ATOM INTERFEROMETRY

Sponsors
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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-Zehnder 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.

We are currently using our apparatus to measure atomic properties—we have completed the first measurement of glory oscillations in the index of refraction for matter-waves, and we have demonstrated a new technique that has the potential to greatly increase the accuracy of interferometric measurements.

Glory Oscillations in the Matter-Wave Index of Refraction

An atom interferometer can be used to measure the matter-wave index of refraction for atomic De Broglie waves passing through a target gas. In analogy to the transmission of light through materials, atom-waves passing through a dilute gas suffer a dispersive phase shift, as well as an attenuation. We measure the ratio, $\rho = Re(n)/Im(n)$, of phase shift to attenuation.

Much theoretical work has been stimulated by our earlier measurements of ρ [SCE95], which prompted new predictions on the *velocity* dependence of ρ. There are conflicting predictions of the dispersion in ρ—i.e. on its dependence on the wavelength (or velocity) of the atom waves [ADV95, FYK97]. The variance in the predictions arises because ρ is very sensitive to both long-range (>5 Angstrom) and medium-range (0.5 to 5 Angstrom) atom-atom interactions. We undertook a new experiment to measure the dispersion in the index of refraction in an effort to clarify conflicting predictions.

We have measured the velocity dependence of ρ for sodium de Broglie waves in gases of Ar, Kr, Xe, and N_2. Our measurement over a wide range of velocities confirmed the presence of *glory oscillations* in the function ρ(v), a novel interference effect arising from the enhancement of quantum forward scattering that had never before been observed in the index of refraction.

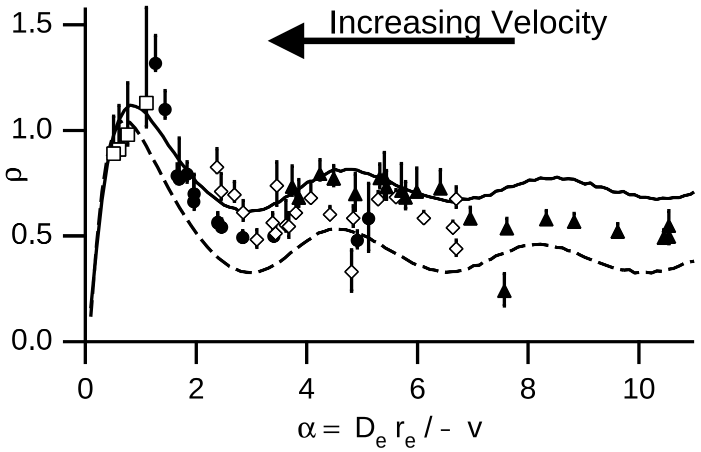

Figure 1: Matter wave index of refraction for sodium de Broglie waves measured in different gases over a wide range of velocities (data points). The variation in the index of refraction indicates a first-ever observation of glory oscillations in the phase shift. Various theoretical predictions (lines) disagree with our measurements.

Our measurements did not confirm any of the theoretical predictions. Rather, they suggest that more work is to be done in the theoretical understanding of the interatomic potentials, especially in the transition region between the exponentially repulsive core and the long-range, attractive Van der Waals potential. Our new measurements will likely stimulate theoretical work to understand the complex interactions better than ever before.

A Phase Multiplexing Technique for Accurate Interferometric Measurements

The velocity distribution of our atom beam limits the accuracy of several different interferometer experiments. Most interactions we seek to study, such as the Stark shift, or rotations, cause a phase shift that depends linearly on interaction time, i.e. is proportional to 1/velocity. A spread in velocity of the atoms in the interferometer therefore causes a spread in phase-shift of the interference patterns of different velocity classes. This lowers the atom-interference contrast if the variation of the applied phase is too large. Inhomogeneous broadening of this nature has limited the strength of any interactions we can study because low contrast means low signal to noise ($S/N \sim C\,[Rt]^{-1/2}$, where C is contrast, R is the average count rate and t is the data collection time).

Velocity multiplexing [HPC95] has been proposed to overcome this de-phasing without losing the count rate R as much as would happen with simple velocity selection. If we pass the beam through two choppers that chop at the proper frequency, the velocities that survive the multiplexing will all accumulate the same phase shift, modulo 2π. This causes a revival in contrast at some large phase shift, greatly increasing our relative accuracy since our phase error is roughly constant whereas the total phase is much larger. The chopping decreases the flux by a factor of four, and degrades the signal even further because atoms at the edges of the selected velocity segments accumulate more or less than exactly 2π N phase.

