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WINTER COLLEGE ON HIGH RESOLUTION SPECTROSCOPY

(8 January - 2 February 1990)

COHERENT TRAPPING IN LASER SPECTROSCOPY EXCITATION AND LASER COOLING

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COHERENT TRAPPING IN

LASER SPECTROSCOPY, EXCITATION AND LASER COOLING

1) what is coherent trapping

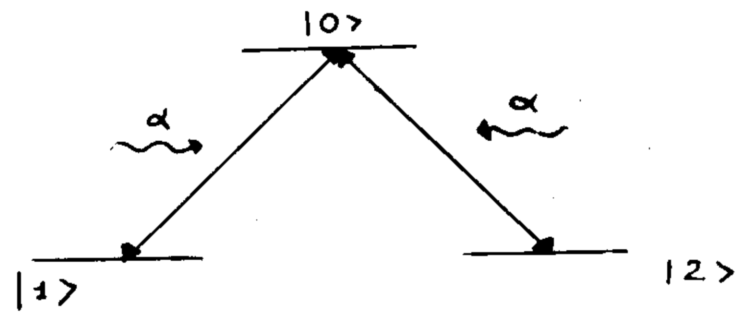
2) experimental observations

3) new applications

4) constants of motion

5) velocity-selective coherent trapping for atom cooling

" Coherent population trapping "



$$|\psi_{NC}\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle - |2\rangle\right)$$

"V" interaction Hamiltonian of atoms with laser fields

$$\langle 0|V|\psi_{NC}\rangle = \frac{1}{\sqrt{2}}\left[\langle 0|V|1\rangle - \langle 0|V|2\rangle\right] = \frac{1}{\sqrt{2}}\left[\alpha - \alpha\right] = 0$$

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first experimental observation in

Alzetta et al. N.C. 36B 5 (1976)

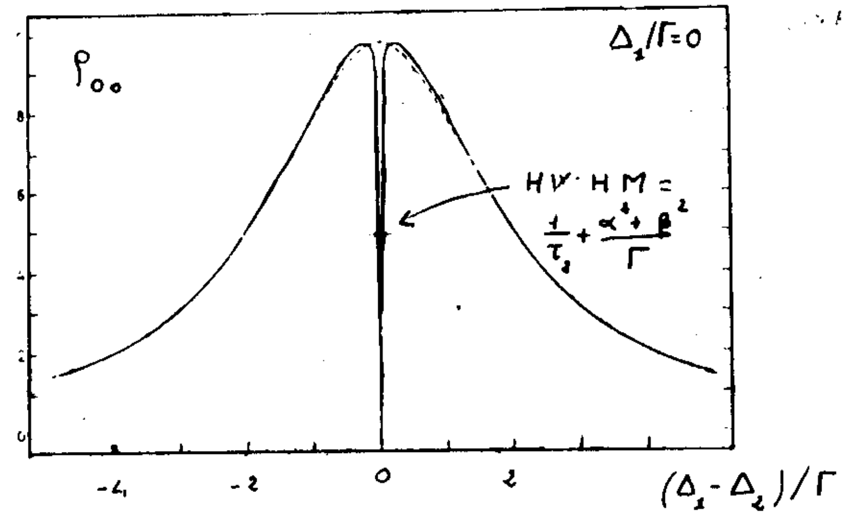
analyses in

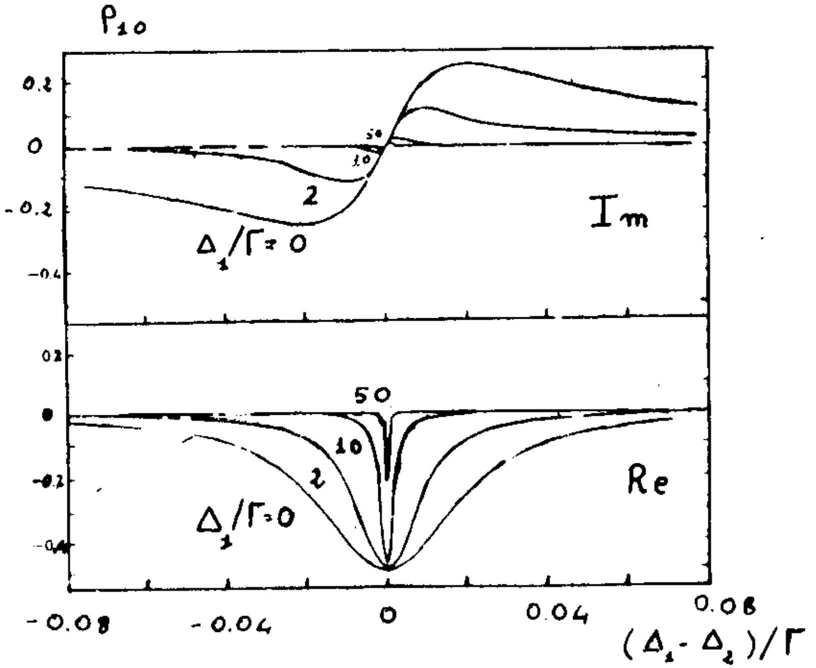
Arimondo et al Lett. N.C. 17 333 (1976)

Gray et al Opt. Lett. 3 218 (1978)

Non-absorption resonances in Na vapour

(Alzetta et al, 1976, 1979)





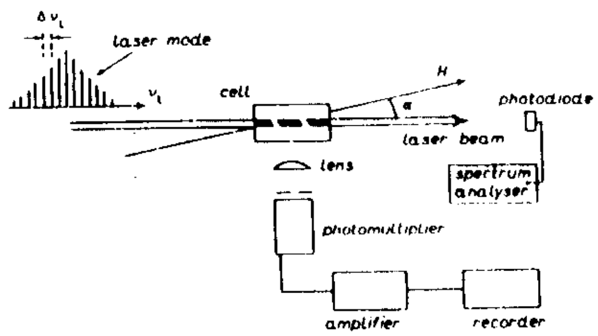


Fig. 2. Sketch of the experimental apparatus.

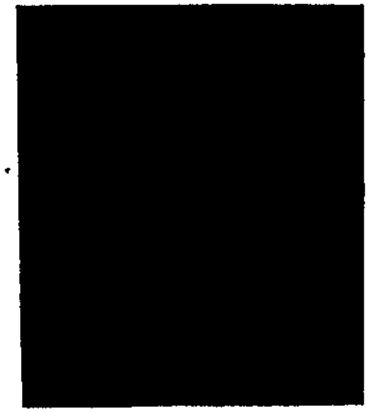
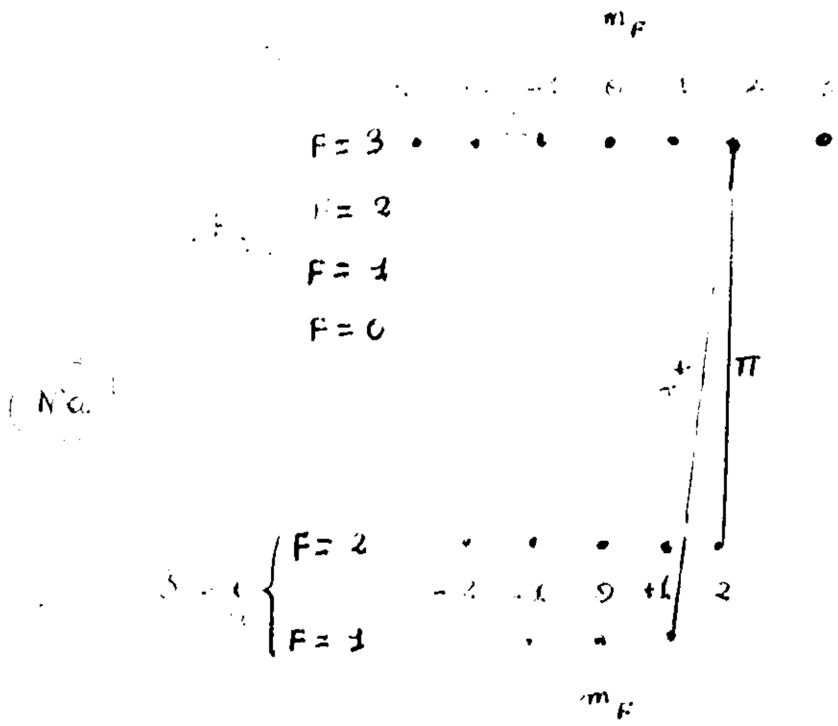
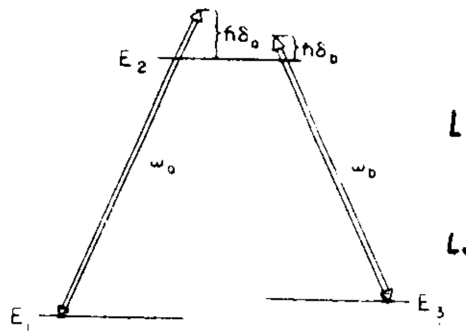


Fig. 1. – Fluorescence of sodium vapour crossed by the circularly polarised beam of a multimode laser tuned to the D_1 line.

Coherent trapping in Na experiment





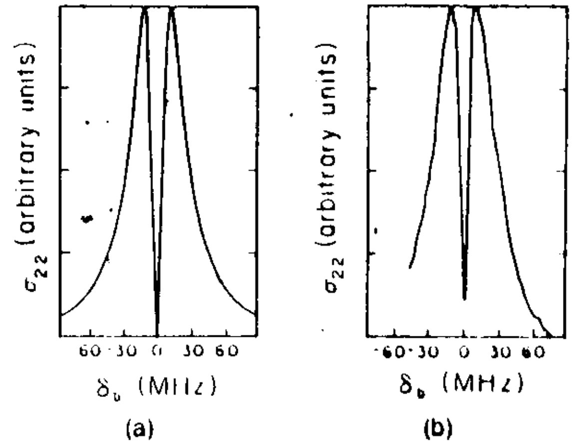
Laser ω_a in resonance

Laser ω_b swept

Fig. 1. Energy-level configuration. E_1 and E_3 are nondegenerate sublevels of the ground state. E_2 is a common excited state. Two monochromatic lasers of frequency ω_a and ω_b are tuned δ_a and δ_b off resonance.

Detection of excited state fluorescence

Theory



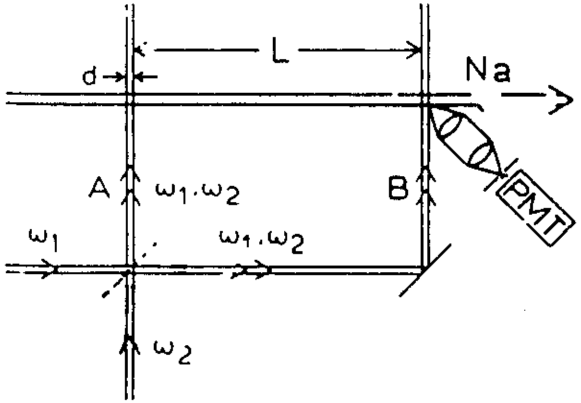
Experiment

Fig. 2. (a) Experimentally observed excited-state population σ_{22}. The fixed-frequency laser is at exact resonance, $\delta_a = 0$, with an intensity of 23 mW/cm². The second laser is detuned δ_b from exact resonance, with an intensity of 54 mW/cm². (b) Theoretical prediction of excited-state population σ_{22}. The fixed-frequency laser is at exact resonance, $\delta_a = 0$. The second laser is detuned δ_b from exact resonance.

Gray, Whitley and Stroud,

Ramsey fringes in Trapping. (Ezekiel et al, 1981)

JOSA B5, 1519 (1989)



Experimental set-up for Na tomic beam studies.

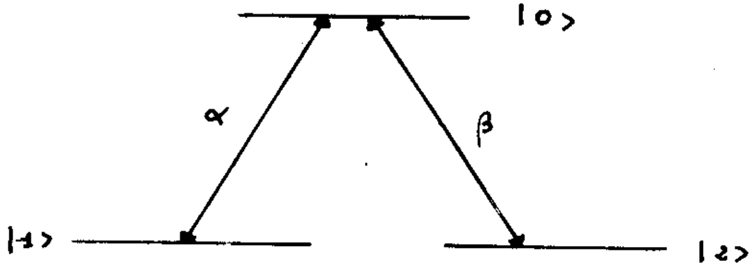
Ramsey fringes using resonance Raman excitation in Na atomic beam.

