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MATTER-WAVE INTERFEROMETRY WITH LASER COOLED ATOMS

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This research program is concerned with matter-wave interferometry of laser cooled atoms. A slow beam of laser cooled rubidium atoms will be used as the matter-wave source. The atom optical elements are microfabricated amplitude transmission gratings which will be used in a three-grating interferometer to split and recombine the rubidium beam. The atomic interferometer will be a useful new tool with which to perform precision experiments in atomic physics, quantum optics, and gravitation.

The research program takes advantage of three new technologies, the combination of which provides a unique opportunity to construct a compact and stable interferometer. The techniques of laser cooling and trapping are used to produce cold rubidium atoms in a well collimated beam. Commercially available diode lasers with optical feedback frequency stabilization are used for the laser cooling and trapping beams and for atomic beam diagnostics. Finally, submicron transmission gratings made with high-resolution electron-beam lithography are used as the coherent beam splitters of the atomic interferometer. Figure 1 shows the proposed interferometer geometry with the two paths that are generally used in such a device. The three-grating Bonse-Hart interferometer is a particularly useful design since it has intrinsically equal path lengths and is relatively insensitive to misalignments.[1,2] Figure 2 shows a schematic of our experiment in which the matter-wave source is a laser cooled rubidium atomic beam.

During the past twelve months of this grant (8/1/94 - 7/31/95) we have been working primarily on characterizing the slow atomic beam and on improvements to the beam.

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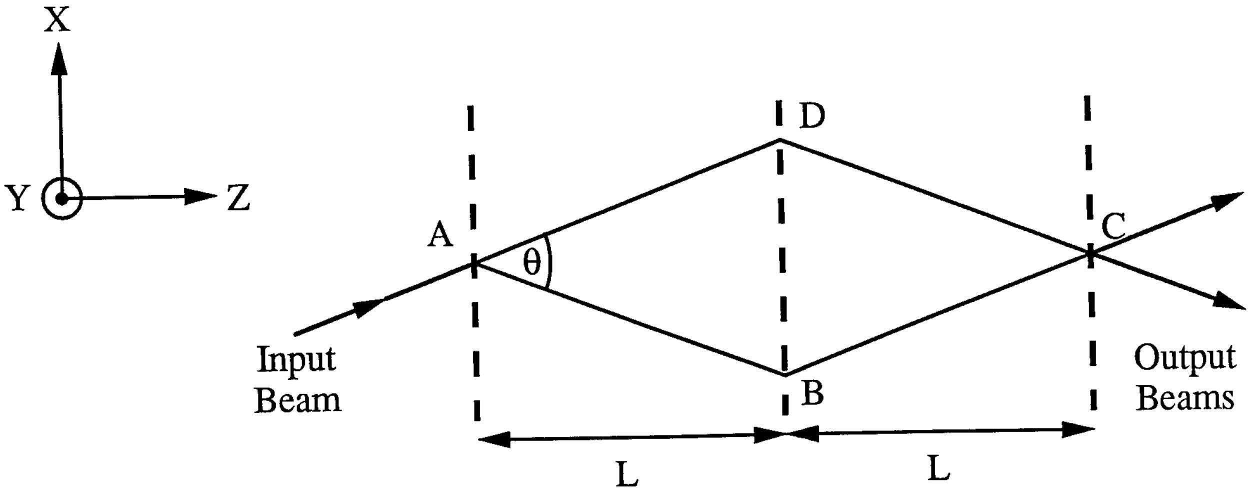

Fig. 1. Three-grating Bonse-Hart interferometer with two-path interference configuration shown.

