Spectroscopy of Cs Atoms

$$ National Science Council, Taiwan $$
$$ 國科會 $$

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Outline

Two-photon transitions of Cs atoms

Cs 6s-8s TPTs

Cs 6s-7d TPTs

What is spectroscopy?

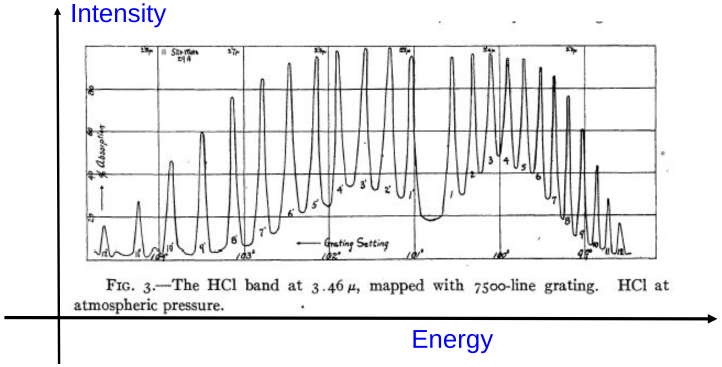


Fig. 3.—The HCl band at 3.46 μ, mapped with 7500-line grating. HCl at atmospheric pressure.

What are the important issues on the spectrum?

Line position, Intensity and Shape

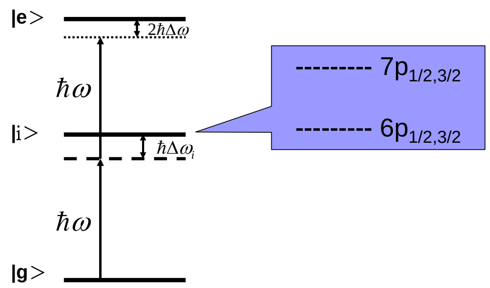
Two-Photon Spectroscopy

6s-8s Two-photon transition in Cesium
(Cell at 50.0˚C)

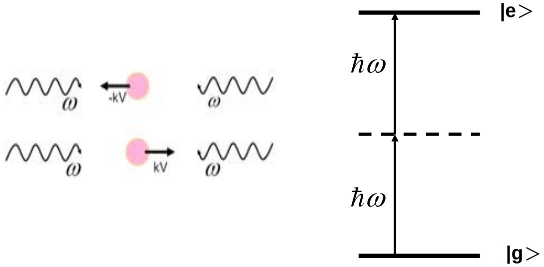
Measurement of the hyperfine structure of the 6s - 7d(J=3/2, 5/2) transitions by two-photon spectroscopy

Two-Photon Transition probability

$$P_{ge}^{(2)}(\Delta\omega)=\left|\sum_i \frac{\langle e|H_1|i\rangle\langle i|H_2|g\rangle+\langle e|H_2|i\rangle\langle i|H_1|g\rangle}{\Delta\omega_i}\right|^2 \frac{\Gamma_e}{4(\Delta\omega)^2+\Gamma_e^2/4}$$

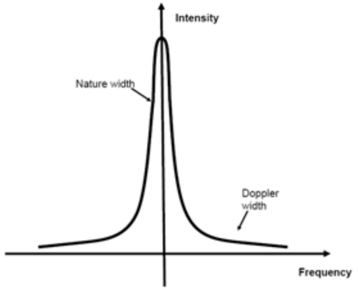


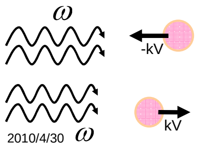
Two-Photon Transition/ Doppler Free



$$E_e-E_g=\hbar(\omega+kV)+\hbar(\omega-kV)=2\hbar\omega$$

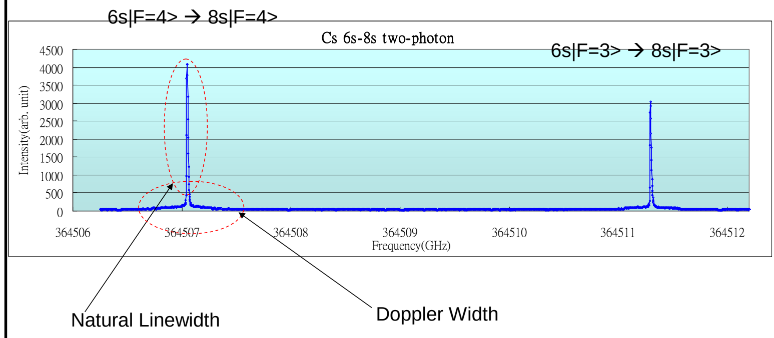
Two-Photon Transition/ Doppler Wings





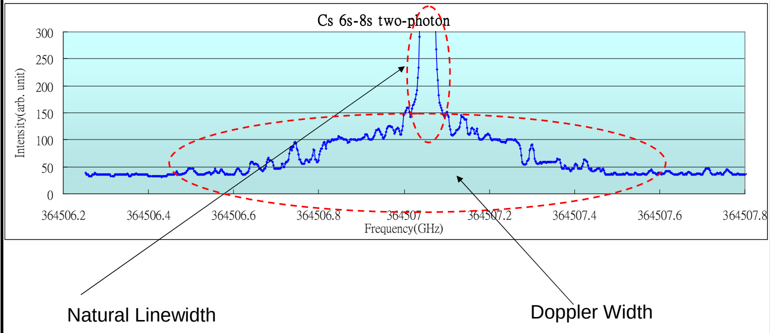
$$E_e-E_g=\hbar(\omega\pm kV)+\hbar(\omega\pm kV)=2\hbar\omega\pm 2kV$$