Full width half maximum: 1.3 KHz

Constants of motion

for the optical Hamiltonian

$$\mathcal{H} = \mathcal{H}_{opt} + \mathcal{H}_{spont}$$



Non-absorbing state $|\psi_{NC}\rangle = \frac{1}{\sqrt{\alpha^2+\beta^2}} \left[\beta|1\rangle - \alpha|2\rangle \right]$

$$\langle \psi_{NC} | \rho | \psi_{NC} \rangle =$$

$$= \frac{1}{\alpha^2+\beta^2} \left[\beta^2 \rho_{11} + \alpha^2 \rho_{22} - \alpha\beta(\rho_{12} + \rho_{21}) \right]$$

not coupled by optical Hamiltonian:

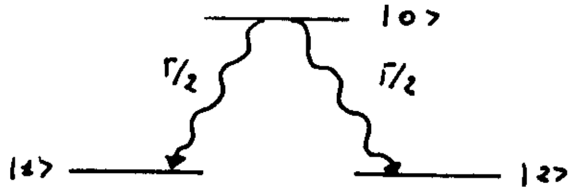
$$\mathcal{H} |\psi_{NC}\rangle = 0$$

for spontaneous emission

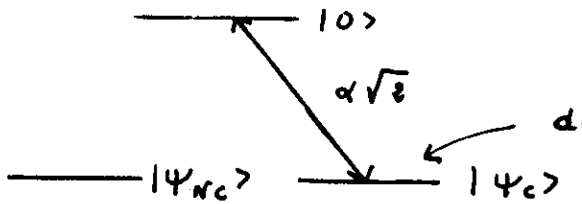
$$\frac{d}{dt} \langle \psi_{NC} | \rho | \psi_{NC} \rangle = \frac{\Gamma}{2} \rho_{00}$$

Preparation of coherent trapping state

through depopulation pumping



both states are statistically equally populated



depopulation

Laser-Induced Continuum Structure in Xenon

M. H. R. Hutchinson and K. M. M. Ness[a]

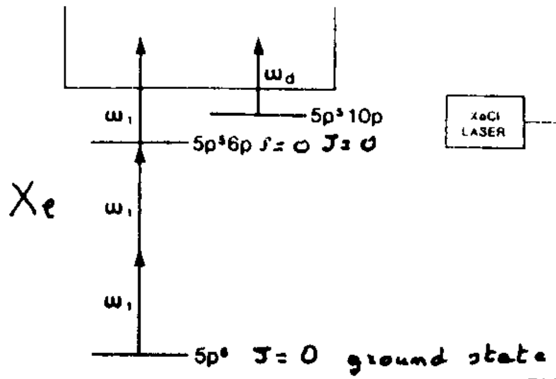


FIG. 2. Energy-level diagram for xenon, dressed by ω_d and :obed by two-photon–resonant, three-photon ionization.

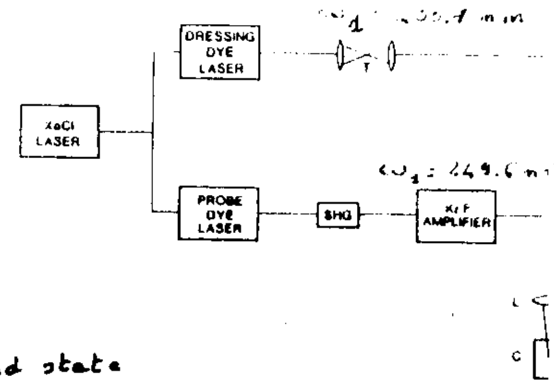


FIG. 3. Schematic diagram of laser system.

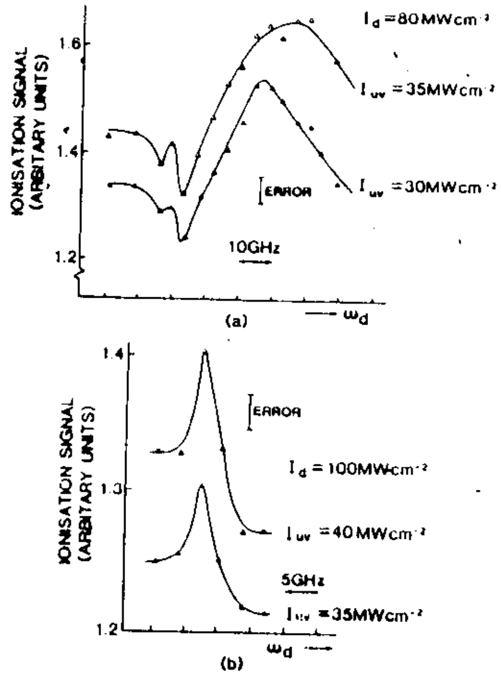
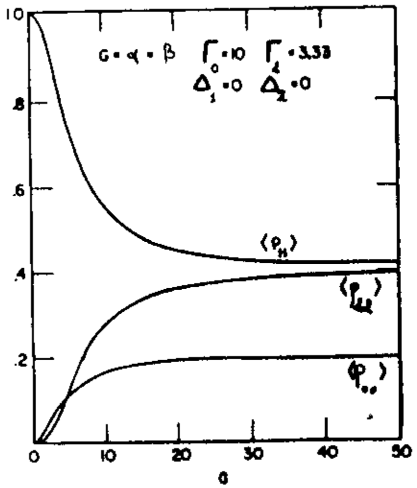
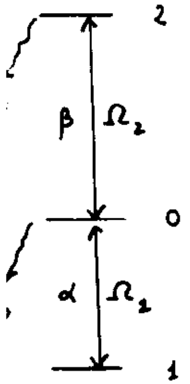
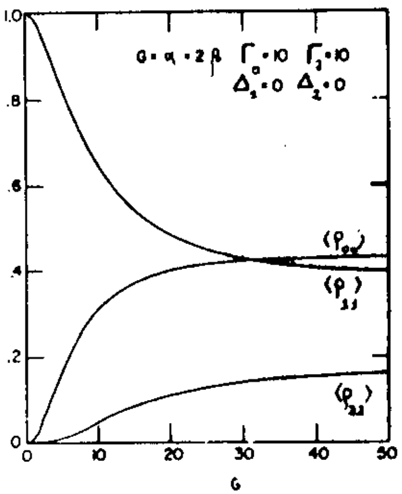


FIG. 4. Plots of the total two-photon–resonant ionization signal vs ω_d: (a) Low-resolution scan and (b) higher-resolution scan of the unknown feature.

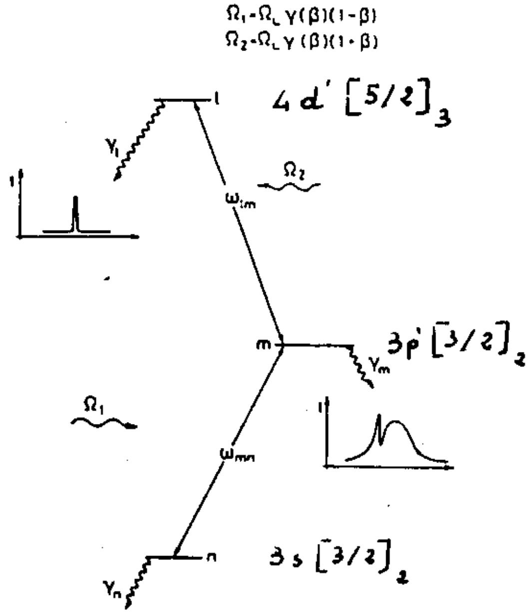
Excited state populations in double resonance







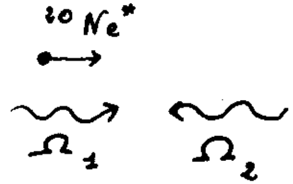
(Whitley and Stroud, 1976)



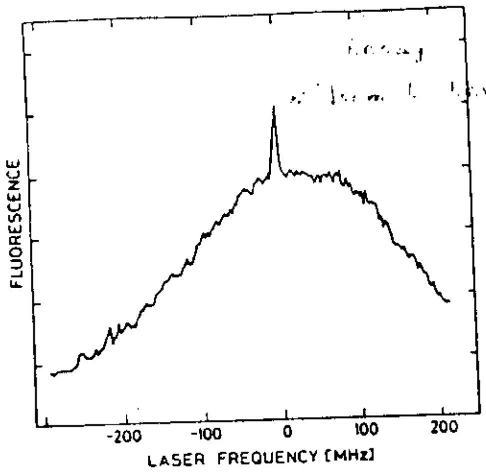
Experiment by Poulsen et al (Opt. Comm. 1984)

on cascade configuration

accelerated $^{20}Ne^*$ metastable beam



Fluorescence from m level (intermediate)

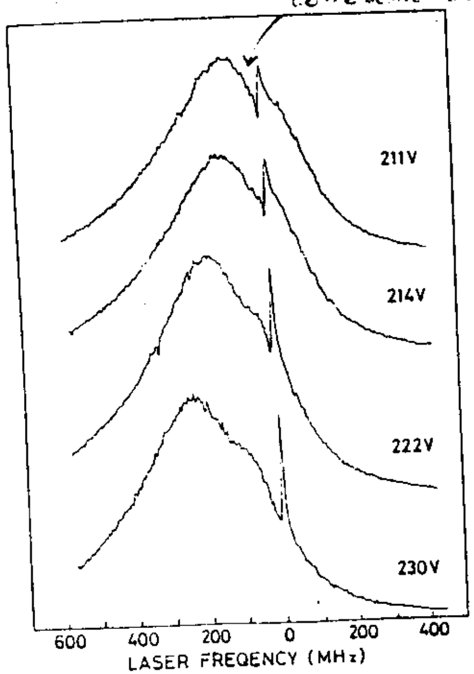


Low

Rabi

frequencies

coherent trapping dip

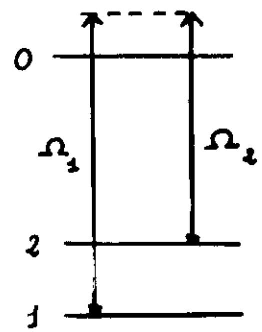


Large

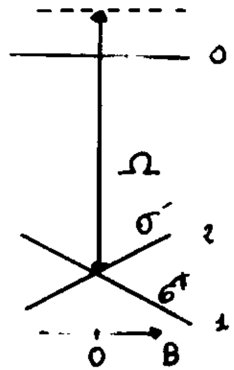
Rabi

frequencies

Hanle non-linear effect

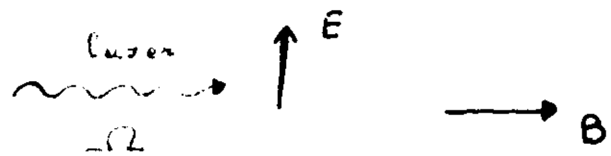


Λ three-level



ground-state level crossing

Laser configuration

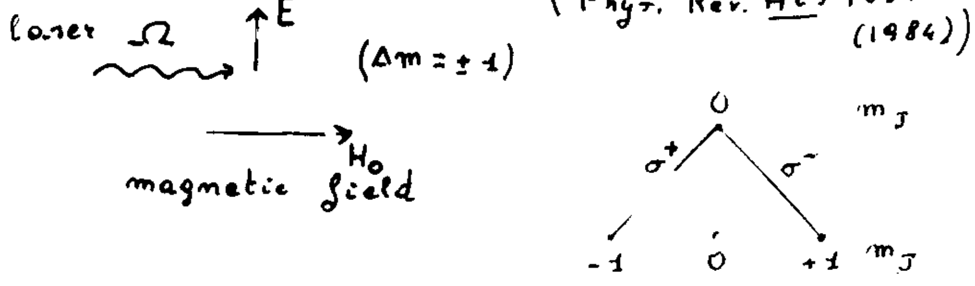


Experimental configuration

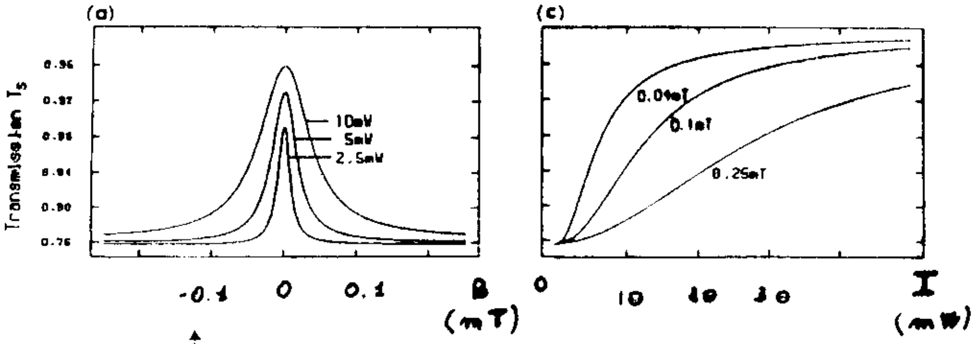
for bistability based on

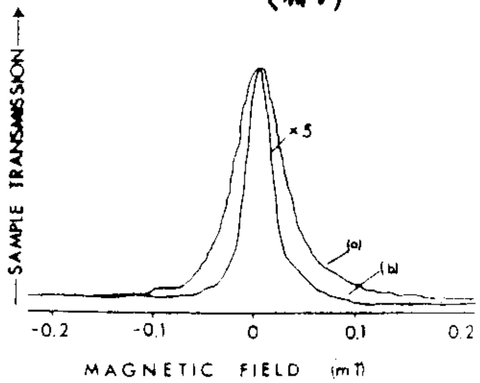
coherent trapping

(Phys. Rev. A29 1297 (1984))



