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Quantum Phenomena in High Resolution Laser Spectroscopy

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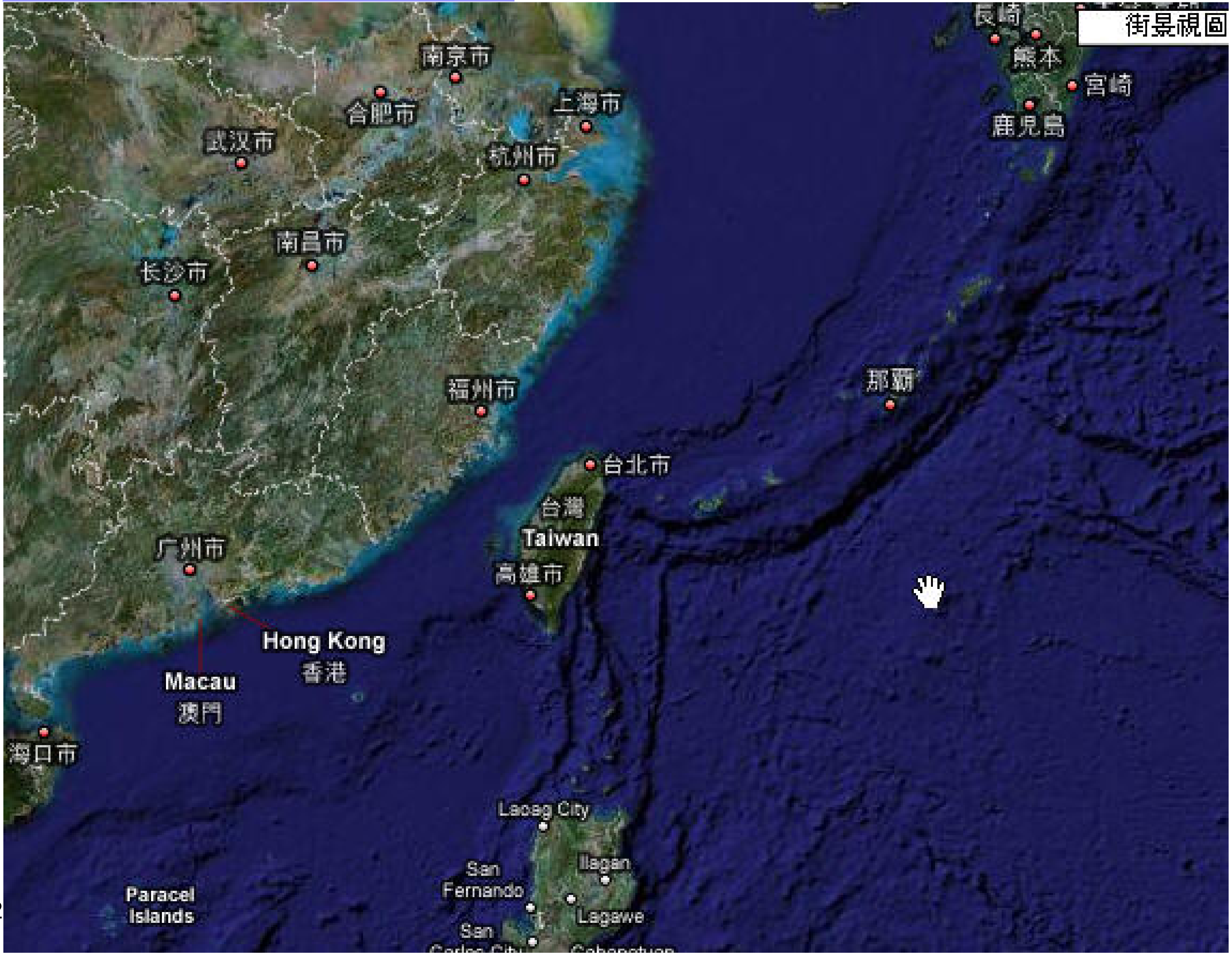

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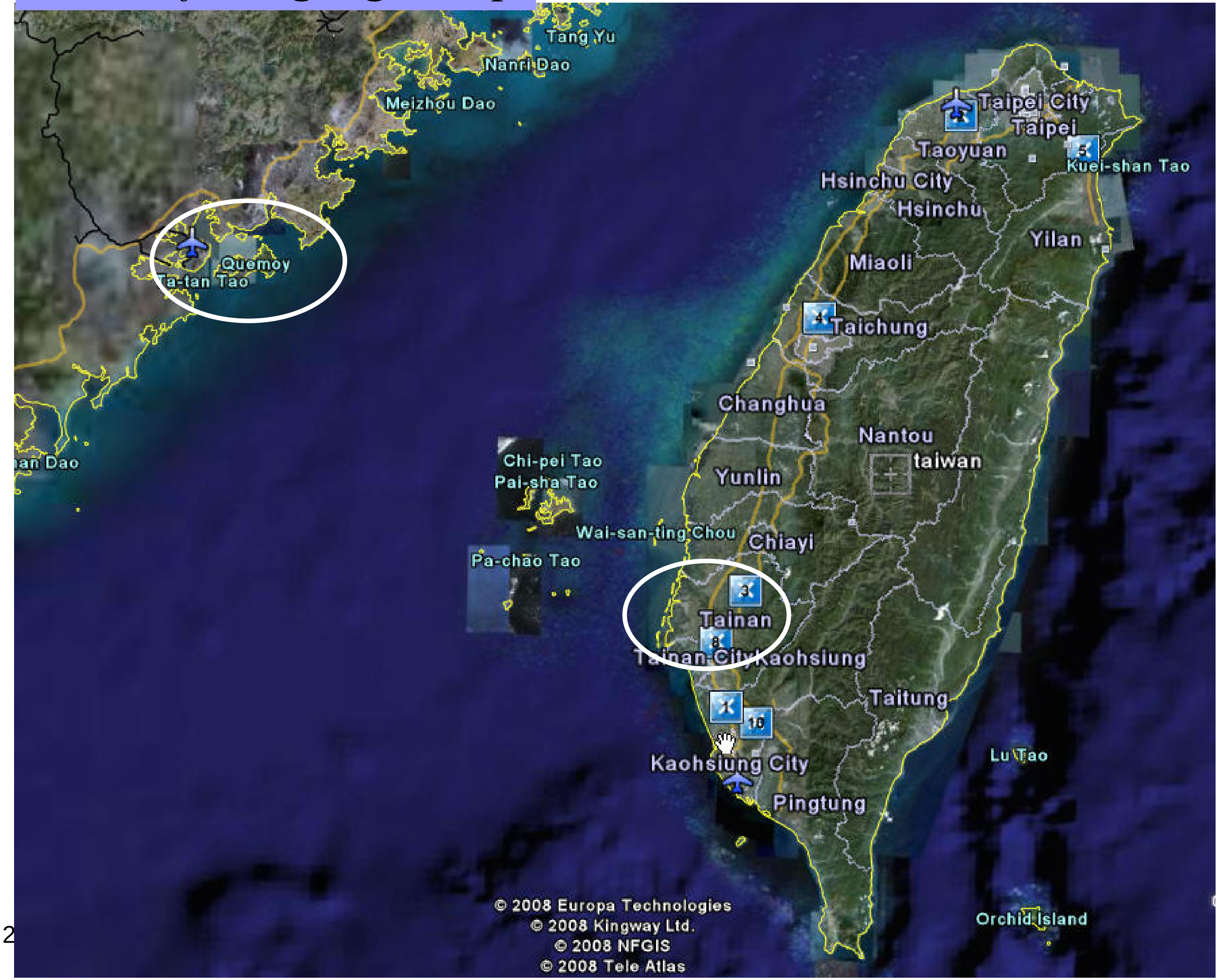

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Outline

* Introduction

High resolution laser spectroscopy and the development of Quantum Mechanics

* Quantum Phenomena in diatomic molecule

Tunnelling, Avoided-crossing, Feno Resonance

* Quantum Phenomena in Cold Atoms

Shape Resonance, Feshbach Resonance, EIT/Decoherence, Pump Probe

* Summary

What is Laser Spectroscopy?

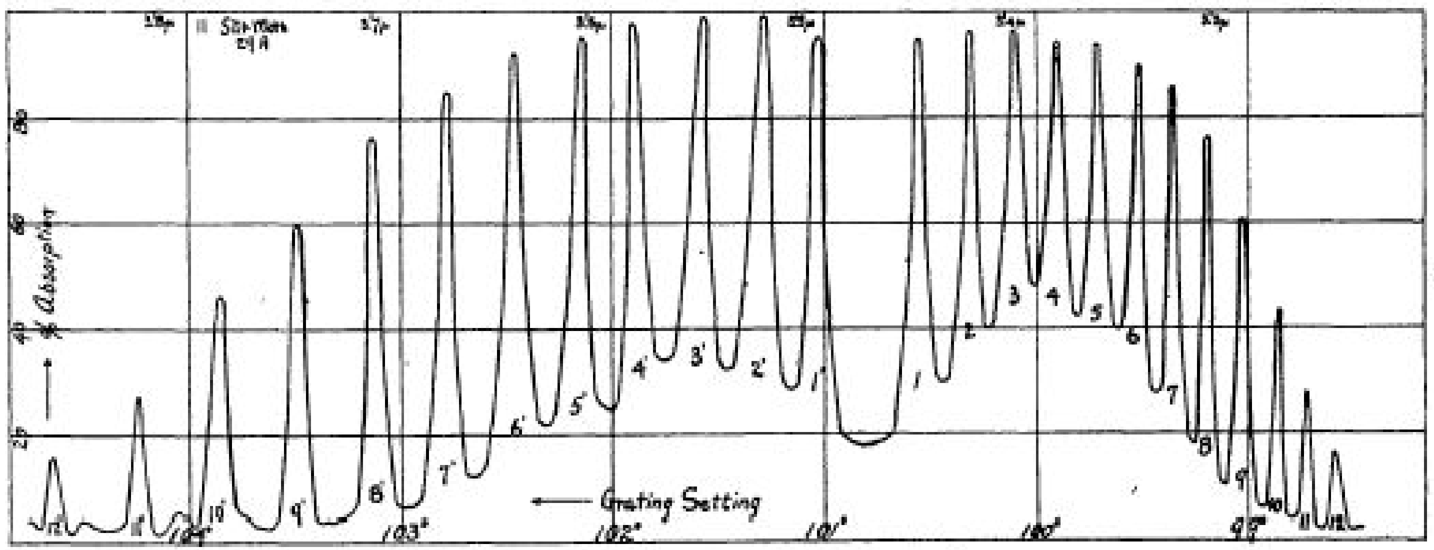
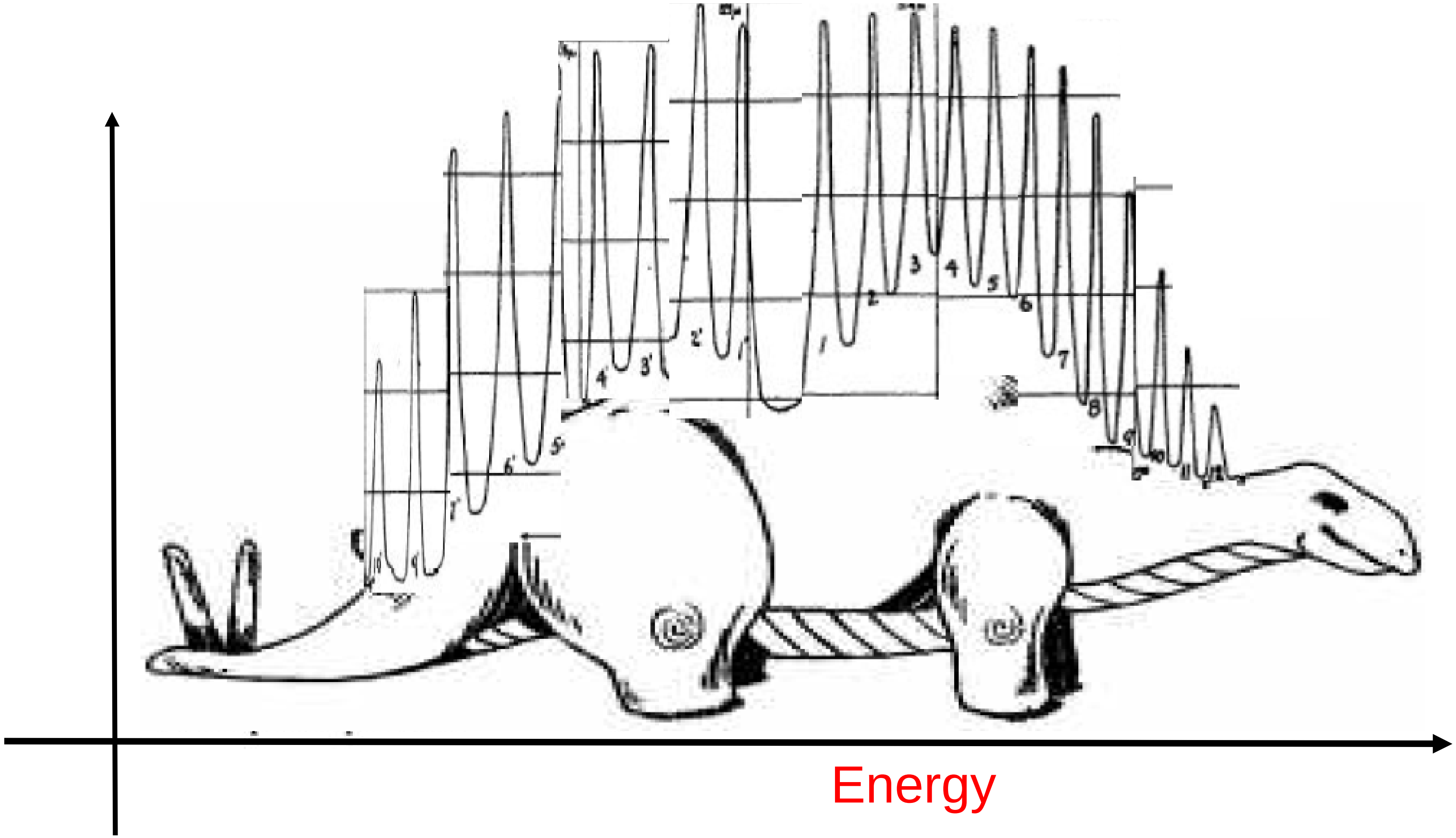


FIG. 3.—The HCl band at 3.46 μ, mapped with 7500-line grating. HCl at atmospheric pressure.

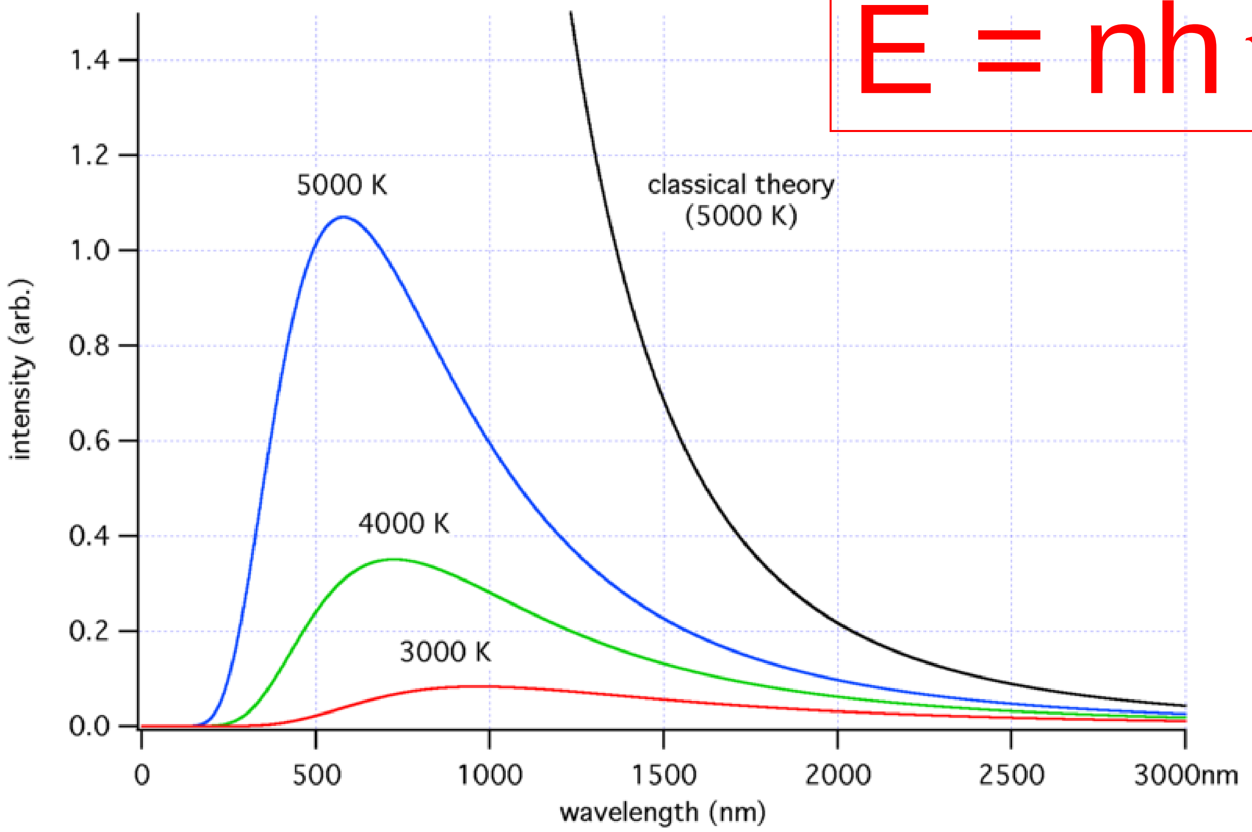
What are the importance of a spectrum?

Line position, Intensity and Shape

When/Where does it start?



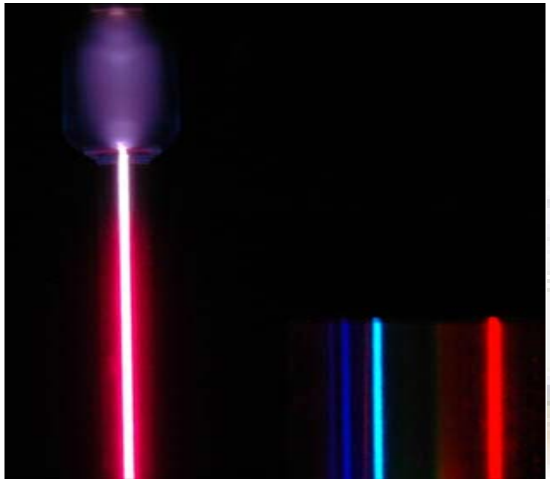
Black body radiation

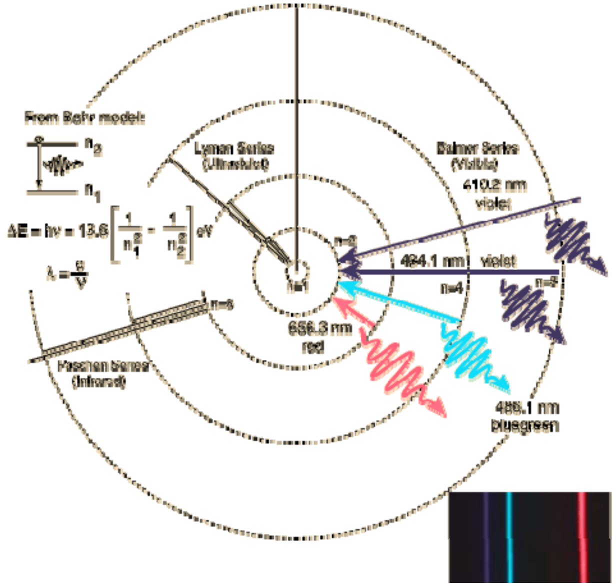


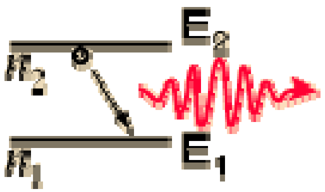
$$E = nh\nu$$

The dawn of Quantum Mechanics!

Higher resolution emission spectrum of Hydrogen







A downward transition involves emission of a photon of energy:

$$E_{photon} = h\upsilon = E_2 - E_1$$

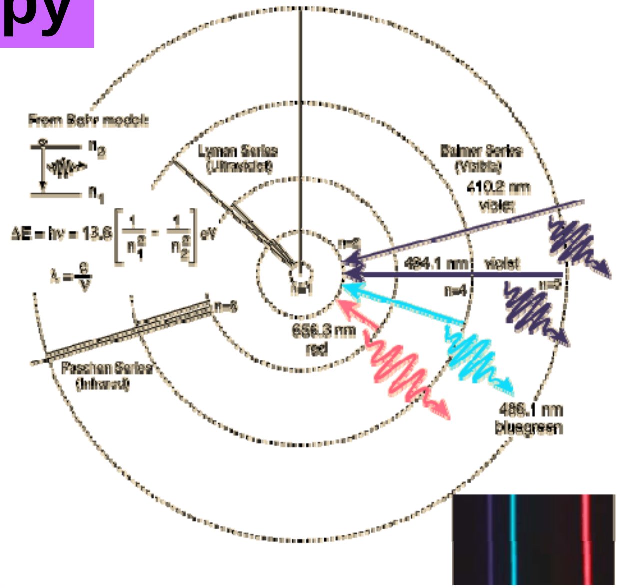
Given the expression for the energies of the hydrogen electron states:

$$h\upsilon = \frac{2\pi^2 me^4}{h^2}\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right] = -13.6\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right] \text{eV}$$

Bohr Model

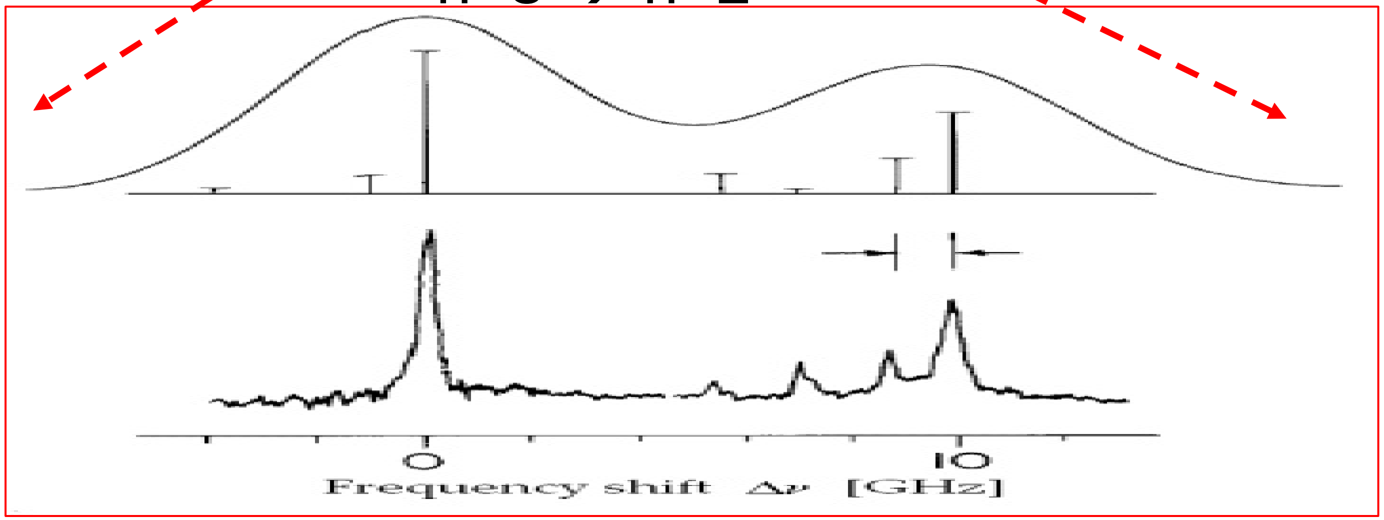
$$L = n\hbar$$

High resolution laser spectroscopy



H_α line

n=3 → n=2



High resolution laser spectroscopy

Schrodinger Equation : $H\Psi = E\Psi$ → Wavefunctions and Eigenvalues

$$E = -\frac{Z^2 m e^4}{8 n^2 h^2 \varepsilon_0^2} = -\frac{13.6 Z^2}{n^2}\ \text{eV}$$

$$r = \frac{n^2 h^2 \varepsilon_0}{Z \pi m e^2} = \frac{n^2 a_0}{Z}$$

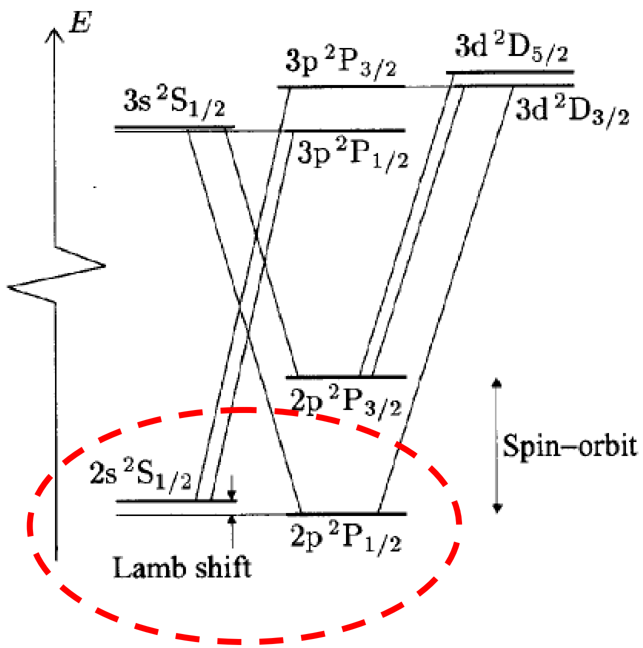
a_0 = 0.529 Å = Bohr radius

Spin Orbital interactions

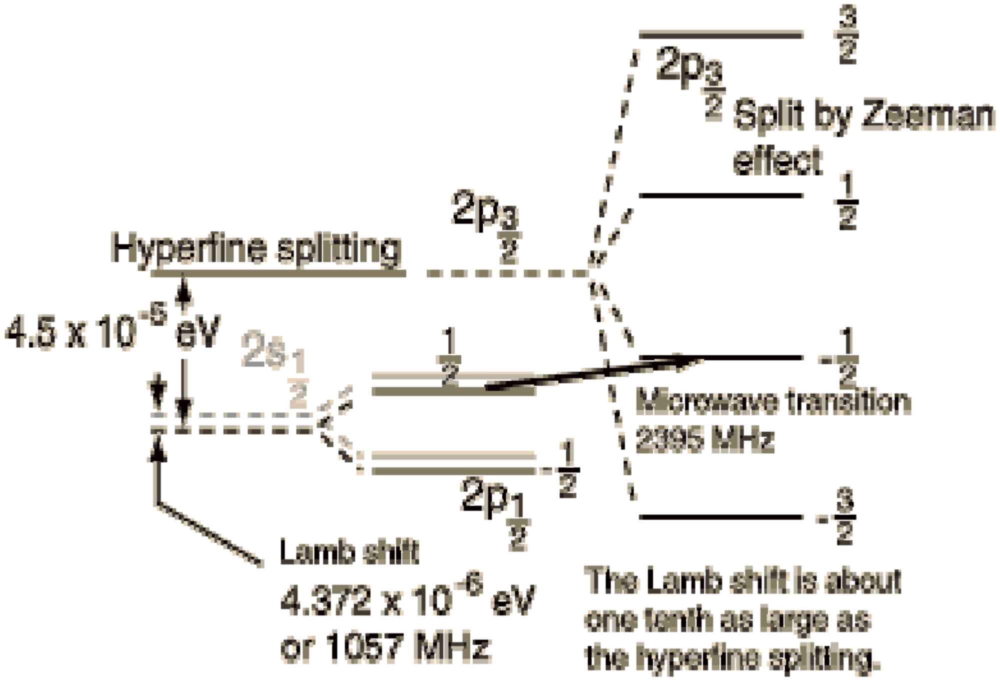
Transition Probabilities, Selection Rules

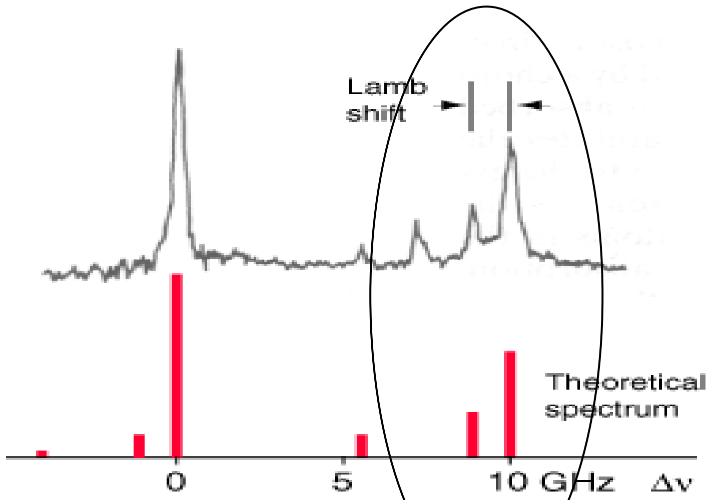
E (n,j)

2s $^2S_{1/2}$, 2p $^2P_{1/2}$ are degenerate.



Lamb Shift → QED



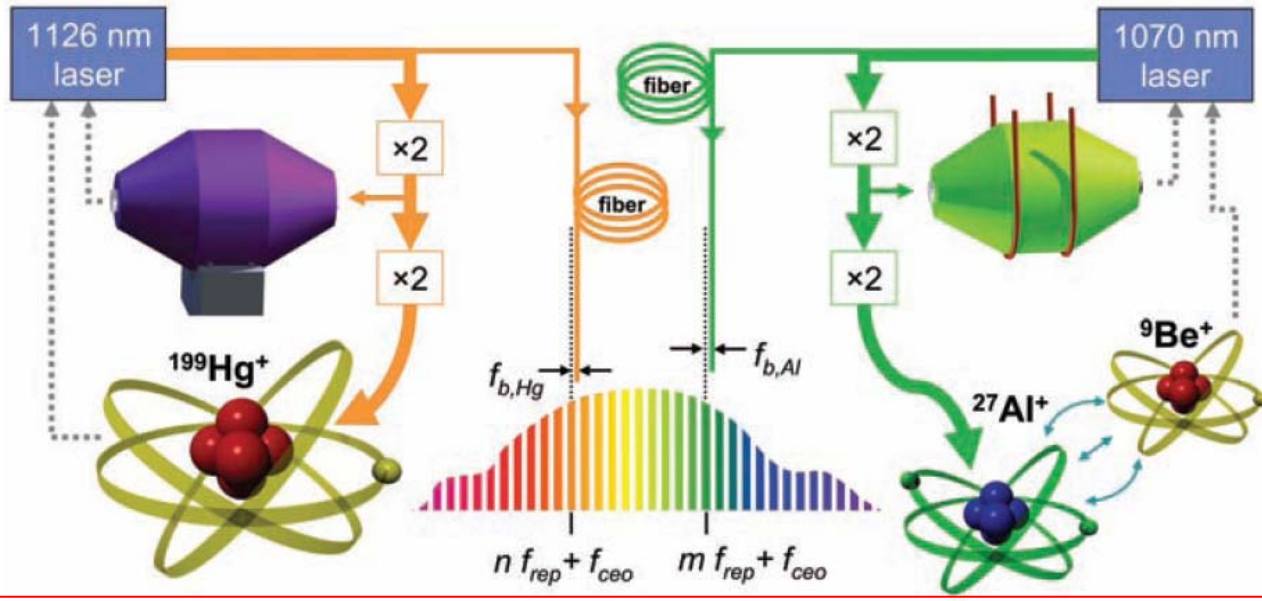


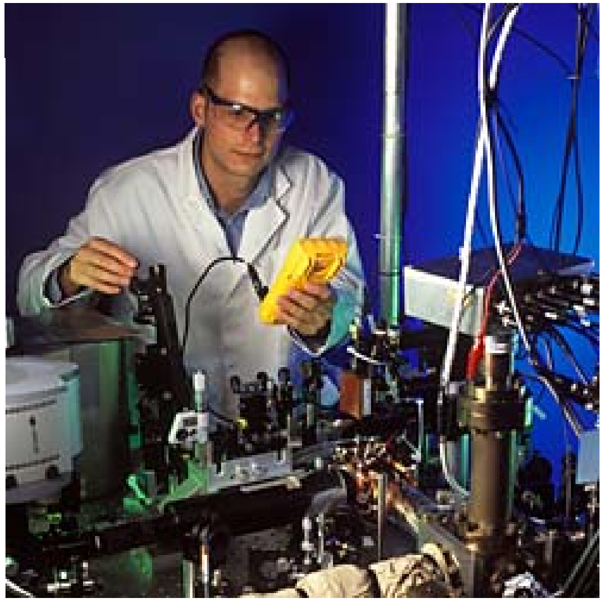
Hydrogen fine structure and hyperfine structure for the n=3 → 2 transition.
(After Ohanian, Modern Physics, Ch 7., spectrum from T. W. Hansch, Stanford Univ.)

It provided a high precision verification of theoretical calculations made with the quantum theory of electrodynamics (QED).

