investigate fundamental concepts in quantum mechanics
- Develop new atom optical components and techniques
- Explore applications in inertial navigation

## APPROACH

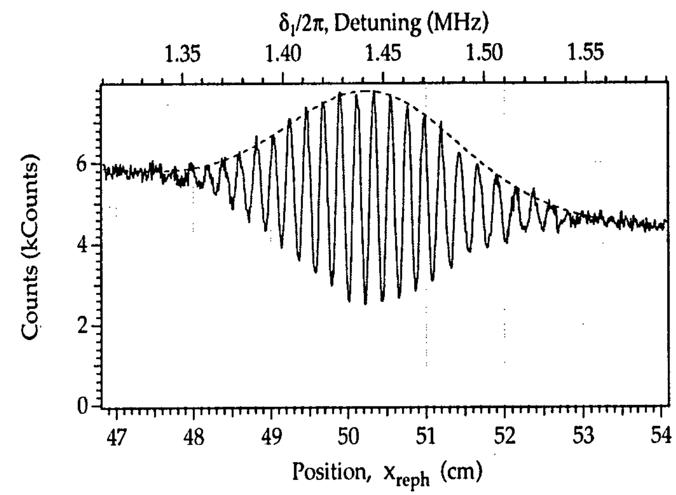
- Separated beam transverse interferometer
- Longitudinal interferometer based on Ramsey's separated oscillatory fields (SOF)

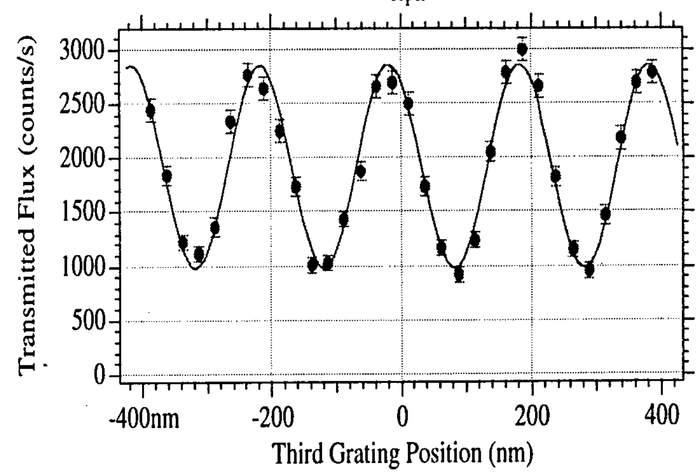
## ACCOMPLISHMENTS

- Demonstration of ultra-sensitivity to intertial motion
- Creation/detection of longitudinal coherences in an atomic beam
- First determination of the density matrix of an atomic beam
- Measurement of decoherence rate due to photon scattering

