ATOM INTERFEROMETRY

Sponsors
ARO Grant: DAAG55-98-1-0429 “New Developments in Atom Interferometry”
NSF Grant: PHY98-77041 “Ionic, Atomic and Molecular Physics”

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Overview

We are pioneering new measurement techniques using coherent atom optics (such as beam-splitters, mirrors and lenses) to manipulate matter waves. We operate an atom interferometer, similar to a Mach-Zhender optical interferometer, which splits deBroglie waves of matter into two physically separated paths. After an interaction region where each atom can pass simultaneously on both sides of a metal foil, the matter waves recombine, forming interference fringes. We monitor the phase and contrast of these fringes, which are extremely sensitive to any interactions experienced by the atoms.

In the year 2000 we completed three experiments on decoherence. Presently, in Spring 2001, we are midway through a measurement of the matter wave index of refraction, and we are developing a novel atom optic for velocity multiplexing. Each project described in this report refines atom interferometry as a tool for making measurements of atomic properties and probing fundamental issues in quantum physics.

Recent Scientific Accomplishments

Decoherence

Using an improved atom interferometer we have completed three new experiments on decoherence, each of which offers insight into the origins of wave-particle duality. Decoherence is of fundamental theoretical importance for any quantum system interacting with its environment, and it is the major practical obstacle to achieving large scale quantum computing.

We studied decoherence in a system which is simple enough that for the first time the measured decoherence rate constant can be compared with ab initio calculations [KRC01]. This offers a benchmark measurement supporting several quite general theories of decoherence (many of which are directly relevant to quantum computation efforts). This recent experiment broadens the scope of our earlier, pioneering work on decoherence due to spontaneous photon emission [CHL95] by exploring decoherence as a function of the average number of photons scattered from each atom. Scattering multiple photons causes the same type of time-evolution of decoherence as interaction with a thermal bath, and is theoretically similar to any situation where the quantum system undergoes multiple independent dephasing events.

The heart of this experiment is the principle of complementarity, which forbids simultaneous observation of wave and particle behavior. Our results confirm that the atomic interference (a manifestly wave-like behavior) must be destroyed when the separation of the interfering paths, *d*, exceeds the wavelength of the probe, λ, (i.e. when it is possible to identify which path the atom traversed). Building upon the simple framework of the single-photon which-way experiment, we can easily derive the effect of continuous atom-light interaction involving many independent scattered photons. Figure 1 summarizes our results.

In the photon scattering experiment, decoherence results from quantum entanglement between an atom (which is referred to as the “system”) and the final momentum of the scattered photons (which collectively constitute the “environment”). In a second experiment, we replaced the random process of photon scattering with a deterministic momentum transfer caused by a diffraction grating. In this case, loss of contrast still occurs, but less abruptly as a function of separation, and this de-phasing arises from a qualitatively different reason. The atom’s own longitudinal momentum plays the role of the environment. This mechanism may not qualify as quantum decoherence, because entanglement between two degrees of freedom of a single particle can never demonstrate what Einstein referred to as “spooky action at a distance”.

Finally, we studied how an atom’s internal state controls its own decoherence rate. Because the same environment that causes decoherence can also optically pump atoms into an internal state which will no longer scatter laser light, the atom’s internal (electronic) state can determines the rate of external (spatial) decoherence.