J. MLYNEK, F. MITSCHKE, R. DESERNO, AND W. LANGE





measured

FIG. 6. Measured optical transmission of Na vapor as a function of transverse magnetic field for two input intensities (a)

Absorptive bistability

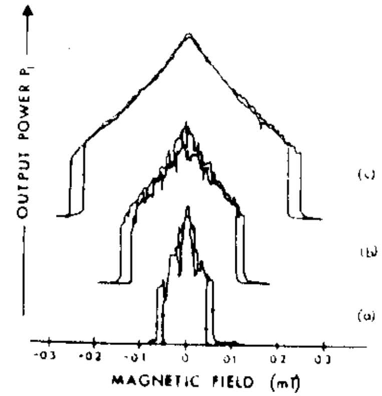
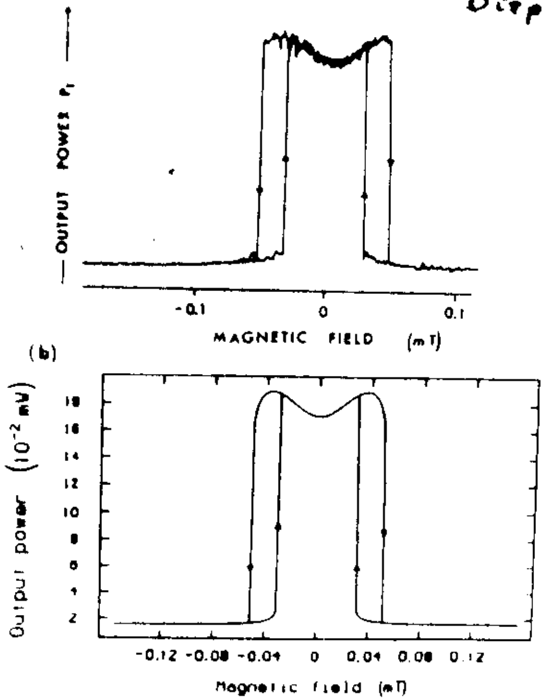


FIG. 8. Measured cavity output power in the absorptive regime as a function of the transverse magnetic field B for three different number densities: (a) $N_{Na} \cong 1.9\times10^{12}$ cm^{-3}, (b) $N_{Na} \cong 2.4\times10^{12}$ cm^{-3}, (c) $N_{Na} \cong 3.9\times10^{12}$ cm^{-3}. Otherwise $p_{Ar} = 120$ mbar, $P_{in} = 150$ mW, zero cavity mistuning;

(a)

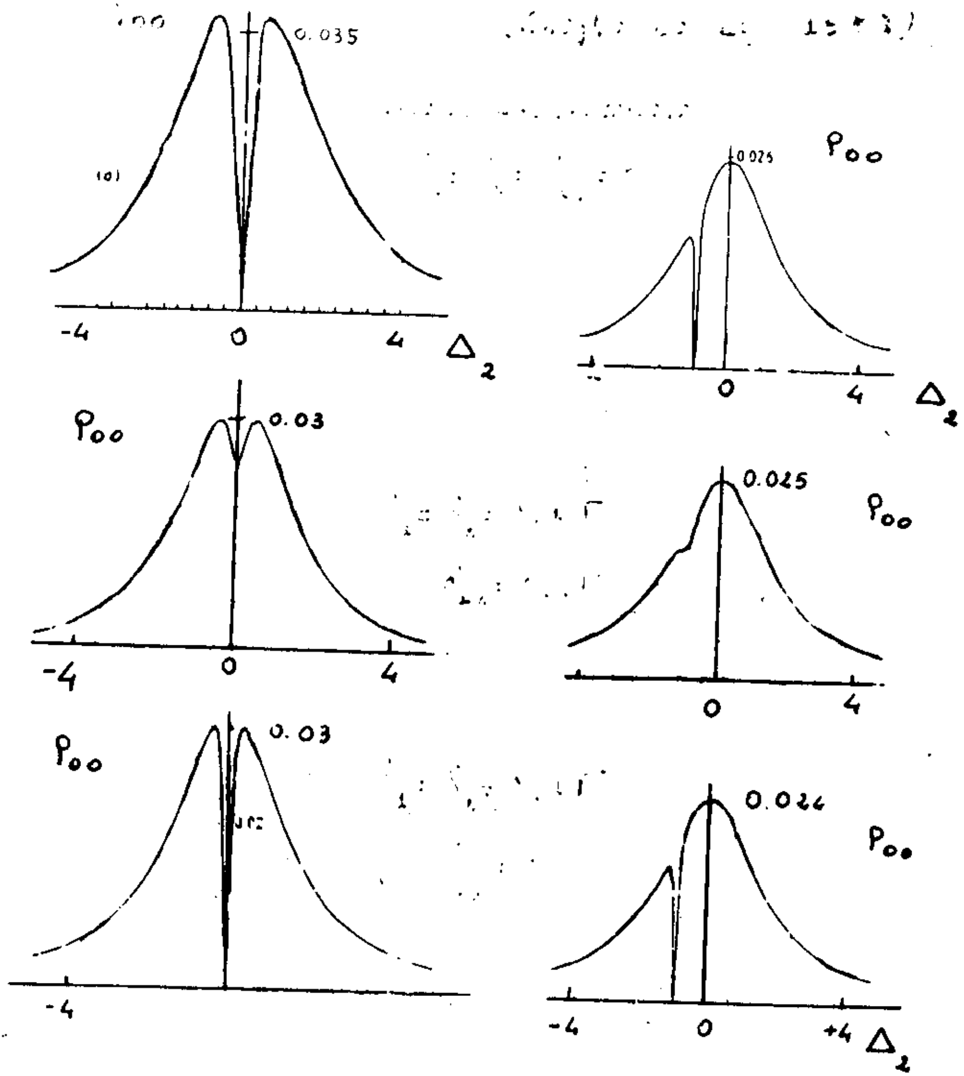
Dispersive bistability



measured

calculated

FIG. 10. Measured (a) and calculated (b) dispersive bistability and hysteresis for $\Delta_0/2\pi = 3.5$ GHz. Parameter values are (a) $N_{Na} \cong 5\times10^{12}$ cm^{-3}, $p_{Ar} = 200$ mbar, $P_{in} = 80$ mW, $d = 240$ μm, cavity mistuning not experimentally determined. (b) $N = 2.7\times10^{12}$ cm^{-3}, $p_{Ar} = 200$ mbar, $P_{in} = 3.7$ mW, $d = 240$ μm,



$\Delta_1 = 0$

$\omega_1 = \omega_2 = 0.4\,\Gamma$

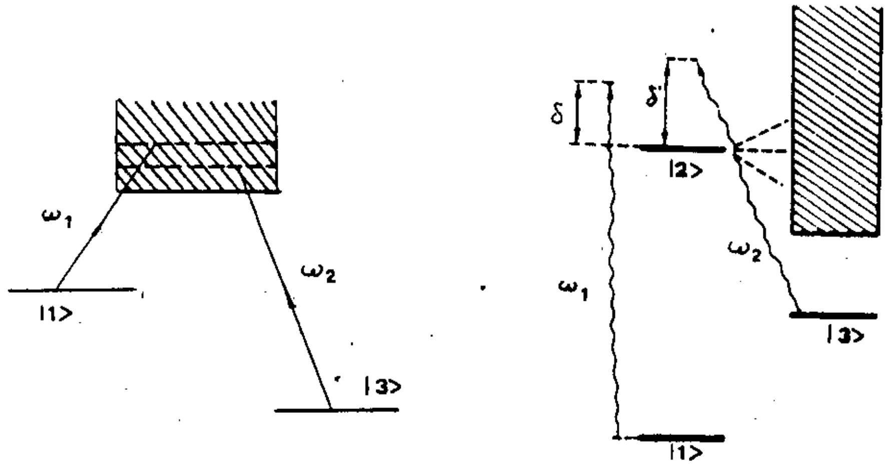
$\Delta_1 = \Gamma$

$\omega_1 = \omega_2 = 0.4\,\Gamma$

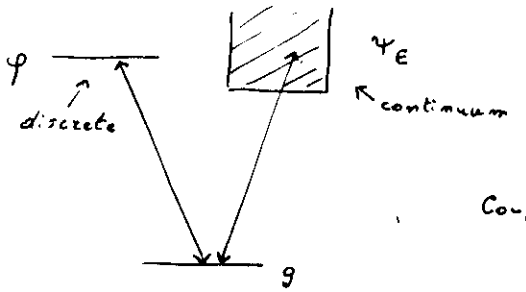
Discrete-continuum states

investigated for

coherence trapping



Fano lineshape



Coupling continuum - autoionization V_E

Eigenstate

$$\Phi_E = a\varphi + \int dE\, b_E \Psi_E$$

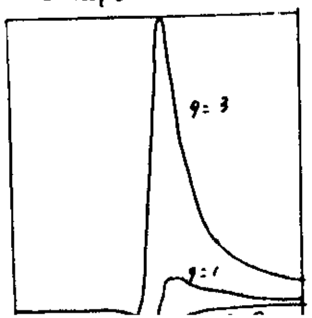
Transition probability

$$|\langle \Phi_E | \mu \cdot \underline{E} | g\rangle|^2 = |\langle \Psi_E | \mu \cdot \underline{E} | g \rangle|^2 \frac{[\epsilon(\omega)+q]^2}{\epsilon^2(\omega)+1}$$

where $\epsilon(\omega) = \dfrac{\omega - E_\varphi - F(\omega)}{\pi |V_E|^2}$

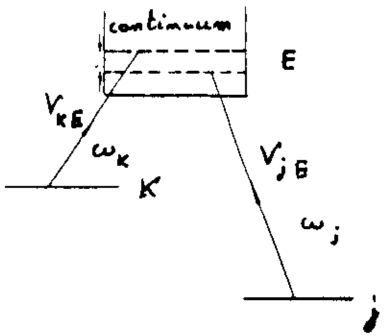
and $q = \dfrac{\langle \Psi_E | \mu \cdot \underline{E} | g \rangle}{\pi V_E \langle \varphi | \mu \cdot \underline{E} | g \rangle}$ asymmetry parameter

lineshape

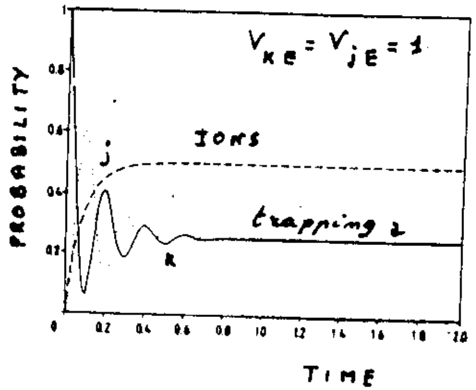


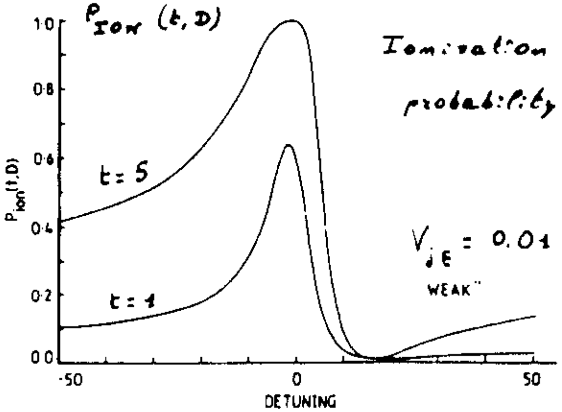
Population trapping in photoionization

(Knight et al, 1982)



$q = 5$





Ionization probability

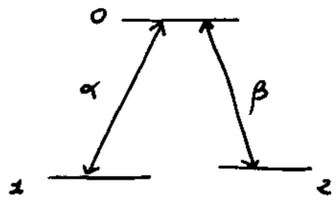
from two-photon resonance

Adiabatic following and

population trapping

(Bergmann, Hioe, (1969))

$$\mathcal{H} = \hbar \begin{pmatrix} 0 & \alpha(t) & 0 \\ \alpha(t) & \Delta(t) & \beta(t) \\ 0 & \beta(t) & 0 \end{pmatrix}$$



$$|\tau(t)\rangle = \frac{\beta(t)}{\sqrt{\alpha^2+\beta^2}}\,|1\rangle - \frac{\alpha(t)}{\sqrt{\alpha^2+\beta^2}}\,|2\rangle$$

$$\mathcal{H}\,|\tau(t)\rangle = 0\,|\tau(t)\rangle$$

$$i\hbar \frac{\partial}{\partial t}|\tau(t)\rangle = \mathcal{H}\,|\tau(t)\rangle = 0$$

adiabatic following realized

if $\quad \dfrac{\alpha(t)}{\beta(t)} \to 0 \quad$ at $\quad t \to -\infty$

and $\quad \dfrac{\beta(t)}{\alpha(t)} \to 0 \quad$ at $\quad t \to +\infty$

Adiabatic transfer (K. Bergmann et al. Kaiserslautern, W. Germany)

