Diode Lasers,
Heavy Atoms, and
Tests of Fundamental Physics

Tiku Majumder
and ~ 25 undergraduates 1995-2007
Williams College

3/27/07 O.D.U.

Thanks to……
Research Corporation
National $cience Foundation
NIST (Precision Measurement Grants program)
Williams College

Outline

0. Motivation
   'Table-top' tests of fundamental physics through search for violations of discrete symmetries

1. Completed Experiment:
   Atomic Beam 'Stark shift' measurement in thallium

2. Current Experiment:
   Ring cavity + atomic beam = detection of very weak absorption
   Time-reversal symmetry violation test

3. Latest developments:
   Blue/UV diode lasers + IR diode laser = two-color spectroscopy
   Indium and thallium, vapor cell, then atomic beam

‘Fundamental’ Physics with Atoms

Given current laser, optical, and electronics technology…..

- High precision experiments, careful experimental design
- Basic theoretical atomic structure (i.e. the QM part) well understood

↓

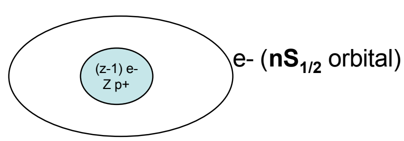
- Atoms now excellent “testing grounds” for studying ‘exotic’ physics

Of course, even the QM part is complicated for ‘heavy’ (Z > 1) atoms.

To extract exotic physics from these atoms requires *independent* information about the QM wavefunction of multi-electron atoms

Alkali Atoms

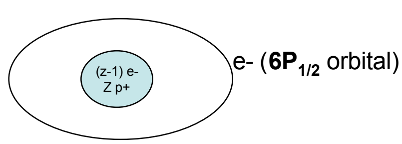
- Spectroscopy, preparation of atoms rather ideal
- Theory has a place to start: ‘Hydrogen -ish’



Precise experimental ‘tests’ abound in Li, Na, K, Rb, Cs, [even radioactive Francium (!)]

Thallium (next best system)

Outer shell has one valence p-electron, $(6s^2)6p$
Z=81 enhances ‘high-energy physics’ effects ~Z^3



Relatively few exp. tests of thallium atomic theory (our lab!)

Testing 'Fundamental' Physics

Freshman mechanics: four fundamental forces are:

~~Normal Force~~, ~~Tension~~, ~~Friction~~, Gravity

E-M Weak Strong

- **State-of-the-art : "Standard Model" of particle physics**
- **Experimental tests mostly high-energy (ACCELERATOR-BASED)**

More exacting test of current Standard Model

Possibly find its limits….

Search for entirely new physics

'ZERO' is an interesting answer

Discrete Symmetries

Parity -- spatial inversion, handedness

Charge conjugation -- particles --> antiparticles

Time Reversal -- direction of all motion

Applied at elementary particle level only!

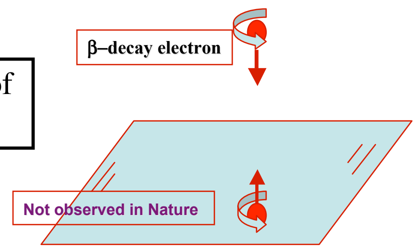
Example: WEAK Force ⟺ "Standard Model"

Weak Force:

Swamped by ordinary E-M forces in ordinary matter

UNIQUE FEATURE: Parity Violating nature

1957 - Discovery of Parity Violation



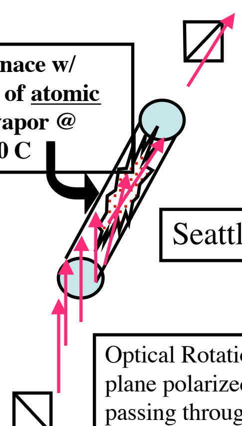
Low-energy experiments now are important contributors

Symmetry and symmetry violation have provided the experimental 'handle' to search for exotic physics amid a large background of 'ordinary' physics

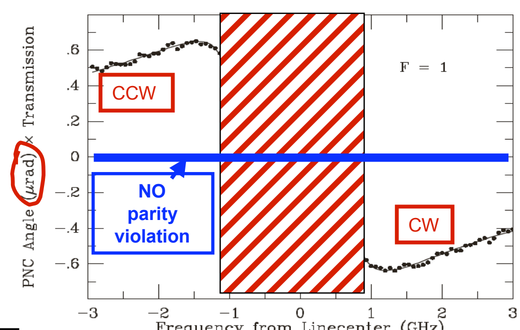
Atomic Thallium PNC Optical Rotation Data

Vetter, Meekhof, Majumder, Lamoreaux, and Fortson
U.W. Seattle (PRL **74**, 2658 (1995))

Furnace w/ 1 m of atomic Tl vapor @ 1000 C



Seattle '95



Optical Rotation of plane polarized light passing through a vapor of atomic thallium in vicinity of absorption line

Summarizing…..

- Parity violation (and hence weak interaction physics) has now been precisely measured in (several) atoms.
- A test of fundamental electroweak theory requires independent multi-electron wave-function calculations since:

$$\mathcal{E}_{PV} = C(Z) * Q_W$$

measured in lab

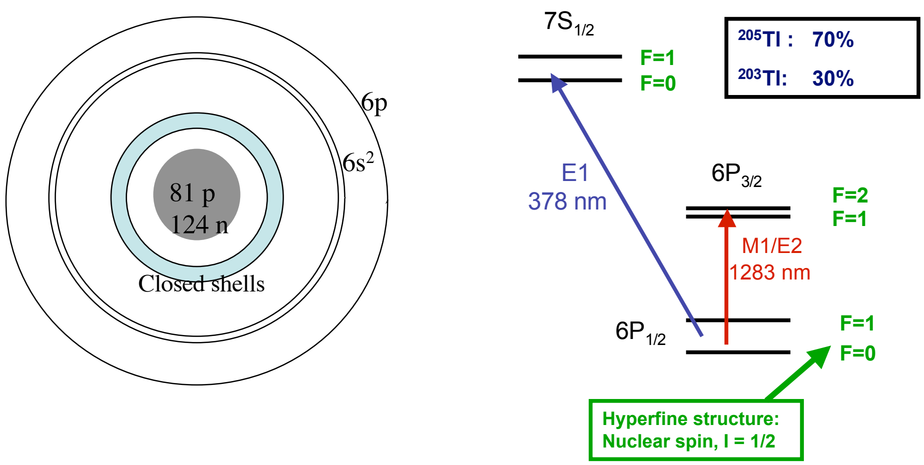
based on element-specific QM wave-function calculation

prediction/test of "Standard Model"

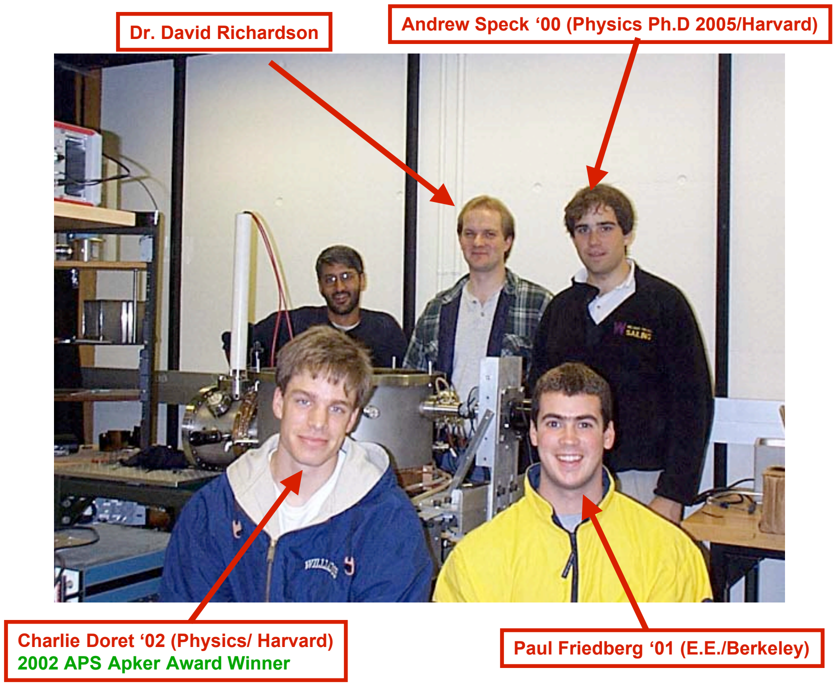
Atomic Experiments already play a significant role in testing various aspects of the 'Standard Model'.

Often our understanding of 'ordinary' multi-electron atomic theory is the LIMITING ISSUE

Thallium (Z=81)



TOXIC !!

