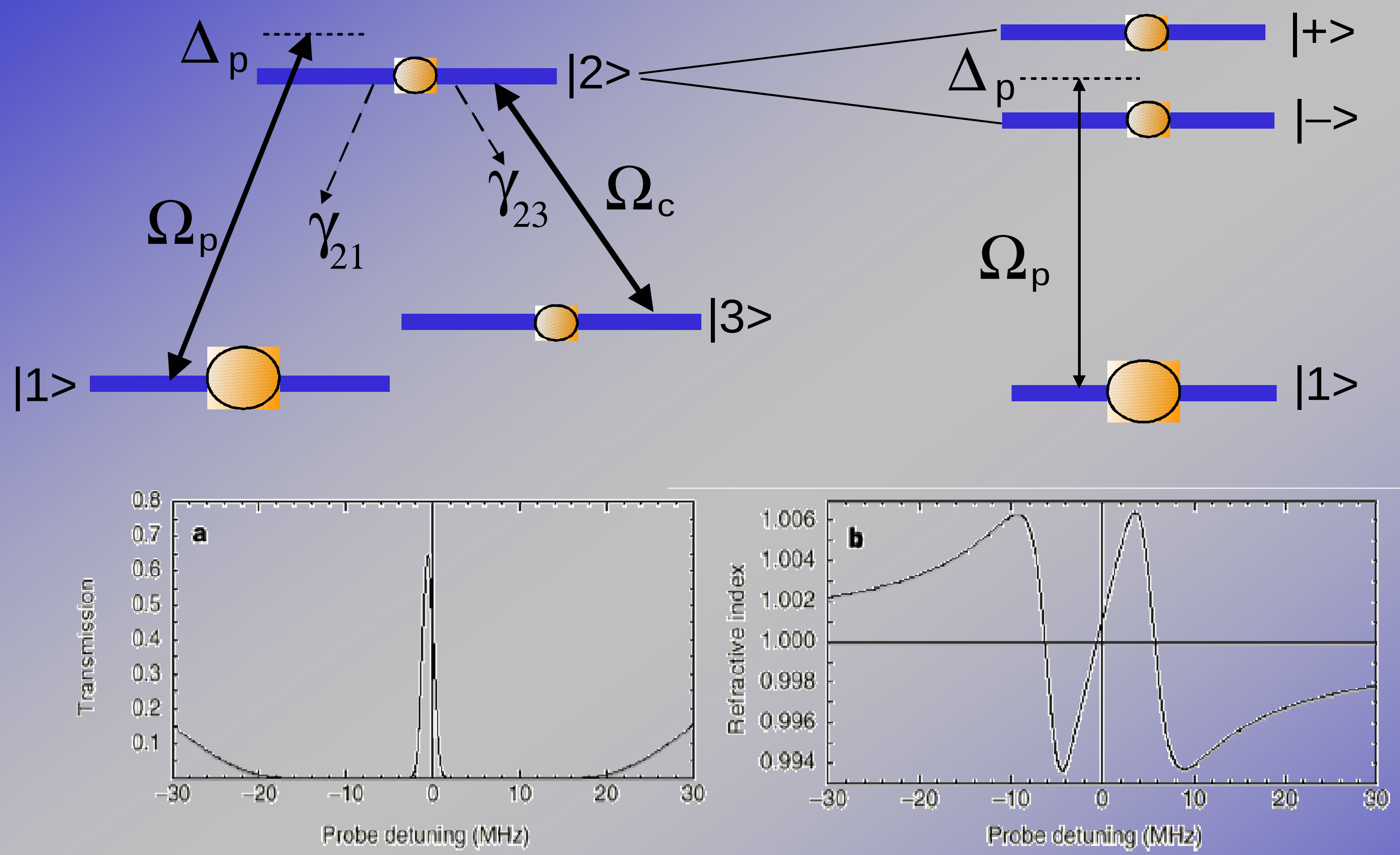


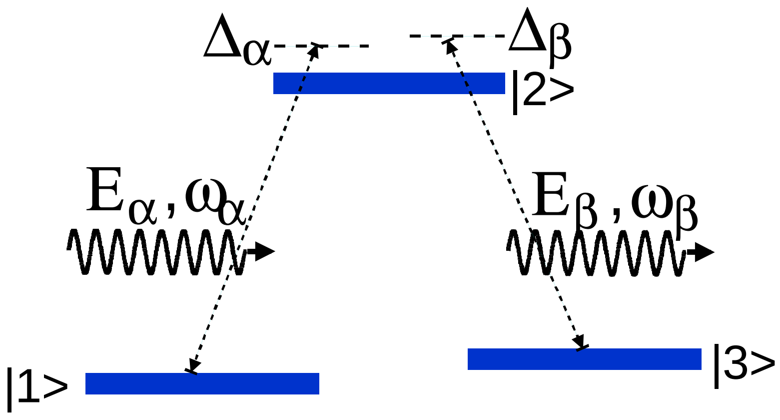
2 THREE-LEVEL OPTICAL SYSTEMS

OUTLINE

- 2.1 BASIC THEORY
- 2.1 STIRAP: STIMULATED RAMAN ADIABATIC PASSAGE
- 2.2 EIT: ELECTROMAGNETICALLY INDUCED TRANSPARENCY
- 2.3 CPT: COHERENT POPULATION TRAPPING
- 2.4 RAP: RAPID ADIABATIC PASSAGE, REVISITED

2.1 BASIC THEORY

Physical Model



$$\vec{E}_\alpha = \vec{E}_{\alpha 0} \cos \omega_\alpha t$$
$$\vec{E}_\beta = \vec{E}_{\beta 0} \cos \omega_\beta t$$
$$\Delta_\alpha = \omega_{21} - \omega_\alpha$$
$$\Delta_\beta = \omega_{23} - \omega_\beta$$

Electric dipole interaction: $V^{(ADE)} = -\vec{\mu}\cdot\vec{E}(t) = -(-e)\vec{r}\cdot\vec{E}(t)$

$$\hat{\mu} = \begin{pmatrix} 0 & \vec{\mu}_{12} & 0 \\ \vec{\mu}_{12}^* & 0 & \vec{\mu}_{23} \\ 0 & \vec{\mu}_{23}^* & 0 \end{pmatrix} \qquad V = \hbar \begin{pmatrix} 0 & \Omega_\alpha \cos\omega_\alpha t & 0 \\ \Omega_\alpha^* \cos\omega_\alpha t & 0 & \Omega_\beta \cos\omega_\beta t \\ 0 & \Omega_\beta^* \cos\omega_\beta t & 0 \end{pmatrix}$$

$$\Omega_\alpha = -\frac{\vec{\mu}_{12}\cdot\vec{E}_{\alpha 0}}{\hbar} \qquad \Omega_\beta = -\frac{\vec{\mu}_{23}\cdot\vec{E}_{\beta 0}}{\hbar}$$

- Total Hamiltonian: $H = H_0 + V$

$$H = \hbar \begin{pmatrix} 0 & \Omega_\alpha \cos\omega_\alpha t & 0 \\ \Omega_\alpha^* \cos\omega_\alpha t & \omega_{12} & \Omega_\beta \cos\omega_\beta t \\ 0 & \Omega_\beta^* \cos\omega_\beta t & \omega_{12} - \omega_{23} \end{pmatrix}$$

- Interaction Picture: $\overline{H} = U H_0 U^{-1}$

with

$$\hat{U} = e^{i\frac{H_{IP} t}{\hbar}}$$

$$H_{IP} = \hbar \begin{pmatrix} 0 & 0 & 0 \\ 0 & \omega_\alpha & 0 \\ 0 & 0 & \omega_\alpha - \omega_\beta \end{pmatrix}$$

RWA $\Rightarrow$

$$\overline{H} = \hbar \begin{pmatrix} 0 & \frac{\Omega_\alpha}{2} & 0 \\ \frac{\Omega_\alpha^*}{2} & \omega_{21} & \frac{\Omega_\beta}{2} \\ 0 & \frac{\Omega_\beta^*}{2} & \omega_{21} - \omega_{23} \end{pmatrix}$$

Density Matrix: coherent dynamics

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho]$$ In the interaction picture: $$\dot{\overline{\rho}} = -\frac{i}{\hbar}[\overline{H} - H_{IP}, \overline{\rho}]$$

With:

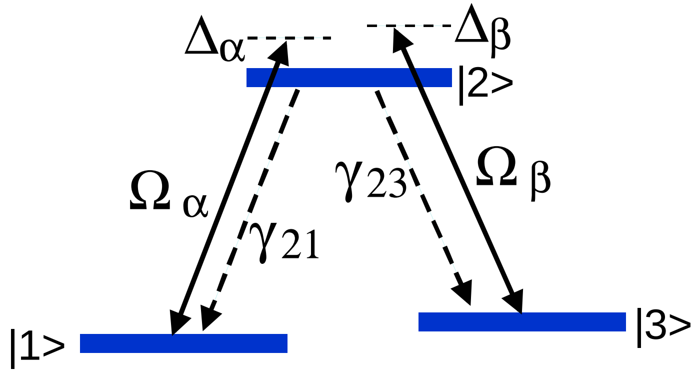
$$\overline{H} - H_{IP} = \frac{\hbar}{2}\begin{pmatrix} 0 & \Omega_\alpha & 0 \\ \Omega_\alpha^* & 2\Delta_\alpha & \Omega_\beta \\ 0 & \Omega_\beta^* & 2(\Delta_\alpha - \Delta_\beta) \end{pmatrix}$$

Density Matrix: adding the incoherent dynamics

$$\dot{\overline{\rho}} = -\frac{i}{\hbar}[\overline{H} - H_{IP}, \overline{\rho}] + L\overline{\rho}$$

where $L\overline{\rho}$ accounts for:

- spontaneous emission
- incoherent pumping
- elastic and inelastic collisions
- fluctuations in the phase and/or amplitude of the laser fields
- ...



$$\dot{\bar\rho} = -\frac{i}{\hbar}[\bar H - H_{IP}, \bar\rho] \qquad + L\bar\rho$$

$$\dot{\bar\rho}_{11} = -\mathrm{Im}\left(\Omega_\alpha^* \bar\rho_{12}\right) \qquad + \gamma_{21}\rho_{22}$$

$$\dot{\bar\rho}_{22} = \mathrm{Im}\left(\Omega_\alpha^* \bar\rho_{12}\right) + \mathrm{Im}\left(\Omega_\beta^* \bar\rho_{32}\right) \qquad - \gamma_{21}\rho_{22} - \gamma_{23}\rho_{22}$$

$$\dot{\bar\rho}_{33} = -\mathrm{Im}\left(\Omega_\beta^* \bar\rho_{32}\right) \qquad + \gamma_{23}\rho_{22}$$

$$\dot{\bar\rho}_{13} = -i\left[(\Delta_\beta - \Delta_\alpha)\bar\rho_{13} - \frac{\Omega_\beta^*}{2}\bar\rho_{12} + \frac{\Omega_\alpha}{2}\bar\rho_{23}\right] \qquad - \Gamma_{13}\rho_{13} \quad \text{with } \Gamma_{13} \geq 0$$

$$\dot{\bar\rho}_{12} = -i\left[(\bar\rho_{22} - \bar\rho_{11})\frac{\Omega_\alpha}{2} - \Delta_\alpha\bar\rho_{12} - \frac{\Omega_\beta}{2}\bar\rho_{13}\right] \qquad - \Gamma_{12}\rho_{12} \quad \text{with } \Gamma_{12} \geq (\gamma_{21} + \gamma_{23})/2$$

$$\dot{\bar\rho}_{23} = -i\left[(\bar\rho_{22} - \bar\rho_{33})\frac{\Omega_\beta^*}{2} - \Delta_\beta\bar\rho_{23} - \frac{\Omega_\alpha^*}{2}\bar\rho_{13}\right] \qquad - \Gamma_{32}\rho_{32} \quad \text{with } \Gamma_{32} \geq (\gamma_{21} + \gamma_{23})/2$$

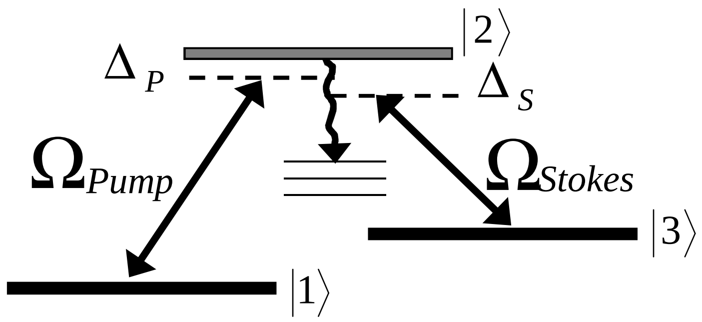
$\dot\Omega_\alpha = -\kappa\Omega_\alpha + ig\bar\rho_{12}$ $\quad$ κ: losses and g : gain constant

For $\Omega_\alpha \in \Re \Rightarrow \mathrm{Im}\,\bar\rho_{12}$ accounts for light absorption/amplification

$\mathrm{Re}\,\bar\rho_{12}$ yields the index of refraction

2.2 STIRAP: STIMULATED RAMAN ADIABATIC PASSAGE

"Coherent population transfer among quantum states of atoms and molecules"
K. Bergmann, H. Theuer, and B. W. Shore
Rev. Mod. Phys. 70, 1003 (1998)



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

Energy eigenstates:

$\Delta_P = \Delta_S = 0$

$$|+\rangle = \frac{1}{\sqrt{2}}\left[\sin\Theta|1\rangle + |2\rangle + \cos\Theta|3\rangle\right] \qquad \tan\Theta = \Omega_P(t)/\Omega_S(t)$$

$$|D\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle \qquad \omega^0 = 0$$

$$|-\rangle = \frac{1}{\sqrt{2}}\left[\sin\Theta|1\rangle - |2\rangle + \cos\Theta|3\rangle\right] \qquad \omega^\pm = \pm\sqrt{\Omega_P^2 + \Omega_S^2}$$

For $\Delta_P = \Delta_S \neq 0$ (Raman resonance condition)we still have $|D\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle$

For $\Delta_P \neq \Delta_S$, there is no dark state

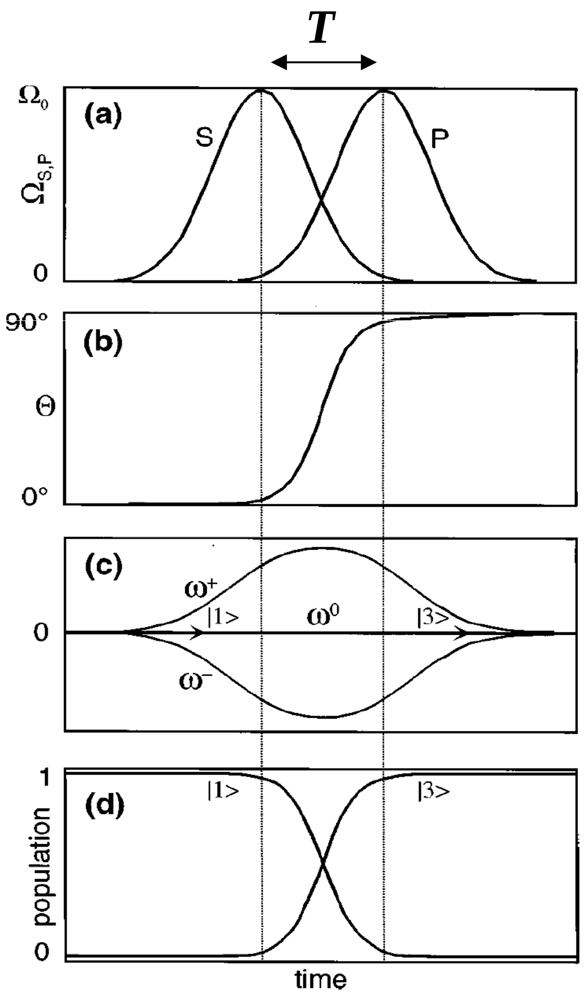
STIRAP: adiabatically following the dark state from $|1\rangle$ to $|3\rangle$, i.e. , $\Theta(t_0) = 0^o \rightarrow \Theta(t_f) = 90^o$