High resolution laser spectroscopy

NIST 'Quantum Logic Clock'





The quantum clock frequencies :

ν_{Al^+} / ν_{Hg^+} is 1.052871833148990438(55);

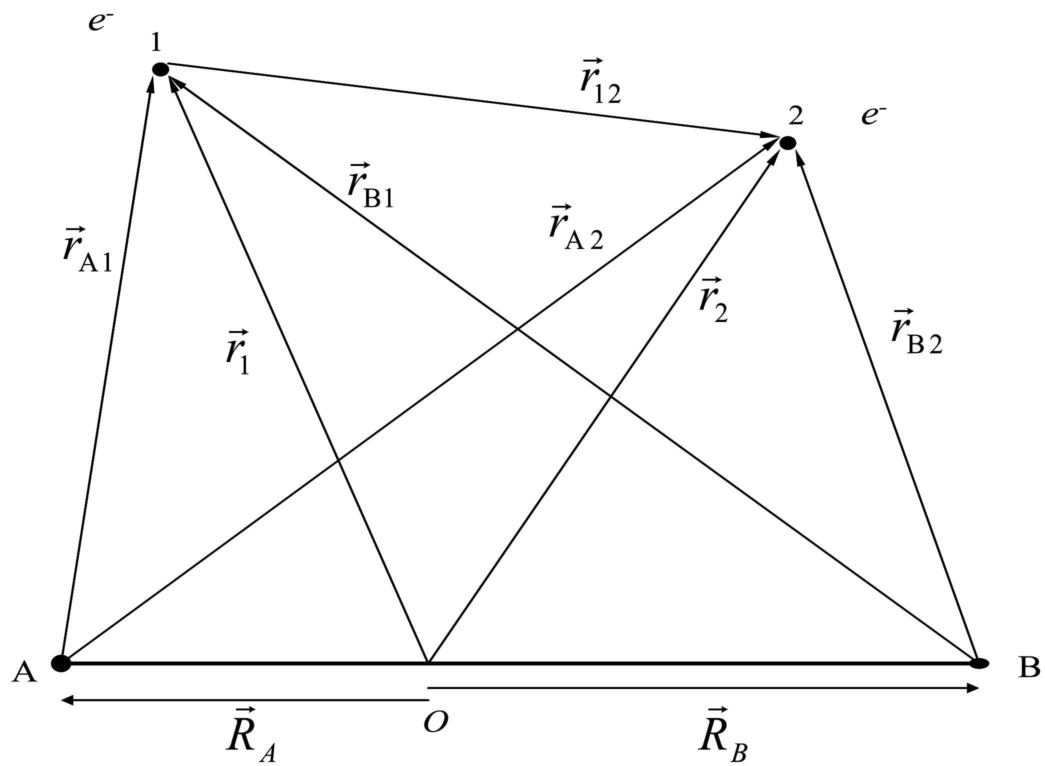
strontium-87 and ytterbium-171, is 2/1,000,000,000,000,000,000.

Clocks based on the latter exhibit stability greater than
a tenth of a second over the age of the universe.

Quantum Phenomena of atom-atom interactions

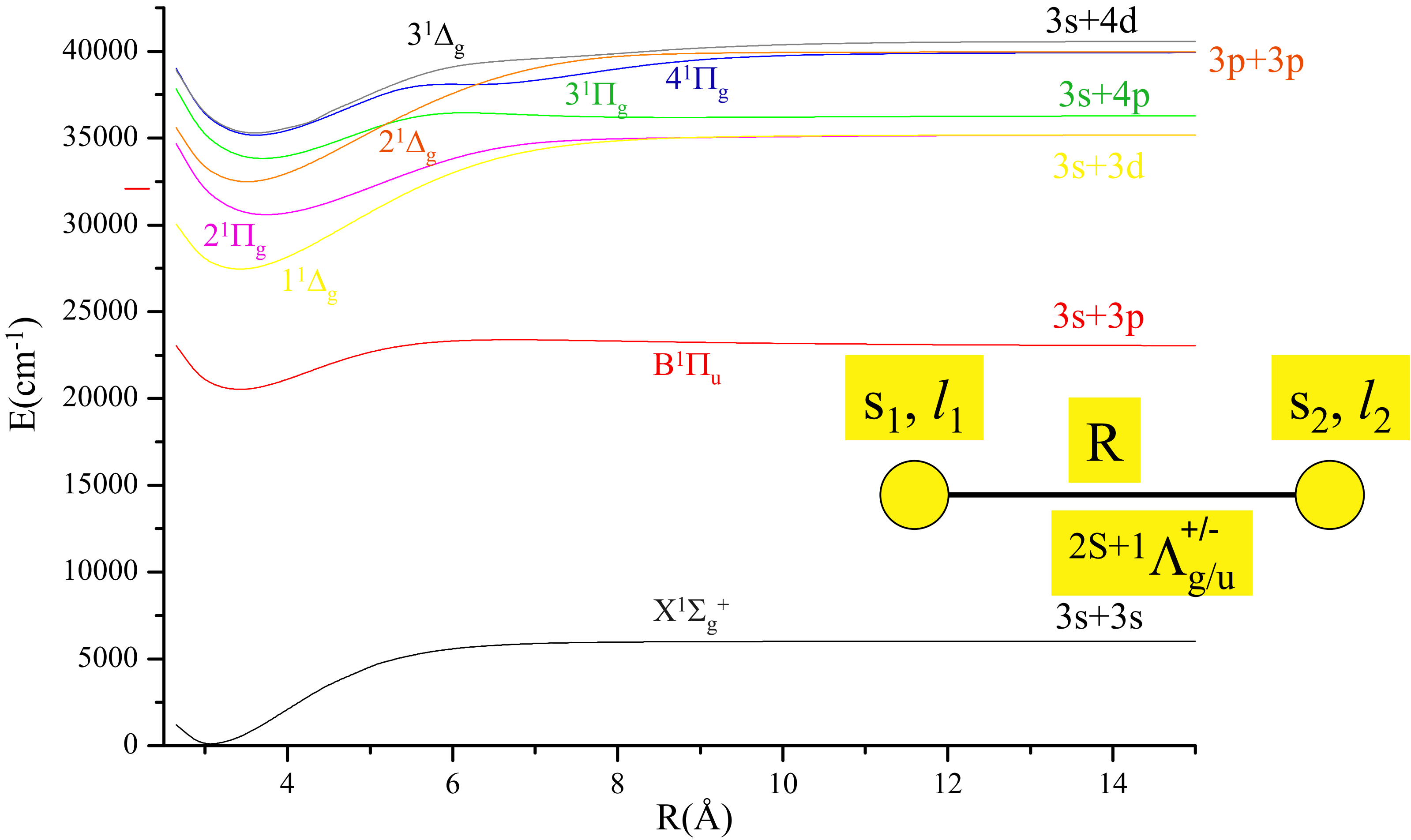
Molecular Spectroscopy

Diatomic molecule



$$H_e\psi_q = \left(T_e + V\right)\psi_q = E_q(R)\psi_q$$

Some Potential curves of Na_2 and asymptotic limits

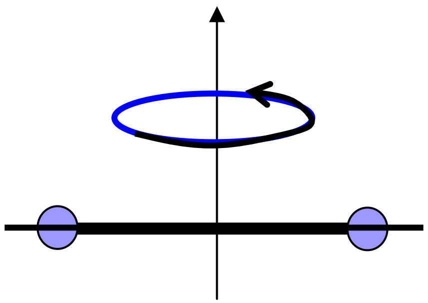


Diatomic molecule

Vibrational Mode

Eigenvalues of Harmonic Oscillator

$$E_v = (v + \frac{1}{2})\hbar\omega$$



Rotational Mode

Eigenvalues as a Rigid Rotator

$$E_J = \frac{J^2}{2I} = \frac{J(J+1)\hbar^2}{2I}$$

Eigenfunctions $\Psi(v, J)$, *v: vibration quantum number, J : Rortation quantum number*

Eigenvalues : Term(v, J)

Dunham Coefficients

$$T_{v,J} = \sum_{i=0}^{\infty}\sum_{j=0}^{\infty} Y_{ij}\left(v+\frac{1}{2}\right)^{i}[J(J+1)-\Lambda^{2}]^{j}$$

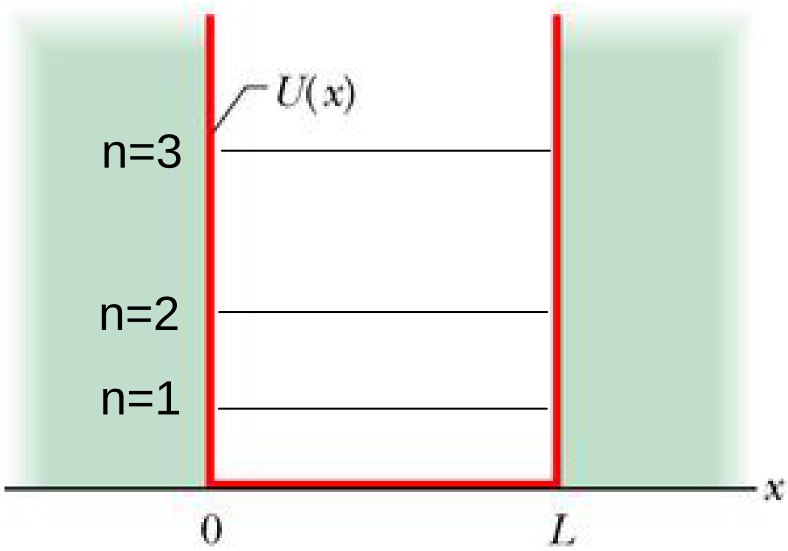
Lower terms of Dunham Coefficients (Y_{ij})

j\i	0	1	2	3	4	……..
0	T_e	ω_e	$-\omega_e x_e$	$\omega_e y_e$	$\omega_e z_e$	
1	B_e	$-\alpha_e$	γ_e	δ_e	..	
2	$-D_e$	$-\beta_e$	..	..	..	
3	H_e	..	..	..	..	
4	L_e	..	..	..	..	
..	..	..	..	..	..	

Harmonic Oscillator (ω_e, B_e)

Parts of Anharmonicity

In quantum mechanics, the eigenvalues are discrete, the space is not isotropic.



$$\frac{d^2\psi}{dx^2} = \frac{2m}{\hbar^2}(V_0 - E)\,\psi = -\frac{2m}{\hbar^2}E\,\psi = -k^2\psi$$

$$\psi(x) = C_1 \sin kx + C_2 \cos kx$$

Boundary conditions：

$$\psi(0) = 0 \quad \psi(L) = 0$$

$$\psi(0) = C_2 = 0 \longrightarrow \psi(x) = C_1 \sin kx$$

$$\psi(L) = 0 \longrightarrow \psi(L) = C_1 \sin kL = 0$$

$$kL = n\pi$$

$$E_n = \left(\frac{h^2}{8mL^2}\right) n^2$$

$$\phi_n(x) = C_1 \sin\left(\frac{n\pi}{L}x\right)$$

$$\lambda = \frac{2L}{n}$$

Transitions are the Difference between Eigenvalues

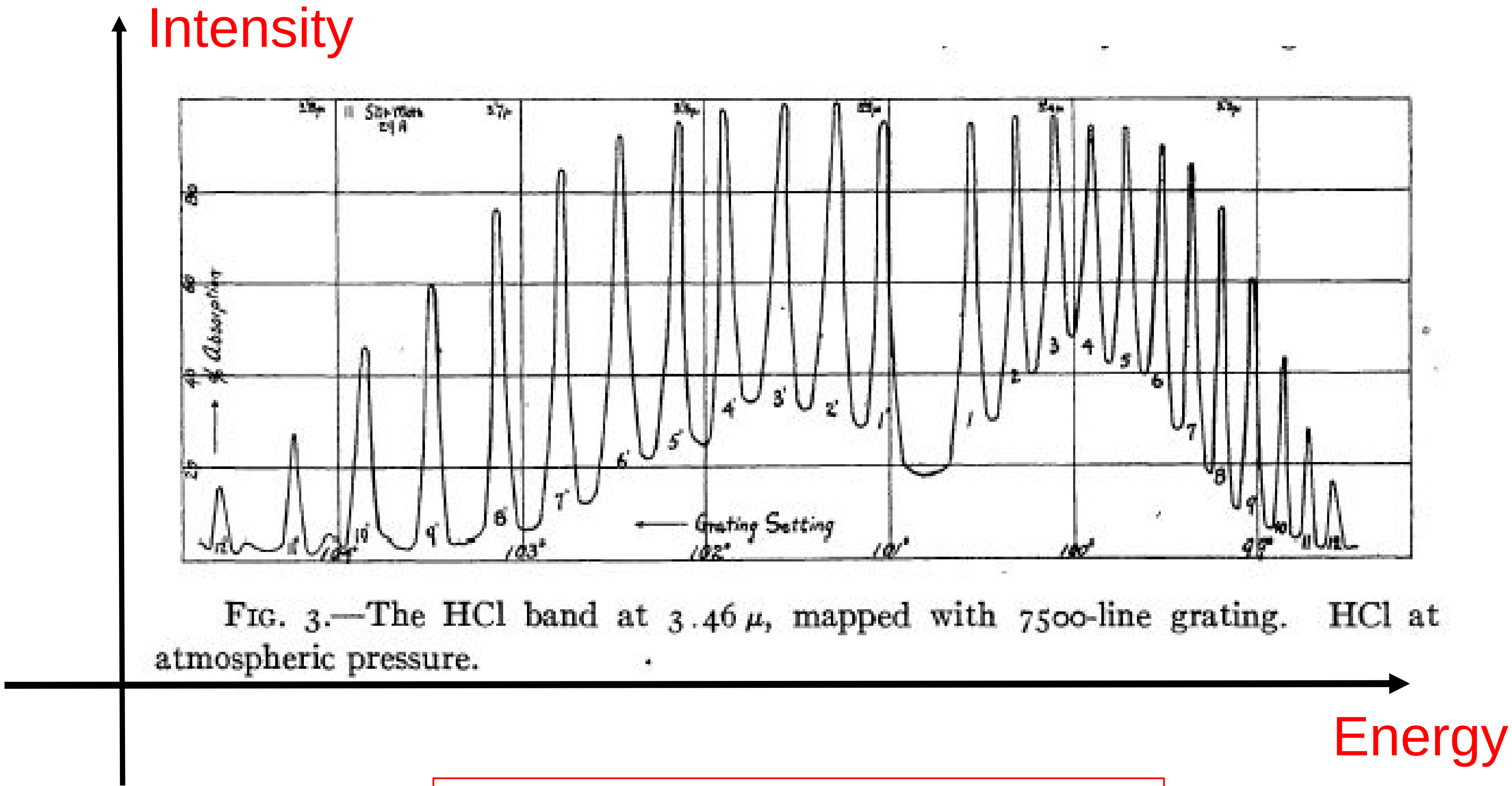
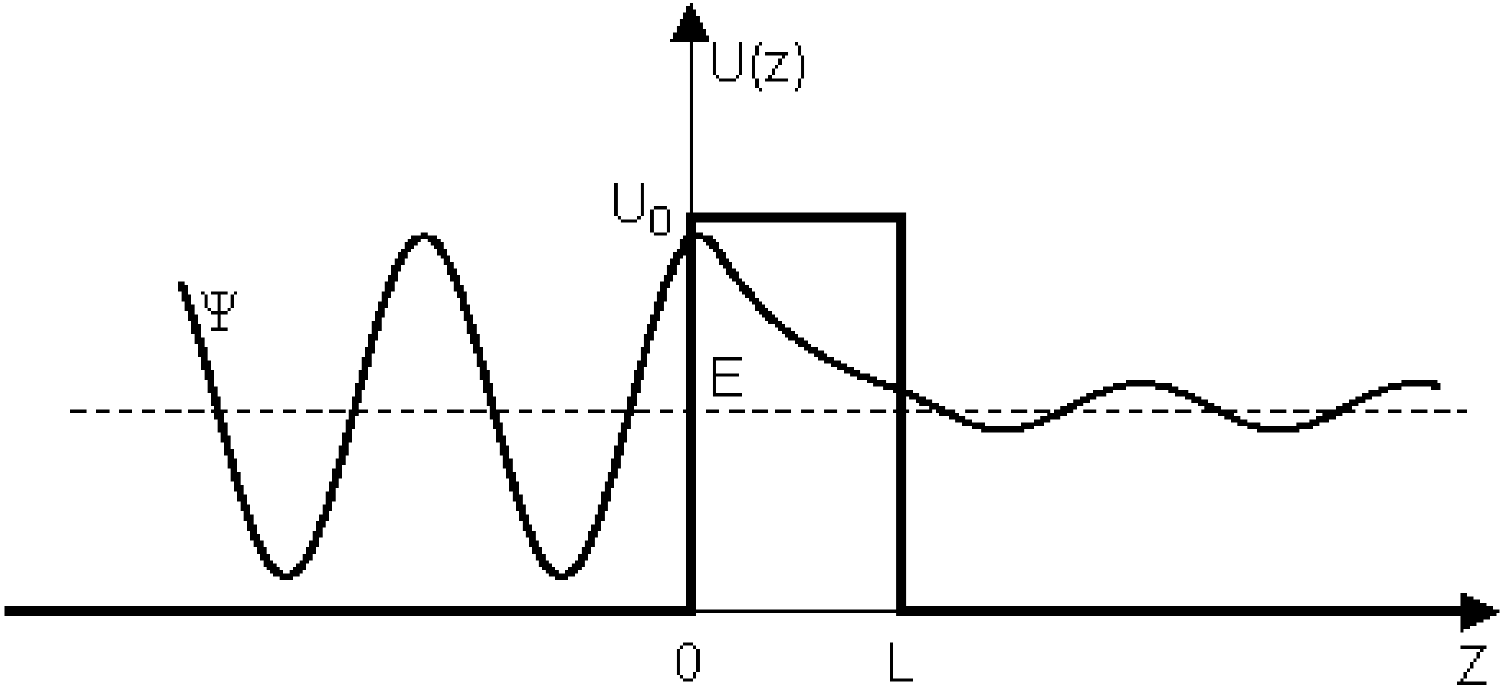


FIG. 3.—The HCl band at 3.46 μ, mapped with 7500-line grating. HCl at atmospheric pressure.

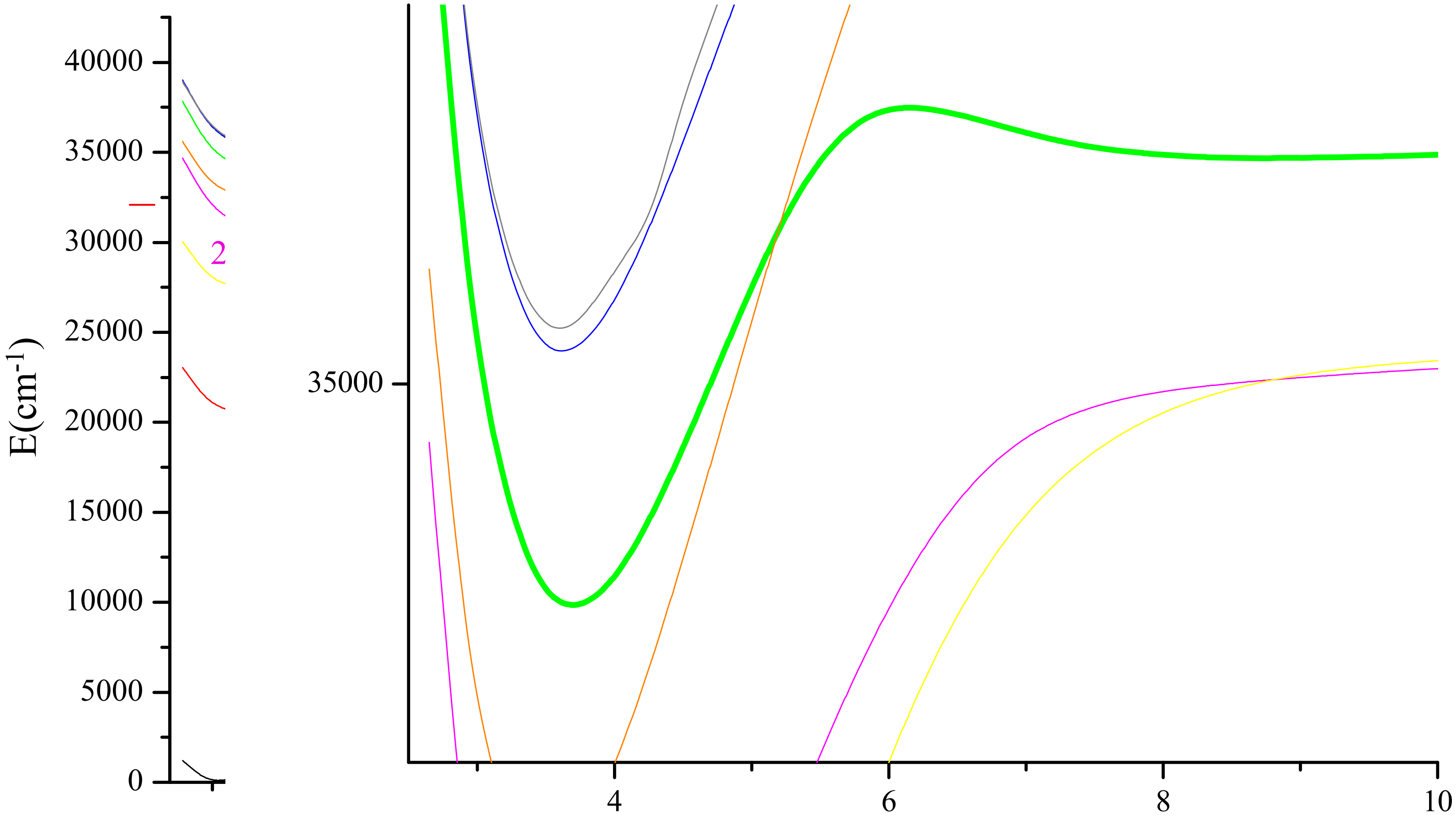
Discrete Eigenvalues

Tunneling Effect

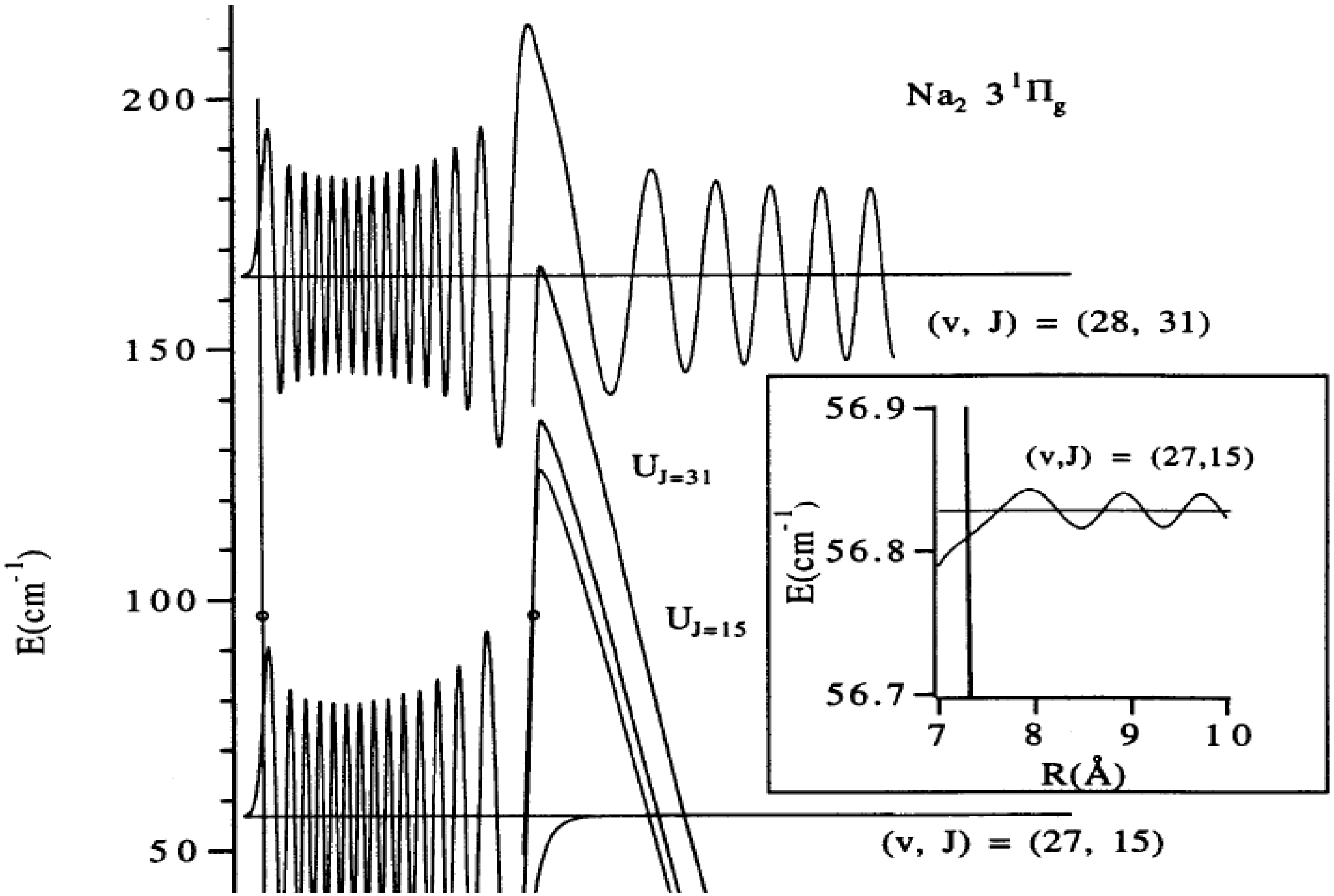


$$D(E) = D_0 \exp\left\{-\frac{2L}{\hbar}\sqrt{2m\left(U_0 - E\right)}\right\}$$

Tunnelling Effect

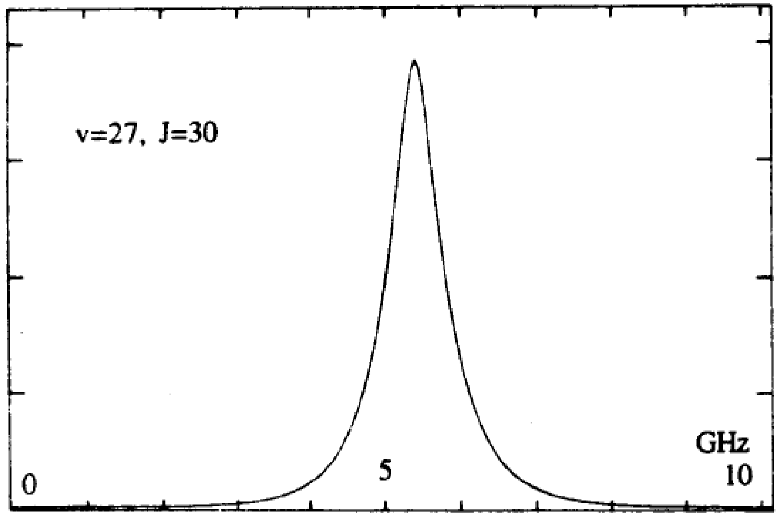


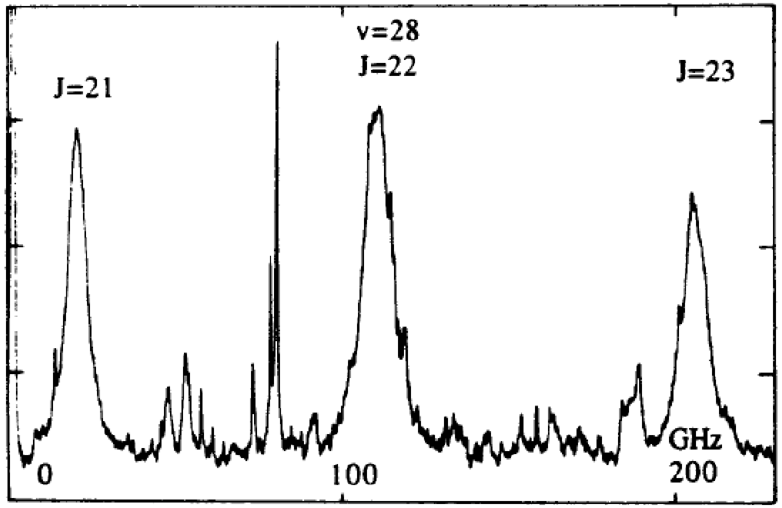
Tunnelling Effect

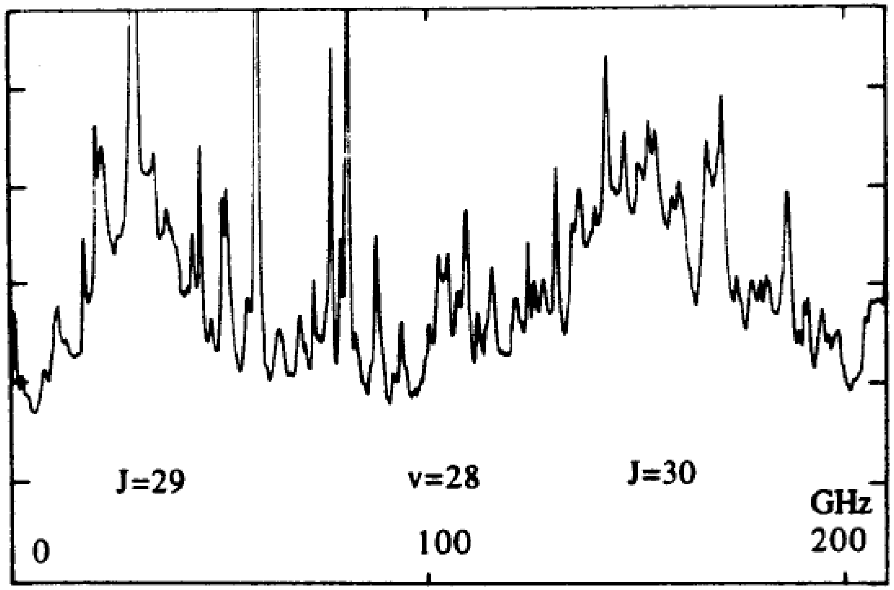


From WKB Approximation: $2\Gamma = \frac{h}{\pi}\left[\frac{1}{2}\tau_0 \exp\left(\frac{4\pi}{h}\int_a^b \sqrt{2\mu(U-E)}\, dR\right)\right]^{-1}$

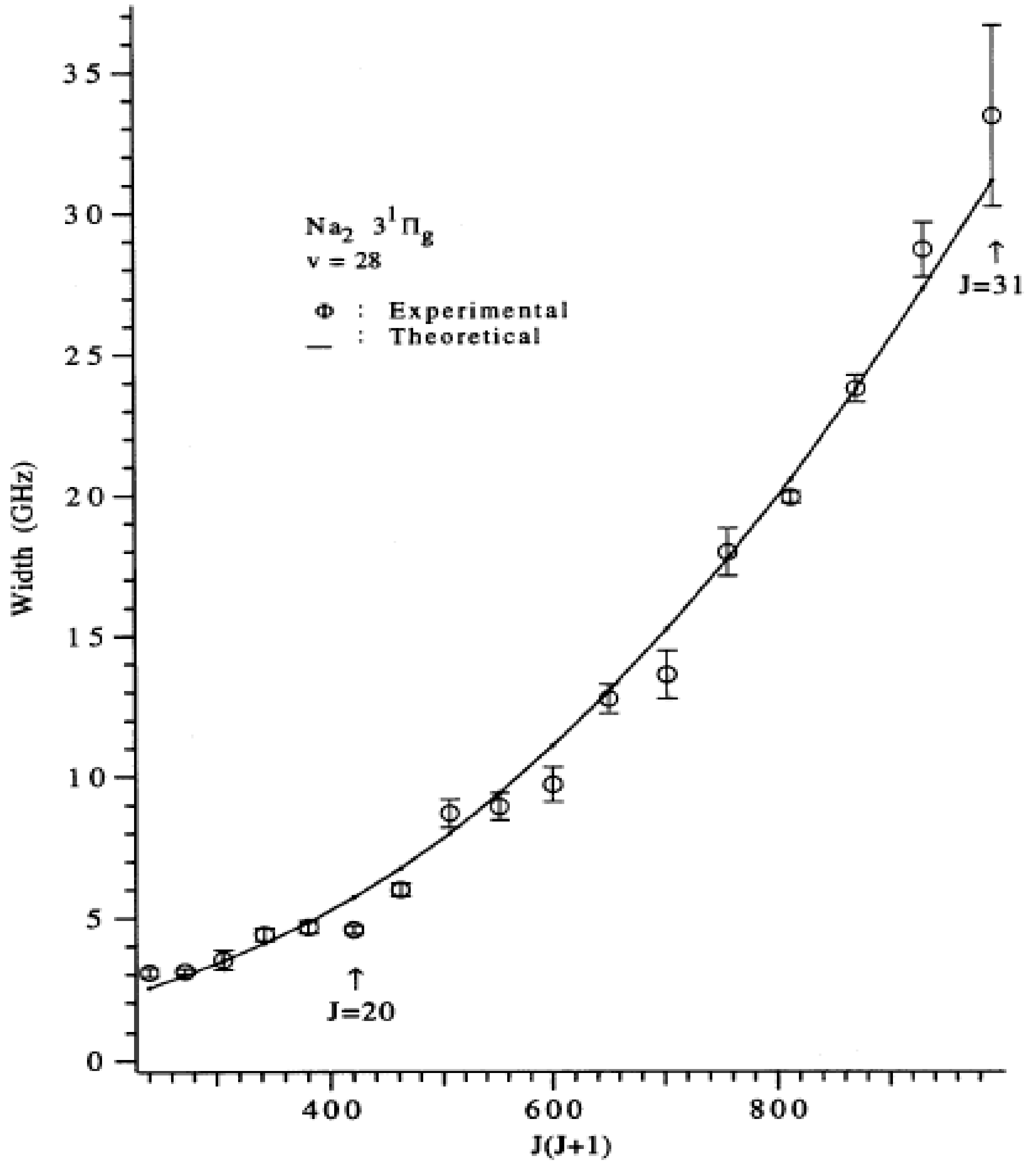
Tunnelling Effect







Tunnelling Effect



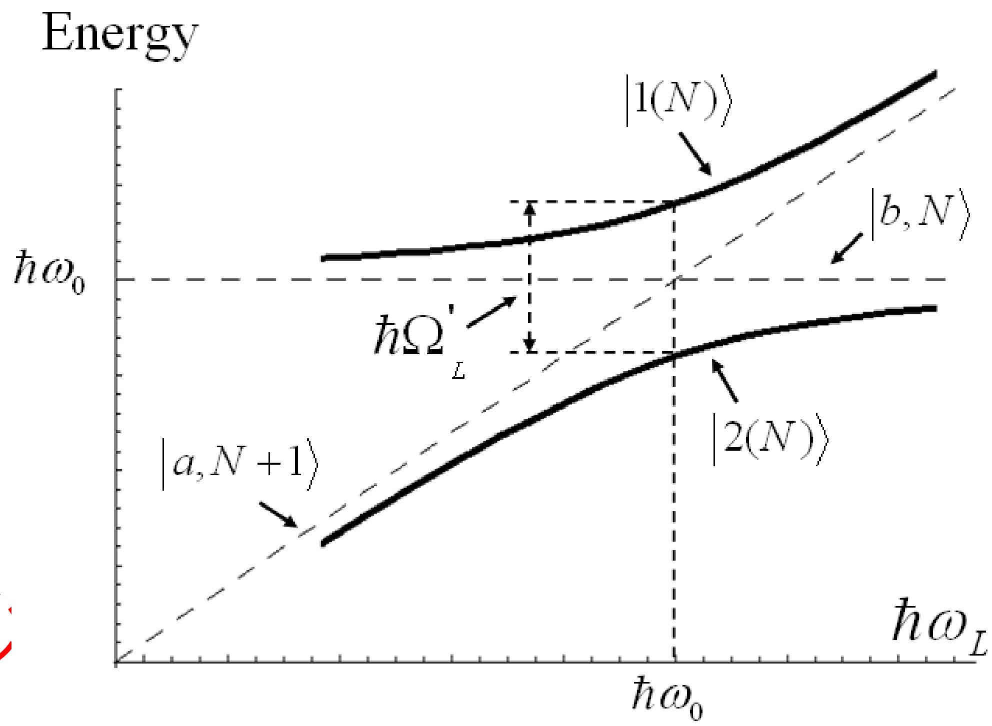
Avoided Crossing

Energy of dressed states :