We have devised and implemented a novel velocity-multiplexing scheme that works on the quantum phase rather than on the classical probability as do choppers. It has the primary advantage over mechanical shutters of transmitting all of the atom beam flux, and furthermore does not lose contrast for atoms of any velocity: The idea is to apply a phase at each of the interaction regions which changes with time in such a way that slower atoms get more than 2π N relative phase after passing through the two short interaction regions which replace the choppers. Under the right conditions, the additional phase is *exactly* cancelled by the greater phase of the main interaction (that is being measured). Achieving this would require a continuously increasing phase at both short interaction regions which is not sensible. Instead, we apply a sawtooth that periodically returns to zero after reaching 2π. This has the advantage that the average effective phase depends on the frequency of the sawtooth, not its amplitude.

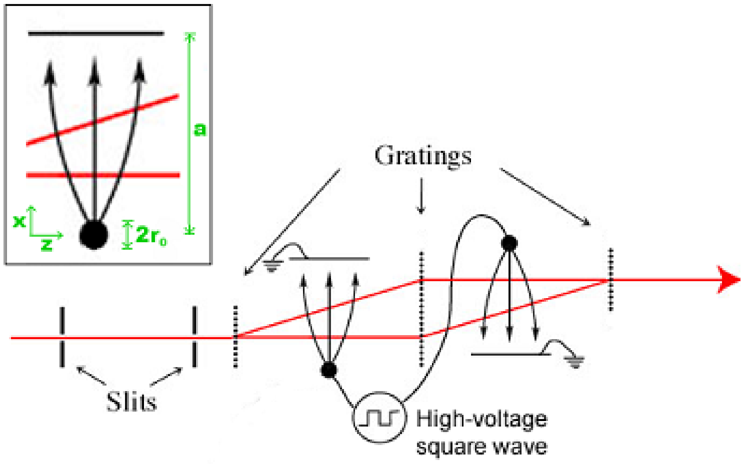

Figure 2: Dispersion compensators. Two regions of electric field gradient each can produce tailored time-dependent phase shifts in the interference fringes. By pulsing the voltage at an exact frequency, we create a situation where contrast revivals can occur. We will use this to improve precision measurements with atom interferometers.

We have implemented this scheme using two separated regions of inhomogeneous electric fields that induce a relative phase shift between the two paths of the interferometer that can be continuously varied in time. The total time-averaged phase shift due to the regions creates a $1/v$ velocity-dependent phase shift that cancels out the velocity dependence of the interaction phase we are trying to measure. The result is a rephasing of the interference pattern that was dephased due to the interaction. Furthermore, the fact that the rephasing is velocity-independent means that the precision of the interaction measurement no longer depends on knowing precisely what the mean velocity of the beam is—only the chopper spacing and period must be known.

Compared to the old velocity-multiplexing method of rephasing, our electronic method allows measurements with the same accuracy in 1/20 of the time. In addition, the electronic multiplexing causes no vibrations or magnetic field fluctuations, and is easily tunable over a wide range of frequencies. We intend to use this technique to improve measurements of atomic and molecular polarizability [ESC95].

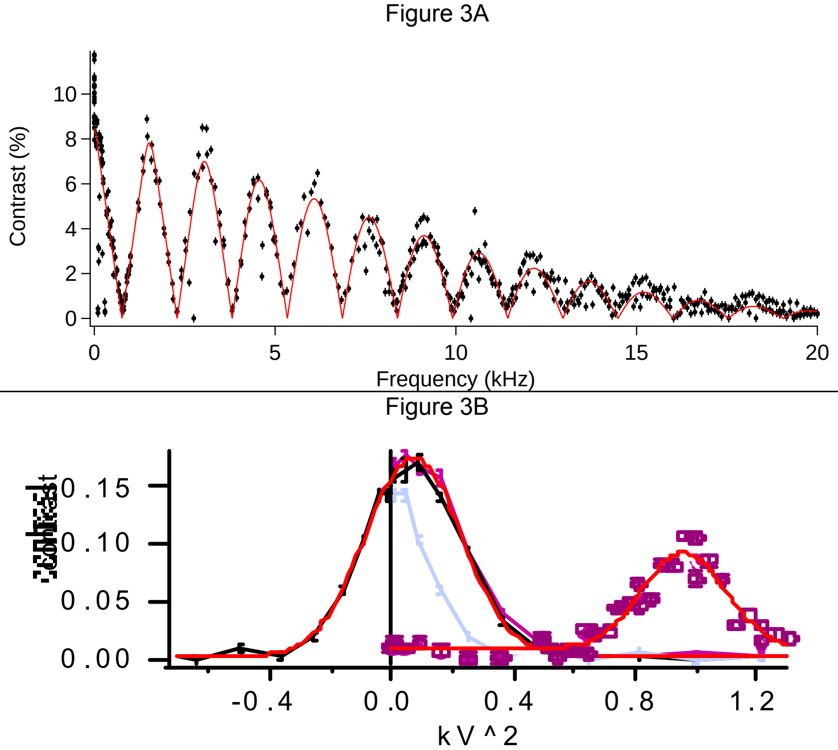
Figure 3A

Figure 3B

Figure 3. A: Contrast revivals as a function of frequency indicate the dispersion compensators are working properly in the absence of an applied electric field. B: The contrast revival (the peak on the right) as a function of applied electric field demonstrates that the polarizability can be measured at fields much higher than the previous method (the peak on the left).