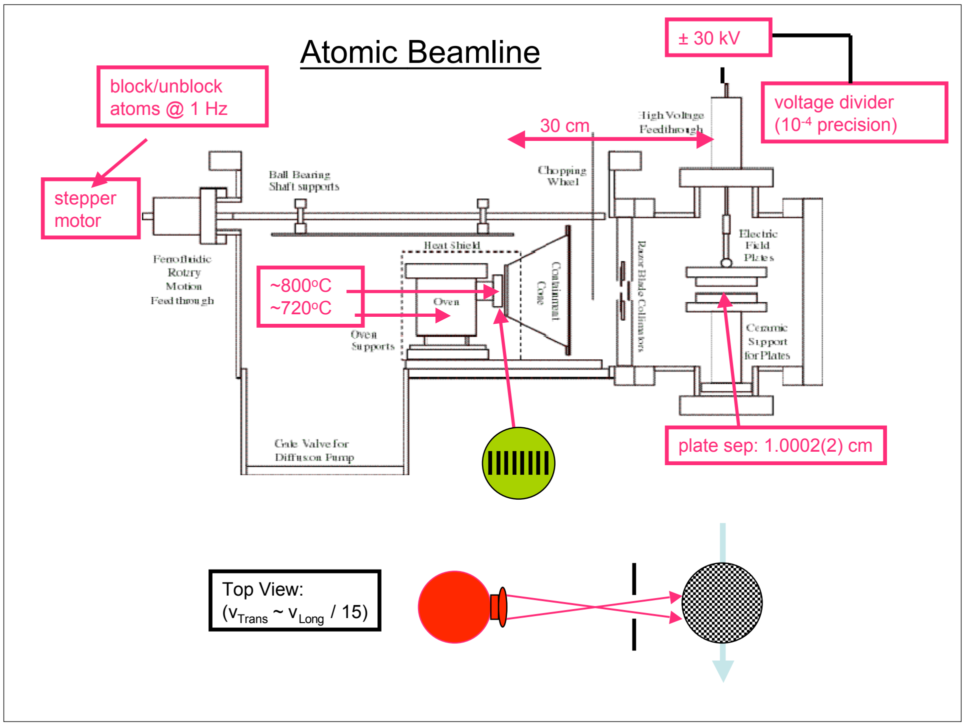


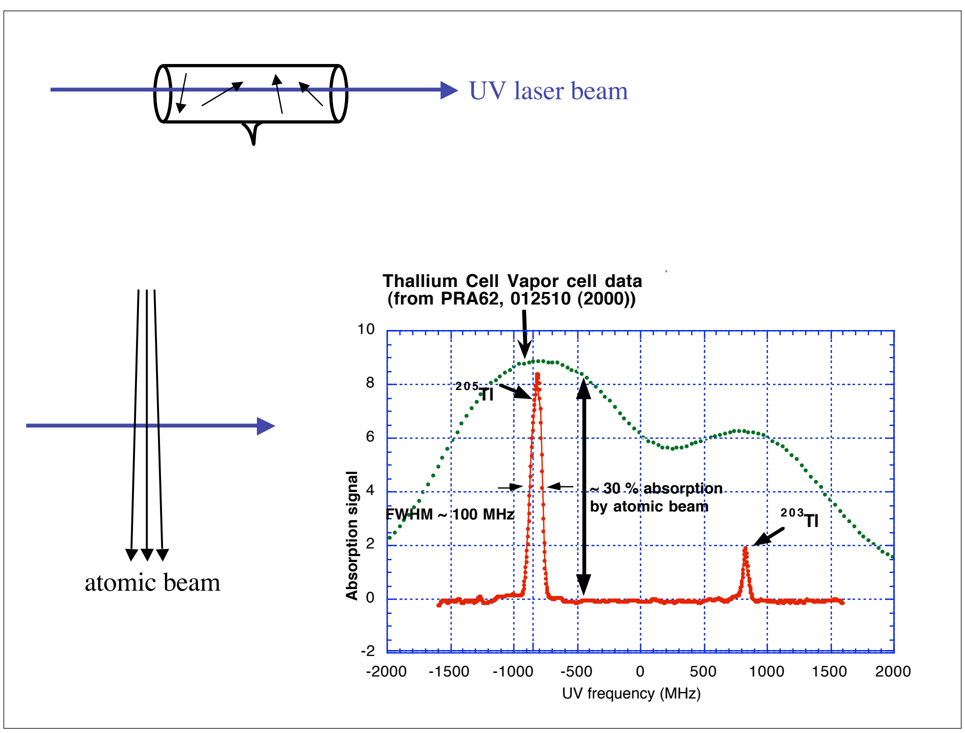
Atomic Beam Stark shift measurement @ 378 nm in Thallium (completed in 2002)

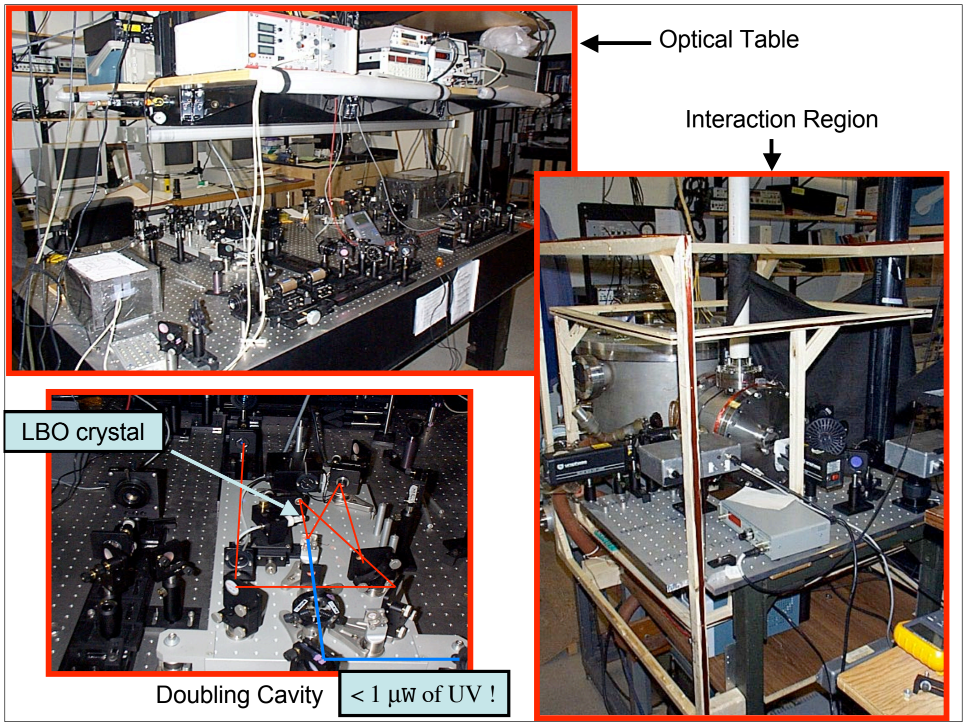
"Scalar Polarizability" of atom
(energy shift in known electric field)

- This can be predicted given a set of theoretical thallium wavefunctions

- Previous measurements in thallium not sufficiently precise to constrain/test state-of-the-art theory

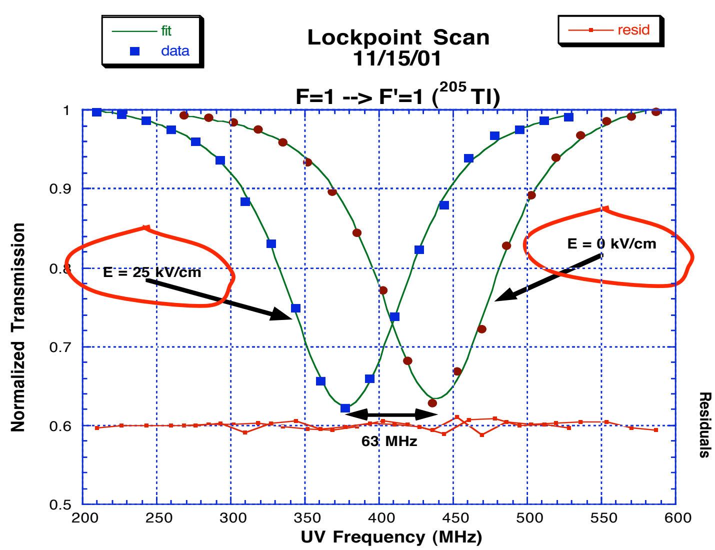

Atomic Beamline
± 30 kV
block/unblock atoms @ 1 Hz
voltage divider (10-4 precision)
30 cm
High Voltage Feedthrough
stepper motor
Ball Bearing Shaft supports
Chopping Wheel
Electric Field Plates
Ferrofluidic Rotary Motion Feedthrough
Heat Shield
~800oC
~720oC
Oven
Oven Supports
Containment Cone
Razor Blade Collimators
Ceramic Support for Plates
Gate Valve for Diffusion Pump
plate sep: 1.0002(2) cm
Top View:
(vTrans ~ vLong / 15)

