Photon Switching by Quantum Interference

— from Reduction of the Light Speed to Quantum Teleportation

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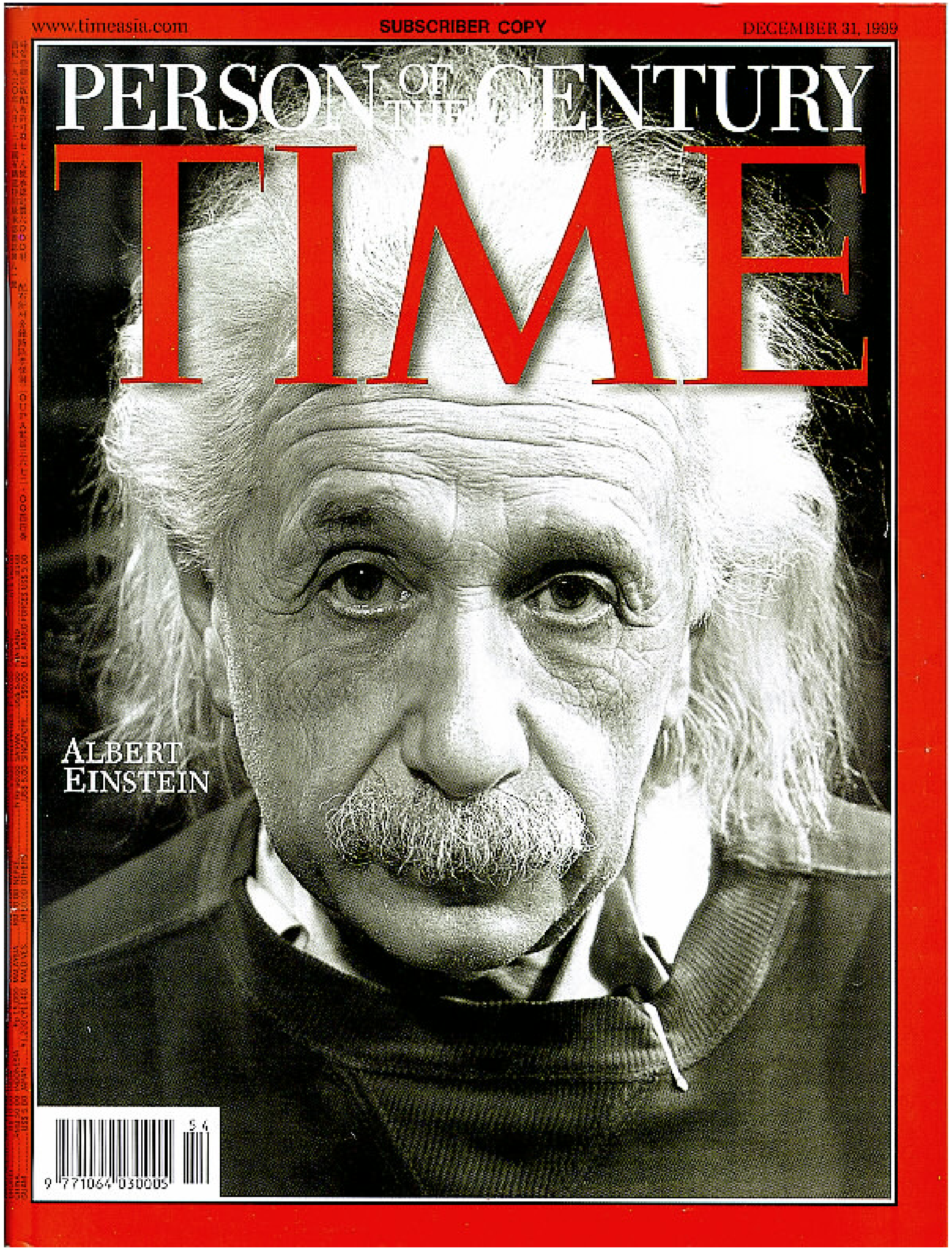
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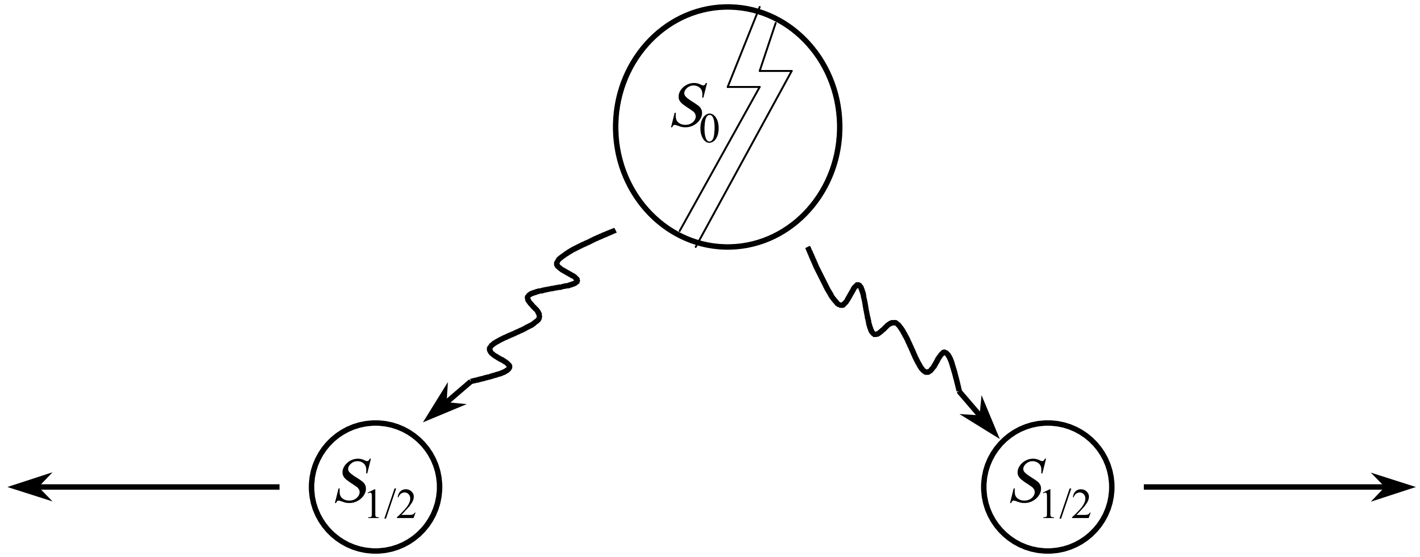
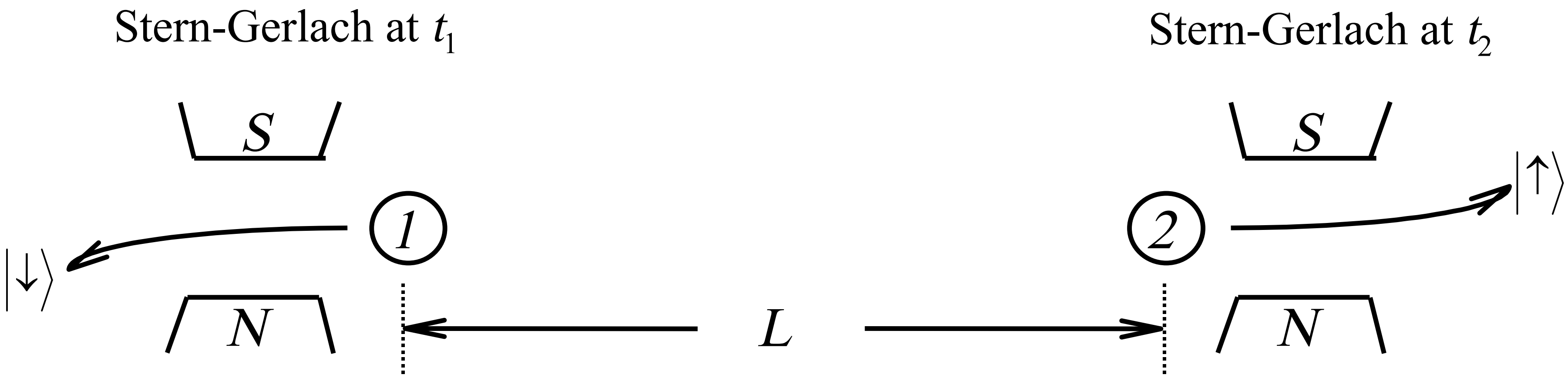
Einstein-Podolsky-Rosen (EPR) Paradox



QM: $$|\psi\rangle_{12} = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2\right)$$

- Particle 1 in spin $\uparrow$ or $\downarrow$ is 50% and so is particle 2.
- The two particles must have opposite spin states.
- Their spin states won't be known until measurements.

Information Propagation Cannot Exceed c



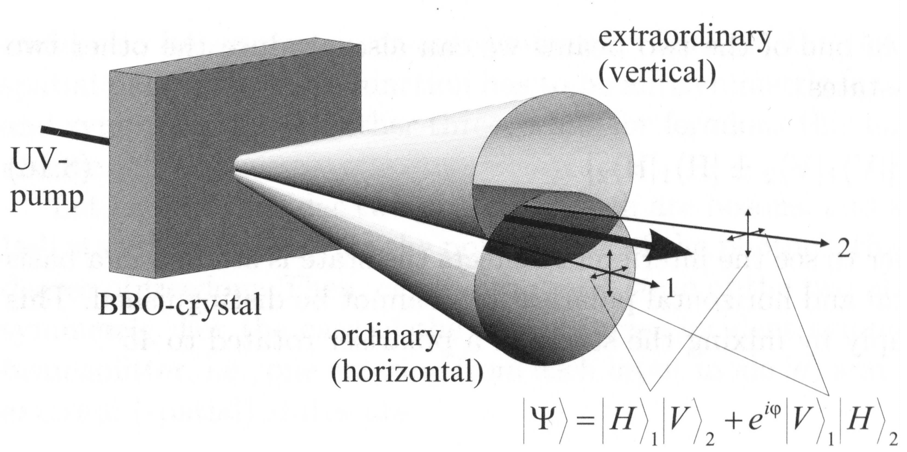
- After the two particles travel far away, their spin states are measured.
- If $L/(t_2 - t_1) > c$, it is not possible for the two to exchange the information of their spin states.

