University of California, Berkeley
Holger Müller
Brian Estey
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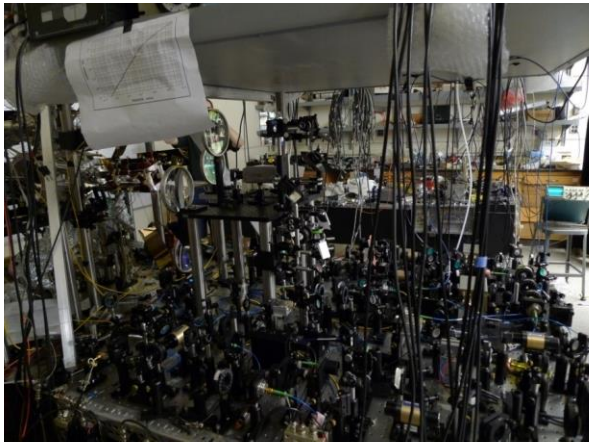
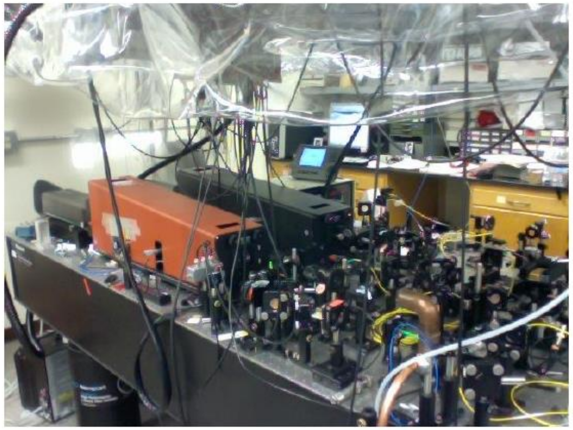
Shau-Yu Lan
Pei-Chen Kuan





Determination of Fine Structure Constant from Photon Recoil Frequency

Rydberg constant in terms of energy $hcR_\infty = \frac{1}{2} m_e c^2 \alpha^2$

$$\alpha = \left[2 \frac{R_\infty}{c} \frac{u}{m_e} \frac{M}{u} \frac{h}{M} \right]^{1/2}$$

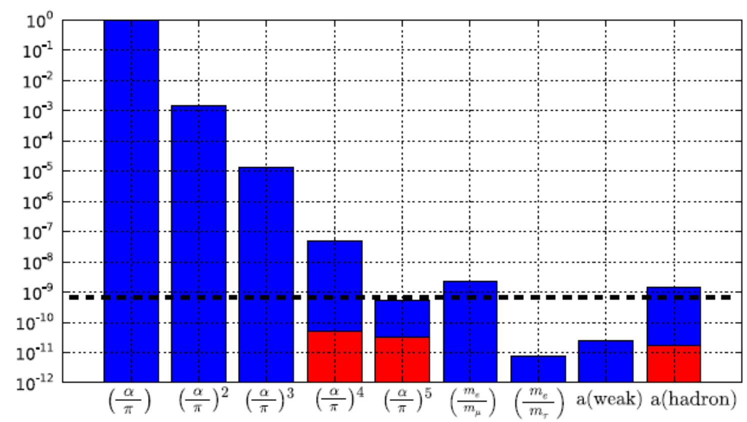
Rydberg Constant

Electron mass

Cs mass

Determined by the photon recoil frequency

$$\frac{h}{M} = \frac{4\pi c^2 \omega_r}{\omega^2}$$



LKB-11 : 6.6x10^{-10} PRL **106,** 080801 (2011)

Harvard-08 : 3.7x10^{-10} PRL **100,** 120801 (2008)

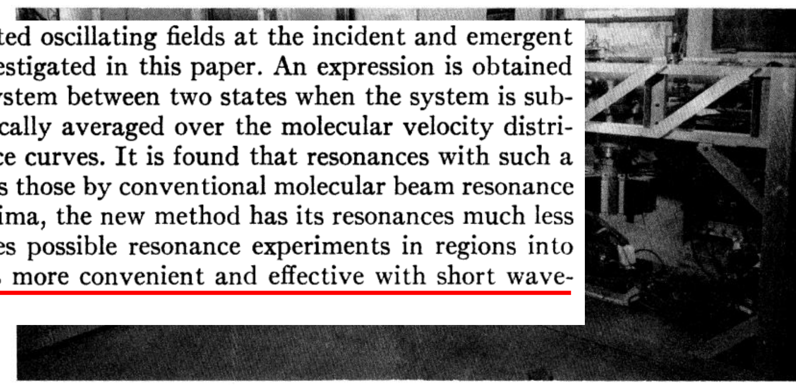
Ramsey Interferometer

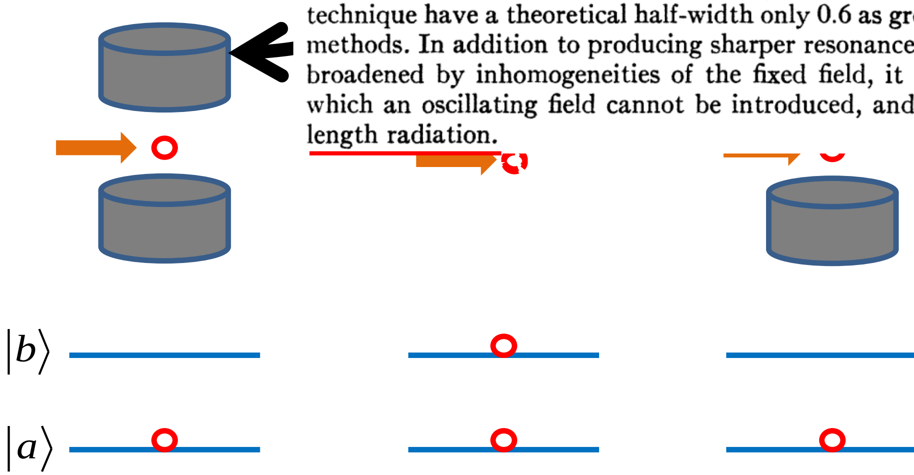
PHYSICAL REVIEW VOLUME 78, NUMBER 6 JUNE 15, 1950