Na_2

A - X

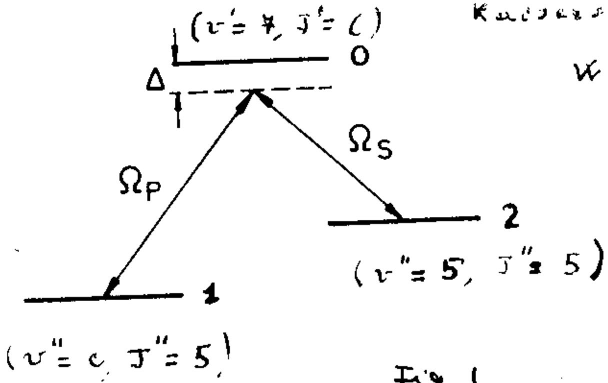


Fig. 1

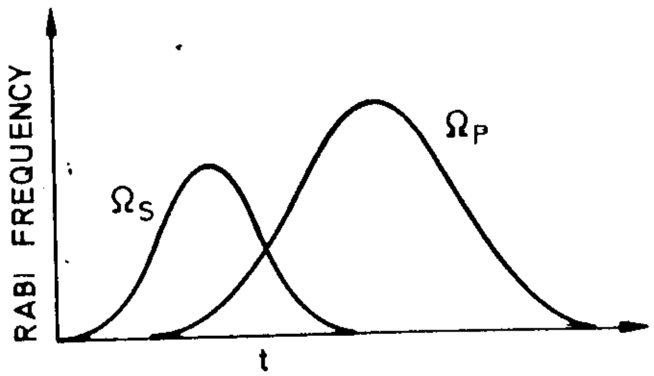


Fig. 2

Transfer to level 3

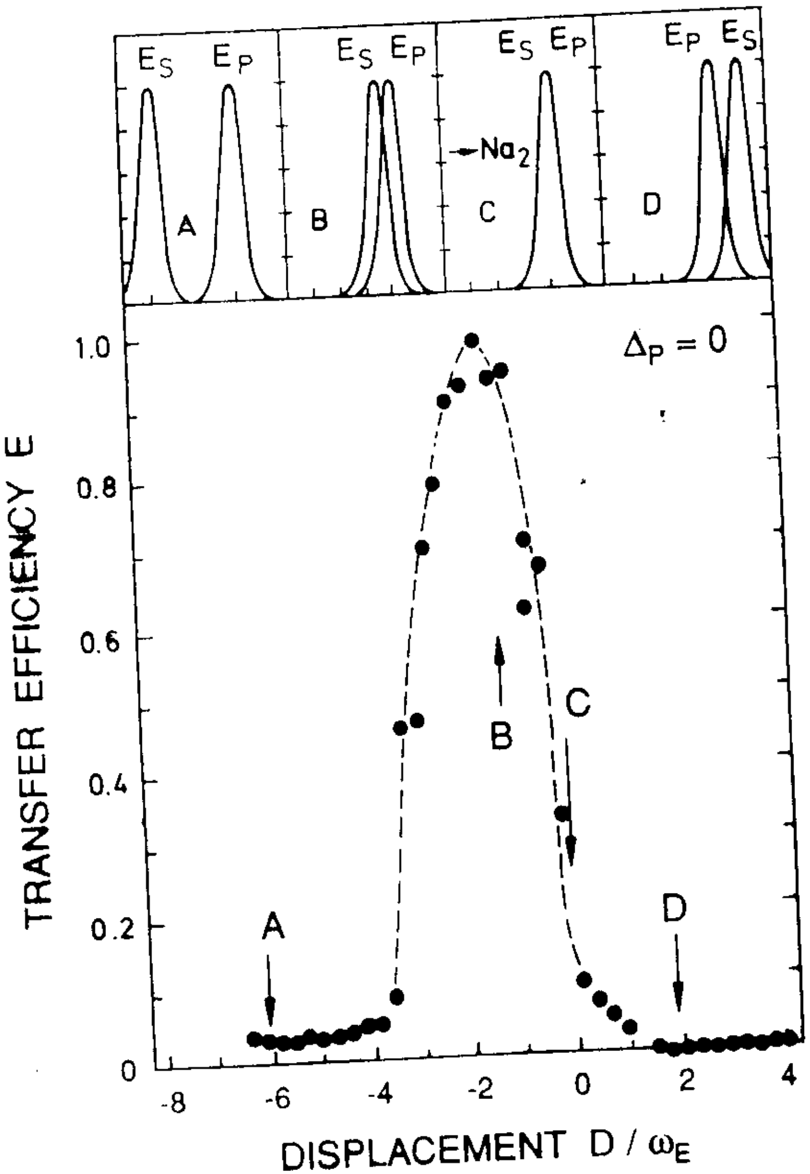
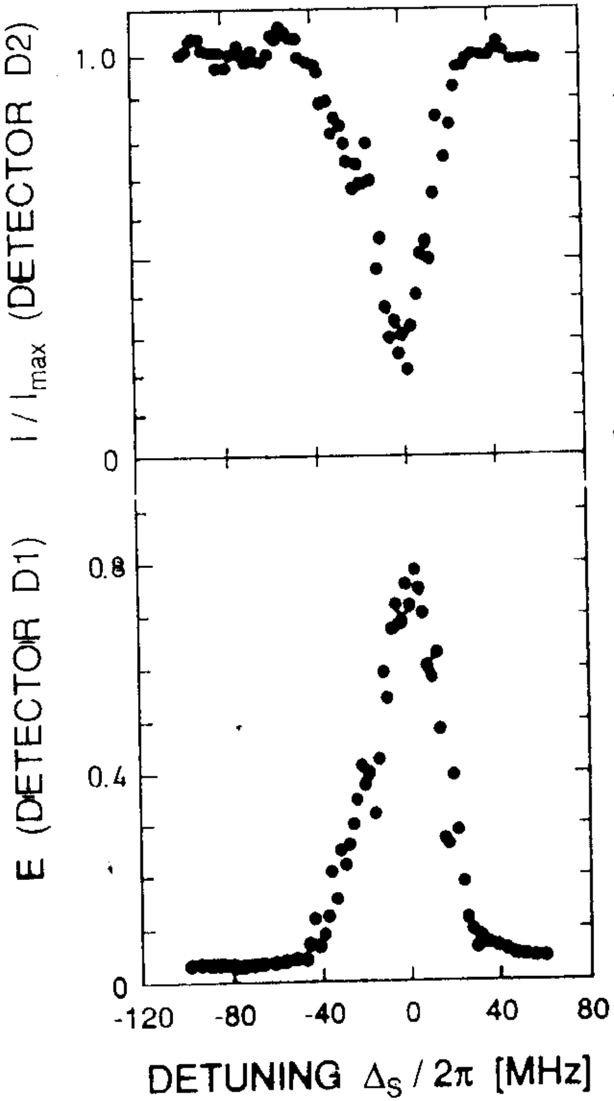


Fig. 6

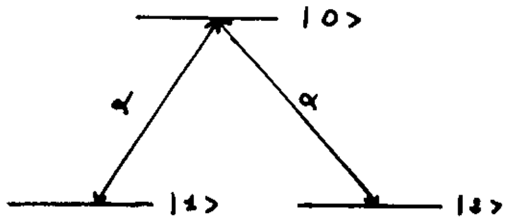


Trapping in state |1>

Transfer to level |2>

Fig. 7

Bases for three-level evolutions



$\rho_{00}, \rho_{11}, \rho_{22}$

$cx = (\rho_{12} + \rho_{21})/2$

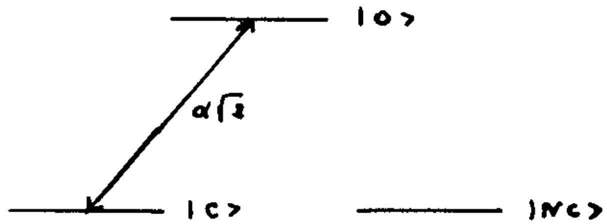
$cy = i(\rho_{12} - \rho_{21})/2$

$s_1x = (\rho_{10} + \rho_{01})/2$

$s_1y = i(\rho_{10} - \rho_{01})/2$

$s_2x = (\rho_{20} + \rho_{02})/2$

$s_2y = i(\rho_{20} - \rho_{02})/2$



$\rho_{00}, \rho_{cc}, \rho_{NCNC}$

$cx^{c,NC} = (\rho_{c,NC} + \rho_{NC,c})/2$

$cy^{c,NC} = i(\rho_{c,NC} - \rho_{NC,c})/2$

$sx^{c} = (\rho_{c,0} + \rho_{0,c})/2$

$sy^{c} = i(\rho_{c,0} - \rho_{0,c})/2$

$sx^{NC} = (\rho_{NC,0} + \rho_{0,NC})/2$

$sy^{NC} = i(\rho_{NC,0} - \rho_{0,NC})/2$

Constants of motion (Hioe & Eberly 1982-89)

In the 3×3 space we introduce the coherence vector $\underline{S}$ with components:

$$\underline{S} \equiv \begin{pmatrix} sx^{c} \\ sy^{c} \\ \rho_{00} - \rho_{cc} \\ cx^{c,NC} \\ cy^{c,NC} \\ sx^{NC} \\ sy^{NC} \\ \rho_{NC,NC} \end{pmatrix} \begin{array}{l} \left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} \equiv \underline{A} \\ \left.\begin{matrix} \\ \\ \\ \\ \end{matrix}\right\} \equiv \underline{B} \\ \} \equiv \underline{C} \end{array}$$

[for α = (

In absence of relaxations,

i) for two-photon resonance $\Delta_1 = \Delta_2 = \Delta$

ii) RWA

iii) same time dependence for fields and frequencies

the space may factor into 3 independent spaces of dimensions 3, 4, 1

$$\frac{d}{dt}\begin{pmatrix} \underline{A} \\ \underline{B} \\ \underline{C} \end{pmatrix} = \begin{bmatrix} \underline{\underline{\Delta}}_3 & 0 & 0 \\ 0 & \underline{\underline{\Delta}}_4 & 0 \\ 0 & 0 & \underline{\underline{\Delta}}_1 \end{bmatrix} \begin{pmatrix} \underline{A} \\ \underline{B} \\ \underline{C} \end{pmatrix}$$

with $\underline{\underline{\Delta}}_1 \equiv 0$

en following quantities are conserved:

$$|A|^2 = (\mathfrak{s}x^c)^2 + (\mathfrak{s}y^c)^2 + (\rho_{oo} - \rho_{cc})^2$$

$$|B|^2 = (\mathfrak{s}x^{NC})^2 + (\mathfrak{s}y^{NC})^2 + (cx^{c,NC})^2 + (cy^{c,NC})^2$$

$$|C|^2 = (\rho_{NC,NC})^2$$

urthermore following quantities are constants

$$C_j = Tr[\rho^j] \qquad j = 1, 2, 3$$

$$C_1 = Tr[\rho] = \rho_{oo} + \rho_{cc} + \rho_{NC,NC}$$

$$C_2 = Tr[\rho^2] = \frac{1}{2}|\underline{S}|^2 + \frac{1}{3}$$

$$C_3 = Tr[\rho^3] = \ldots$$

For treatment of

laser cooling phenomena

internal variables (states $|0\rangle, |1\rangle, |2\rangle$)

external variables (X_{at}, P_{at}) → atomic momentum

treated simultaneously

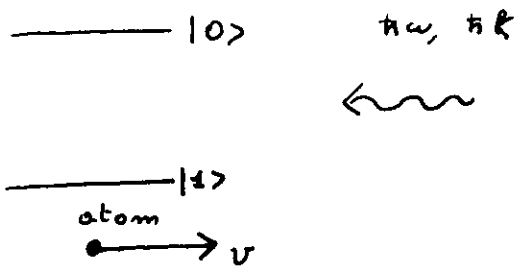
Wavefunction $\Psi(i, P_{at})$

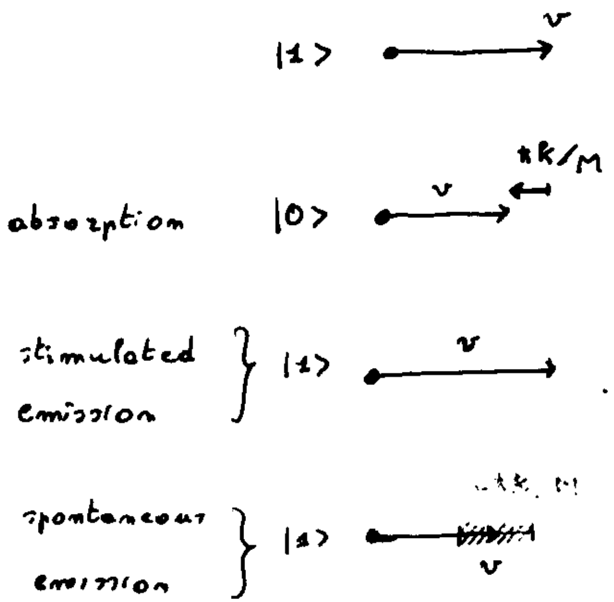
Hamiltonian
- internal $\mathcal{H}_{in}|i\rangle = E_i|i\rangle$
- Kinetic energy $\mathcal{H}_{KE}|p\rangle = \frac{p^2}{2M}|p\rangle$
- optical $\mathcal{H}_{opt}$

Evolution equation for density matrix

$$\rho_{ij}(p, p') = \langle i, p|\, \rho\, | j, p'\rangle$$

$$i\hbar \frac{d}{dt}\rho = [\rho, \mathcal{H}_{in} + \mathcal{H}_{KE} + \mathcal{H}_{opt}]$$





By one - photon absorption / emission

atomic energy becomes $\frac{(\hbar k)^2}{2M}$

recoil landmark $T_{rec} = \frac{1}{k_B} \frac{(\hbar k)^2}{2M}$

Statistical evolution in laser cooling.