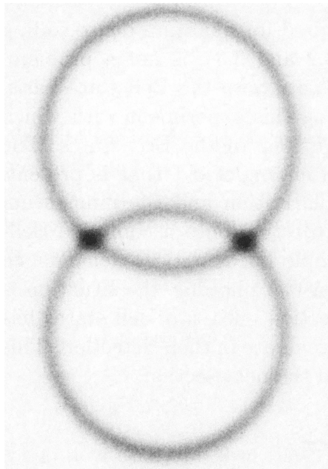
$\Rightarrow$ The probabilism concept of QM is wrong.

Quantum Non-locality

- The wavefunction $|\psi\rangle_{12}$ is everywhere.
- Particles 1 and 2 do not need to exchange any information.
- Since the two particles must have opposite spin states, they are entangled.

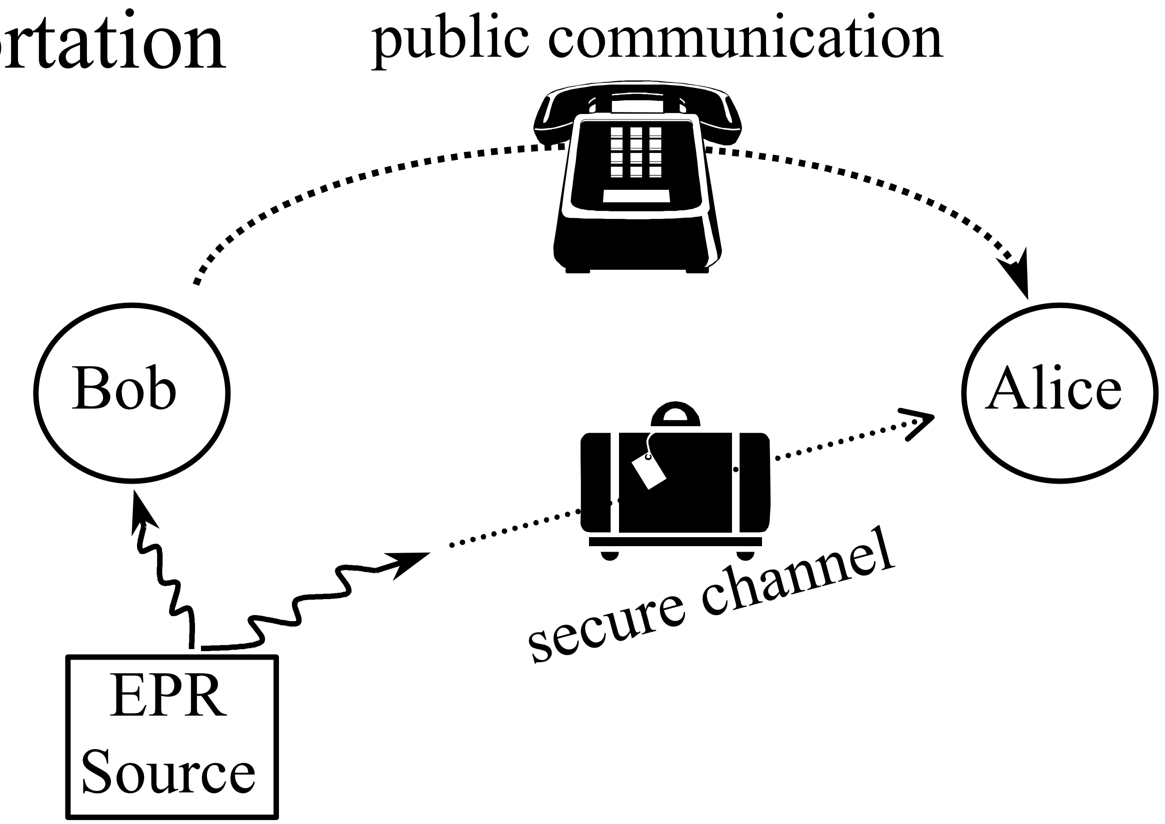
$\Rightarrow$ An EPR or entangled pair.





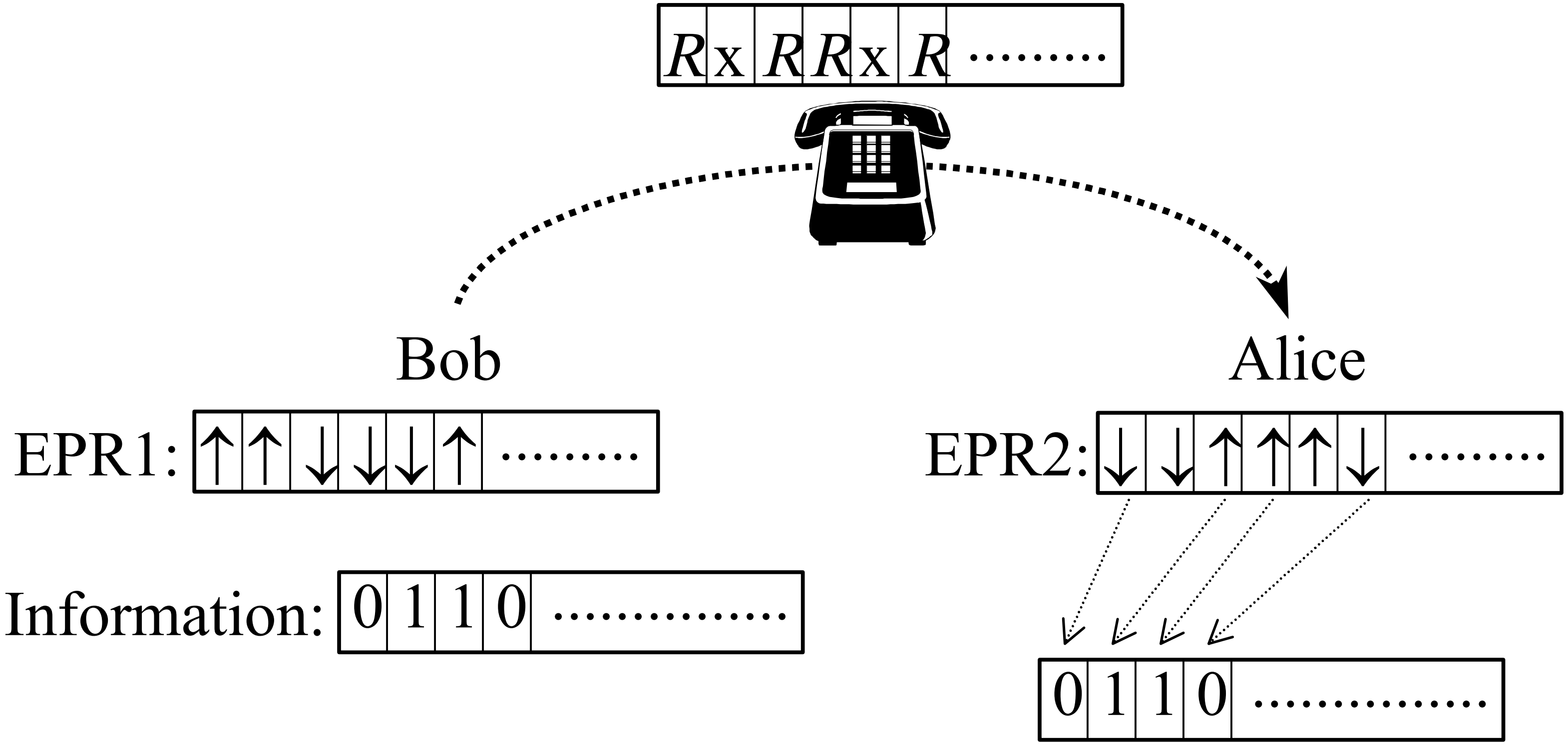
Down-conversion by a BBO crystal to generate two entangled photons along the intersecting directions of the cones.

Teleportation



- An EPR source generates thousands of entangled pairs.
- Bob keeps one of the entangled pair and the counterpart is sent to Alice.
- Once Alice receives all her particles, Bob starts to transmit information based on the measurements of his particles.

Information Encoding and Decoding

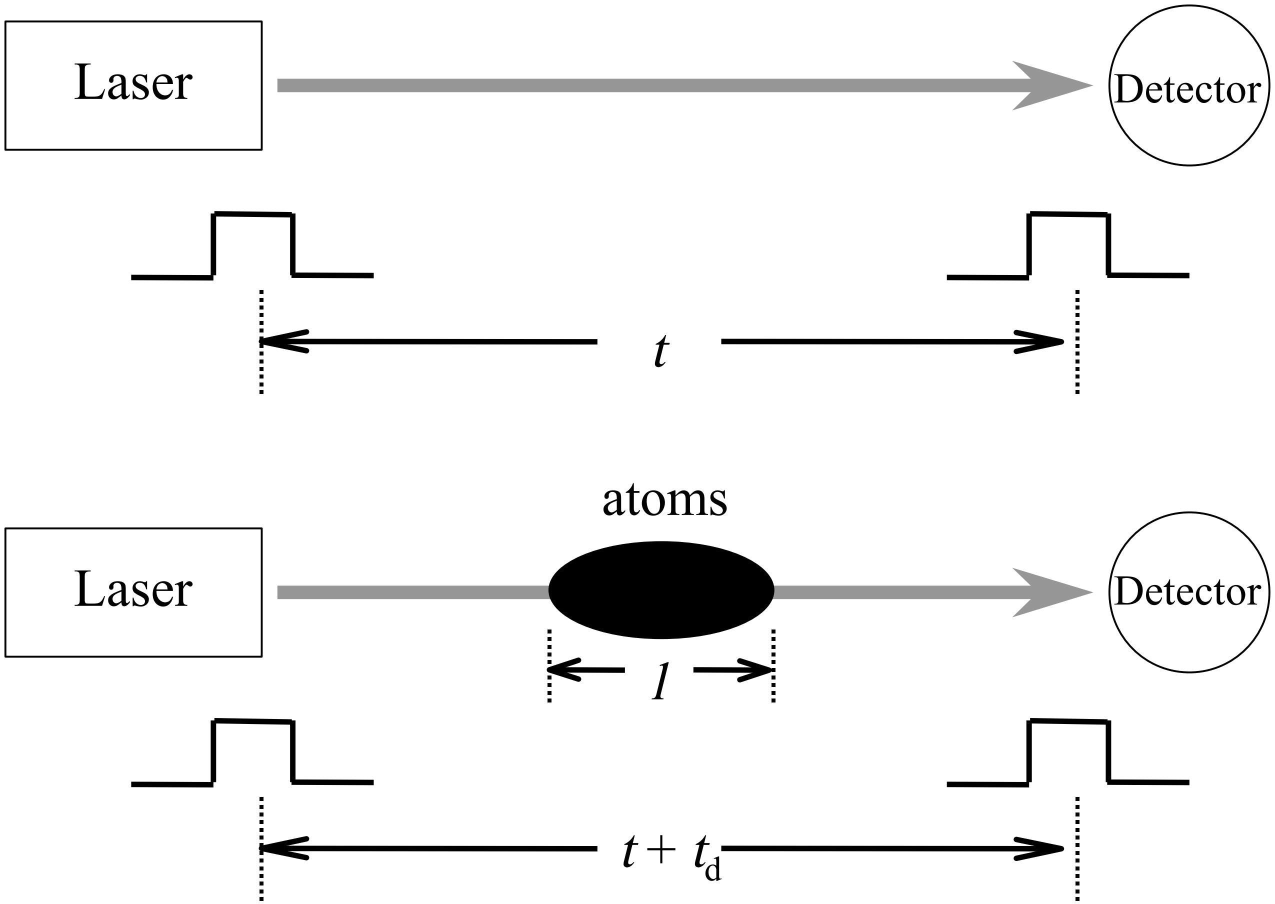


- Data transmitted through the public communication do not reveal real information.
- Only the random numbers are sent in the secure channel.