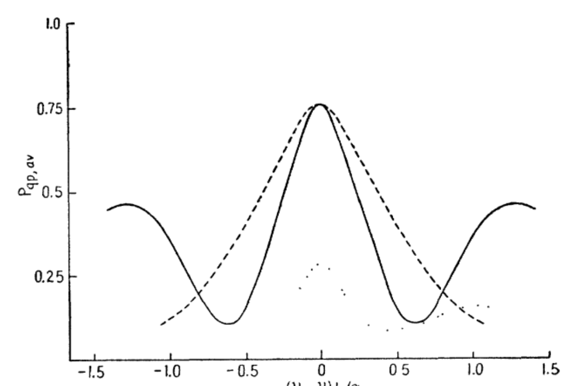
A Molecular Beam Resonance Method with Separated Oscillating Fields*

NORMAN F. RAMSEY
Harvard University, Cambridge, Massachusetts
(Received February 21, 1950)

A new molecular beam resonance method using separated oscillating fields at the incident and emergent ends of the homogeneous field region is theoretically investigated in this paper. An expression is obtained for the quantum mechanical transition probability of a system between two states when the system is subjected to such separated oscillating fields. This is numerically averaged over the molecular velocity distribution and provides the theoretical shape of the resonance curves. It is found that resonances with such a technique have a theoretical half-width only 0.6 as great as those by conventional molecular beam resonance methods. In addition to producing sharper resonance minima, the new method has its resonances much less broadened by inhomogeneities of the fixed field, it makes possible resonance experiments in regions into which an oscillating field cannot be introduced, and it is more convenient and effective with short wavelength radiation.





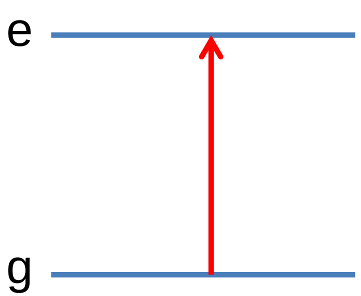


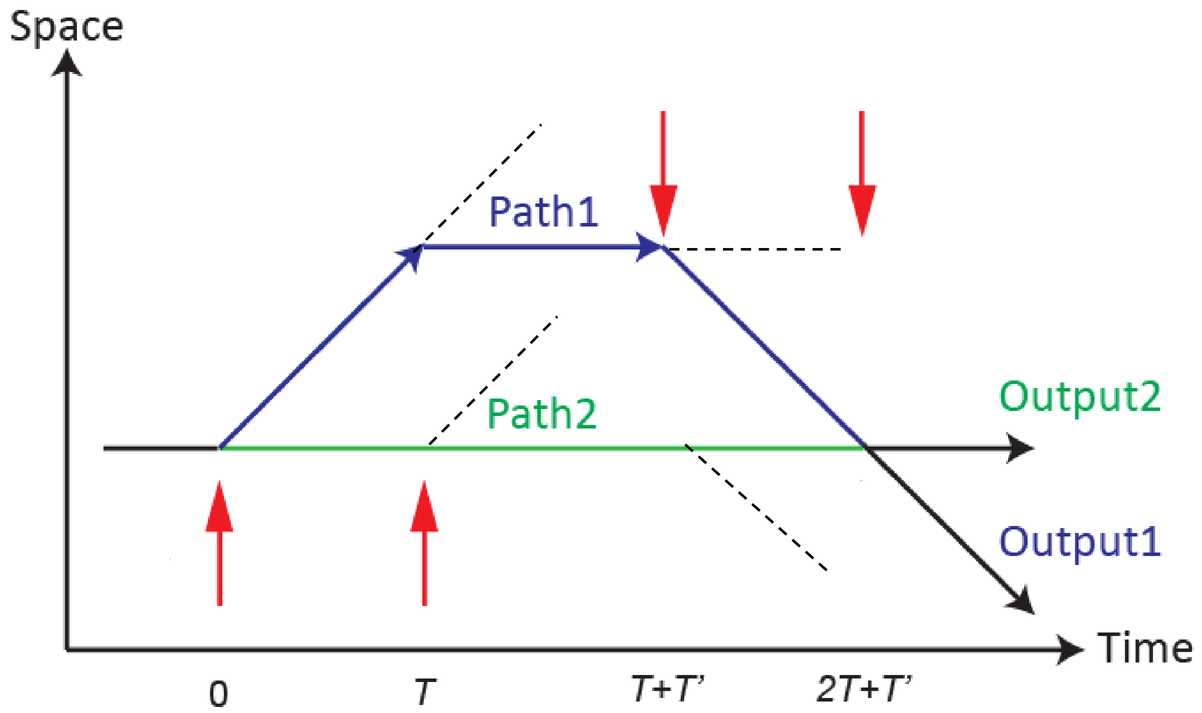
Ramsey-Bordé Interferometer

• Designed to improve microwave clock

• Significant photon recoil shift ~mm/s

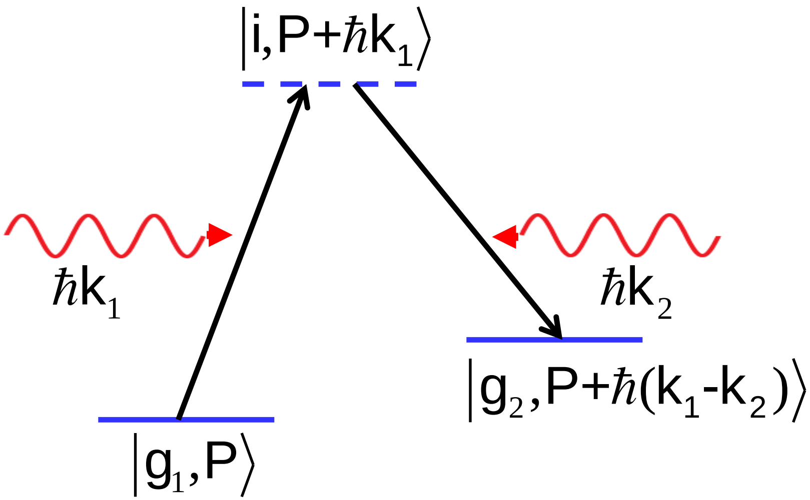
• Two additional pulses to close the interferometer