The eigenvalues of

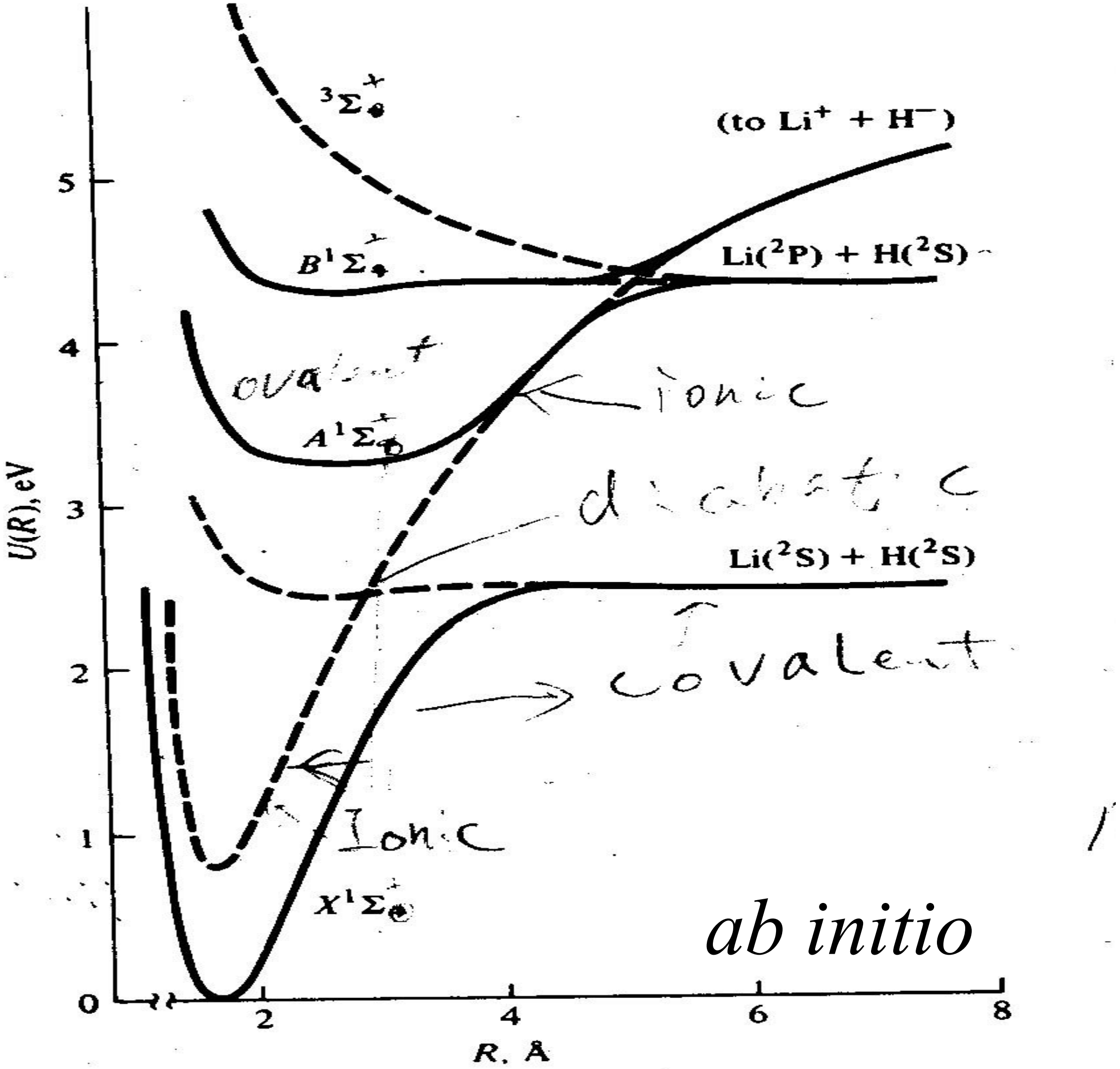
$$V_{AL} = \hbar \begin{pmatrix} 0 & \Omega_L/2 \\ \Omega_L/2 & \Delta_L \end{pmatrix}$$

$$E_{AL} = \frac{\hbar\Delta_L \pm \hbar\sqrt{\Delta_L{}^2 + \Omega_L{}^2}}{2}$$

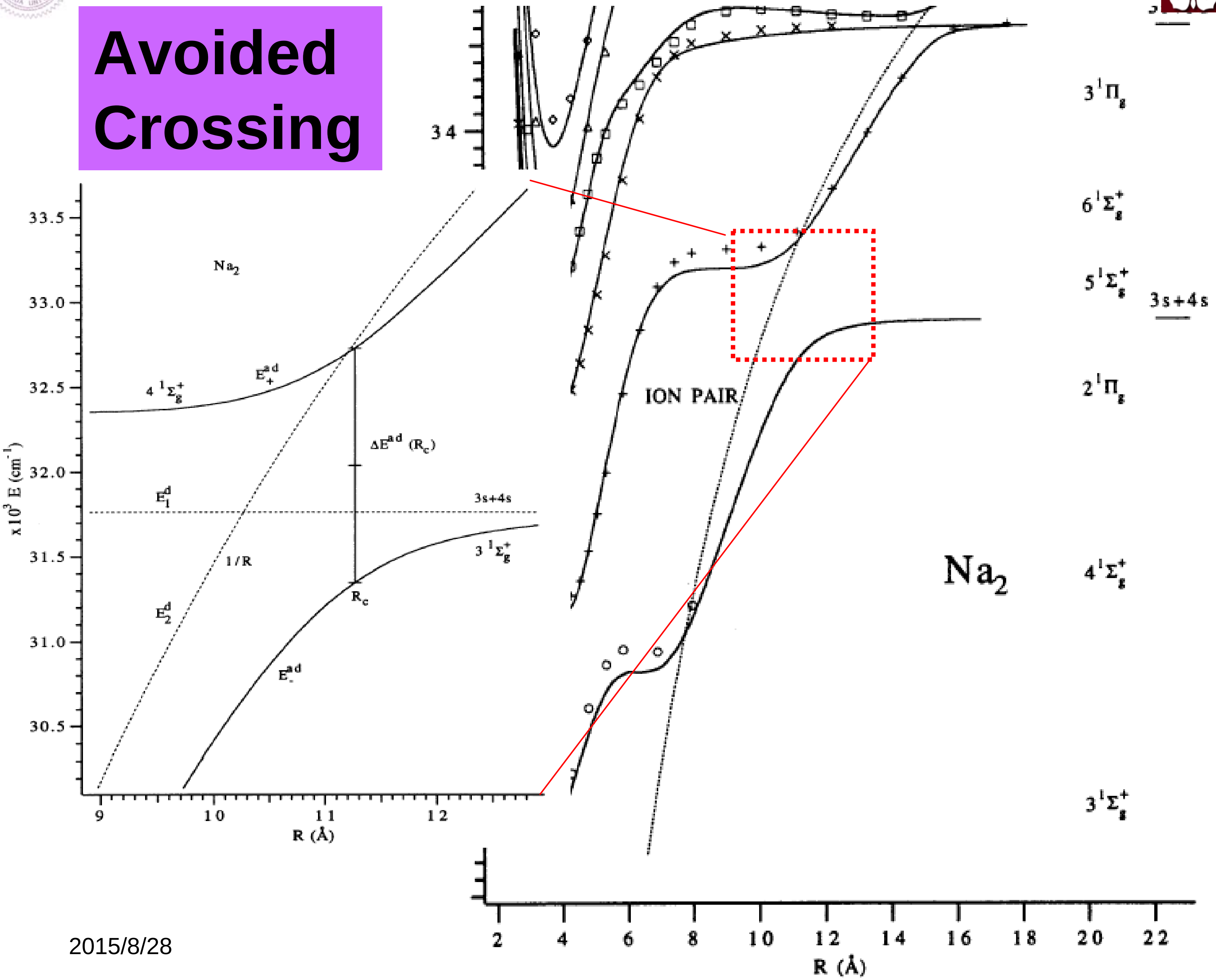


Avoided Crossing

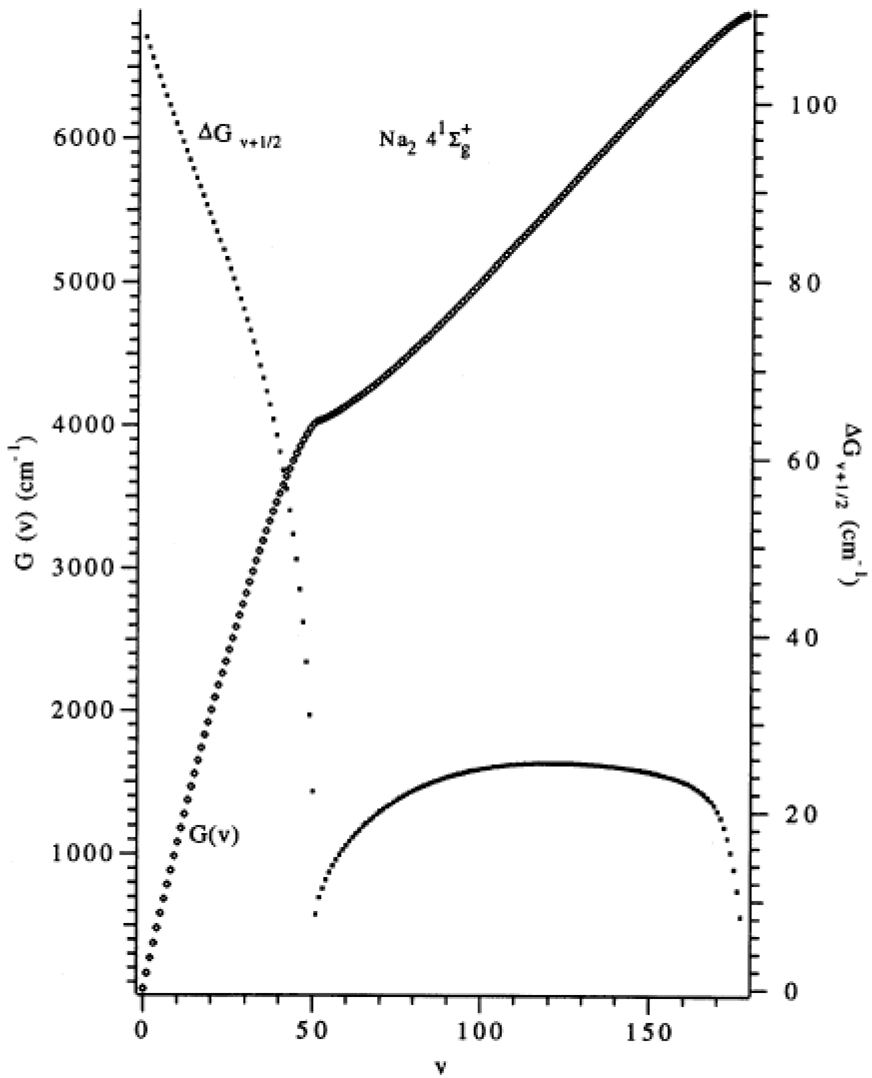
Intermolecular Potentials

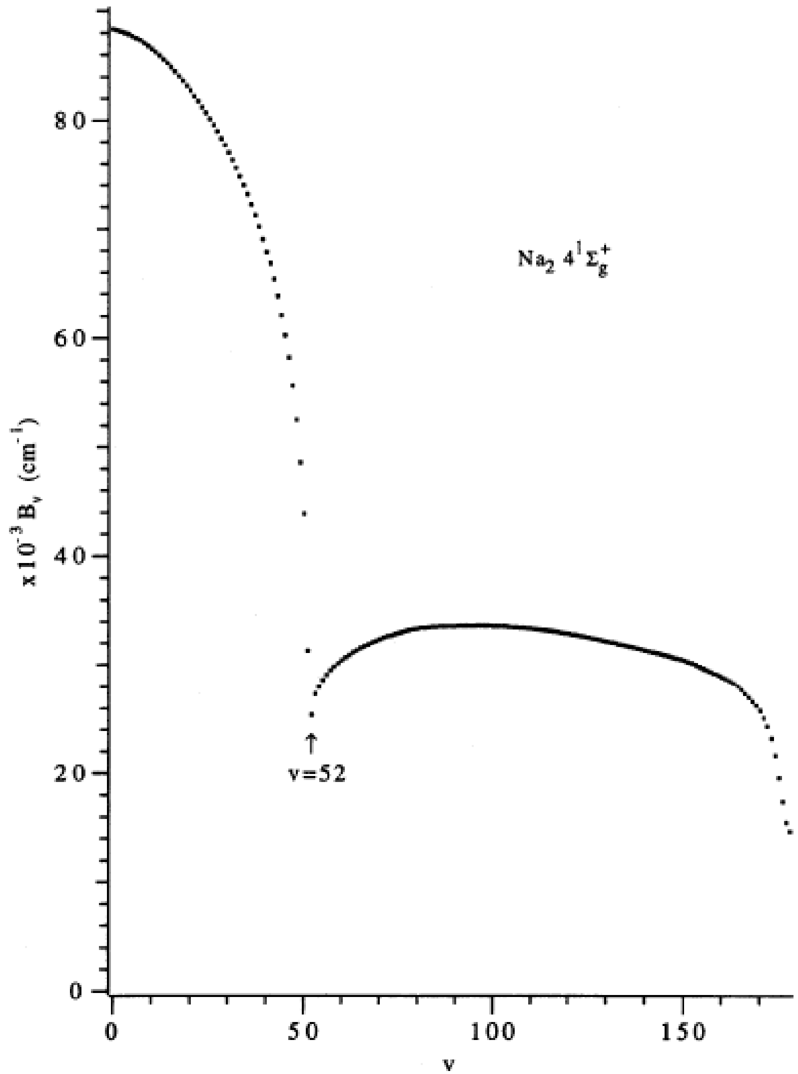


Avoided Crossing

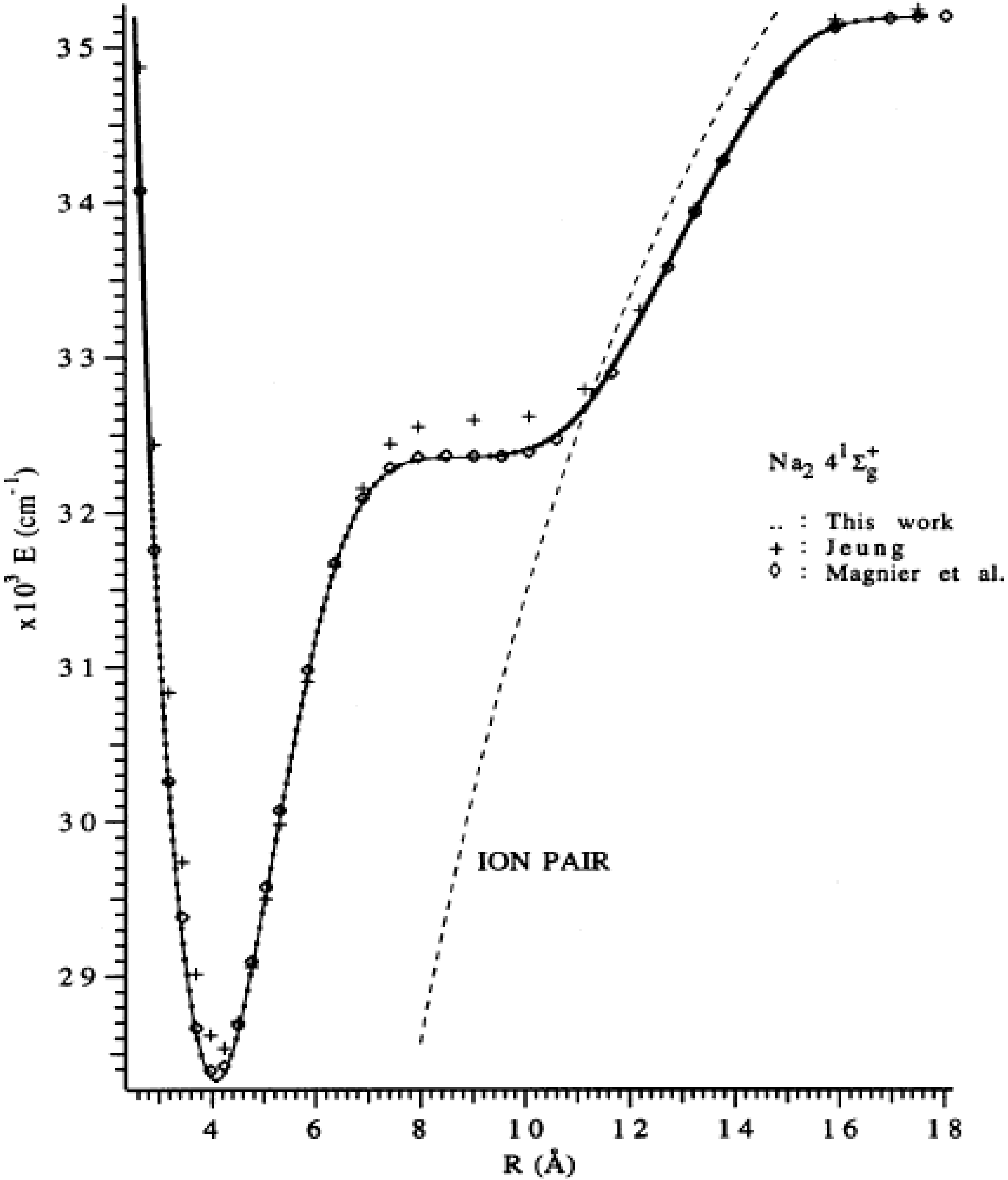


Avoided Crossing





Avoided Crossing



Fano Resonance

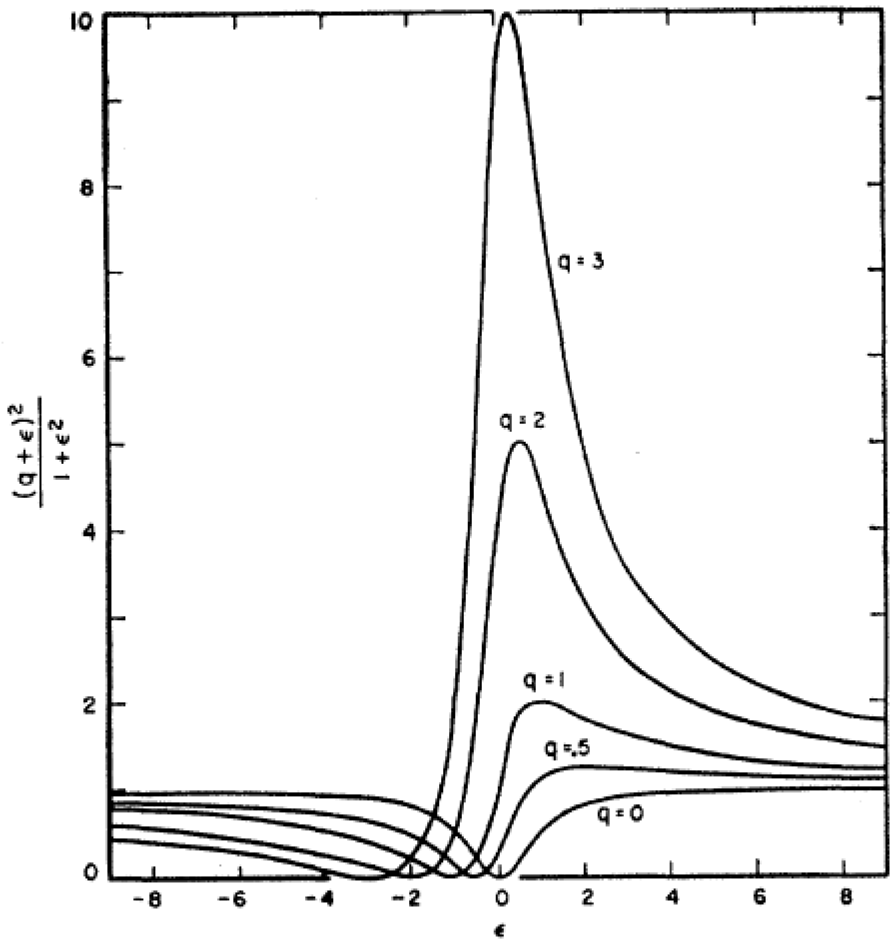
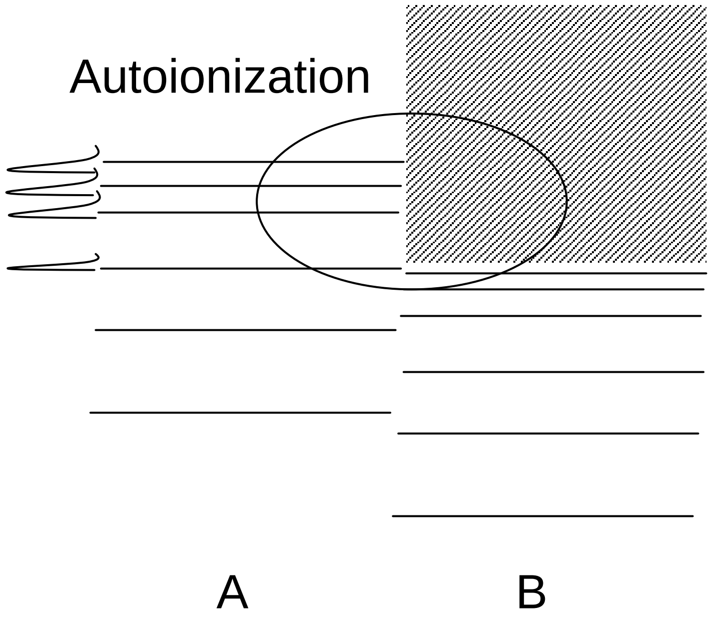


FIG. 1. Natural line shapes for different values of q. (Reverse the scale of abscissas for negative q.)

$$\frac{(q+\varepsilon)^2}{(1+\varepsilon^2)}$$



Fano Resonance

Na(3p)+Na(4s)

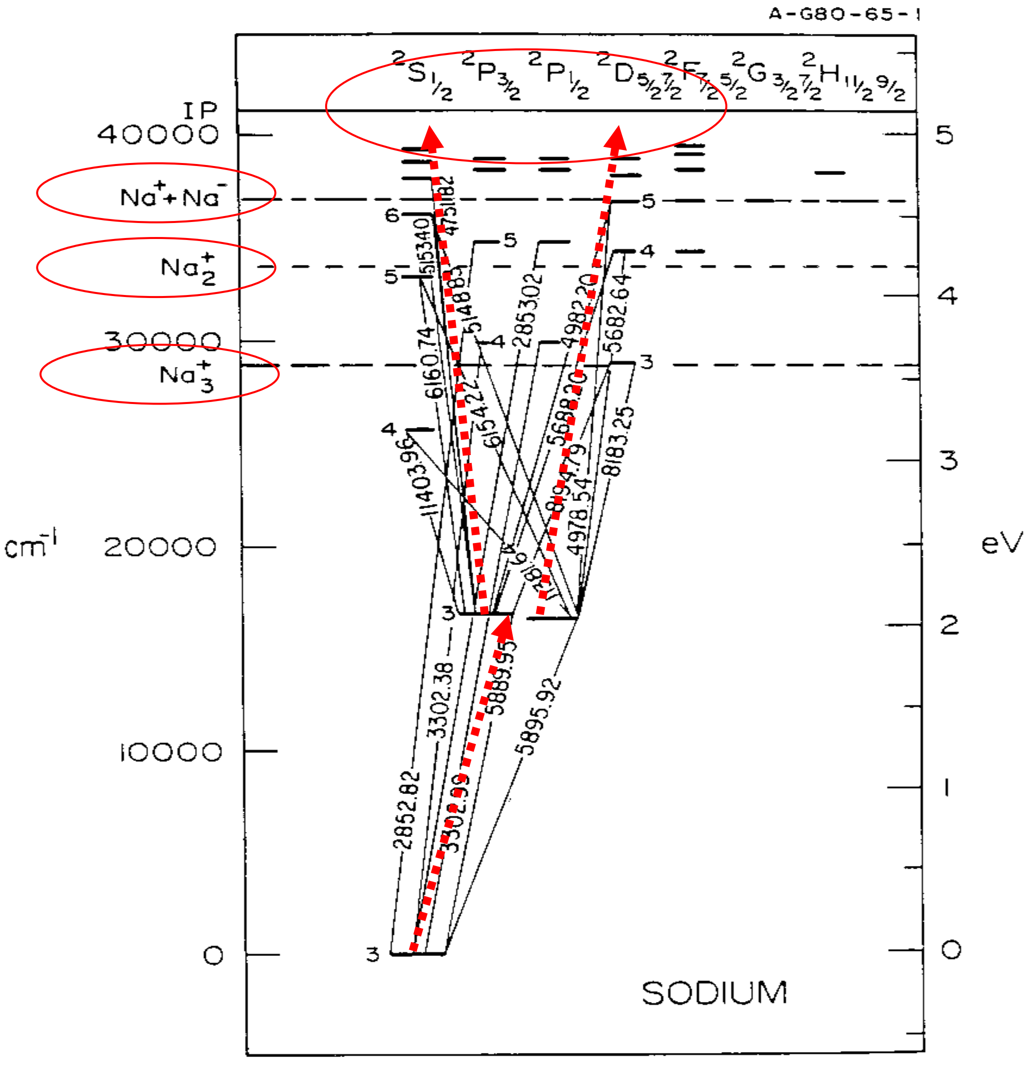


Figure 23. Grotian Diagram of Na.

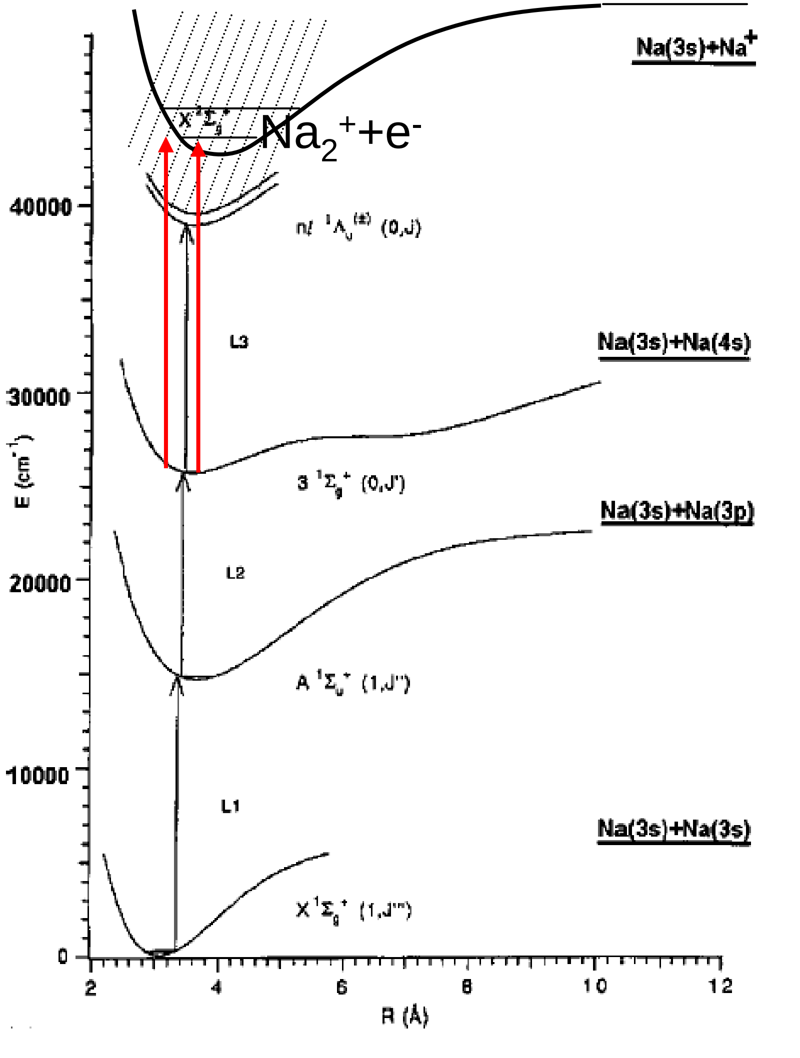
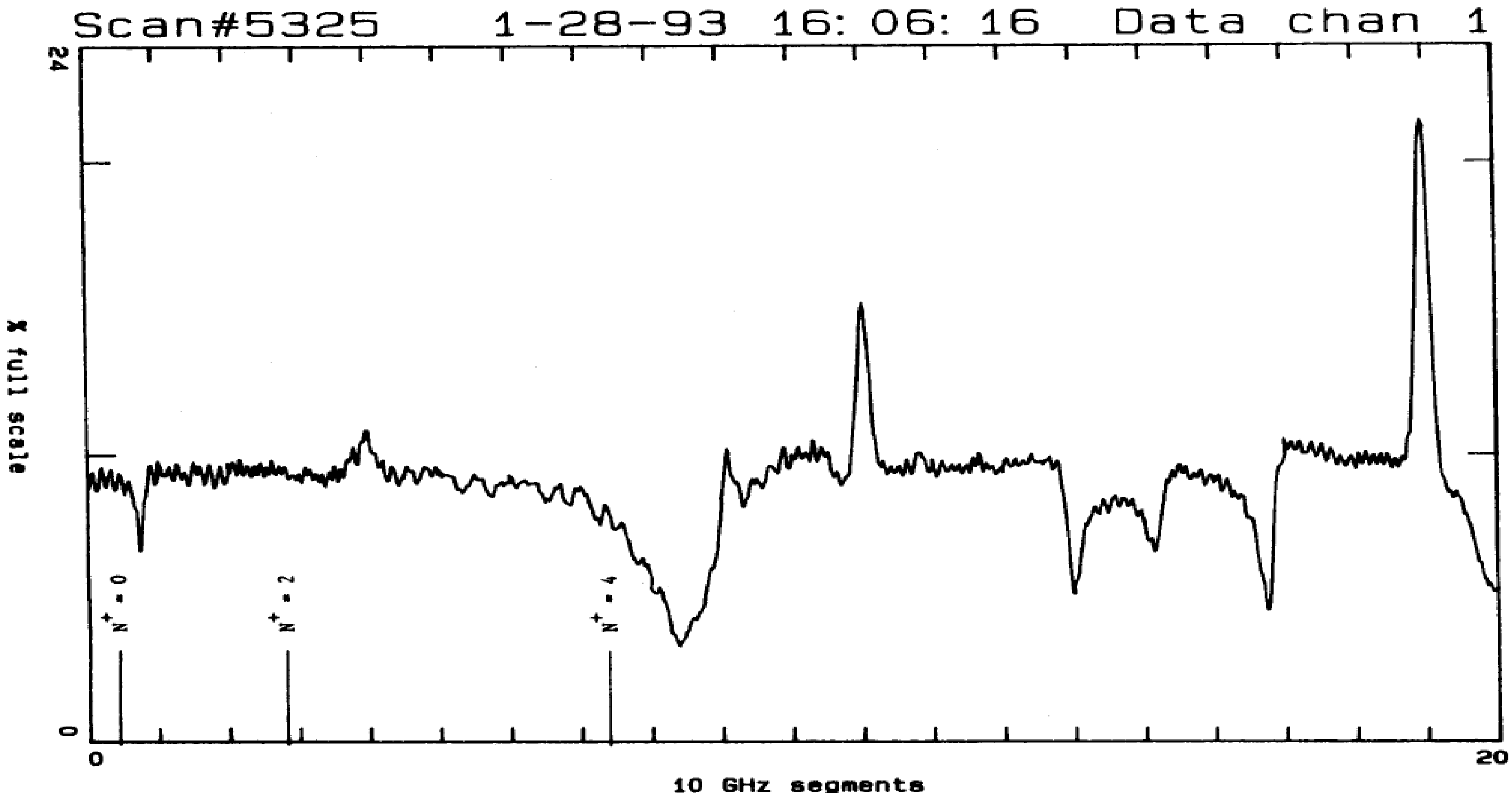


FIG. 2. Relevant potential curves of the AOTR experiment.