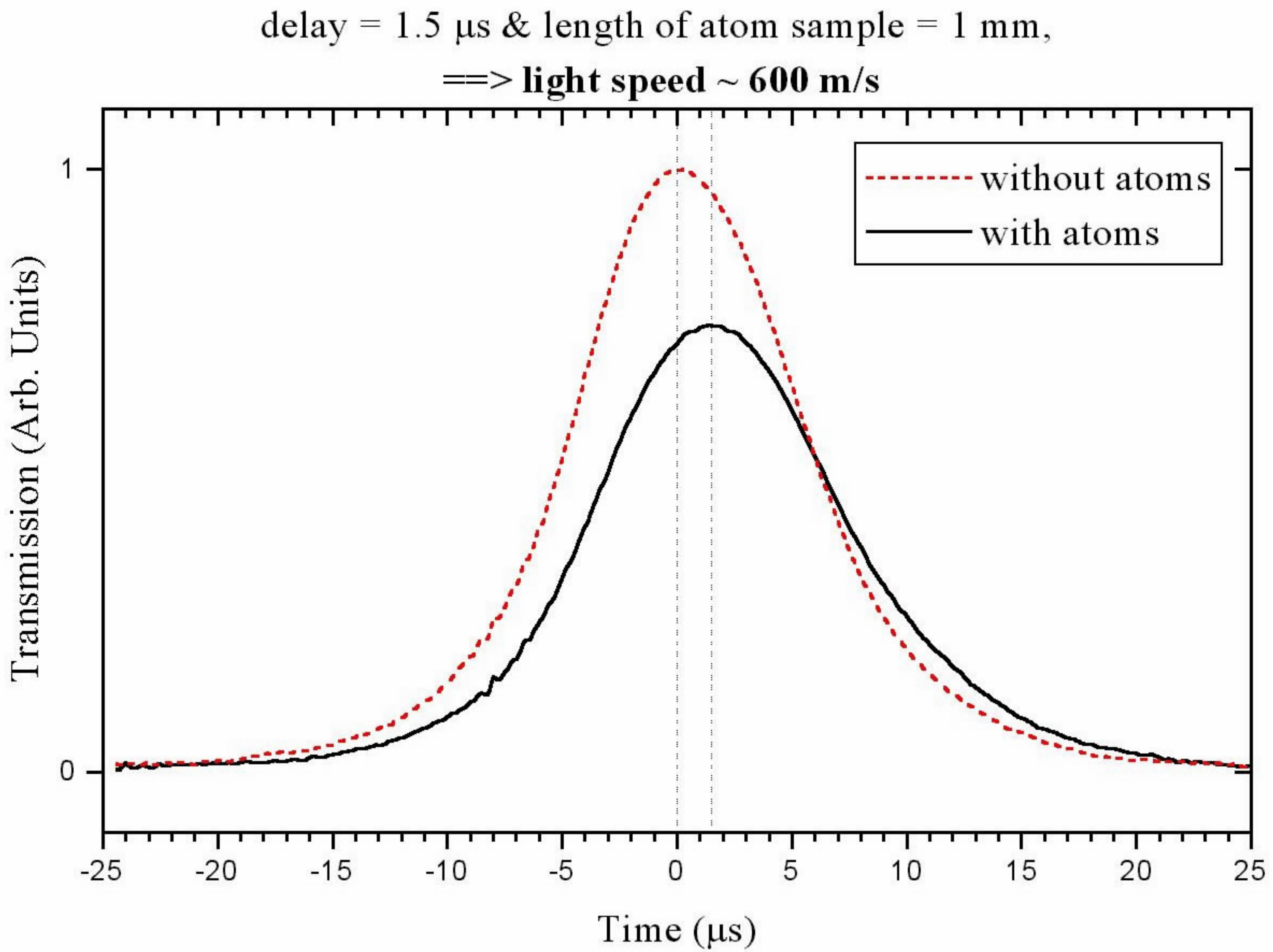
⇒ The information can only be known by Bob and Alice.

L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, “Light speed reduction to 17 metres per second in an ultracold atomic gas,” *Nature* 397, 594-598 (18 February 1999).

Measure Light Speed in a Medium



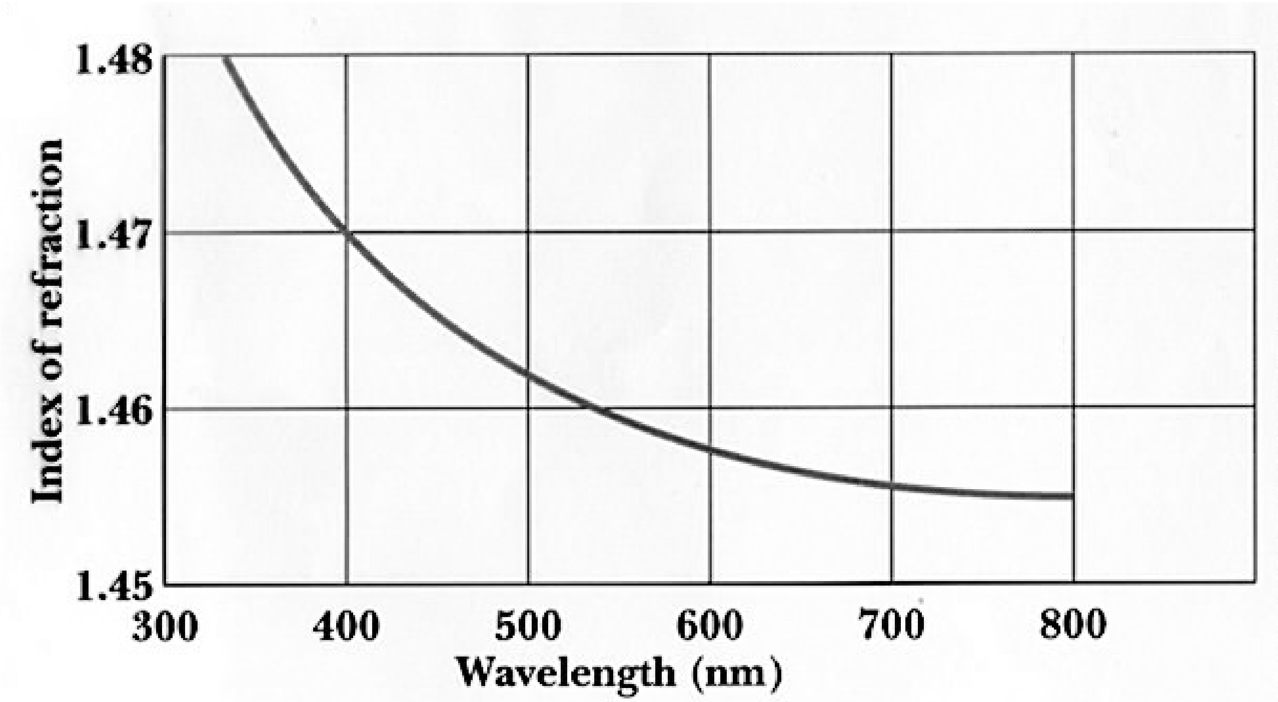
$$v \approx l \,/\, t_d$$


delay = 1.5 μs & length of atom sample = 1 mm,
==> **light speed ~ 600 m/s**
without atoms
with atoms
Transmission (Arb. Units)
1
0
-25
-20
-15
-10
-5
0
5
10
15
20
25
Time (μs)