Two-Photon Transition/ Expt spectrum

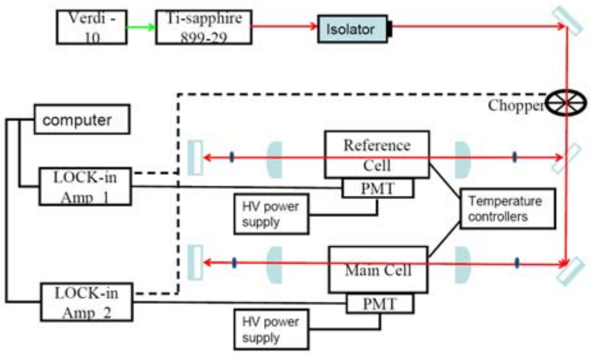


Two-Photon Transition/ Expt spectrum

6s|F=4> → 8s|F=4>

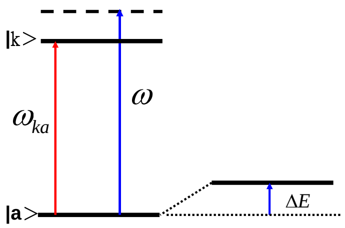


Experimental Setup

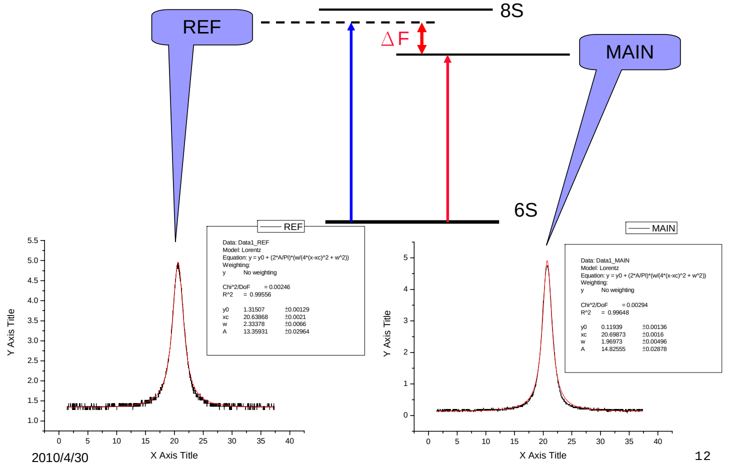


Light Shift or AC Stark Effect

$$\overline{\Delta E_a} = -\frac{E_0^2}{2\hbar}\sum_{k\neq a}\left|\langle k|D_z|a\rangle\right|^2 \frac{\omega_{ka}}{\omega_{ka}^2-\omega^2}$$

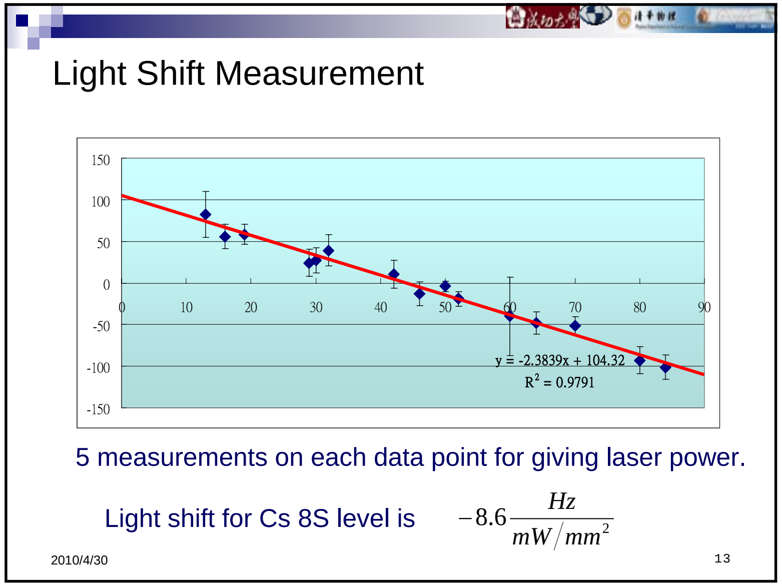


Light Shift Measurement



```
REF
Data: Data1_REF
Model: Lorentz
Equation: y = y0 + (2*A/PI)*(w/(4*(x-xc)^2 + w^2))
Weighting:
y          No weighting

Chi^2/DoF        = 0.00246
R^2      =  0.99556

y0       1.31507          ±0.00129
xc       20.63868         ±0.0021
w        2.33378          ±0.0066
A        13.35931         ±0.02964
```

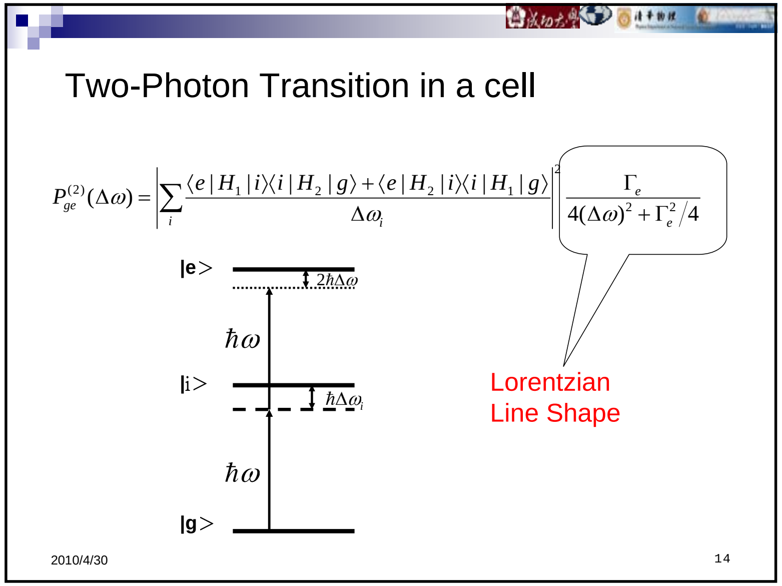
```
MAIN
Data: Data1_MAIN
Model: Lorentz
Equation: y = y0 + (2*A/PI)*(w/(4*(x-xc)^2 + w^2))
Weighting:
y          No weighting

Chi^2/DoF        = 0.00294
R^2      =  0.99648

y0       0.11939          ±0.00136
xc       20.69873         ±0.0016
w        1.96973          ±0.00496
A        14.82555         ±0.02878
```



Light Shift Measurement

5 measurements on each data point for giving laser power.

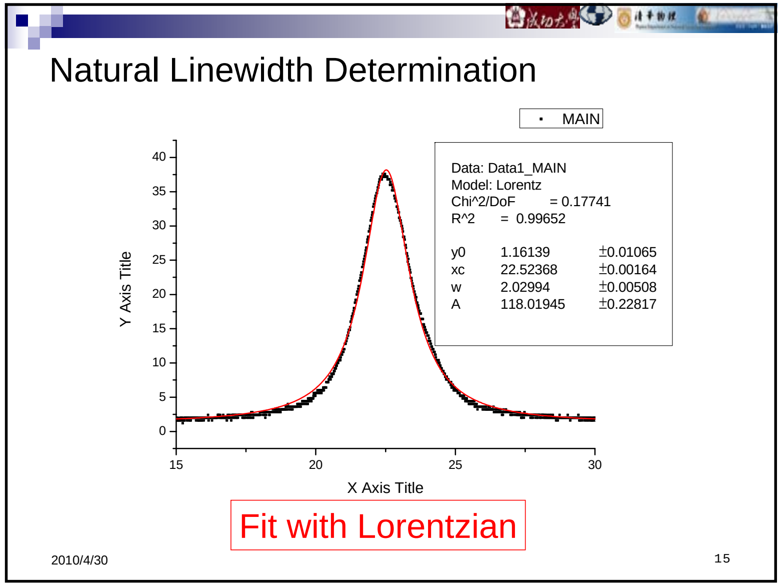
Light shift for Cs 8S level is $-8.6\dfrac{Hz}{mW/mm^2}$



Two-Photon Transition in a cell

$$P_{ge}^{(2)}(\Delta\omega)=\left|\sum_i \frac{\langle e|H_1|i\rangle\langle i|H_2|g\rangle+\langle e|H_2|i\rangle\langle i|H_1|g\rangle}{\Delta\omega_i}\right|^2 \frac{\Gamma_e}{4(\Delta\omega)^2+\Gamma_e^2/4}$$