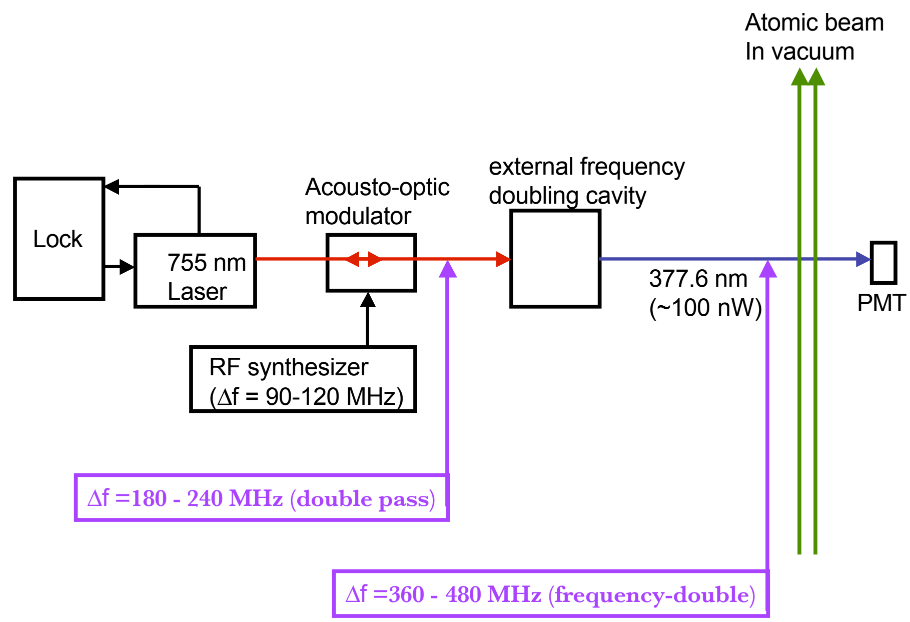

UV laser beam
atomic beam
Thallium Cell Vapor cell data
(from PRA62, 012510 (2000))
205Tl
203Tl
~ 30 % absorption
by atomic beam
FWHM ~ 100 MHz
Absorption signal
UV frequency (MHz)
10
8
6
4
2
0
-2
-2000
-1500
-1000
-500
0
500
1000
1500
2000



First thing you might think of:

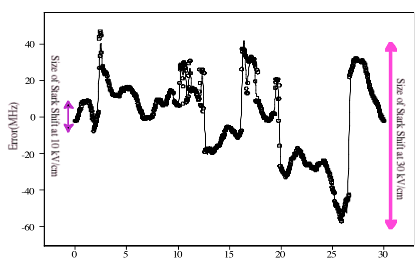
Scan over single line of ^{205}Tl.
Fit data to 'Voigt' transmission profile

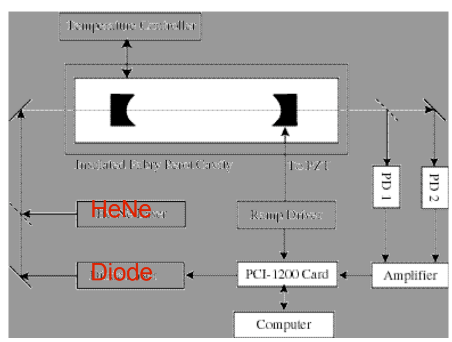




→ Precise, calibrated laser tunability over > 100 MHz

Address Frequency drift in free-running diode laser





- ❑ Remove long-term drift by comparing diode signal to a stabilized HeNe laser in a scanning Fabry-Perot cavity
- ❑ ~1-2 MHz resid. noise in ~30 Hz bandwidth via all-digital lock loop

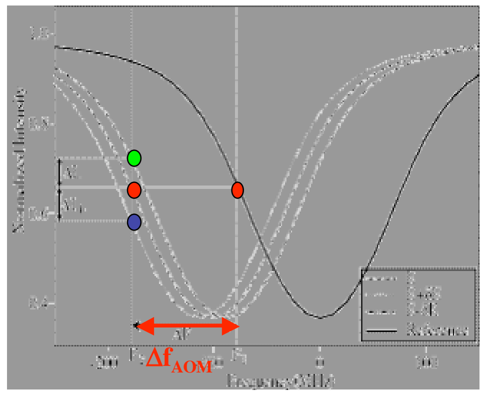
Experimental Method #2: "TRANSMISSION CHANGE"

1. Lock laser to inflection point of transmission curve
2. Simultaneously shift AOM frequency and turn on E-field
3. Vary E-field over small range, keep Δf fixed,
   Search for "zero" transmission change

❖ Built in frequency calibration

❖ Does not require full scan/fit

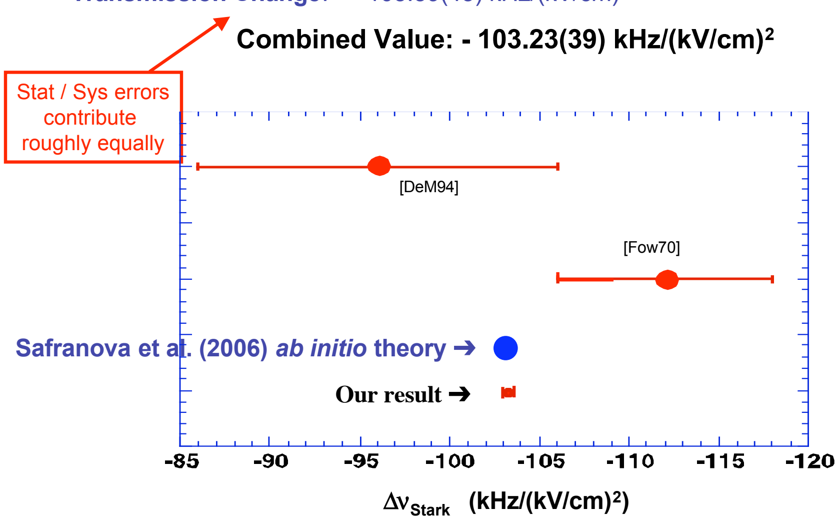
❖ excellent systematic error check!



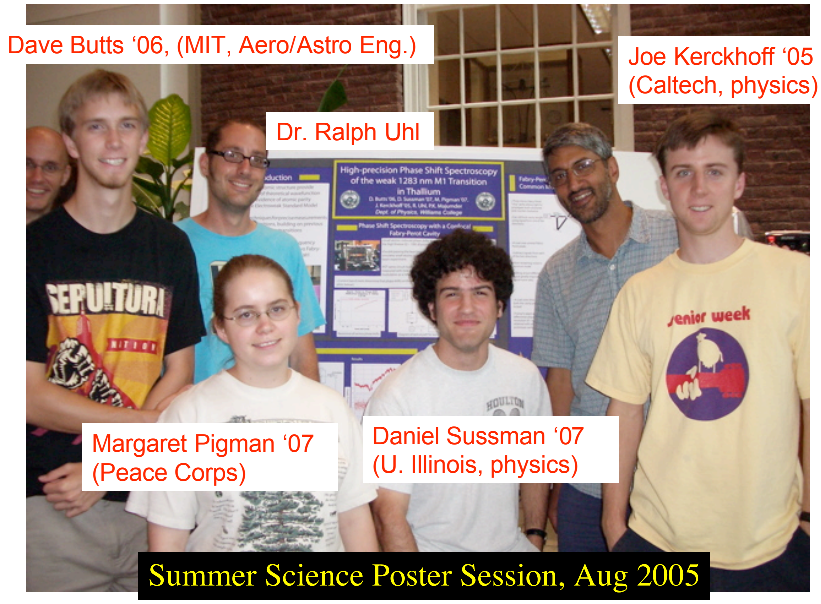
Final results of Stark shift measurement

Frequency Scan: -103.02(62) kHz/(kV/cm)^2
Transmission Change: -103.39(43) kHz/(kV/cm)^2

Combined Value: - 103.23(39) kHz/(kV/cm)^2



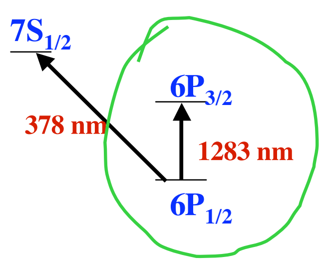
Onto experiment #2…..



Focus now on the OTHER ground-state transition:

(1) Atomic structure measurements in same transition in which atomic parity violation was measured

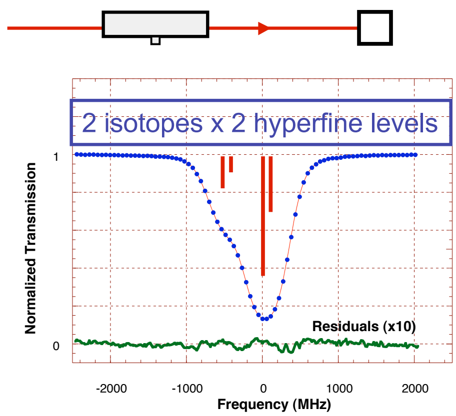
(2) New test of long-range Time-reversal-violating forces in thallium



$\langle M1\rangle^2 / \langle E1\rangle^2 \sim 10^{-4} - 10^{-5}$!!

Develop and test a new spectroscopy method capable of VERY sensitive detection of small absorption

Absorption measurements in a vapor cell @ 900 C !