Chromatic dispersion

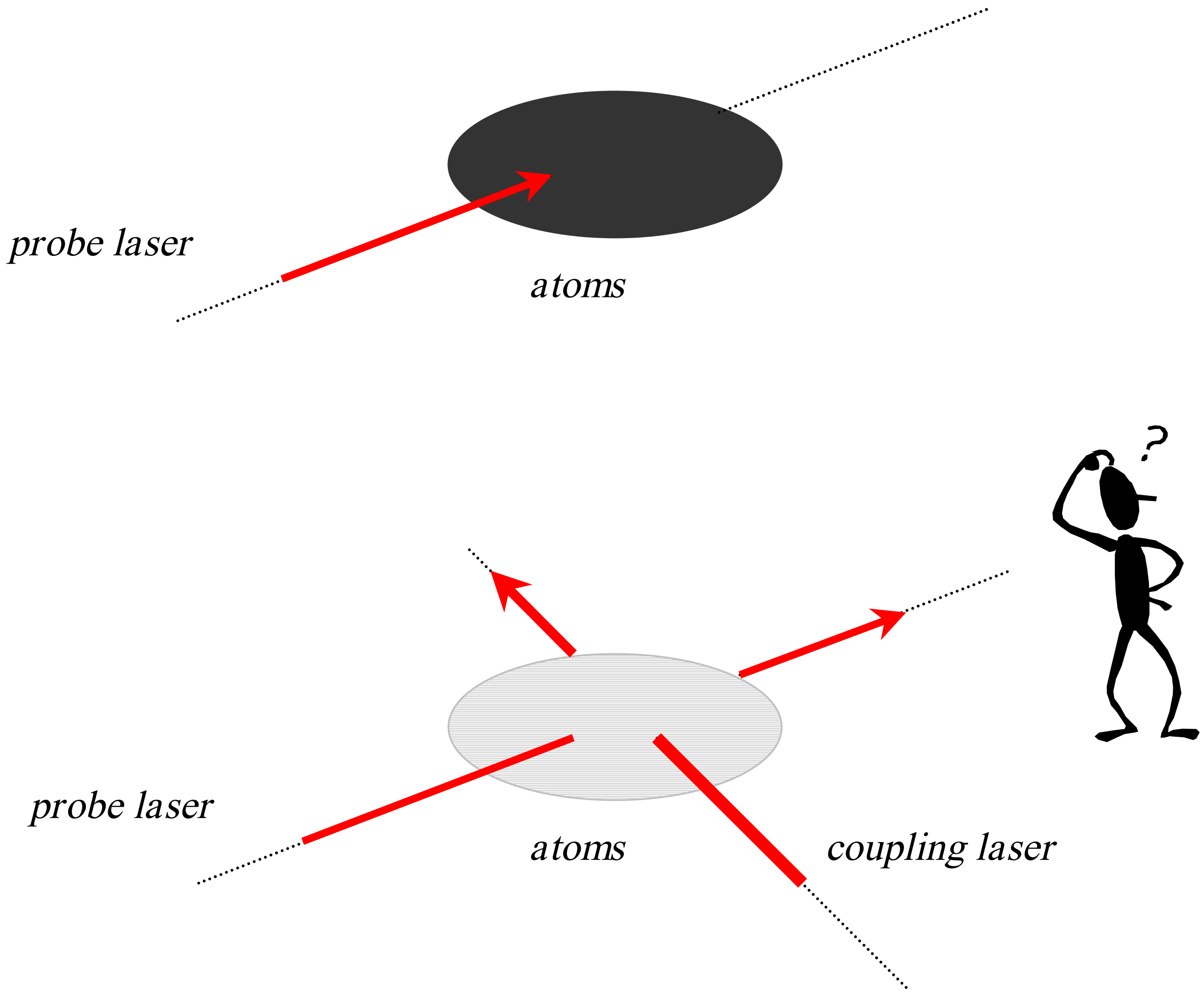
 

$$k = n\frac{}{c}, \quad v_g = \frac{d}{dk} = \frac{1}{\frac{dk}{d}} = \frac{1}{\frac{n}{c} + \frac{}{c}\frac{dn}{d}} = \frac{c}{n + \frac{dn}{d}}$$

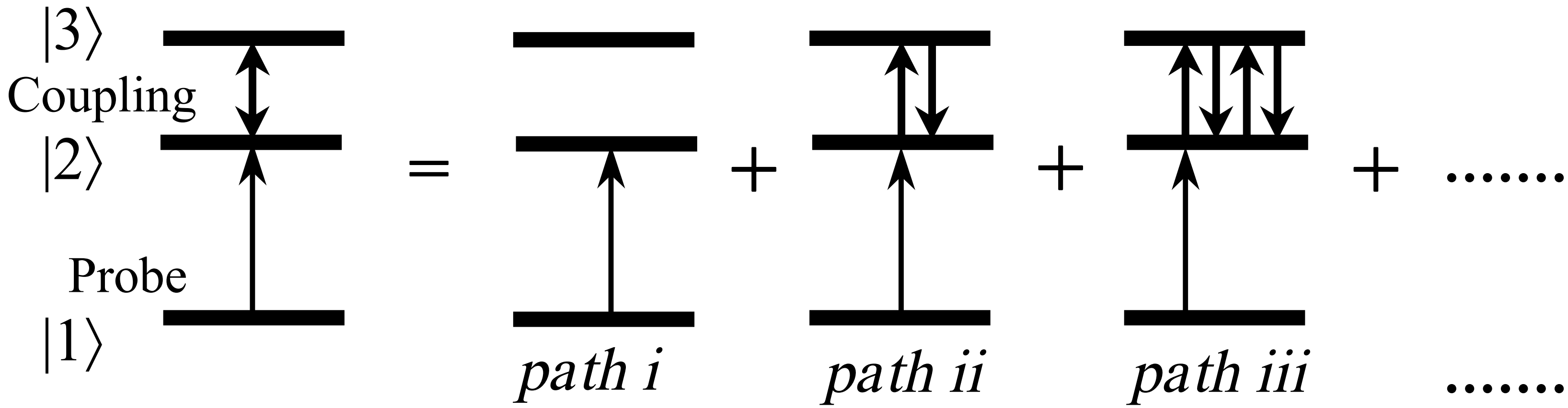


The index refraction of fused quartz. $\omega \frac{dn}{d\omega} \approx 0.01$

The Phenomenon of Electromagnetically Induced Transparency (EIT)



Quantum Interference



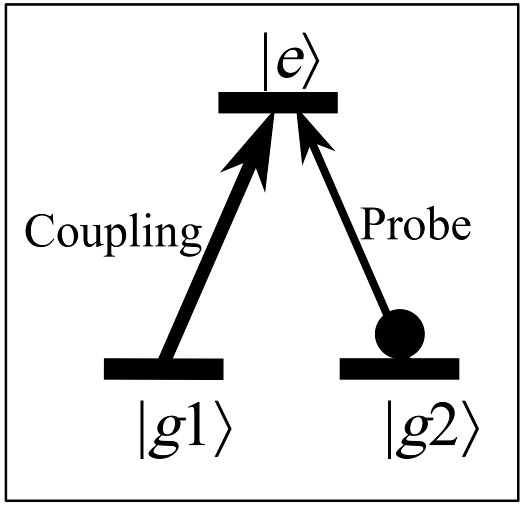
Transition amplitudes: A_i A_{ii} A_{iii} ....

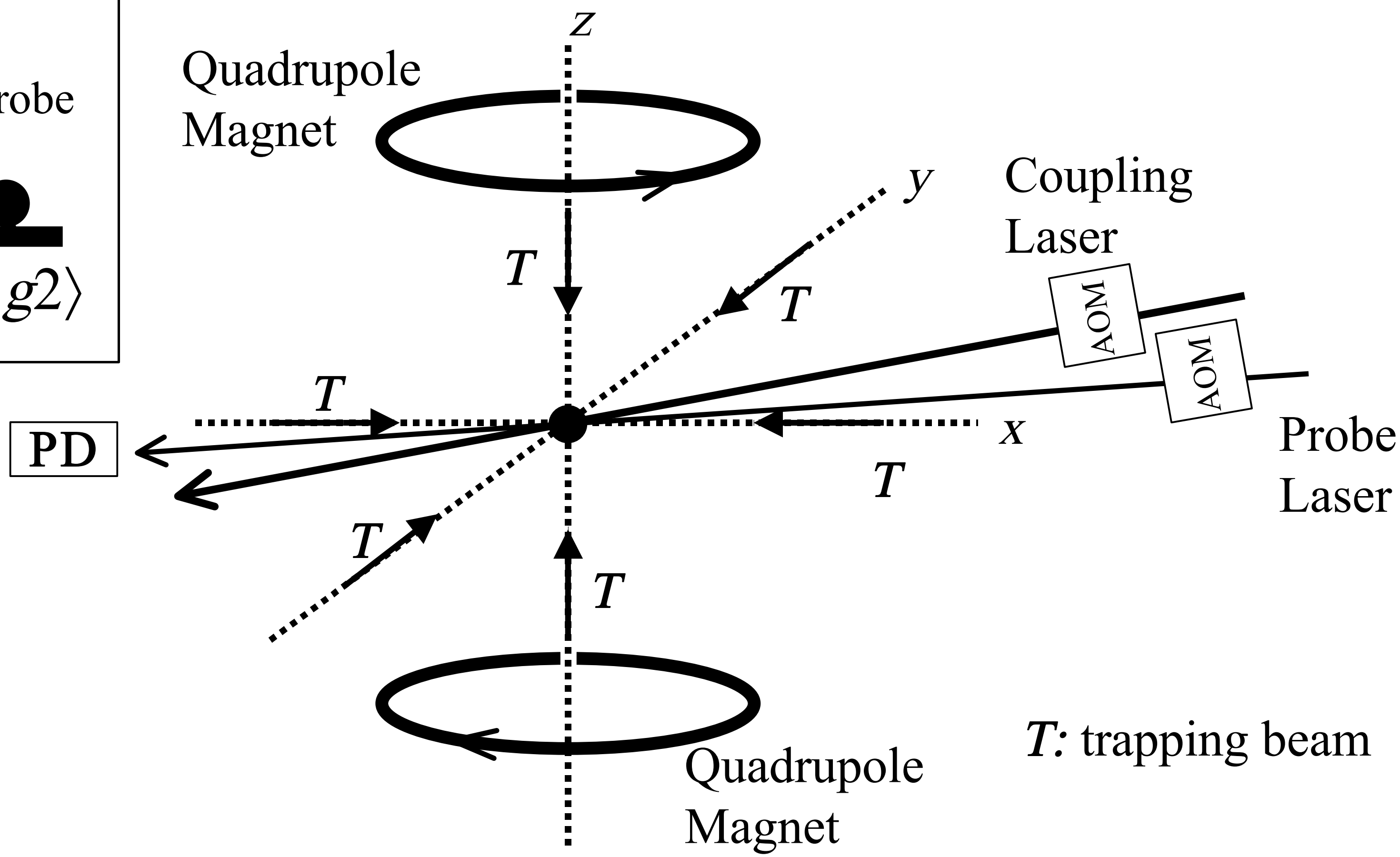
Transition probability of $|1\rangle \rightarrow |2\rangle = |\, A_i + A_{ii} + A_{iii} + \cdots\cdots \,|^2$

EIT is the destructive interference between A_i, A_{ii}, A_{iii}, $\cdots\cdots$

$\Rightarrow$ The probe absorption is suppressed.