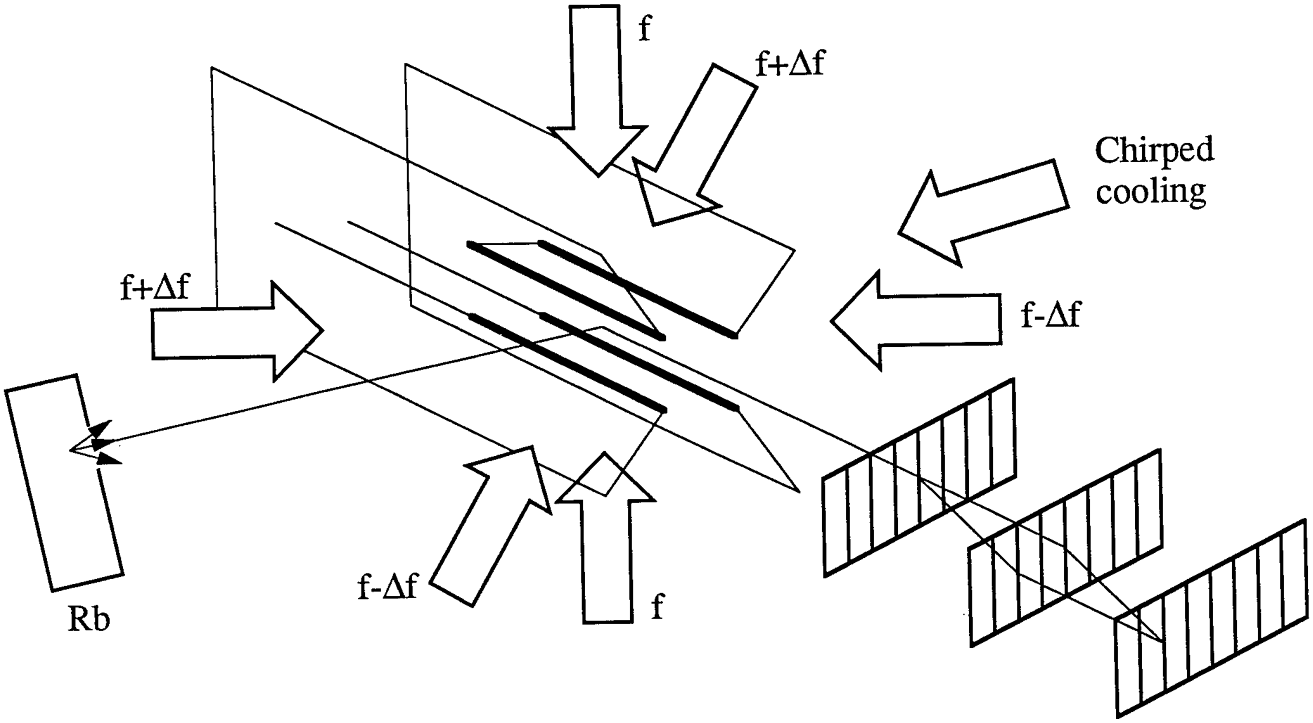

Fig. 2. Experimental schematic for three-grating interferometry with laser cooled atomic beam. The pieces of the magnetic field coils shown in bold are the ones mainly responsible for the two-dimensional quadrupole field forming the funnel.

As shown in Fig. 2, rubidium atoms from the oven are slowed and cooled by the scattering force from a counterpropagating laser beam tuned below the $F = 3$ to $F' = 4$ hyperfine transition of the D_2 line of ^{85}Rb. During the cooling, the laser frequency is ramped toward the resonance frequency to compensate for the decreasing Doppler shift of the decelerating atoms.[3,4] By adjusting the frequency of the laser at the end of this ramp, we can control the characteristic velocity of the cooled beam, which is important for loading the atoms into a trap.[5] A second chirped diode laser is used to counteract optical pumping of the atoms to the other hyperfine level of the ground state.