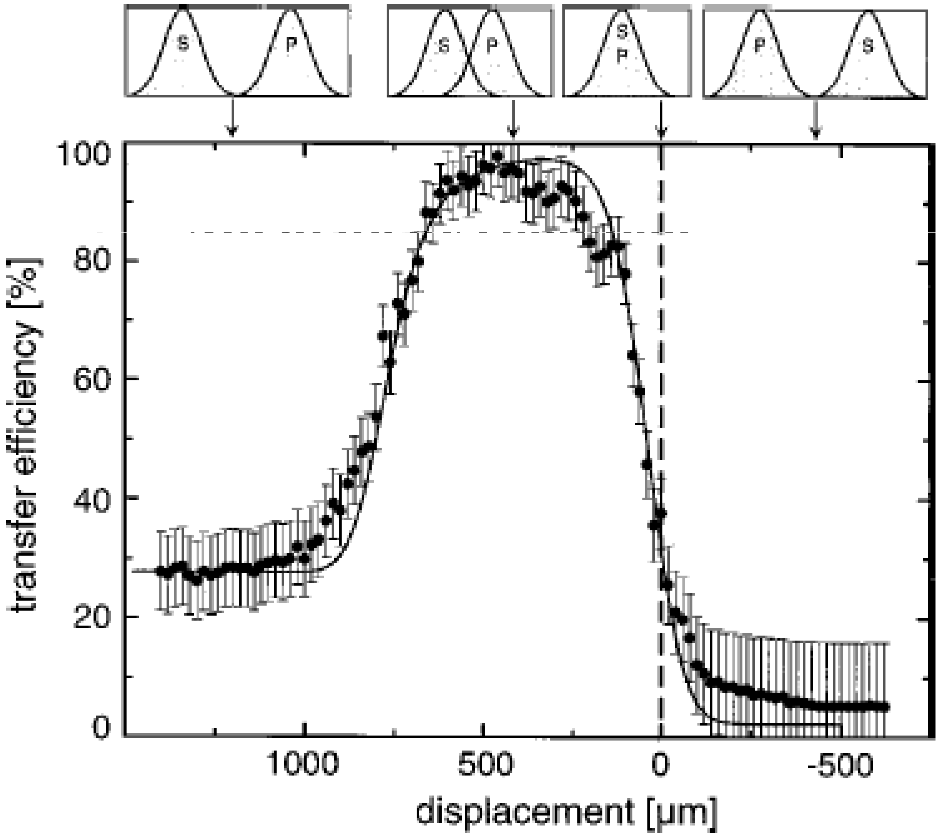
Reviews of Modern Physics, Vol. 70, No. 3, July 1998

Coherent population transfer among quantum states of atoms and molecules

K. Bergmann, H. Theuer, and B. W. Shore*

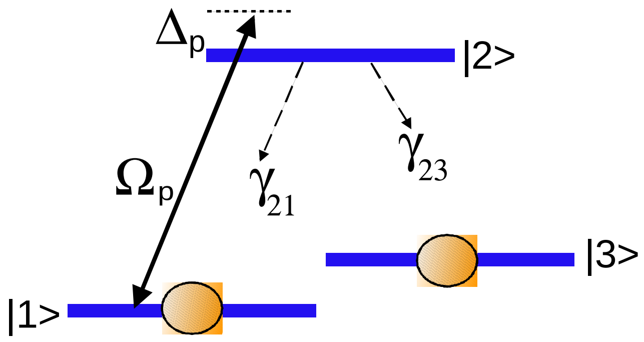
Fachbereich Physik der Universität Kaiserslautern, 67653 Kaiserslautern, Germany

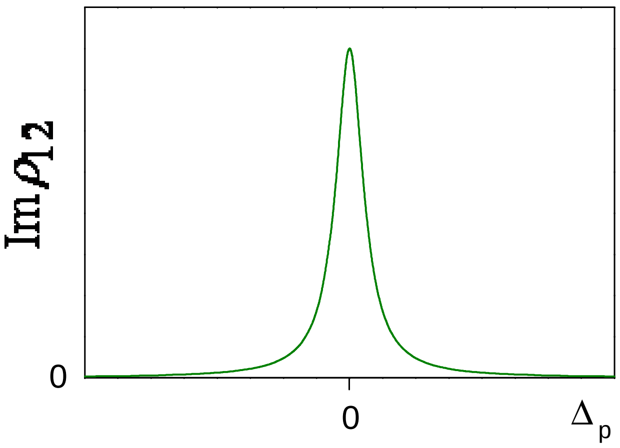




2.3 EIT: ELECTROMAGNETICALLY INDUCED TRANSPARENCY

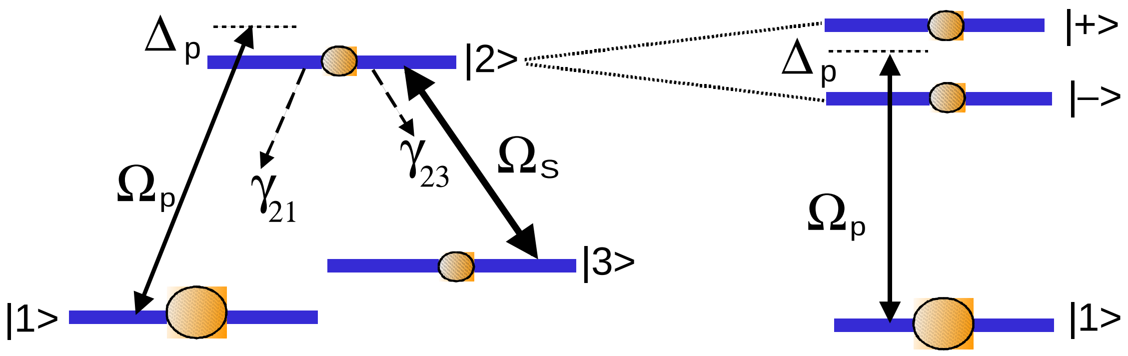
- For $\Omega_S = 0$, the probe absorption profile is Lorentzian

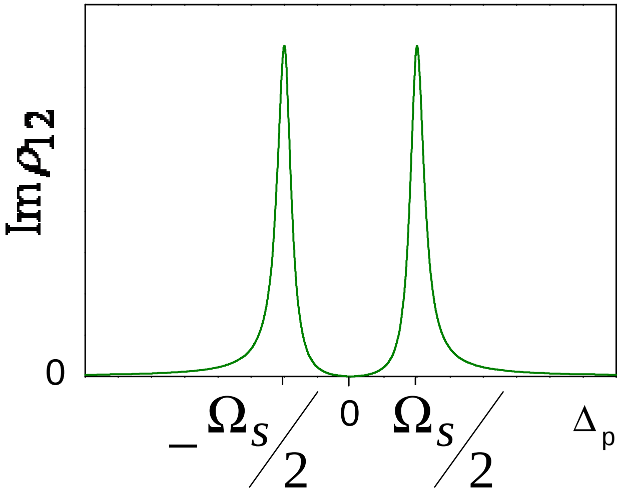


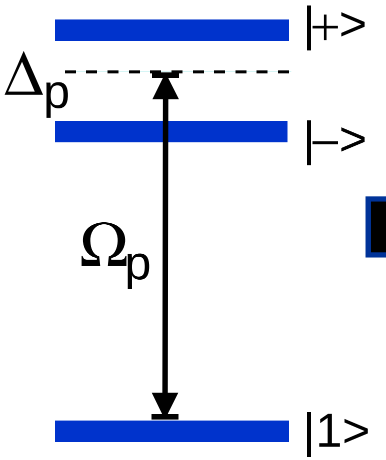


- For $\Omega_S \neq 0$, Δ_S=0 and $\Omega_P << \Omega_S$

K. J. Boller *et al.*, Phys. Rev. Lett. **66**, 2593 (1991)
J. E. Field *et al.*, Phys. Rev. Lett. **67**, 3062 (1991)
J. R. Boon *et al.*, Phys. Rev. A **57**, 1323 (1998)







$$P_{abs} \alpha \left| A_{1-} + A_{1+} \right|^2 = \left| A_{1-} \right|^2 + \left| A_{1+} \right|^2 + 2\,\mathrm{Re}\left\{ A_{1-} A_{1+}^* \right\}$$

Interference term due to quantum interference

Steady-state solution for $\Omega_p << \Omega_s \in \Re$ with $\Delta_S = 0$

$$\left(\frac{\mathrm{Im}\,\bar{\rho}_{12}}{\Omega_p} \right)_{steady\ state} \equiv K_1 + K_2$$

Two Lorentzian resonances ⟶

$$K_1 = (\bar{\rho}_{11} - \bar{\rho}_{22}) \frac{(\Omega_S/2)^2 \Gamma_{13} + \left(\Delta_p^2 + \Gamma_{13}^2\right)\Gamma_{12}}{\left((\Omega_S/2)^2 - \Delta_p^2 + \Gamma_{12}\Gamma_{13}\right)^2 + \Delta_p^2 (\Gamma_{12} + \Gamma_{13})^2}$$

Two dispersive resonances = quantum intereferncе contribution ⟶

$$K_2 = -\frac{\Omega_S}{2} \mathrm{Im}\,\bar{\rho}_{23} \frac{(\Omega_S/2)^2 - \Delta_p^2 + \Gamma_{12}\Gamma_{13}}{\left((\Omega_S/2)^2 - \Delta_p^2 + \Gamma_{12}\Gamma_{13}\right)^2 + \Delta_p^2 (\Gamma_{12} + \Gamma_{13})^2}$$

K. J. Boller, A. Imamoglu, S. Harris, Phys. Rev. Lett. **66**, 2593 (1991)

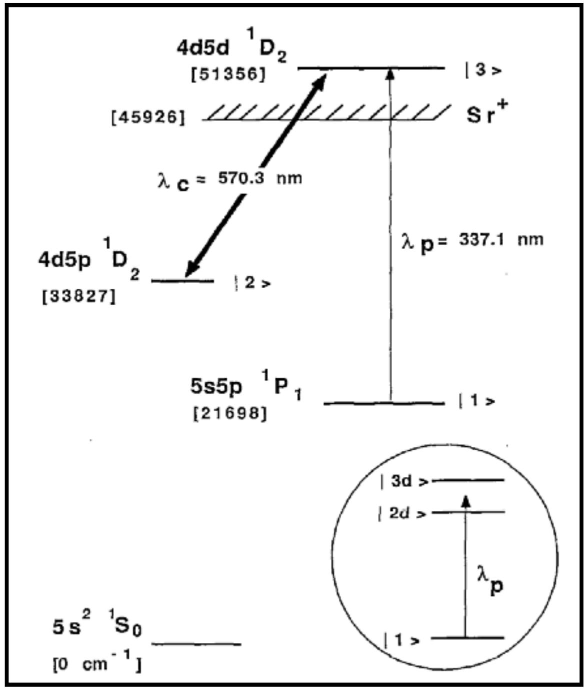
VOLUME 66, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1991

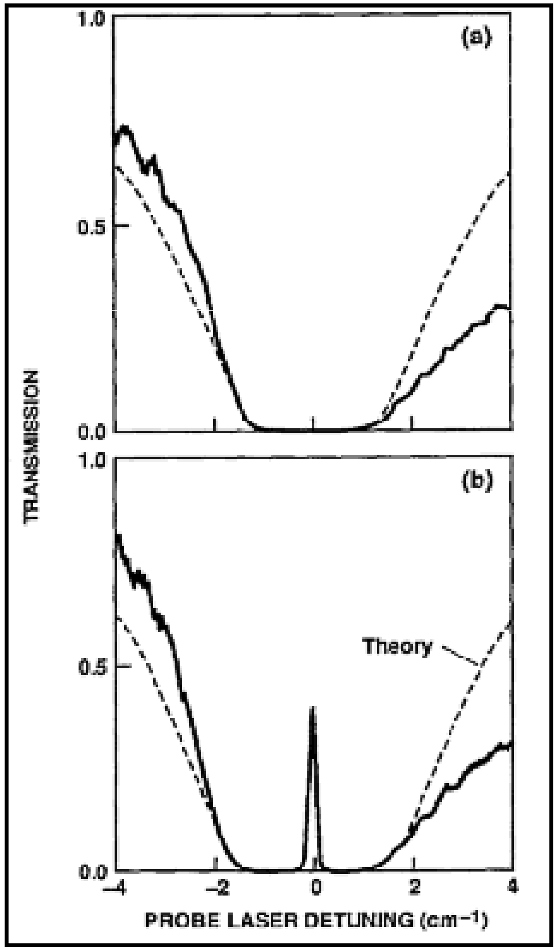
Observation of Electromagnetically Induced Transparency

K.-J. Boller, A. Imamoğlu, and S. E. Harris
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

(Received 12 December 1990)

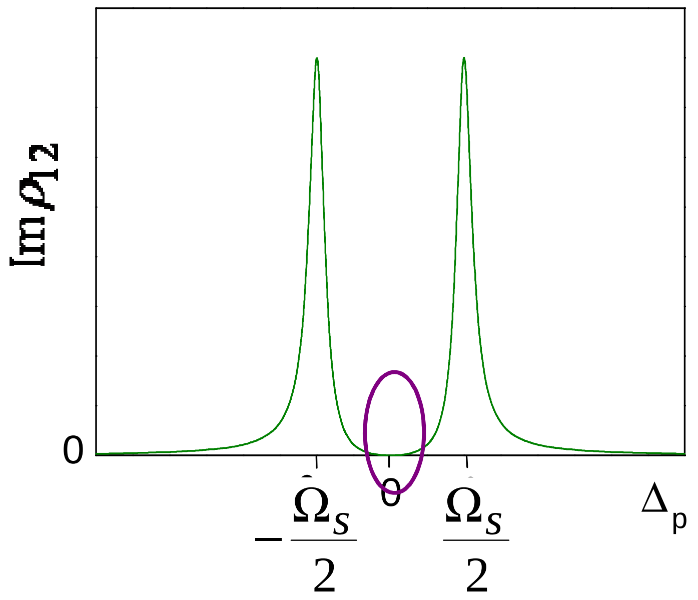
We report the first demonstration of a technique by which an optically thick medium may rendered transparent. The transparency results from a destructive interference of two dressed states which are created by applying a temporally smooth coupling laser between a bound state of an atom and the upper state of the transition which is to be made transparent. The transmitance of an autoionizing (ultraviolet) transition in Sr is changed from exp(-20) without a coupling laser to exp(-1) in the presence of a coupling laser.