Fano Resonance

$$nf\ ^1\Pi_u\ (0,0\text{~}1) \longleftarrow 3^1\Sigma_g^+\ (0,0) \longleftarrow A^1\Sigma_u^+\ (1,1) \longleftarrow X^1\Sigma_g^+\ (1,2)$$



Fano Resonance

Discrete : U (Na 3p + Na 4s), Energy : 42000 cm-1 ~

Continuum : $Na_2^+ + e^-$

$$\frac{(q+\varepsilon)^2}{(1+\varepsilon^2)}$$

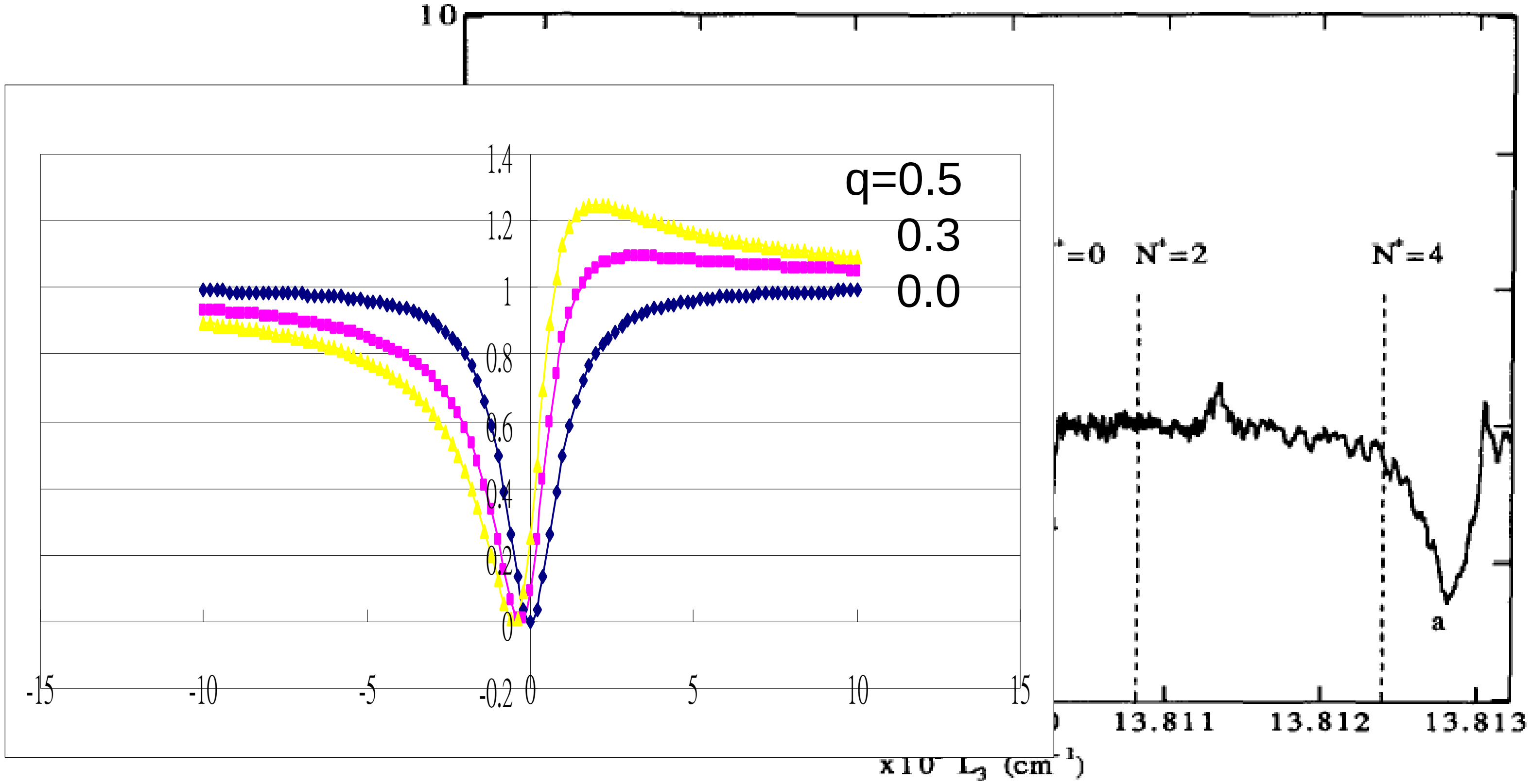


Fig. 3. The AOTR spectrum near the series limit clearly shows the continuum (a) (and quasi-continuum (b)) Fano autoionization profiles. The intermediate level is the Na_2 $3\,^1\Sigma_g^+$ (0, 0) level. Line (c) is an experimental artifact.

Quantum Phenomena in Cold Collisions

Photoassociation Spectroscopy in Rb

Motivations for using cold collisions:

Study the atoms free from spectral line broadening and shifts that arise from atomic motions and collisions

Advantages:

I. Cold collisions are highly quantum-mechanical in nature

II. Cold collisions are simple, involving only a few partial waves

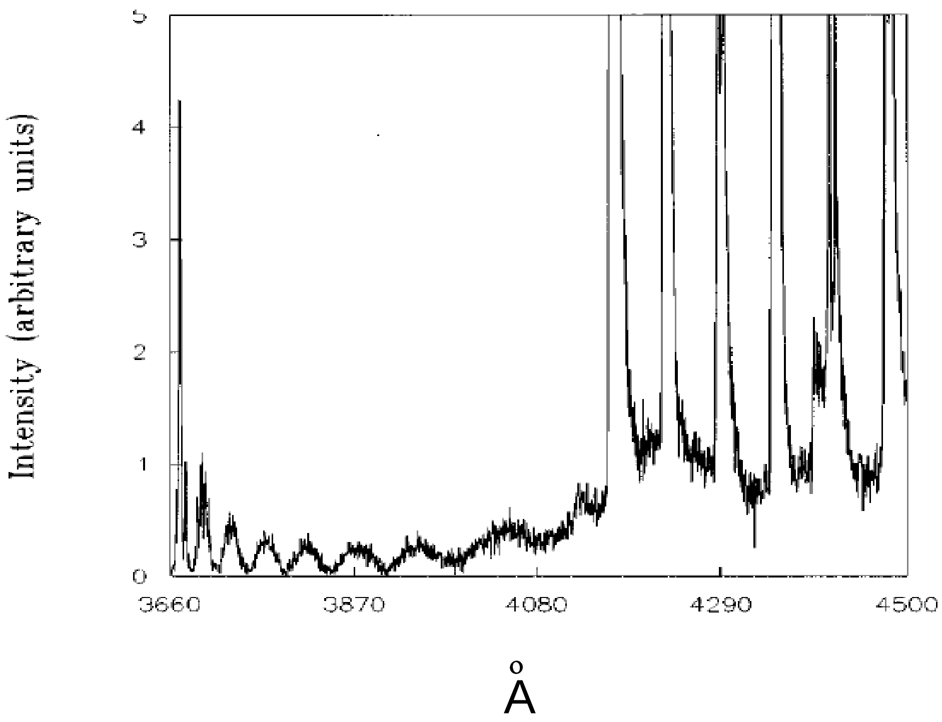
III. Cold collisions are sensitive to long-range interatomic forces

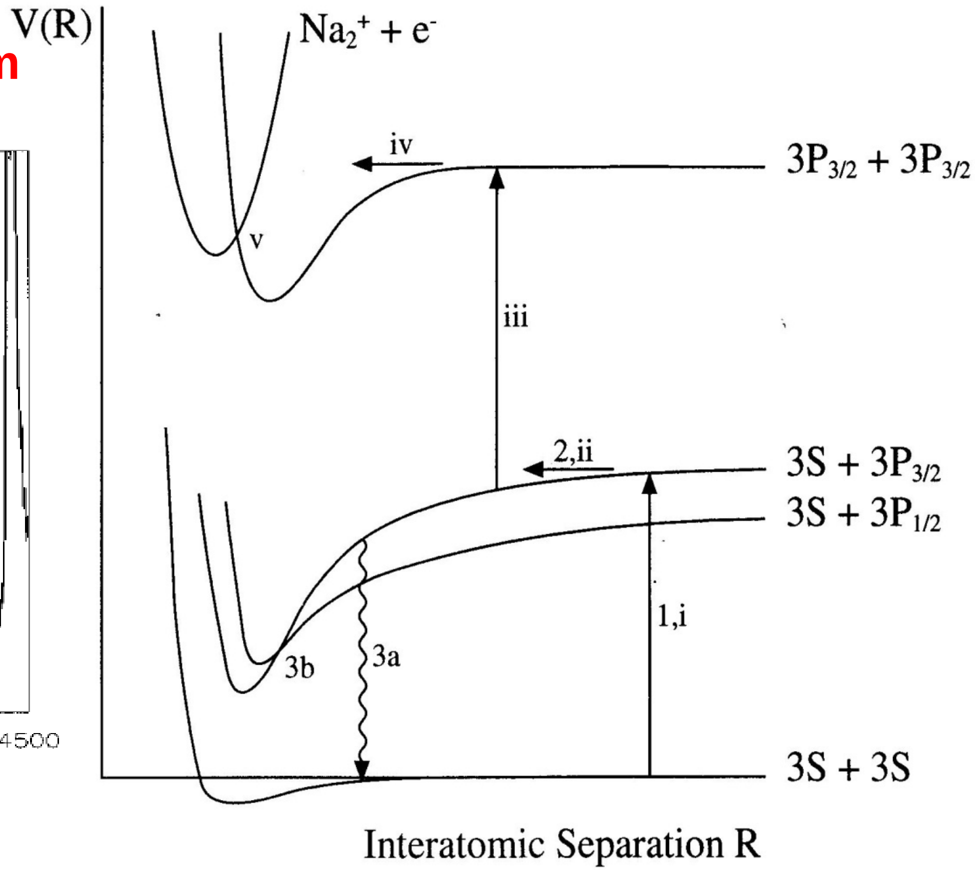
IV. Long collision times can significantly affect the collision dynamics

V. Spontaneous emission during the collision may occur to change the collision channels involved.

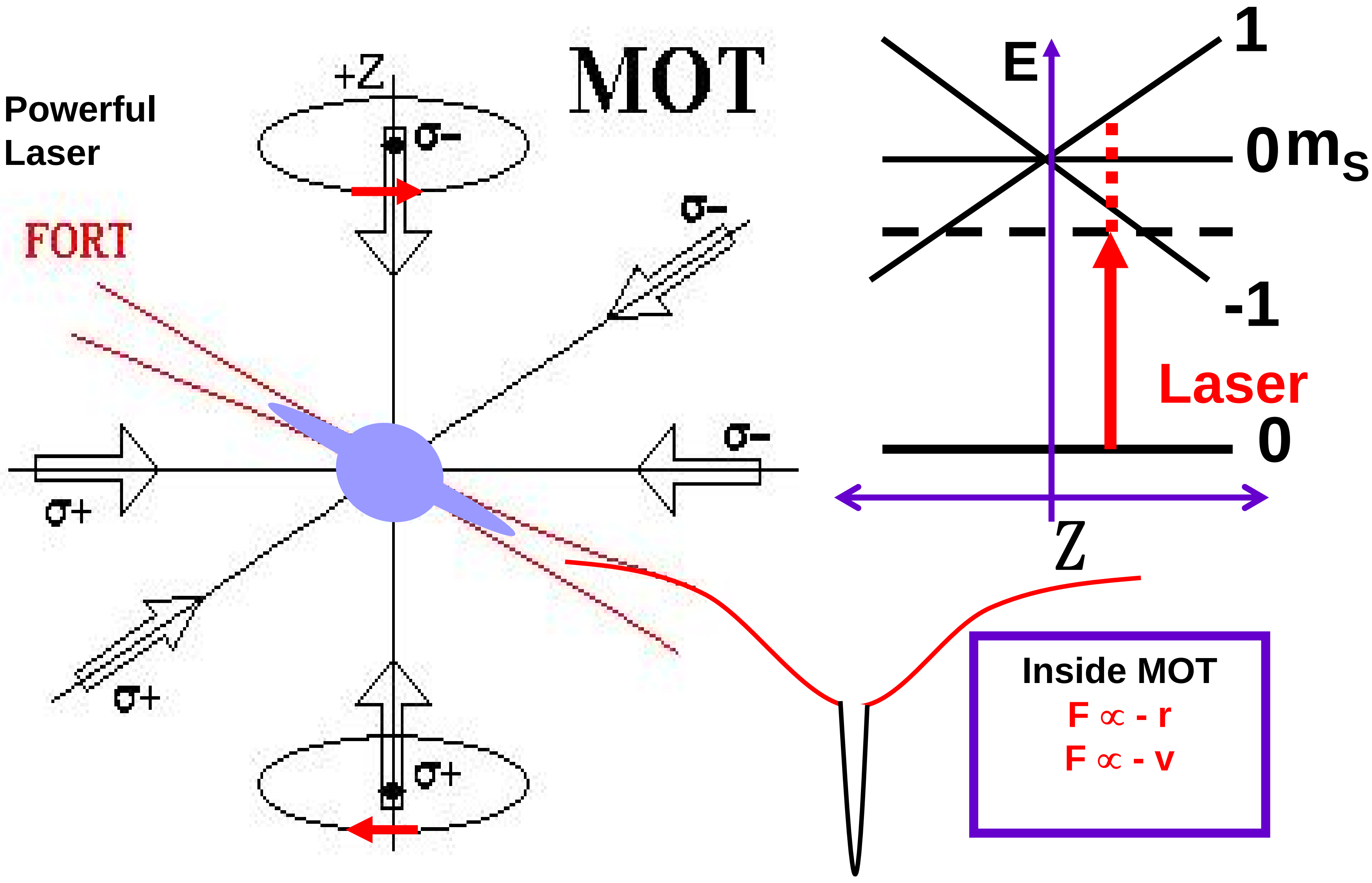
Bound Free Transitions

Conventional Bound Free Spectrum

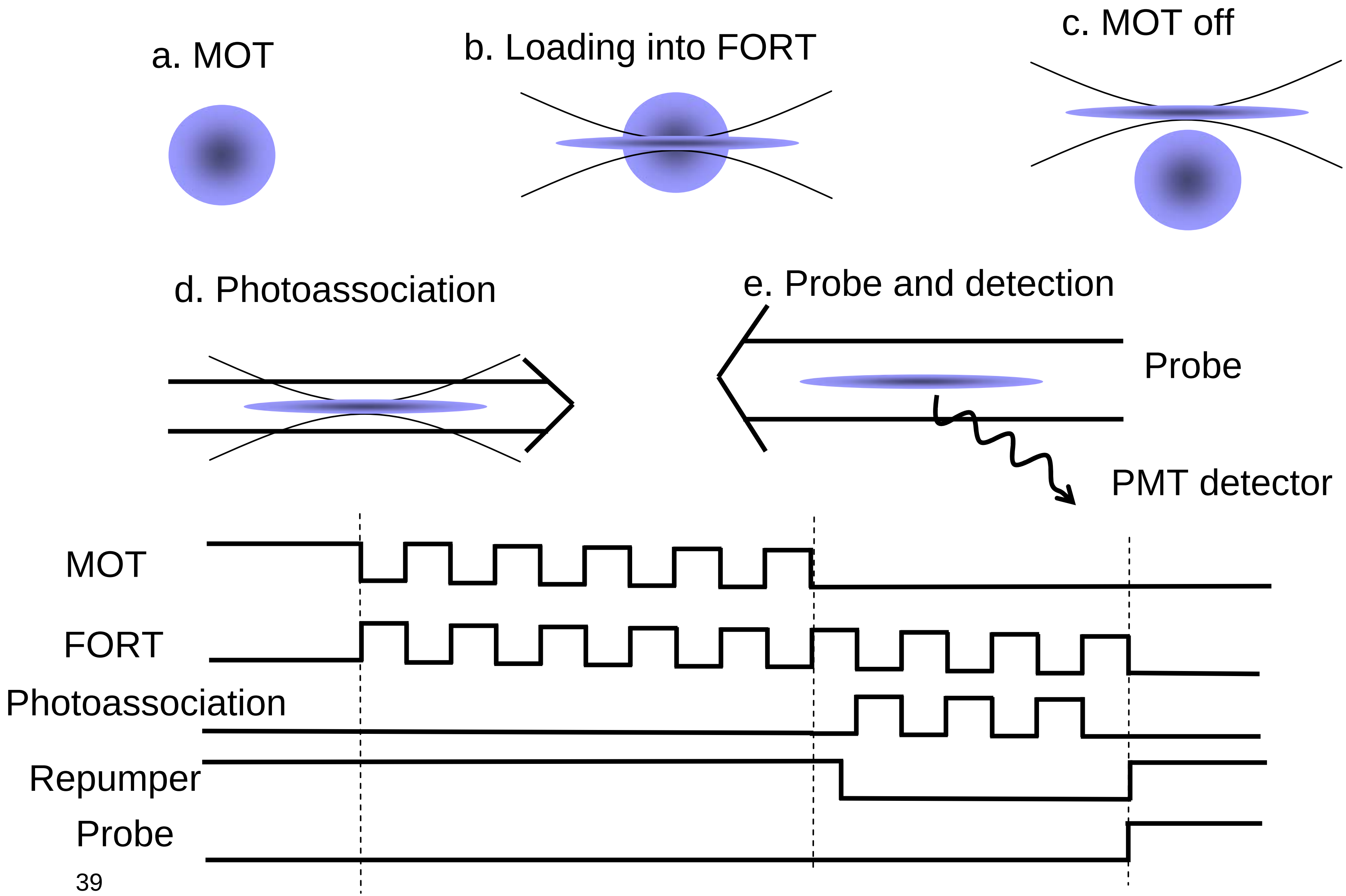




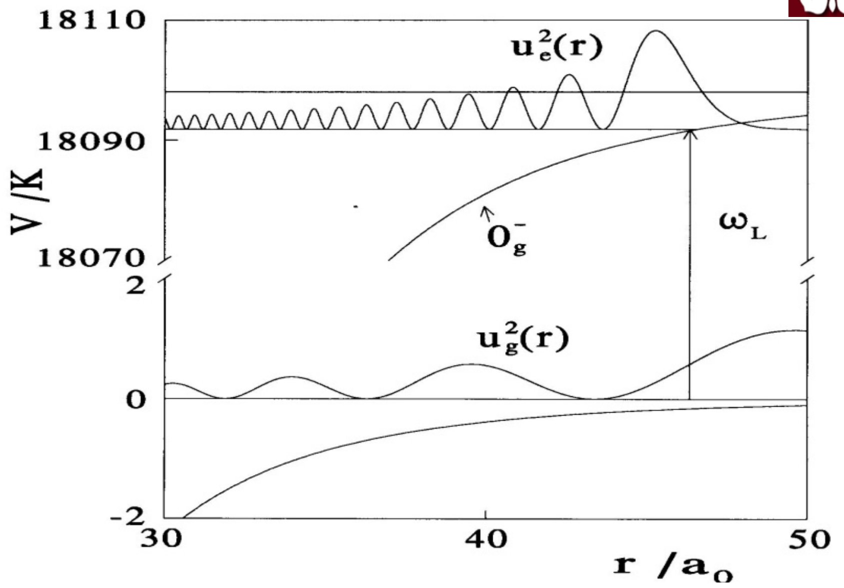
A. Cold collisions in a far-off resonance trap (FORT)