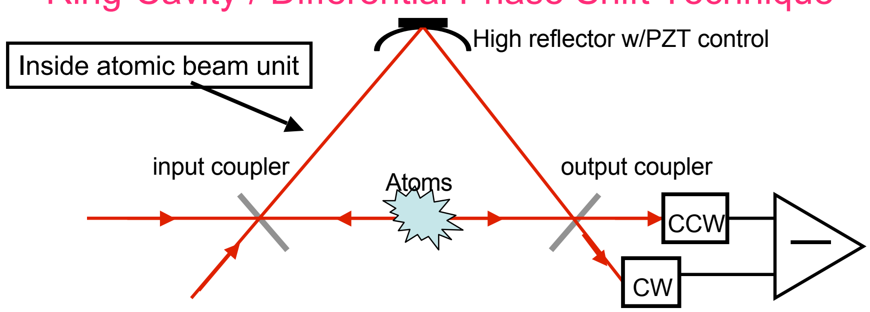
Done (1999)

- Huge number density by heating cell, but….
- Can’t apply E-field
- Unresolved structure (Doppler broadening)

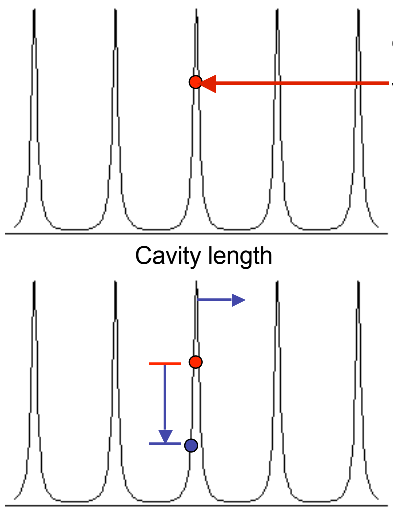
Atomic beam apparatus affords clean, controlled, spectrally-resolved laser/atom interaction

Must deal with x 10^4 fewer atoms, weaker signal !!

“Ring-Cavity / Differential Phase Shift Technique”



- Lock cavity - high sensitivity to small optical phase shifts due to ‘sharpness’ of cavity fringes
- Separate CW, CCW beam detection allows differential measurement, common-mode noise rejection
- Technique has potential for detection of other weak lines



CCW Transmission signal
Stabilize length by locking cavity signal

- High finesse cavity provides sensitivity

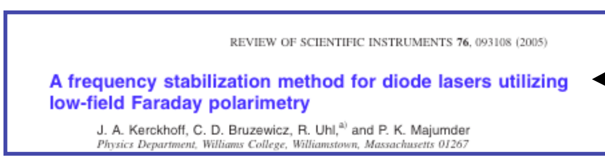
CW Transmission signal

Detect phase shift via relative cavity transmission change

- Laser frequency, cavity mechanical noise: COMMON MODE
- Excellent sensitivity to DIFFERENTIAL shifts

DEVELOPMENT PIECES

I. Lock laser to this ‘forbidden’ transition. Use Faraday rotation in vapor cell + sensitive polarimetry…..



REVIEW OF SCIENTIFIC INSTRUMENTS **76**, 093108 (2005)

A frequency stabilization method for diode lasers utilizing low-field Faraday polarimetry

J. A. Kerckhoff, C. D. Bruzewicz, R. Uhl,[a)] and P. K. Majumder
Physics Department, Williams College, Williamstown, Massachusetts 01267

Rev. Sci. Instrum. (Sept. ‘05)

❈ II.   Construct stable optical ring cavity suitable for in-vacuum use.

❈ III.   Demonstration of differential phase shift sensitivity -- Use frequency shifted beams

❈ IV. Simulation of expected signal for atom/laser beam interaction.

First: Index of Refraction - reminders

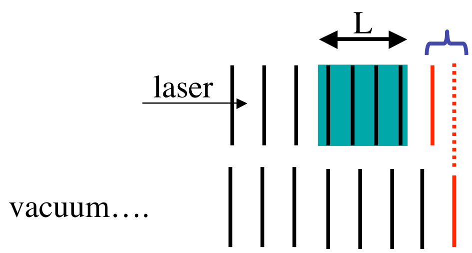
v = c/n

Microscopically speaking, index of refraction is due to atomic/molecular absorption. Larger ‘n’ from: (1) denser stuff; (2) proximity to absorption line

$$n(\nu) = n_r(\nu) + i\, n_i(\nu)$$

Wave propagation ~ $\exp(ikx) = \exp[i\, 2\pi\, n(\nu)\, x / \lambda]$

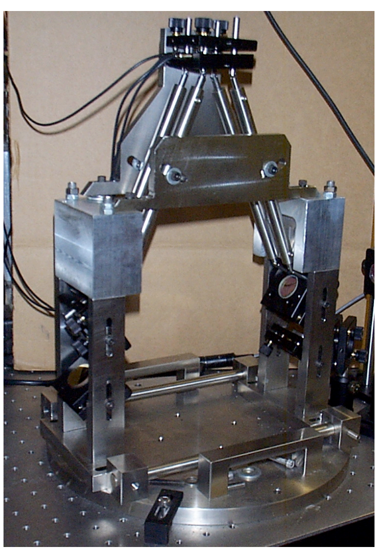
Real part: ‘speed’, phase shift; **Imag part: absorption**

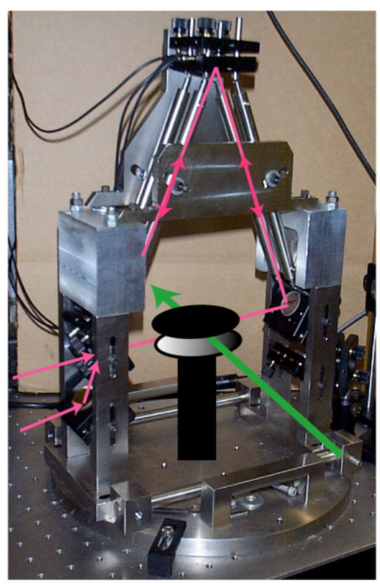


$$\Delta\Phi(\nu) = 2\pi\, n_r(\nu)\, L/\lambda$$

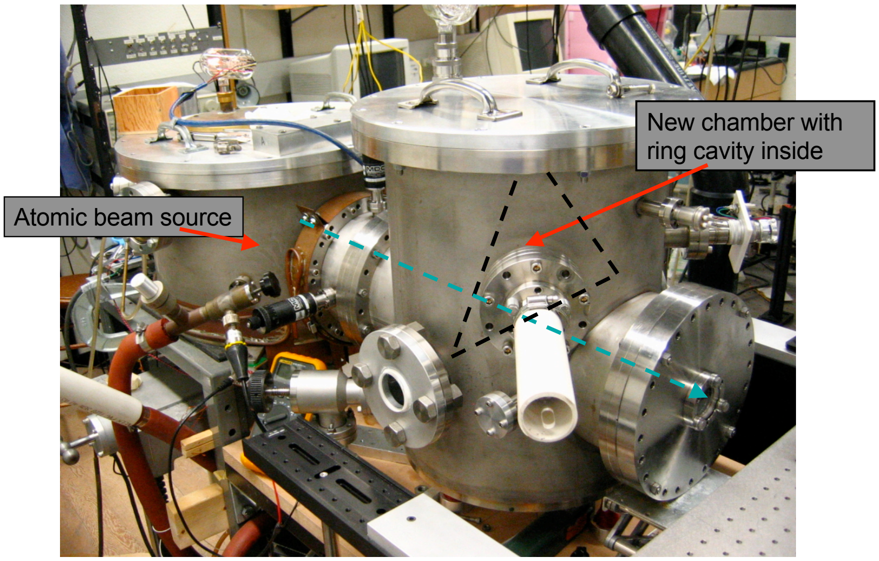
CHALLENGE:
For us, $\Delta\phi \sim 10^{-4} - 10^{-5}$ rad !!

II. The Ring Cavity, v1.0





Atomic beamline has grown to accommodate this new piece:



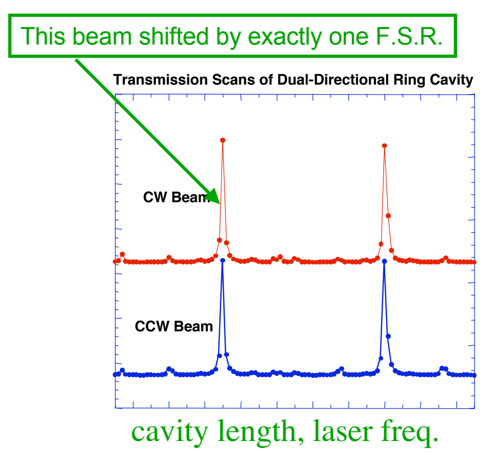
Trick for first set of experiments:

COUNTER-PROPAGATING RING CAVITY BEAMS, BUT…
Use acousto-optic modulator to frequency shift CW beam relative to CCW beam by EXACTLY ONE FSR

- Finesse ~ 75
- FSR = 438 MHz
- FWHM ~ 6 MHz

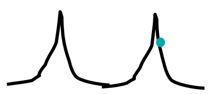
- CAVITY does not care about frequency shift...