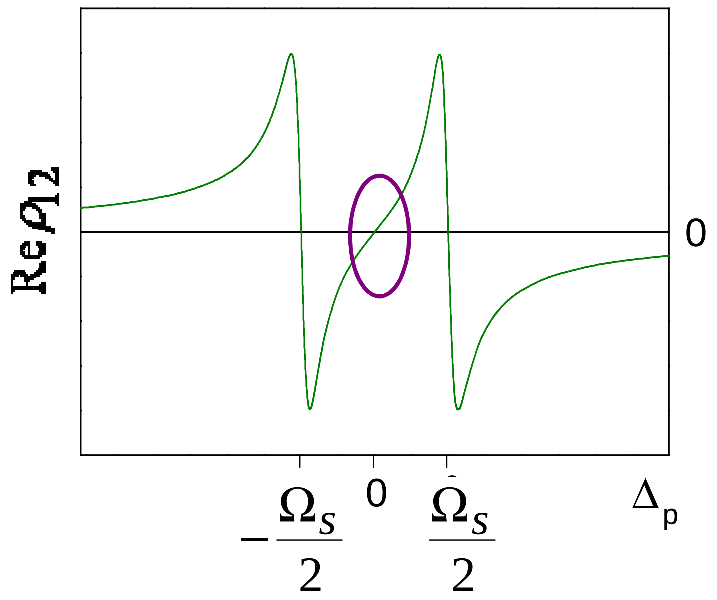




Slow light. Reducing group's velocity via EIT

L. H. Hau et al., Nature **397**, 594 (1999).
M. M. Kash et al., Phys. Rev. Lett. **82**, 5229 (1999).





Phase velocity: $v = c/n$

Group velocity: $v_g = \dfrac{c}{n(\nu) + \nu \dfrac{dn}{d\nu}}$ $\xrightarrow{\frac{dn}{d\nu} > 0}$ $v_g << c$

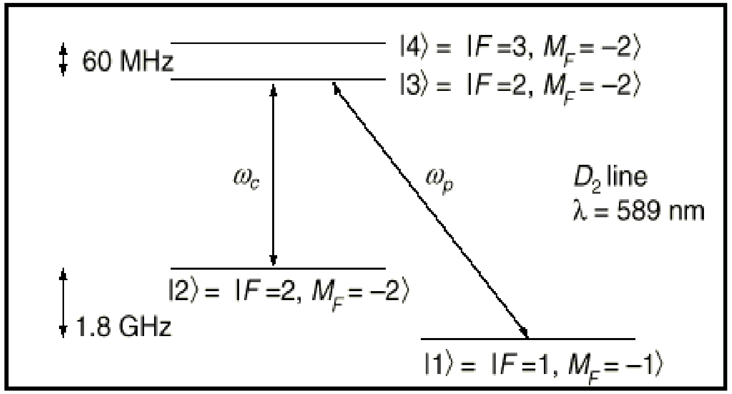
L. H. Hau *et al.*, Nature **397**, 594 (1999).

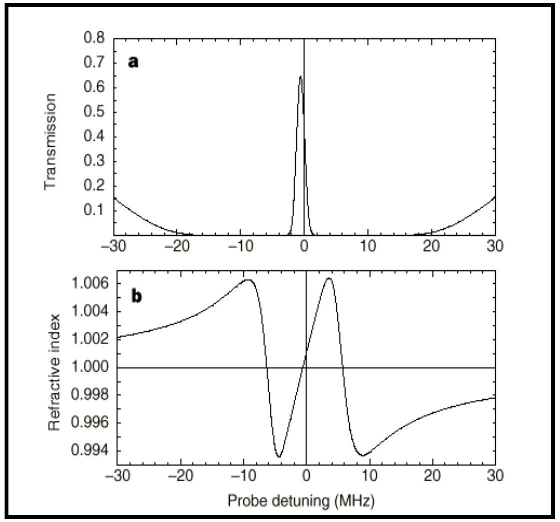
letters to nature

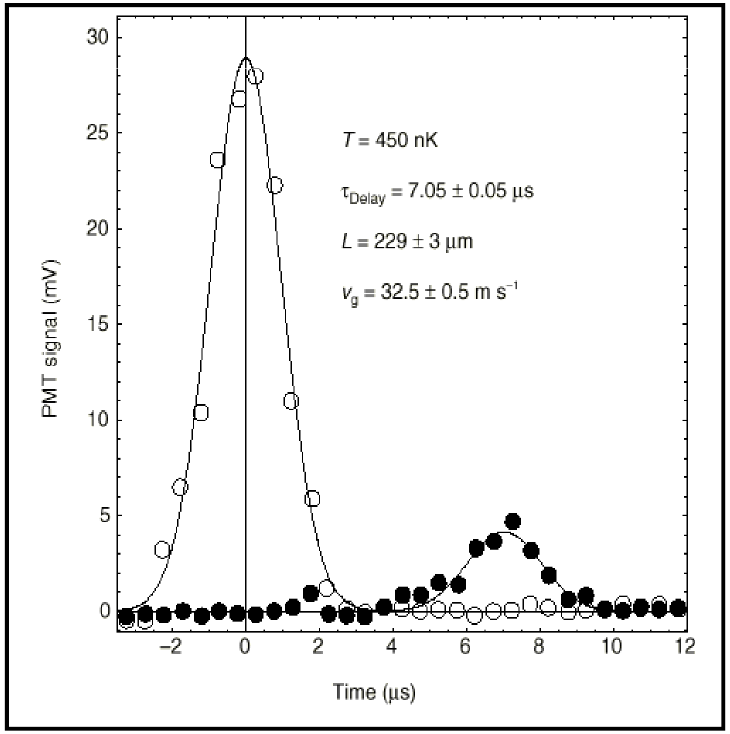
Light speed reduction to 17 metres per second in an ultracold atomic gas

Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

** Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA*
† Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
‡ Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA





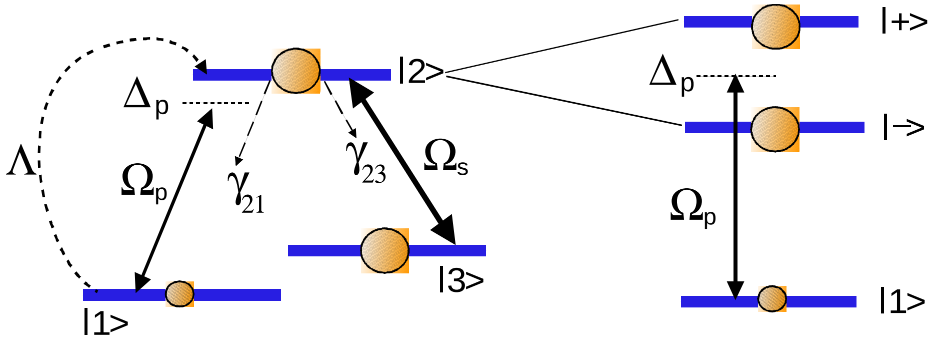


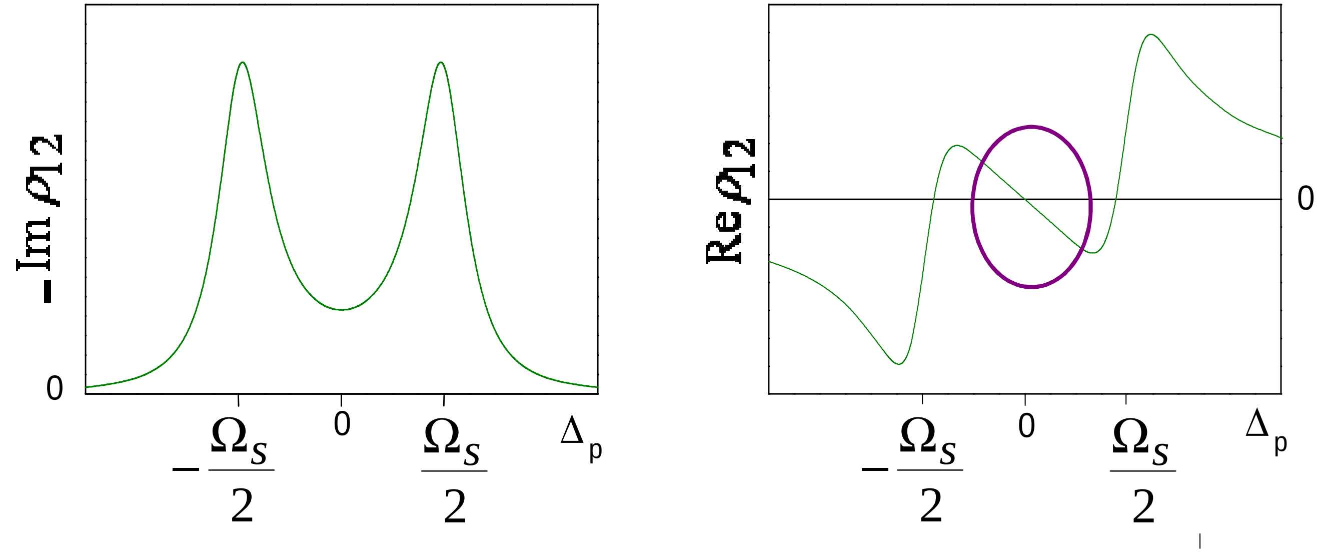
Superluminical light

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

$$\frac{dn}{d\nu} < 0$$

$$v_g >> c$$





D. Mugnai *et al.*, Phys. Rev. Lett. **84**, 4830 (2000). ← microwaves
L. J. Wang *et al.*, Nature **406**, 277 (2000). ← visible

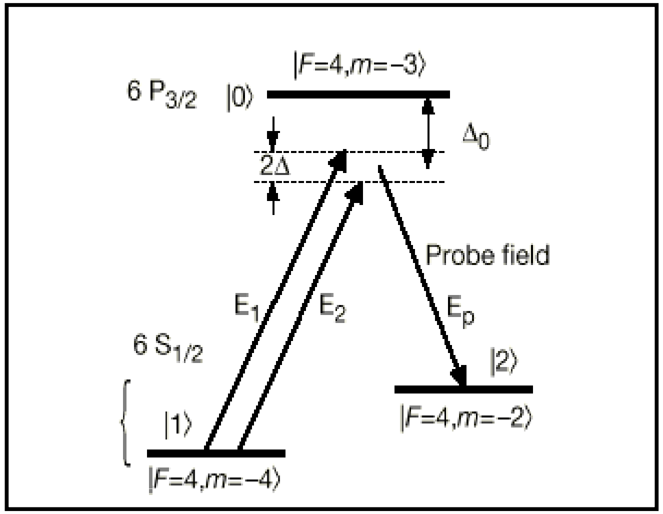
L. J. Wang *et al.*, Nature **406**, 277 (2000)

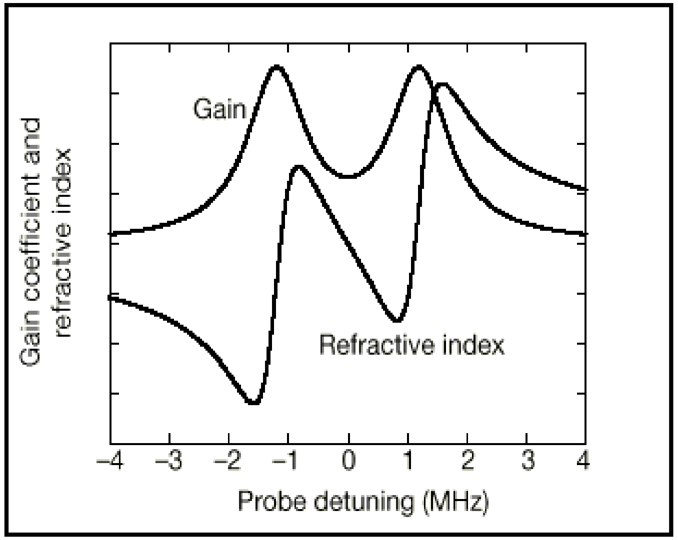
letters to nature

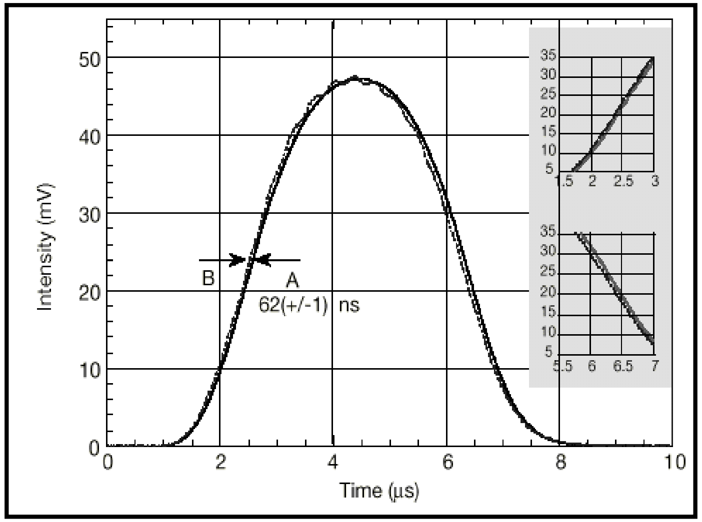
Gain-assisted superluminal light propagation

L. J. Wang, A. Kuzmich & A. Dogariu

NEC Research Institute, 4 Independence Way, Princeton, New Jersey 08540, USA







…other non-linear optics induced by atomic coherences

VOLUME 82, NUMBER 23 PHYSICAL REVIEW LETTERS 7 JUNE 1999

Nonlinear Optics at Low Light Levels

S. E. Harris
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

Lene Vestergaard Hau
Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142
and Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 21 December 1998)

We show how the combination of electromagnetically induced transparency based nonlinear optics and cold atom technology, under conditions of ultraslow light propagation, allows nonlinear processes at energies of a few photons per atomic cross section.

VOLUME 84, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 2000

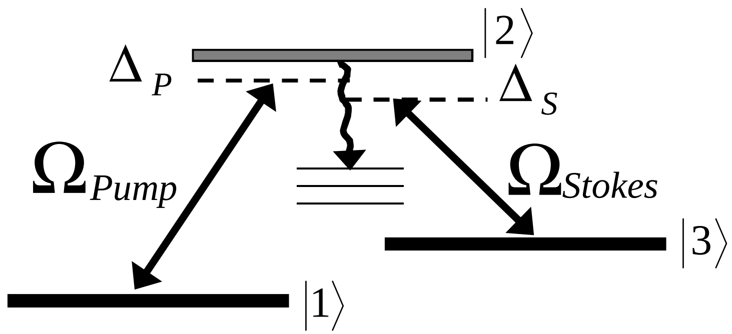
Nonlinear Optics and Quantum Entanglement of Ultraslow Single Photons

M. D. Lukin[1] and A. Imamoğlu[2]
[1]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
[2]*Department of Electrical and Computer Engineering, and Department of Physics, University of California, Santa Barbara, California 93106*
(Received 19 October 1999)

Two light pulses propagating with slow group velocities in a coherently prepared atomic gas exhibit dissipation-free nonlinear coupling of an unprecedented strength. This enables a single-photon pulse to coherently control or manipulate the quantum state of the other. Processes of this kind result in generation of entangled states of radiation field and open up new prospectives for quantum information processing energies of a few photons per atomic cross section.