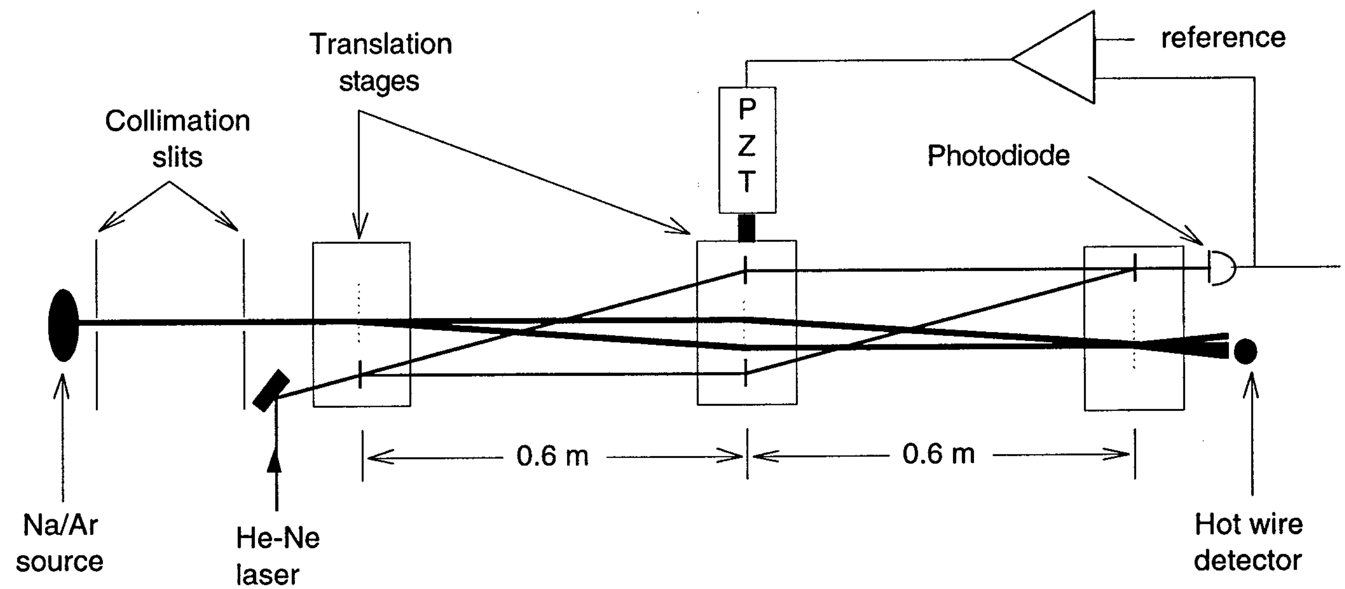
## IMPACT

- Rotational sensitivity comparable to commercial laser gyro, with potential for considerable improvement
- Development of versatile atom optical elements: beamsplitters, amplitude modulators, and velocity selectors
- Atom interferometry as a unique tool for many types of precision measurements