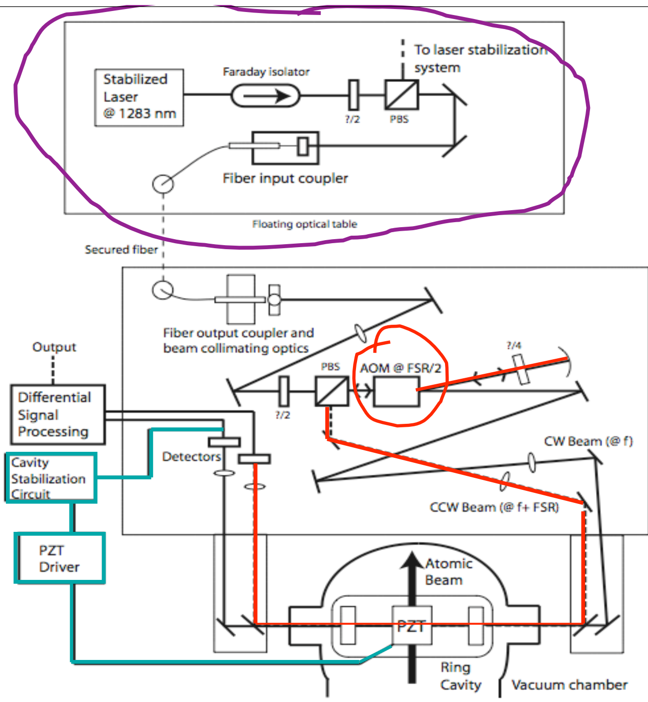
  [but ATOMS will !!]

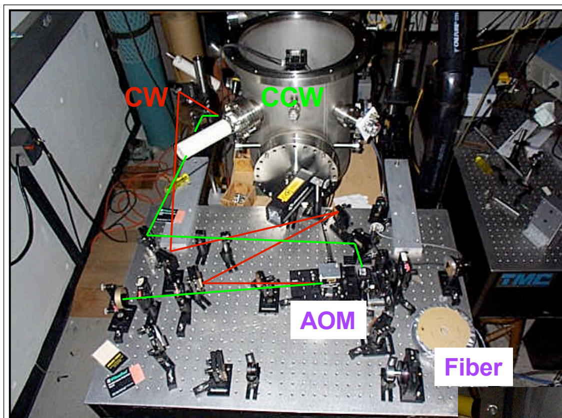


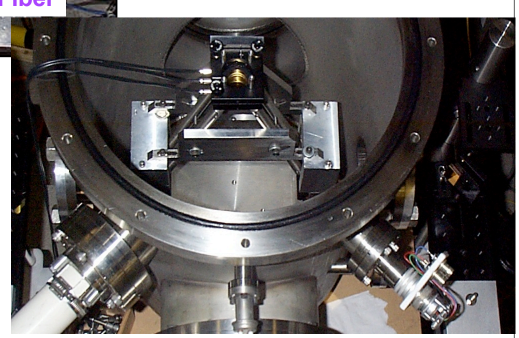
III. Differential phase shift sensitivity

Experimental layout

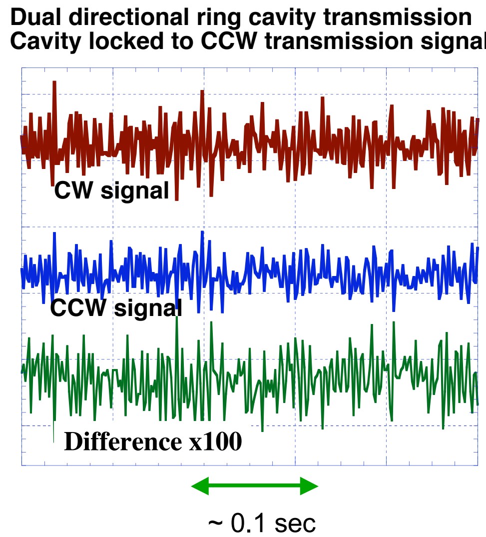








- LOCK CCW signal to inflection point of F-P fringe
- Tune differential amp to subtract optimally at this point



‘Simulate’ atomic phase shift:

Step synthesizer frequency driving the AOM for CW beam
Easy to quantify phase shift: $\Delta\phi / 2\pi = \Delta f$ / FSR

Does [CW - CCW] signal show discernable response ??

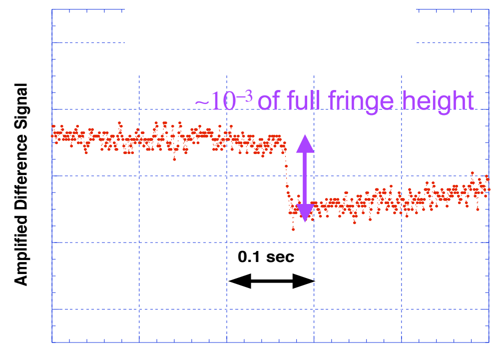
KEEP IN MIND:

- COMMON MODE NOISE still subtracts even with frequency shift.
- ATOMS will be in resonance with only one laser beam at a time.
- Get two copies of atomic spectrum (with sign flip) in differential signal due to locking scheme….

10 kHz shift to AOM frequency
→ $\Delta\phi \approx 3 \times 10^{-4}$ rad

Signal/noise ≈ 10/1

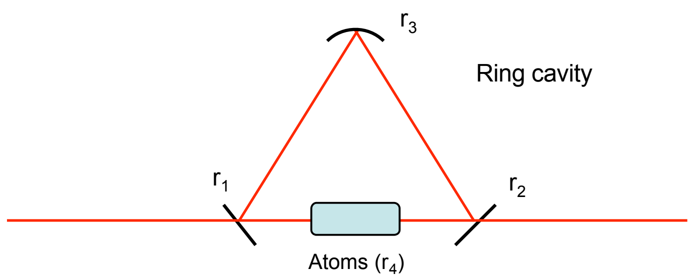
100 Hz detector bandwidth
phase resolution limit:
$\phi_{noise} \approx 3 \times 10^{-6}$ rad/√Hz



Seems promising for detection of
(very small) expected atomic phase shift

Modeling the expected atomic signal

- Model *actual* signal- eventually fit experimental data
- Derive 'perturbed' cavity Airy function with atoms present
- Complex index of refraction phase shifts AND attenuates light in cavity



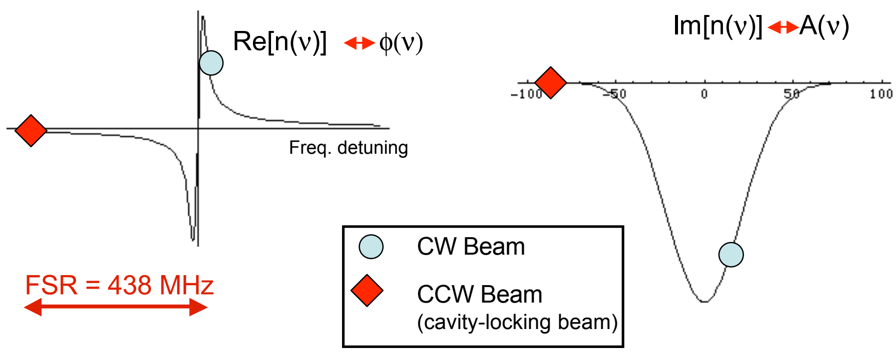
- **Treat atoms as an extra 'mirror'**
- **Complex reflection coefficient depends on frequency of laser:**

$$r_4 = (1 - A(\nu))^{1/2} e^{i\,\phi(\nu)}$$

‘Turn on’ a single atomic absorption line….

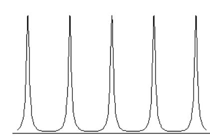
- Cavity-locking beam (◆) is NOT resonant.
- CW beam (○) frequency-shifted, IS near resonance

Phase shift, absorption induced in resonant beam produces non-zero differential signal with atoms present.



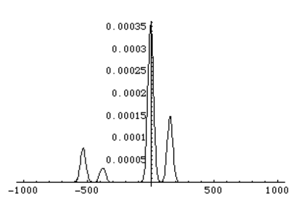
With the help of **Mathematica**…generate Airy functions,
Include full atomic sub-structure, appropriate atomic lineshapes

$$T_{CCW}(\delta,\nu)=\frac{(1-r)^2}{\left(1-r\sqrt{1-A(\nu)}\right)^2}*\frac{I_0}{1+\frac{4r\sqrt{1-A(\nu)}}{\left(1-r\sqrt{1-A(\nu)}\right)^2}\mathrm{Sin}[\delta+\phi(\nu)]^2}$$