EIT from an adiabatic point of view.

Let us assume that the Stokes laser is a continuous wave (cw) laser:



$$\Delta_P = \Delta_S$$

$$|D\rangle = \cos\Theta|1\rangle - \sin\Theta|3\rangle$$

In this case:

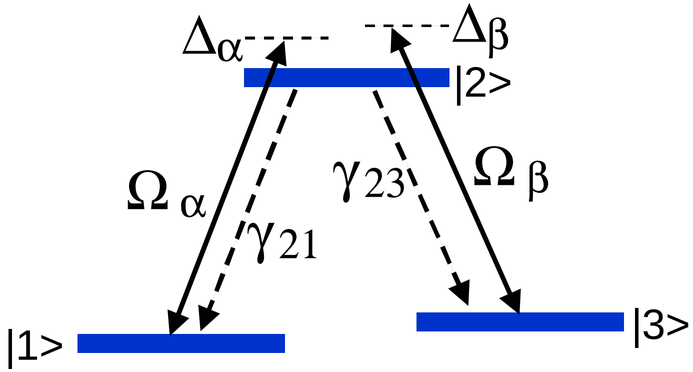
$$\Theta = 0^o \rightarrow \Theta = X^o \rightarrow \Theta = 0^o \quad \Longrightarrow \quad |1\rangle \rightarrow a|1\rangle + b|3\rangle \rightarrow |1\rangle$$

$$X^o = \tan^{-1}\frac{(\Omega_{Pump})_{MAX}}{\Omega_{Stokes}}$$

The atom starts in state |1>, interacts with the laser fields and, eventually, it ends up again in state |1>, without absorbing any photon.

ELECTROMAGNETICALLY INDUCED TRANSPARENCY

2.4 CPT: COHERENT POPULATION TRAPPING



Let us assume now:

- $\Omega_\alpha, \Omega_\beta$ are continuous wave
- The initial state of the atom is not known
- $\gamma_{21} = \gamma_{23}$ for simplicity

In the interaction picture, the Hamiltonian of the three-level system is:

$$H_{3L} = \overline{H} - H_{IP} = \frac{\hbar}{2}\begin{pmatrix} 0 & \Omega_\alpha & 0 \\ \Omega_\alpha^* & 2\Delta_\alpha & \Omega_\beta \\ 0 & \Omega_\beta^* & 2(\Delta_\alpha - \Delta_\beta) \end{pmatrix}$$

Let's define the dark and bright states as:

$$|D\rangle \equiv \frac{1}{N}\left[\Omega_\beta |1\rangle - \Omega_\alpha^* |3\rangle\right]$$

$$|B\rangle \equiv \frac{1}{N}\left[\Omega_\alpha |1\rangle + \Omega_\beta^* |3\rangle\right]$$

$$N \equiv \sqrt{\left|\Omega_\alpha^2\right|^2 + \left|\Omega_\beta^2\right|^2}$$

$$H_{3L}|D\rangle = -\frac{\hbar}{N}(\Delta_\alpha - \Delta_\beta)\Omega_\alpha^* |3\rangle = 0$$

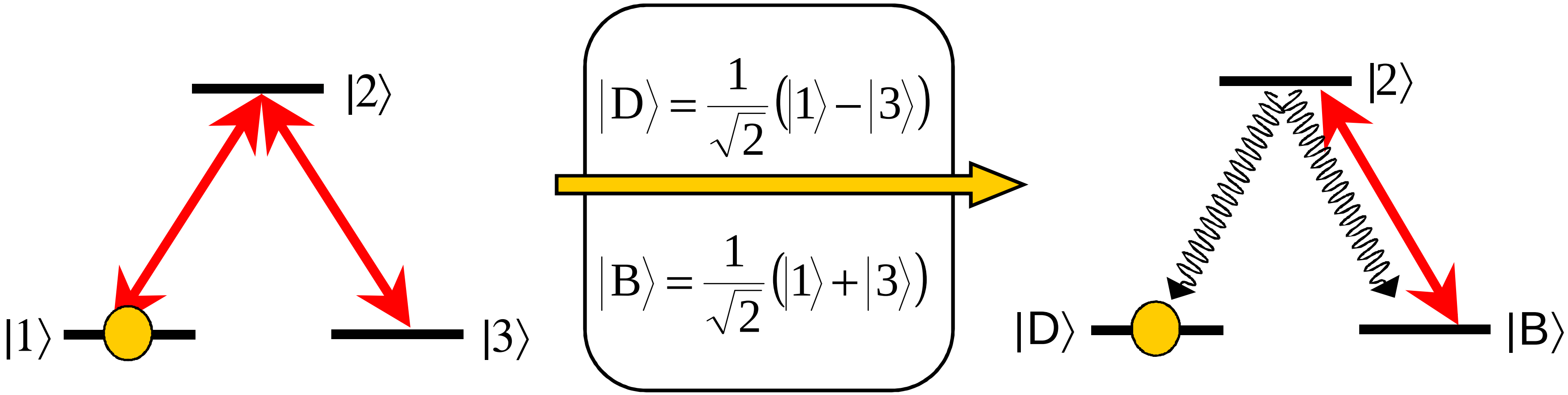
$$H_{3L}|B\rangle = \frac{\hbar}{2N}\left(\left|\Omega_\alpha\right|^2 + \left|\Omega_\beta\right|^2\right)|2\rangle + \frac{\hbar}{N}(\Delta_\alpha - \Delta_\beta)\Omega_\beta^* |3\rangle = \frac{\hbar}{2}\sqrt{\left|\Omega_\alpha\right|^2 + \left|\Omega_\beta\right|^2}\,|2\rangle$$

$$\Delta_\alpha = \Delta_\beta$$

$$H_{3L}\left|D\right\rangle = -\frac{\hbar}{N}(\Delta_\alpha - \Delta_\beta)\Omega_\alpha^*\left|3\right\rangle = 0$$

$$H_{3L}\left|B\right\rangle = \frac{\hbar}{2N}\left(\left|\Omega_\alpha\right|^2 + \left|\Omega_\beta\right|^2\right)\left|2\right\rangle + \frac{\hbar}{N}(\Delta_\alpha - \Delta_\beta)\Omega_\beta^*\left|3\right\rangle = \frac{\hbar}{2}\sqrt{\left|\Omega_\alpha\right|^2 + \left|\Omega_\beta\right|^2}\left|2\right\rangle$$

$\Rightarrow$ Let us assume, for simplicity: $\Omega_\alpha = \Omega_\beta \in \Re$; $\Delta_\alpha = \Delta_\beta$; $\gamma_{21} = \gamma_{23}$



$\Rightarrow$ After several cycles of absorption and spontaneous emission, the atom is eventually trapped in the dark state

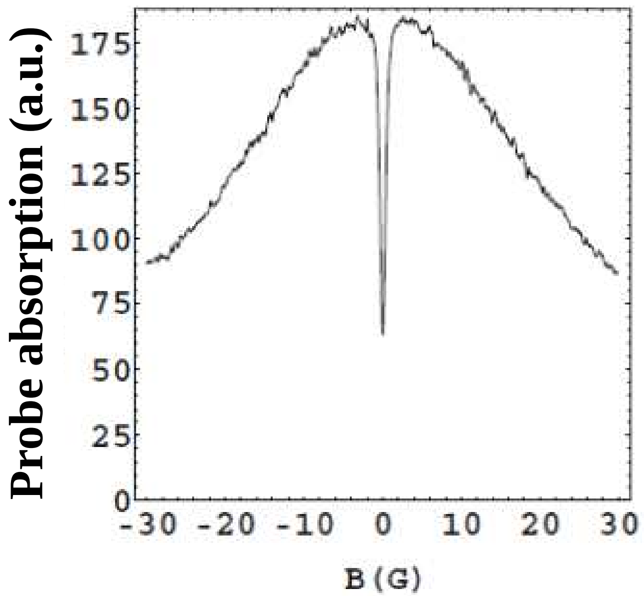
G. Alzetta, A. Gozzini, L. Moi and G. Orriols, Nuovo Cimento B **36** (1976) 5.

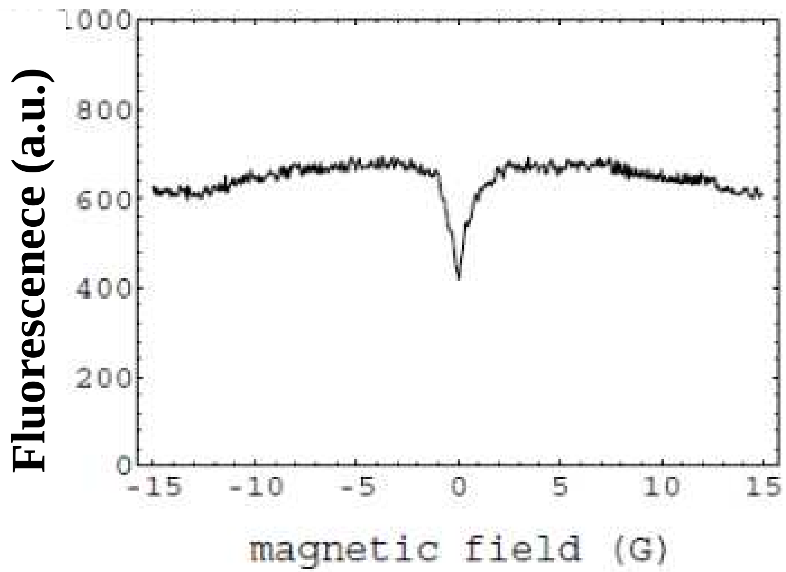
E. Arimondo, and G. Orriols, Nuovo Cimento Lett. **17** (1976) 333.

G. Orriols, Nuovo Cimento B **53** (1979) 1.

E. Arimondo, Coherent population trapping in laser spectroscopy, Progress in Optics, vol **35**, ed. E. Wolf (Amsterdam: Elseveier) 1996.

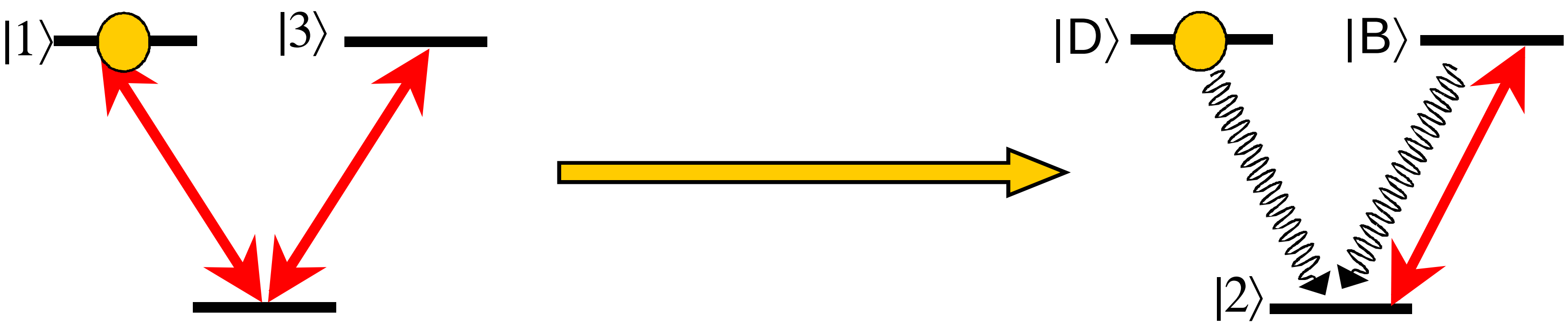
F. Renzoni, W. Maichen, L. Windholz, and E. Arimondo, Phys. Rev. A **55**, 3710 (1997)



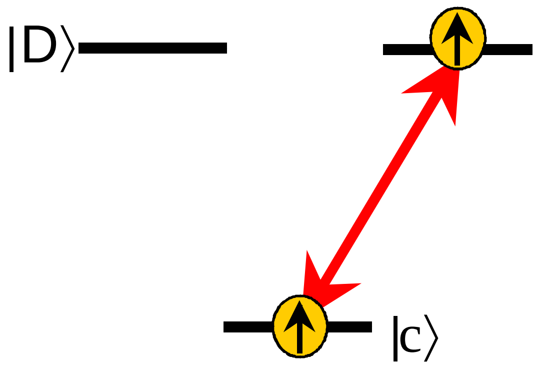


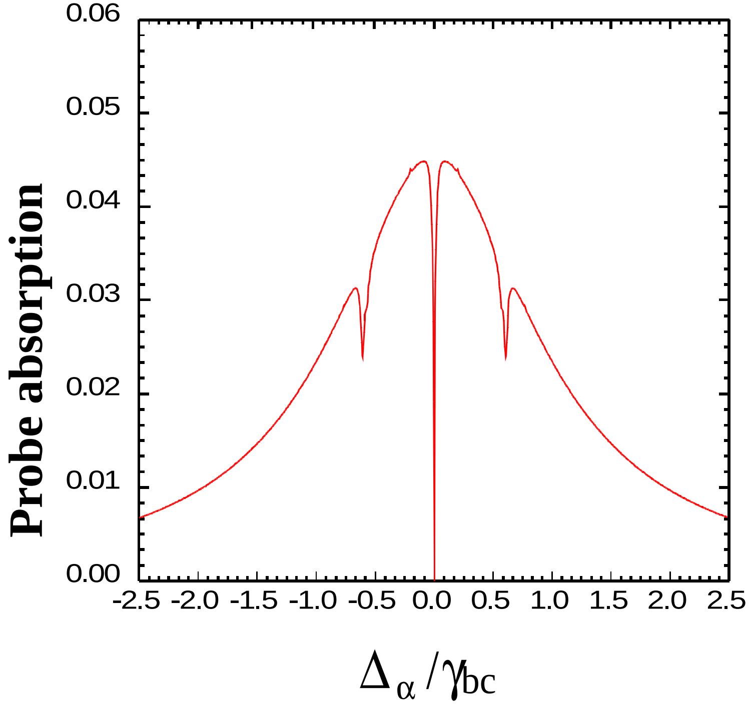
Coherent population trapping on the D_1 line of a thermal sodium beam

⇒ In the V-scheme, there is no CPT due to spontaneous emission.



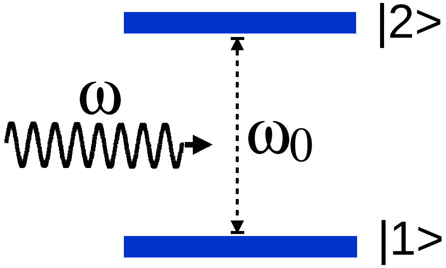
Coherent population trapping in two-electron three-level systems with aligned spins
J. Mompart, R. Corbalán, L. Roso, Phys. Rev. Lett. **88**, 023603 (2002).