Random walk process

with damping force

$F = -\gamma v_{at}$

and diffusion term D

Equazione di Fokker-Planck

per $\mathcal{P}(p_{at}, t)$:

$$\frac{\partial \mathcal{P}}{\partial t} = \gamma \frac{\partial (p_{at} \mathcal{P})}{\partial p_{at}} + \frac{\partial}{\partial p_{at}} \left(D \frac{\partial \mathcal{P}}{\partial p_{at}} \right)$$

dove $\gamma = - \frac{2 \hbar k^2}{M} n_0 \frac{\omega - \omega_A}{(\omega - \omega_A)^2 + \Gamma^2/4}$

$$D = n_0 \frac{(\hbar k)^2}{2} \left(1 + \overline{\cos^2 \theta} \right)$$

Soluzione stazionaria:

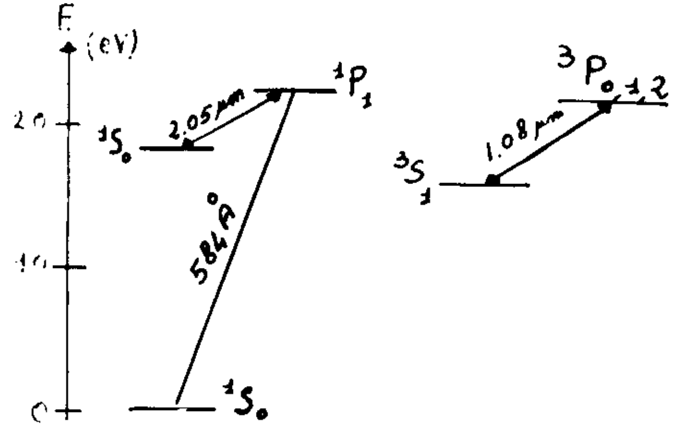
$$\mathcal{P}_{st}(p_{at}) = C^{te} \exp\left(- \frac{\gamma p_{at}^2}{2D} \right) =$$

$$= C^{te} \exp\left(- \frac{p_{at}^2}{2 M k_B T} \right)$$

per $\omega = \omega_A - \Gamma/2$

$$k_B T_{lim} = \frac{D}{\gamma M} = \hbar \Gamma \frac{1 + \overline{\cos^2 \theta}}{4}$$

Helium



^4He metastable atoms in $^3S_1$ state irradiated by 1.08 μm radiation

$$\Delta v_{Recoil} = \frac{\hbar k}{M} = 9.16 \text{ cm/sec}$$

$$T_{Recoil} = \frac{\hbar^2 k^2}{2 M k_B} = 4 \ \mu K$$

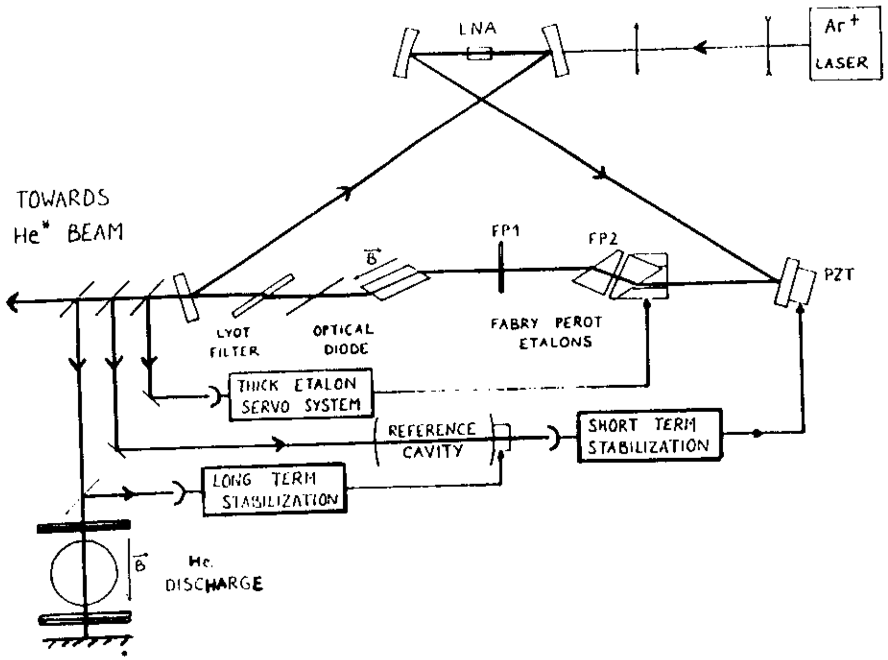
$$T_{Cooling, 1D} = \frac{7 \hbar \Gamma}{20 k_B} = 26 \ \mu K$$

^4He experiment at ENS - Paris

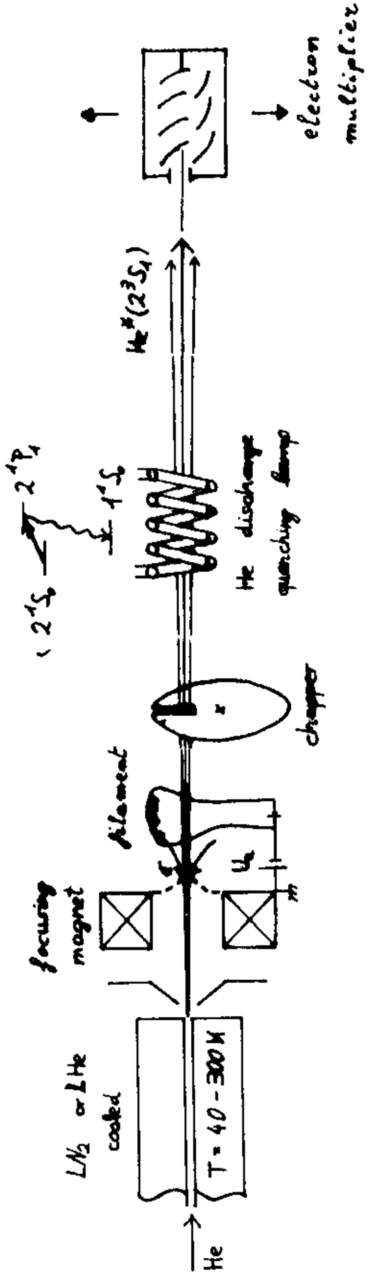
(A. Aspect, E.A., R. Kaiser, N. Vansteenkiste, C. Cohen-Tannoudji)

LNA Laser

$La_{0.9}\,Nd_{0.1}\,Mg\,Al_{11}\,O_{19}$



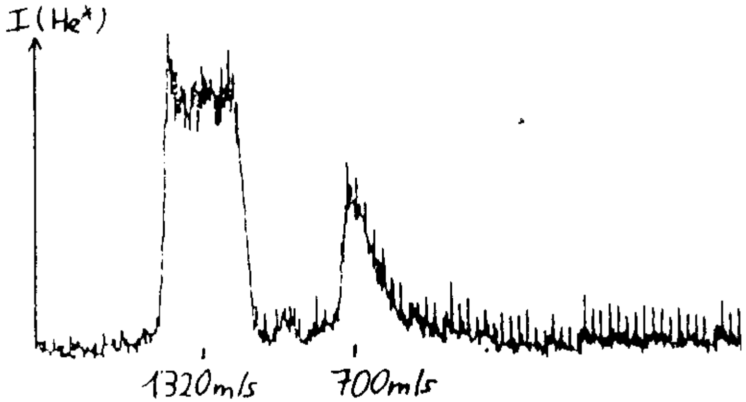
He metastable beam



TOF

velocity distribution

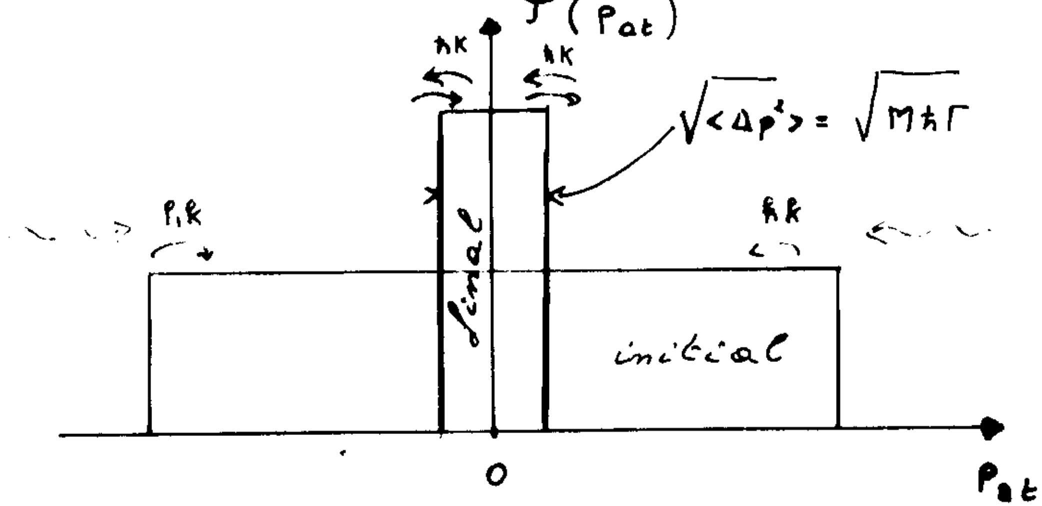
liquid nitrogen He beam



Velocity optical pumping in

spontaneous or stimulated

optical molasses:



"Optical pumping in a

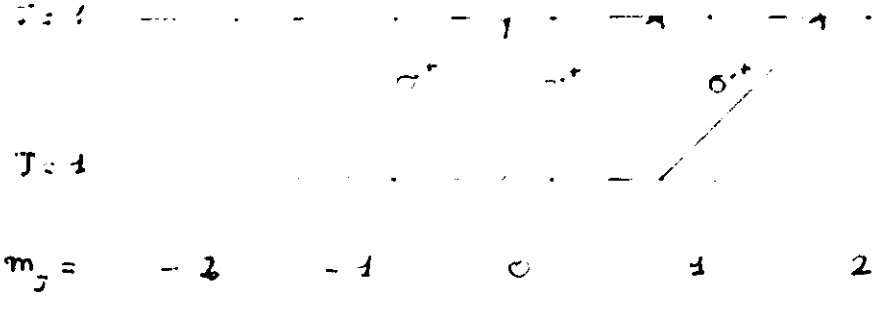
non-absorbing velocity selective state?