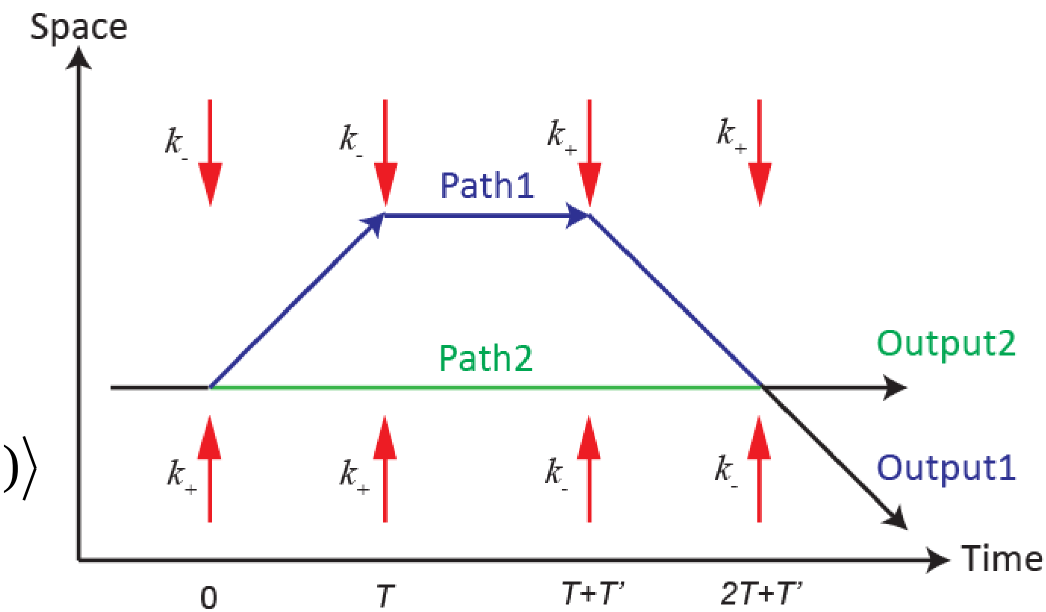




Ch.J. Bordé, *et al*.Phys. Rev. A, **30** (1984), p.1836

Stimulated Raman Transition



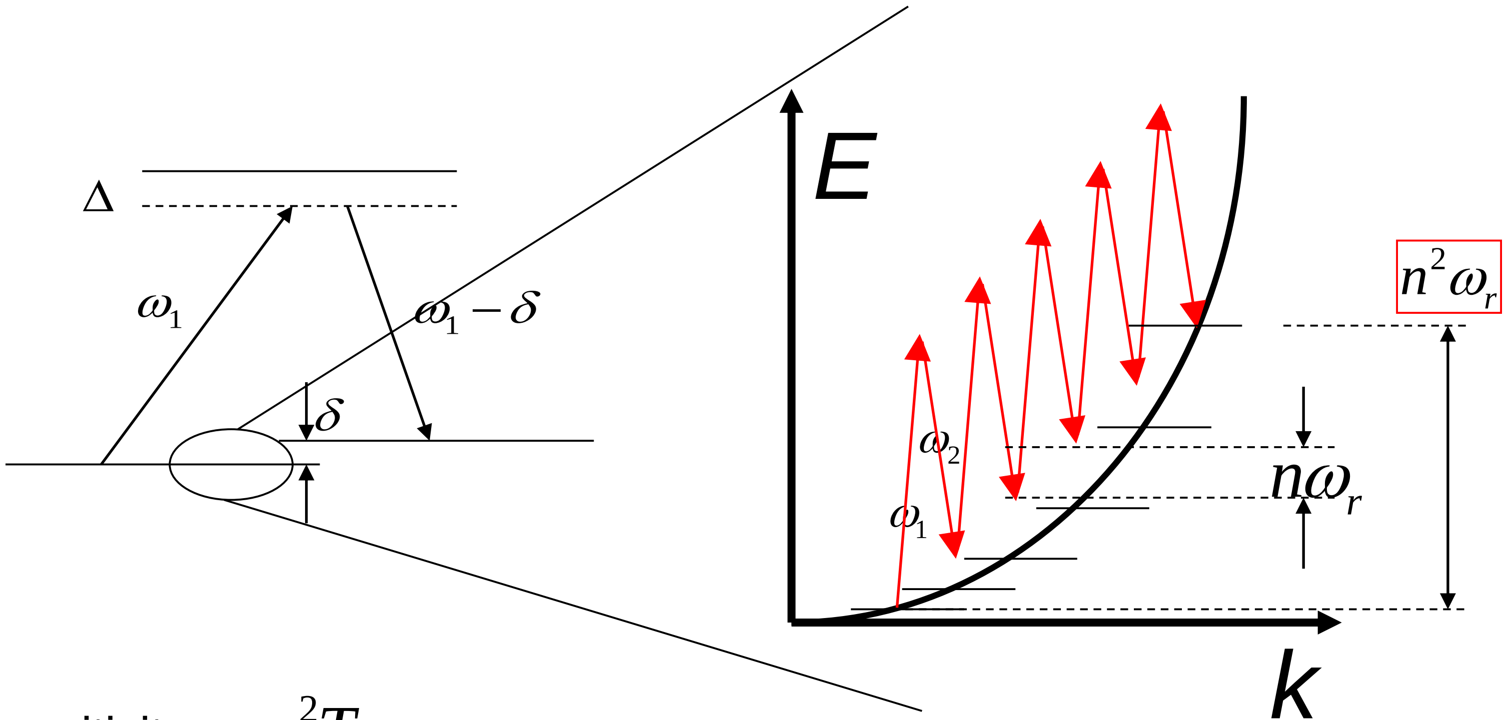


$$\Delta\Phi = 8n^2\omega_r \mathrm{T} + n\Phi_L \quad \text{where}\ \omega_r = \frac{1}{2}\frac{\hbar}{m}k^2$$