2.5 RAP: RAPID ADIABATIC PASSAGE, REVISITED

N. V. Vitanov and B. W. Shore. Stimulated Raman adiabatic passage in a two-state system.
Phys. Rev. A **73**, 053402 (2006)



$$\Omega \equiv -\frac{\vec{\mu}_0 \cdot \vec{E}_0}{\hbar}$$

$$\Delta \equiv \omega - \omega_0$$

$$|\psi(t)\rangle = a_1(t)e^{-i\omega_1 t}|1\rangle + a_2(t)e^{-i(\omega_1+\omega)t}|2\rangle$$

$$i\begin{pmatrix}\dot{a}_1\\ \dot{a}_2\end{pmatrix} = \begin{pmatrix}0 & -\Omega/2\\ -\Omega/2 & -\Delta\end{pmatrix}\begin{pmatrix}a_1\\ a_2\end{pmatrix}$$

We define new variables: $u = 2\,\mathrm{Re}\{a_1 a_2^*\} = 2\,\mathrm{Re}\,\rho_{12}$

$$v = 2\,\mathrm{Im}\{a_1 a_2^*\} = 2\,\mathrm{Im}\,\rho_{12}$$

$$w = |a_2|^2 - |a_2|^2 = \rho_{22} - \rho_{11}$$

$$u^2 + v^2 + w^2 = 1$$

Following:

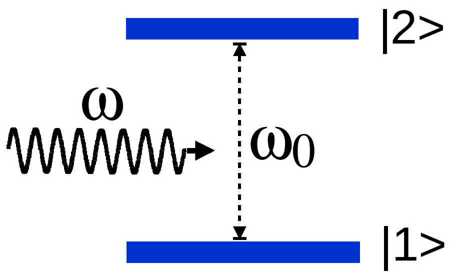
$$\frac{d}{dt}\begin{pmatrix}u\\ v\\ w\end{pmatrix} = \begin{pmatrix}0 & -\Delta & 0\\ \Delta & 0 & -\Omega\\ 0 & \Omega & 0\end{pmatrix}\begin{pmatrix}u\\ v\\ w\end{pmatrix}$$

There is one eigenvector with null eigenvalue:

$$d(\theta) = w\cos\vartheta - u\sin\theta = 0$$

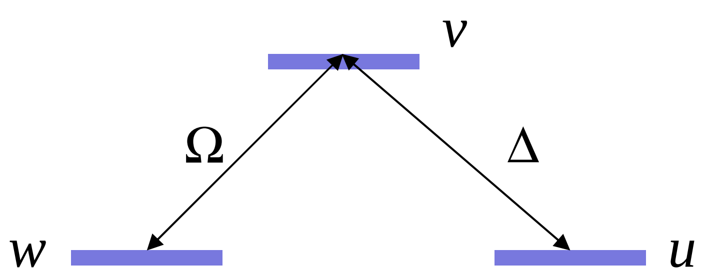
with $\tan\theta = \dfrac{\Omega}{\Delta}$

2.5 RAP: RAPID ADIABATIC PASSAGE, REVISITED



$$\Delta \equiv \omega - \omega_0$$

$$\Omega \equiv -\frac{\vec{\mu}_0 \cdot \vec{E}_0}{\hbar}$$



$$d(\theta) = w\cos\vartheta - u\sin\theta = 0 \quad \text{with} \quad \tan\theta = \frac{\Omega}{\Delta}$$

$$u = 2\,\mathrm{Re}\{a_1 a_2^*\} = 2\,\mathrm{Re}\,\rho_{12}$$

$$v = 2\,\mathrm{Im}\{a_1 a_2^*\} = 2\,\mathrm{Im}\,\rho_{12}$$

$$w = |a_2|^2 - |a_2|^2 = \rho_{22} - \rho_{11}$$

$$u^2 + v^2 + w^2 = 1$$

$$\frac{d}{dt}\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 0 & -\Delta & 0 \\ \Delta & 0 & -\Omega \\ 0 & \Omega & 0 \end{pmatrix}\begin{pmatrix} u \\ v \\ w \end{pmatrix}$$

RAP, revisited:

The atom is initially in the ground state with:

$$\Delta > 0;\ |\Delta| >> \Omega \ \Rightarrow\ \theta(t_0) = 0$$

$$w = -1, u = v = 0 \ \Rightarrow\ d(t_0) = 0$$

At the end: $\Delta < 0;\ |\Delta| >> \Omega \ \Rightarrow\ \theta(t_f) = \pi$

As: $d(t) = 0 \ \forall t$

Then, at the end:

$$w = 1, u = v = 0 \ \Rightarrow\ \rho_{22}(t_f) = 1$$

3 LA 'RIGA NERA'

MAIN ARTICLES

FIRST EXPERIMENT

G. Alzetta, A. Gozzini, L. Moi and G. Orriols, Nuovo Cimento B 36 (1976) 5.

FIRST THEORY

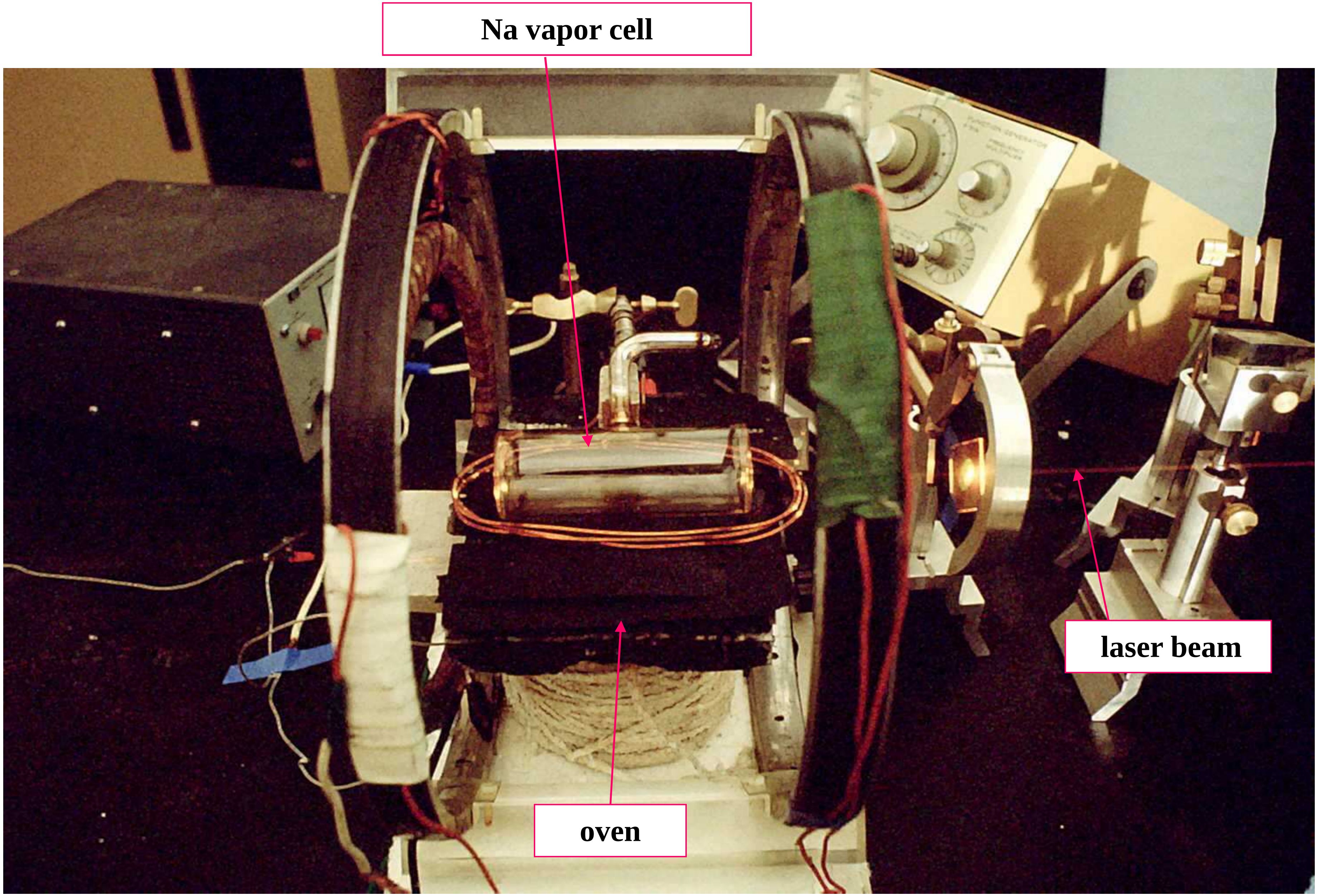
E. Arimondo, and G. Orriols, Nuovo Cimento Lett. 17 (1976) 333.

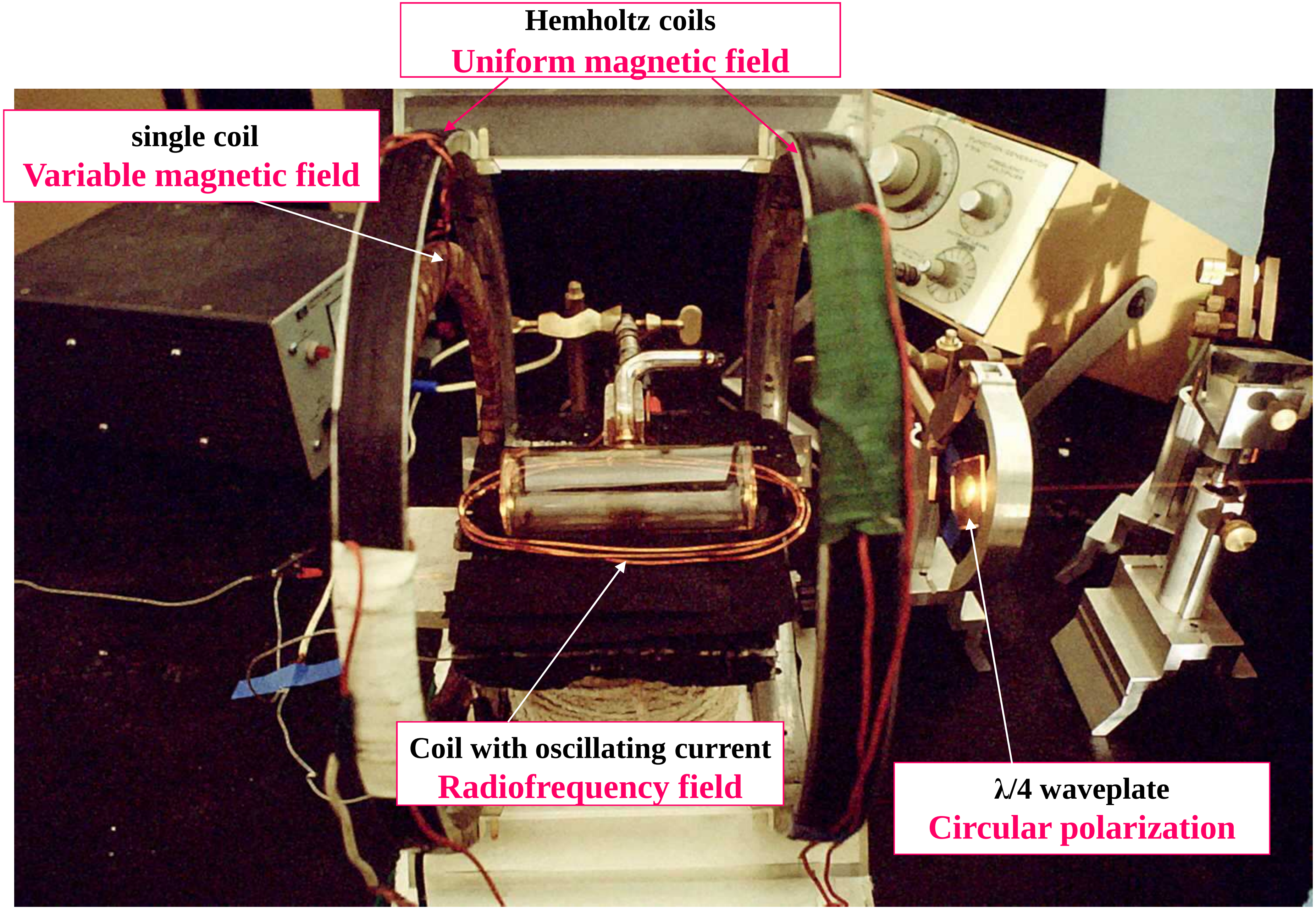
G. Orriols, Nuovo Cimento B 53 (1979) 1.