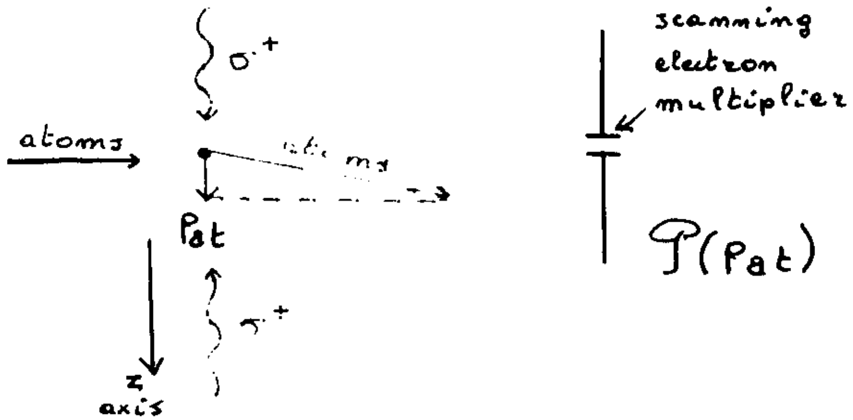
Experiments of

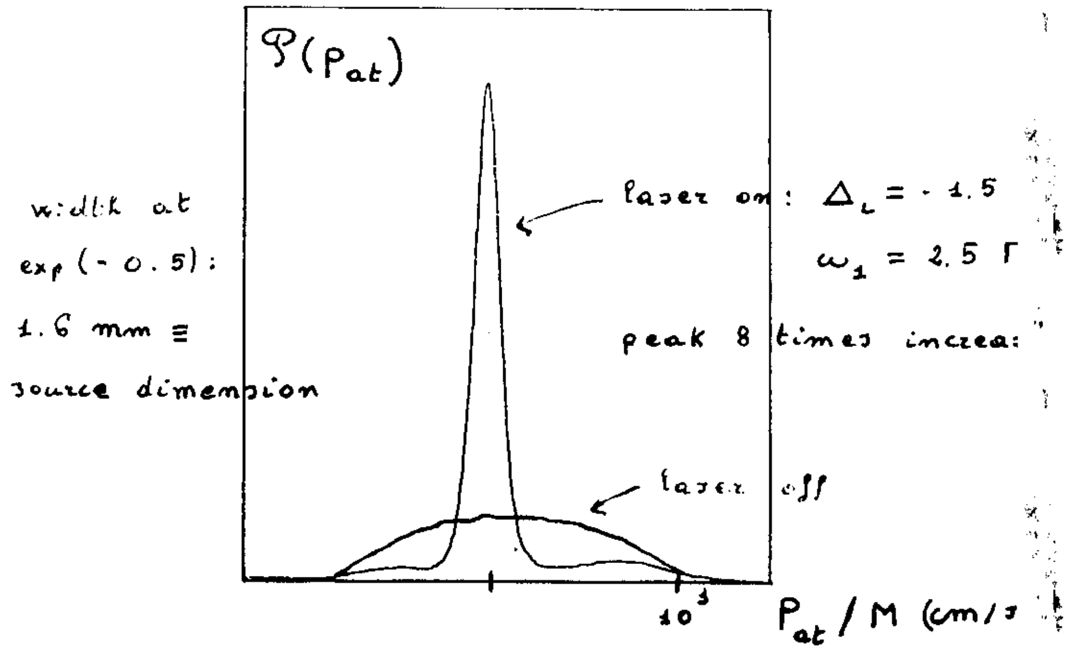
radiation pressure molasses

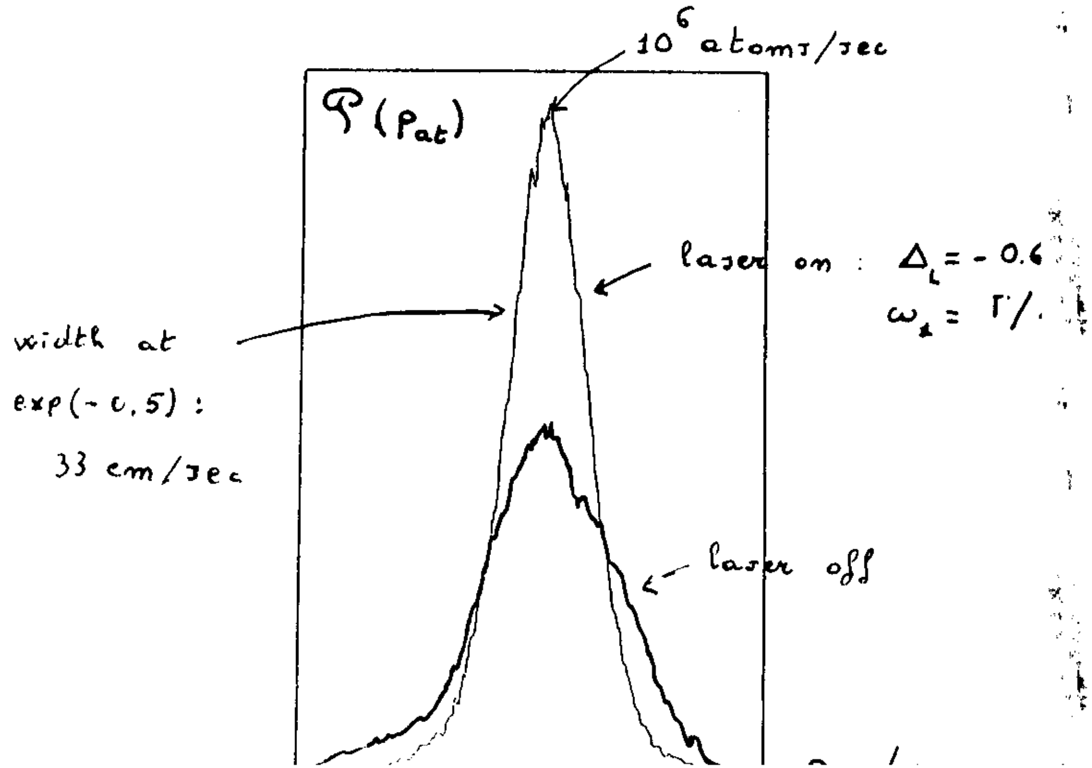
on $2^3S_1 \longrightarrow 2^3P_2$ transition

σ^+ light.

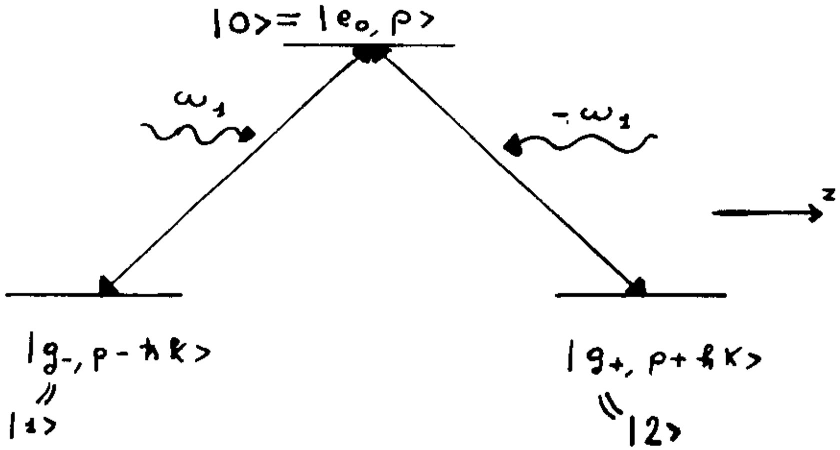








"Velocity-selective coherent population trapping"



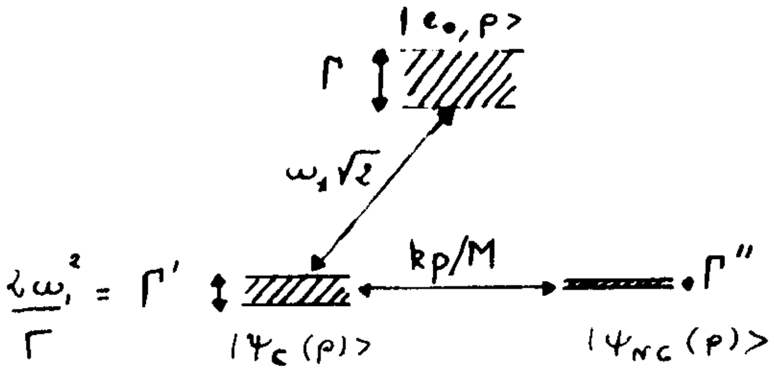
Non-absorbing state:

$$|\Psi_{NC}(p)\rangle = \frac{1}{\sqrt{2}}\Big[\,|g_-, p - \hbar k\rangle + |g_+, p + \hbar k\rangle\,\Big]$$

Absorbing state

$$|\Psi_{C}(p)\rangle = \frac{1}{\sqrt{2}}\Big[\,|g_-, p - \hbar k\rangle - |g_+, p + \hbar k\rangle\,\Big]$$

$$E_{\text{kinetic}} = \quad \frac{(p-\hbar k)^2}{2M} \qquad \frac{(p+\hbar k)^2}{2M}$$



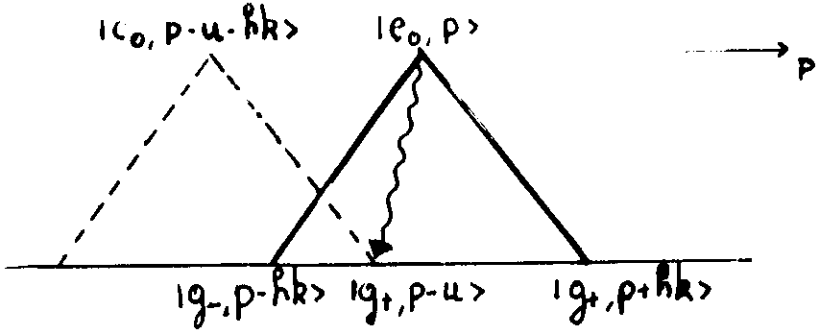
The state

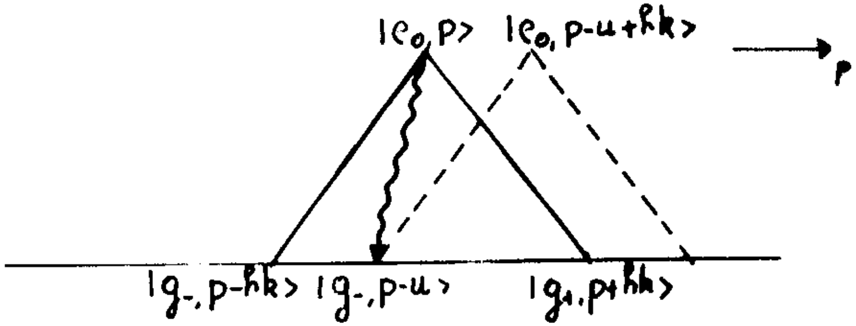
$$|\Psi_{NC}(0)\rangle = \frac{1}{\sqrt{2}}\Big[\,|g_-, -\hbar k\rangle - |g_+, +\hbar k\rangle\,\Big]$$

is a perfect trap:

an atom prepared in this state will remain there indefinitely.

Accumulation into the non-absorbing and trapping state $|\Psi_{NA}(0)\rangle$ through p-diffusion





A measurement of the momentum p_{at} on the $|\Psi_{NC}(0)\rangle$ state

$$|\Psi_{NC}(0)\rangle = \frac{1}{\sqrt{2}}\left[\,|g_-, -\hbar k\rangle + |g_+, +\hbar k\rangle\,\right]$$

yields

either $p_{at} = -\hbar k$

or $p_{at} = +\hbar k$

The atomic momentum distribution $\mathcal{P}(p_{at})$ has peaks at $p_{at} = \pm \hbar k$

Density matrix equations for coherent trapping:

velocity-selective

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

$$\mathcal{H} = E_0|0\rangle\langle 0| + E_1|1\rangle\langle 1| + E_2|2\rangle\langle 2|$$

$$+ \left\{\alpha\,|0\rangle\langle 1|\, e^{-i\omega_L t} + \beta|0\rangle\langle 2|\, e^{-i\omega_L t} + c.c.\right\}$$

$$+ \frac{P^2}{2M}$$

$$\frac{d}{dt}\rho_{00}\Big)_{rel} = -\Gamma\rho_{00}$$

(p)

$$\frac{d}{dt}\rho_{01}\Big)_{rel} = -\frac{\Gamma}{2}\rho_{01}, \quad etc$$

$$\frac{d}{dt}\rho_{11}\Big)_{rel} = \frac{\Gamma}{2}\rho_{00} - \frac{1}{\tau_1}\left(\rho_{11} - \rho_{22}\right), \quad etc$$