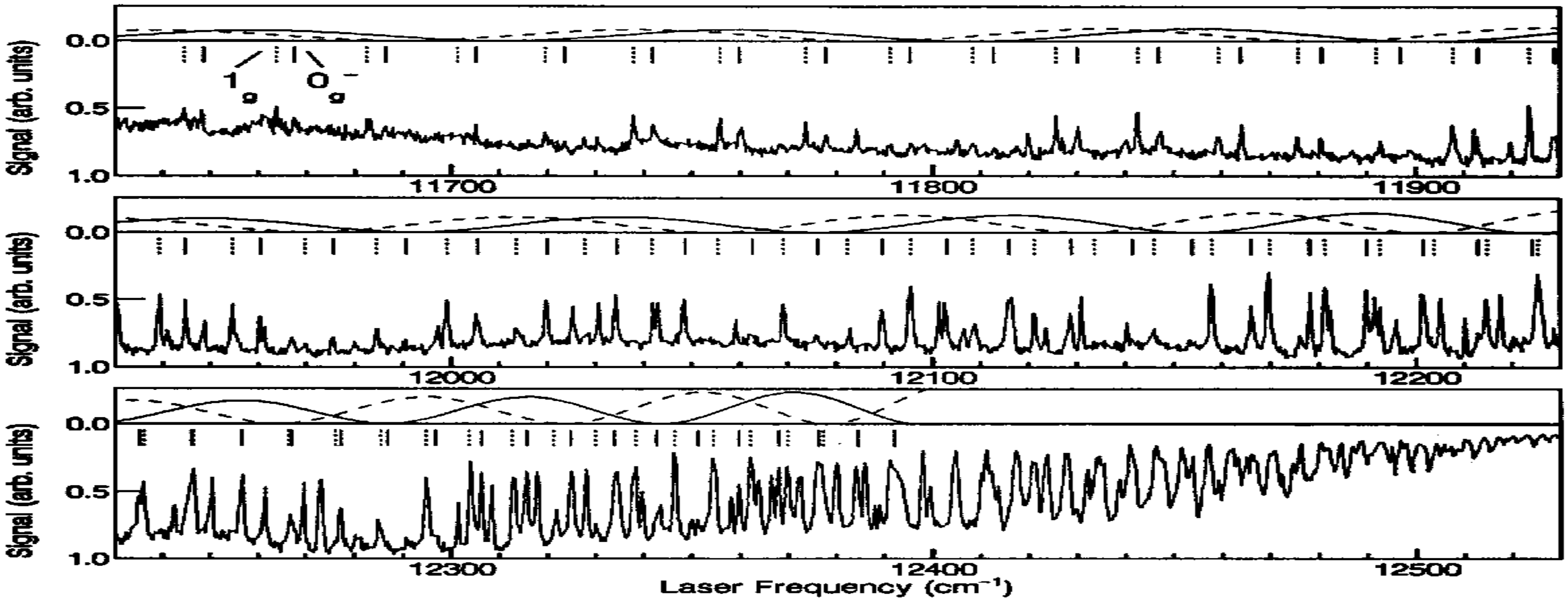


B. Cold collisions under high resolution laser spectroscopy



Bound Free Transitions

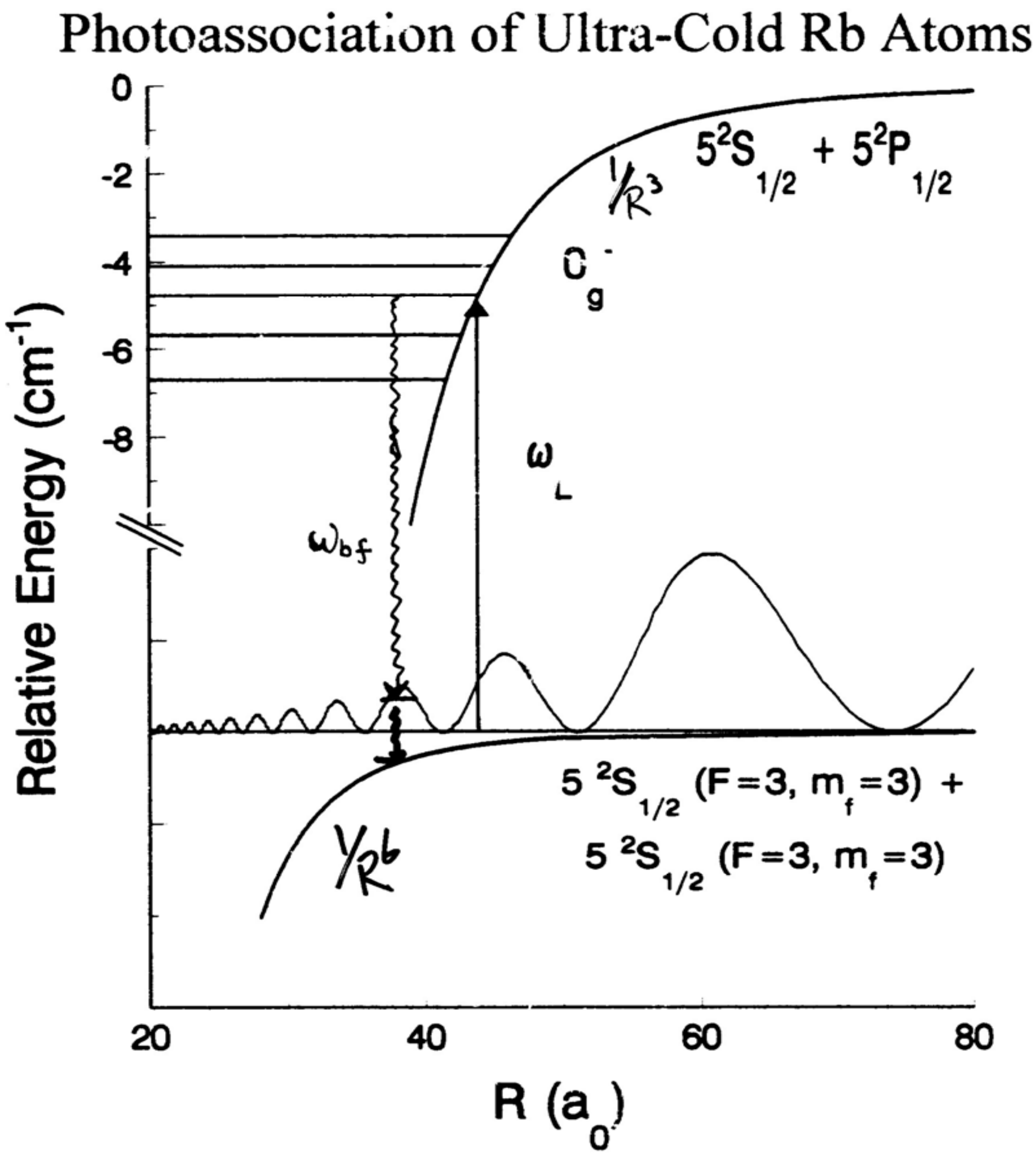




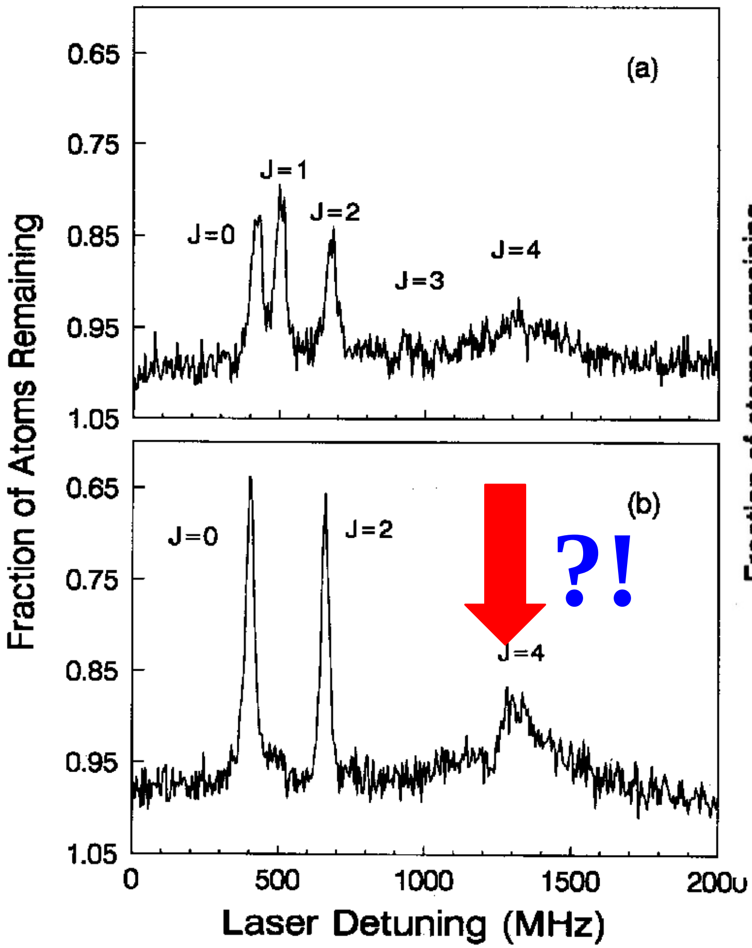
Shape Resonance

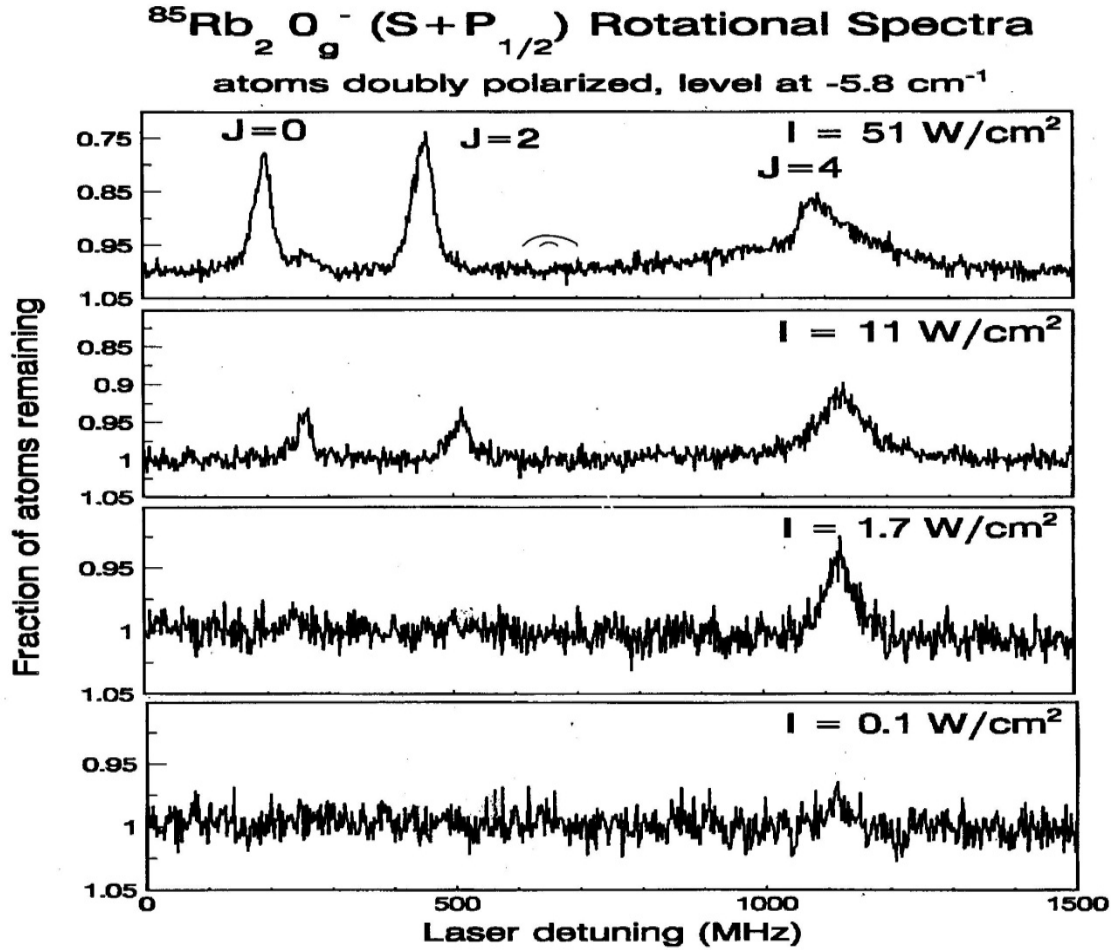
Atom trapped in the MOT or FORT

Detecting the trap loss



Shape Resonance



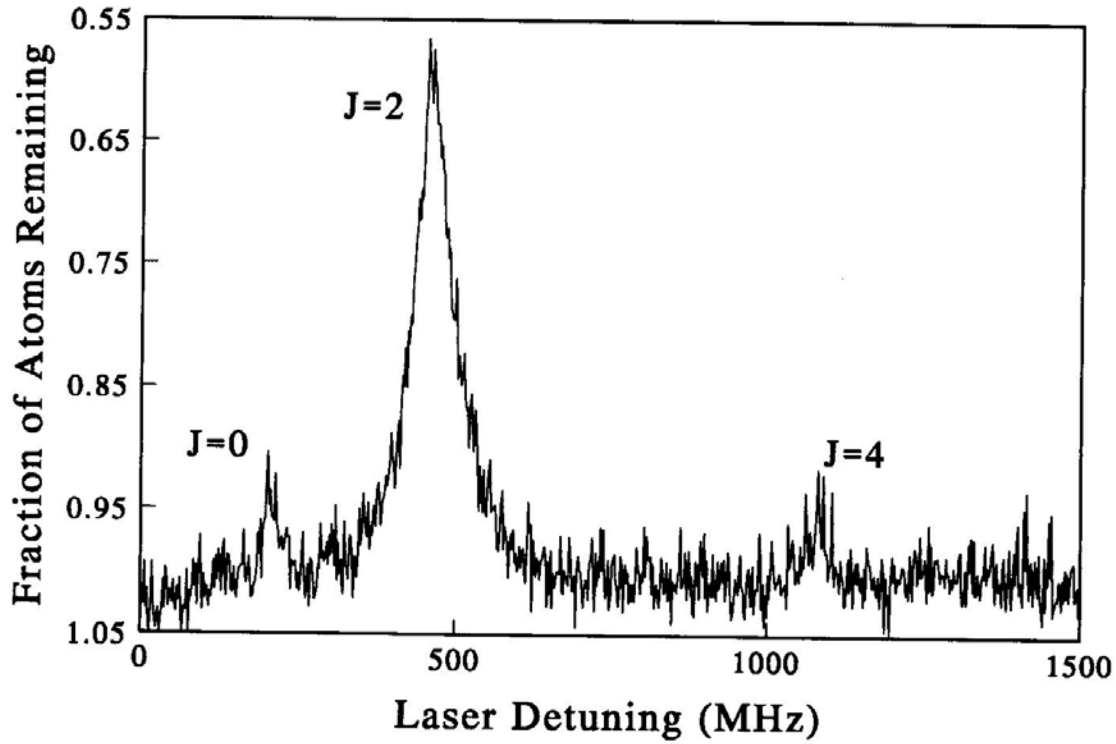


$^{85}Rb + ^{85}Rb$

Shape Resonance

Cold collisions under **d-wave shape resonance**

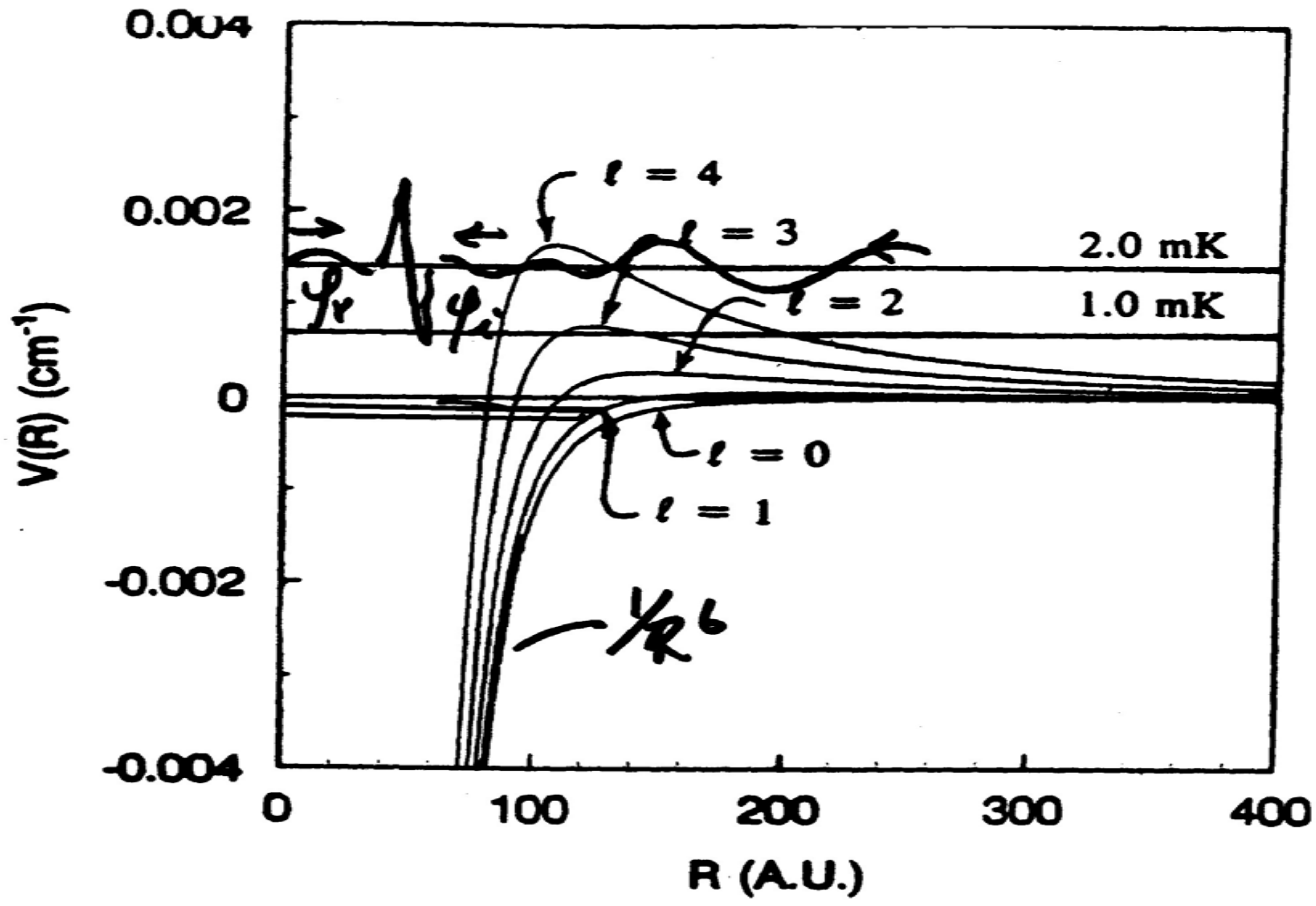
How about the PA spectrum of $^{87}Rb+^{87}Rb$



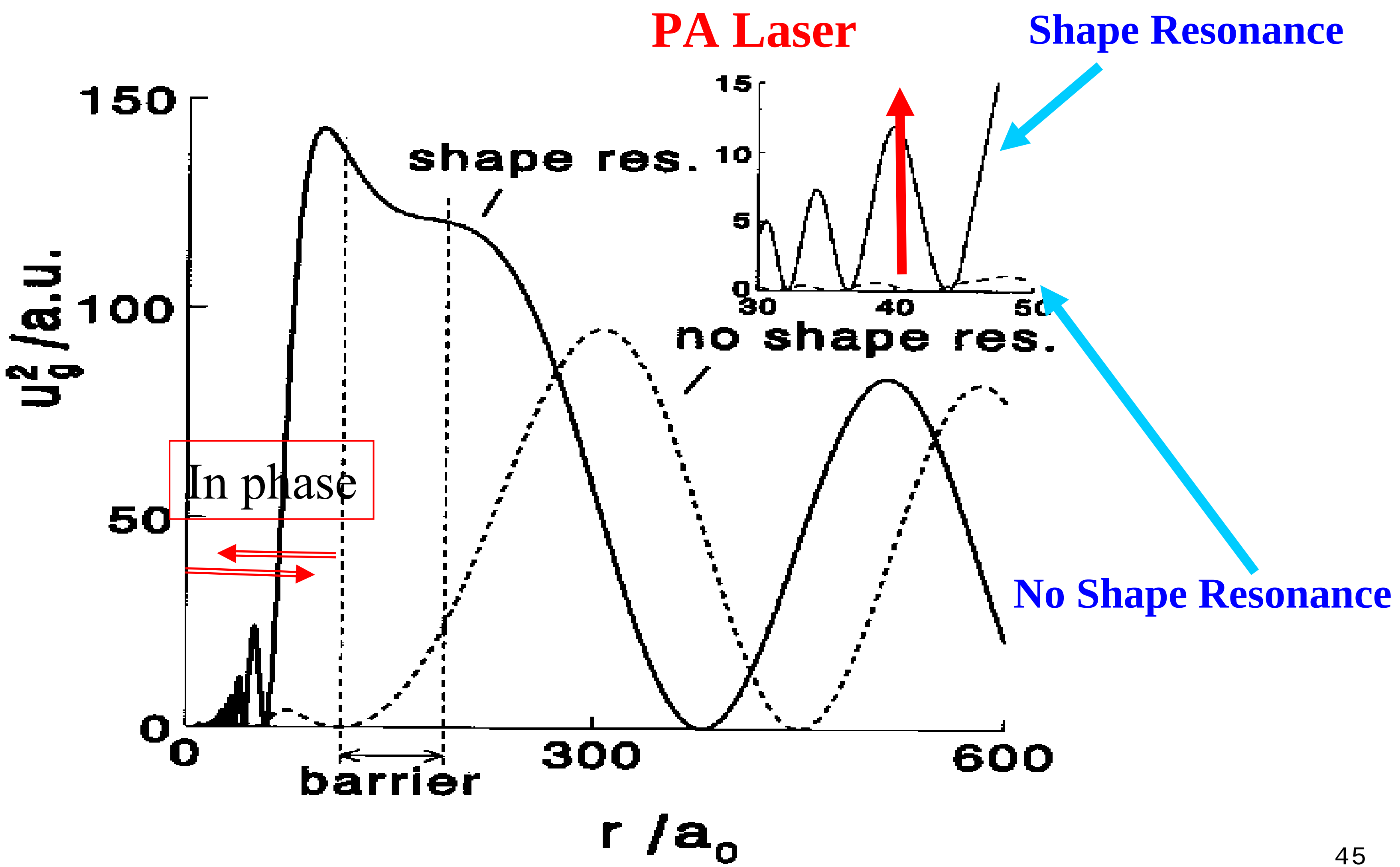
Vibrational level of 0_g^- state at 5.9 cm^{-1} below $5^2S_{1/2}+5^2p_{1/2}$

Shape Resonance

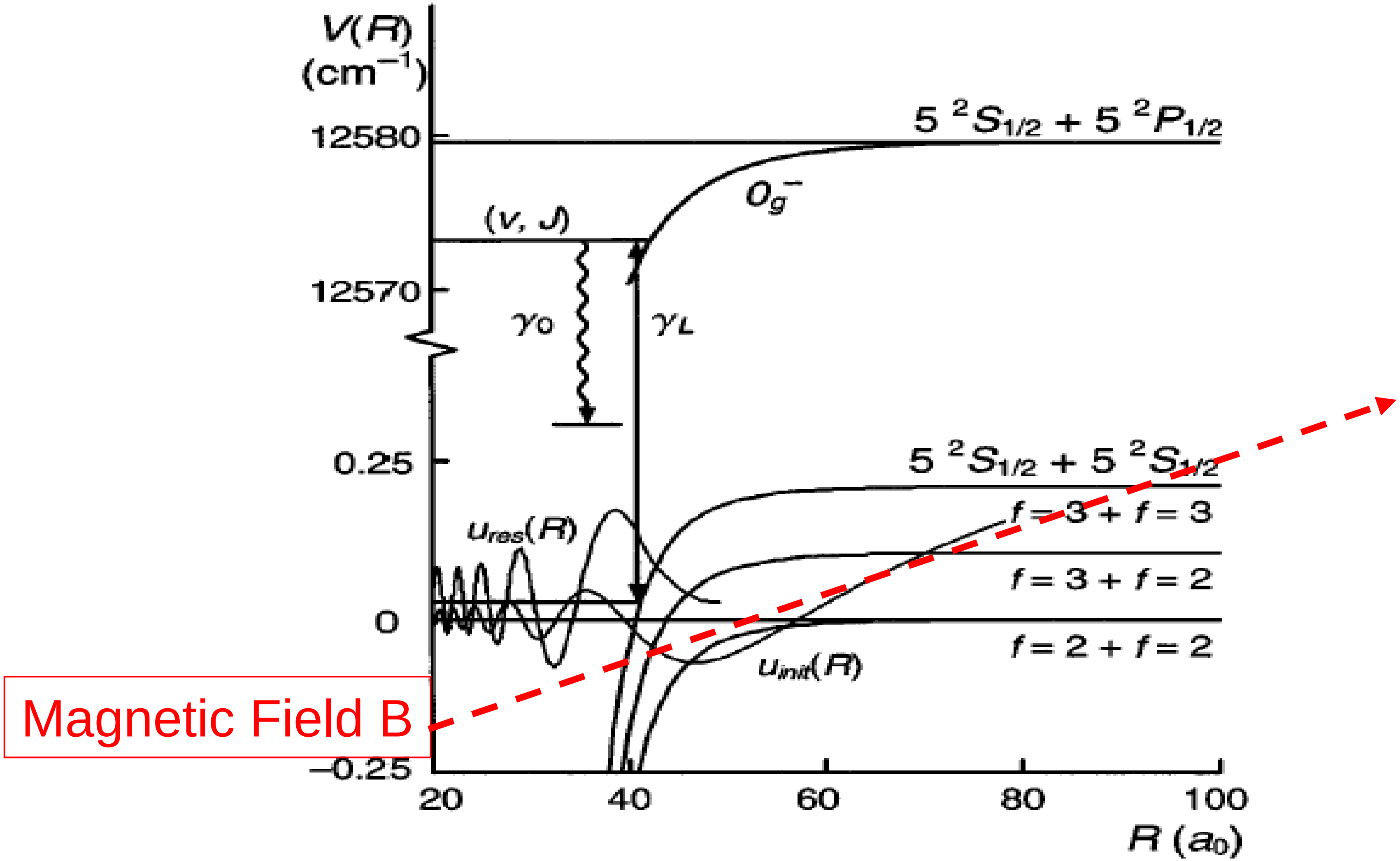
Rb$_2$ Ground State Potentials at Long Range



Shape Resonance



Feshbach Resonance



Feshbach Resonance

Cold collisions

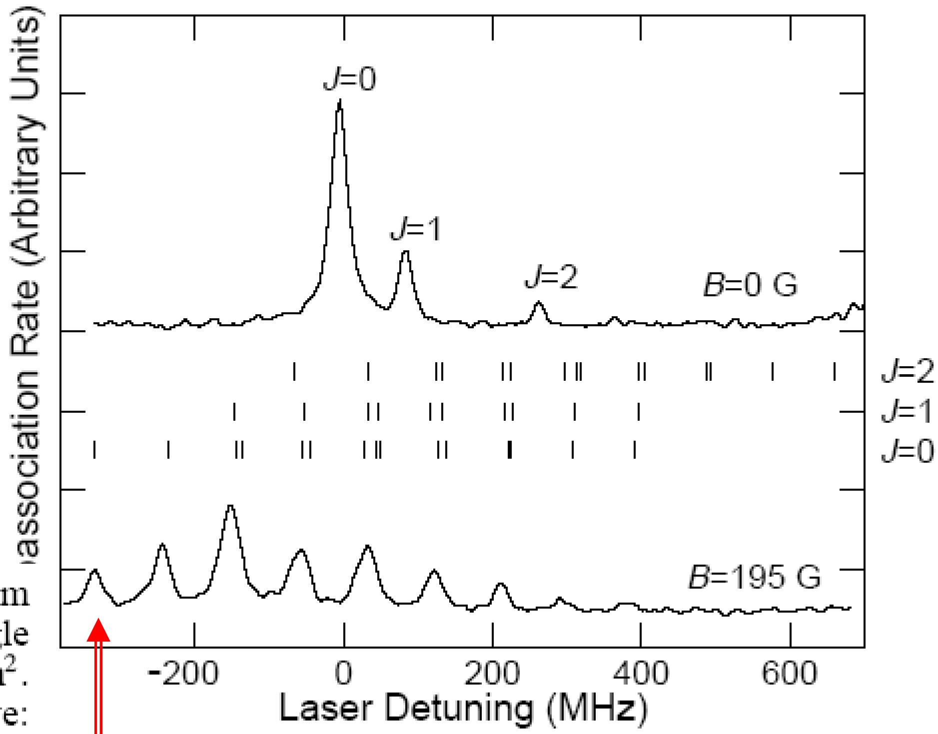
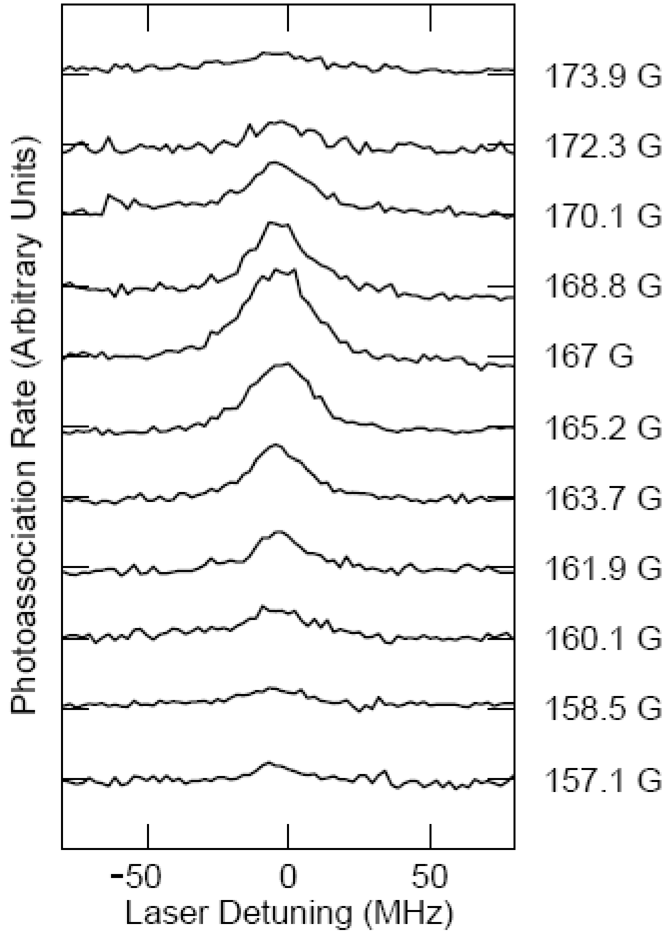
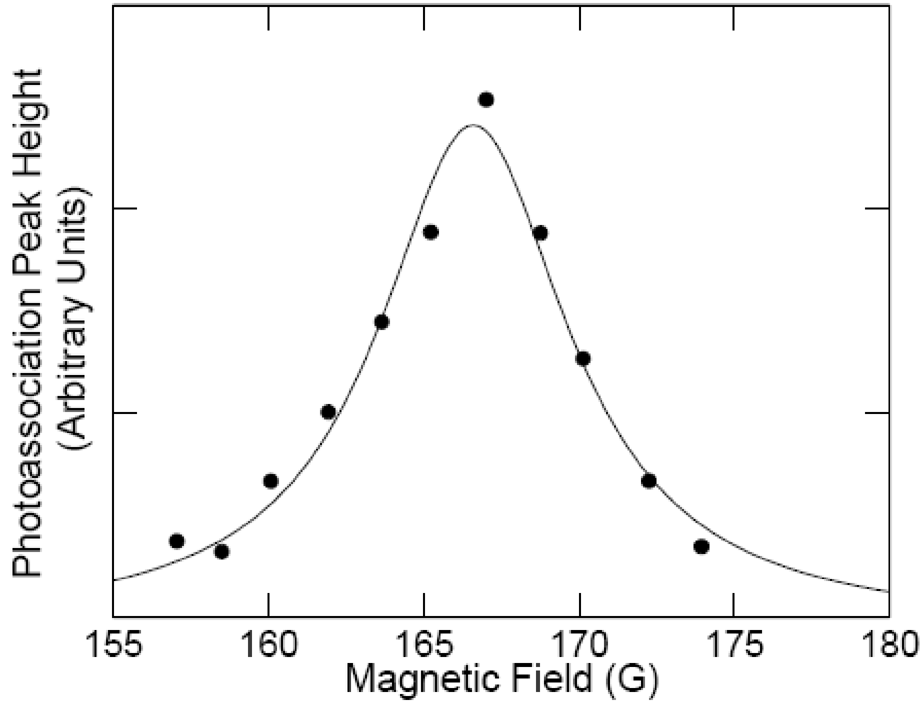


FIG. 2. $^{85}Rb_2$ photoassociation spectra for excitation from lower $(f = 2 + f = 2)$ hyperfine state collisions to a single excited vibrational level, at a laser intensity of 20 W/cm^2. Upper curve: spectrum at zero magnetic field. Lower curve: spectrum at a magnetic field of 195 G. Each of the zero field components splits into 10 or 15 distinct components due to Zeeman splitting of the ground state atoms; calculated splittings are shown by the vertical dashed marks. The successive peaks in the lower spectrum correspond mainly to $J = 0$, and (from left) $M_F = -4, -3, -2, -1, 0, 1,$ and 2.

J=0, M_F= -4

Feshbach Resonance

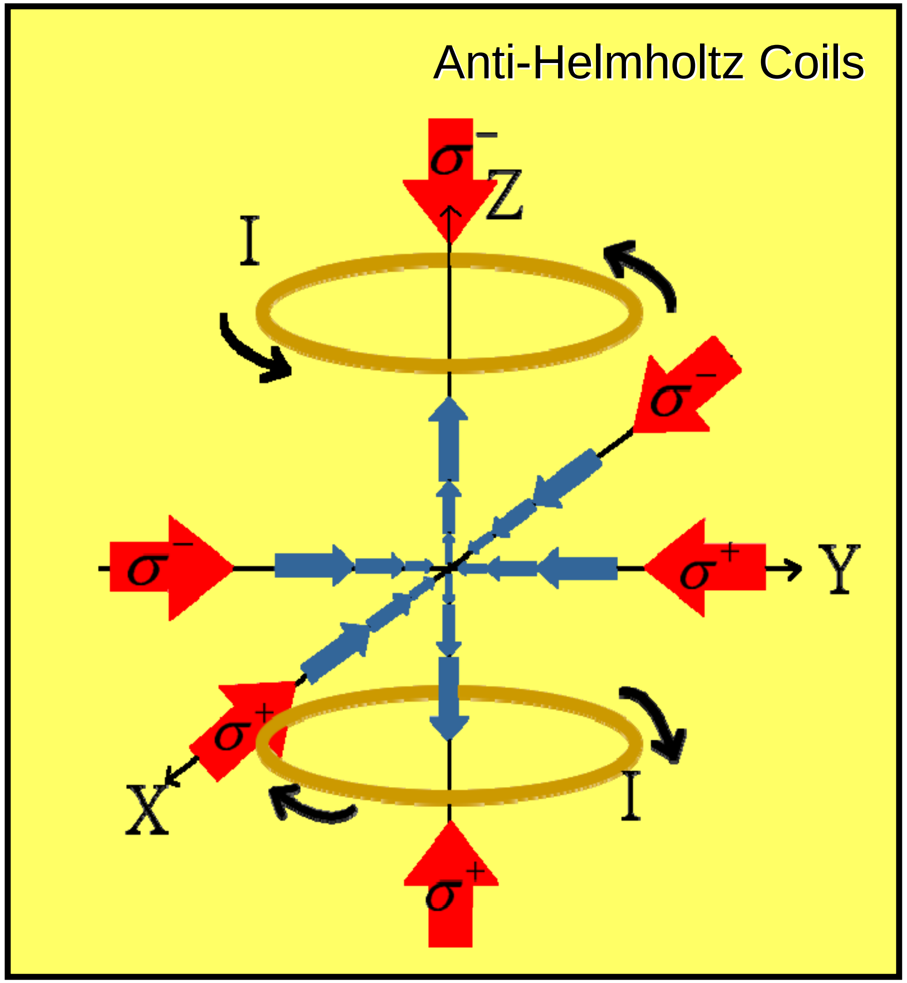


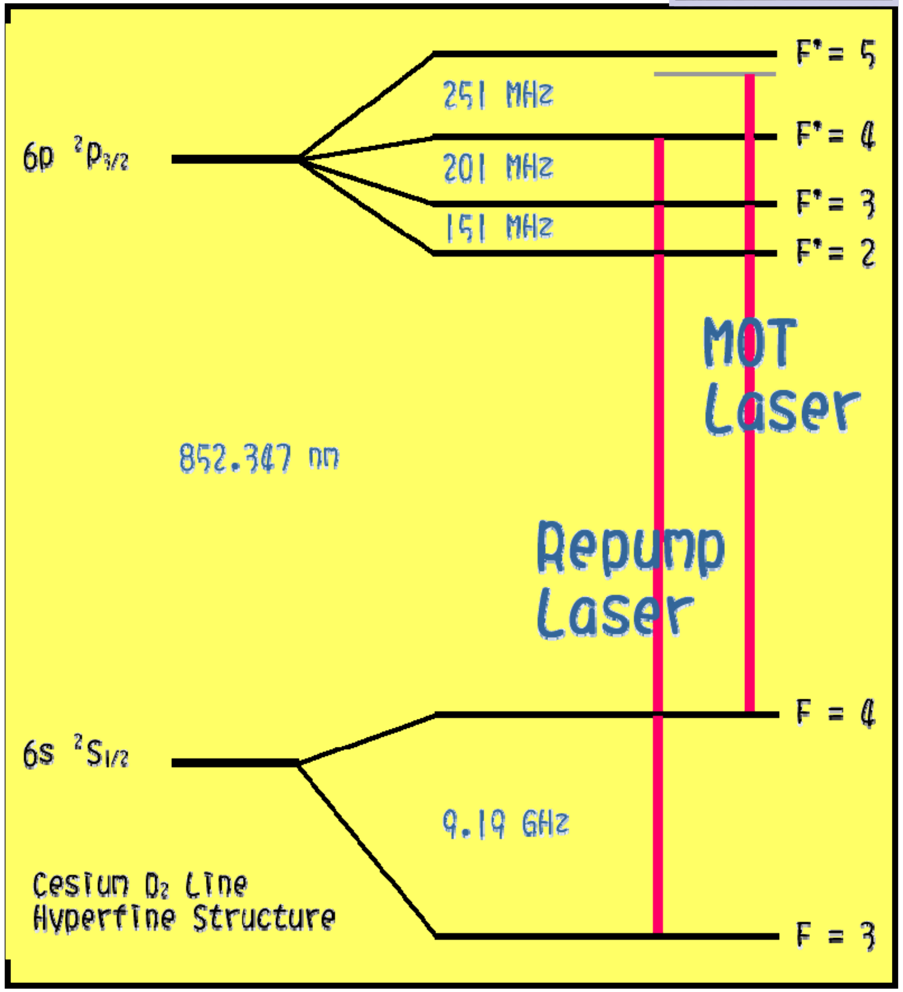


Quantum Interference in Cold Cs

Electromagnetically Induced Transparency
EIT

Magneto-Optical Trap of Cesium atoms

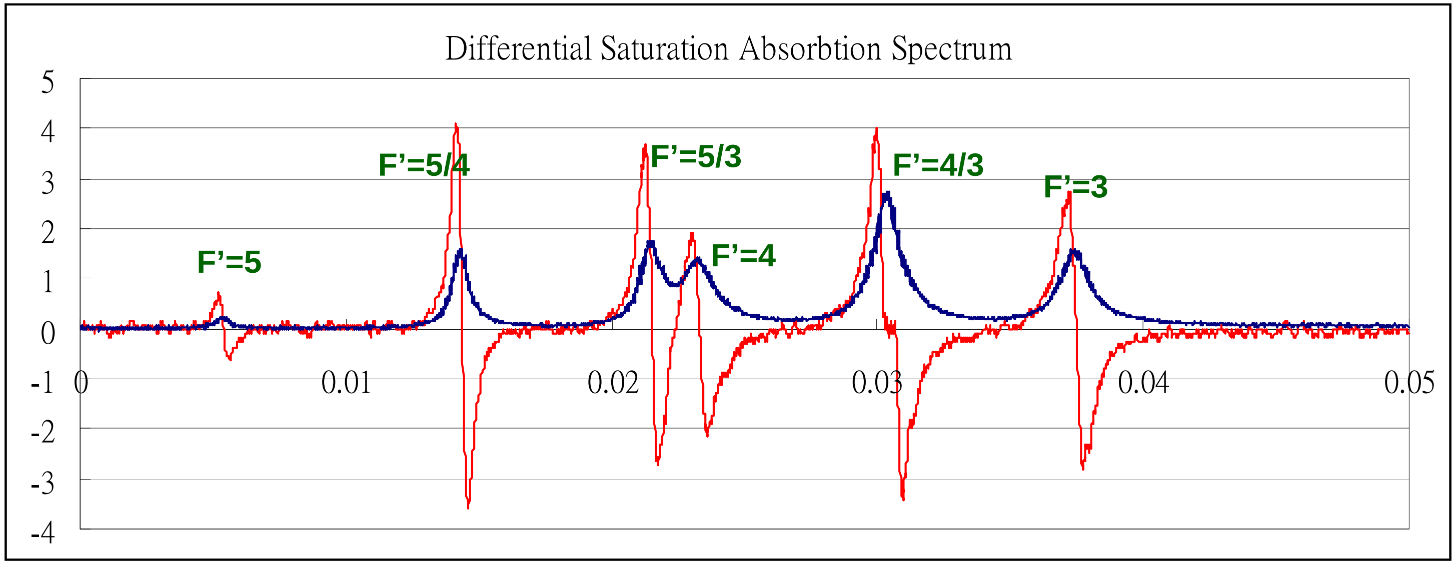




High-Precision and High-Resolution Laser Spectroscopy on Magneto-Optical Trap of Cesium Atoms

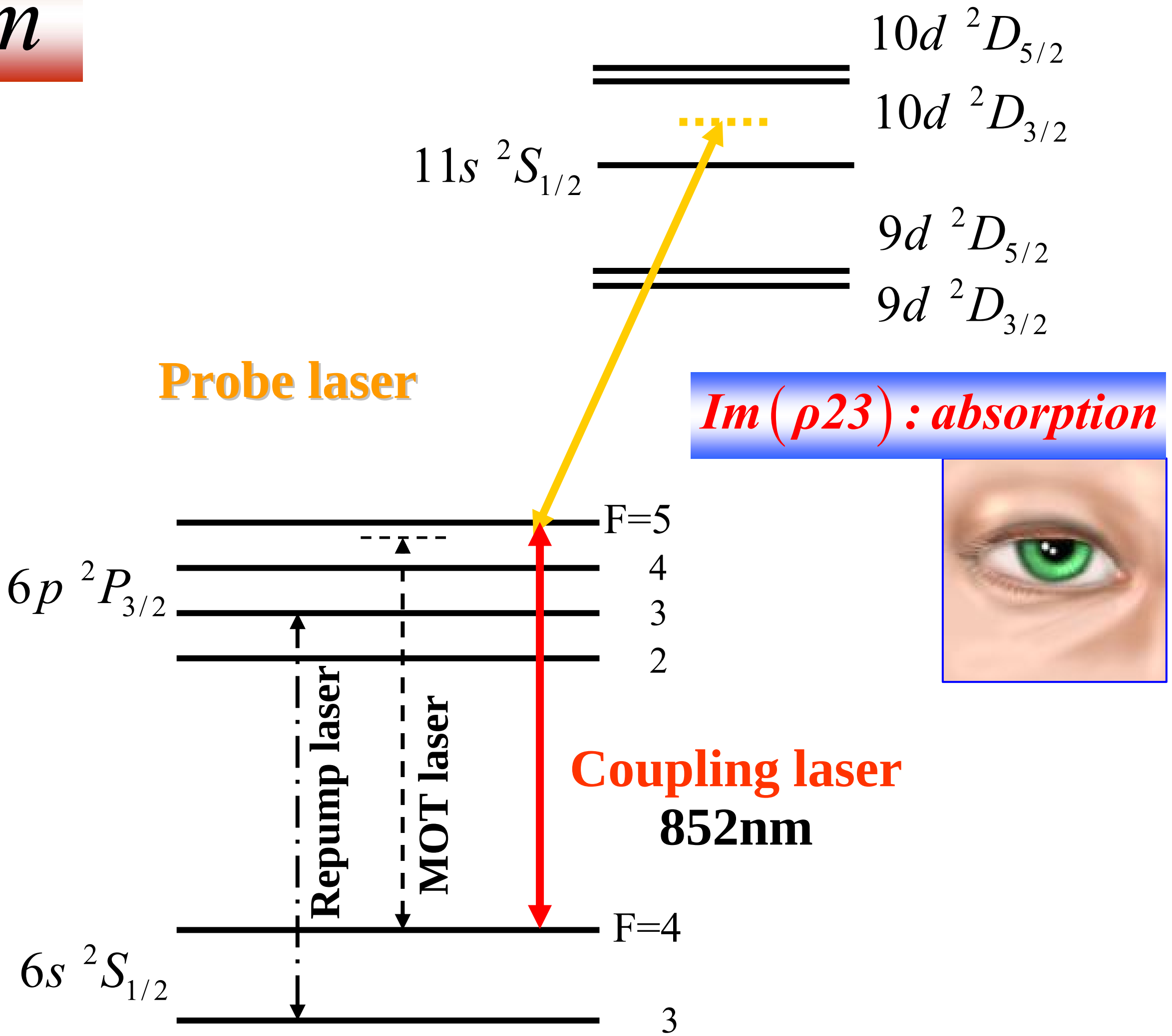
Atom number $4x10^9$, Cloud size 5 mm, Density $5x10^{10}/cm^3$