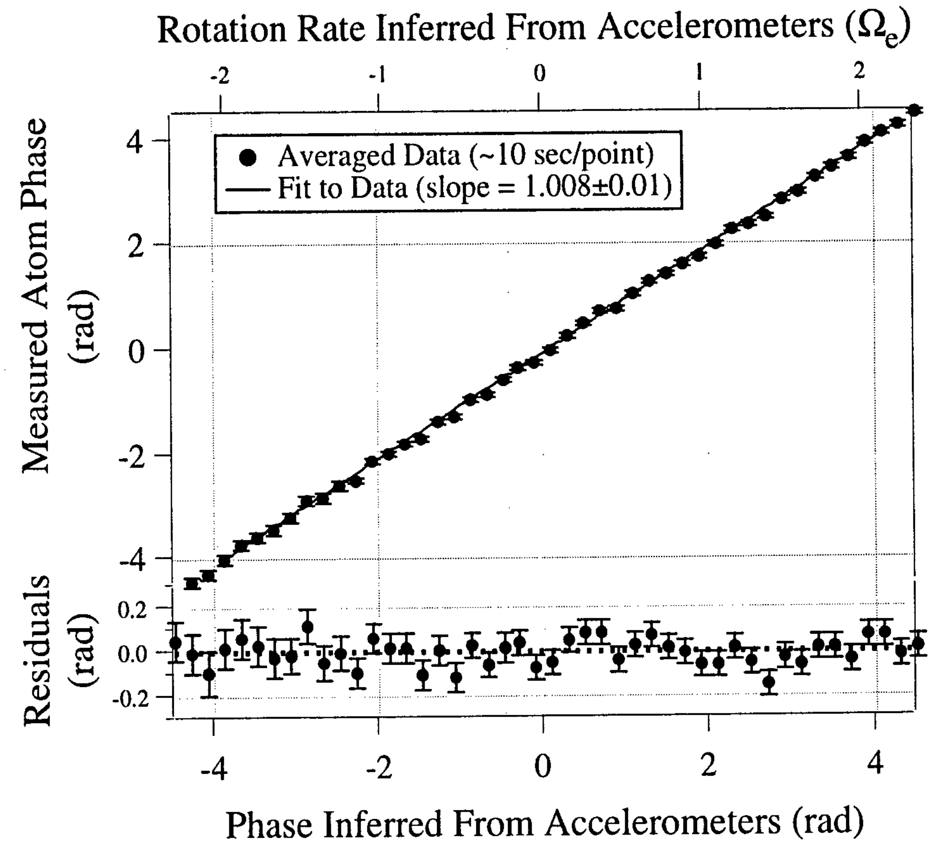



# TRANSVERSE INTERFEROMETER



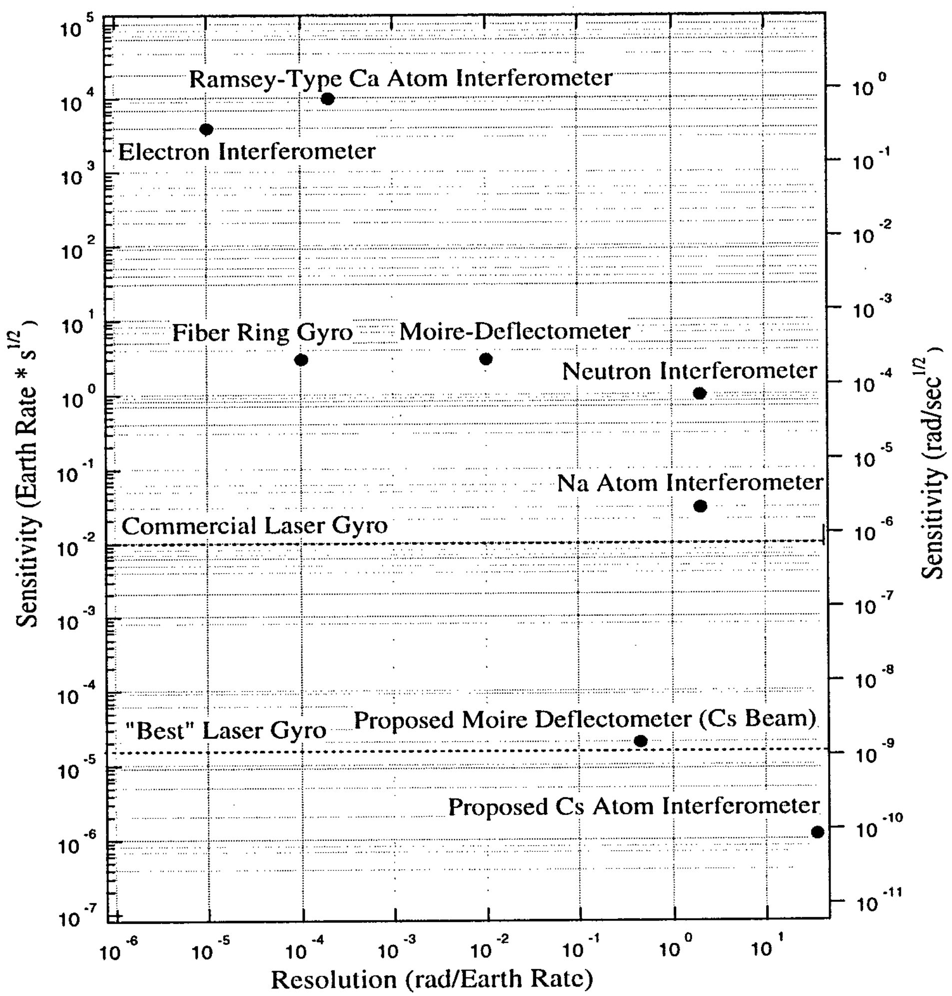

In our transverse interferometer, a supersonic beam of atoms is coherently split, then recombined. The resulting fringe pattern is imaged using three transmission diffraction gratings. Note the physical separation of interfering beam paths.