The slow atoms drift into a two-dimensional magnetic quadrupole field in which six laser beams intersect to form a two-dimensional magneto-optic trap or so-called atomic funnel.[6,7] The coils that produce the two-dimensional quadrupole magnetic field are shown in Fig. 2. The funnel is presently oriented horizontally. Figure 3 shows a schematic of the experiment as viewed from above. The atoms experience molasses-type damping in all three dimensions and are trapped in the two dimensions transverse to the axis of the trap. Along the axis of the trap, the atoms move with a velocity determined by the intersecting laser beam frequencies. Three lasers at frequencies f and $f \pm \Delta f$ are used, with the laser at frequency f used for the vertical pair of beams. In the horizontal plane, the laser beams are aligned at 45° with respect to the funnel axis, with the two beams coming toward the funnel output beam at frequency $f - \Delta f$ and the two beams coming from behind at frequency $f + \Delta f$. This moving molasses configuration results in atoms moving with a velocity that Doppler shifts the horizontal beams up and down respectively to the mean frequency f. This produces a beam of atoms moving along the axis of the magnetic field with a mean velocity of $\sqrt{2}\, \Delta f \lambda$. The three lasers are each frequency-offset locked to a fourth reference laser that is stabilized to a rubidium absorption cell using polarization spectroscopy. Thus we can independently change the detuning of the mean laser frequency f with respect to the atomic resonance frequency f_0 to optimize the cooling and trapping, as well as the detuning Δf that controls the funnel beam velocity. Velocities much less than 10 m/s are too strongly influenced by gravity to be used in a horizontal interferometer but could be used in a vertical geometry. All the

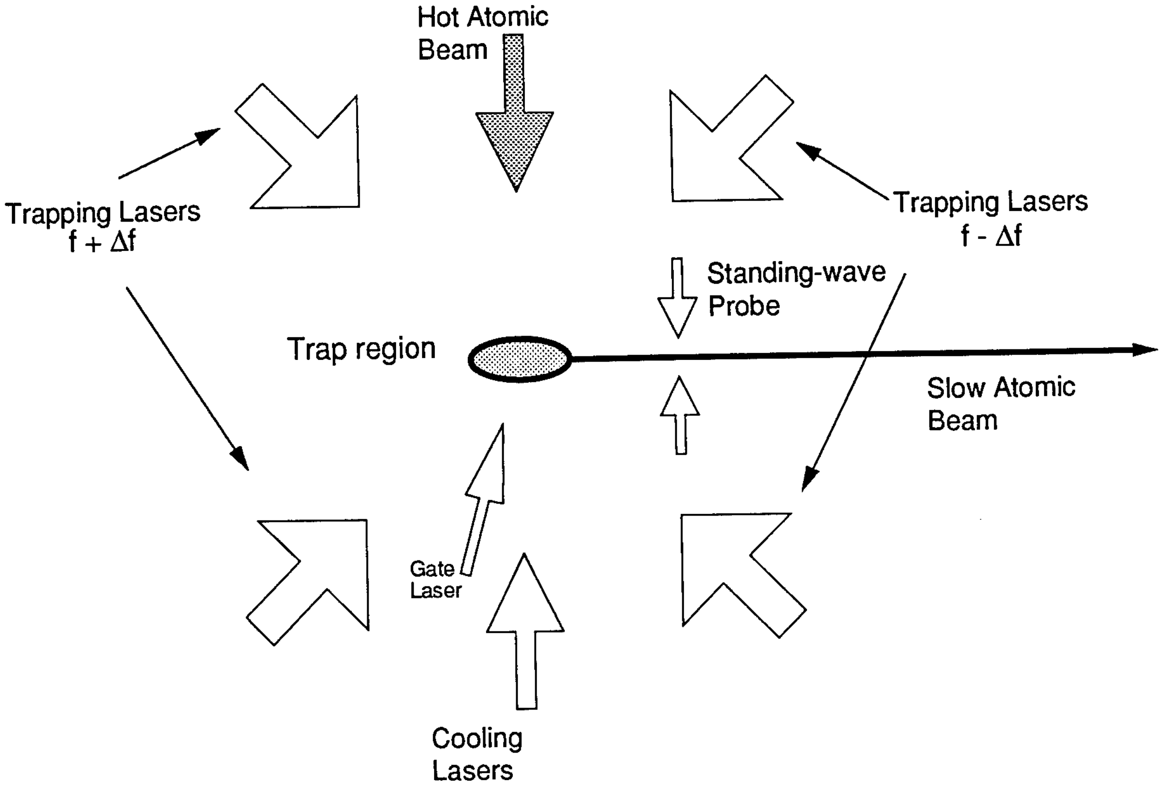

Fig. 3. Top schematic view of the atomic funnel. Not shown are the counterpropagating vertical lasers at frequency *f* and the coils used to create the two-dimensional quadrupole magnetic field.

