Interferometry with Bose-Einstein Condensates

Toward a sub-ppb Measurement of α

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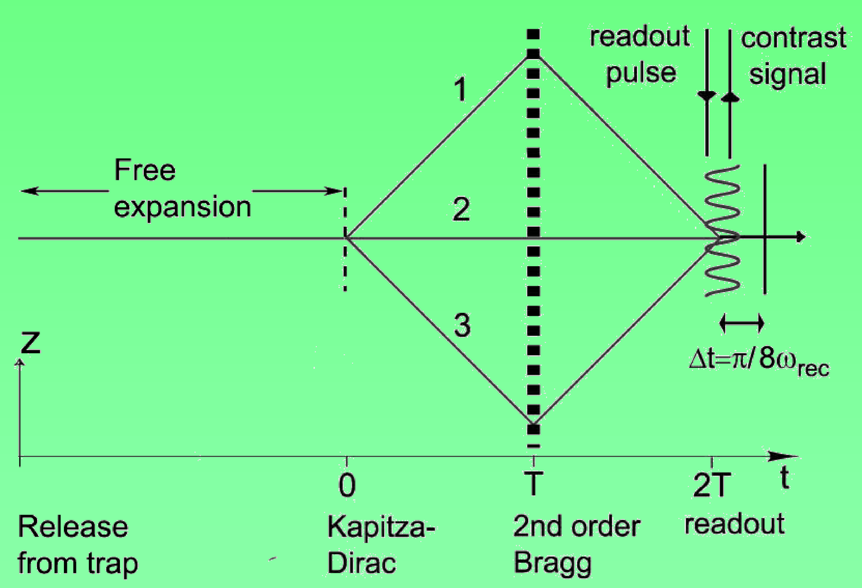
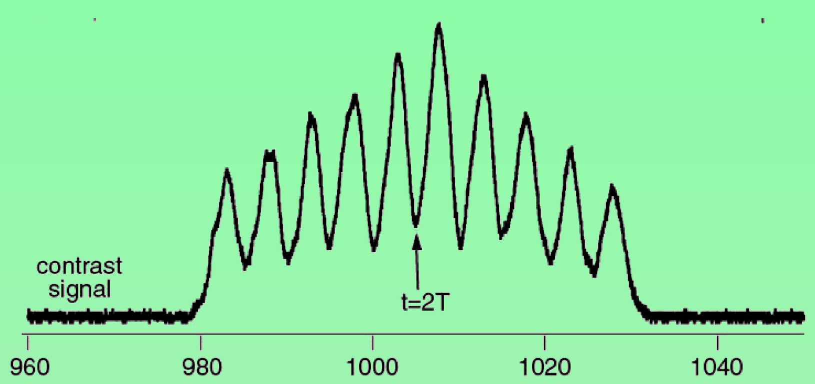
Contrast Interferometry for α

Measuring atomic recoil frequencies allows determination of the fine structure constant, α. A prototype experiment[1] (see accompanying figures) conducted in 2002 using sodium BECs proved the robustness of the contrast interferometry technique. This symmetric three-arm interferometer has signal determined by (ϕ_i = phase accumulated on path i)

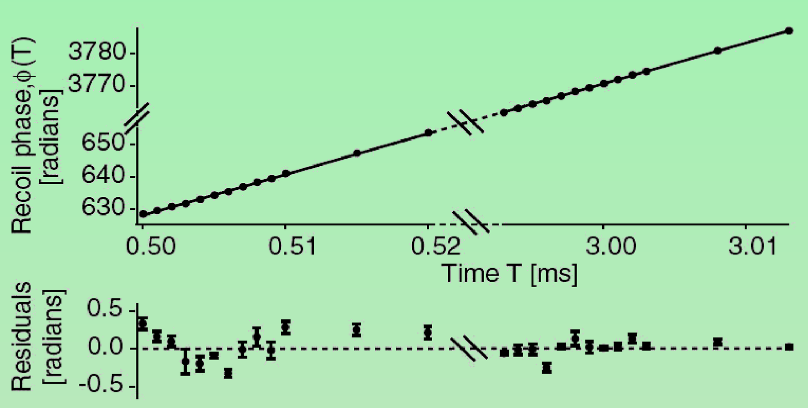
$$A(t)\sin^2\left(\frac{\phi_1(t)+\phi_3(t)}{2}-\phi_2(t)\right)$$

eliminating many systematic effects.