# INERTIAL SENSITIVITY

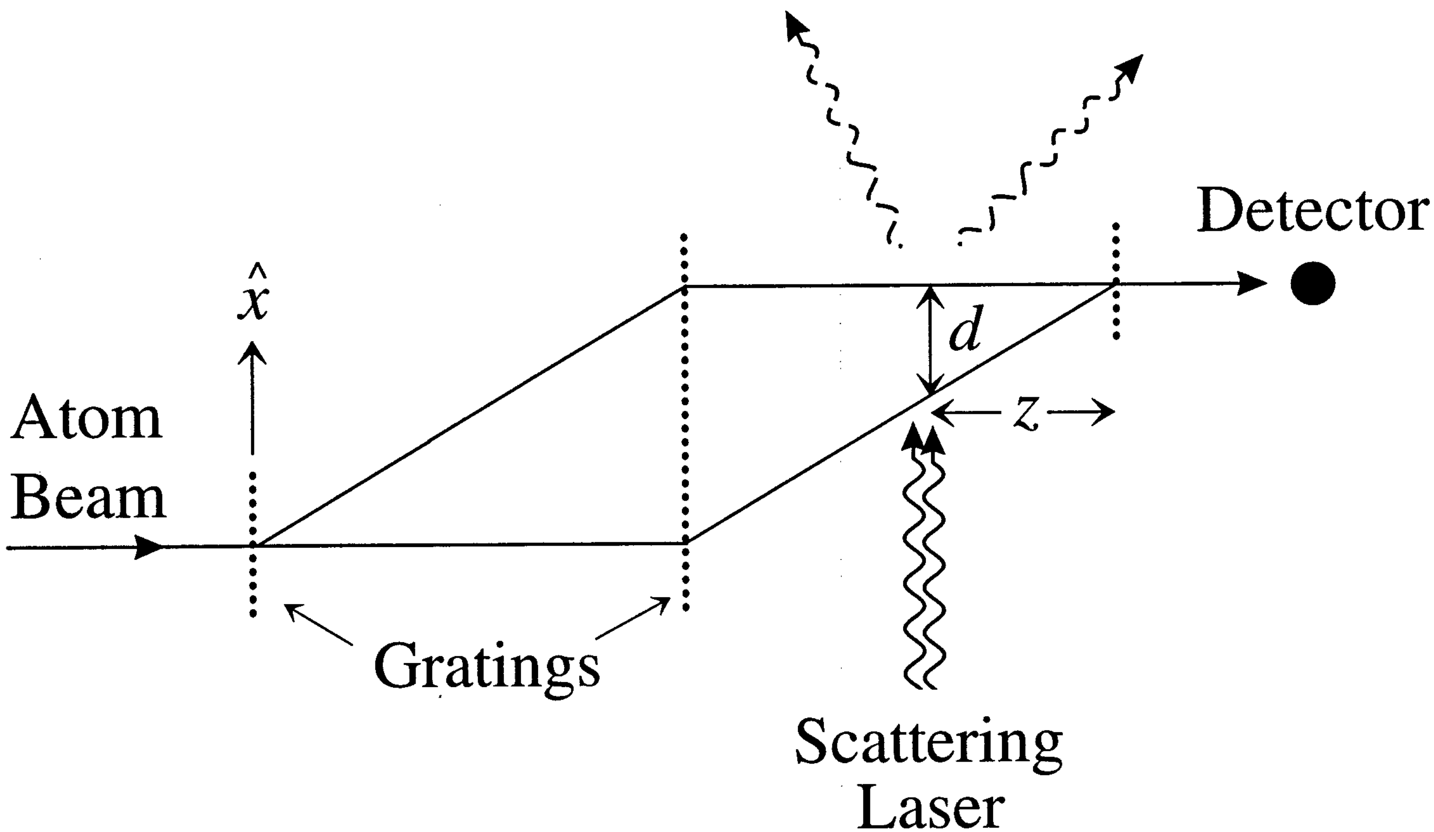



Rotation rate as inferred by the atomic interference pattern versus that measured directly using a pair of accelerometers.