Atom temperature (Time of flight) : 100 μK

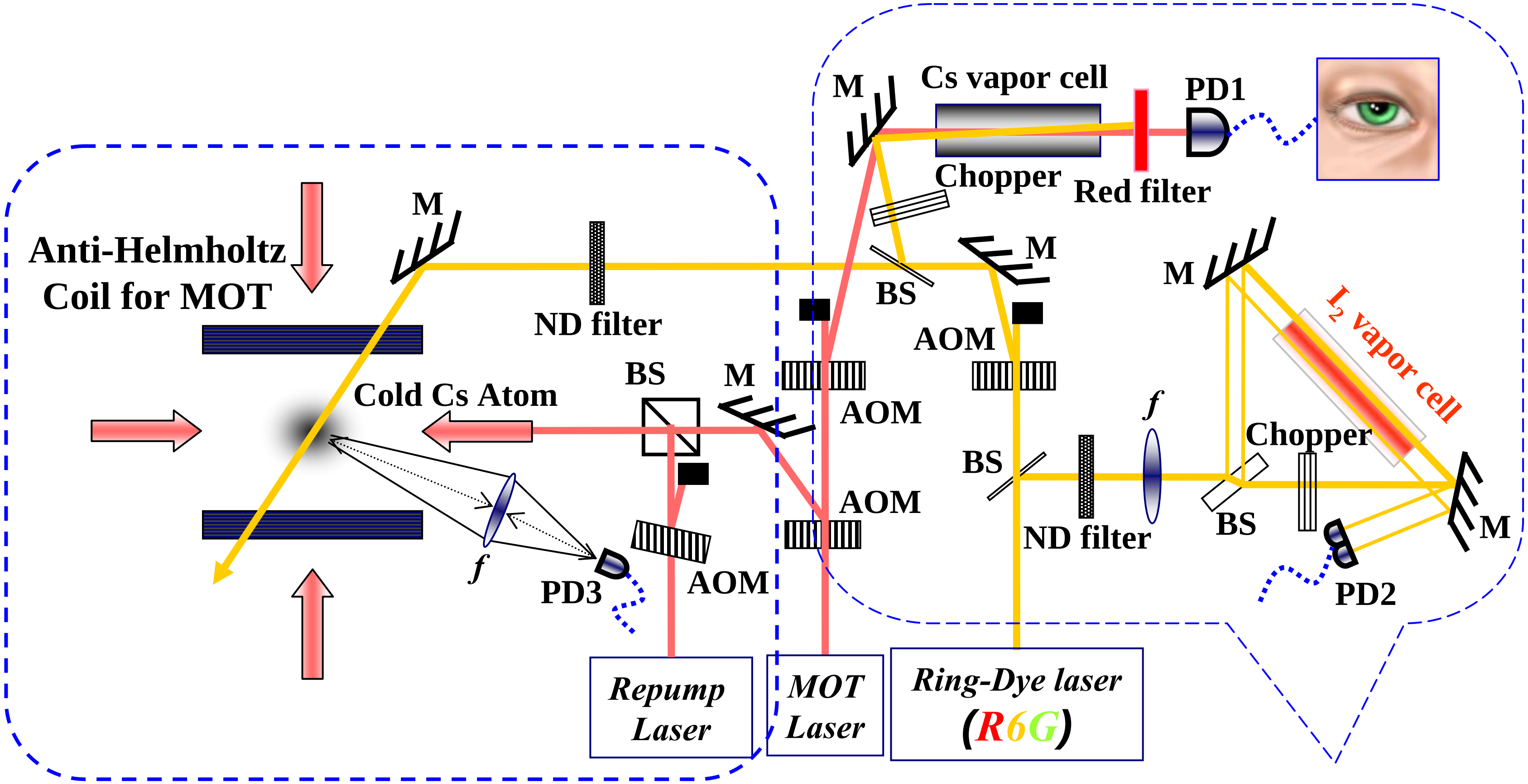


Energy level diagram

^{133}Cesium



Experimental Setup



EIT setup

Precision measurement

Visible Cs MOT

Visible Cs MOT :

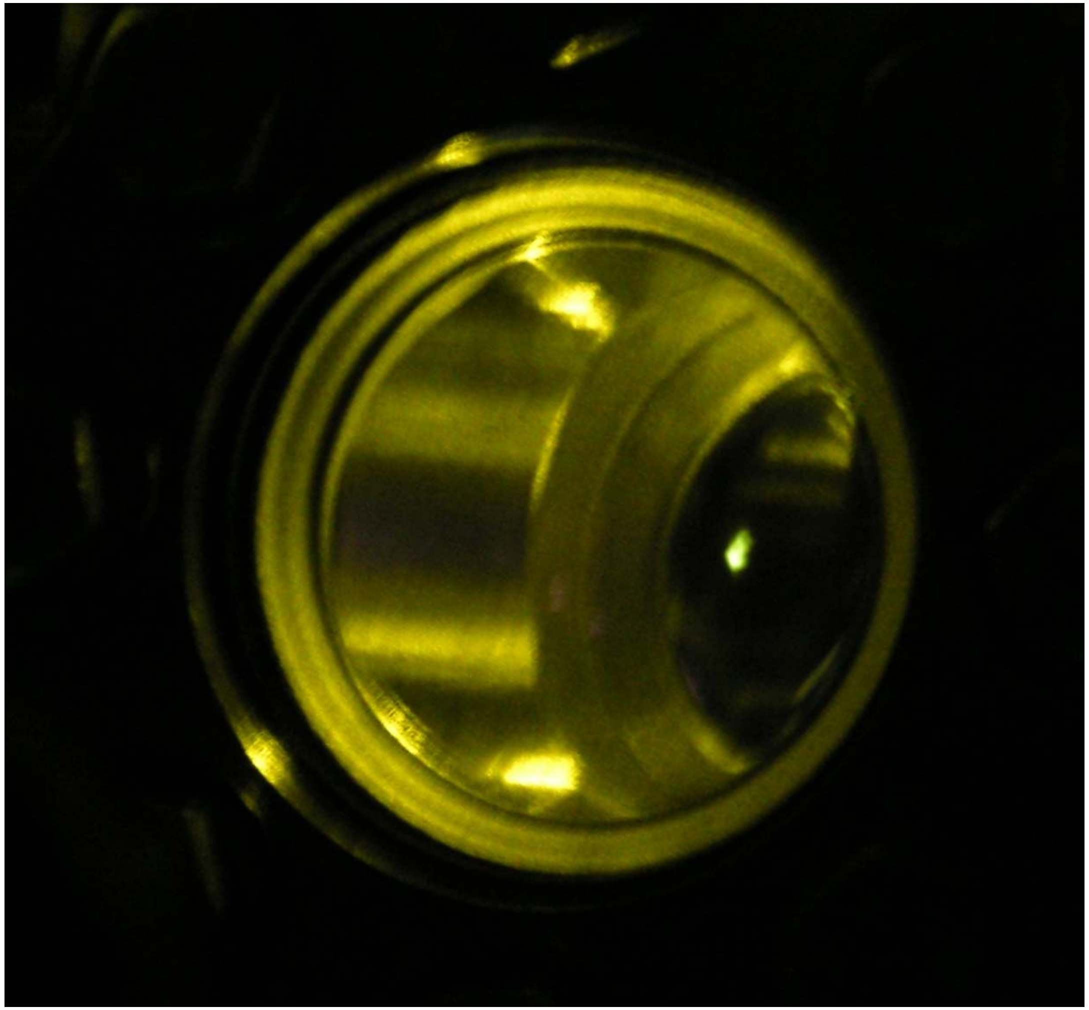
Probe laser transition

$\left|6p\ ^2P_{3/2}\right\rangle \rightarrow \left|10d\ ^2D_{5/2}\right\rangle$

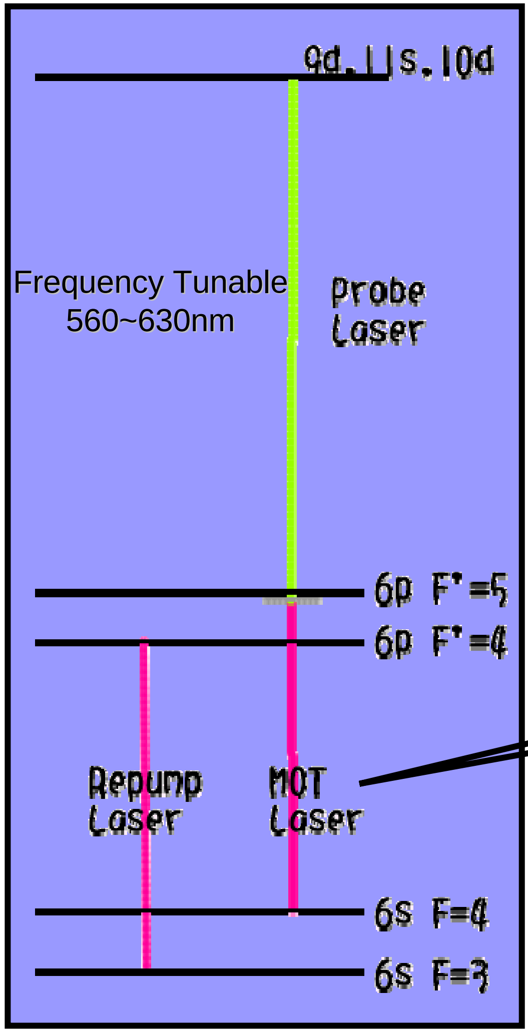
563.6nm

Atom number ~10^8

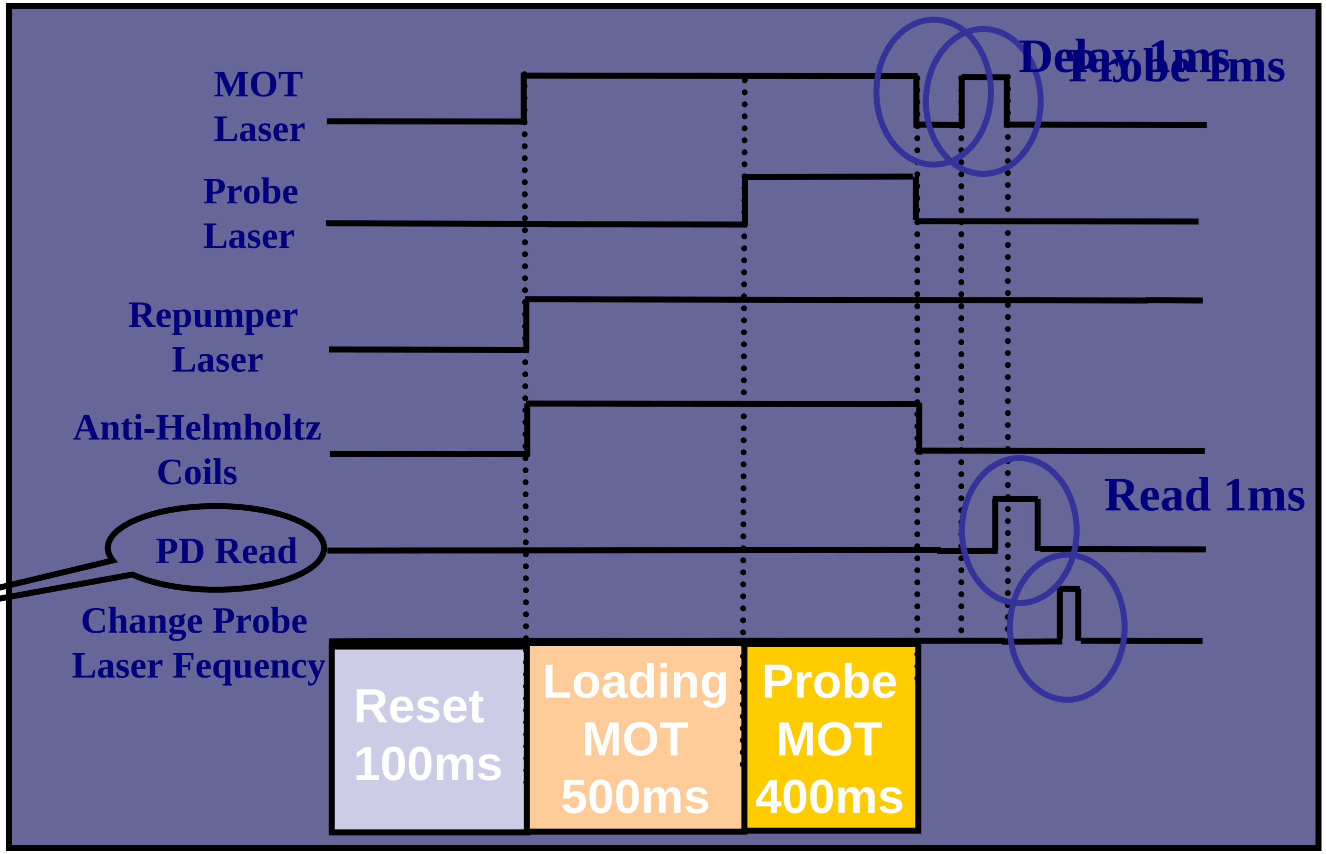
Temperature~200μK



Data Acquisition by External Scan

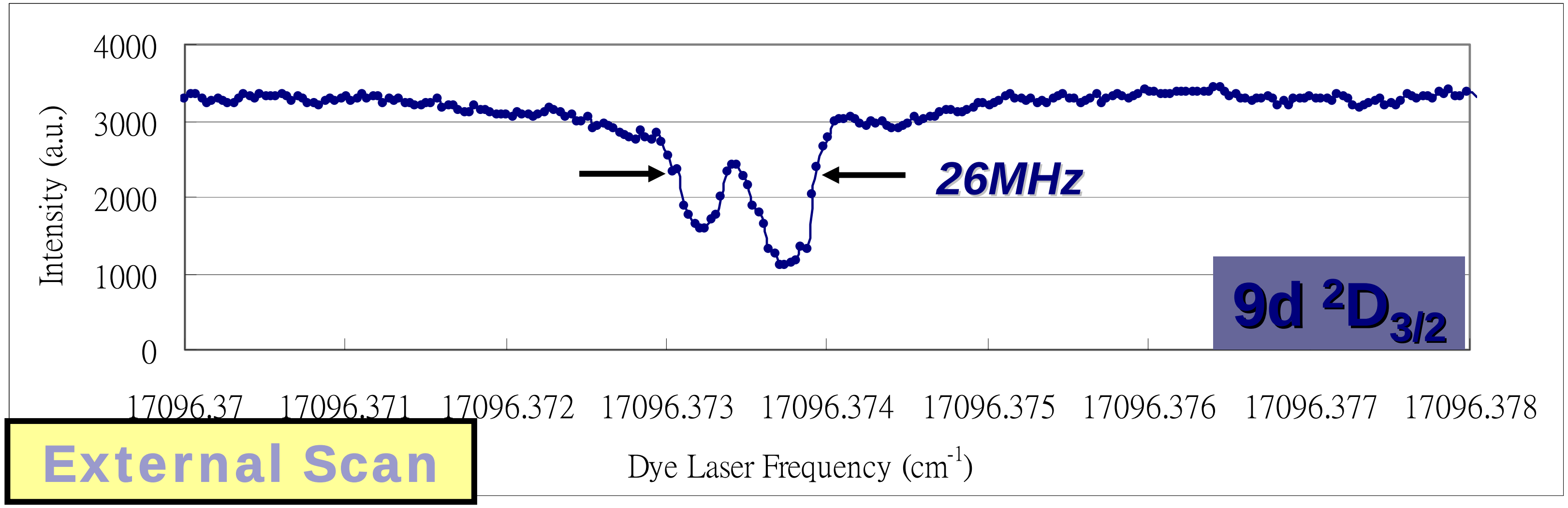


Trap Loss

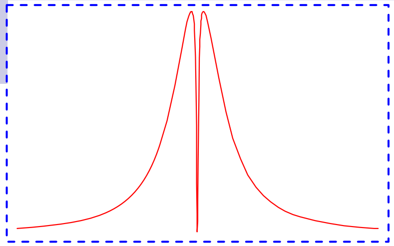


Atomic Transitions

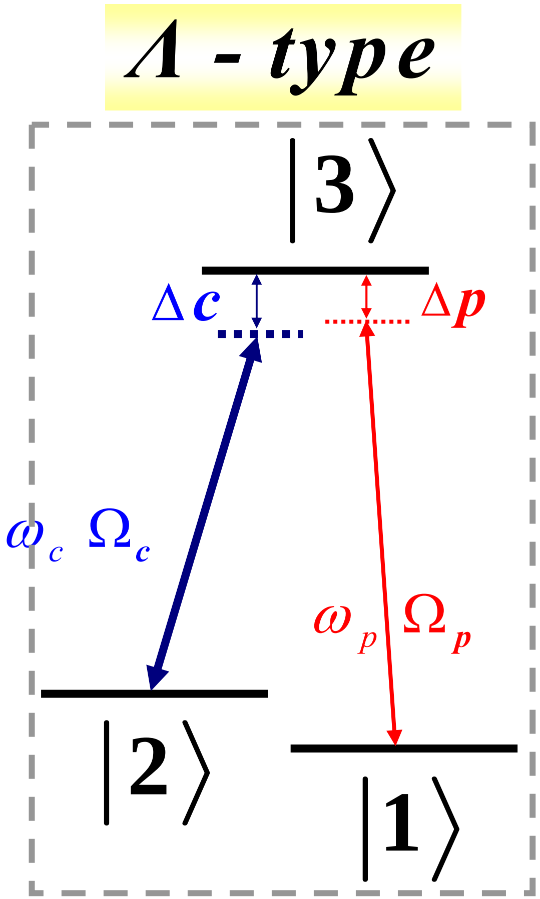
$$\left|6s\ ^2S_{1/2}, F=5\right\rangle \rightarrow \left|6p\ ^2P_{3/2}, F=4\right\rangle \rightarrow \left|9d\ ^2D_{5/2}, F\right\rangle$$

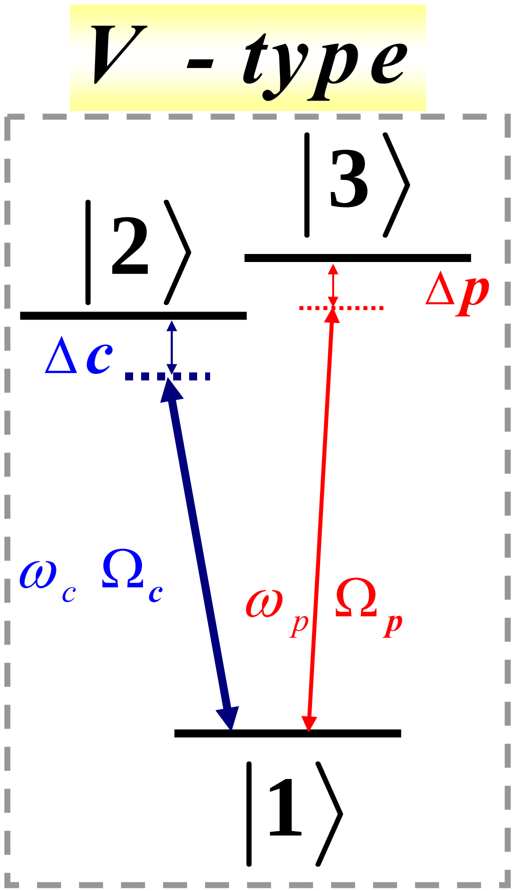


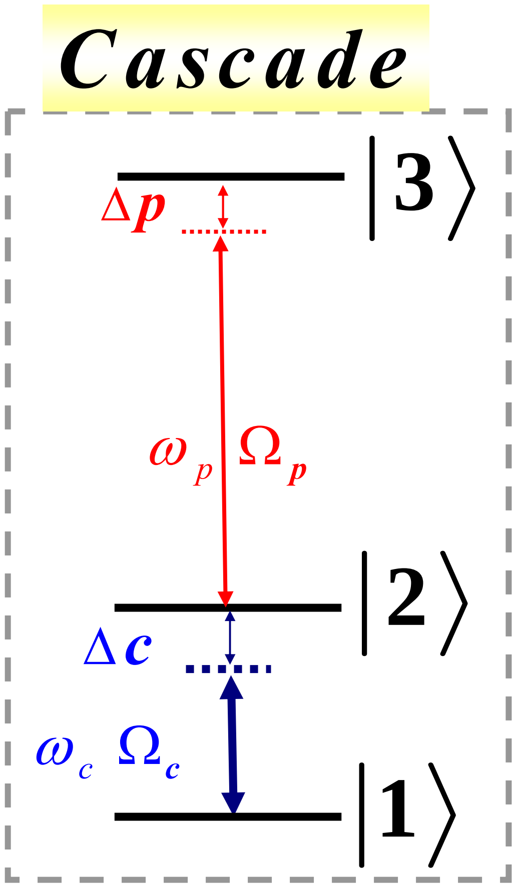
Electromagnetically Induced Transparency



Quantum Interference

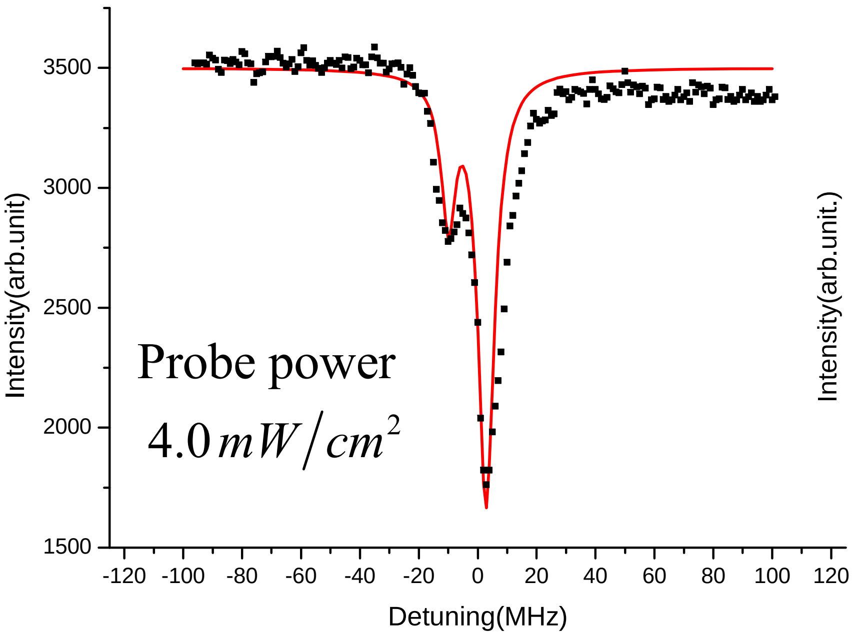


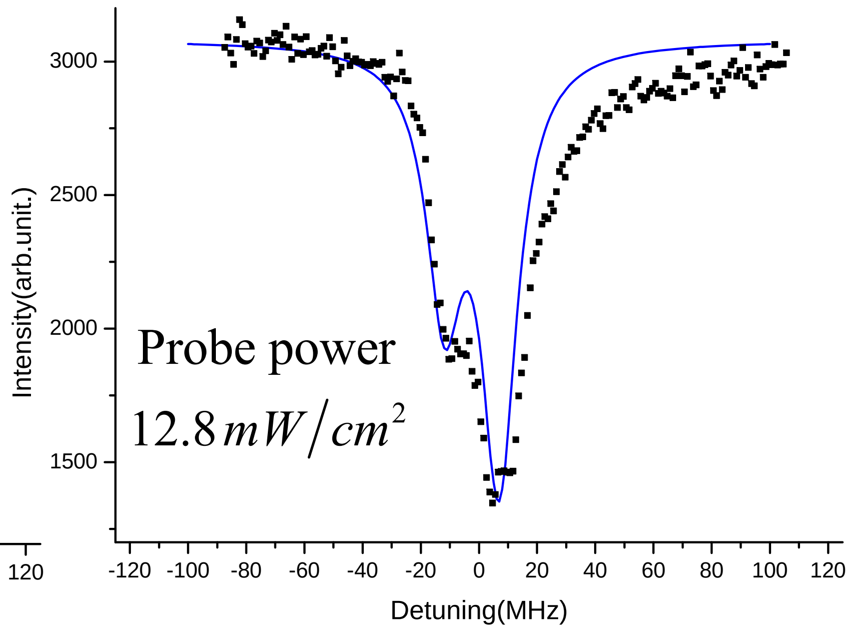




Numerical Simulation

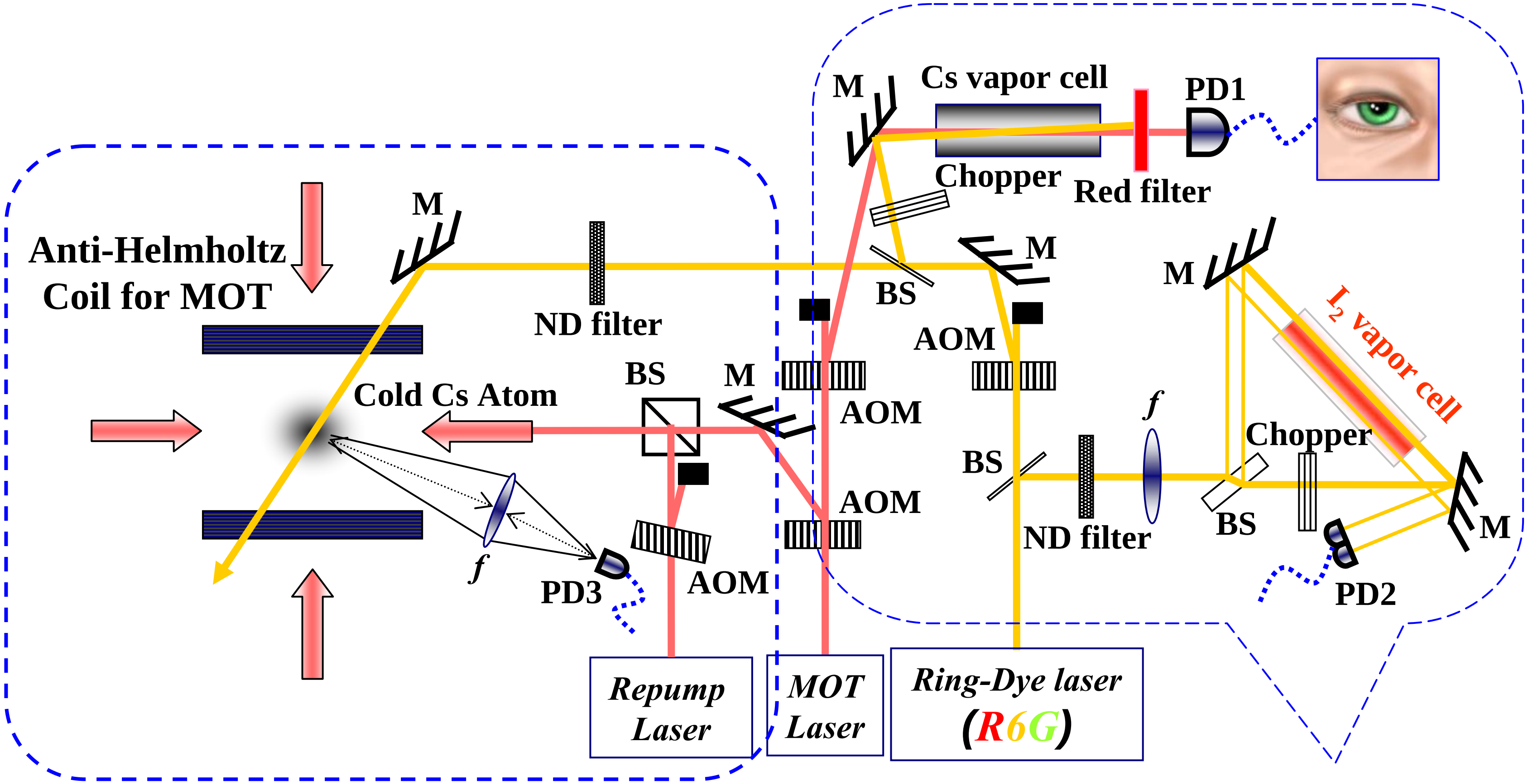
$$\left|6s\ ^2S_{1/2}, F=5\right\rangle \rightarrow \left|6p\ ^2P_{3/2}, F=4\right\rangle \rightarrow \left|11s\ ^2S_{1/2}, F\right\rangle,\ \text{wc: 10mW/cm}^2$$