Contrast Interferometry using BECs to Measure α

The fine structure constant α is one of the most fundamental and best-measured quantities in physics, but the discrepancies between different precision measurements of α are noteworthy [KIN96]. A new route to measure α has emerged over the past decade, involving only atomic physics measurements [TAY94]. The photon recoil frequency ω_{rec}, which corresponds to the kinetic energy of an atom recoiling due to absorption of a photon, is an important link in this new method. Using an atom interferometer based on Bose-Einstein condensates (BEC), we have demonstrated a method for a high precision measurement of this frequency. This technique may well lead to the most accurate value for α.

We constructed a prototype of our interferometric scheme (figure 1(a)) using sodium Bose condensates in our first generation BEC machine [MAV96]. Using optical standing waves as diffraction grating [GLC01], we split the BEC into three paths (1, 2 and 3) and then recombined these paths after a controllable evolution time 2T. Path 2 is at rest, while paths 1 and 3 have kinetic energies corresponding to 2 photon recoils. Around the recombination time 2T, paths 1 and 2 and paths 2 and 3 produce interference patterns (matter wave gratings) of identical periodicity, which travel in opposite directions, resulting in an oscillatory contrast of the net matter wave grating. The relative phase accumulated due to the recoil energy is encoded in this contrast. This was read out continuously by reflecting a weak probe beam from the matter wave grating. Figure 1(b) shows a typical signal from a single shot in our three-path contrast interferometer. The long coherence time of a BEC allows the matter wave grating to persist for many oscillations of the contrast, allowing a precise determination of Φ(T), the phase of the grating at t=2T.

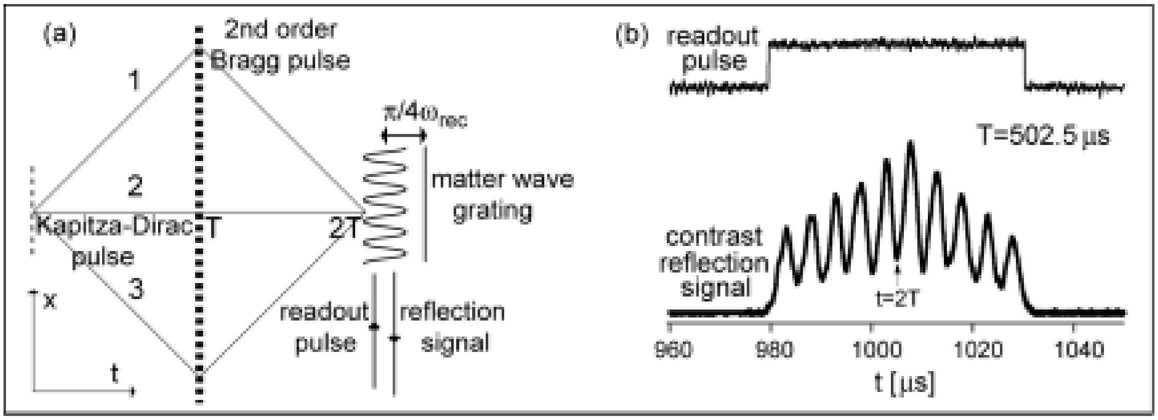

Figure 1. Three-Path Contrast Interferometer. (a) shows the basic scheme in a space-time representation. An optical standing wave pulse at t=0 splits the BEC into three momentum states (paths 1, 2 and 3). A second pulse at t=T reverses 1 and 3, while leaving 2 unaffected. Pulse 1 is in the Kapitza-Dirac regime and pulse 2 is in the Bragg regime [GLC01]. Around t=2T, a matter wave grating with contrast oscillating at $8\omega_{rec}$ is formed, which is readout by reflection with a weak probe beam. (b) shows a typical signal from a single shot (T=502.5μs for this shot). The oscillation period for sodium is 5μs.

The recoil frequency is obtained from the variation of Φ(T) with interferometer time T (figure 2). We have obtained a 15ppm measurement of ω_{rec} for sodium from a linear fit. Increasing the momenta of paths 1 and 3 using additional optical gratings increases In addition, we have doubled the momenta of paths 1 and 3 between t=0 and t=T and observed that the recoil phase increases quadratically with the final momentum order chosen. This suggests that we could make a much more precise measurement by increasing the order.