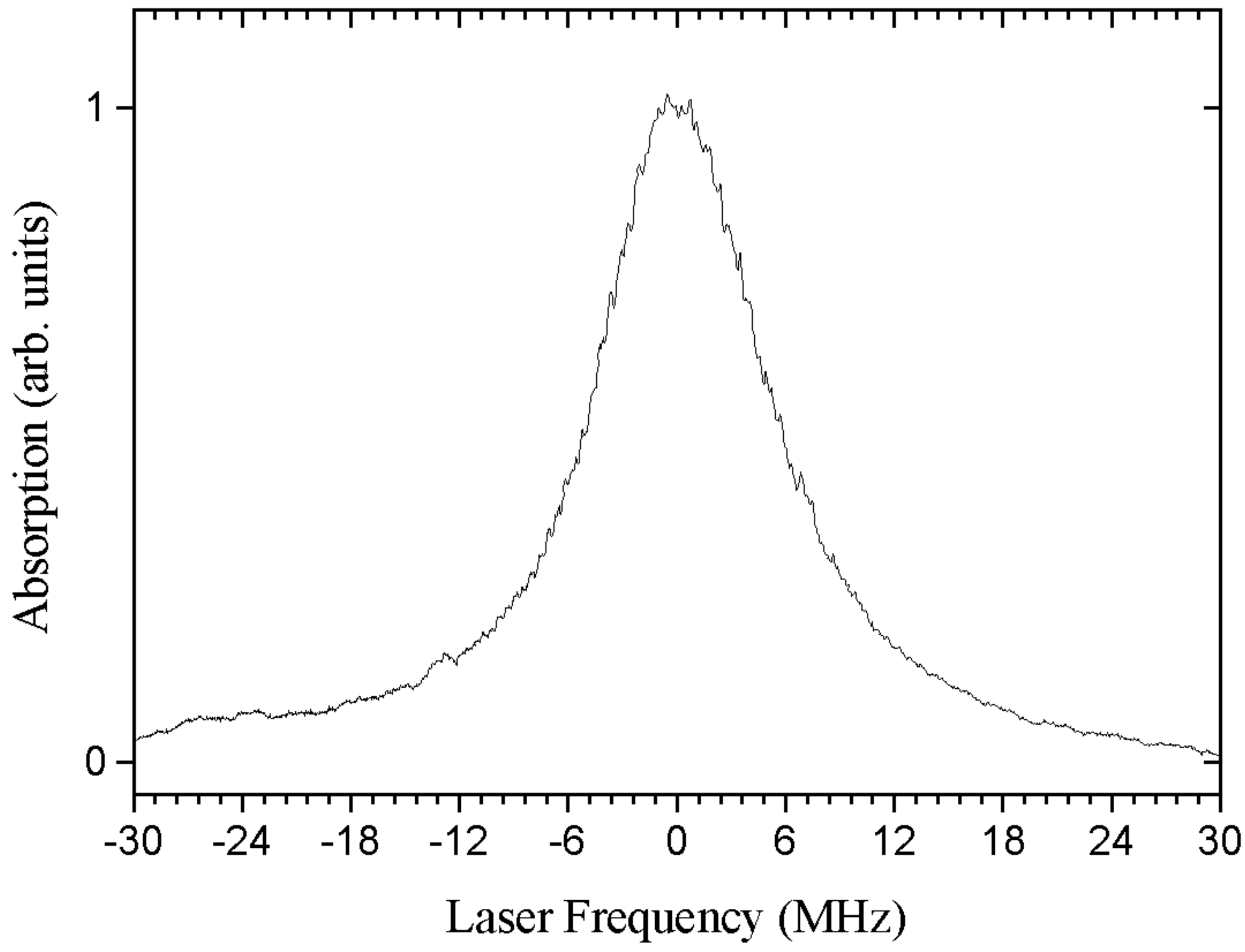
Experimental Setup





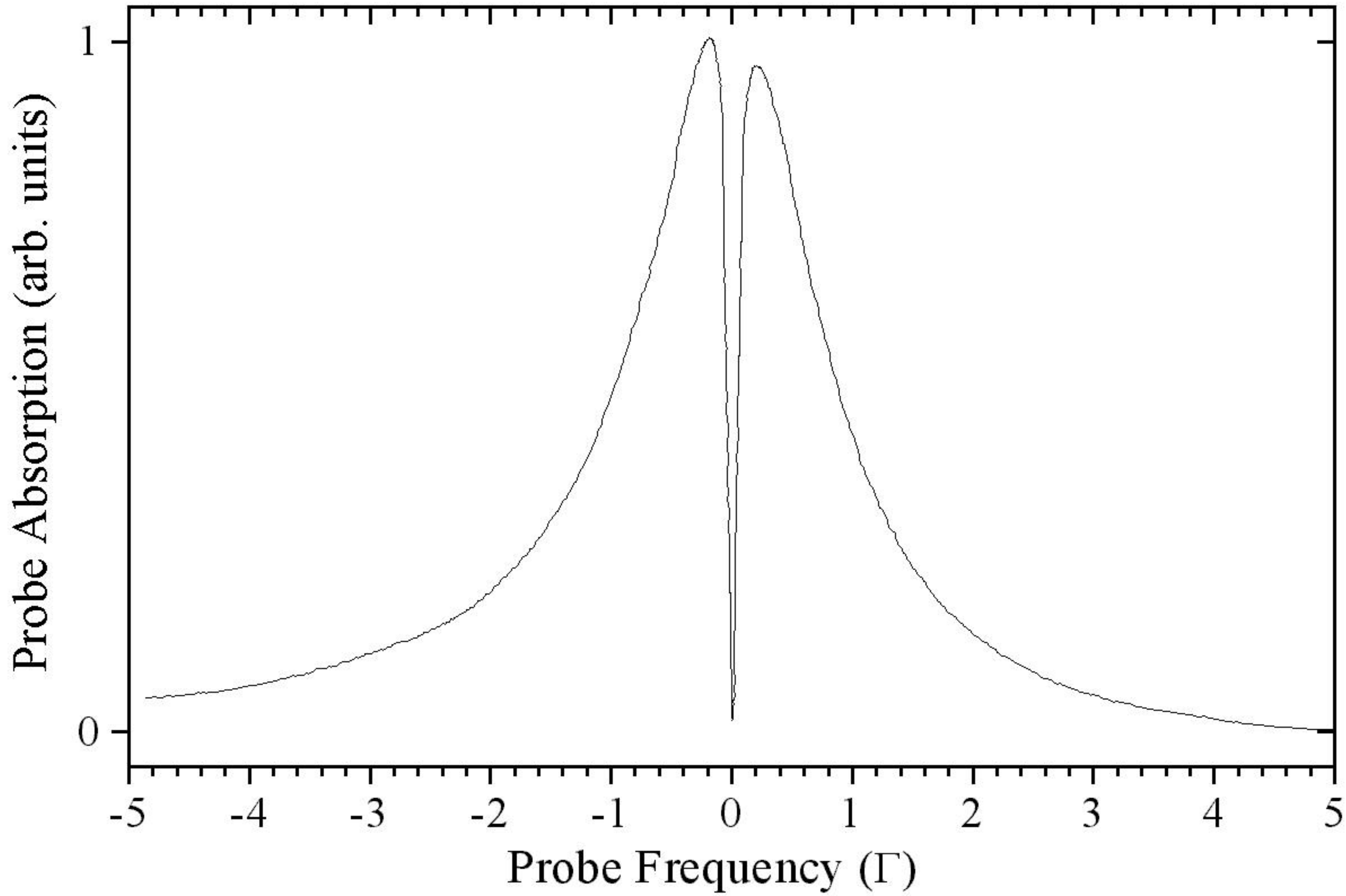
- Typically, we trap 4×10^7 ^{87}Rb atoms in a vapor-cell MOT. All fields of the MOT are shut off during the measurement of spectra.
- The coupling and probe fields propagate nearly in the same direction and they are switched by AOMs.