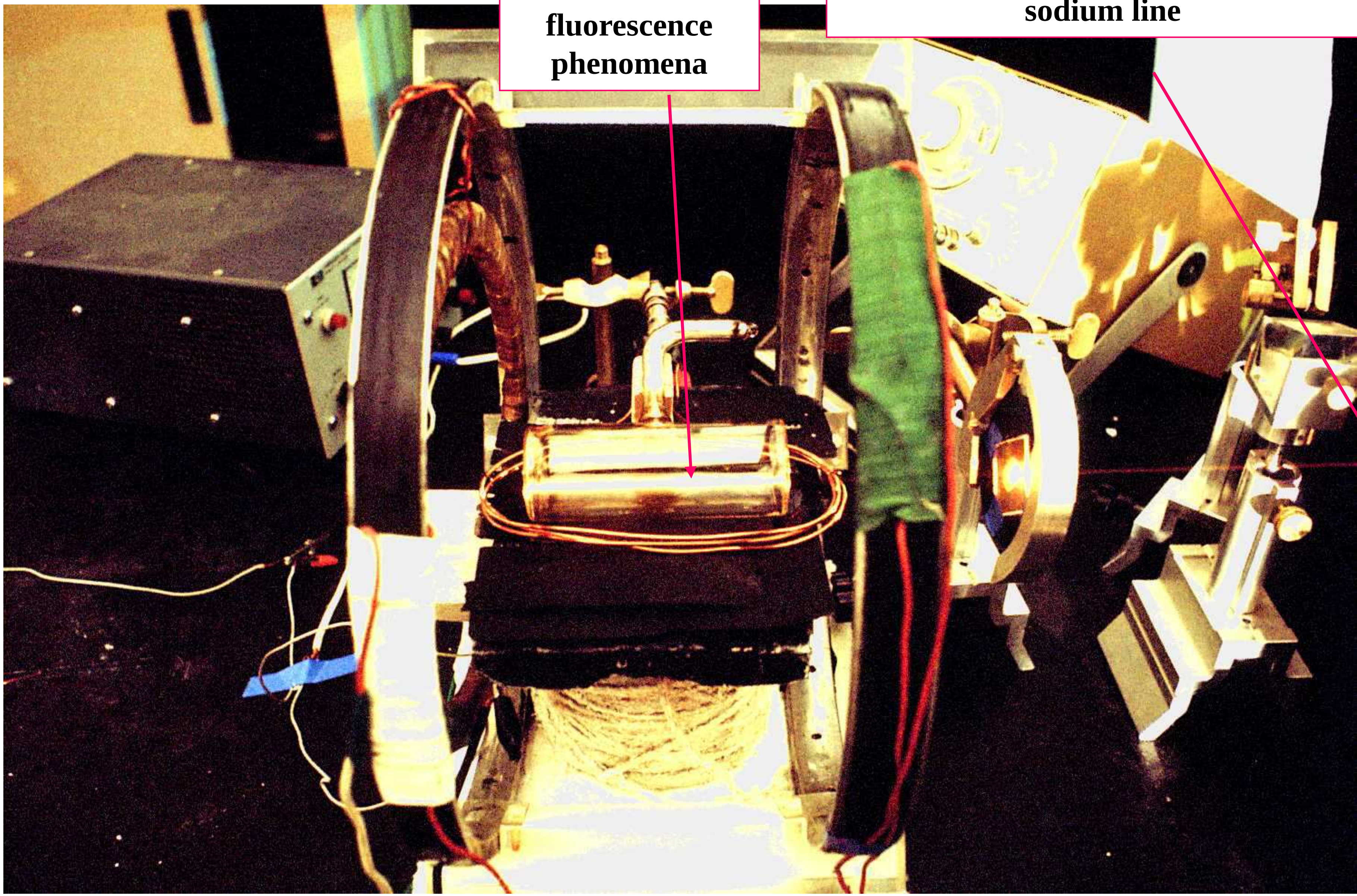
MAIN REVIEW ARTICLE

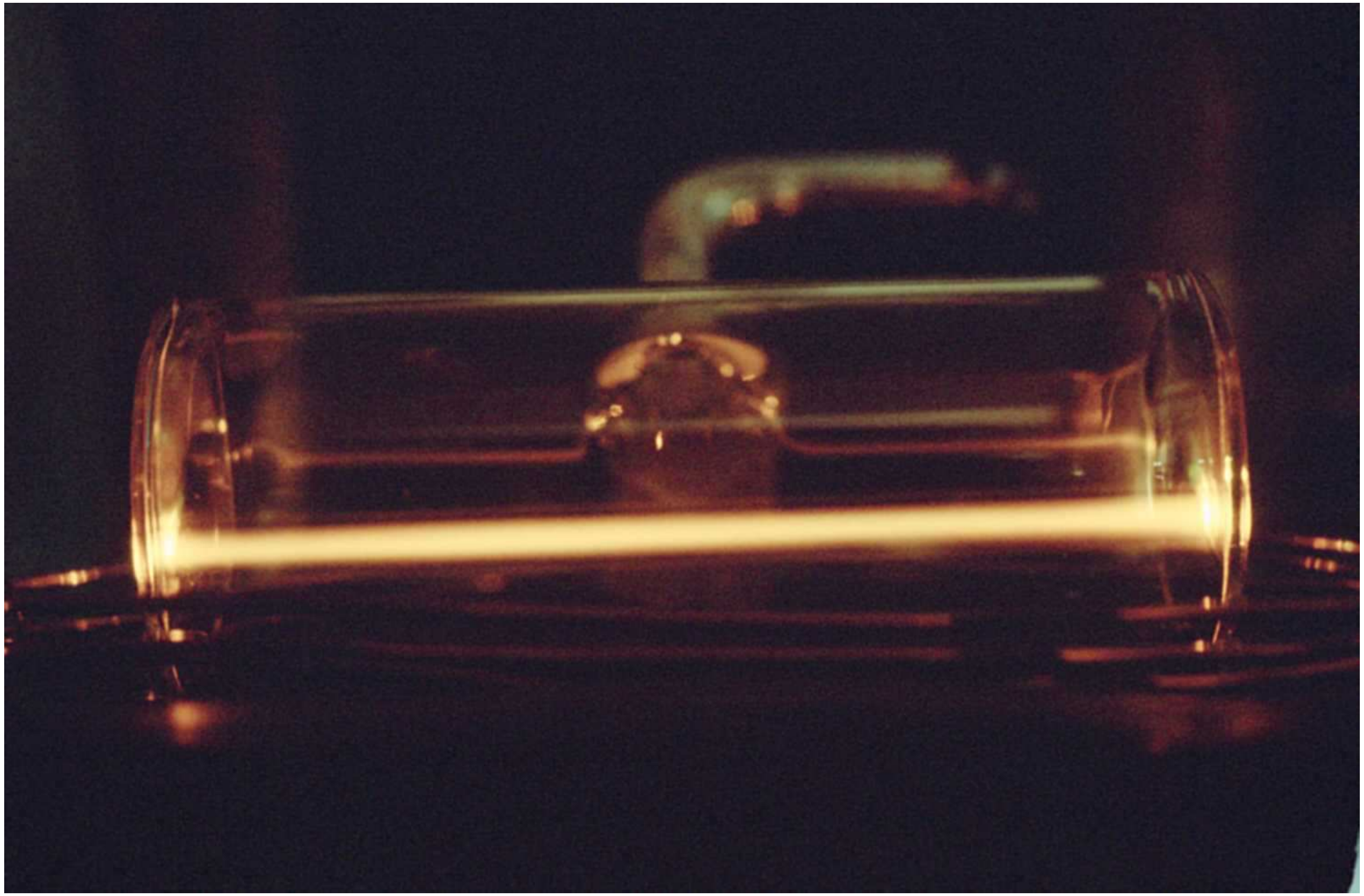
E. Arimondo, Coherent population trapping in laser spectroscopy, Progress in Optics, vol 35, ed. E. Wolf (Amsterdam: Elseveier) 1996.

Experiments with a sodium vapor cell

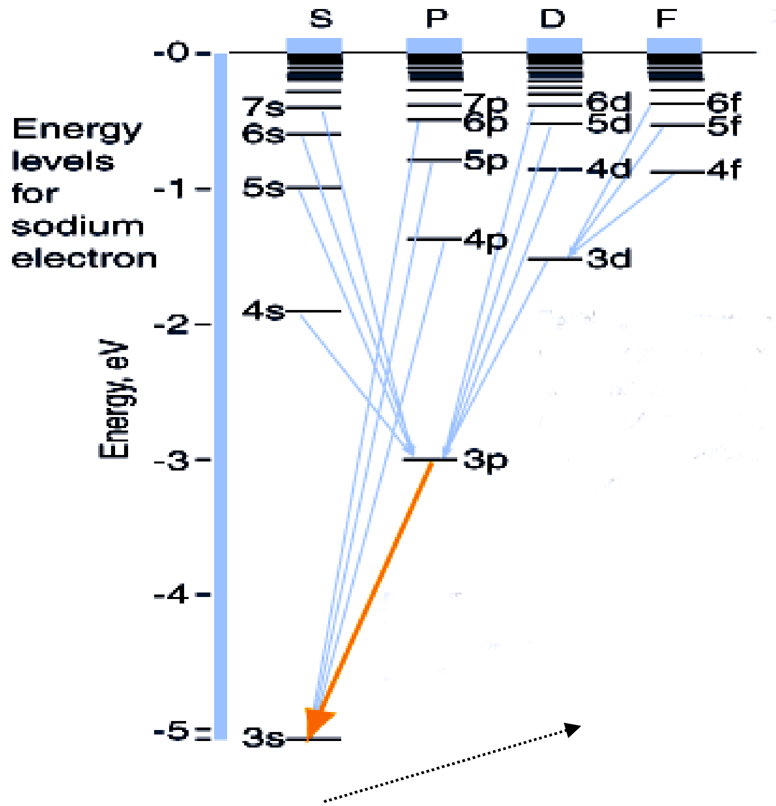


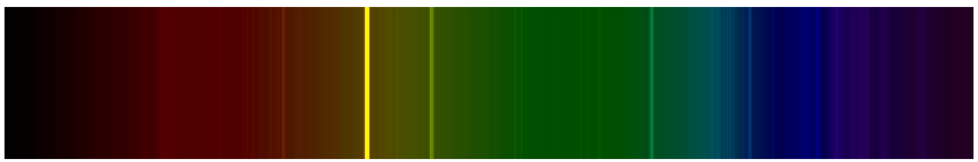

Hemholtz coils
Uniform magnetic field
single coil
Variable magnetic field
Coil with oscillating current
Radiofrequency field
λ/4 waveplate
Circular polarization

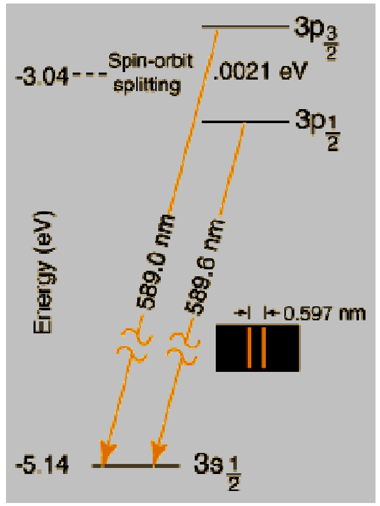

resonant fluorescence phenomena
Tuning the laser wavelength to the D_1 sodium line



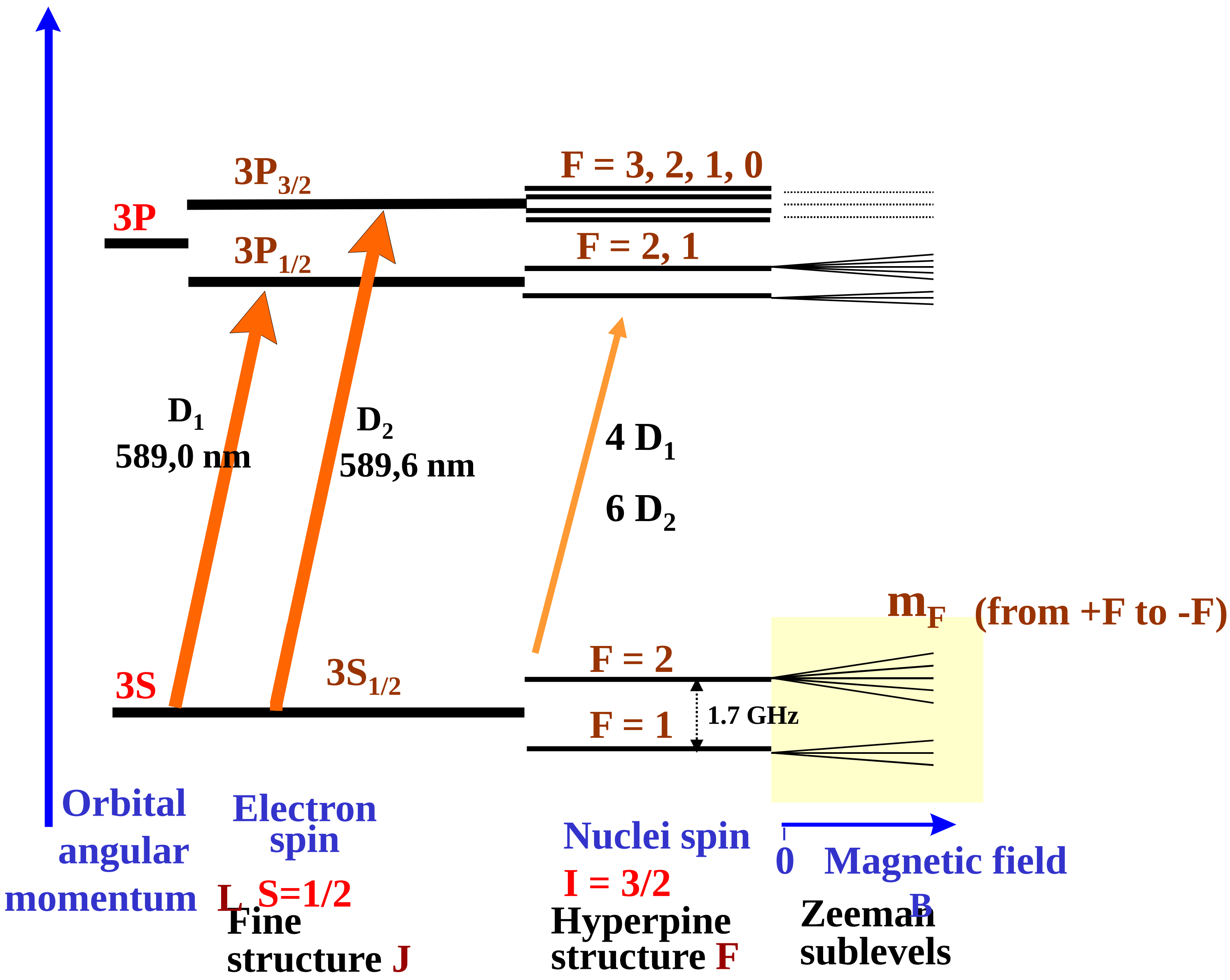
Sodium atom


S
P
D
F
-0-
-1-
-2-
-3-
-4-
-5-
7s
6s
5s
4s
3s
7p
6p
5p
4p
3p
6d
5d
4d
3d
6f
5f
4f
Energy levels for sodium electron
Energy, eV



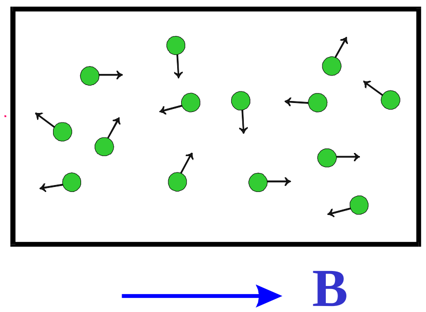

$3p_{3/2}$
-3.04
Spin-orbit splitting
.0021 eV
$3p_{1/2}$
Energy (eV)
589.0 nm
589.6 nm
0.597 nm
-5.14
$3s_{1/2}$

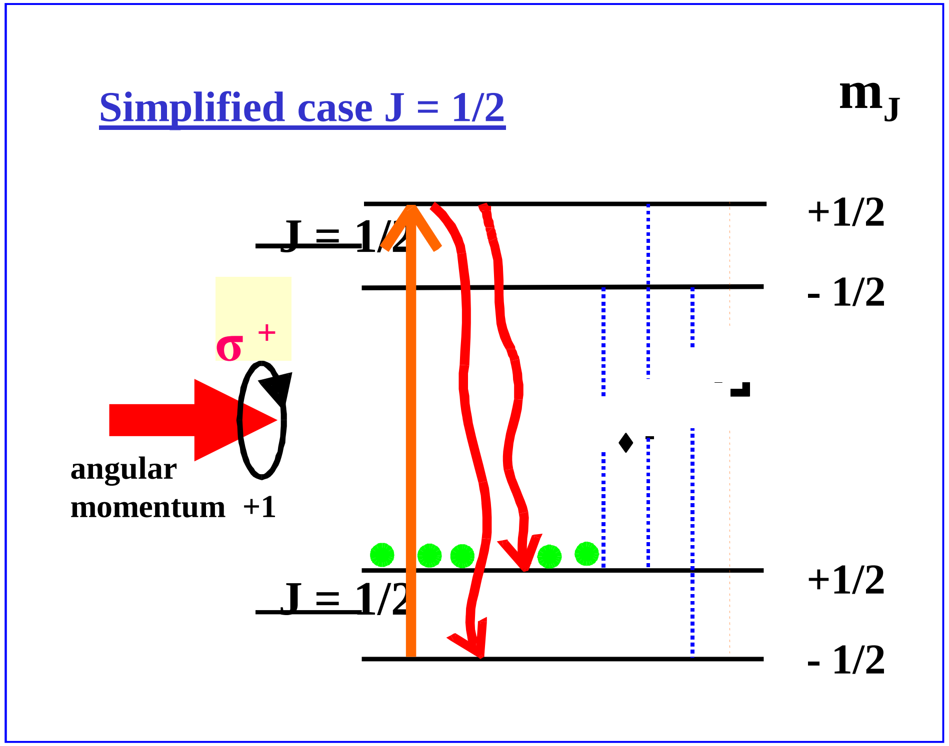
Energy levels of the Na electron (ground and first excited)