Our scheme is insensitive to the phase of the atomic fringes at t=2T, since the reflection only records the contrast. Optical phase noise from mirror vibrations is thus suppressed. We have demonstrated this by electronically simulating phase variations in our optical gratings and observing the immunity of the contrast signal to this variation.

The measurement precision scales linearly with the total recoil phase accumulated during the free evolution time of the atoms. We plan to scale up our interferometer to long times and high momentum order by changing from the current horizontal setup to a vertical setup in an atomic fountain geometry. Such a configuration is feasible in our new BEC machine where the condensate can be created in one chamber and transported into another [GCL02]. We expect to reach ppb precision for T~100ms and a ten-fold increase in the momenta of paths 1 and 3. In addition, our scheme is insensitive to the AC Stark shift of the atomic energy levels due to the intensity of nearby laser light, as well as to magnetic field gradients. This will improve our measurement accuracy. The immunity to phase noise will alleviate the difficulty of maintaining complete vibration isolation during the long free evolution times.

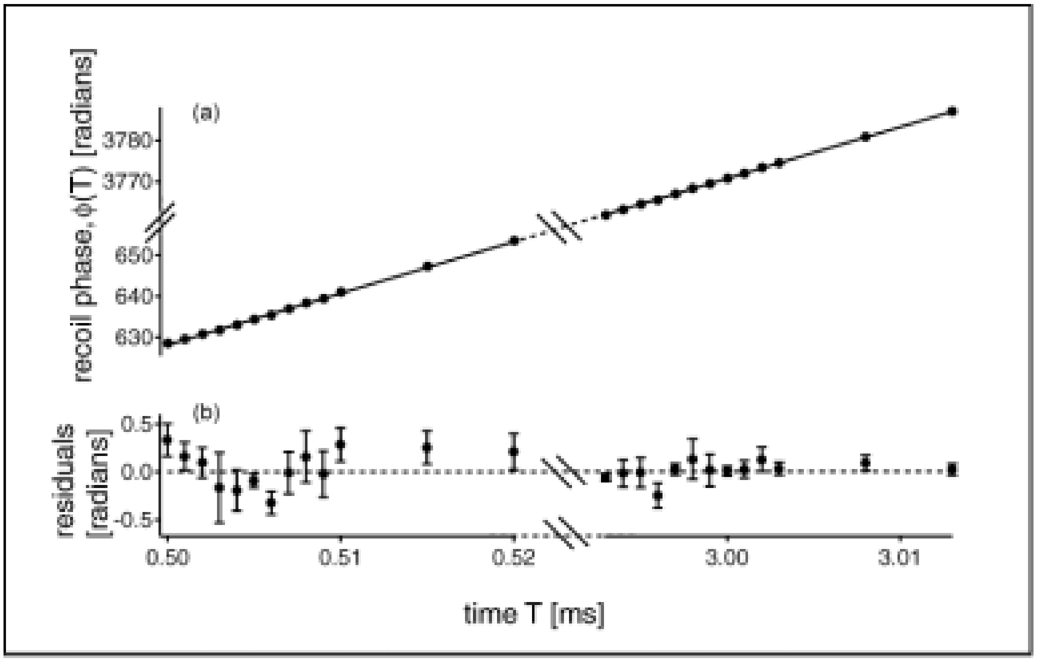

Figure 2. Measurement of the photon recoil frequency. (a) shows $\Phi(T)$, the measured phase of the contrast signal at t=2T, for two datasets with T around 0.5ms and 3ms. The linear fit determines ω_{rec} to 15ppm. (b) shows the residuals from (a). The error bars are about half as large for the longer times (~3ms) due to the decay of spurious matter wave gratings which contribute more at shorter times (~0.5ms). This is encouraging for the prospect of scaling up the interferometer to very long times (~100ms).

New Publications

[RCK02] T.D. Roberts, A.D. Cronin, D.A. Kokorowski, and D.E. Pritchard, “Glory Oscillations in the Index of Refraction for Matter-Waves”, to be submitted.

[KCR01] D.A. Kokorowski, A.D. Cronin, T.D. Roberts, and D.E. Pritchard, “From Single to Multiple-Photon Decoherence in an Atom Interferometer” PRL 86 pg 2191, (2001)

[PCG01] D. E. Pritchard, A. D. Cronin, S. Gupta, D.A. Kokorowski, “Atom Optics: Old Ideas, Current Technology, and New Results” Ann. Phys. 10 pg 35, (2001)

Invited Conference Presentations

Physics of Quantum Electronics Conference, Snowbird, UT, January 8, 2001
DAMOP 2001: APS meeting, London, Ontario May 2001
Mechanisms for Decoherence, Austin, TX, October 2001

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