Above: Sample of data from a single shot of the original contrast interferometry experiment
Below: Phase versus free propagation time is fit to find recoil frequency.



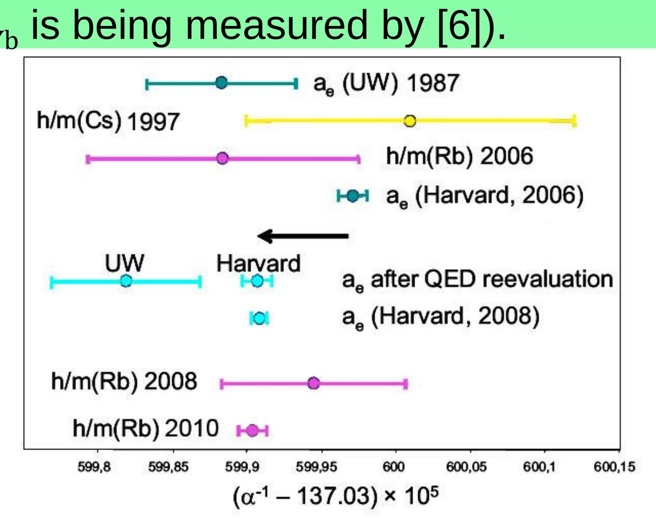
Finding α

The most precise determination of the fine structure constant α comes from measurement of the electron's gyro-magnetic ratio (g) and complex QED calculations[3].

Recoil experiments compare the momentum and energy of an atom to determine h/m, from which α maybe calculated using

$$\alpha^2=\left(\frac{e^2}{\hbar c}\right)^2=\frac{2R_\infty}{c}\frac{M_{Yb}}{M_e}\frac{h}{m_{Yb}}$$

Comparison of the values of α obtained by these two methods constitutes a stringent test of QED theory. (M_{Yb} is being measured by [6]).



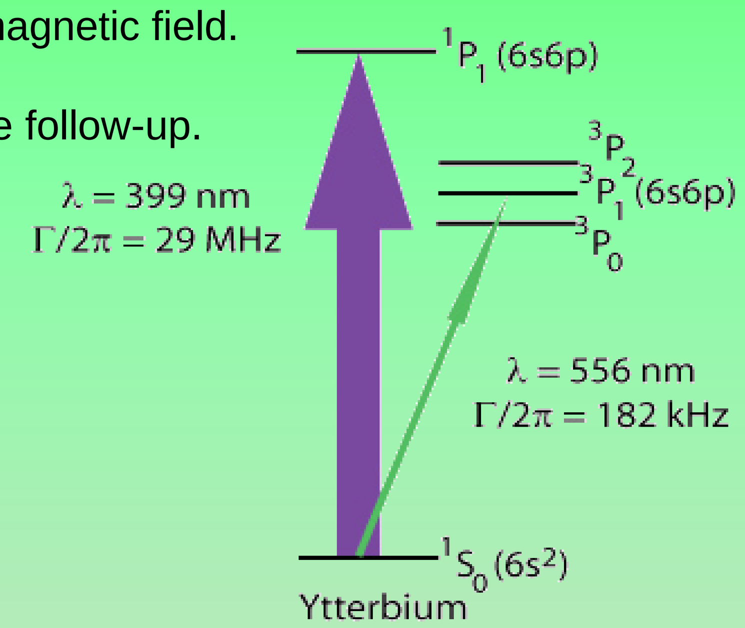
A comparison[4] of recent α measurements.