lasers used in this experiment are diode-lasers that use diffraction gratings as an optical feedback element.[8] These lasers have a FWHM linewidth of 150 kHz.[9] When frequency-offset locked together, they have relative jitters of 10 kHz, which is very important for a well defined velocity of the slow beam.

Atoms in the funnel are monitored by viewing their fluorescence with a CCD camera and a photomultiplier. Atoms that leave the funnel along the axis will enter a region with no laser fields and so will not fluoresce. To detect these atoms, we have introduced a horizontal standing-wave laser field approximately 1 cm beyond the end of the funnel, as depicted in Fig. 3. With red detuning, this standing-wave probe also provides one-dimensional transverse molasses damping of the atomic beam. From the CCD images of the atoms in the trap and the probe, we can measure the transverse spread of the beam as it travels downstream. The observed spread implies a transverse temperature of approximately 500 μK.

To determine the velocity and longitudinal temperature of the slow atomic beam, we have done time-of-flight experiments.[6] Atoms near the exit end of the funnel are deflected away with a resonant traveling-wave laser beam (gate laser in Fig. 3). The frequency of this gate laser is then quickly switched away from resonance and then back again 2-3 ms later to allow a short pulse of atoms to travel to the probe region. The transit time and spreading of this pulse as measured with the downstream probe fluorescence yields the mean beam velocity and the longitudinal temperature. The measured signals are fit to a function that models the funnel as a line of point sources, each with the same mean drift velocity and velocity spread. Figure 4 shows a sample signal and the resultant fit. For most of our data, the pulse of atoms is long enough that the mean beam velocity is determined primarily by the delay of the leading edge of the pulse with respect to the gate and the longitudinal temperature is determined primarily by the slopes of the leading and trailing edges of the pulse. Data were taken for a range of values of the detuning Δf of the horizontal lasers from the vertical laser. Figure 5 shows the results of the measured beam velocity. The expected straight line $v = \sqrt{2}\Delta f \lambda$ is shown as a dotted line. The data show consistently higher velocities over the complete range of detuning. Intensity imbalances in our system are small and cannot explain the large deviations seen. Displacement of the trapped atoms from the axis of the trap would subject them to axial magnetic fields that could shift the expected drift velocity of the beam. This effect is estimated to be less that 0.3 m/s for our experiment. The most likely explanation for the observed deviations is that the atoms experience an axial magnetic field caused by the earth's field and other magnetic equipment in the vicinity of the vacuum chamber. A magnetic field B along the axis of σ^+-σ^- molasses leads to a drift velocity of the atoms of $v = -g_e \mu_B B / \hbar k$, where g_e is the excited state Lande factor, μ_B is the Bohr magneton, and k is the laser beam wavevector.[10] This effect would result in a change in the offset of the dotted line shown in Fig. 5, but would not affect the slope. A change in slope can be explained by examining the dynamics of atoms as they enter and leave the trap. Atoms are damped to their final velocity