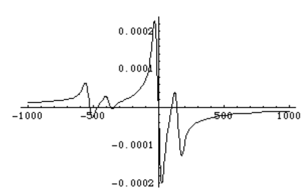


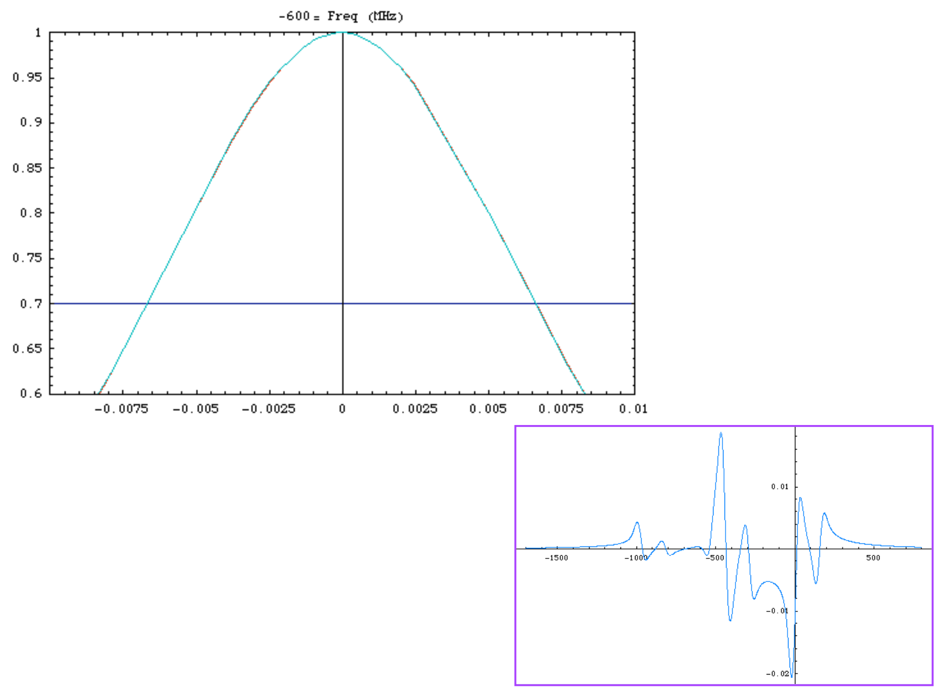
$$T_{CW}(\delta,\nu_{+FSR})=\frac{(1-r)^2}{\left(1-r\sqrt{1-A(\nu_{+FSR})}\right)^2}*\frac{I_0}{1+\frac{4r\sqrt{1-A(\nu_{+FSR})}}{\left(1-r\sqrt{1-A(\nu_{+FSR})}\right)^2}\mathrm{Sin}[\delta+\phi(\nu_{+FSR})]^2}$$

A(ν) looks like:



φ(ν) looks like:





Final comments -
Differential phase shift idea

- Predicted lineshape is complicated (good!)
- Lineshape has “built-in” frequency calibration
- Given resolution demonstrated, simulation predicts that we can detect absorption down to 1 part in 10^5

TAKING DATA NOW.

- Expected Stark shift @40 KV/cm more than full linewidth in atomic beam (~ 50 MHz)

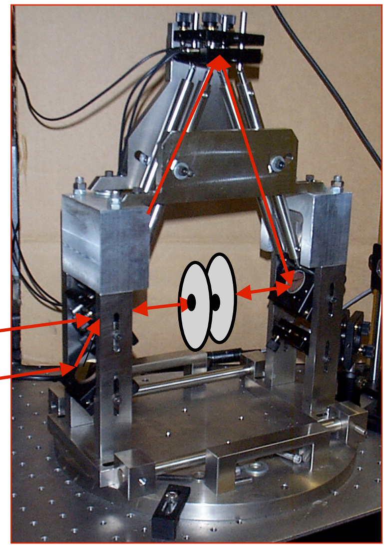
Straightforward re-design for T-Violation experiment:

- ❖ Remove relative frequency shift
- ❖ Install E-field plates to provide co-linear field

Search for $"\hat{k}_{\text{laser}} \bullet \vec{E}"$
Interaction
(a manifestly "T-odd" quantity)

↓

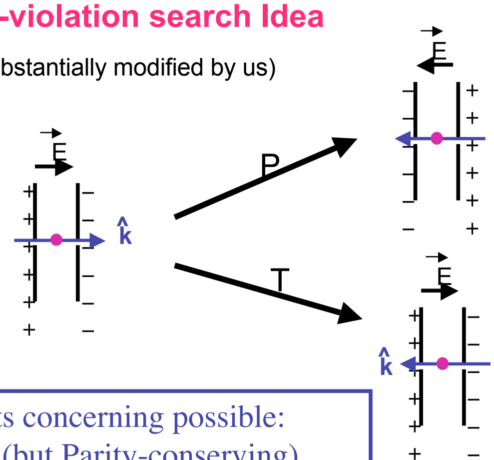
Cavity phase shift now depends on both propagation direction AND Static field direction



Origin of the Symmetry-violation search Idea

(Kozlev and Porsev 1990….substantially modified by us)

"T-violating, P-conserving"
$\hat{k} \bullet \vec{E}$



~ No experimental limits concerning possible:
Time Reversal-violating, (but Parity-conserving),
electron-nucleon forces (T-odd, P-even; 'TOPE')

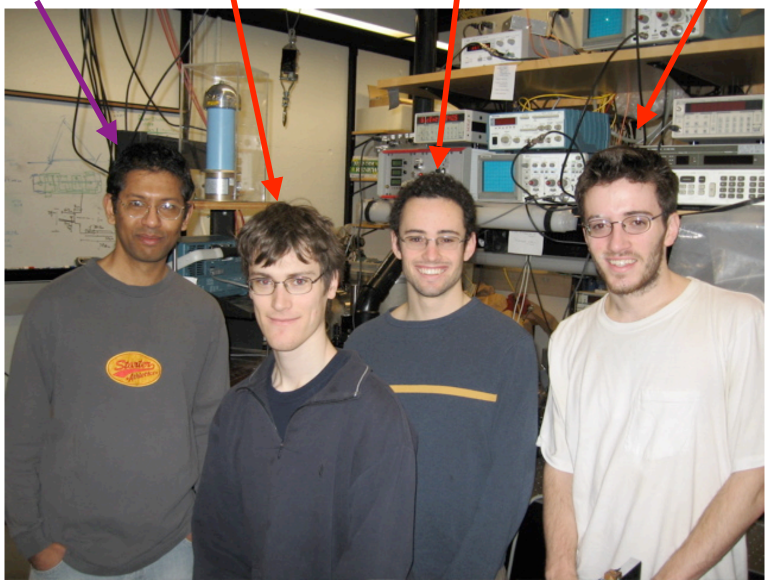
Search for differential cavity phase shift (just as before), now correlated with E-field reversal.

Toby Schneider '07
➔MIT/Woods Hole (ocean eng.)

Jared Strait '07
➔ Cornell (EE)

Owen Simpson '07
➔ Princeton (physics)

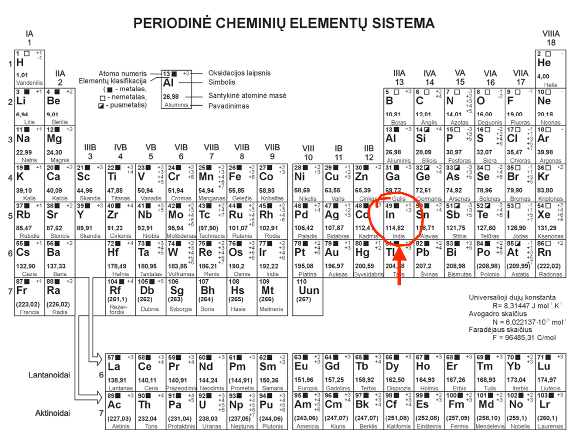
Dr. Mevan Gunawardena



Latest news in the lab…..

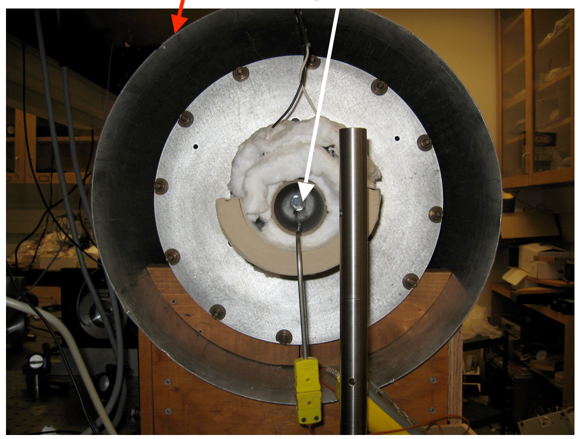
Further test techniques of hard 3-valence-electron calculations