Experimental Spectrum without the Coupling Laser

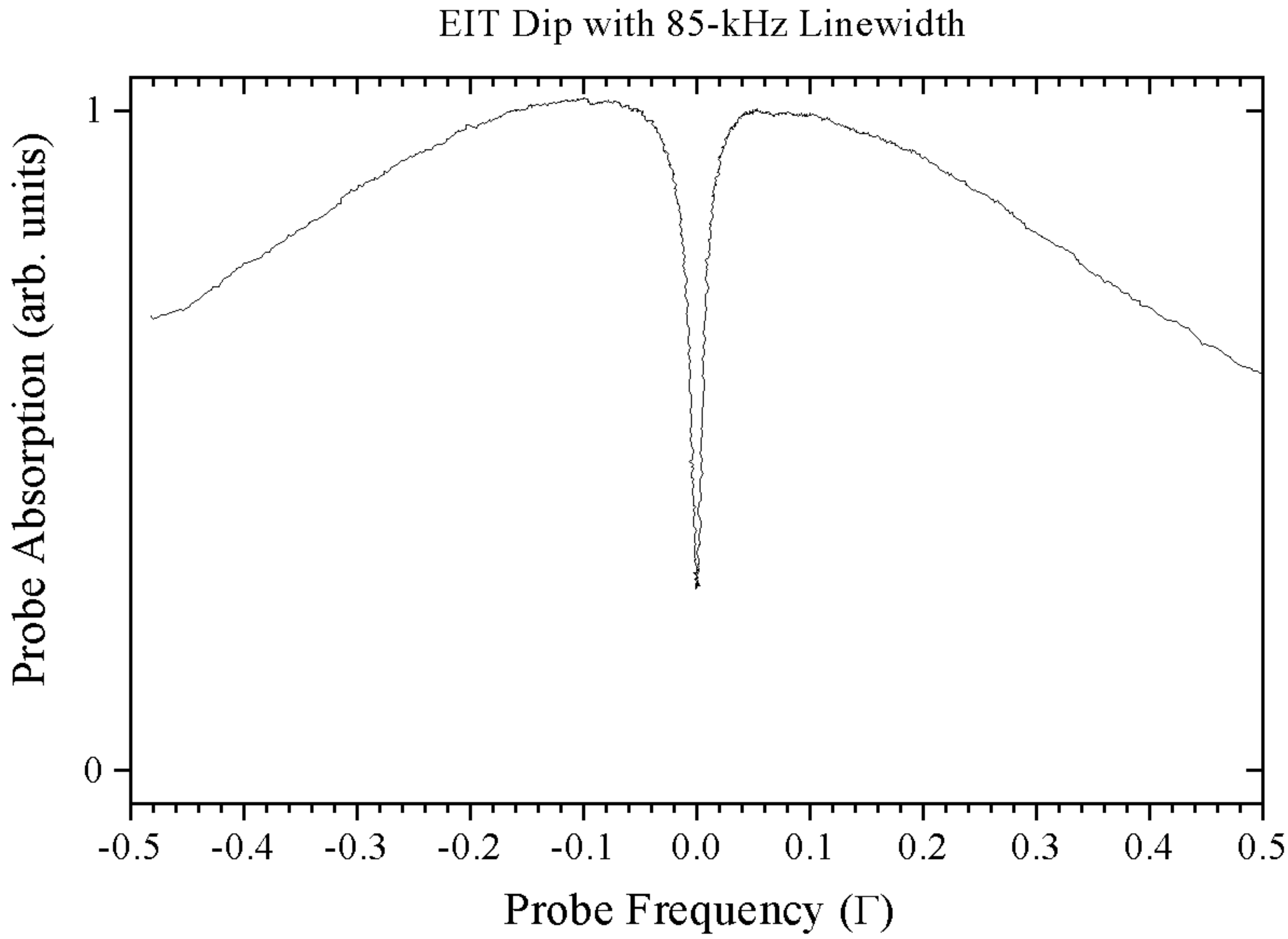


Experimental Spectrum in the Presence of the Coupling Laser

Nearly 100% Transparency at the Resonance

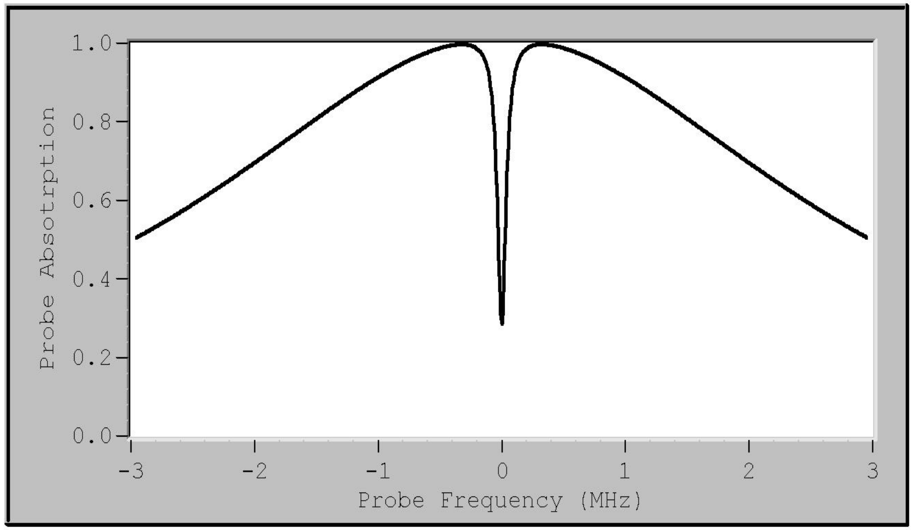


Ultrahigh Contrast near the Resonance



Group Velocity Predicted from the Experimental Data

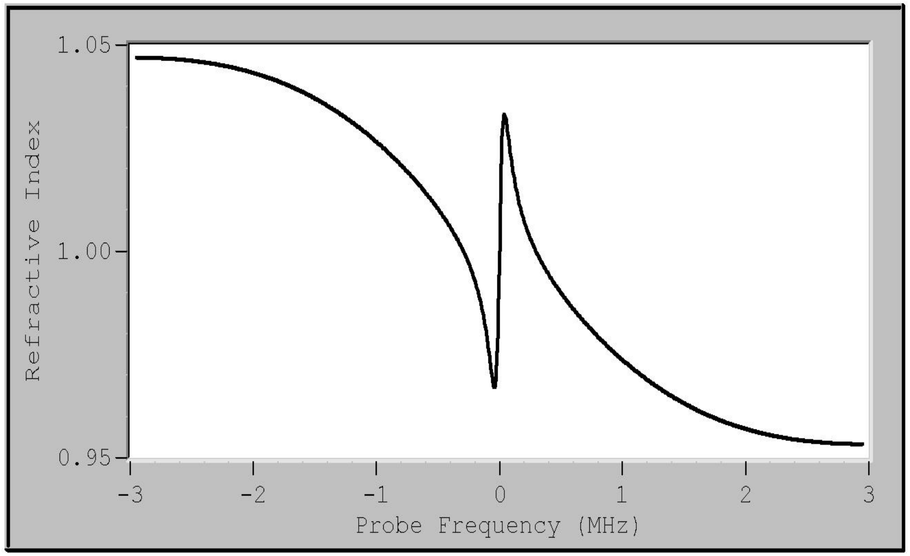
$$v_g = \frac{c}{n + \frac{dn}{d}}$$

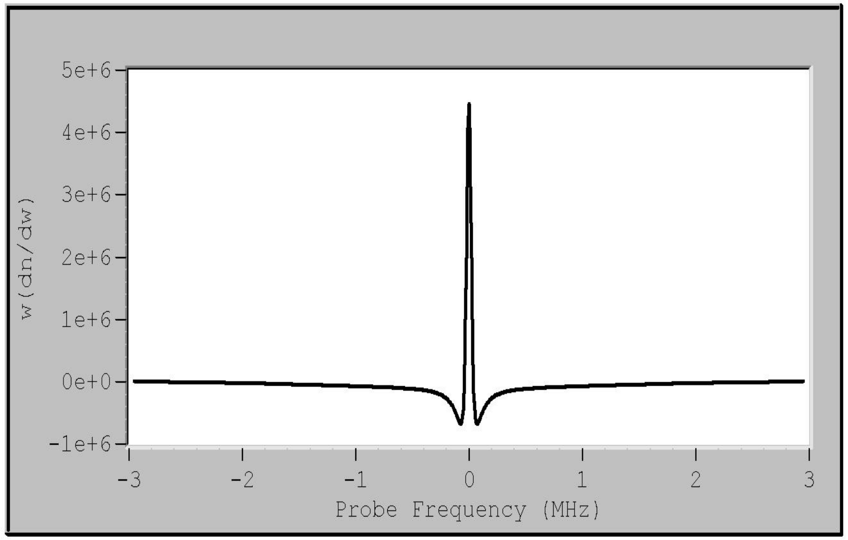


吸收率

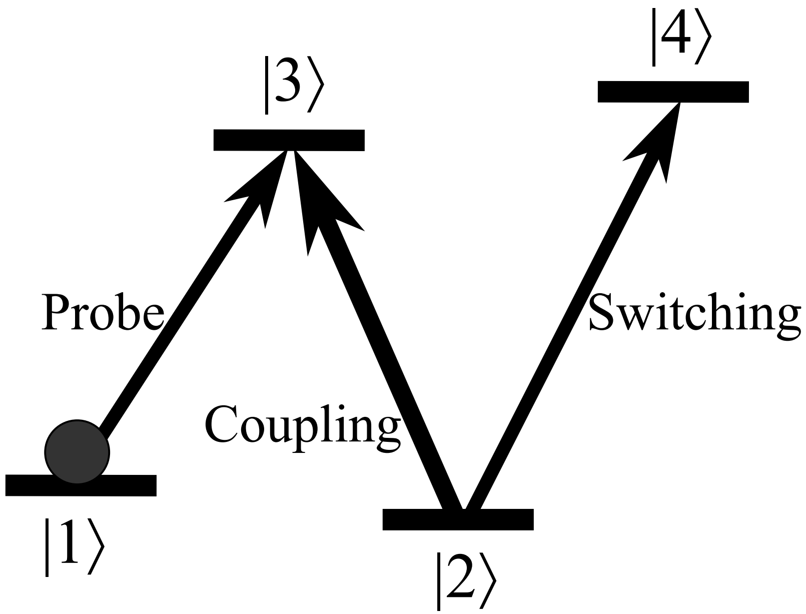
色散

折射率



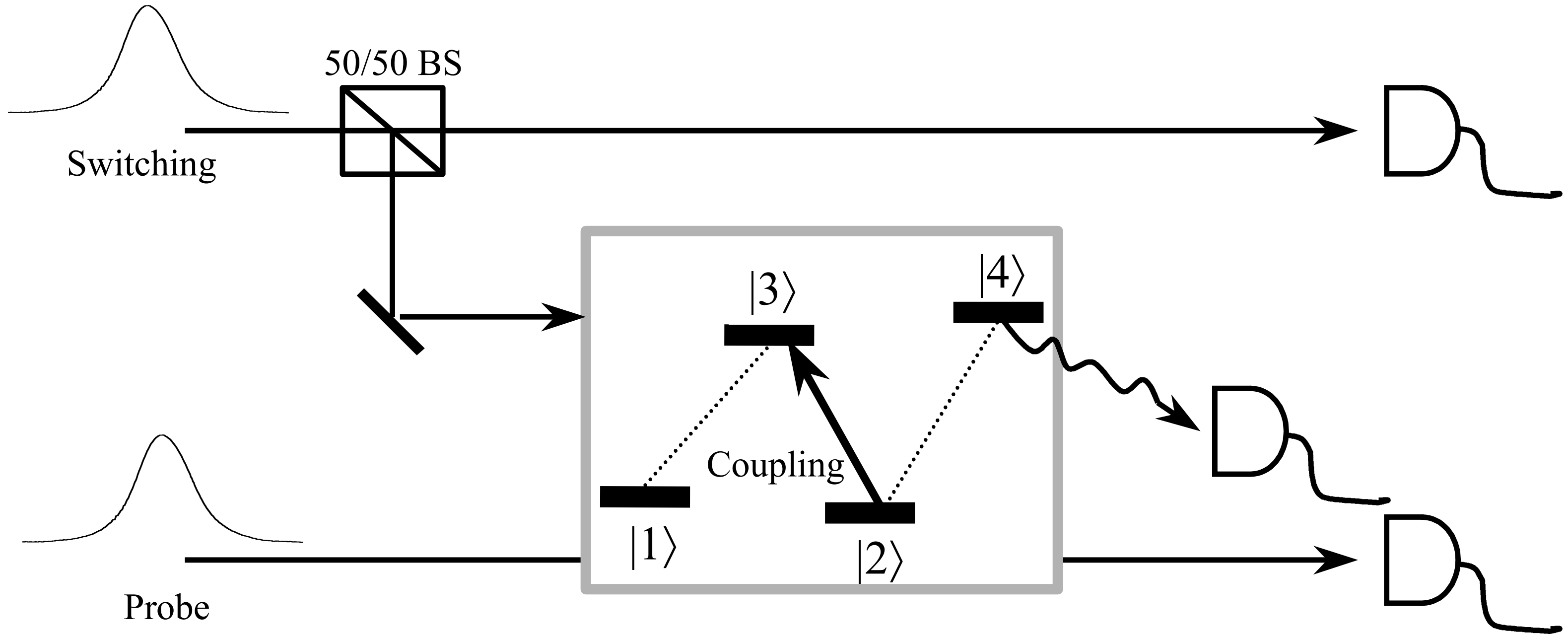


Photon Switching by Quantum Interference



- A weak probe field and a strong coupling field form the EIT configuration.
- Presence of the switching field enables the probe absorption and induces the three-photon transition from the ground state $|1\rangle$ to the excited state $|4\rangle$.
- One switching photon is enough to cause one probe photon absorbed under the ideal condition. (Harris and Yamamoto, PRL81, 3611)

The Three-Fold Entangled State



$\frac{1}{\sqrt{2}}\left(|0\rangle_s|0\rangle_p|1\rangle_f + |1\rangle_s|1\rangle_p|0\rangle_f\right)$, where 1 or 0 in the $|\,\rangle_s$, $|\,\rangle_p$, and $|\,\rangle_f$ denotes presence or absence of the switching, probe, and fluorescence photons measured by the detectors.