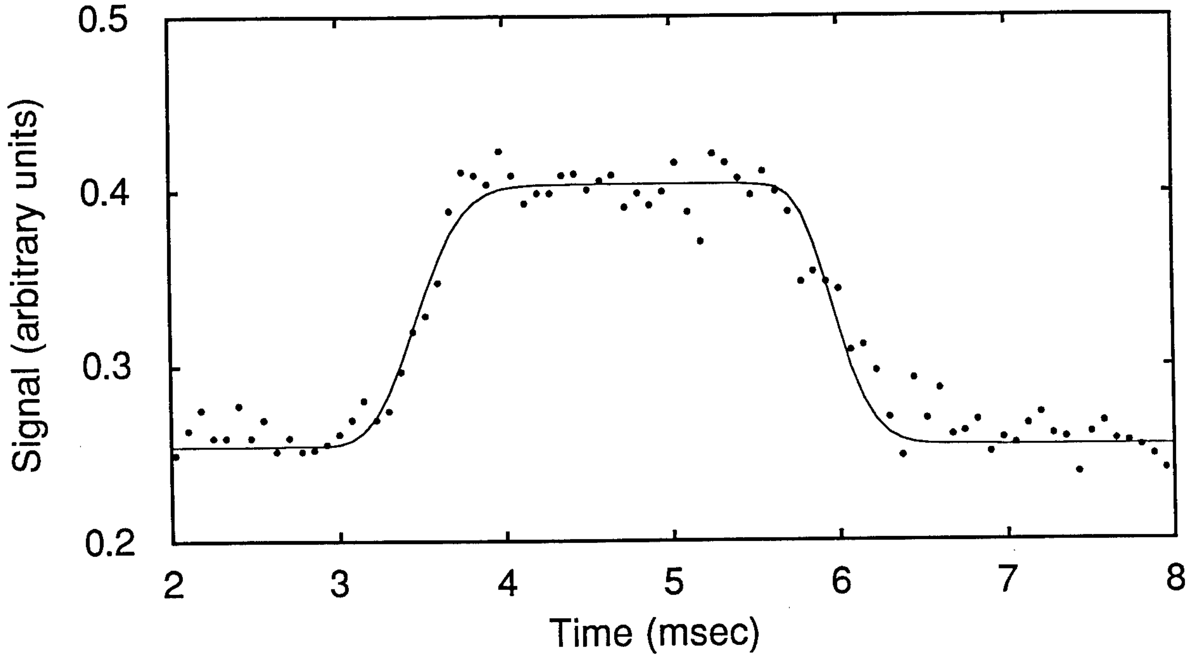

Fig. 4. Measured fluorescence of atoms from standing wave probe (filled circles) and fitted theoretical model (solid line). This data yields a beam velocity of 4.8 m/s and a longitudinal temperature of 500 μK.