Lorentzian
Line Shape

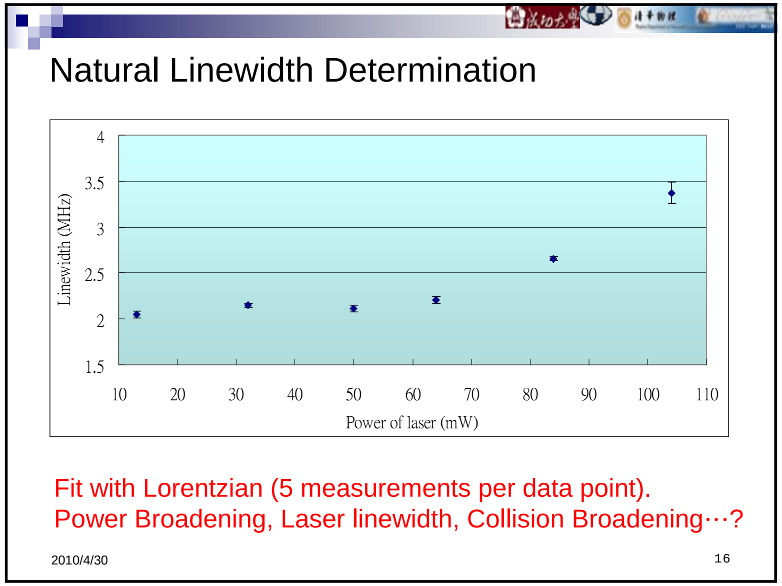


Natural Linewidth Determination

Data: Data1_MAIN
Model: Lorentz
Chi^2/DoF = 0.17741
R^2 = 0.99652

y0	1.16139	±0.01065
xc	22.52368	±0.00164
w	2.02994	±0.00508
A	118.01945	±0.22817

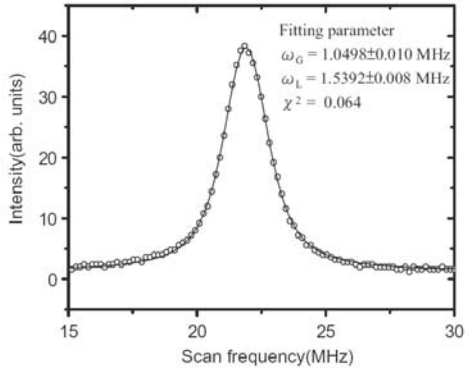
Fit with Lorentzian



Natural Linewidth Determination

Fit with Lorentzian (5 measurements per data point).
Power Broadening, Laser linewidth, Collision Broadening…?

Natural Linewidth Determination/Fit with Voigt



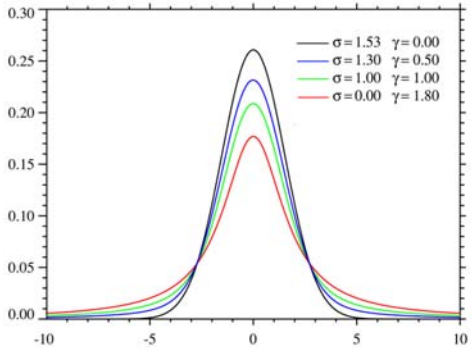
The observed spectrum is fitted with a Voigt Distribution to separate the Lorentzian width (Natural linewidth) and Gaussian width (other broadenings).

Voigt profile

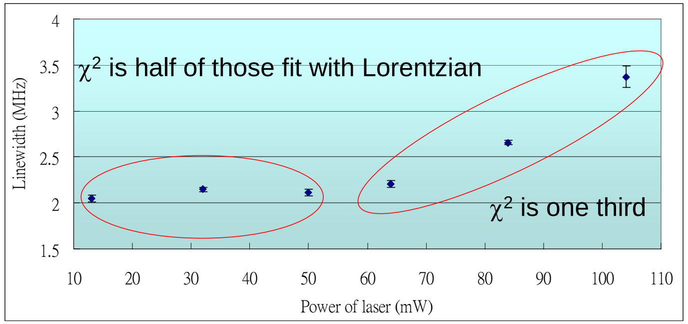
$$V(x;\sigma,\gamma) = \int_{-\infty}^{\infty} G(x';\sigma)L(x-x';\gamma)\,dx'$$

$$L(x;\gamma) \equiv \frac{\gamma}{\pi(x^2+\gamma^2)}.$$

$$G(x;\sigma) \equiv \frac{e^{-x^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}}$$

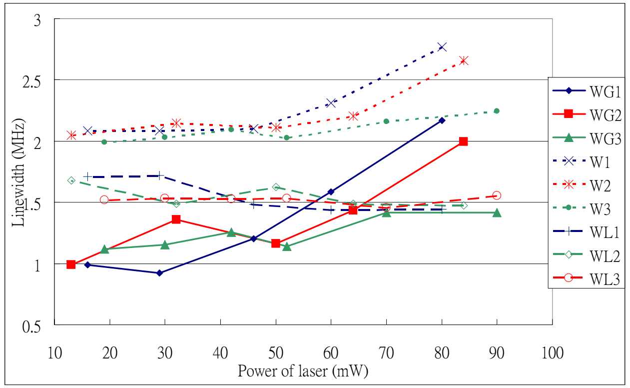


Natural Linewidth Determination

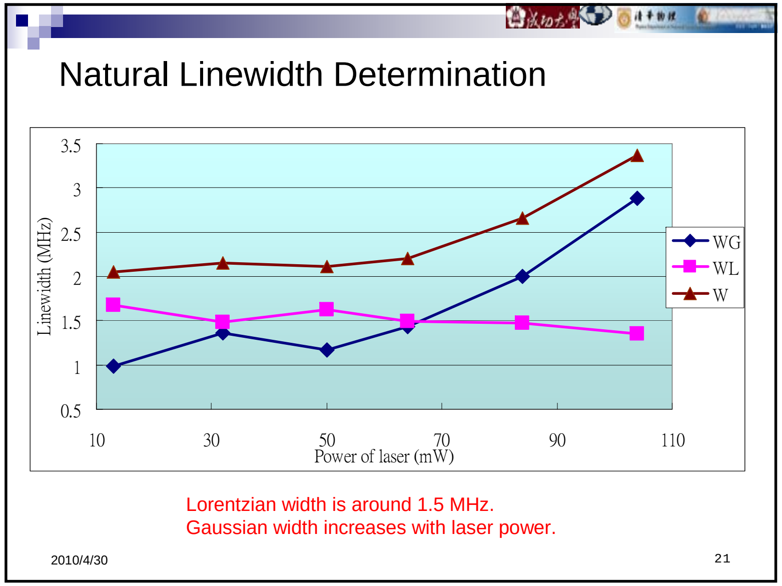


Fit with Lorentzian (5 measurements per data point).
Power Broadening, Laser linewidth, Collision Broadening…?