D. S. Weiss, *et al.* Phys. Rev. Lett. **70**, 2706 (1993)

Large Momentum Transfer

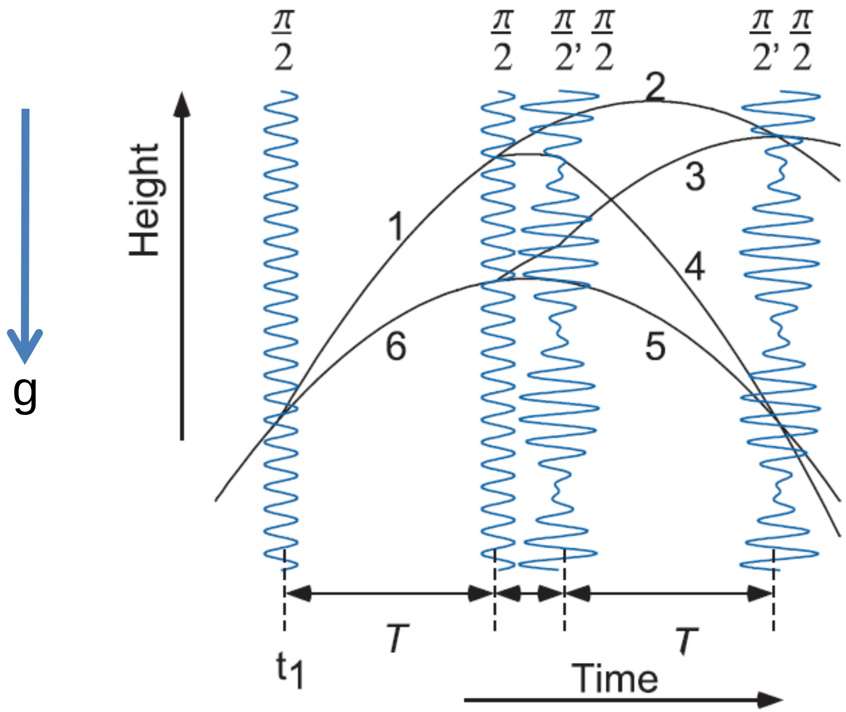
Multi-Photon Bragg Diffraction

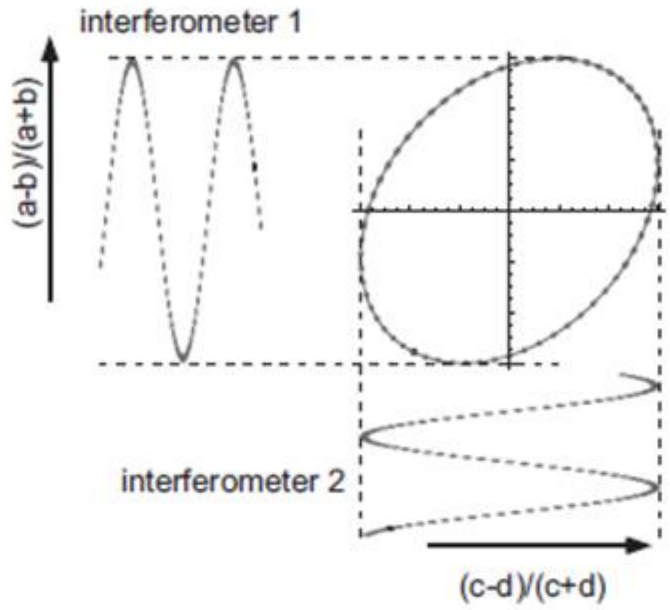


- Sensitivity $\propto n^2 T$
- $|g, p = p_0\rangle \rightarrow |g, p = n\hbar k_{eff}\rangle$