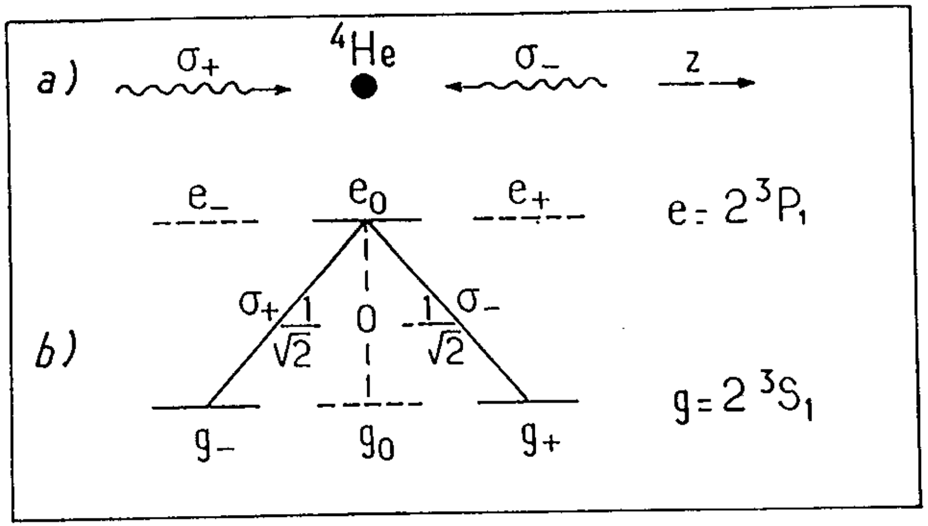
(p)

$$\frac{\Gamma}{2}\int_{-\hbar k}^{+\hbar k} du\, H(u)\, \rho_{00}(p+u)$$

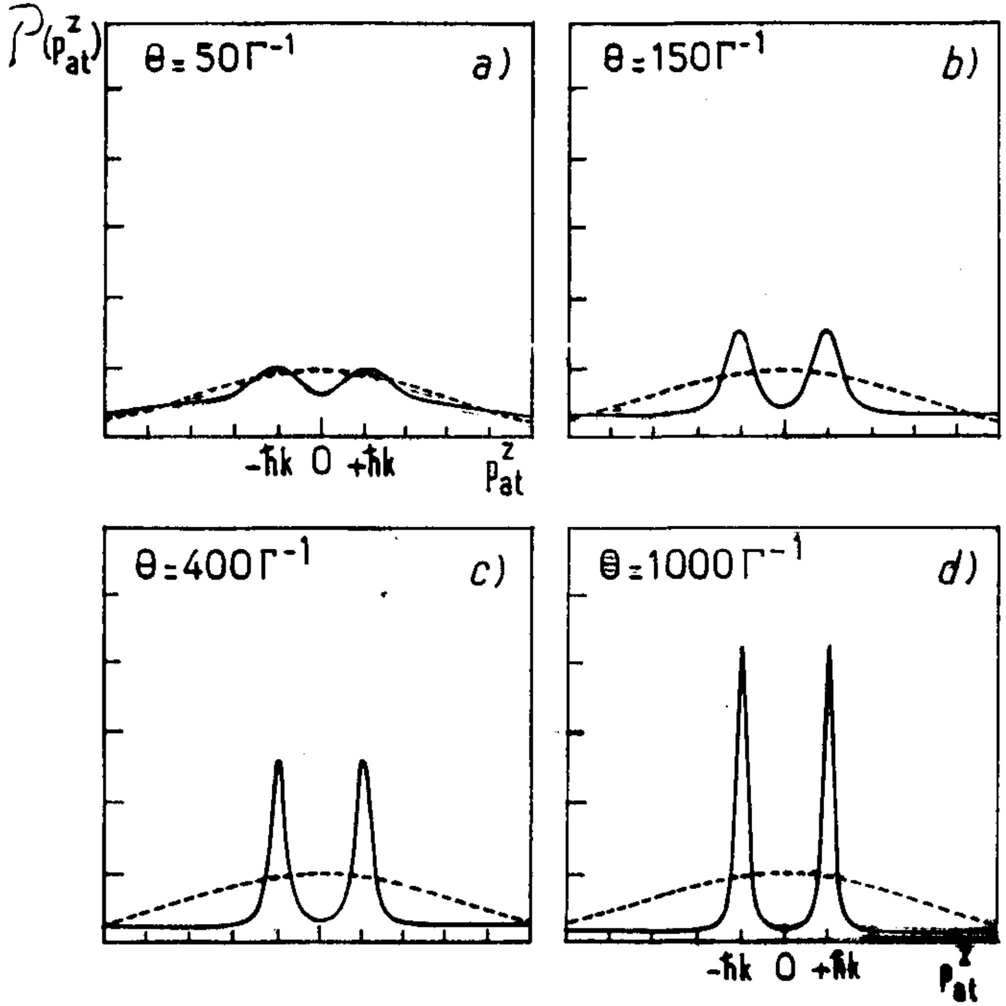
$$\frac{d}{dt}\rho_{12}\Big)_{rel} = -\frac{1}{\tau_2}\rho_{12}$$

Calculated atomic momentum distribution

^4He level scheme for laser cooling based on Velocity selective Coherent population trapping



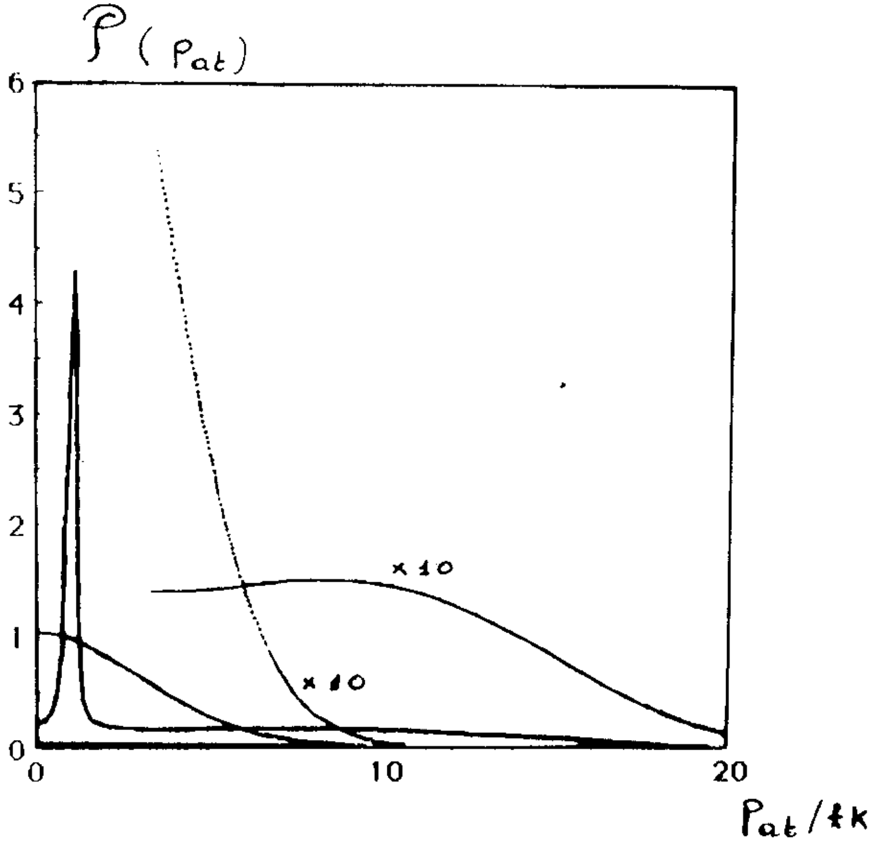
A. Aspect, E.A., R. Kaiser, N. Vansteenkiste, C. Cohen-Tannoudji
Phys. Rev. Lett. 61 826 (1988)