Natural Linewidth Determination

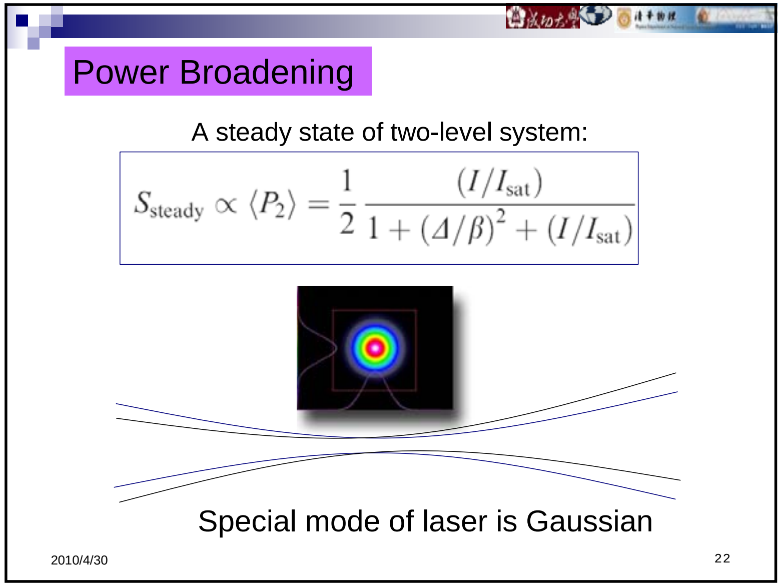


Natural Linewidth (Lorentzian) is 1.51 MHz



Natural Linewidth Determination

Lorentzian width is around 1.5 MHz.
Gaussian width increases with laser power.

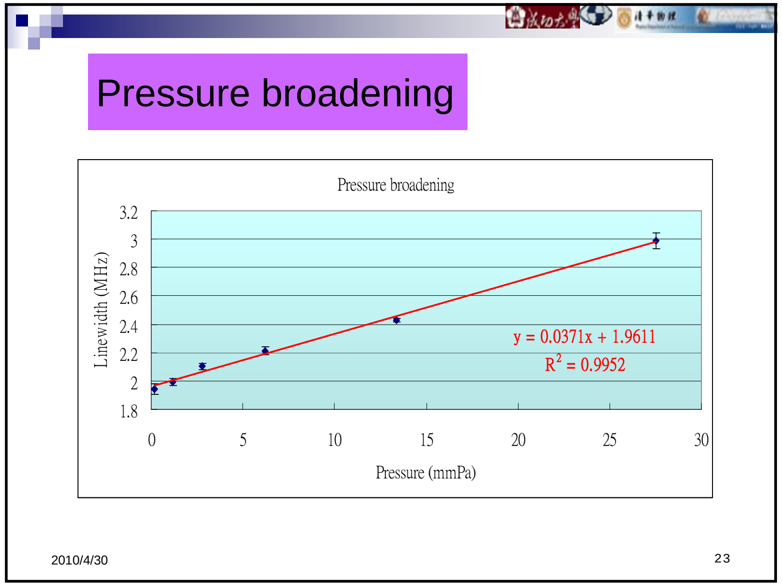


Power Broadening

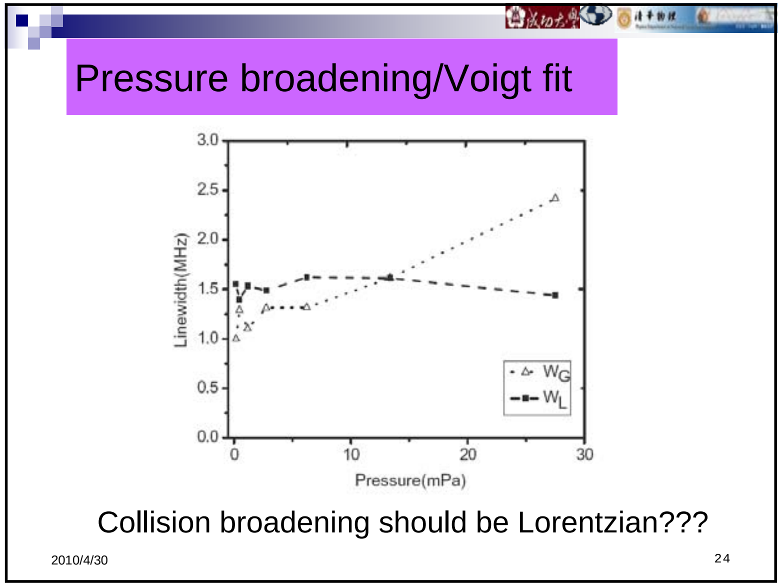
A steady state of two-level system:

$$S_{\text{steady}} \propto \langle P_2 \rangle = \frac{1}{2}\,\frac{(I/I_{\text{sat}})}{1+(\Delta/\beta)^2+(I/I_{\text{sat}})}$$

Special mode of laser is Gaussian



Pressure broadening



Pressure broadening/Voigt fit

Collision broadening should be Lorentzian???

Pressure (Collision)broadening

ening. Although the collision broadening is a homogeneous broadening, however, we increased the temperature to change the vapor pressure but also the velocity of atoms. The increasing of collision rate depends on the atom density and velocity [7]. The velocity dependence will arise the contribution to Gaussian broadening. Under the range of our temperature setting, Fig. 6 shows that the

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Pressure (Collision)broadening

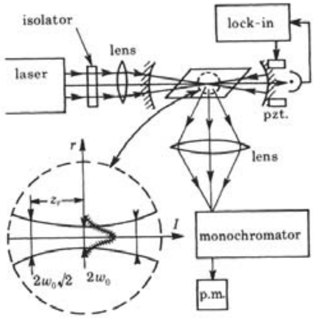


FIGURE 7. Experimental set-up for Doppler-free two-photon spectroscopy. Inside the dotted circle is represented the waist of the laser Gaussian beam which replaces the focus of geometrical optics: the superimposed curve with small bars represents the light intensity I as a function the radial distance r.

Pressure (Collision)broadening

(*e*) The line shapes of two-photon transitions are very simple, as they are simple Lorentzian curves, whereas the line shape in the saturation technique is quite complicated (its calculation involves the averaging of a nonlinear effect that depends on the velocity component v_z). If collisions are taking place, the two-photon line shape remains Lorentzian and it is easy to measure the broadening and the shift, whereas the velocity-changing collisions complicate still more the saturation line shape.

(*f*) The finite transit time of the atoms through the laser beam produces analogous broadenings in the two techniques. The large light beams (10 cm or more) used in the saturation technique to reduce this broadening in very narrow molecular transitions seems not to be possible with two-photon transitions because the energy density would be too small. But it is possible to use the Ramsey fringes technique (Baklanov *et al.* 1976; Salour *et al.* 1977).

Pressure (Collision)broadening

(i) natural broadening (which (involves OR affects)the lifetime of the excited level)

(ii) collisions (pressure broadening)

(iii) the finite interaction time (transit-time broadening, mainly in beam experiments, and (unimportant OR not important) here)

(iv) the second-order Doppler effect

(v) instrumental width (laser bandwidth)

(vi) external Fields (Zeeman and Stark effects)

(vii) residual Doppler broadening (if the beams are not exactly counter-propagating),

(viii) power broadening (related to the saturation of the transition)

(iv) the A.C. Stark effect (a shift caused by the electric field of light in the TPT)[20].