Requirements: $OD \geq 10$ and $\gamma < 10^{-3}\Gamma$.

The Optical Bloch Equation

$$\frac{d\hat{\rho}}{dt} = \frac{1}{i\hbar}\left[H_0 + H_c + H_s + \boxed{H_p}, \hat{\rho}\right] + \left\{\frac{d\hat{\rho}}{dt}\right\}$$

$\hat{\rho}_{31}(t) = \rho_{31}(t)\, e^{-i\omega_p t}$, where $\hat{\square}$ is the slowly-varying part of $\square$.

- Treat the probe field as perturbation and solve the optical Bloch equation to the first order.

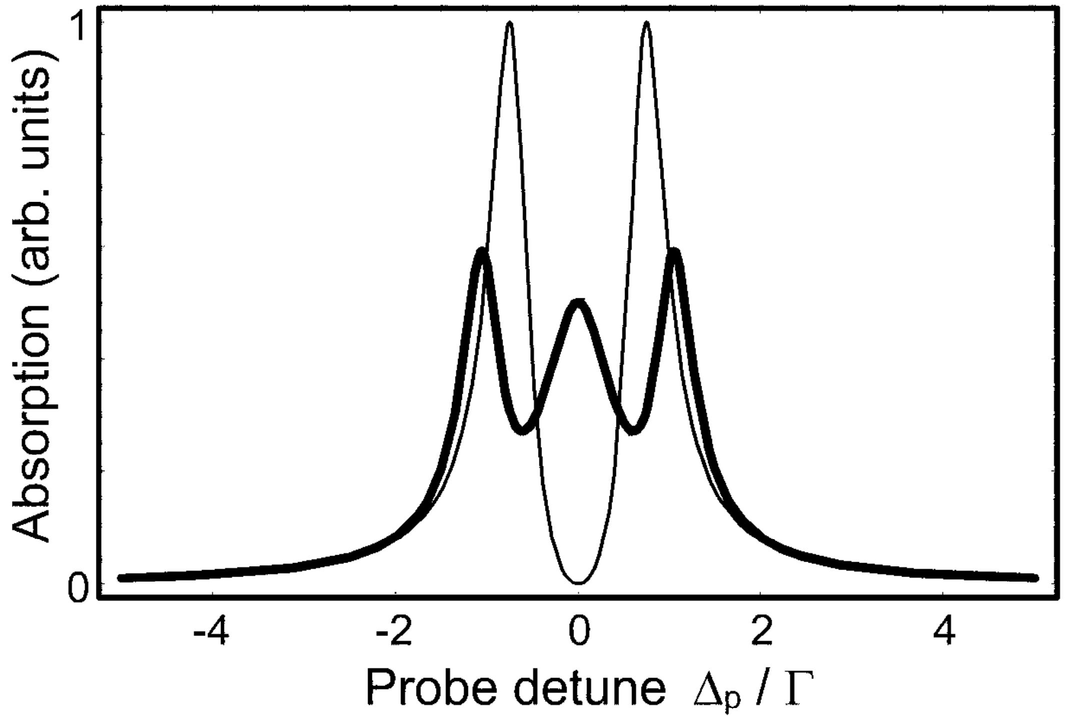
$\Rightarrow \quad OD = N L\,(3\lambda^2/2\pi)\ Im[\rho_{31}]\ (\Gamma/\Omega_p)$,

$n = N(3\lambda^3/8\pi^2)\ Re[\rho_{31}]\ (\Gamma/\Omega_p)$, where N is atomic density.

- T_D calculated from the phase shift induced by the refractive index, n, of the medium.

$$\Rightarrow \qquad T_D = \frac{\partial}{\partial \omega_p}\left(\frac{2\pi}{\lambda}\, n\, L\right).$$

Frequency Spectrum

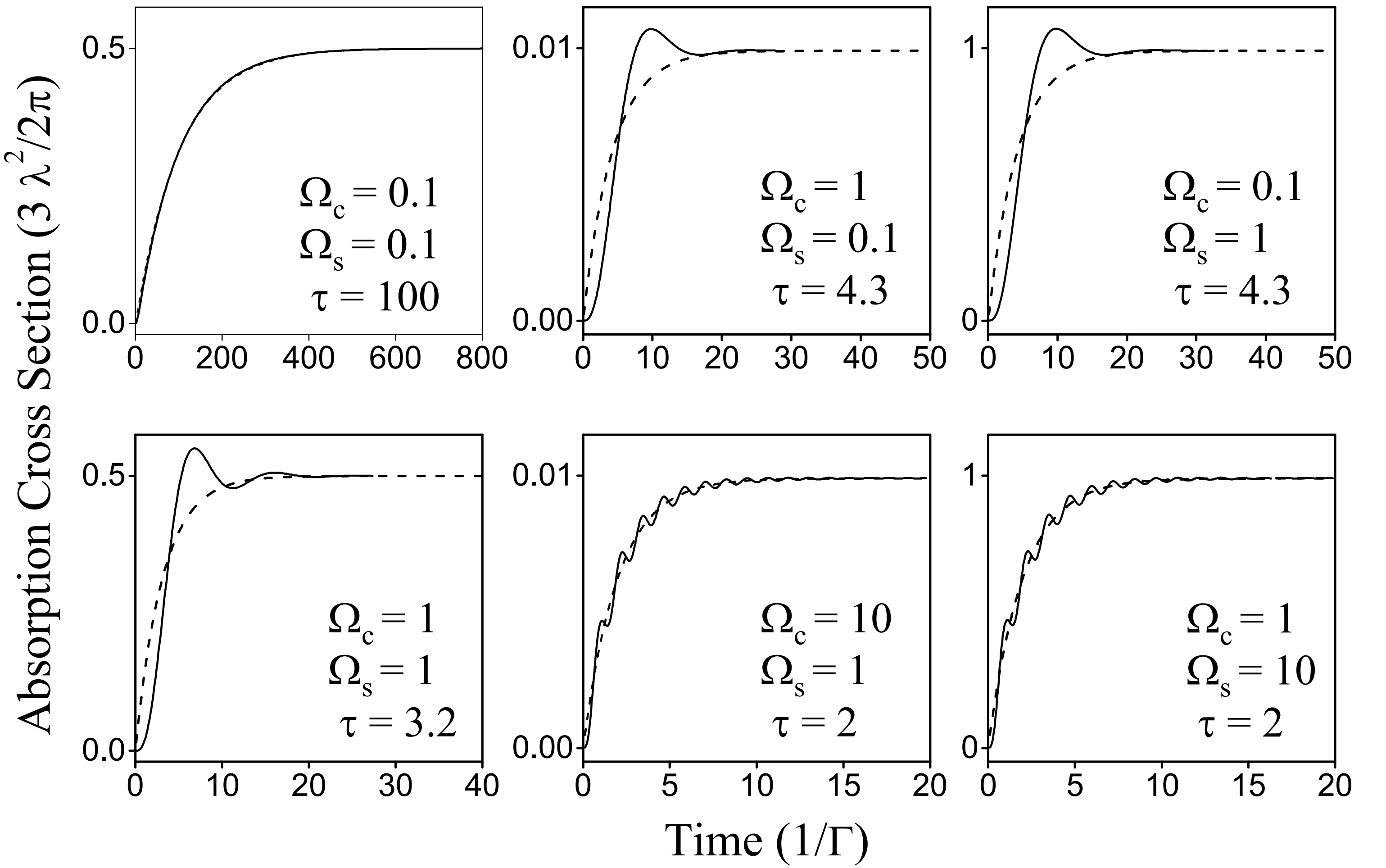


$\Omega_c = 1.5\ \Gamma$

$\Omega_s = 1.5\ \Gamma$

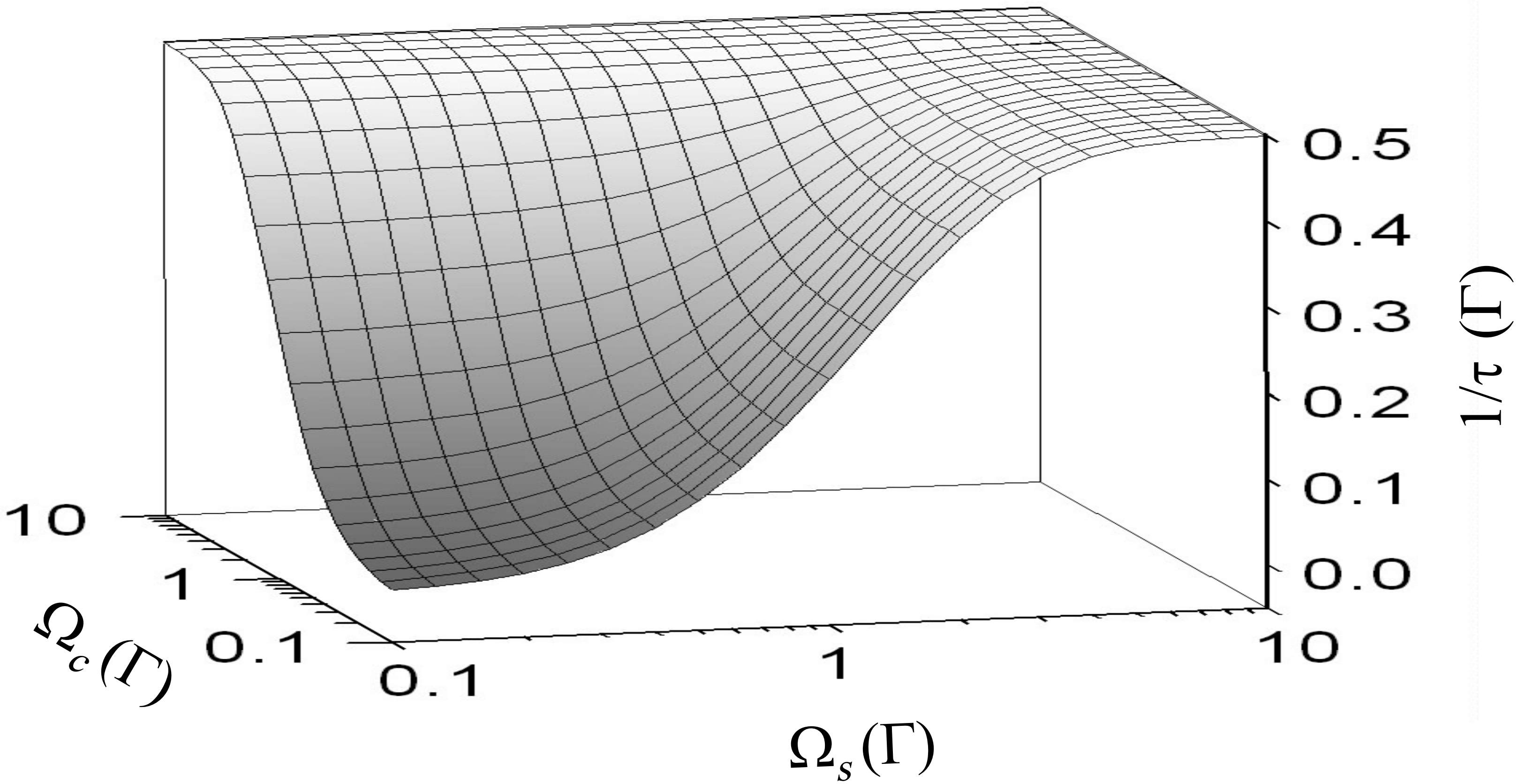
Thin and thick lines are the spectra of probe absorption without and with the switching field, respectively.

