ATOM INTERFEROMETRY

Annual progress report to RLE

Sponsors:
Army Research Office
DAAH04-94-G-0170 (61702)
DAAG55-97-1-0236 (65672)
DAAH04-95-1-0533 (63619)
DAAG55-98-1-0429 (67135)
Office of Navel Research Contract
N00014-96-1-0432 (64312)
Joint Services Electronics Program
DAAG55-98-1-0080 (66512)
National Science Foundation
PHY-9514795 (64503)

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Keywords:
Atom Optics, Atom Interferometry

Introduction:

deBroigle's 1924 suggestion that material particles such as atoms should have wave properties was arguably the key that unlocked quantum mechanics two years later. Starting in the mid 1980's, workers in the new field of atom optics put this suggestion to use by developing ways to manipulate atoms as waves that can be diffracted and focussed. Our lab combined three atom gratings to create an interferometer in which atomic deBroglie-waves are coherently split and separated by a metal foil before they recombine and produce interference fringes. Because our atomic beam deBroglie wavelength is only 1/5 of an Angstrom (20,000 times smaller than the wavelength of blue light), the fringe pattern is an extremely sensitive indicator of any perturbation to the interferometer. Our ability to accurately measure interactions that displace the deBroglie-wave phase has led to qualitatively new measurements in atomic and molecular physics, fundamental tests of quantum mechanics and new ways to measure accelerations and rotation.

• Atom interferometers permit completely new investigations of atoms and molecules including precision measurements of atomic polarizabilities that test atomic structure models, determination of long range forces important in cold collisions and Bose-Einstein condensation, and measurements of molecular polarizability tensor components.

• Atom interferometers can be used to investigate basic phenomena in quantum mechanics. These include measurements of topological and geometric phases, and quantum decoherence.

• The large mass and low velocities of atoms makes atom interferometers especially useful in inertial sensing applications, both as precision accelerometers and as rotation sensors. They have a potential sensitivity to rotations ~10^{10} greater than that of optical interferometers with the same enclosed area.

• In the future we anticipate atom interferometers will be used to precisely measure atom-surface interactions.

• Atom lithography using coherently manipulated fringe patterns that are directly deposited onto substrates is another promising application.

Our group has pioneered many of these areas, including the first atom interferometry experiments that employed physically separated paths to make precision measurements [1], the first quantitative demonstration of an atom interferometer inertial sensor [2], and the development of longitudinal atom interferometry [3].

Longitudinal Atom Interferometry

Over the past year, we published papers on a series of atom optical experiments using a longitudinal interferometer (Figure 1). This interferometer consists of a pair of differentially detuned, separated oscillatory fields (DSOF), that separate the two interfering paths in longitudinal momentum space rather than position space. In a first experiment [3], we demonstrated that the dephasing of an amplitude-modulated atomic beam due to the large dispersion of the vacuum for matter waves can be reversed, using DSOF, in a process analogous to half a spin echo. Turning the process around, we were able to produce ‘remote’ amplitude modulation at any desired location in the beam. We went on to measure the quantum state of a beam which had been non-trivially modulated [4], in the first demonstration of our general technique for using DSOF to determine the longitudinal density matrix of such systems [5]. Finally, we performed a search of our supersonic beam source [6], looking for evidence of inherent coherences which would be undetectable using conventional techniques. The results of this last experiment have resolved a long standing controversy over the correct quantum description of the atomic beams used in all sorts of atomic physics experiments. We have also developed a fully quantum mechanical formalism [5] for describing molecular beam resonance. This formalism provides a new perspective on the resonance phenomena which should lead to further theoretical and experimental advances in the area of longitudinal atom optics.

Rephased Amplitude Modulation

When high-frequency (> 100 kHz) amplitude modulation is applied to our atomic beam, the ‘packets’ of atoms produced quickly separate due to the distribution of their atomic velocities. A detector placed more than a few centimeters downstream will see no evidence of the modulation, but rather simply a constant flux of atoms. The DSOF interferometer, however, introduces a velocity dependent phase shift that can be tailored to cancel this natural dephasing. This allows us to detect the ‘hidden’ amplitude modulation, which appears as a time-independent interference signal easily observed by a dc detector.

Measuring the Density Matrix of a Matter-Wave Beam

As indicated above, amplitude modulation of an atomic beam can be detected using the DSOF interferometer. An amplitude modulated beam will exhibit a characteristic interference signal at a particular frequency setting of the DSOF resonance coils. The modulation can then be deduced from the relative frequencies of the two DSOF coils;

and the modulator's location can be inferred from the average detuning of the coils from atomic resonance.