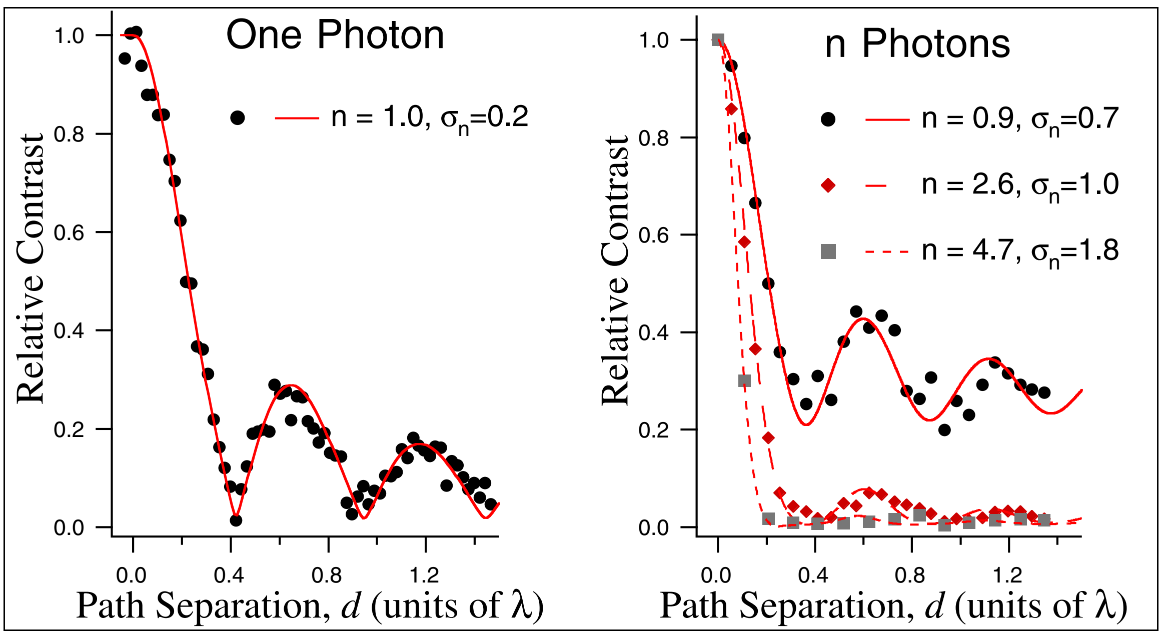

Figure1. Decoherence as a function of path separation. For increasing number of scattered photons, the overall amount of decoherence increases, and the contrast revivals present in the single-photon case disappear.

Matter-wave index of refraction

We are now in the process of measuring the matter-wave index of refraction for Na matter waves passing through a cell of Ar gas. In analogy to the transmission of light through materials, atom-waves passing through a dilute gas suffer a dispersive phase shift, We measure the ratio, $\rho = Re(n)/Im(n)$, of phase shift to amplitude attenuation, and we are searching for oscillations in ρ as a function of Na wavelength. Much theoretical work has been stimulated by our earlier measurements of ρ [SCE95], and there are conflicting predictions on the dependence of ρ on velocity [ADV95, FYK97]. The variance in the predictions arises because ρ is very sensitive to both long-range (>5 Angstrom) and medium-range near the well of the atom-atom interaction potential. By studying oscillations in ρ (which have never yet been observed) we hope to constrain the theoretical models of van der Waals molecular potentials.

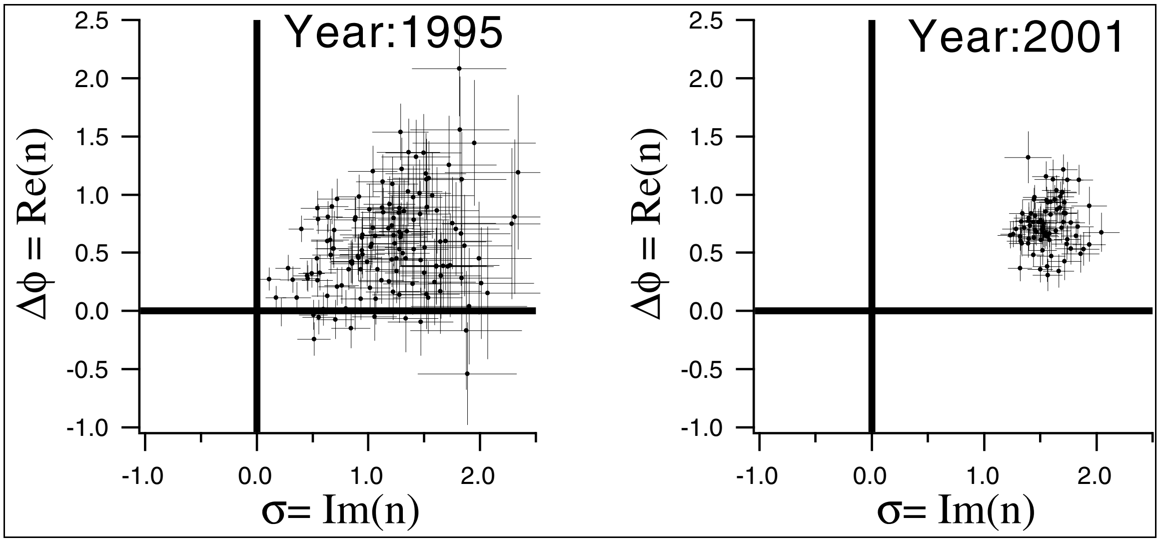

Figure 2. Raw data on the matter wave index of refraction. The improvement in raw data quality will help refine basic knowledge of molecular potentials.