γ_2=5.2MHz, γ_3=2.5MHz, wc=3MHz, wp=1MHz, Δc=-10MHz Ωc=20MHz

Experimental Setup

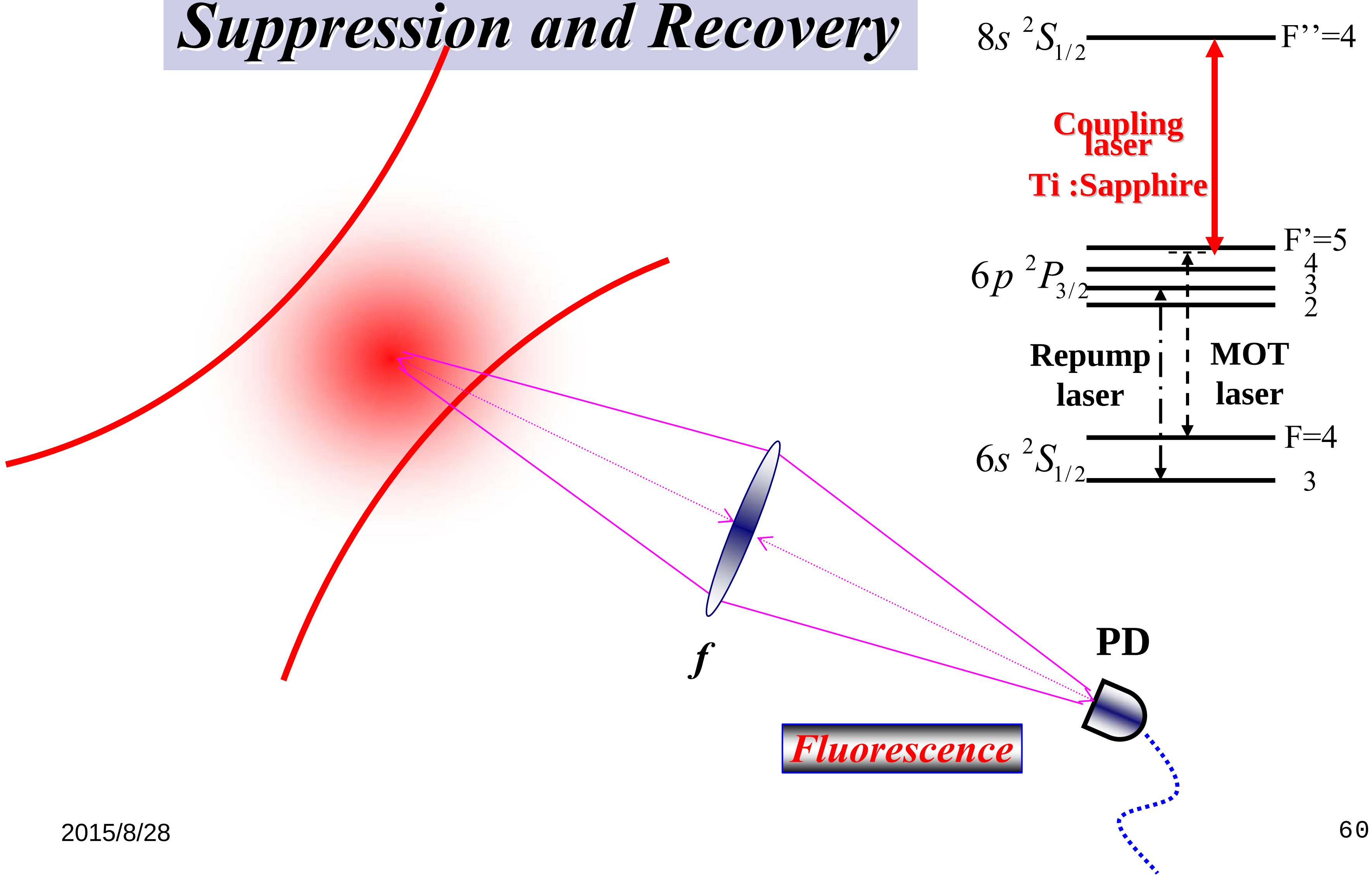


EIT setup

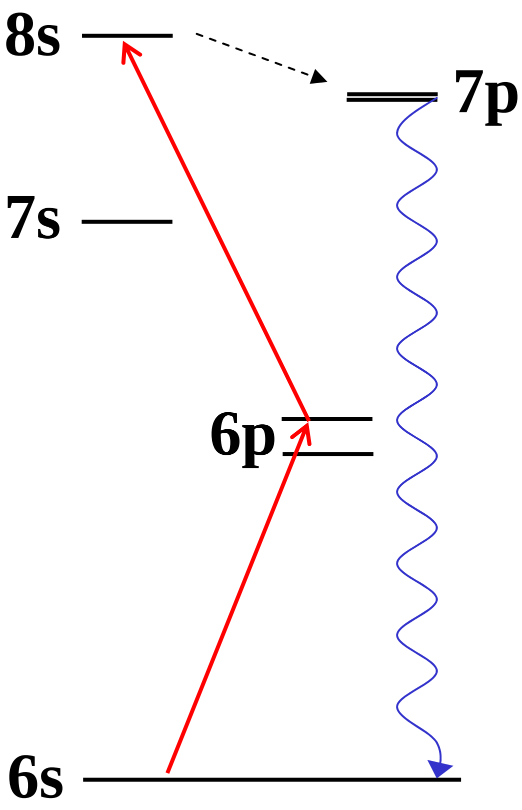
Precision measurement

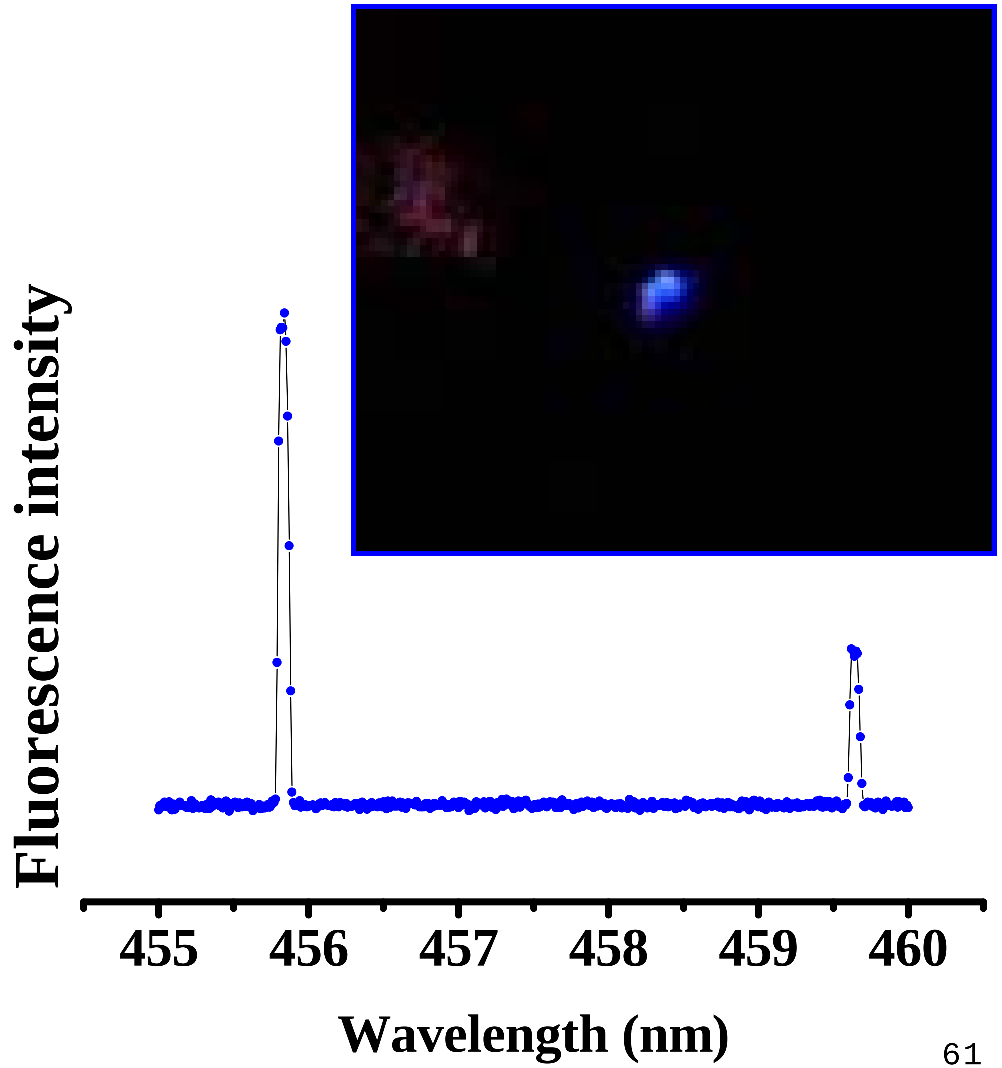
Quantum Decoherence

Suppression and Recovery

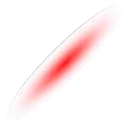


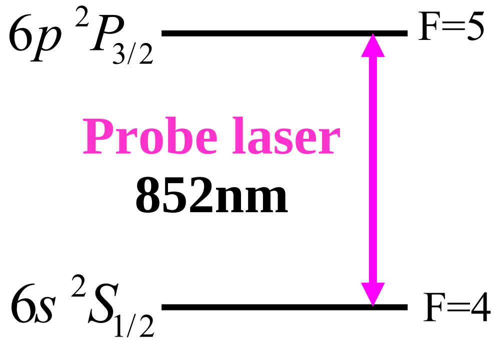
Decay fluorescence



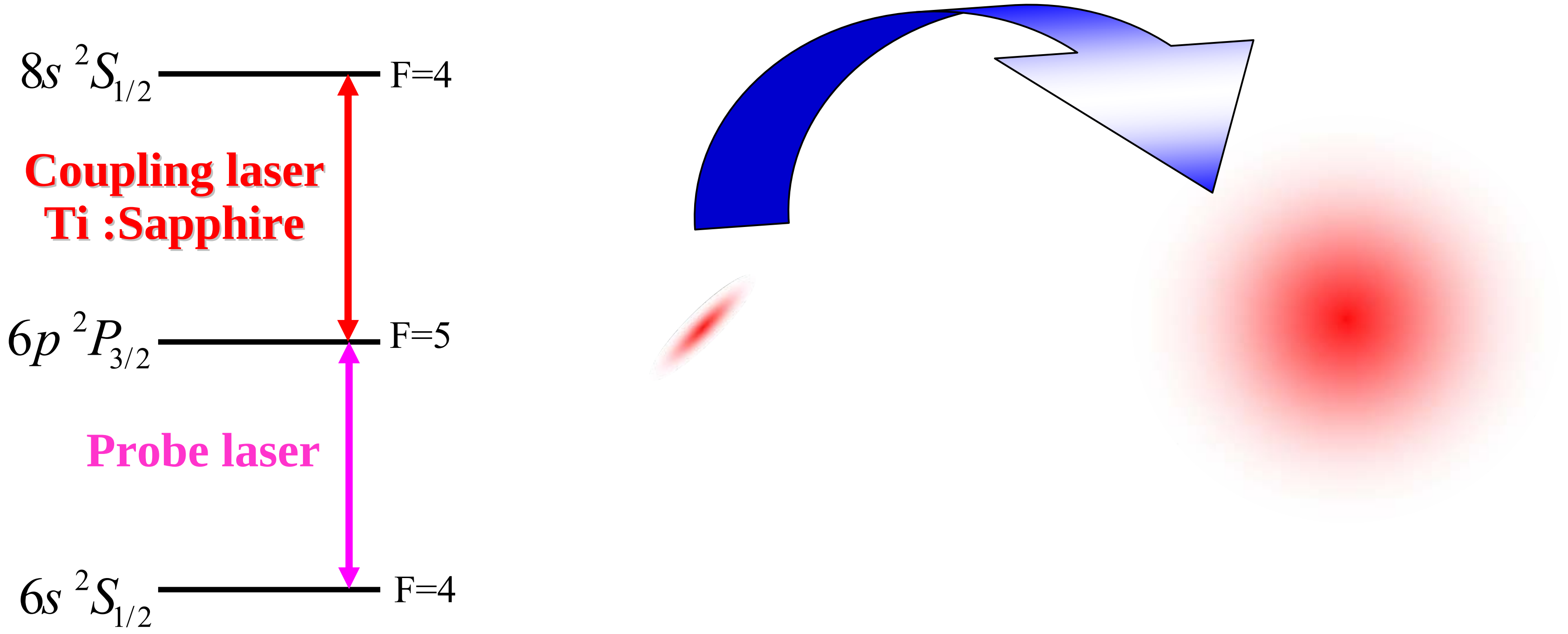


Suppression

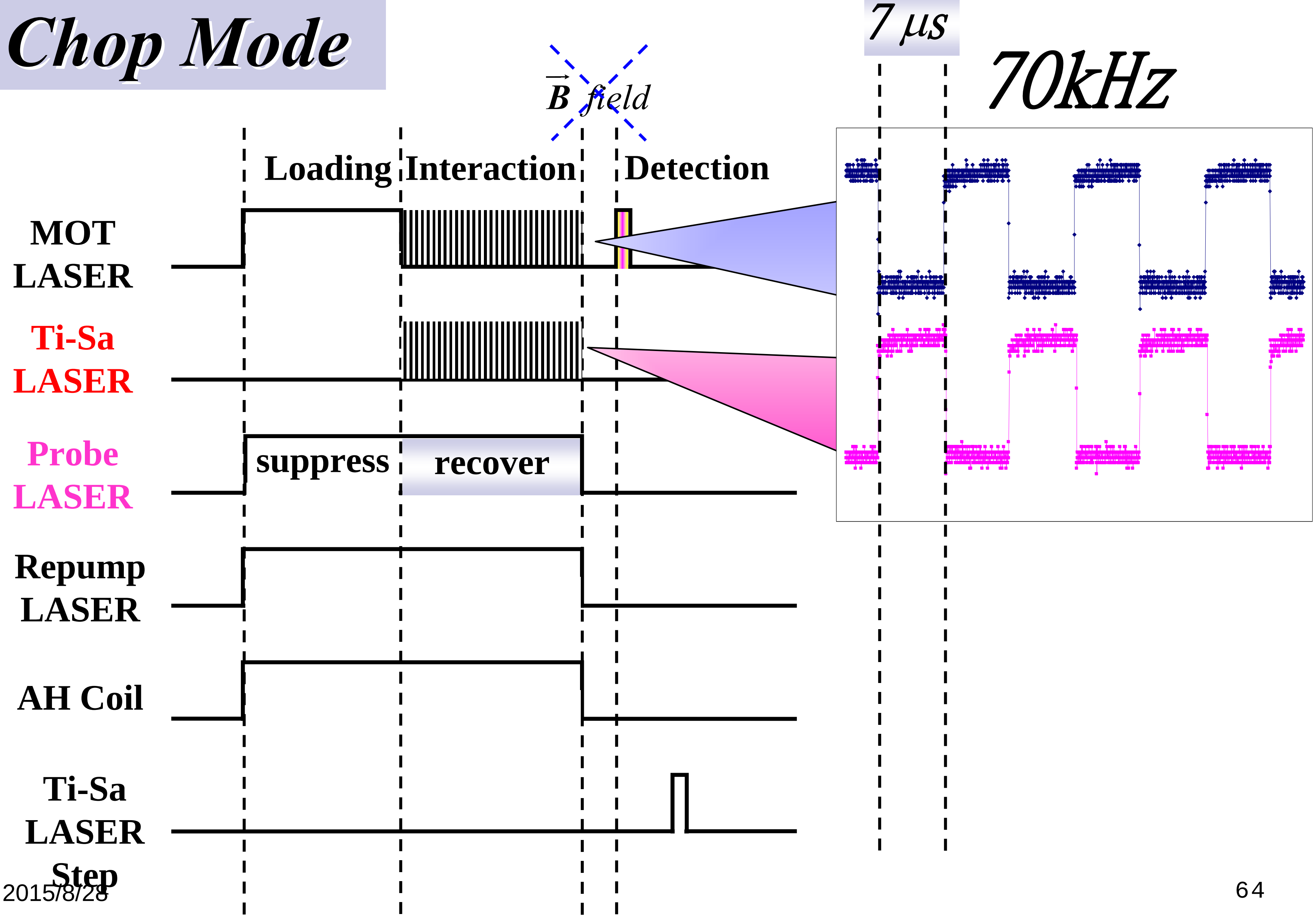




Suppression & Recovery

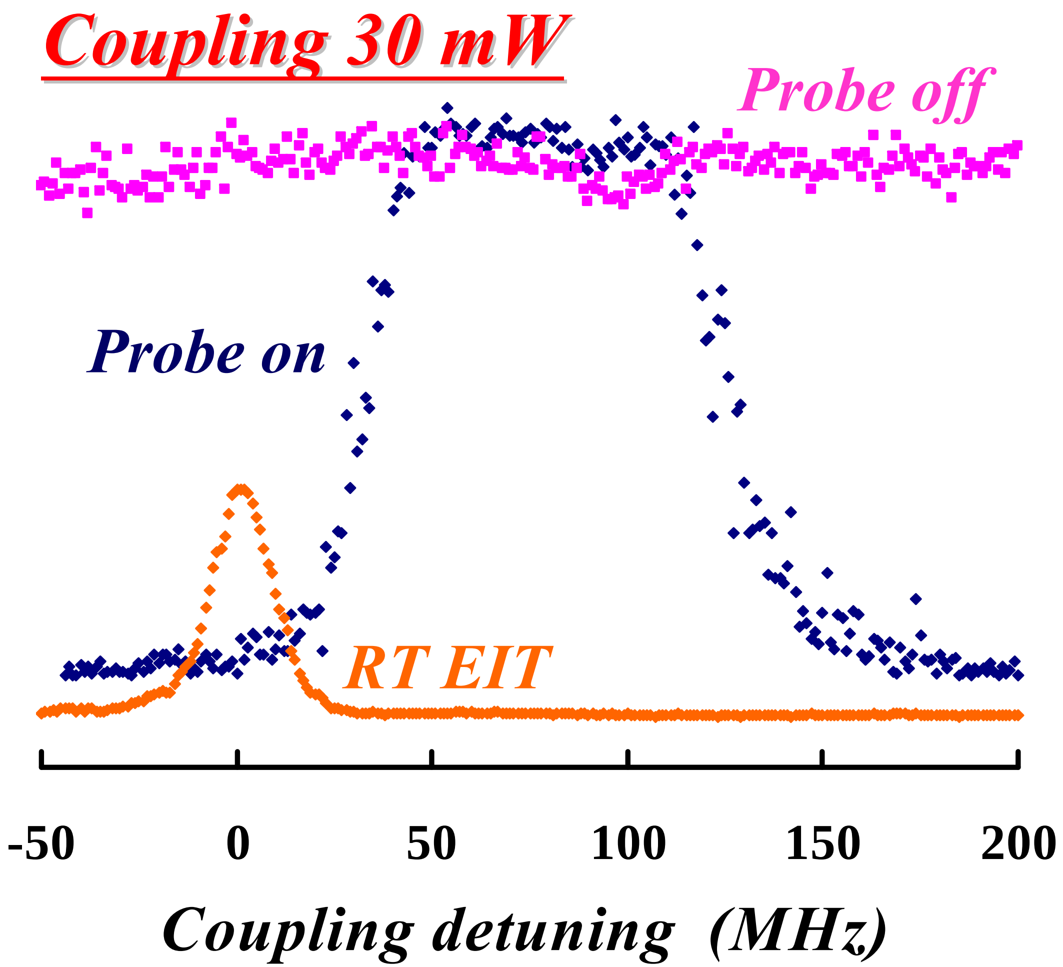


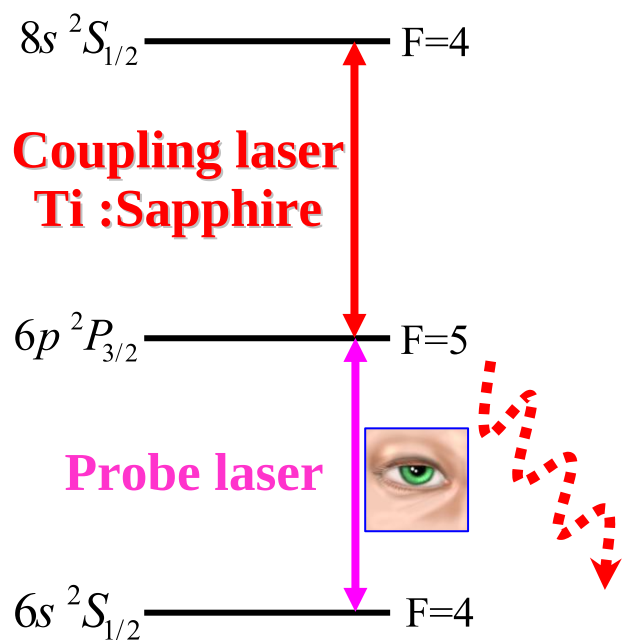
Chop Mode



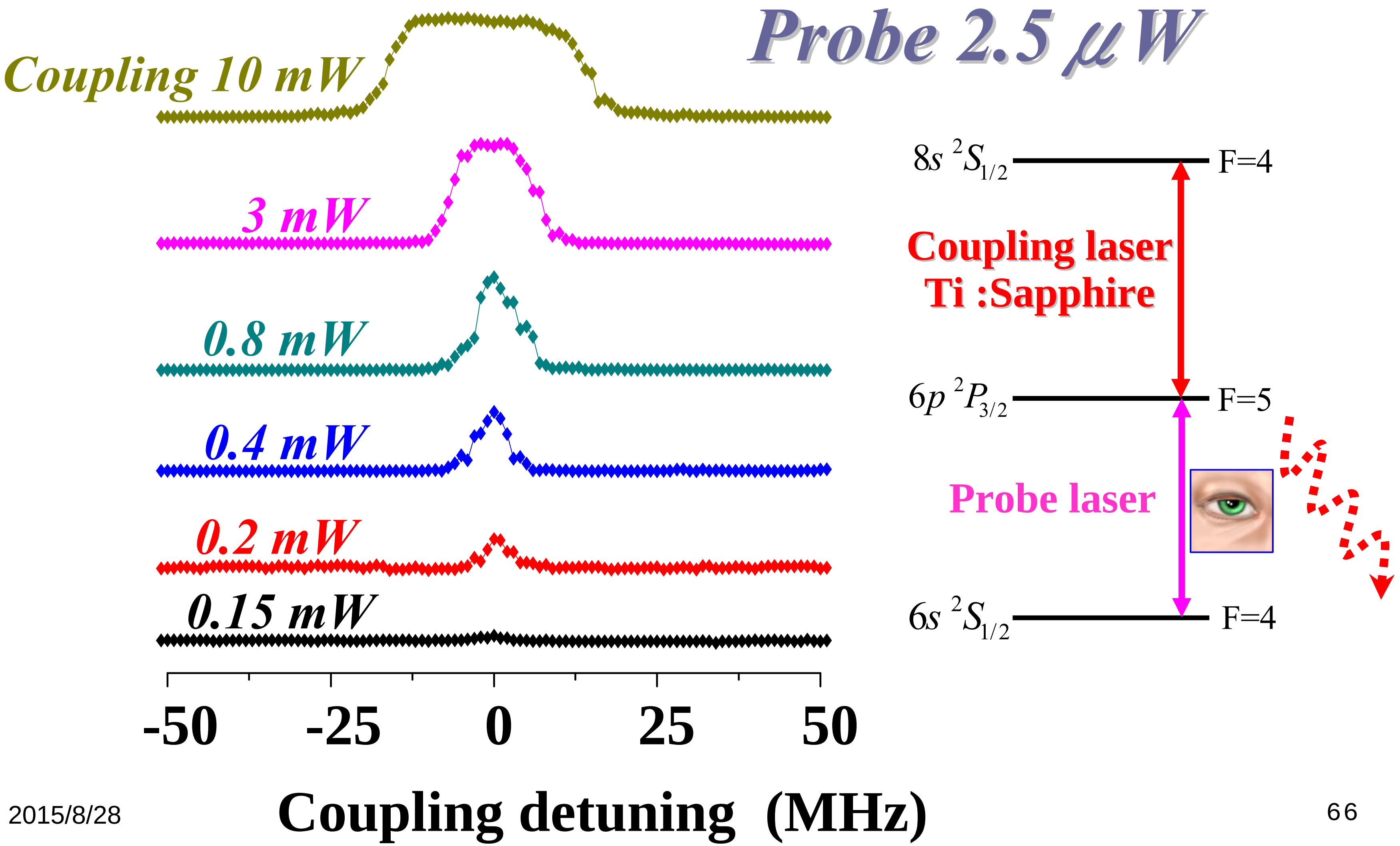
7 μs
70kHz
B field
Loading
Interaction
Detection
MOT
LASER
Ti-Sa
LASER
Probe
LASER
suppress
recover
Repump
LASER
AH Coil
Ti-Sa
LASER
Step

Suppression & Recovery

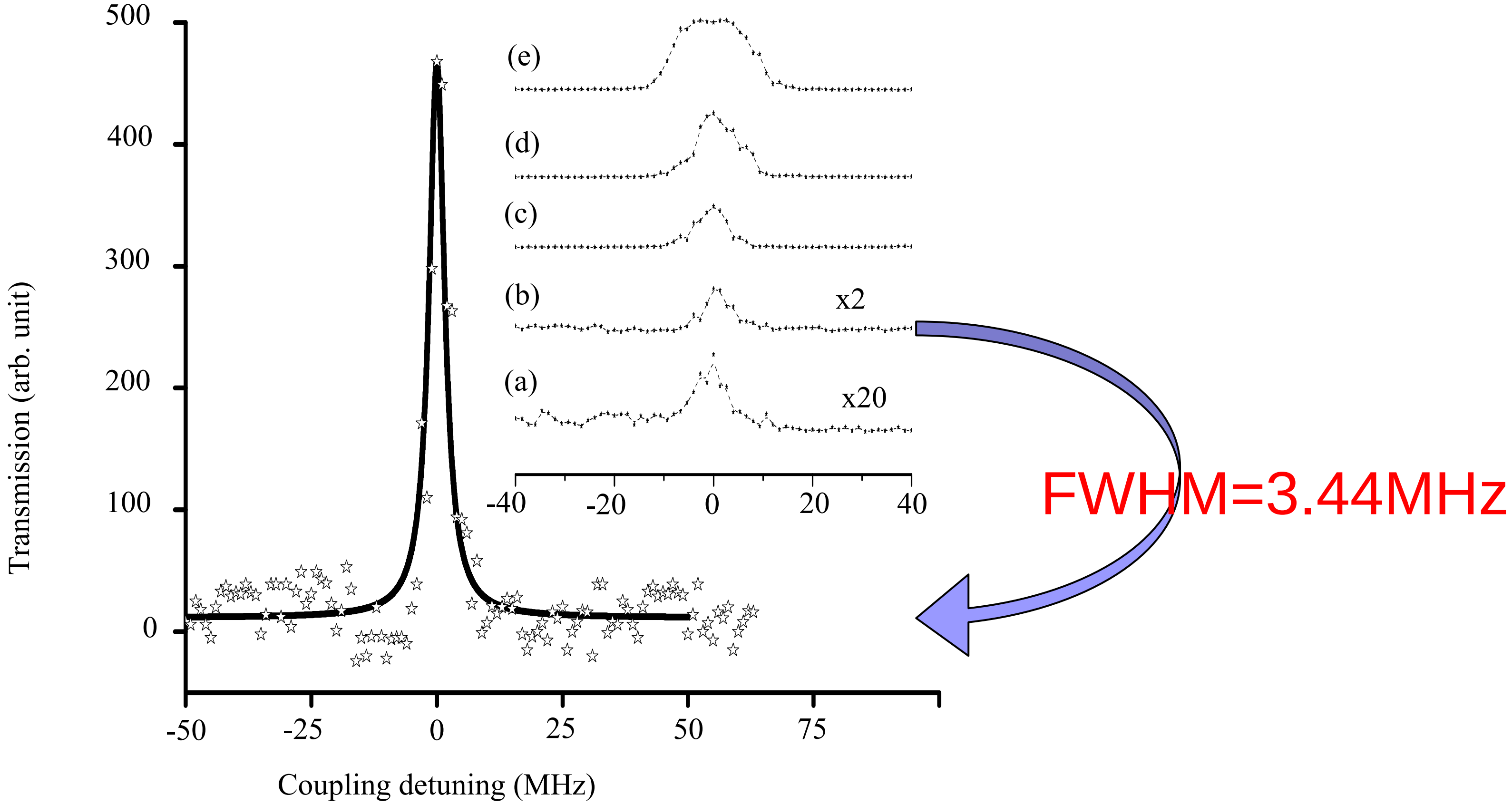




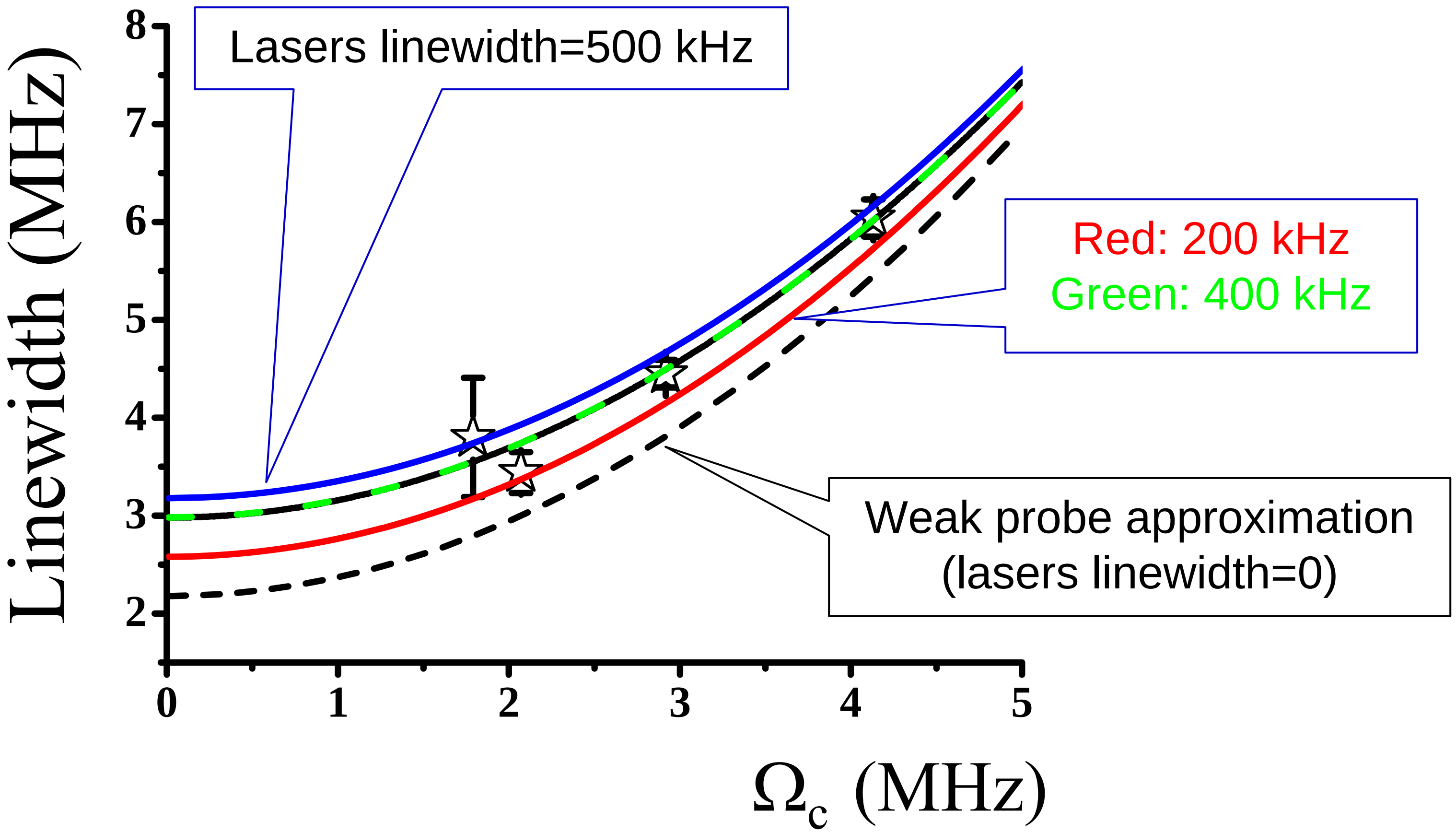
Power dependence



Power dependence



Linewidth vs. coupling Rabi frequency

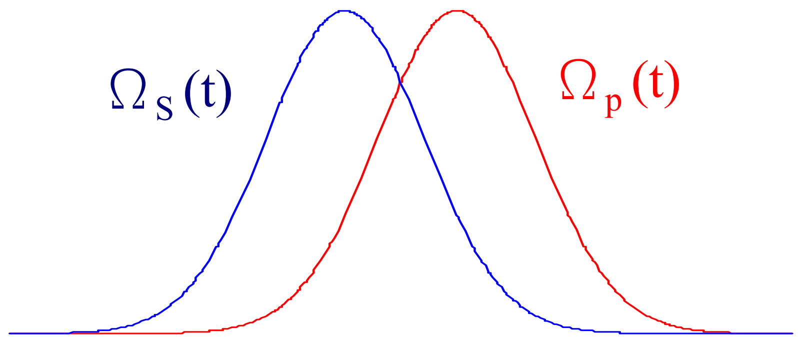


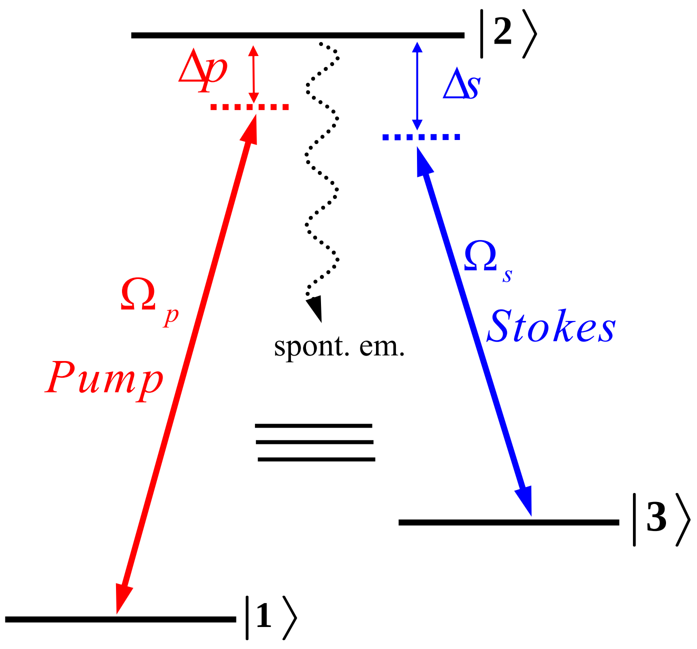
Laser linewidth is a de-coherence source.