Orientation of an atomic vapor by optical pumping

Orientation of the atomic angular momenta

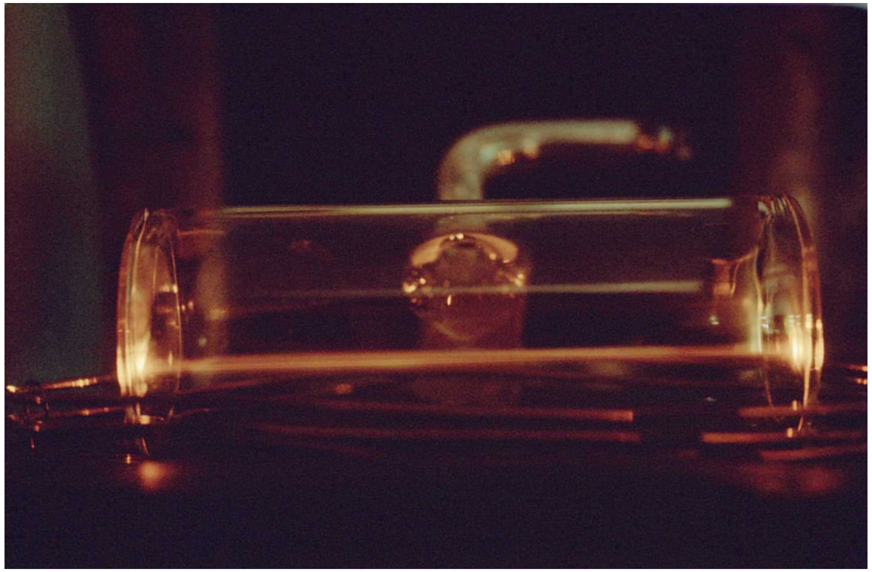




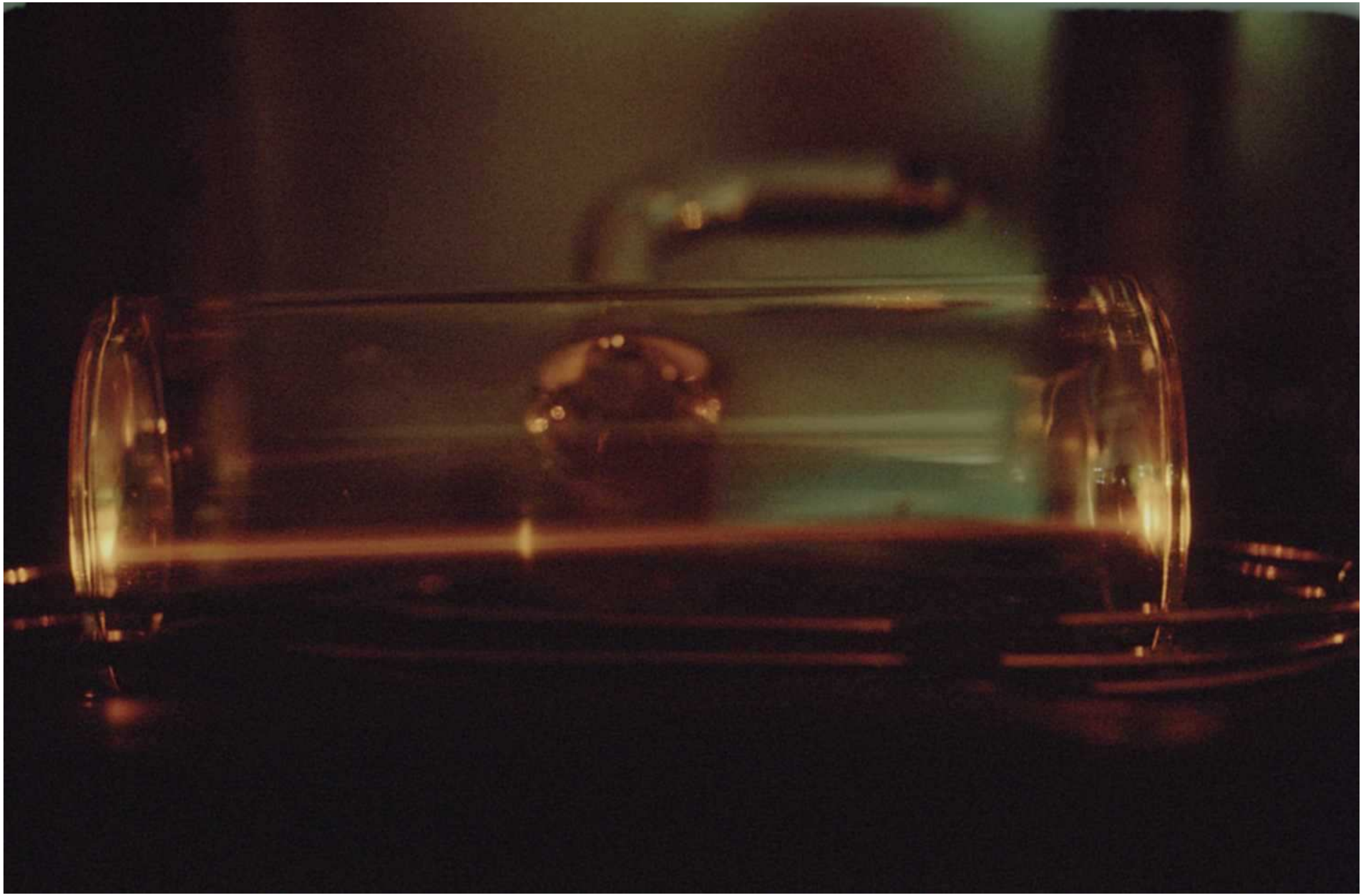
- **conservation of angular momentumr → selective excitation**
- **spontaneous emission to all states**
- **atoms acumulate in a particular Zeeman sublevel that corresponds to an orientation of the angular momentum**
- **atoms do not absorb light and, eventually, do not produce fluorescence**

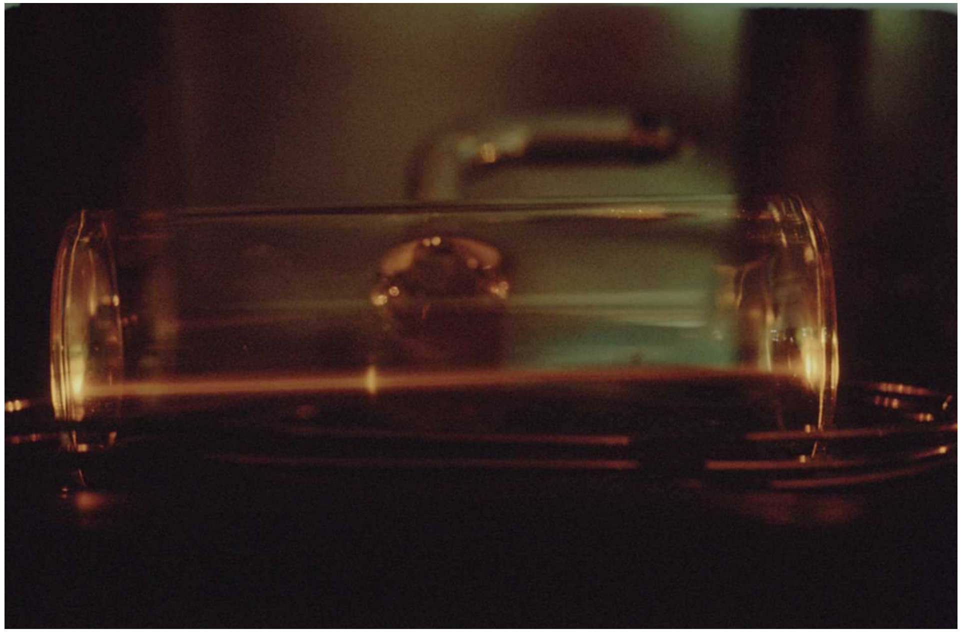
Linearly polarized laser beam tuned to the sodium D_1 line

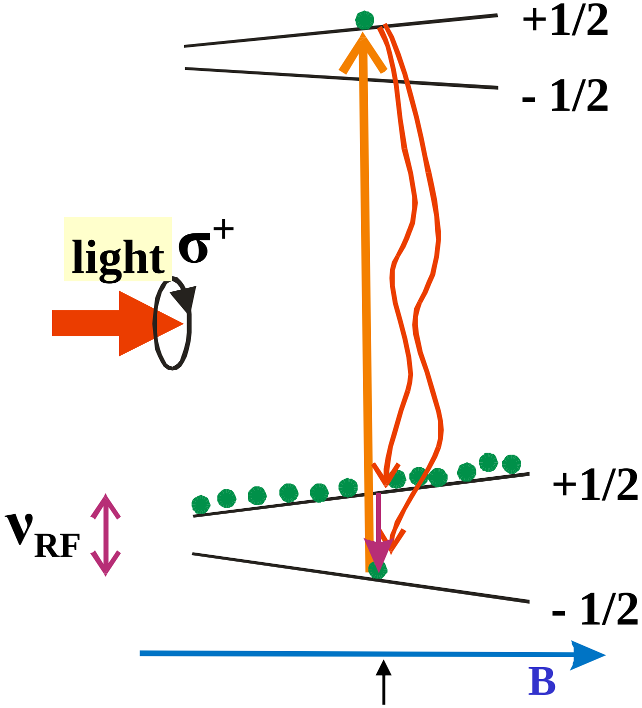
Circularly polarized beam (by means of a $\lambda/4$ waveplate)



Magnetic resonance induced by the radiofrequency field







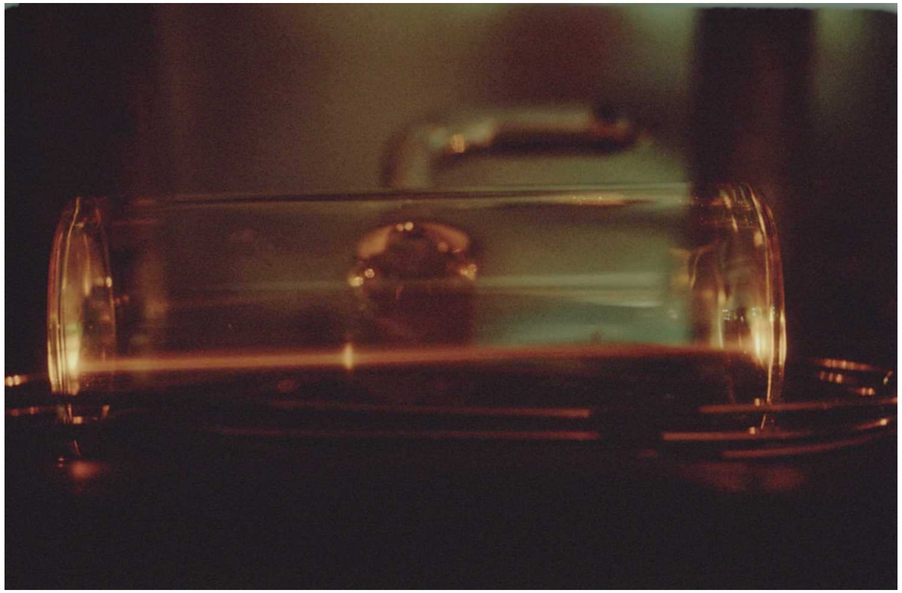
Resonance condition

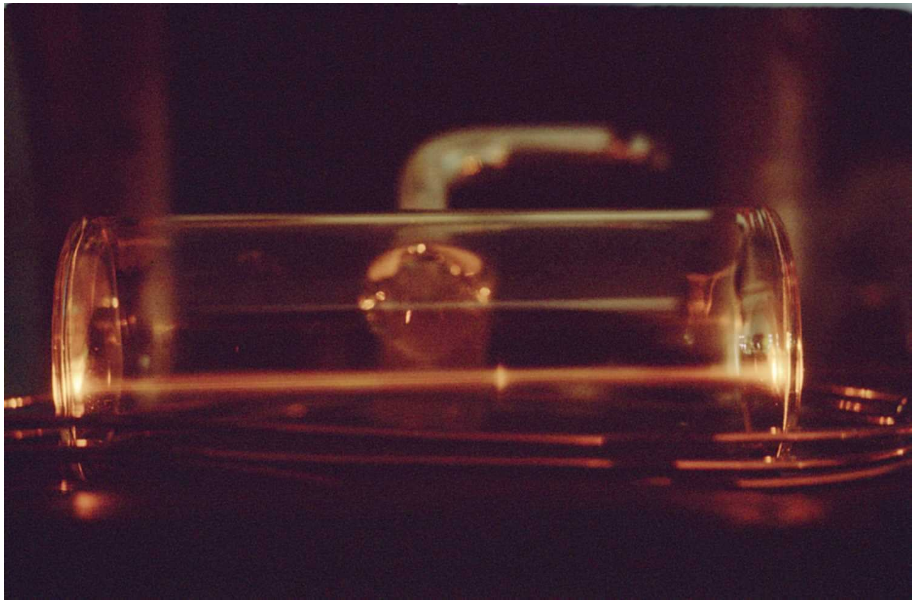
$$\nu_{RF} = \nu_{\text{àtom}} = (E_{+1/2} - E_{-1/2})/h$$