Electronic phase chopping

We have prototyped a novel atom optic, which we are developing for use as a velocity multiplexing tool. Velocity multiplexing using a pair of slotted wheels was previously proposed for improving experiments on dispersive interactions [HPC95]. While this could improve absolute measurements of atomic polarizability [ESC95], spinning mechanical disks have disadvantages such as: vibrations, reliability, mechanical timing alignment, and a reduction of atom flux to ¼ of the unchopped level. Our new chopping method will use two compact electric-field gradients, which can be electronically pulsed to give a phase shift of π radians to atoms in a comb of velocity space. This technology should retain 100% of the atom flux, be widely tunable, and ultimately improve measurement accuracy for any dispersive phase shift by an order of magnitude.

NEW PUBLICATIONS

[KCR01] D.A. Kokorowski, A.D. Cronin, T.D. Roberts, and D.E. Pritchard, "From Single to Multiple-Photon Decoherence in an Atom Interferometer"
Accepted for publication in Phys. Rev. Lett., quant-ph/0009044

[PCG01] D. E. Pritchard, A. D. Cronin, S. Gupta, D.A.Kokorowski, "Atom Optics: Old Ideas, Current Technology, and New Results"
Accepted for publication in Annalen der Physik, 2001

[GLC01] S. Gupta, A.E. Leanhardt, A.D. Cronin, and D.E. Pritchard, ”Coherent Manipulation of Atoms with Standing Light Waves”
To be published in Conference Proceedings of Cargesse Summer School 2000 on Atom Lasers.

Conference Presentations:

Versions of the research talk: “Measuring the Quantum Decoherence Rate due to Multiple-Photon Scattering in an Atom Interferometer”, with published abstracts were given at:

DAMOP 2000: APS meeting, Storrs, CT June 14, 2000
Summer School on Atom Interferometry, Cargese, France, July 14, 2000
Colloquium, Williams College, Williamstown, MA., October 13, 2000
Modern Optics and Spectroscopy Seminar, MIT, Cambridge, MA November 7,2000
Colloquium, University of Connecticut, Storrs CT, November 20, 2000
Colloquium, University of Puget Sound. Tacoma, WA November 27, 2000
Coherent Spectroscopy Seminar, University of Washington, Seattle, WA, Nov. 29,00
Physics Colloquium, Whitman College, Walla Walla, WA, December 1, 2000
100 Years of Quantum Theory Conference, Vienna, Germany, December 2000
Physics of Quantum Electronics Conference, Snowbird, UT, January 8, 2001

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[ADV95] E.Audouard, P. Duplaa, and J. Vigue, “Glory and Resonance Effects in the Index of Refraction for Atomic Waves”, Europhys. Lett. 32 pg 397 (1995)

[SCE95] J. Schmiedmayer, M.S. Chapman, C.R. Eksrom, T.D.Hammond, S.Wehinger, and D.E. ritchard, “Index of Refraction of Various Gases for Sodium Matter Waves”, Phys. Rev. Lett. 74 pg 1043 February (1995)

[CHL95] M.S. Chapman, T.D. Hammond, A.L. Lenef, J.Schmiedmayer, R.A.Rubenstein, E.Smith, and D.E.Pritchard, “Photon Scattering from Atoms in an Atom Interferometer: Coherence Lost and Regained” Phys. Rev. Lett. 75 pg. 3783 (1995)

[ESC95] C.R.Ekstrom, J.Schmiedmayer, M.S. Chapman, T.D.Hammond, and D.E.Pritchard, “Measurement of the Electric Polarizability of Sodium with an Atom Interferometer” Phys. Rev. A 51 pg. 3883 (1995)

[HPC95] T.D. Hammond, D.E. Pritchard, M.S. Chapman, A. Lenef, and J. Schmiedmayer,. “Multiple Velocity Selection for Precision Matter Wave Interferometry”, Appl. Phys. B 60, 193 (1995)