More generally, a Fourier transform of the interference fringes observed at a given DSOF setting corresponds to a slice of the atomic density matrix. Thus, by sweeping the DSOF coil frequencies, we were able to measure the entire density matrix, obtaining the complete set of knowable information about the quantum state of out atomic beam. In a recently completed experiment, we measured the density matrix of a beam that had been doubly amplitude modulated. In Figure 2 are plotted our results, 'slices' of the density matrix for this system, as determined using our DSOF interferometer.

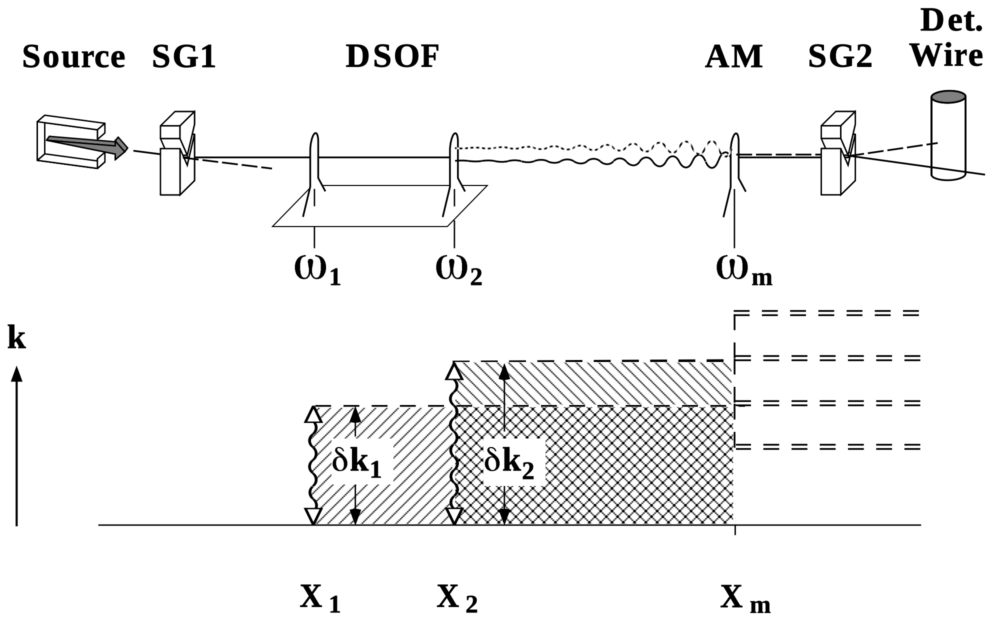

Figure 1: Longitudinal interferometer: the interfering paths are separated in momentum and internal state space, rather than position space. Atoms incident in the ground state are excited either in the first or second of two "DSOF" (for Differentially Detuned Separated Oscillatory Fields) coils. As the 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.

Searching for Coherences

Using the same Fourier transform technique as in the density matrix measurement, we have performed a search of our atomic beam source for any intrinsic momentum coherences (which would appear as amplitude modulation) up to a frequency of 100 kHz. To do this, we simply looked for interference fringes at all possible modulation frequencies and relative phase shifts. Our data primarily indicate the absence of any such intrinsic modulation. This confirms a long standing, yet never proven, assumption that the density matrix of an atomic beam is essentially diagonal—that is, there are no detectable correlations between different momentum components of the beam. This implies that there is no regular emission of wavepackets from the oven, for example. This knowledge will be important to the field of atom optics as we attempt to exert ever finer control over the quantum state of atomic beams (e.g. in atom lithography).