Yb

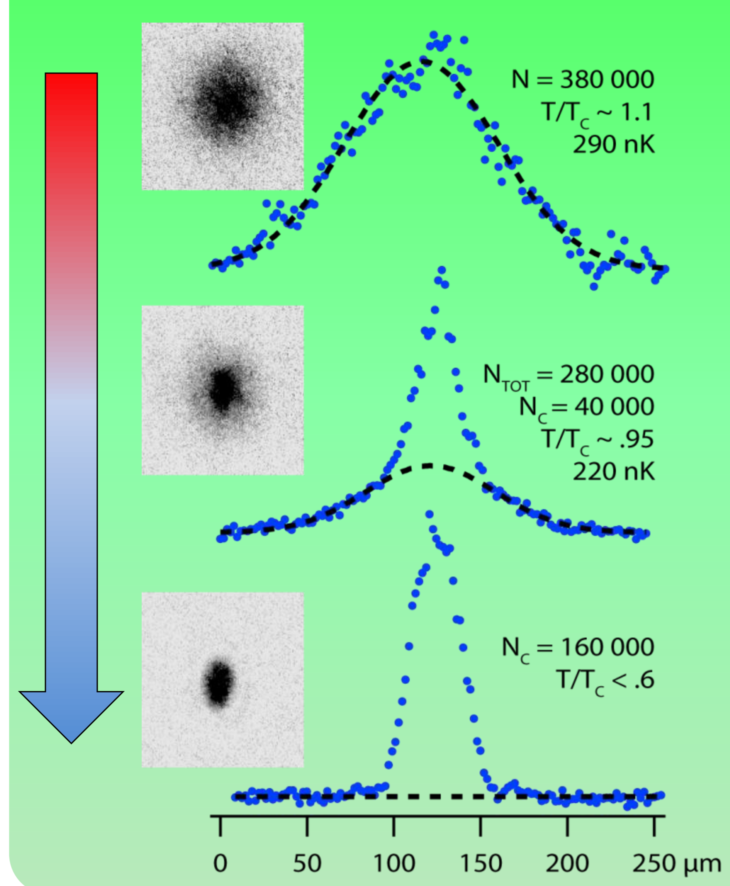
Yb has several advantages for interferometry:

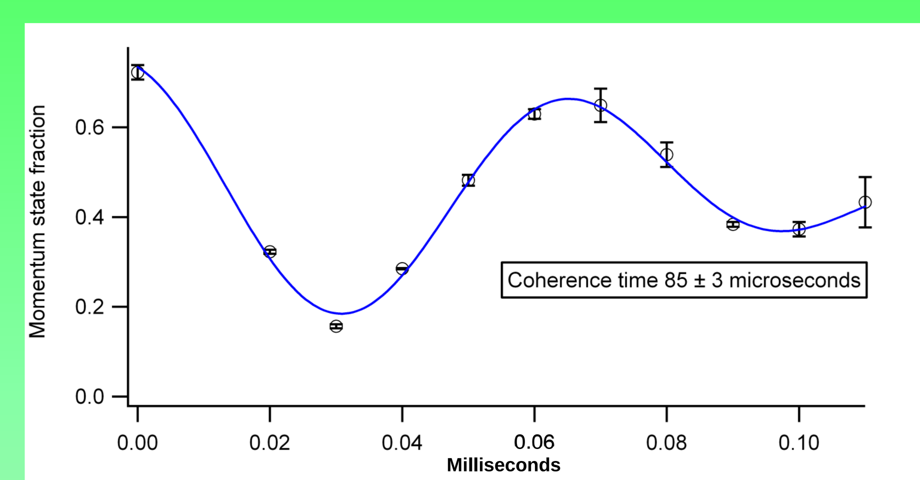
- Ground state insensitive to magnetic fields.
- Two available optical transitions (399nm and 556nm).
- Multiple stable bosonic isotopes (current work with 174):
  - Allows comparisons of systematics between different isotopes.
  - Variation of scattering length without introducing magnetic field.
- Multiple stable fermionic isotopes:
  - Interferometry with degenerate fermions a possible follow-up.