# INERTIAL SENSING TECHNOLOGIES

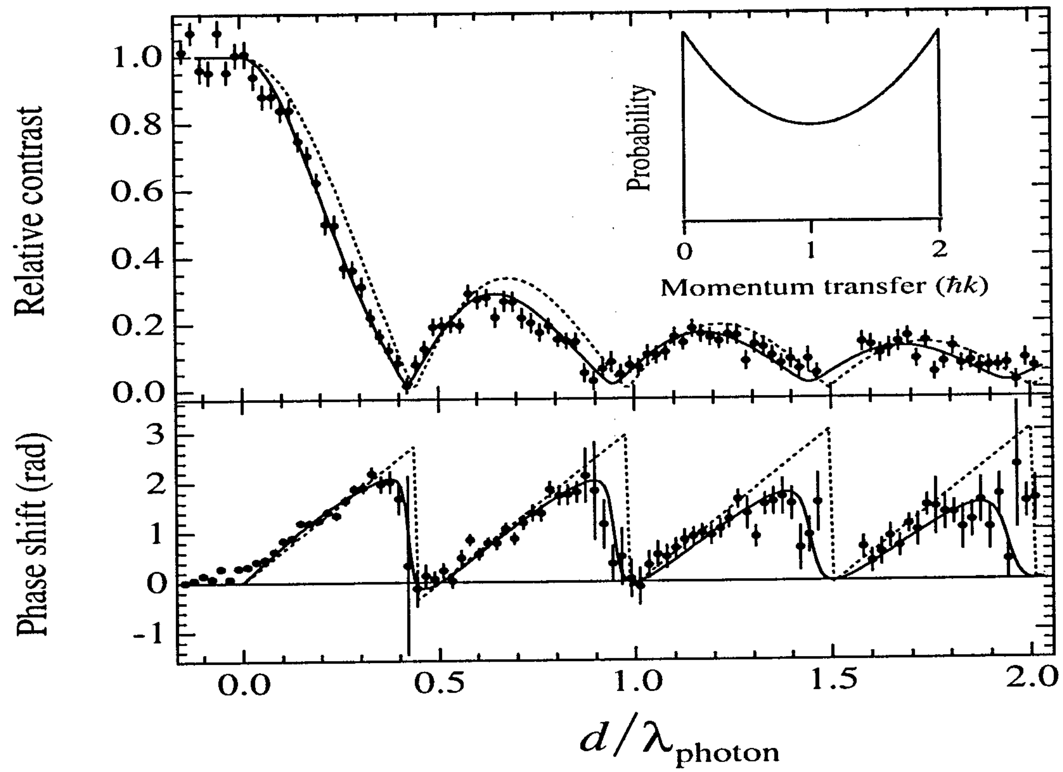


# MULTIPLE DECOHERENCE REGEIMES



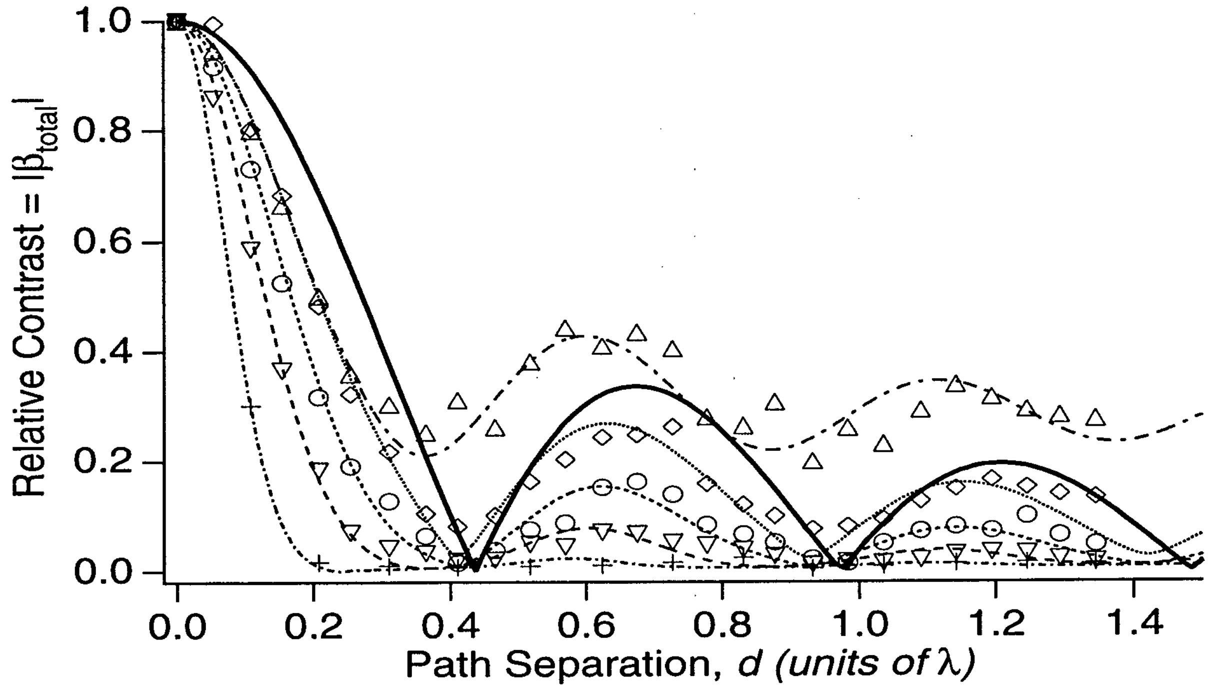

Decoherence caused by multiple scattering events (scattering several photons off of each atom in the interferometer) is qualitatively different than single-photon decoherence, and is relevant for qantum computers.

# SINGLE PHOTON DECOHERNECE




Previous data from our lab showing the loss of contrast, or decoherence, due to scattering one photon per atom at different locations within the interferometer. The insert shows the angular distribution of spontaneously emitted photons projected onto the initial laser beam axis.

# MULTIPLE PHOTON DECOHERNECE




Decoherence due to scattering many photons per atom, as a function of location within the interferometer can be modeled as phase diffuision. Each successive scattering event causes additional loss of phase coherence. The solid line is the single photon decoherence function. Also displayedd are the best fits from which we determined the average number of photons scattered per atom, n = 0.9 (upper triangles), 1.4 (diamonds), 1.8 (circles), 2.6(lower triangles), and 8.2 (crosses).

ATTACHMENT NUMBER 1

REPORTS AND REPORT DISTRIBUTION

REPORT TYPES

(a) Performance (Technical) Report(s) (Include letter report(s)) Frequency: Annual