Cs 8s natural Linewidth

The second-order Doppler effect is approximately 162 Hz

$$\Delta f_{D2} \approx \frac{u^2}{c^2} f_0 = (\frac{200\mathrm{m}/s}{3\times10^8\mathrm{m/s}})^2 \frac{3\times10^8\mathrm{m/s}}{822\times10^{-9}m} = 162Hz$$

Ti:sapphire laser (Coherent 899-29) used in this study has a linewidth of

$$\Delta\nu_{RMS} = 500kHz$$

data fitting yields a standard deviation of approximately 80 kHz

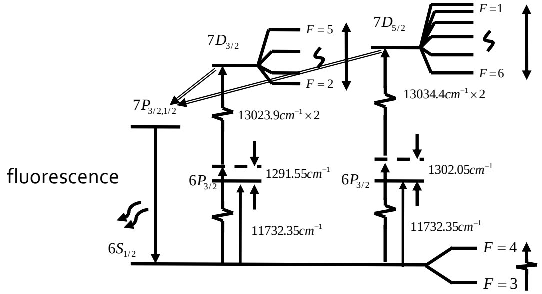
Error arises from the laser frequency drift during the scan through a 2 MHz spectrum 10 kHz

Lorentzian width (WL, 1.53 MHz)
convolution of the 500 kHz laser bandwidth and Errors
natural linewidth of 1.03 (+20)MHz.

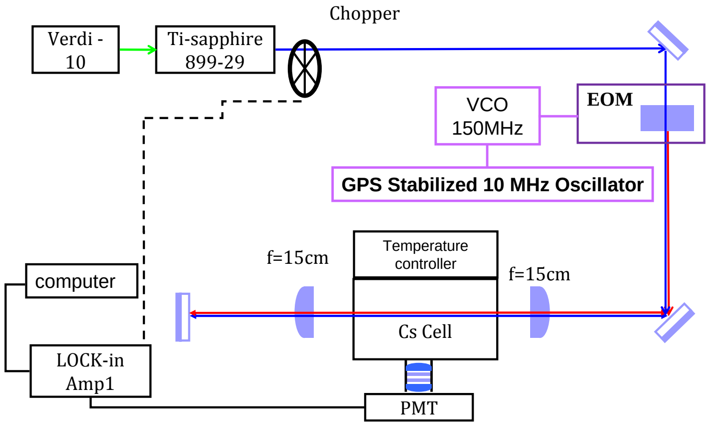
Two-Photon Spectroscopy

Measurement of the hyperfine structure of the 6s - 7d(J=3/2, 5/2) transitions by two-photon spectroscopy

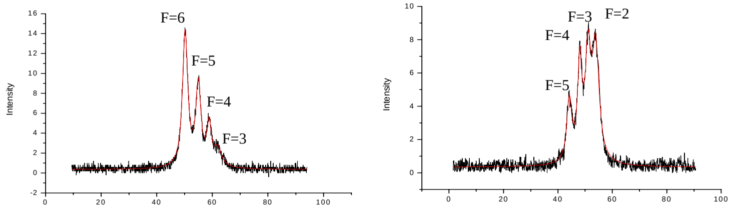
Energy levels of 6s-7d 2-photon transitions



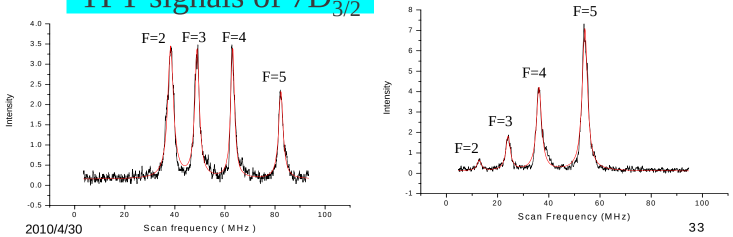
Calibration setup



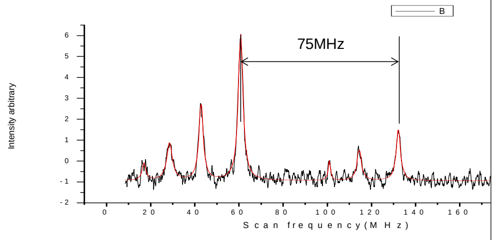
TPT signals of 7D$_{5/2}$



TPT signals of 7D$_{3/2}$



Date	6S$_{1/2}$ -7D$_{3/2}$	Scan	Time C PMT	Sensitivity PMT	High Voltage	Power	Temp MAIN	Temp REF	File name
	F=3 +EOM	200MHz	10ms	20mv	950v	146mv	2.09/65^{0}C	2.99/55^{0}C	09022306 ~09022312

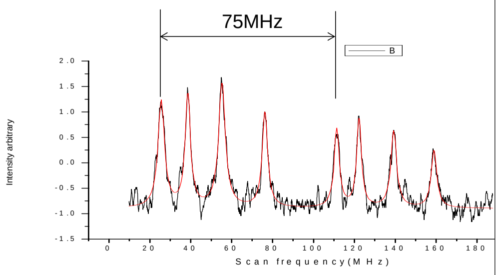


```
Data: Data1_B
Model: user7
Weighting:
y         No weighting

Chi^2/DoF       = 0.04232
R^2      =  0.94418

Ya        -0.13424          ±--
A1        2.64485           ±0.22198
W1        2.08255           ±0.2423
C1        16.99003          ±0.08313
Yb        -0.13424          ±--
A2        8.35808           ±0.27008
W2        2.97164           ±0.13221
C2        28.54991          ±0.04492
Yc        -0.13424          ±--
A3        13.47454          ±0.23634
W3        2.34397           ±0.0572
C3        42.8289           ±0.01971
Yd        -0.13424          ±--
A4        28.13475          ±0.24942
W4        2.56202           ±0.03159
C4        60.76369          ±0.01089
Ye        -0.13424          ±--
A5        1.90293           ±0.17242
W5        1.2709  ±0.17933
C5        100.92137         ±0.06925
Yf        -0.13424          ±--
A6        5.60911           ±0.24376
W6        2.4395  ±0.15257
C6        114.44076         ±0.05427
Yg        -0.13424          ±14938.81226
A7        8.97485           ±0.23842
W7        2.32239           ±0.09041
C7        132.17745         ±0.03276
```

Date	6S$_{1/2}$ -7D$_{3/2}$	Scan	Time C PMT	Sensitivity PMT	High Voltage	Power	Temp MAIN	Temp REF	File name
	F=4 +EOM	200MHz	100ms	20mv	1000v	146mv	2.09/65^{0}C	2.99/55^{0}C	09022511