Isotope	Natural Abundance	Nuclear spin
^{168}Yb	0.0013	0
^{170}Yb	0.0305	0
^{171}Yb	0.143	1/2
^{172}Yb	0.219	0
^{173}Yb	0.161	5/2
^{174}Yb	0.318	0
^{176}Yb	0.127	0



Yb BECs

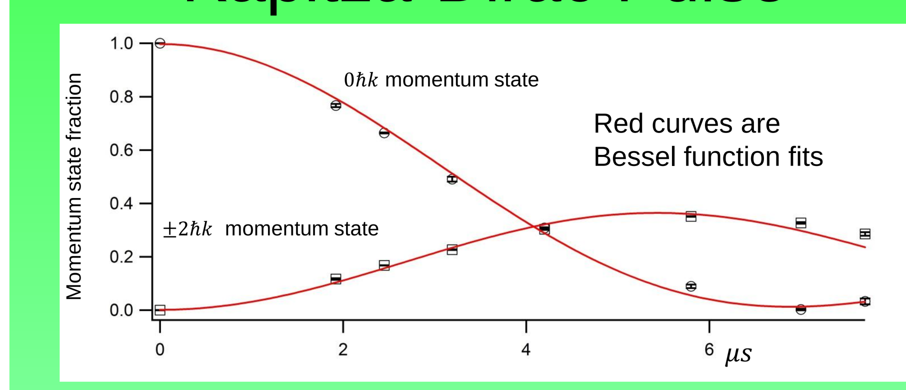




Left:Yb atomic clouds at temperatures near T_c. Plots are density slices through cloud centers. Insets are corresponding absorption images.

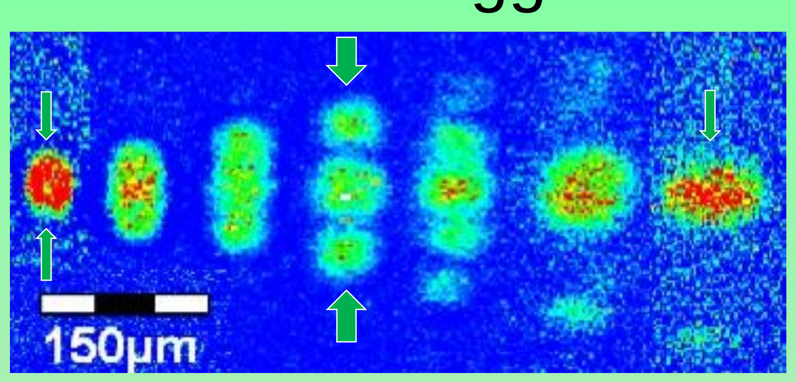
Above: Measurement of coherence time for a large condensate after release from trap and some free expansion. Long coherence time aids in interferometry.

Kapitza-Dirac Pulse



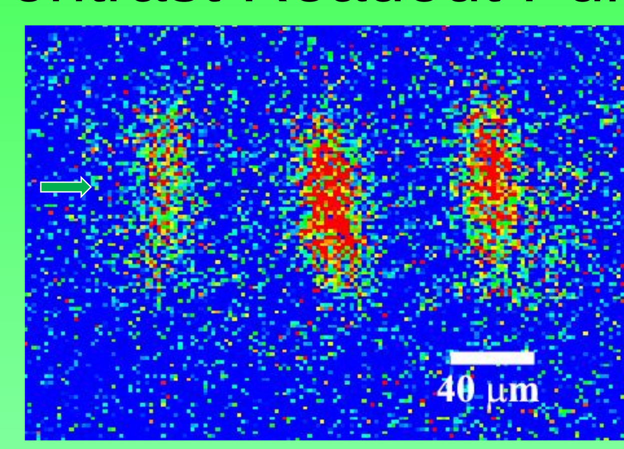
Above: Momentum state fraction vs pulse width for a Kapitza-Dirac pulse.