$\Rightarrow$ external field insensitive

Simultaneous Conjugate Interferometer





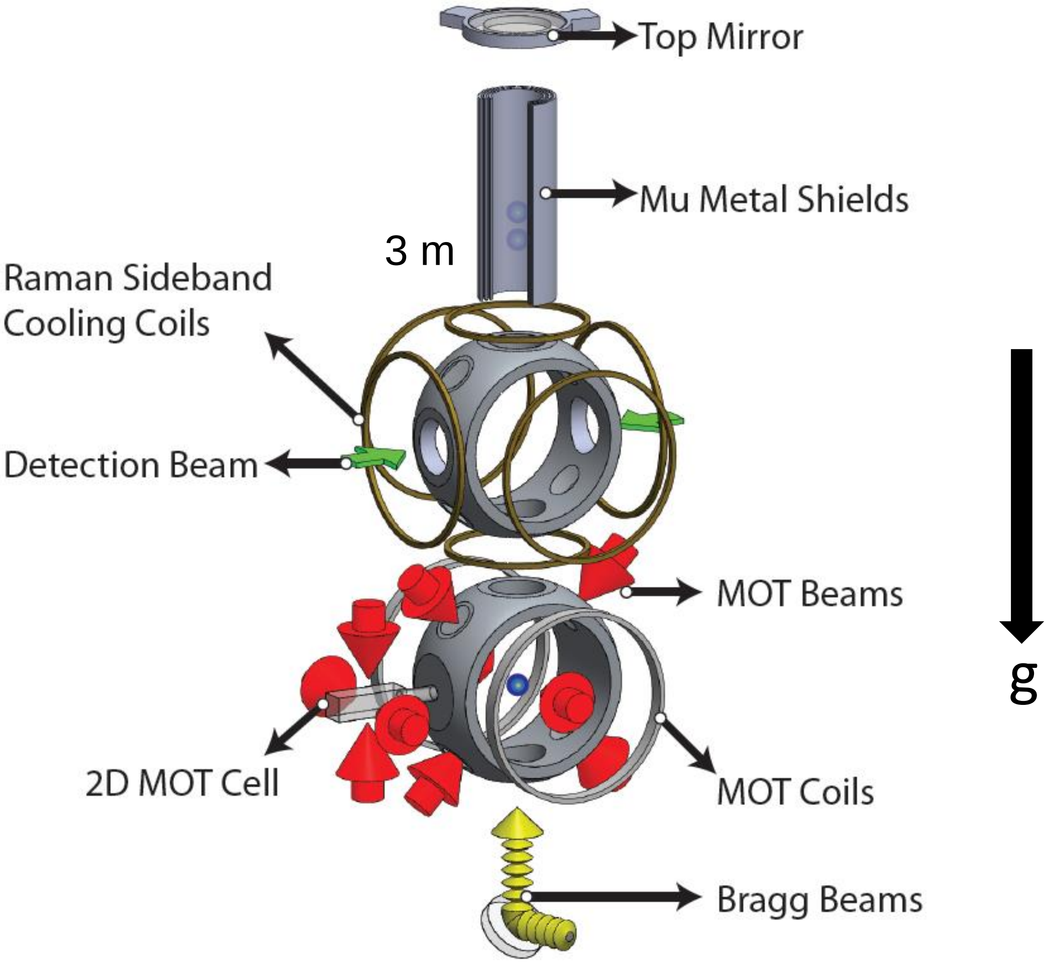
$$\Delta\Phi = \Delta\Phi^{+} - \Delta\Phi^{-} = 16n^{2}\omega_{r}\mathrm{T} + n\Phi_{beamsplitter}$$

$$\Phi_{\text{beamsplitter}} = (\Phi_{3}^{+} - \Phi_{3}^{-}) + (\Phi_{4}^{-} - \Phi_{4}^{+})$$

Common Mode Rejection

Experimental Setup

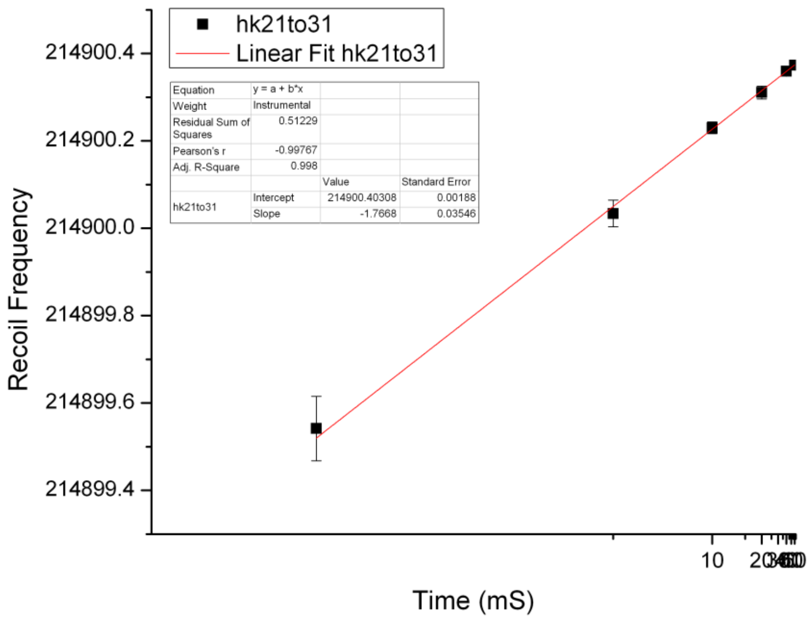
Atomic Fountain



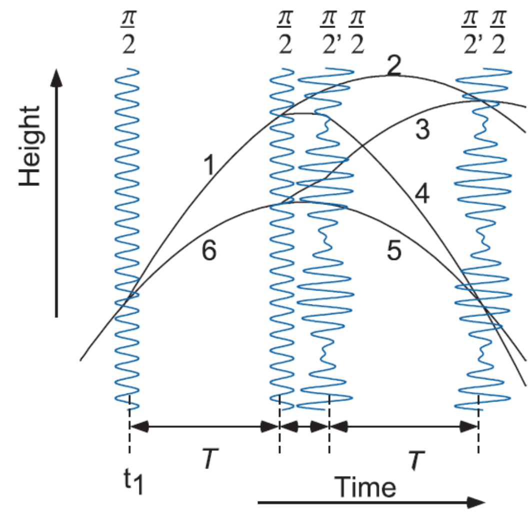
- 3D magneto-optical trap
- Molasses cooling
- Adiabatic cooling
- Launch
- Raman sideband cooling
- Adiabatic microwave transfer
- F= 3, m=0 state selection
- Velocity selection
- Interferometer sequence
- Florescence detection

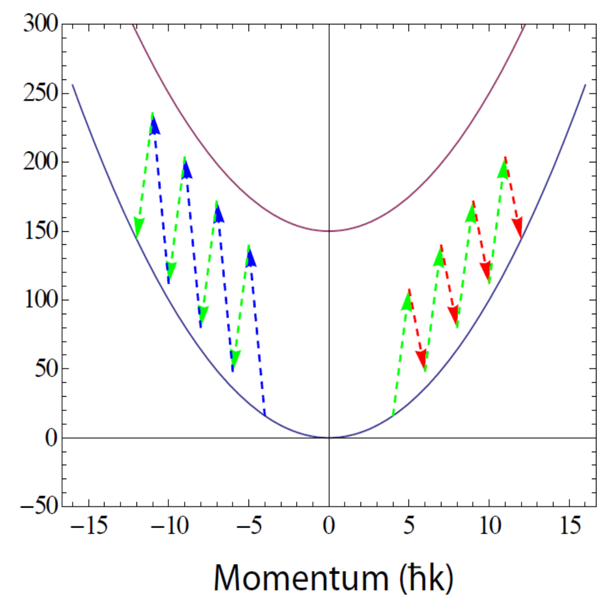
S.-Y. Lan *et al.* Phys. Rev. Lett. **108,** 090402 (2012), S.-Y. Lan *et al.*, Science **339**, 554 (2013).