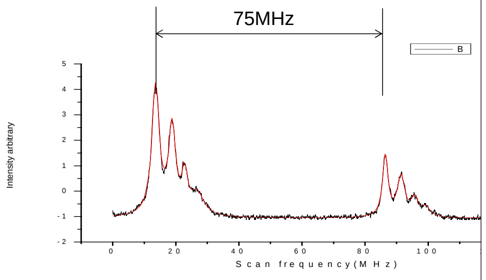
```
Data: Data1_B
Model: peeak8
Weighting:
y         No weighting

Chi^2/DoF       = 0.01934
R^2      =  0.93536

Ya        -0.11213          ±7270.30591
A1        12.70079          ±0.21978
W1        3.86447           ±0.08934
C1        25.5646           ±0.02959
Yb        -0.11213          ±--
A2        10.88339          ±0.19349
W2        3.14556           ±0.07599
C2        38.55242          ±0.02549
Yc        -0.11213          ±--
A3        15.21361          ±0.22187
W3        3.97728           ±0.07778
C3        55.25212          ±0.02594
Yd        -0.11213          ±--
A4        9.49189           ±0.19792
W4        3.22279           ±0.09126
C4        76.27254          ±0.0308
Ye        -0.11213          ±--
A5        7.36016           ±0.19305
W5        3.04658           ±0.11054
C5        111.35966         ±0.03774
Yf        -0.11213          ±--
A6        7.7618  ±0.18392
W6        2.83494           ±0.0948
C6        122.27908         ±0.03288
Yg        -0.11213          ±--
A7        8.08418           ±0.20434
W7        3.42336           ±0.12016
C7        139.2627          ±0.04144
Yh        -0.11213          ±--
A8        5.86543           ±0.20277
W8        3.30303           ±0.1598
C8        158.94238         ±0.05555
```

11

Date	6S$_{1/2}$ -7D$_{5/2}$	Scan	Time C PMT	Sensitivity PMT	High Voltage	Power	Temp MAIN	Temp REF	File name
	F=4 +EOM	150MHz	30ms	100mv	900v	57.2*2mv	2.09/65^{0}C	2.99/55^{0}C	09022501 ~09022503



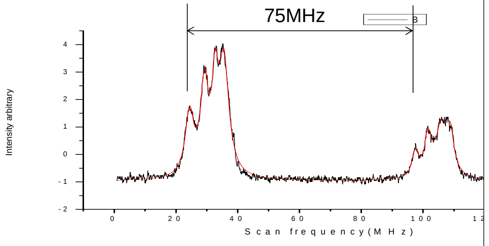
```
Data: Data1_B
Model: peeak8
Weighting:
y         No weighting

Chi^2/DoF       = 0.00377
R^2      =  0.99575

Ya        -0.13293          ±--
A1        22.85824          ±0.08784
W1        2.874   ±0.01367
C1        13.56719          ±0.00422
Yb        -0.13293          ±--
A2        14.34757          ±0.11563
W2        2.69583           ±0.02466
C2        18.80452          ±0.00657
Yc        -0.13293          ±9535.8545
A3        5.38877           ±0.15516
W3        2.32527           ±0.06241
C3        22.79355          ±0.01485
Yd        -0.13293          ±--
A4        6.88234           ±0.1928
W4        5.10745           ±0.14471
C4        26.80515          ±0.04947
Ye        -0.13293          ±--
A5        7.91524           ±0.07277
W5        2.11551           ±0.02465
C5        86.43297          ±0.00805
Yf        -0.13293          ±8871.46315
A6        7.15028           ±0.12365
W6        2.89991           ±0.05594
C6        91.41888          ±0.01577
Yg        -0.13293          ±--
A7        2.76212           ±0.1732
W7        2.62844           ±0.15528
C7        95.67691          ±0.04022
Yh        -0.13293          ±6731.64582
A8        1.93682           ±0.16376
W8        3.44034           ±0.30712
C8        99.22681          ±0.09516
```

01

Date	$6S_{1/2}$ $-7D_{5/2}$	Scan	Time C PMT	Sensitivity PMT	High Voltage	Power	Temp MAIN	Temp REF	File name
	F=3 +EOM	150MHz	100ms	50mv	900v	57.2*2mv	2.09/65⁰C	2.99/55⁰C	09022506 ~09022510



06

```
Data: Data1_B
Model: peeak8
Weighting:
y          No weighting

Chi^2/DoF        = 0.00833
R^2       =  0.99359

Ya        -0.1218 ±5189.22769
A1        11.95418          ±0.17845
W1        3.3612  ±0.05468
C1        24.40616          ±0.01677
Yb        -0.1218 ±16896.68297
A2        15.32959          ±0.29225
W2        3.05293           ±0.05509
C2        29.22999          ±0.01351
Yc        -0.1218 ±18911.27527
A3        11.50032          ±0.40794
W3        2.49425           ±0.06888
C3        32.68474          ±0.01474
Yd        -0.1218 ±8760.98995
A4        25.04398          ±0.36795
W4        3.85509           ±0.04469
C4        35.53818          ±0.01782
Ye        -0.1218 ±23687.19414
A5        3.58414           ±0.14234
W5        2.44758           ±0.10787
C5        97.47734          ±0.03563
Yf        -0.1218 ±23899.8467
A6        6.31923           ±0.32373
W6        2.84617           ±0.1215
C6        101.61106         ±0.03099
Yg        -0.1218 ±36262.49944
A7        12.60721          ±1.0686
W7        4.40202           ±0.22654
C7        105.9681          ±0.07449
Yh        -0.1218 ±14165.53525
A8        6.5368  ±0.78137
W8        2.98409           ±0.22657
C8        108.78646         ±0.0628
```

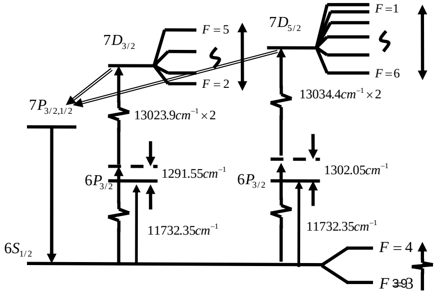
Determine hyperfine coupling constant

$$\Delta E_{hfs} = \frac{1}{2} A_{hfs} K + B_{hfs} \frac{\frac{3}{2} K(K+1) - 2I(I+1)J(J+1)}{2I(2I-1)2J(2J-1)}$$

$$K = F(F+1) - I(I+1) - J(J+1)$$

Magnetic dipole coupling constant A

Electrical quadrupole coupling constant B

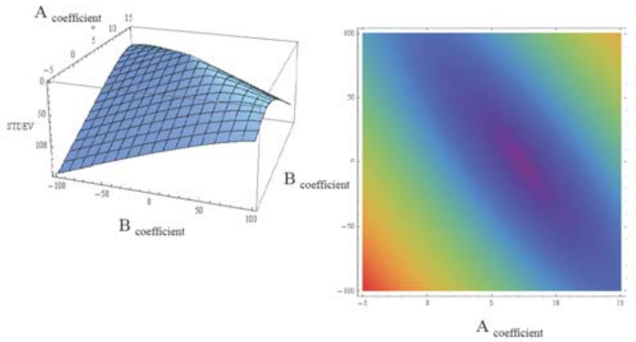


EOM			STDEV(+)		STDEV(-)		Reference
7D(5/2)	F =4		A=-1.77 B=-0.73	A=-1.78 B=0.36	A=-1.78 B=1.29	A= -1.78±0.01 B=0.36±0.93	1.7±2
		w/o △F6~6', onlyF=6、5、4	A=-1.78 B=-0.13	A=-1.78 B=0.32	A=-1.78 B=0.76	A= -1.78±0.05 B=0.32±0.4	
	F =3		A=-1.88 B=0.86	A=-1.73 B=3.47	A=-1.63 B=5.41	A= -1.73±0.15 B=3.47±3	
		w/o △F5~5', only F=5、4、3	A=-1.83 B=1.88	A=-1.74 B=3.01	A=-1.63 B=5.41	A= -1.74±0.1 B=3.01±2	