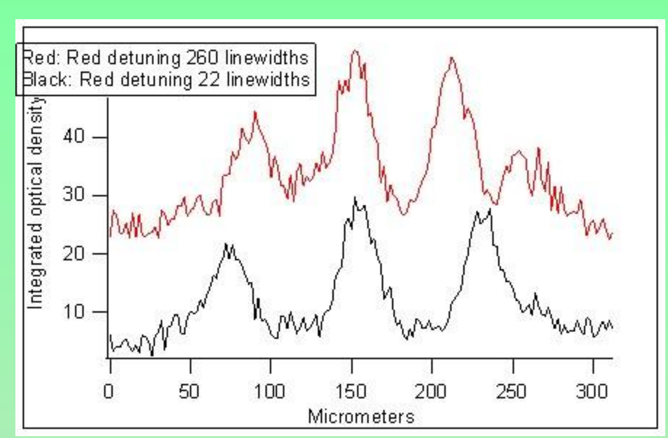
2nd Order Bragg Pulse



Above: Series of 7 absorption images. The leftmost image is concurrent with the Kapitza-Dirac pulse. The fourth image is 6 ms later, during the 2nd order Bragg pulse. The rightmost image is 12 ms later, during the readout pulse.

Contrast Readout Pulse

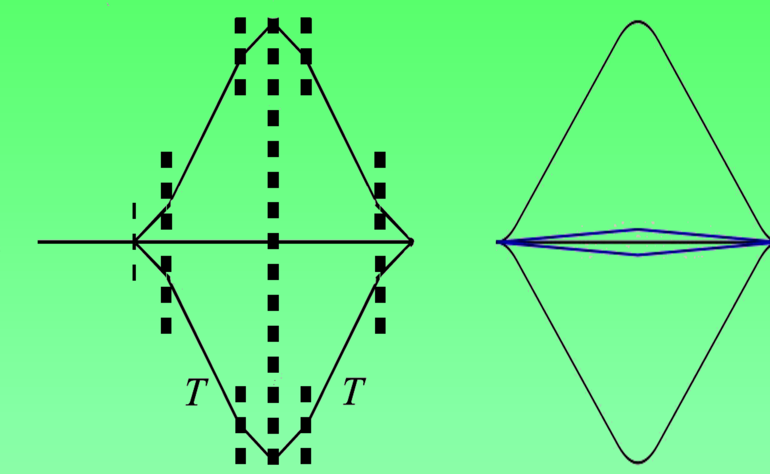




Top: Absorption image after a small detuning readout pulse.
Above: Vertically integrated density from absorption images taken after readout pulse (artificially offset)

Precision: Acceleration and Scaling

Greater recoil energies are achieved with extra acceleration pulses. Each recoil imparts momentum $\pm 2\hbar k$ to an atom, while phase accumulates as the square of momentum.



Left: Sequence with extra acceleration pulses
Right: Trajectories for N=1 (blue) and N=20 (black) contrast interferometry experiments of equal time are shown,

The relative error of our recoil frequency measurement can be estimated as:

$$\frac{\delta\omega_{rec}}{\omega_{rec}}=\frac{\delta\phi_{rec}}{\phi_{rec}}\approx\frac{\sqrt{N_{Yb}}}{8\omega_{rec}N^2T},$$