(b) Final Technical Report, issued at completion of Grant.
NOTE: Technical Reports must have a SF-298 accompanying them.

(c) Final Financial Status Report (SF 269)

(d) Final Patent Report (DD 882)

| REPORTS DISTRIBUTION | | |
|---|---|---|
| ADDRESSEES | REPORT TYPES | NUMBER OF COPIES |
| Office of Naval Research<br>Program Officer Herschel S. Pilloff ONR 331<br>Ballston Centre Tower One<br>800 North Quincy Street<br>Arlington, VA 22217-5660 | (a) & (b)<br>w/(SF-298's) | 3 |
| Administrative Grants Officer<br>OFFICE OF NAVAL RESEARCH REGIONAL OFFICE BOSTON<br>495 SUMMER STREET ROOM 103<br>BOSTON, MA 02210-2109 | (c), (d) & SF-298's only for (a) & (b) | 1 |
| Director, Naval Research Laboratory<br>Attn: Code 5227<br>4555 Overlook Drive<br>Washington, DC 20375-5326 | (a) & (b)<br>w/(SF-298's) | 1 |
| Defense Technical Information Center<br>8725 John J. Kingman Road<br>STE 0944<br>Ft. Belvoir, VA 22060-6218 | (a) & (b)<br>w/(SF-298's) | 2 |
| Office of Naval Research<br>Attn: ONR 00CC1<br>Ballston Centre Tower One<br>800 North Quincy Street<br>Arlington, VA 22217-5660 | (d) | 1 |

If the Program Officer directs, the Grantee shall make additional distribution of technical reports in accordance with a supplemental distribution list provided by the Program Officer. The supplemental distribution list shall not exceed 250 addresses.