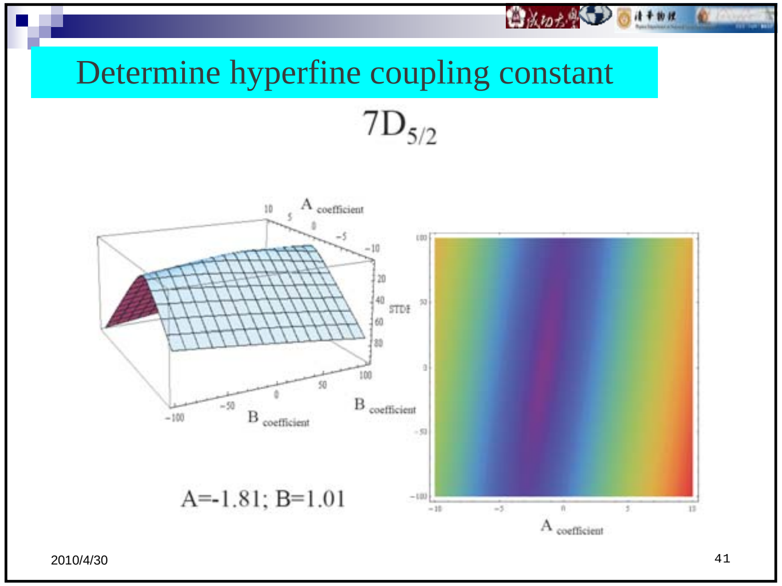
							Reference
7D(3/2)	F =4		A=7.6 B=-1.85	A=7.35 B=-0.17	A=7.05 B=2.01	A=7.35±0.3 B=-0.17±2	±7.4±2
		w/o △F5~5', only F=3、4、5	A=7.5 B=-1.41	A=7.31 B=-0.899	A=7.11 B=1.32	A=7.31±0.2 B=-0.899±1.5	
	F =3		A=8.38 B=-16.73	A=8.14 B=-15.07	A=7.89 B=-13.3	A=8.14±0.3 B=-15.07±2	
		w/o △F3~3', only F=3、4、5	A=8.29 B=-15.94	A=8.17 B=-15.11	A=8.04 B=-14.18	A=8.17±0.2 B=-15.11±1	

Determine hyperfine coupling constant

$7D_{3/2}$



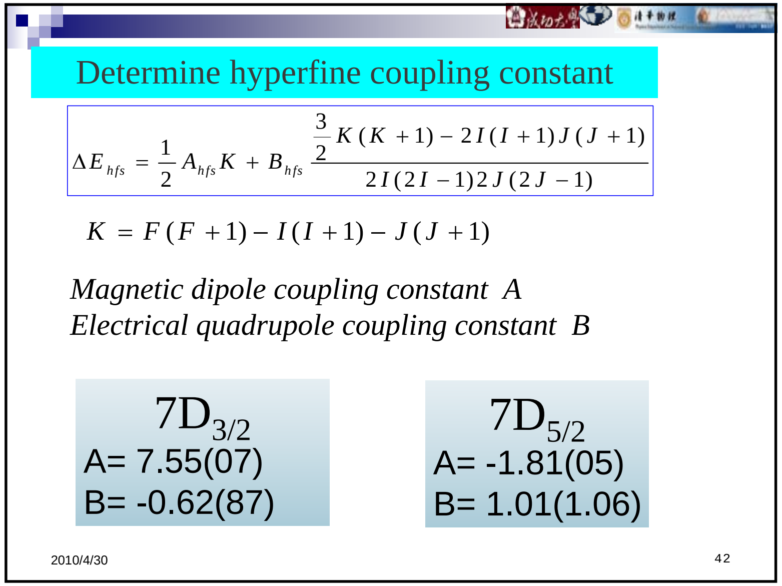
A=7.55; B=-0.62



Determine hyperfine coupling constant

$7D_{5/2}$

A=-1.81; B=1.01



Determine hyperfine coupling constant

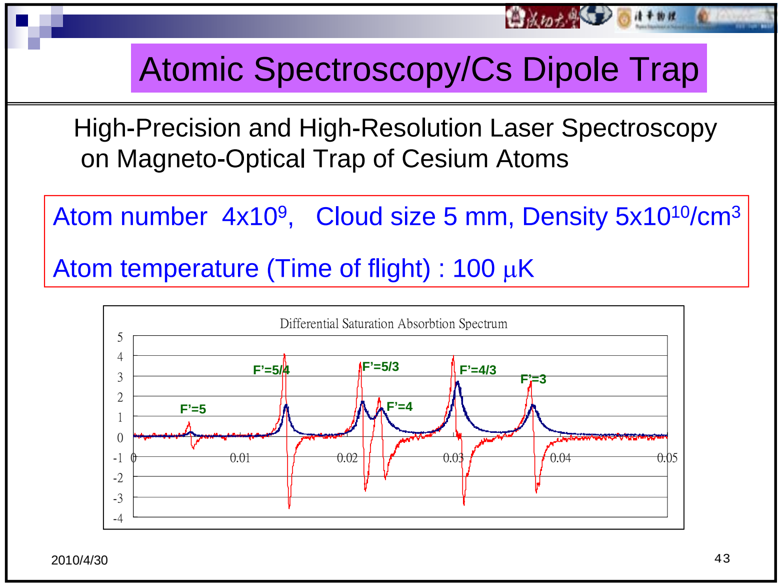
$$\Delta E_{hfs} = \frac{1}{2} A_{hfs} K + B_{hfs} \frac{\frac{3}{2} K(K+1) - 2I(I+1)J(J+1)}{2I(2I-1)2J(2J-1)}$$

$$K = F(F+1) - I(I+1) - J(J+1)$$

Magnetic dipole coupling constant A
Electrical quadrupole coupling constant B

$7D_{3/2}$
A= 7.55(07)
B= -0.62(87)

$7D_{5/2}$
A= -1.81(05)
B= 1.01(1.06)