Transient Behaviors of the Probe Absorption



- In the low-intensity limit, the probe absorption is just an exponential function.
- At large Ω_c or Ω_s, the probe absorption has some oscillations other than increases exponentially. The oscillation becomes more rapid at larger Rabi frequencies.

Rise Time of the Probe Absorption



- The rise time can not be shorter than $2/\Gamma$ and is equal to $2\Gamma/(\Omega_c^2+\Omega_s^2)$ in the low-intensity limit.
- In the low-intensity limit, the delay time is longer than the rise time as long as $OD(0,0) > 2(1+\Omega_s^2/\Omega_c^2)$.

Defects in the Current Calculation

- The perturbation method may fail at $\Omega_c \approx 3\Omega_s$ and $\Omega_s \approx \Omega_p$.
- Entire sample is considered as a single atom.
- Decay and deformation of the probe and switching pulses during the propagation have not been taken into account.

$$\Omega_{in}(t) \longrightarrow \rho(t) \longrightarrow \Omega_{out}(t)$$

$$\frac{d\hat{\rho}(t)}{dt} = \frac{1}{i\hbar}\left[H(t), \hat{\rho}(t)\right] + \left\{\frac{d\hat{\rho}(t)}{dt}\right\}$$

$$\Omega^2_{out}(t) = \Omega^2_{in}(t)\, e^{-OD(t)}$$

Pulse Propagation in a Medium

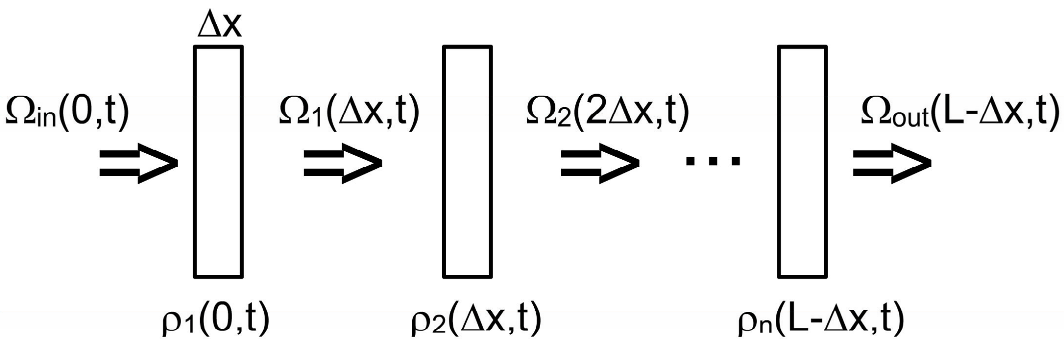
Probe propagation: $$\frac{1}{c}\frac{\partial\Omega_p(x,t)}{\partial t}+\frac{\partial\Omega_p(x,t)}{\partial x}=i\frac{3\lambda^2\Gamma N}{4\pi}\rho_{31}(x,t)$$

Switching propagation: $$\frac{1}{c}\frac{\partial\Omega_s(x,t)}{\partial t}+\frac{\partial\Omega_s(x,t)}{\partial x}=i\frac{3\lambda^2\Gamma N}{4\pi}\rho_{42}(x,t)$$

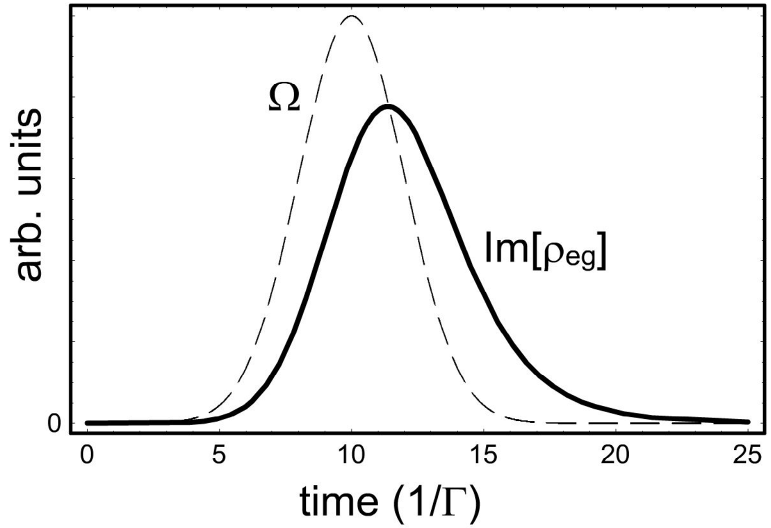
Atomic coherence:

$$\frac{\partial\hat{\rho}(x,t)}{\partial t}=\frac{1}{i\hbar}[H_0+H_c+H_s(\Omega_s(x,t))+H_p(\Omega_p(x,t)),\ \hat{\rho}(x,t)]+\left\{\frac{\partial\hat{\rho}(x,t)}{\partial t}\right\}?$$

Slice Sample and Neglect Propagation Delay



$$\Omega_{i+1}(x+\Delta x,t)=\Omega_i(x,t)\left\{1-\frac{3\lambda^2\Gamma N}{4\pi}\frac{Im[\rho_{31}(x,t)]}{\Omega_i(x,t)}\Delta x\right\}$$



However, $Im[\rho_{31}]/\Omega$ can diverge.

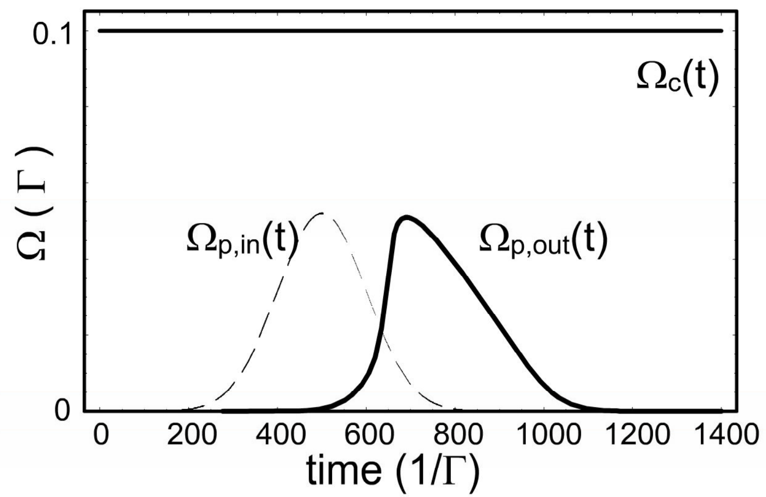
Treat $\partial\rho/\partial t$ Term as Perturbation

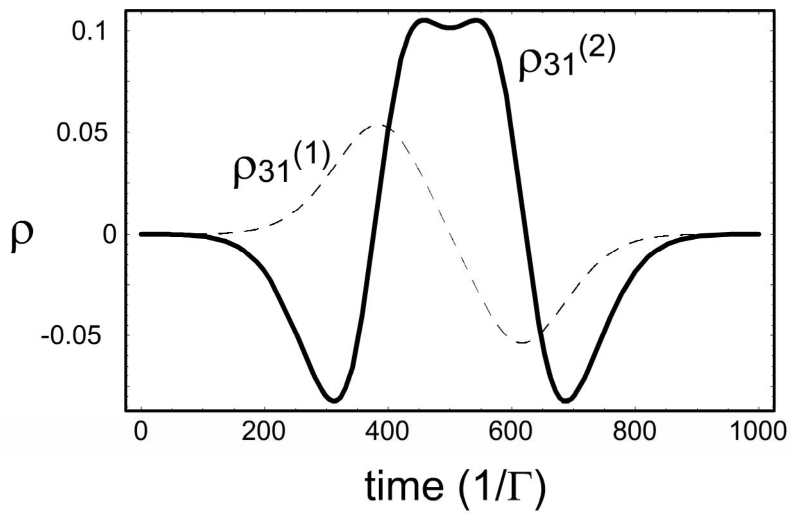
$$0 = \frac{1}{i\hbar}[H,\ \hat{\rho}^{(0)}(x,t)] + \left\{\frac{\partial\hat{\rho}^{(0)}(x,t)}{\partial t}\right\}$$

$$\frac{\partial\hat{\rho}^{(0)}(x,t)}{\partial t} = \frac{1}{i\hbar}[H,\ \hat{\rho}^{(1)}(x,t)] + \left\{\frac{\partial\hat{\rho}^{(1)}(x,t)}{\partial t}\right\}$$

$$\vdots$$

Find the analytical solution of $\rho_{31}(\Omega_p(x,t))$ and numerically solve the equation of probe propagation.





$\Omega_c = 0.1$ and $\Omega_{p,\max} = 0.052$.

Summary

- We have experimentally studied the transient behaviors of the photon switching by quantum interference. The results are consistent to our theoretical predictions.
- Propagation of the single-photon pulse in the system of photon switching has not been understood quantitatively.
- The pulse propagation in the Bose condensate is a rather interesting subject.
- We have been developing an experimental system suitable for the observation of the photon entanglement ($OD > 10$ and $\gamma < 10^{-3}\Gamma$).
- Our ultimate goal is to achieve the quantum teleportation.