Quantum Interference in Cold Cs

Stimulated Raman Adiabatic Passage (STIRAP)

STIRAP





$$H(t)=\frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P(t) & 2\Delta_P & \Omega_S(t) \\ 0 & \Omega_S(t) & 2(\Delta_P-\Delta_S) \end{bmatrix}$$

$$\begin{cases} |a^+\rangle=\sin\Theta\,\sin\Phi|1\rangle+\cos\Phi|2\rangle+\cos\Theta\,\sin\Phi|3\rangle, \\ |a^0\rangle=\cos\Theta|1\rangle-\sin\Theta|3\rangle, \\ |a^-\rangle=\sin\Theta\,\cos\Phi|1\rangle-\sin\Phi|2\rangle+\cos\Theta\,\cos\Phi|3\rangle, \end{cases}$$

$$\begin{cases} \omega^+=\Delta_P+\sqrt{\Delta_P^2+\Omega_P^2+\Omega_S^2}, \quad \omega^0=0, \\ \omega^-=\Delta_P-\sqrt{\Delta_P^2+\Omega_P^2+\Omega_S^2}. \end{cases}$$

$$\tan\Theta=\frac{\Omega_P(t)}{\Omega_S(t)}$$

mixing angle

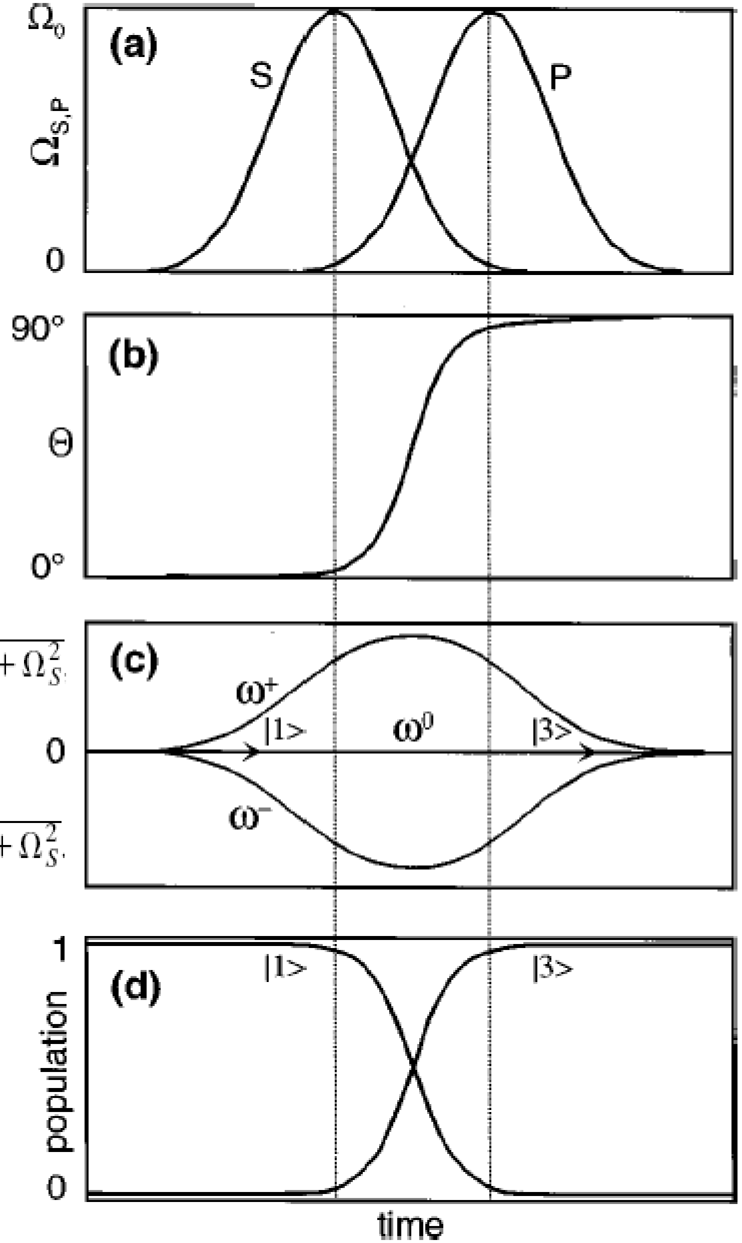
Reviews of Modern Physics, Vol. 70, No. 3, July 1998

$$\tan\Theta = \frac{\Omega_P(t)}{\Omega_S(t)}$$

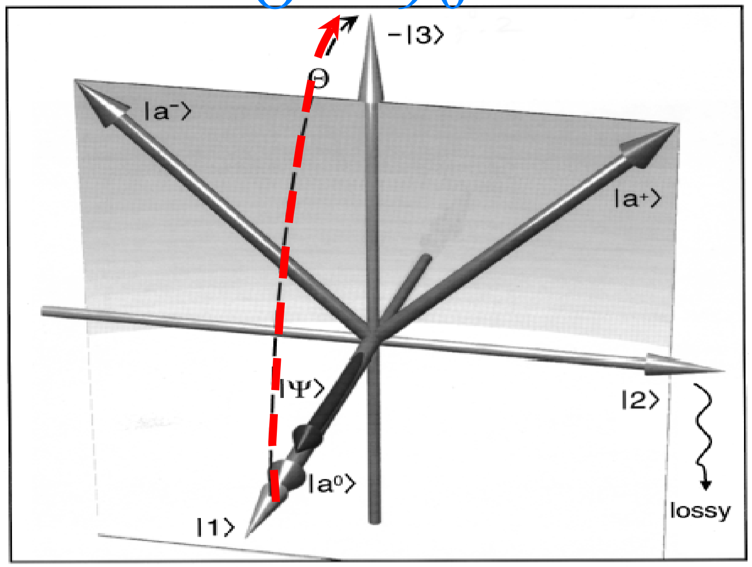
$$\omega^+ = \Delta_P + \sqrt{\Delta_P^2 + \Omega_P^2 + \Omega_S^2}$$

$$\omega^0 = 0$$

$$\omega^- = \Delta_P - \sqrt{\Delta_P^2 + \Omega_P^2 + \Omega_S^2}$$

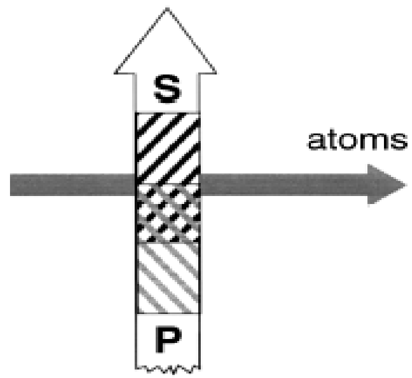


$\Theta = 90^o$



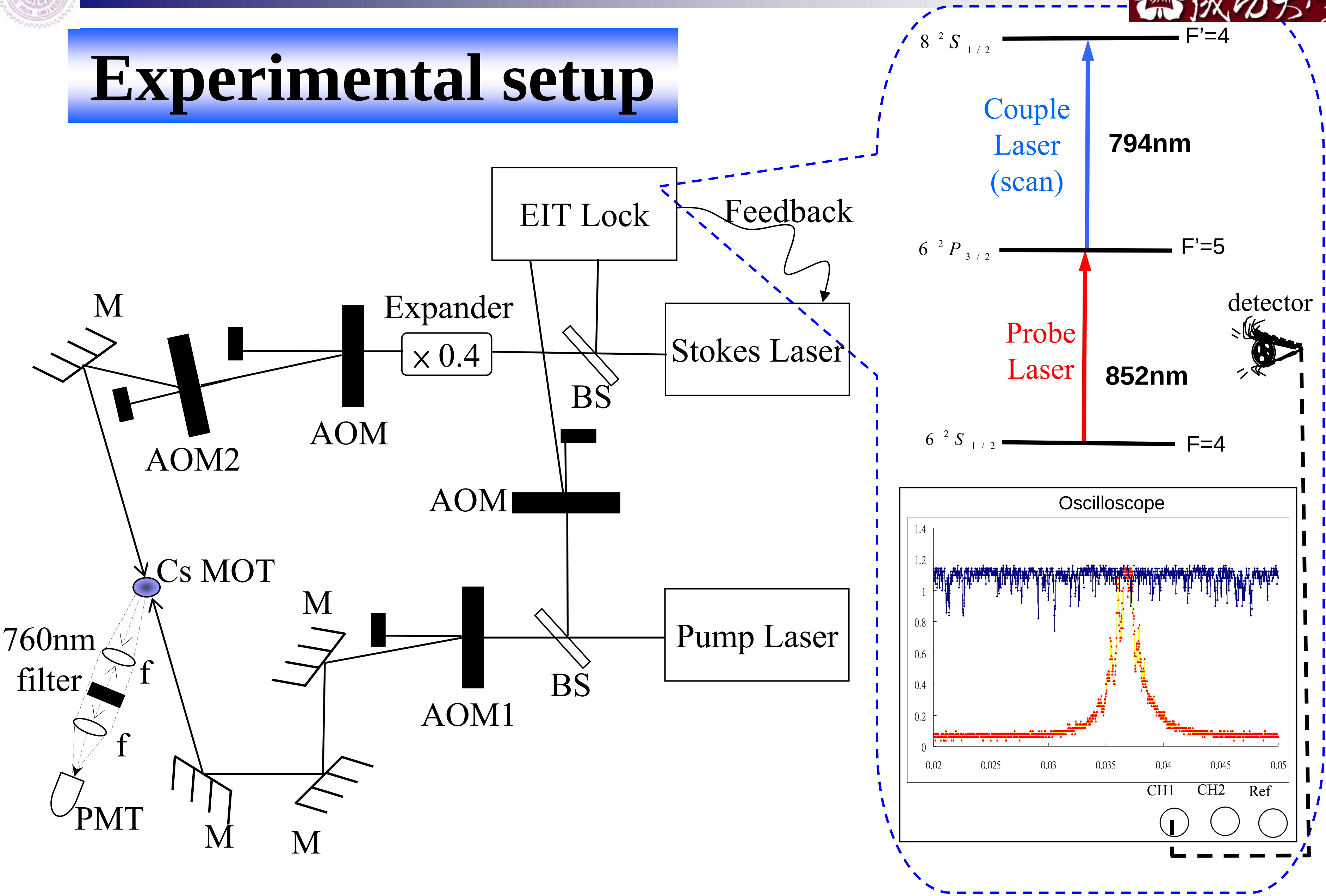
$\Theta = 0$

pulsed

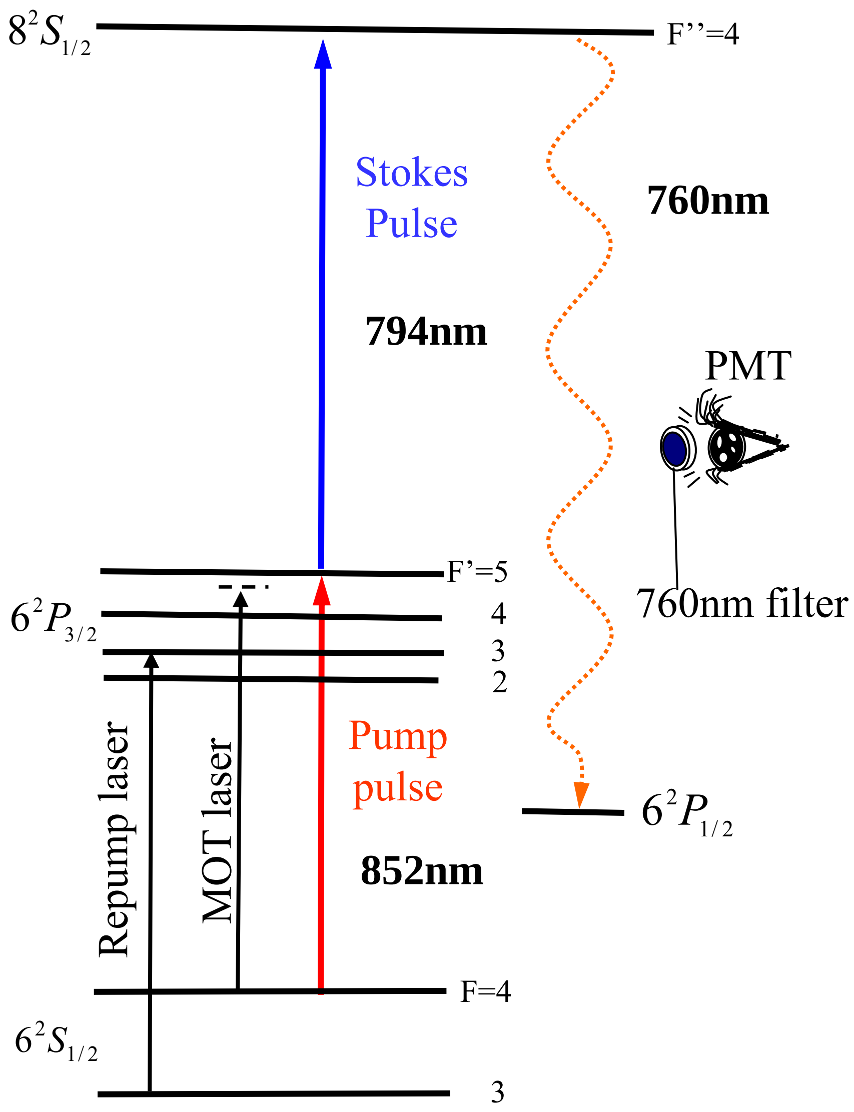


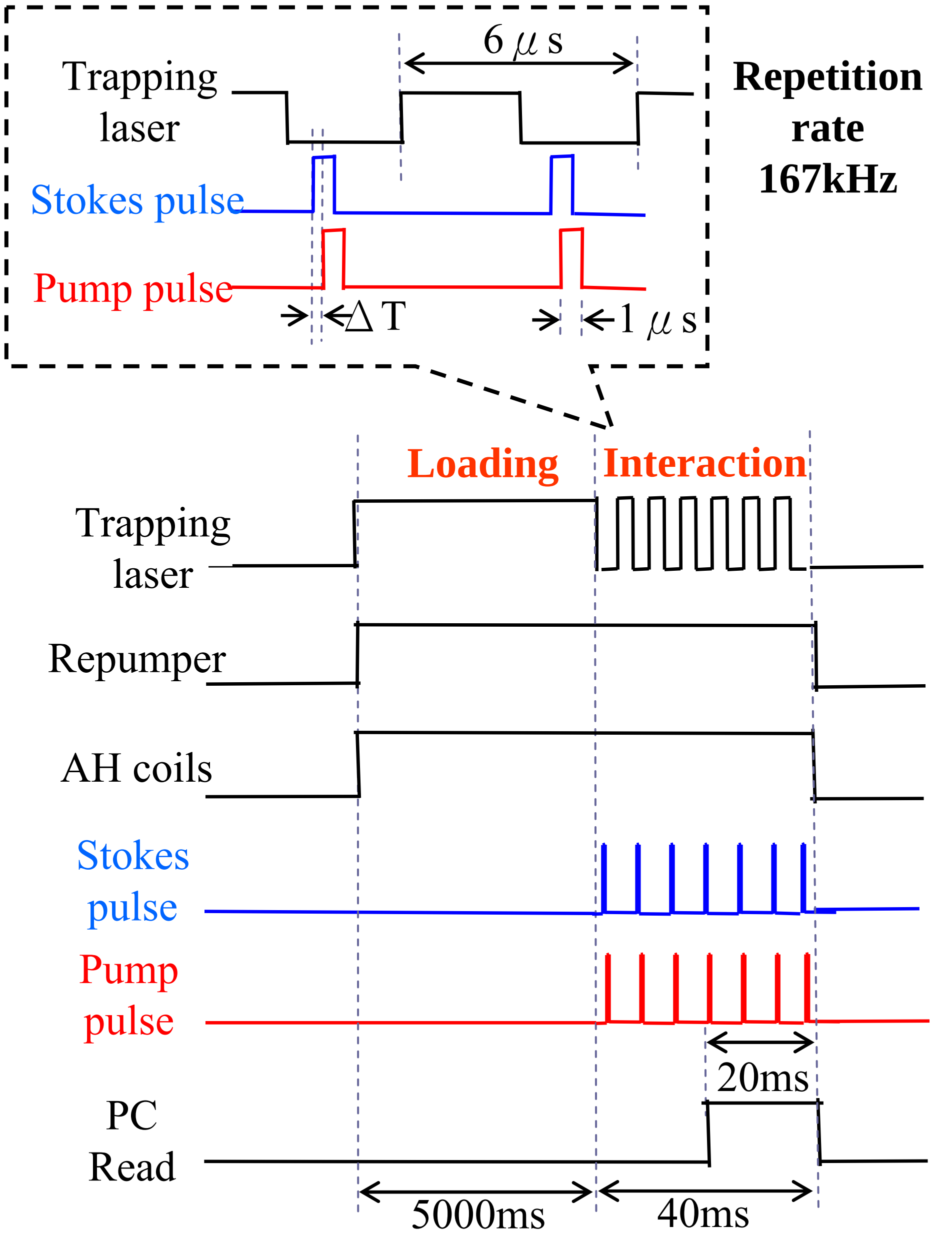
Reviews of Modern Physics, Vol. 70, No. 3, July 1998

Experimental setup

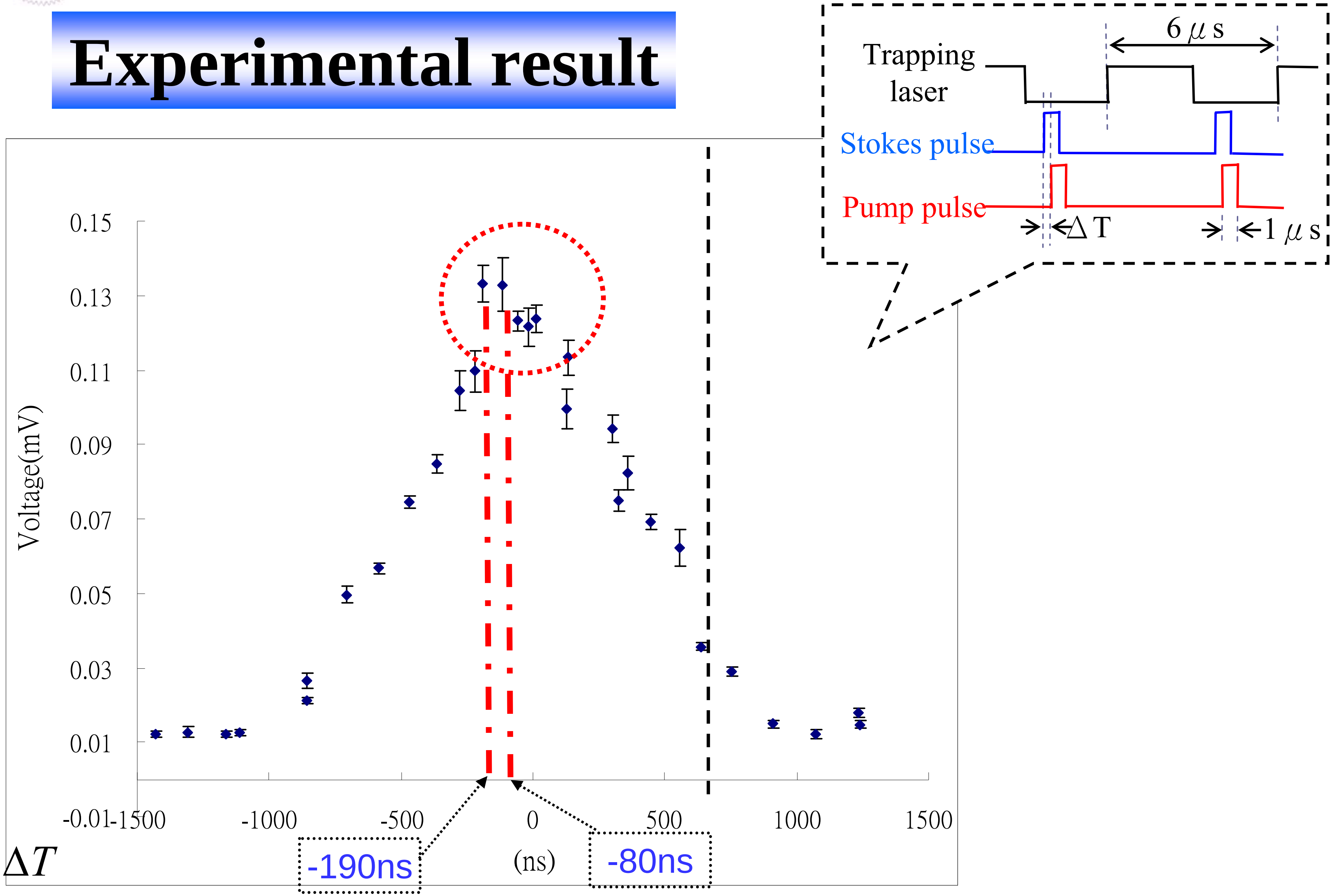


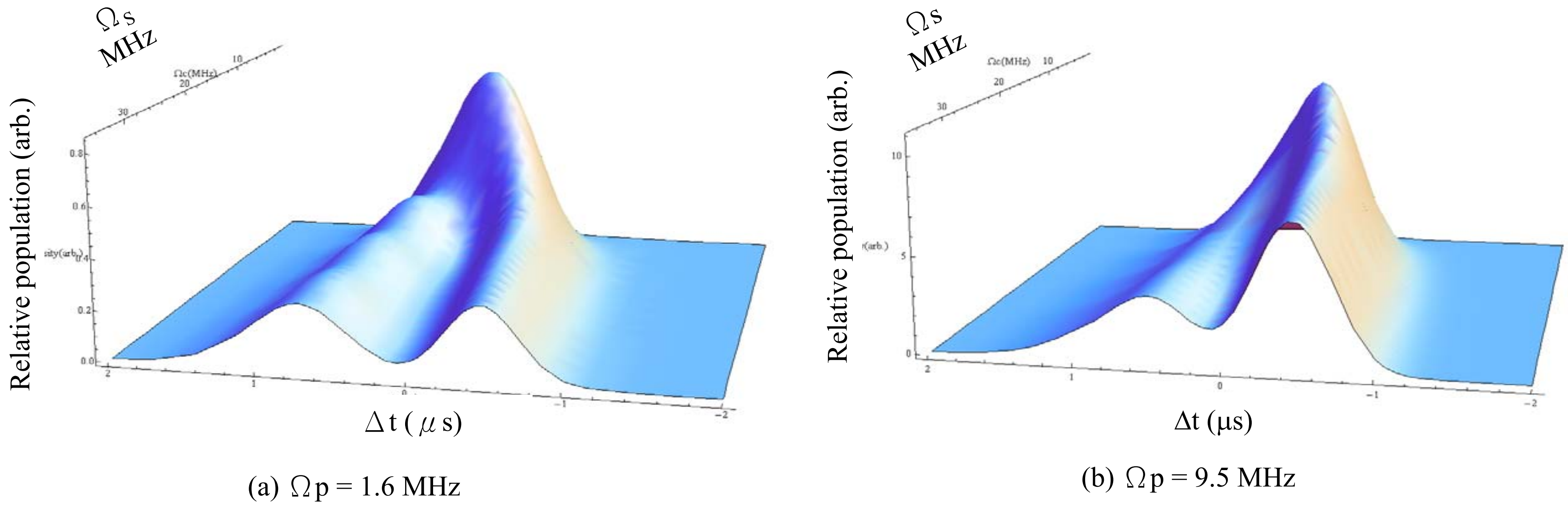
time sequence



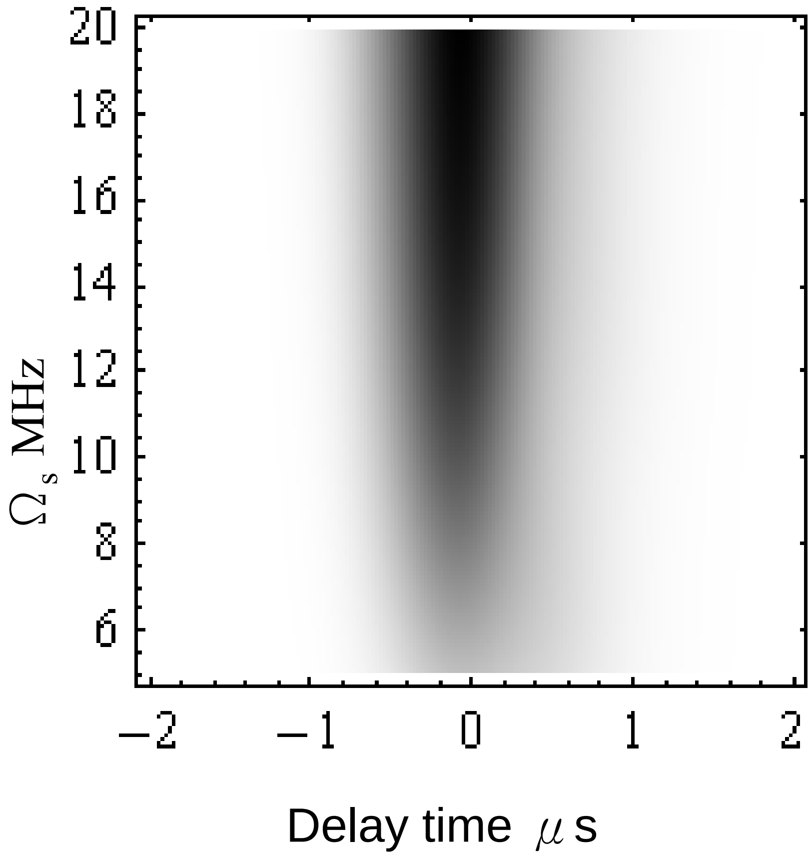


Experimental result

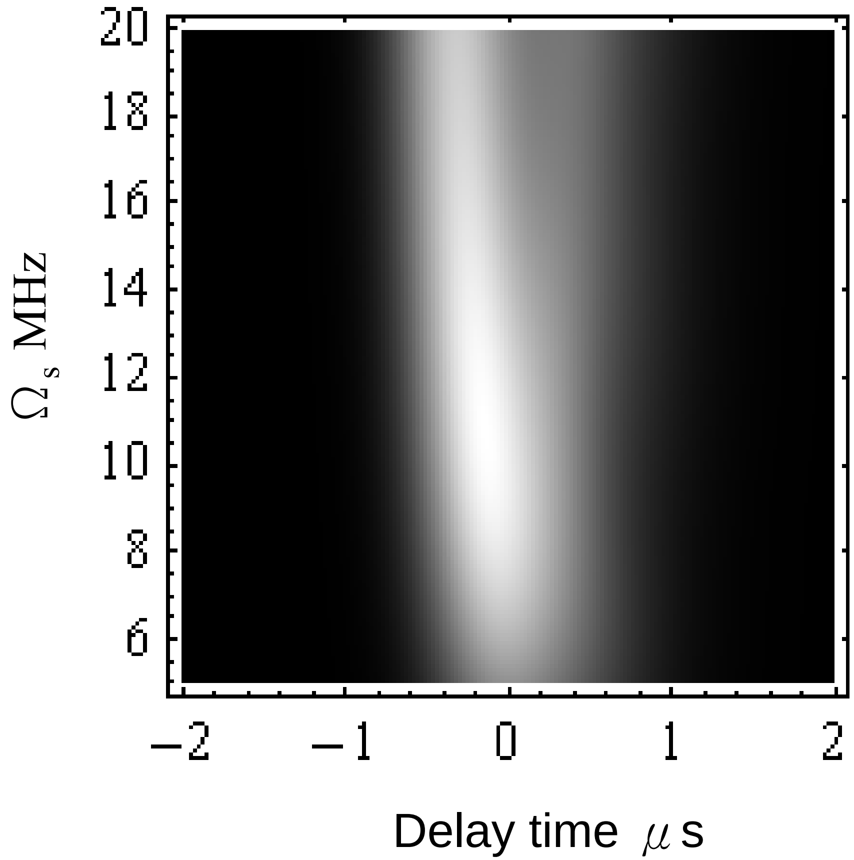




Contour of the relative populations as functions of Ω_S and delay time for (a) Ωp=1.6 MHz and (b) Ωp=9.5 MHz,



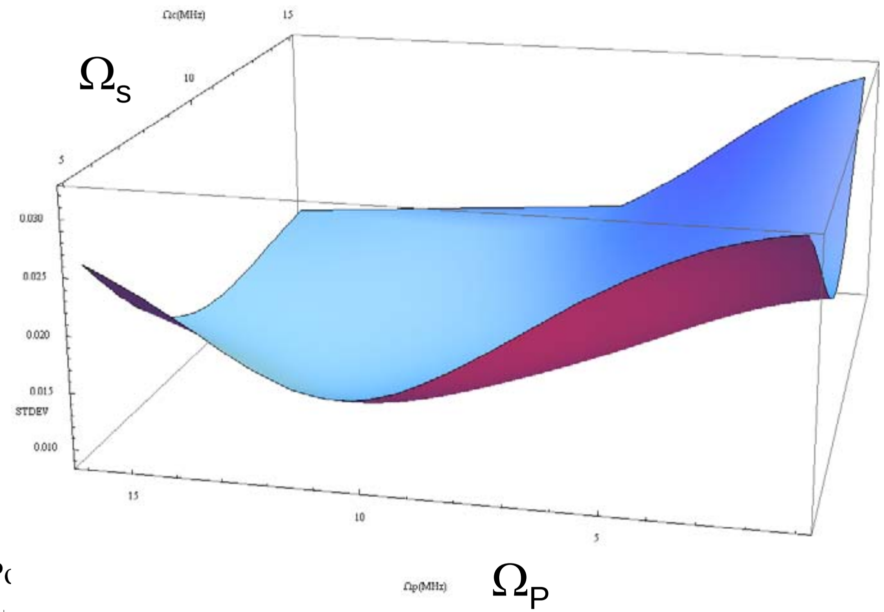
ρ_{22} population



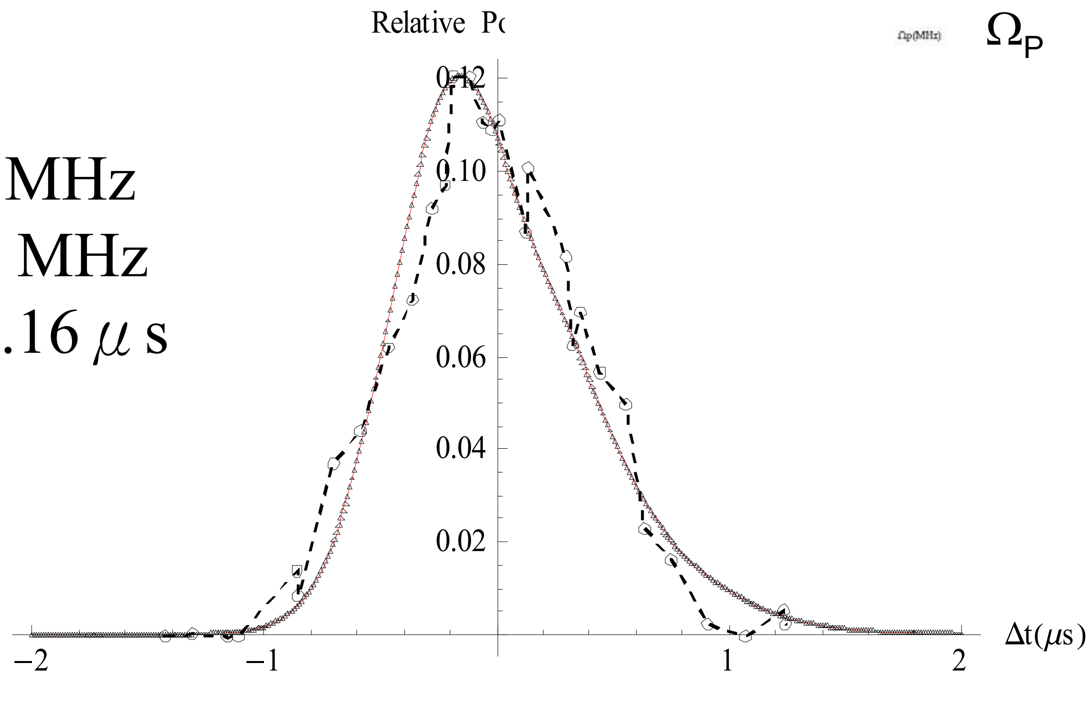
ρ_{33} population

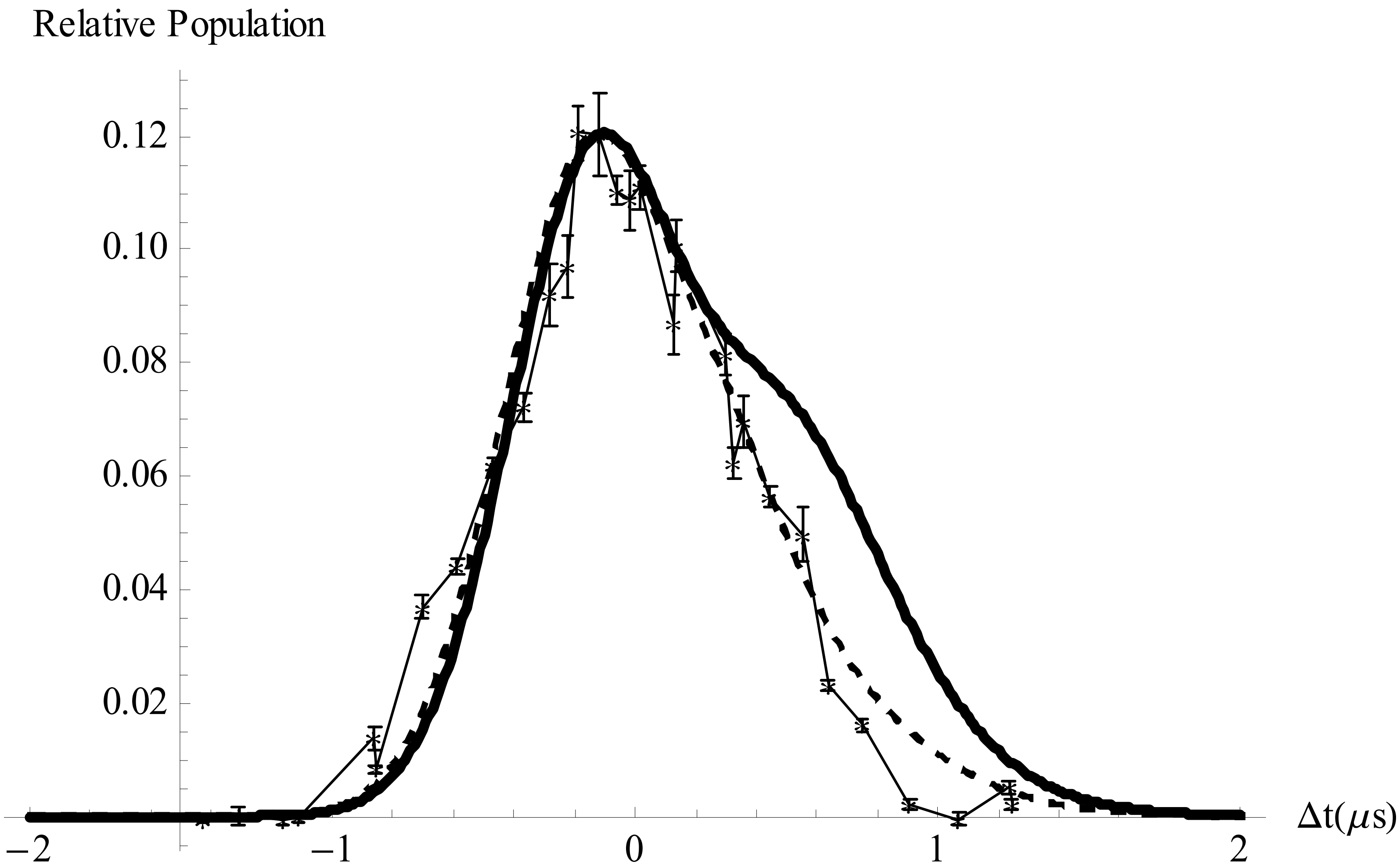
STDEV vs. Ωs & Ωp

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N}(Exp_n - Simu_n)^2}{N-1}}$$



Ωp = 9.5 MHz
Ωs = 10.0 MHz
Δt_{mas} = -0.16 μs





Minimized STDEV simulation: Ωp = 9.5 MHz and Ωs = 10.0 MHz.

The thick line is another simulation: Ωp =3.1 MHz and Ωs =11.5 MHz.

Summery

** Quantum Phenomena in diatomic molecule*

Tunnelling, Avoided-crossing, Feno Resonance

** Quantum Phenomena in Cold Atoms*

Shape Resonance, Feshbach Resonance, EIT/Decoherence, STIRAP

Group Reunion