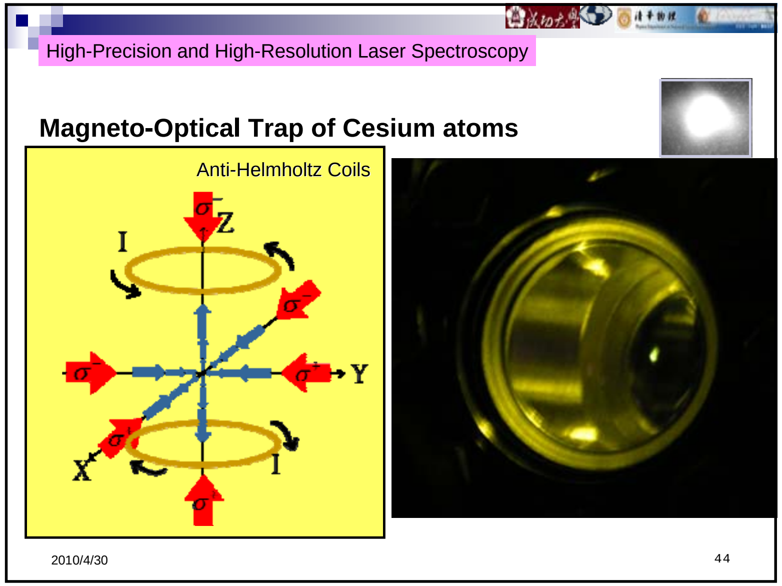
Atomic Spectroscopy/Cs Dipole Trap

High-Precision and High-Resolution Laser Spectroscopy on Magneto-Optical Trap of Cesium Atoms

Atom number $4x10^9$, Cloud size 5 mm, Density $5x10^{10}/cm^3$

Atom temperature (Time of flight) : 100 μK

Differential Saturation Absorbtion Spectrum



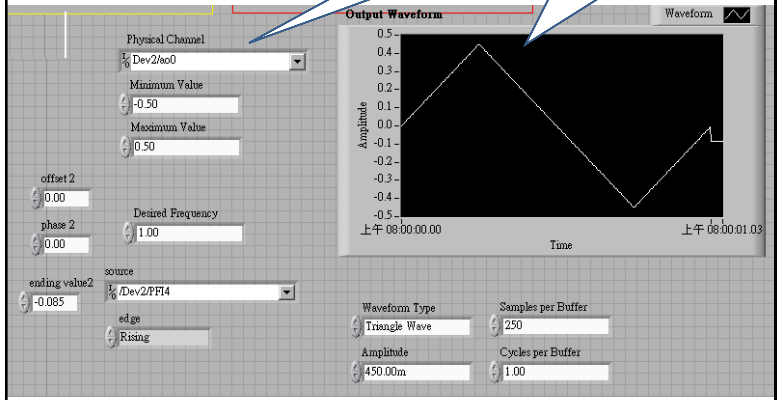
High-Precision and High-Resolution Laser Spectroscopy

Magneto-Optical Trap of Cesium atoms

Cs Dipole Trap

Traping laser
detune control

From -80MHz detune
To -100MHz detune



Physical Channel: Dev2/ao0

Minimum Value: -0.50

Maximum Value: 0.50

offset 2: 0.00

phase 2: 0.00

Desired Frequency: 1.00

ending value2: -0.085

source: /Dev2/PFI4

edge: Rising

Waveform Type: Triangle Wave

Samples per Buffer: 250

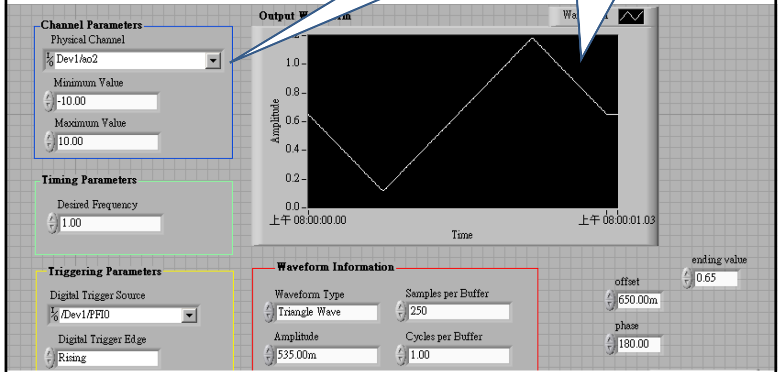
Amplitude: 450.00m

Cycles per Buffer: 1.00

Cs Dipole Trap

Repumping
Power control

Voltage 在0.115V時
Power=0



Channel Parameters

Physical Channel: Dev1/ao2

Minimum Value: -10.00

Maximum Value: 10.00

Timing Parameters

Desired Frequency: 1.00

Triggering Parameters

Digital Trigger Source: /Dev1/PFI0

Digital Trigger Edge: Rising

Waveform Information

Waveform Type: Triangle Wave

Samples per Buffer: 250

Amplitude: 535.00m

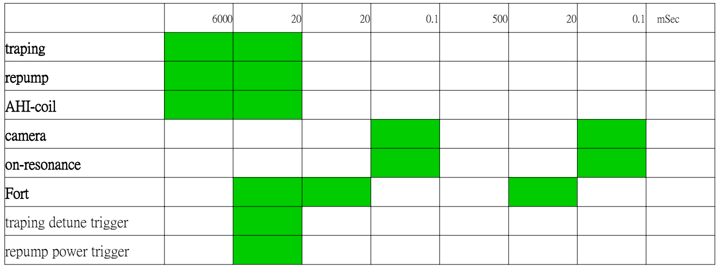
Cycles per Buffer: 1.00

offset: 650.00m

phase: 180.00

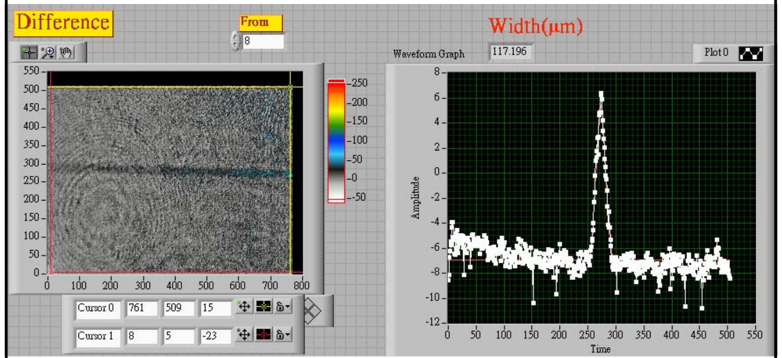
ending value: 0.65

Cs Dipole Trap/ Time sequence



	6000	20	20	0.1	500	20	0.1	mSec
traping	🟩	🟩						
repump	🟩	🟩						
AHI-coil	🟩	🟩						
camera				🟩			🟩	
on-resonance				🟩			🟩	
Fort		🟩	🟩			🟩		
traping detune trigger		🟩						
repump power trigger		🟩						

Cs Dipole Trap /Nd:YAG, 1064nm, cw 3W, @150 μm
N: $1x10^5$ n: $6x10^{10}$



From: 8

Width(μm): 117.196

Cursor 0	761	509	15
Cursor 1	8	5	-23

Thanks for your attention!

Collaboration: 黃守仁老師, Chemistry, NCKU

Postdoctoral : 李益志博士

PhD Students: 何宗勳

And many many master students……

我們的實驗室出現在 [日本料理] 中的帥哥們…

還有平面模特兒