Diffraction phase shift

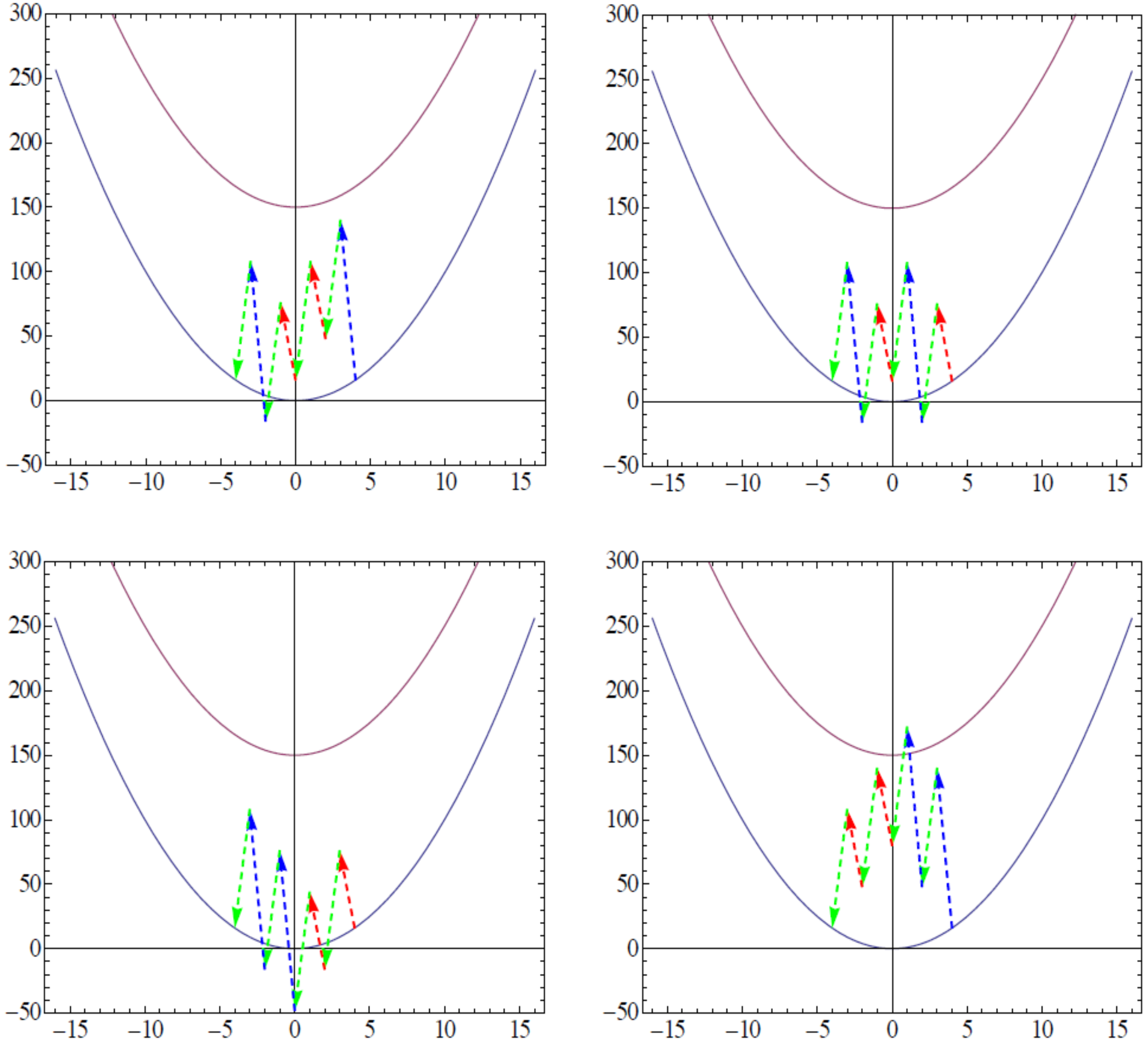


$$\omega_m = \omega_r + \frac{\varphi_o}{T}$$

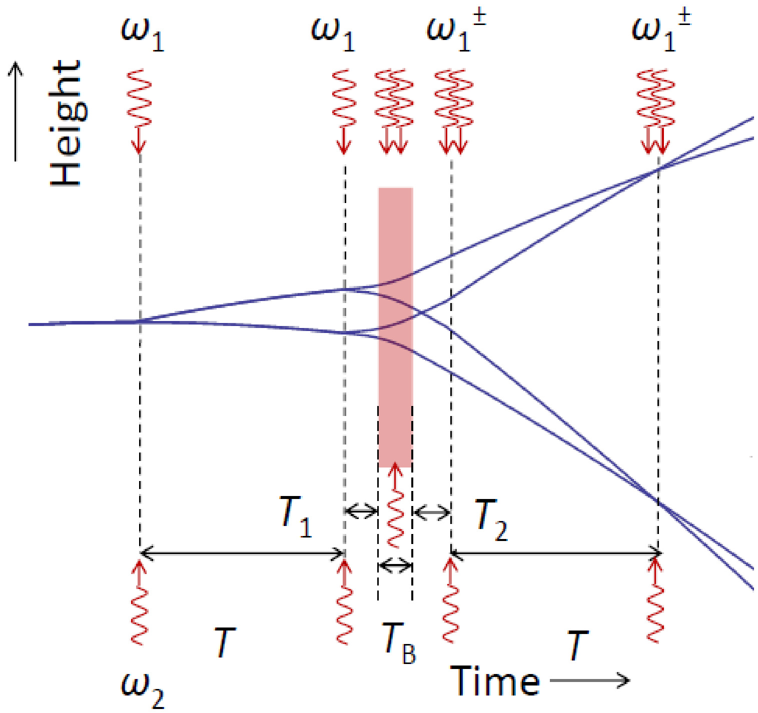


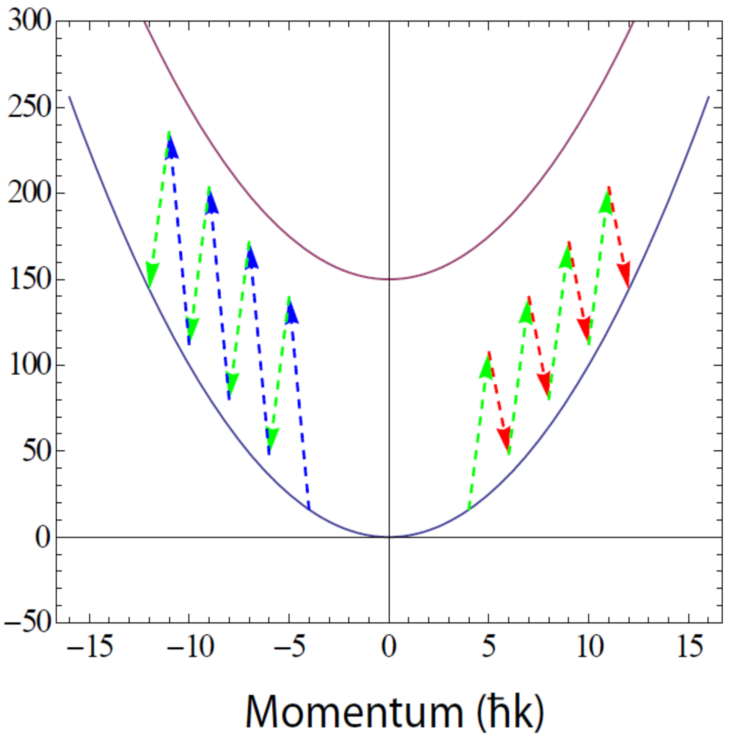


Cross coupling



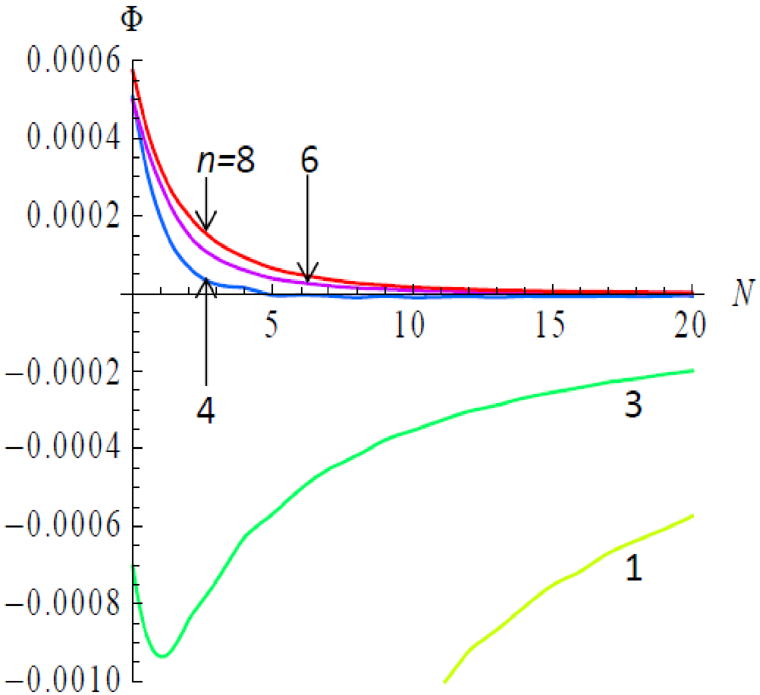
Bloch Oscillation

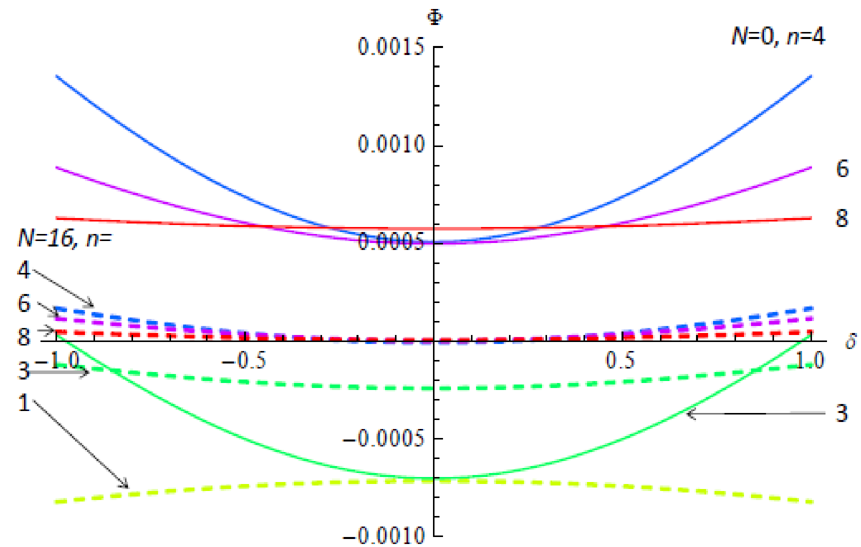




$$\Phi = 16n(n+N)\omega_r T$$