New atomic system. Make use of new technology…

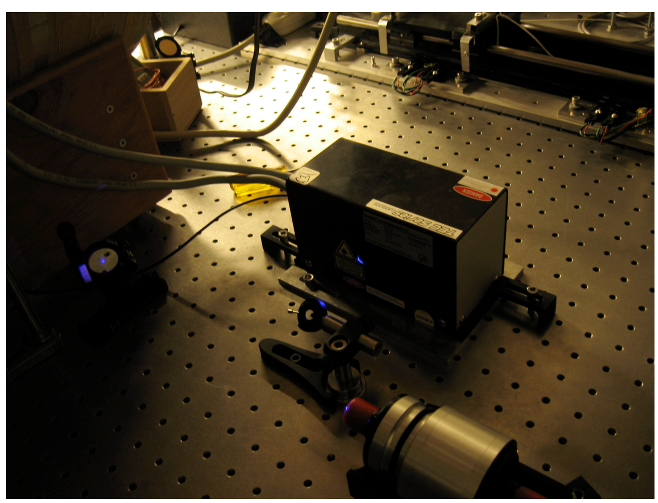


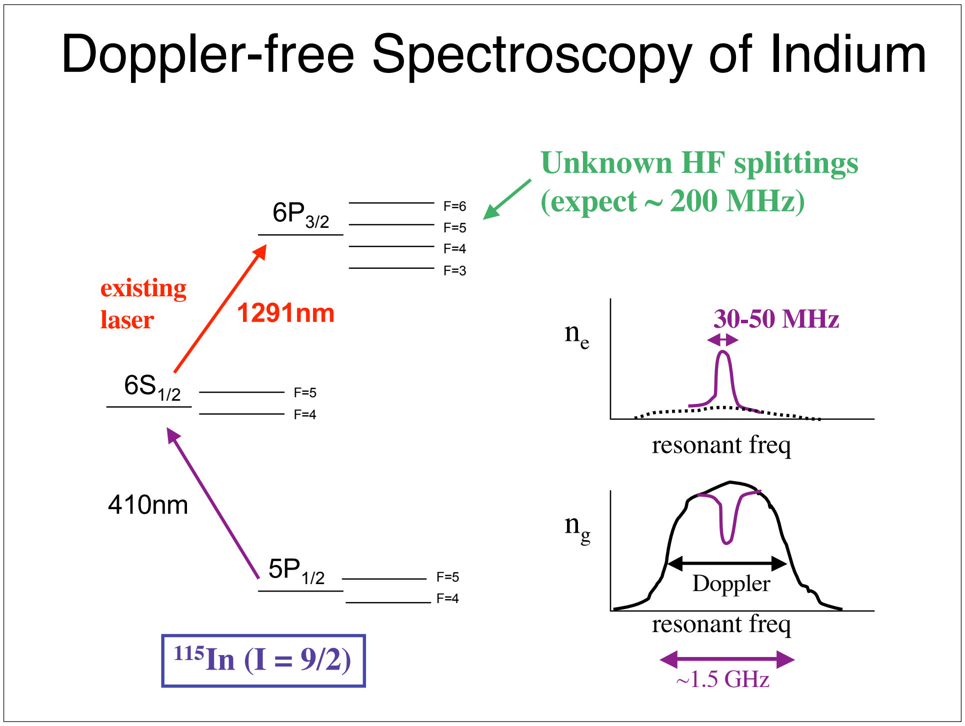
Vapor Cell Spectroscopy

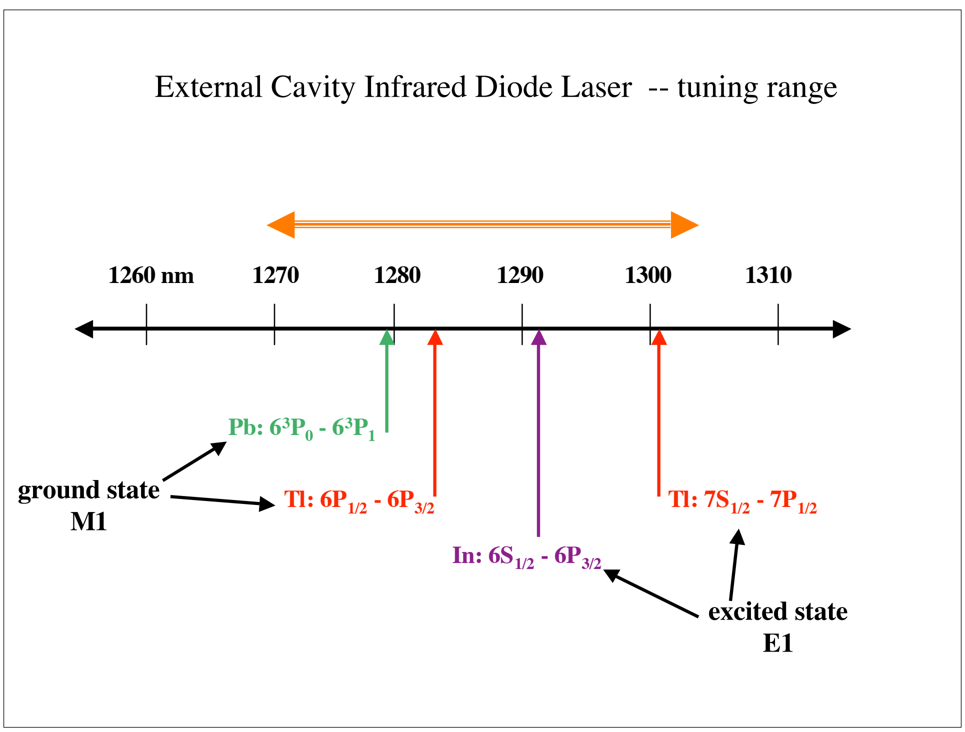
- Must heat substantially to get sufficient vapor pressure
- $\sim 600^{o}$ C $\rightarrow$ Doppler width of 1-2 GHz



GaN violet/UV laser diodes (Nichia Corp.)



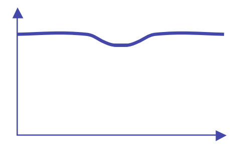

Doppler-free Spectroscopy of Indium
Unknown HF splittings
(expect ~ 200 MHz)
6P3/2
F=6
F=5
F=4
F=3
existing
laser
1291nm
6S1/2
F=5
F=4
410nm
5P1/2
F=5
F=4
115In (I = 9/2)
ne
30-50 MHz
resonant freq
ng
Doppler
resonant freq
~1.5 GHz


External Cavity Infrared Diode Laser -- tuning range
1260 nm
1270
1280
1290
1300
1310
Pb: 6³P0 - 6³P1
ground state
M1
Tl: 6P1/2 - 6P3/2
In: 6S1/2 - 6P3/2
Tl: 7S1/2 - 7P1/2
excited state
E1

Detecting the weaker second-step absorption signal with high S/N

Options:

Direct transmission detection……….
(accurate line center determination
is difficult!)



Fluorescence detection - optical access difficult,
plans for future Stark shift work - even trickier access

Use frequency modulation and RF lock-in detection of infrared signal

RF spectroscopy

IDEA:

(1) Create laser field E(t) that has RF sideband structure
(2) Tune this set of multiple frequencies through
atomic absorption spectrum (assumed WEAK)
(3) Each frequency component records absorption spectrum
(4) Detect transmitted INTENSITY, which includes
'cross terms' at RF 'beat frequencies'.
(5) Demodulate signal at RF frequency to reveal spectrum

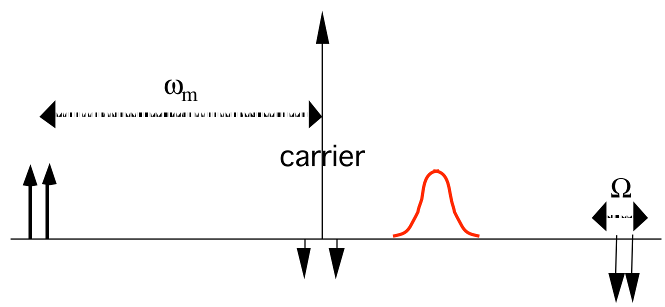
- Eliminates troublesome "1/f" noise source at low frequency
- Allows simple detection of laser transmission signal
- Demodulated spectrum has zero-background spectrum
- RF 'copies' in final spectrum
  - ideal frequency calibration feature!

"Two-tone" RF Modulation scheme ($\omega_m >> \Omega$)

[Gallagher et al. 1988]

ω_m ~ 750 MHz, large FM frequency, less 1/f noise

$\Omega \sim 2$ MHz, easy detection w/standard equipment.



$$E(t) = E_0 \exp(i\omega_0 t) \bullet \sum_n J_n(\beta_1) \exp(i\, n[\omega_m+\Omega/2]t) \bullet \sum_k J_k(\beta_2) \exp(i\, k\, [\omega_m-\Omega/2]\, t)$$

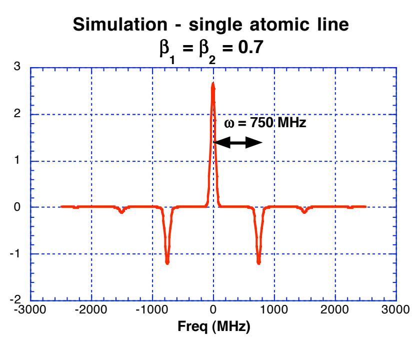
Simulation procedure:

(1) Propagate the expanded E(t) through known atomic lineshape

(2) Assume small absorption, $E_{TRANS} = E(\omega_0, t) \bullet (1 - \mathcal{A}(\omega-\omega_0))$

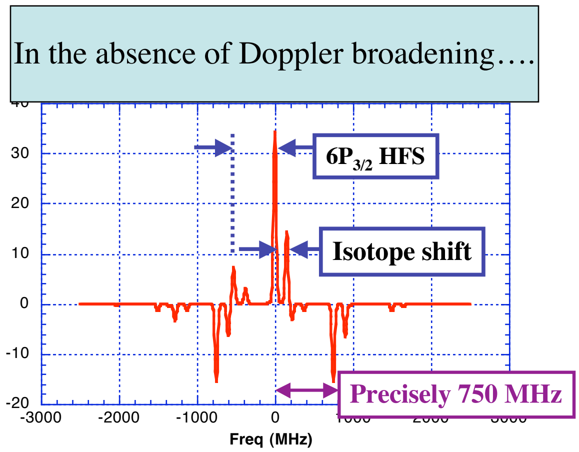
(3) Compute $I_T = |E_{TRANS}|^2$; [pick out term ~ cos (Ωt).....]