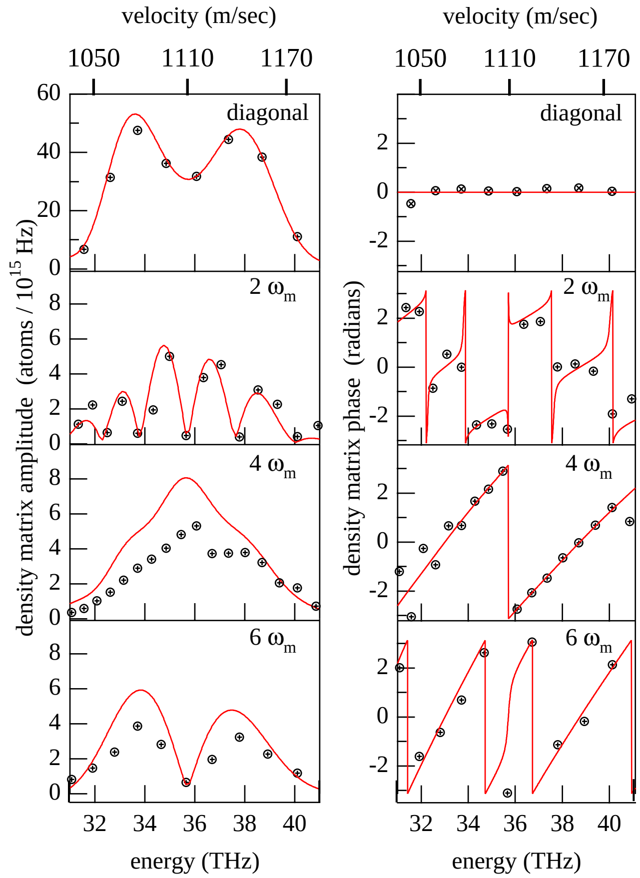

Figure 2: Measured amplitude (a) and phase (b) of the doubly amplitude modulated density matrix with modulation frequency $\omega_m = 2\pi \times 60.9$ kHz. The solid lines are a theoretical prediction based on the parameters of the modulation.

Transverse Atom Interferometery

We have recently upgraded our transverse interferometer by mounting the atomic diffraction gratings on a rigid board which is suspended within the apparatus. This improves the vibrational and thermal stability of the interferometer; and accordingly, we observe dramatically less phase drift between the two separated paths. We also redesigned the vacuum chamber for greater access to the experimental components. It now includes a test facility which we use to charactarize several atomic diffraction gratings at a time.

Having made these improvements, we plan now to emphasize new and more precise measurements in atomic physics as well as fundamental experiments in quantum mechanics. Exploiting the unique capability of our separated beam interferometer to apply well defined interactions to only one arm of the interferometer, we aim to significantly improve our knowledge of atomic and molecular properties.

Polarizability of Multiple Alkalis

An atom's polarizability governs its interaction with electric fields and is an important parameter in Van der Waals interactions, electric dipole transition rates, and long-range interatomic potentials. We will measure the polarizabilities of the alkali metals through cesium to <0.1% accuracy—more than an order of magnitude better than current values, and to measure their relative polarizability at the 0.01% level. The species independence of our gratings (cf light gratings) allows us to switch alkalis easily, and velocity multiplexing will increase our accuracy and precision to the 0.1% and 0.01% targets. Our relative measurements will ultimately be normalized by a single, higher precision experiment using a sodium BEC.

Anisotropic Polarizability of Sodium Molecules

We will also make the first measurement of both the parallel and the perpendicular components of the polarizability of the dimer molecule Na_2. This will permit tests of various approximations used in molecular structure calculations. The asymmetry of the polarizability causes the electric field induced phase shift to depend on the molecule's rotational state. The beating of interference patterns for molecules in different rotational states generates considerable structure as a function of field strength and permits the accurate determination of both polarizability components.

Velocity Dependent Index of Refraction

We were the first to investigate the index of refraction of gasses for sodium matter waves, by measuring the phase shift when the sodium (and molecular sodium) de Broglie waves in one arm of our interferometer passed through a gas cell [7]. We now propose to extend our study by varying the velocity of our sodium beam to adjust the average center of mass energy of the inter-atomic collisions, and to reduce the uncertainty in center-of-mass energy by cooling the gas cell to liquid nitrogen temperatures. In optical parlance, we will measure the dispersion, i.e. the variation of index with wavelength. These measurements will test the new theoretical predictions inspired by our earlier work and refine the shapes of the long-range potentials between sodium and other gases. We hope to observe glory oscillations; a novel interference effect manifest as oscillations in the index of refraction as a function of velocity [8].

Decoherence

In a recent experimental realization [9] of Feynman's gedankenexperiment, we explicitly demonstrated that the loss of interference due to scattering a single photon from an atom in our interferometer is directly related to the degree of "which-path" information contained in the final state of the scattered photon. While this supports the general picture of decoherence as "monitoring by the environment," theorists warn [10] that the intuition derived from simple experiments does not necessarily extend to cover more realistic systems such as might be encountered in quantum computers. We will extend our previous experiment to approach the limit of a single quantum object interacting with a thermal environment (i.e. blackbody radiation), the mechanism most often invoked to explain the fragility of superposition states in quantum computation.

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