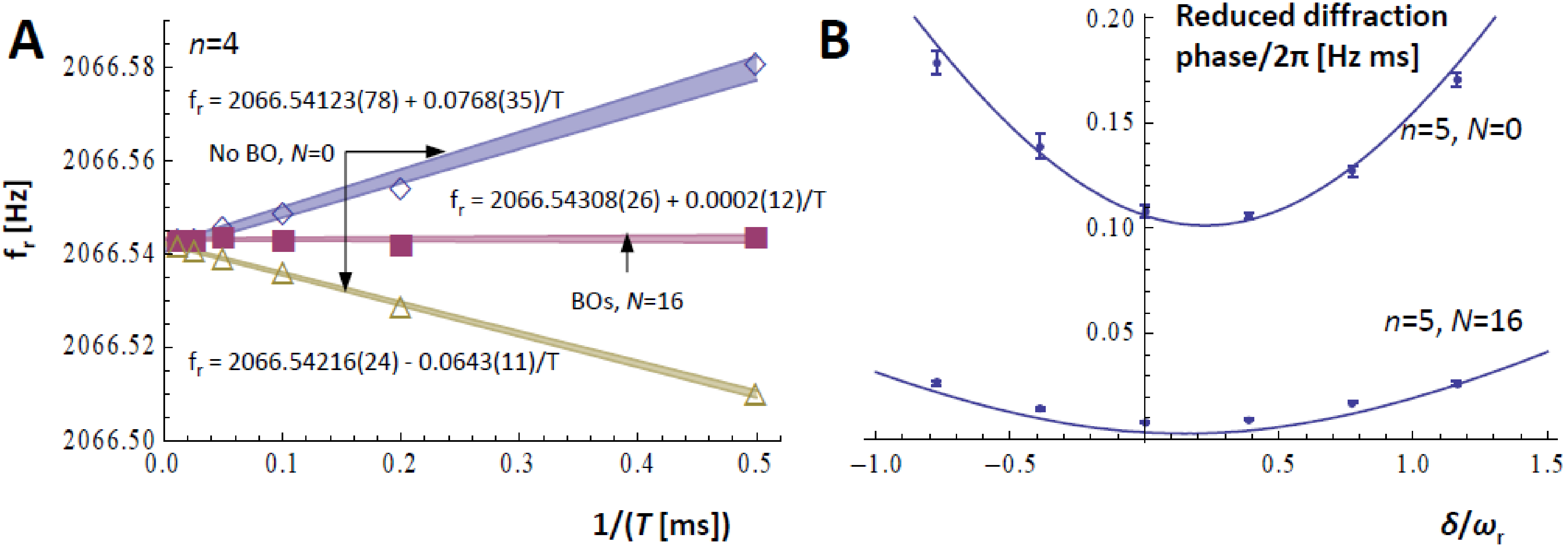
Simulation of diffraction phase





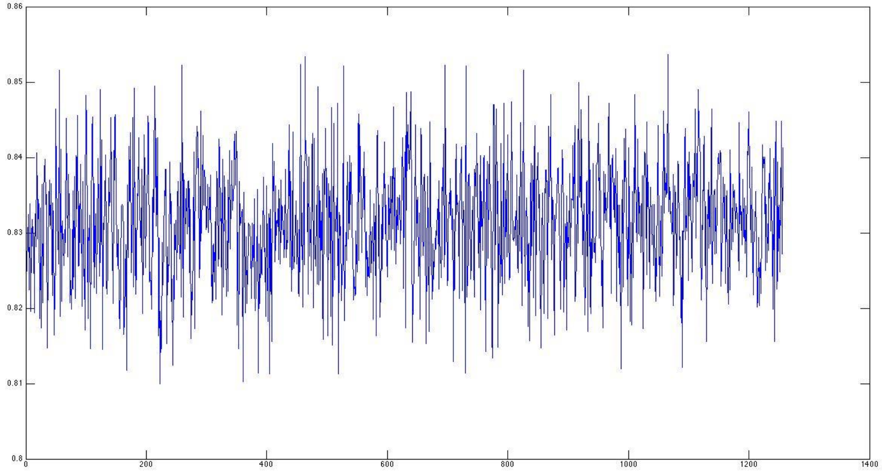
B. Estey *et al.*, arxiv:1410.8486

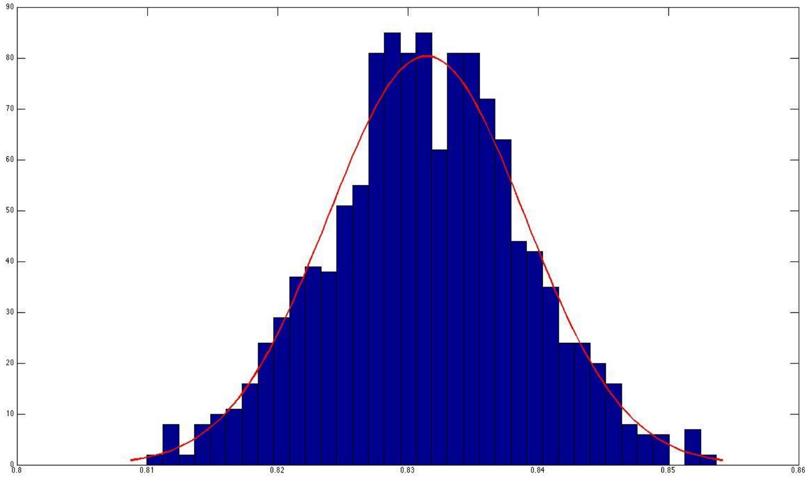
Suppression of diffraction phase



B. Estey *et al.*, arxiv:1410.8486

Long data





0.33 ppb/sqrt(6hr)

More Systematic Effects

Laser frequency	351,730,902,093(10) kHz
Gravity gradient	-2.954(85) ppb
Guoy phase	-1.902(46) ppb
Wavefront curvature	0.111(55) ppb
Beam alignment	-0.085(49) ppb
Zeeman effect	-0.051(14) ppb

- Mean Field Shift
- Value Different Bragg order
- Atom temperature effect
- Detection method

Thank You

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