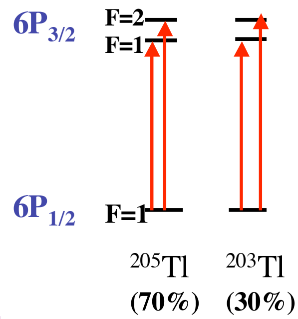
For a single atomic line we expect a demodulated signal that looks like ….



Let’s test out this scheme on that ground-state “M1” transition in thallium at 1283 nm.

Spectrum consists of four hyperfine/isotopic lines…

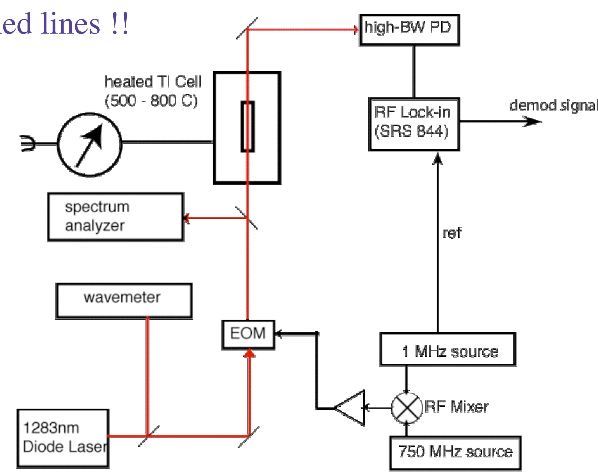


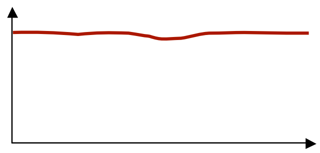


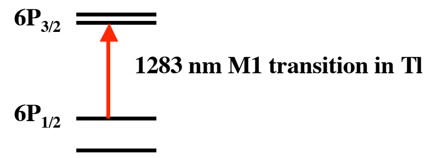
Proof of Viability

Vary temperature of cell (number density, absorptivity), look at RF demodulated signal.

Note - Doppler broadened lines !!



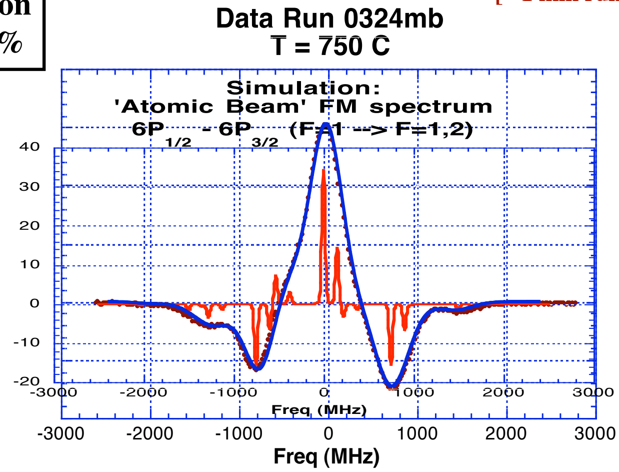


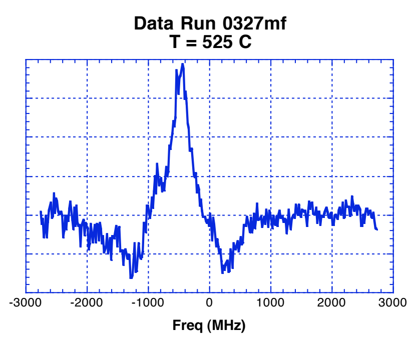


actual absorption in cell: ~ few %

Vapor Cell

[~ 1 min run]





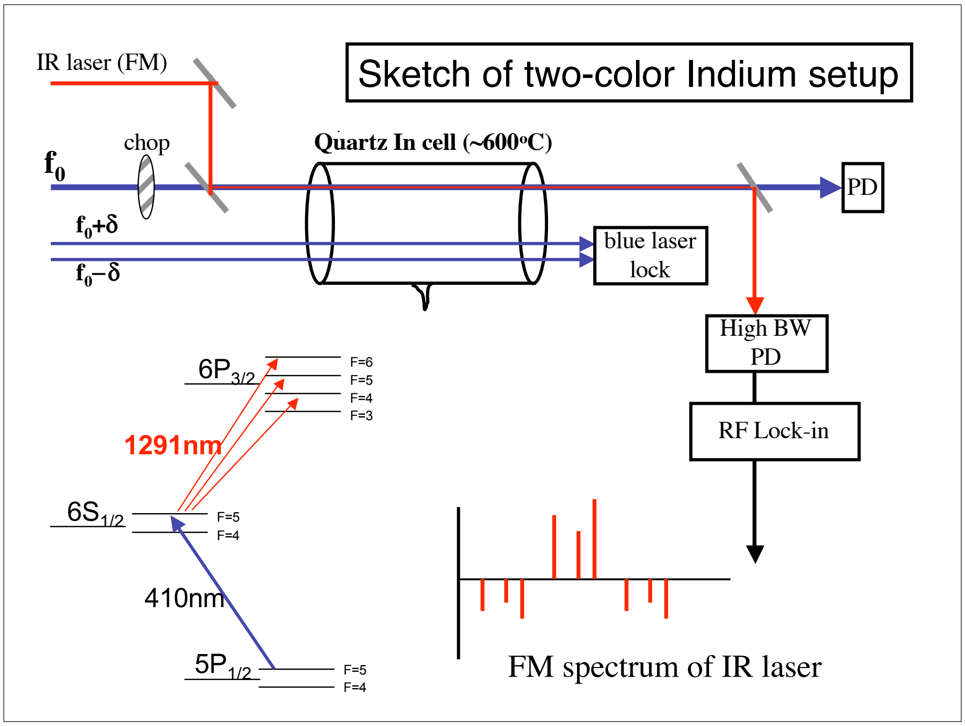
We can even see an RF-demodulated signal when the thallium number density is ~ 1000 x smaller !

recall - this is an M1 transition

Should give excellent S/N for second of two E1 transition steps Given ability to optically saturate the first step.

FM spectrum for Indium two-step will be Doppler-free

Will contain RF sideband 'copies' of spectrum at precisely known frequency separation -- CALIBRATION!



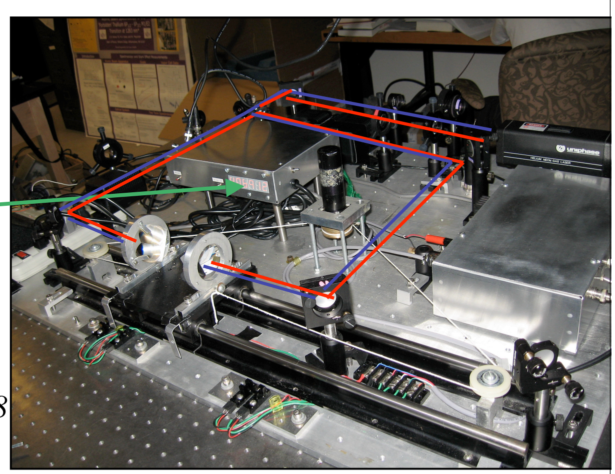
Tools already constructed

- Oven, heating control
- Optics, diagnostics, detectors, external Fabry-Perot for blue laser
- RF spectroscopy scheme

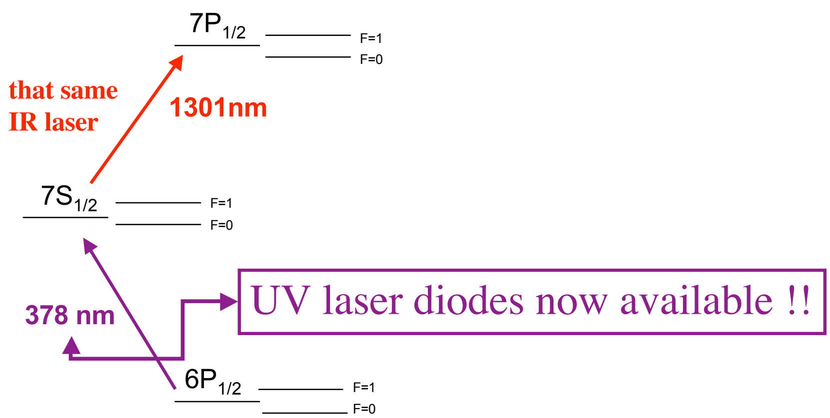
- FINDING THE LINE at 410 nm !!

1 ppm readout of Blue wavelength

"Wavemeter" optics, electronics, mechanicals built/tested by J. Strait '07, P. Hess '08



And after this…..back to thallium



Conclusions

- ➢ Low-energy, table-top atomic physics experiments CAN provide insights into elementary-particle physics questions
- ➢ Heavy atoms are attractive testbed, but require challenging, independent atomic structure calculations

- Diode lasers, suitably stabilized and controlled are ideal probes
- Development of S/N enhancement techniques is key
  [**Differential phase shifts, RF modulation spectroscopy**]
- Design experiments to reject (or reveal) systematic errors

Wonderful research-training opportunities for many undergraduates