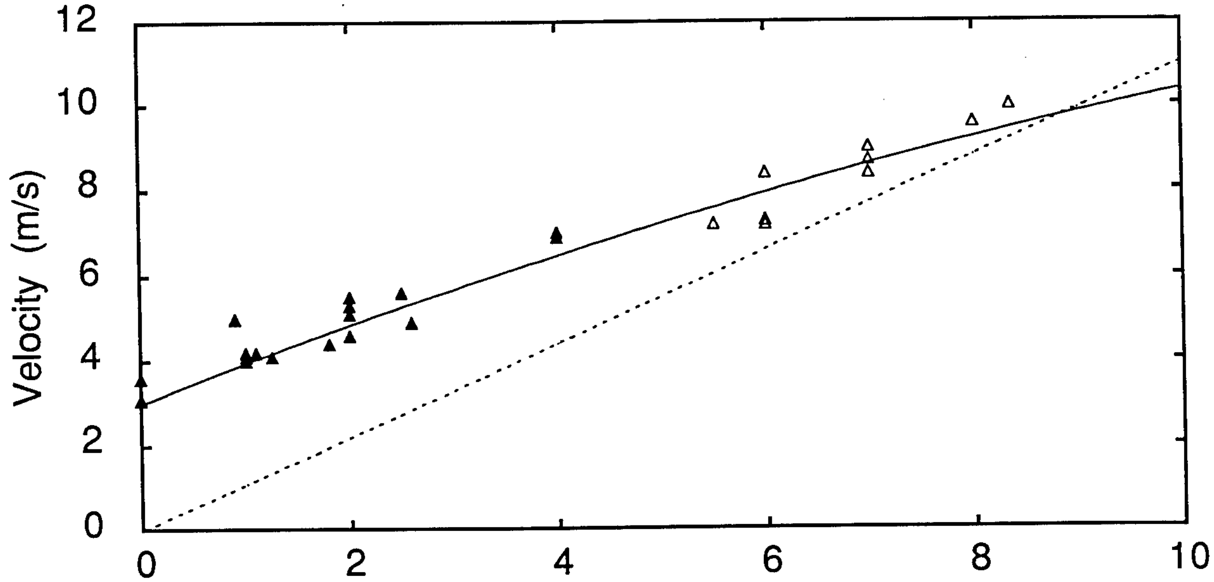

Fig. 5. Velocity of atoms leaving funnel as a function of the frequency offset Δf of the horizontal lasers. The filled (open) triangles correspond to a mean laser detuning of 2Γ (3Γ) from resonance. The dotted line is the expected velocity of atoms from a moving molasses. The solid curve represents a more detailed model that includes an axial magnetic field of 4 G and a finite velocity damping time of the atoms in the molasses of 1.2 ms.

with a characteristic time $\tau = m / \alpha$, which for simple one-dimensional Doppler cooling can be as short as 83 μs for rubidium, with a laser detuning of Γ/2. The damping time in our funnel is expected to be of order 1 ms, because of larger detunings used (2Γ and 3Γ) and deviations from an ideal two-level system. If the transit time of the atoms through the funnel is of the order of or less that the damping time, then the atoms will not have enough time to accelerate to the final expected velocity. The solid curve in Fig. 5 shows the expected velocity for atoms that enter the funnel with no axial velocity and must travel 1 cm to leave the funnel. An assumed 4 G axial field is responsible for the non-zero velocity of atoms in the stationary molasses ($\Delta f = 0$), while an assumed damping time of 1.2 ms is responsible for the nonlinearity in the curve. The time of flight signals yield a longitudinal temperature of $500\ ^{+500}_{-250}\ \mu K$, which is consistent with the Doppler cooling limit for rubidium of 300 μK (for $\Delta = 2\Gamma$).

From the magnitude of the photomultiplier signal we have estimated that there are approximately 4 x 10^8 atoms in the funnel each time it is loaded. With a chirp frequency of 25 Hz, we thus have 10^{10} atoms/s in the slow beam. Atoms loaded from one chirp are ejected from the trap well before atoms from the next chirp arrive.

We have recently completed construction of a tapered magnetic solenoid that we will use to implement σ^- Zeeman cooling in our experiment.[11] The magnet consists of 18 layers of wire with a varying pitch that will produce a longitudinal magnetic field designed to keep decelerating atoms in resonance with a fixed laser frequency. This will produce a continuous beam of slow atoms to load into the funnel, instead of the pulsed beam from the chirped laser cooling scheme we now employ. From previous experiments, we can expect a large increase in flux from this new cooling scheme.[11,12]

We have recently placed a hot wire detector 30 cm downstream of the funnel. The hot tungsten wire ionizes rubidium ions and the resulting current can used as a measure of the atomic flux. Preliminary work indicates rubidium atoms at the detector, but more work is required to quantify the results.

We are now preparing to put the diffraction gratings into the vacuum chamber. The amplitude transmission gratings have a period of 250 nm and are made from free-standing silicon nitride films on silicon substrates.[13] The three gratings will be separated by 5 cm and will diffract the rubidium beam by 2 mrad into the first order. Compared to the other interferometers which have been demonstrated using material structures,[14] ours is relatively compact. The ability to tune the velocity of the funnel output beam also provides our experiment with another degree of flexibility.

A report on the rubidium atomic funnel work was presented at the Fourteenth International Conference on Atomic Physics, Boulder, Colorado, July 31- August 5, 1994,[15] and will be presented at the Optical Society of America Annual Meeting, Portland, Oregon, September 10-15, 1995.[16]

During the 1994-1995 academic year there were three graduate students working full time on this research. Two were funded fully by this grant, and the third was funded partly by this grant and partly by a department teaching assistantship. Two graduate students were working part time on this research, funded by department teaching assistantships. During this summer, three graduate students are working full time on this research. All are funded by this grant. One student has completed a Ph.D. thesis during the summer.

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