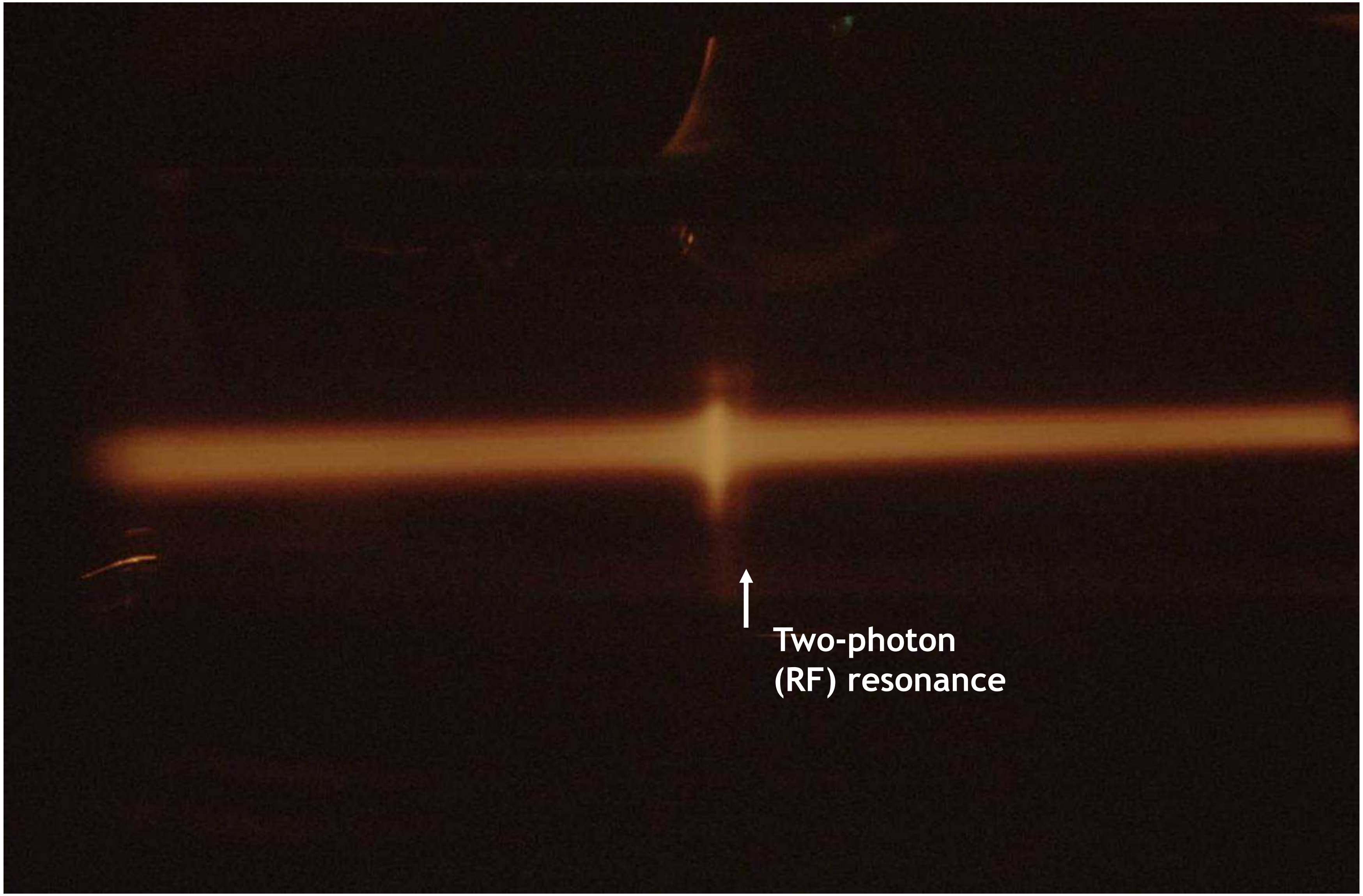
Modifying the frequency

or

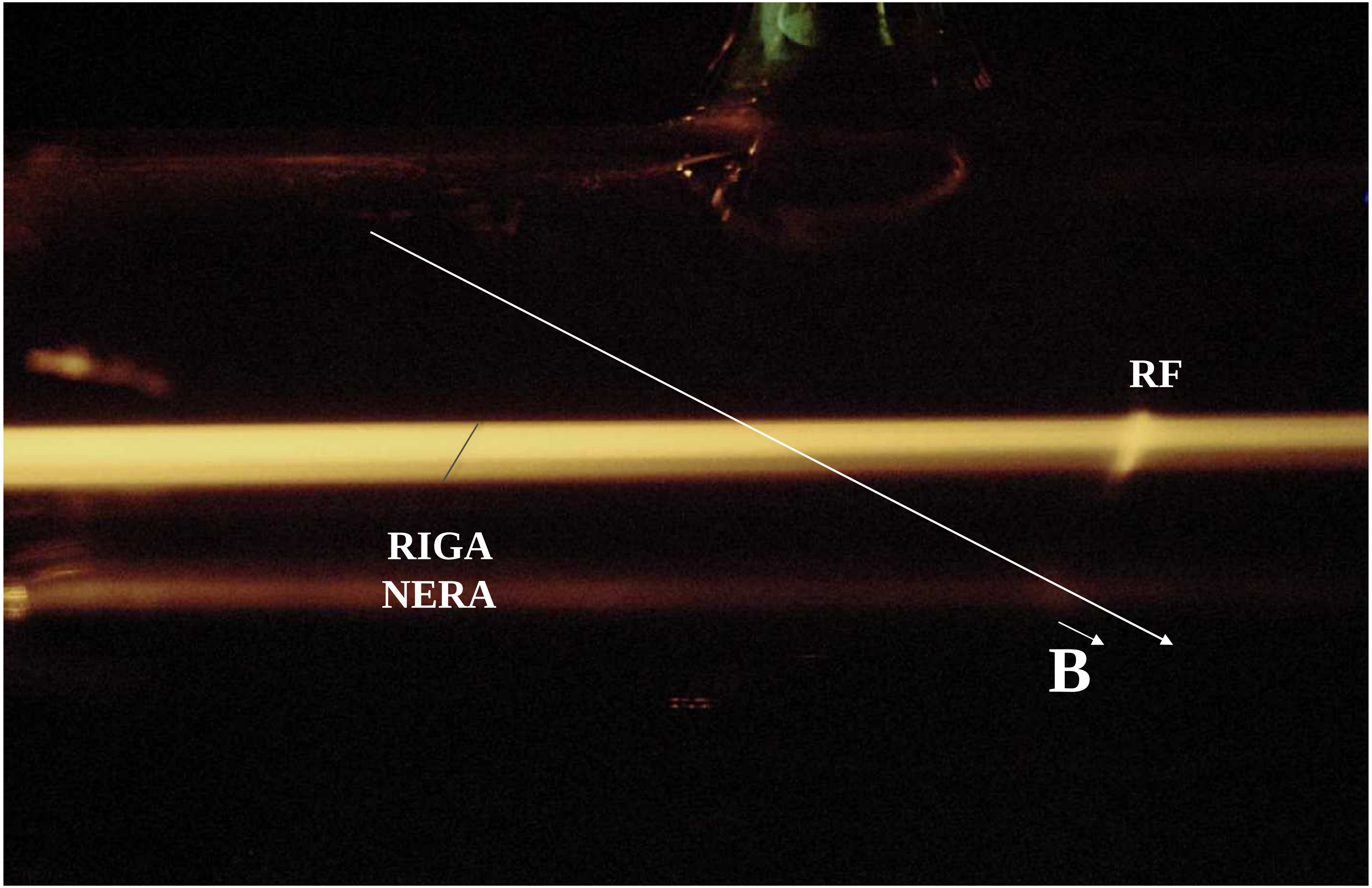
Modifying the magnetic field

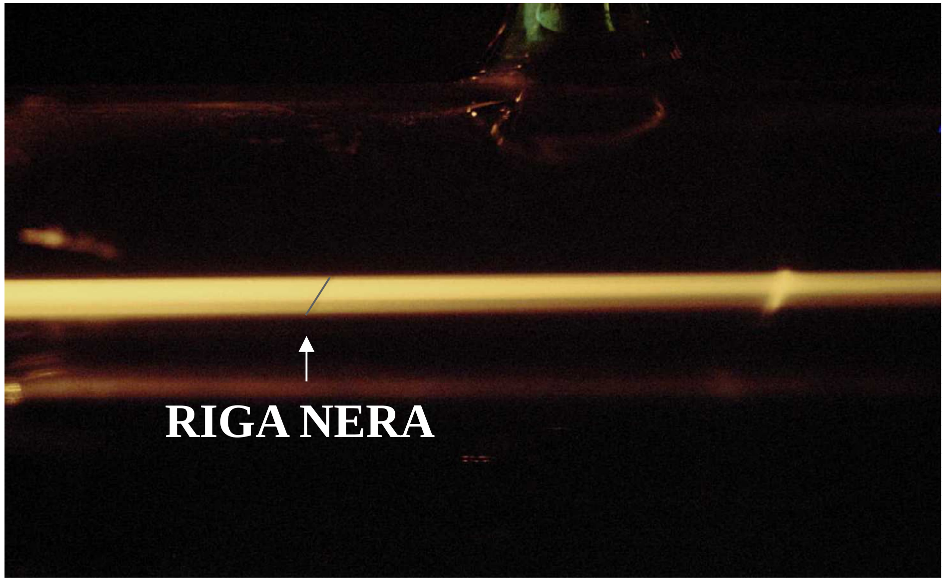


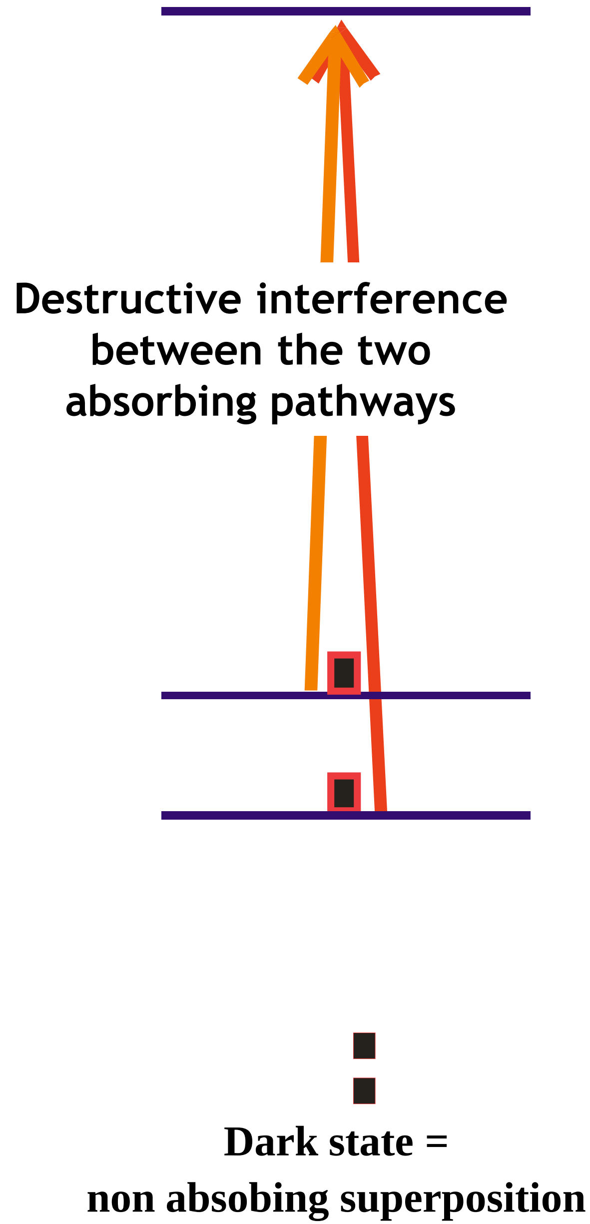



Two-photon
(RF) resonance

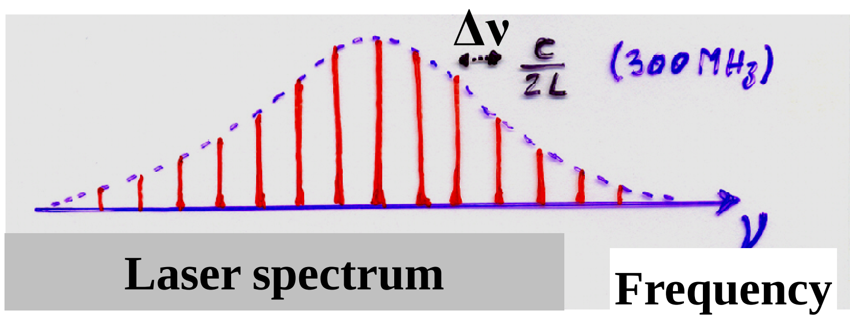
Laser induced non-absorbing resonance





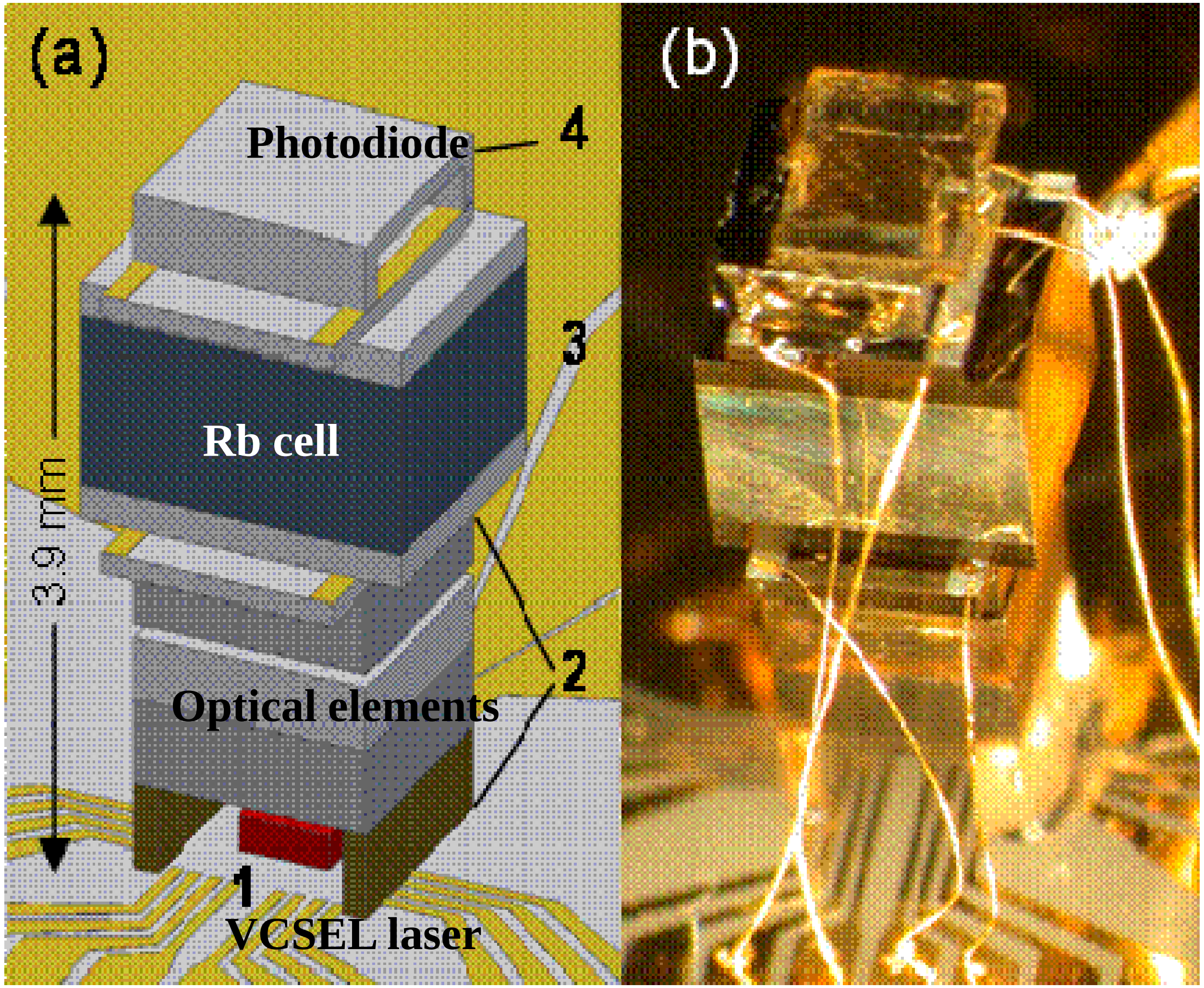


At the “Riga Nera”, there is a resonance between the Δν hyperfine splitting and the frequency of two consecutive light modes



Frequency standards and atomic clocks based on the dark line

Micromagnetometer and atomic clocks based on the D1 line



NIST, Boulder