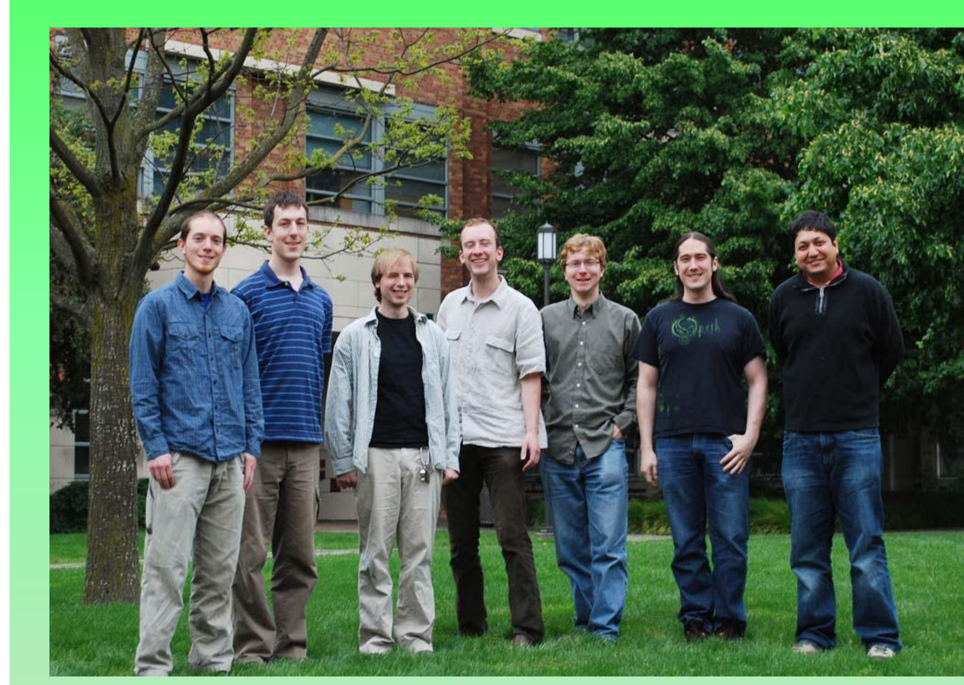
assuming atom shot-noise limited measurement, where $\pm 2N\hbar k$ is the atomic momentum during the free propagation and ϕ_{rec} is the phase accumulation due to kinetic energy. With our current cycle time of 20s, operating on the 556nm transition with $N_{Yb}=10^4$, T=5ms and N=20 , we can achieve a precision of 3×10^{-8} per shot. This scales to a 10^{-9} precision in ω_{rec} and 5×10^{-10} in α in less than 6 hours.

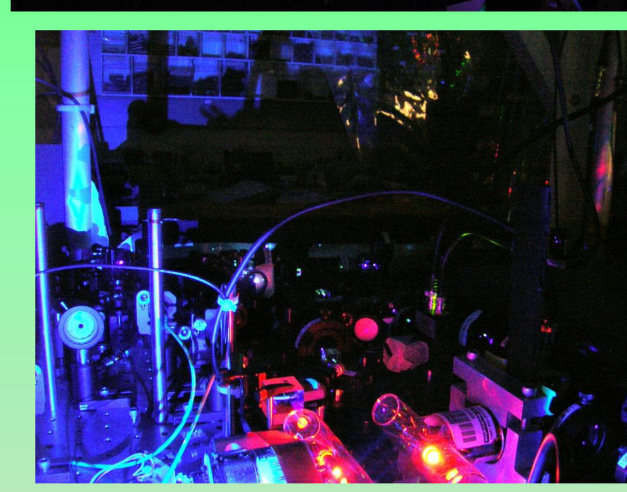
Accuracy: Projected Systematics

Systematics have been estimated for 30 mW Bragg beams of waist 8 mm red detuned ~1000 Γ from the 556 nm intercombination line. These parameters are achievable in our lab using known techniques.

Effect	$N=1$, $T=5$ms	$N=20$, $T=5$ms	Correctable?
Magnetic fields	0 ppb	0 ppb	easily testable
Electric fields	<0.1 ppb	<0.1 ppb	measurable
Gravitational curvature	0.08 ppb	0.08 ppb	measureable, scales with T^2
Differential AC Stark shift	<0.001 ppb	<0.001 ppb	
Wavefront curvature	0.2 ppb	0.2 ppb	measure & maximize ϕ_{rec}
Beam alignment	0.6 ppb	0.6 ppb	measure & maximize ϕ_{rec}
Index of refraction	20 ppb	1 ppb	scales w/ initial momentum or detuning
Readout back-action/ spontaneous scattering	---	---	believed to degrade signal, no shift (currently simulating)
Atomic interactions	400 ppb	1 ppb	known scaling with atom number/scattering length[2,5]

Our Lab





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6. Edmund Myers, private communication

Group website: http://www.phys.washington.edu/users/deepg

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