$\Delta p_{at}(0) = 3\hbar k$

$\Delta_L = 0 \; ; \quad \omega_1 = 0.3\,\Gamma$

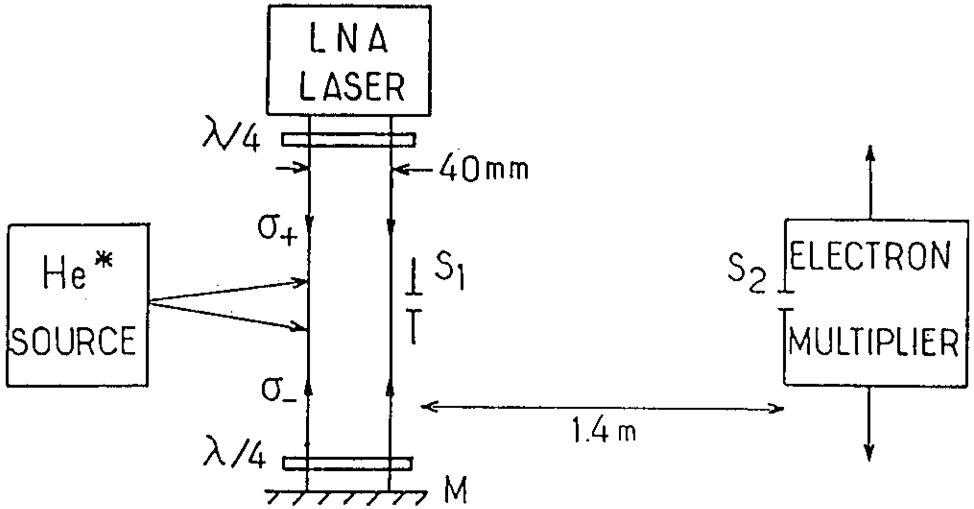
Calculated atomic momentum distribution



— initial $\Delta p_{at} = 3\hbar k$

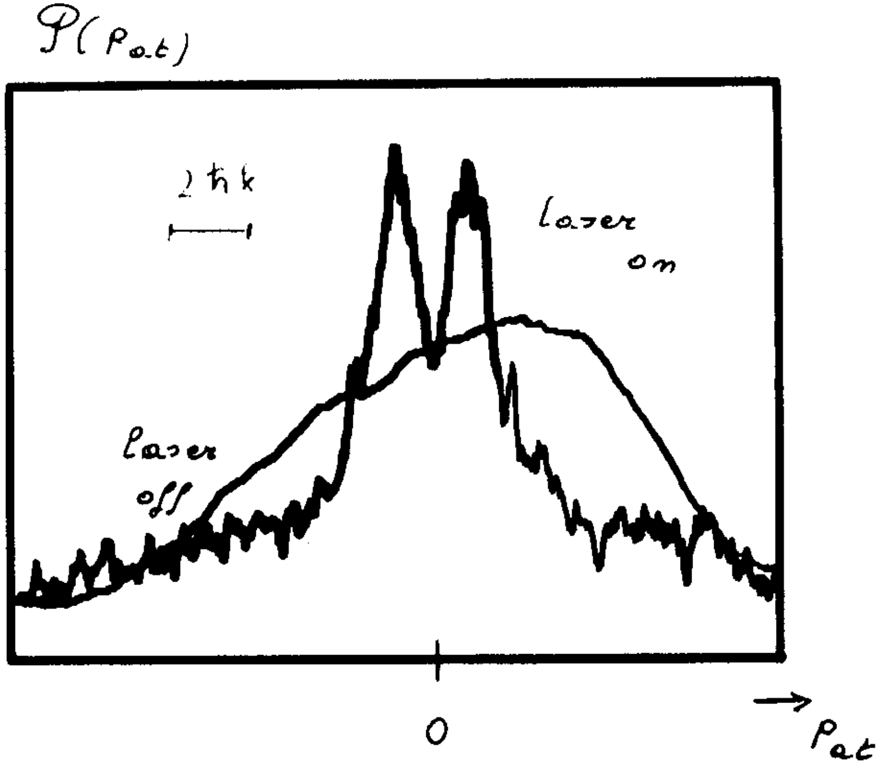
— final at $\Theta\Gamma = 1000$

$\Delta_L = 0 \quad \omega_1 = 0.3\Gamma$



Schematic set-up

Transverse atomic momentum profile

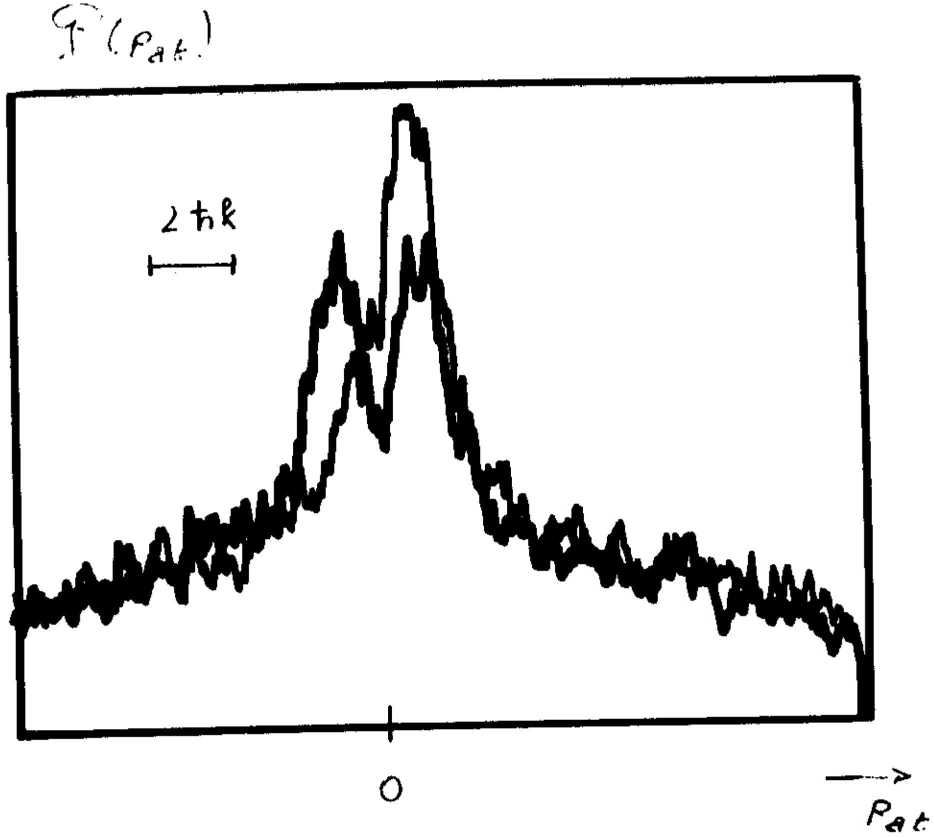


$\Delta_L = 0$

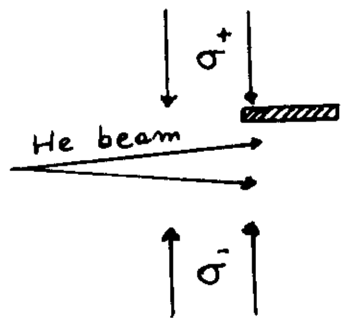
$\omega_1 = 0.6\ \Gamma$

40 mm interaction region

$T = 2\ \mu K$



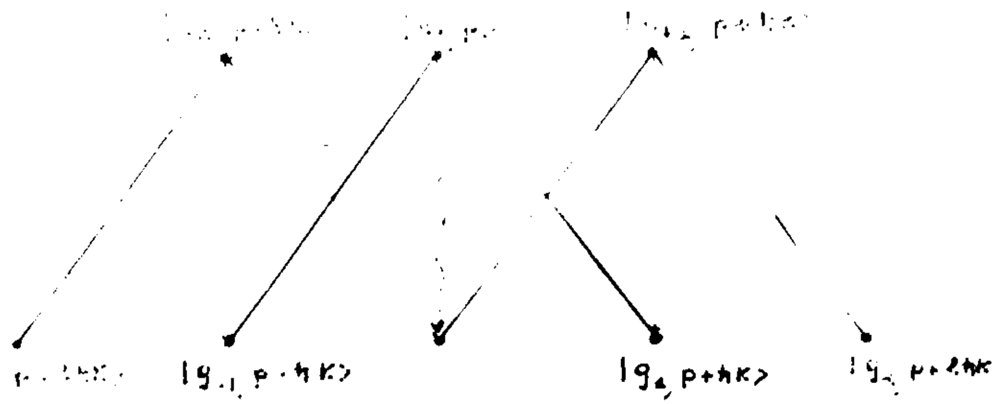
Depopulation pumping from trapping state:



$|\Psi_{NC}(0)\rangle =$

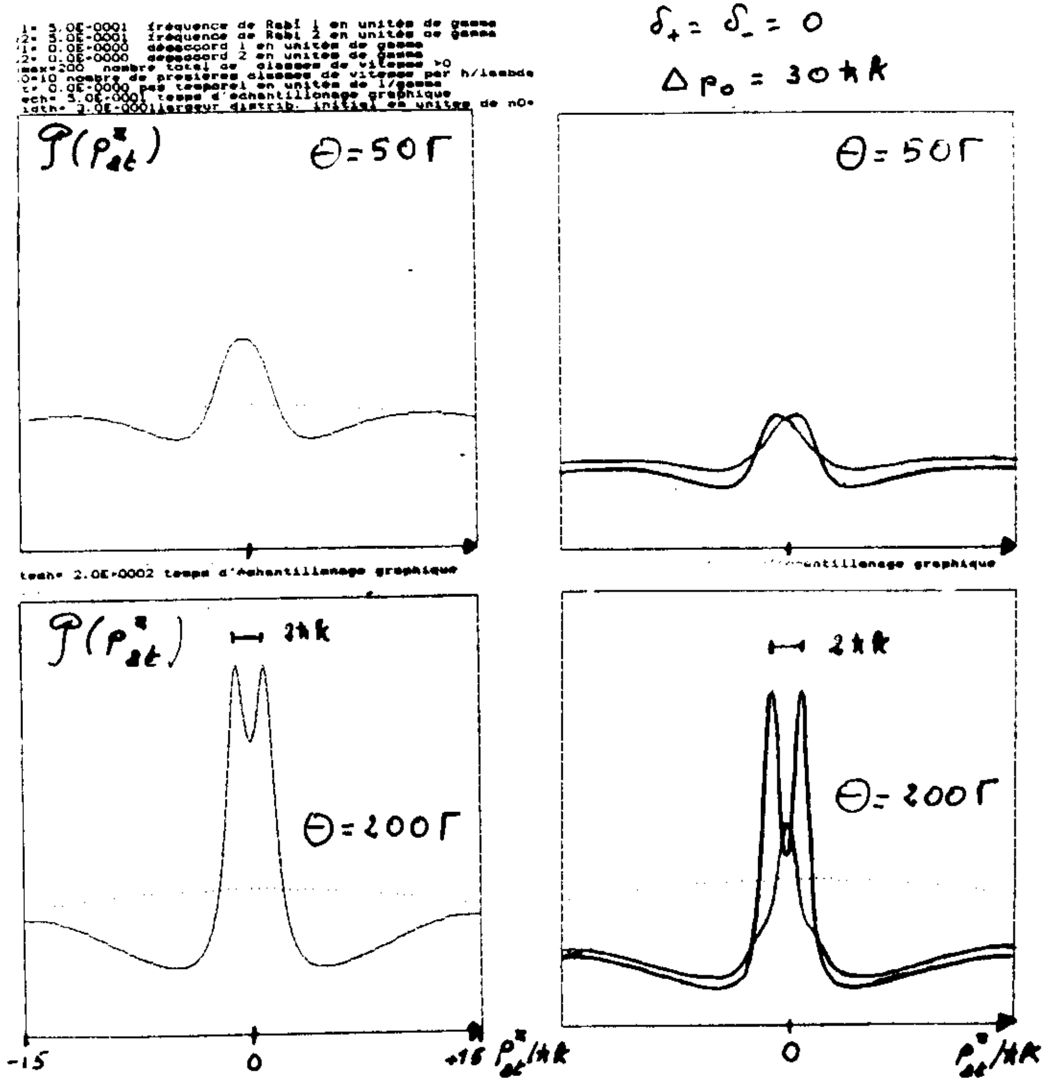
$= \frac{1}{\sqrt{2}}\left[|g_{-1}, -\hbar k\rangle + |g_{+1}, \hbar k\right.$

The $J=2 \rightarrow J=1$ transition is composed by following configurations



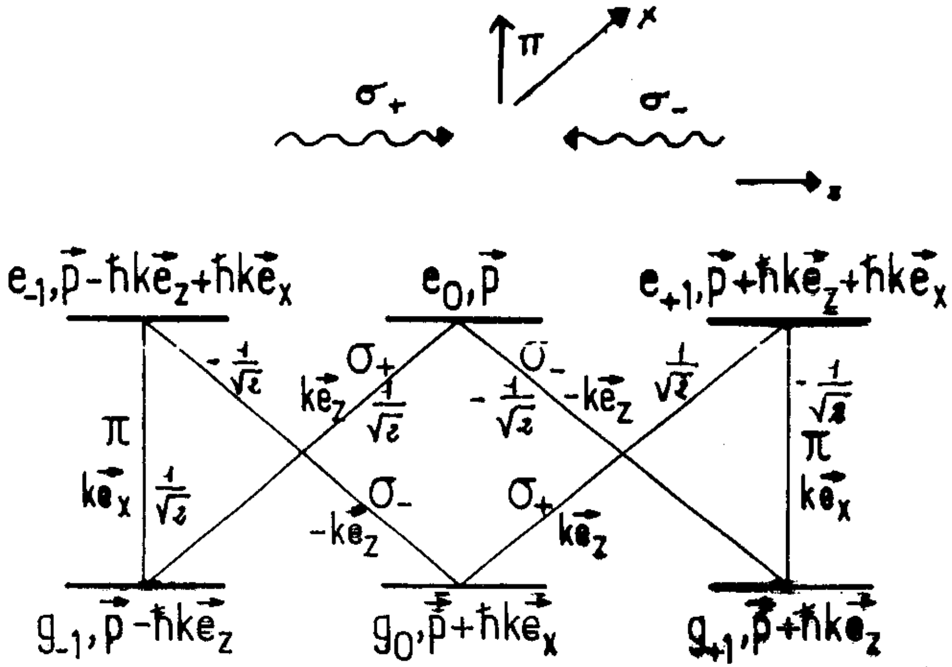
He trapping on $J=2 \rightarrow J=1$ transition

$\omega_+ = \omega_- = 0.5\,\Gamma$



Contribution of each configuration:

Generalization to two dimensions

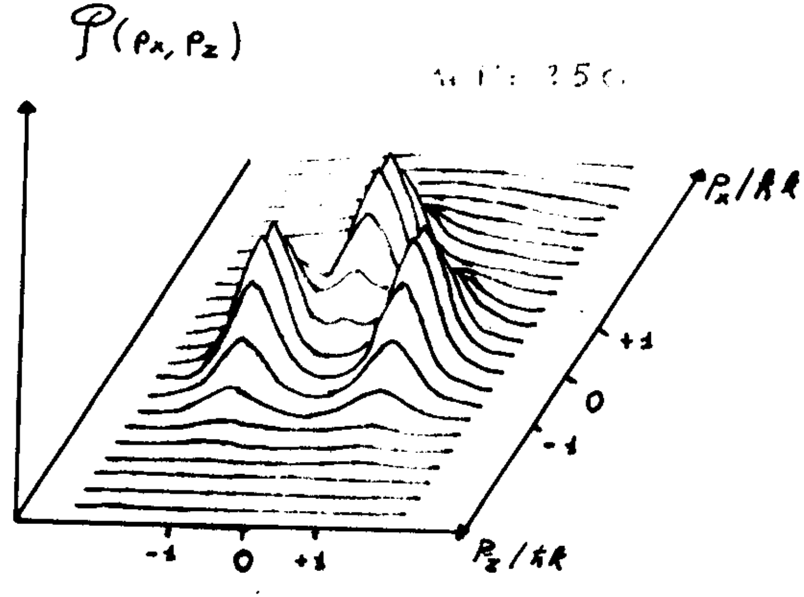


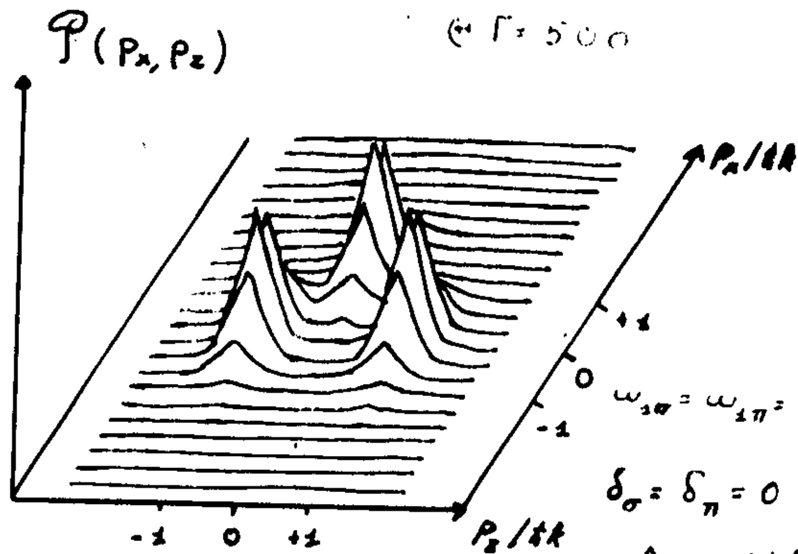
Non-coupled state

$$|\psi_{NC}(p_x, p_z)\rangle =$$

$$\frac{1}{\sqrt{3}}\Big[\,|g_{-1}, p_x, p_z - \hbar k\rangle + |g_0, p_x + \hbar k, p_z\rangle + |g_1, p_x, p_z + \hbar k\rangle\Big]$$

Atomic distribution in two dimension cooling





$\omega_{1\sigma} = \omega_{1\pi} = 0.1$

$\delta_\sigma = \delta_\pi = 0$

$\Delta p_0 = 4\hbar k$

Main features of

"velocity selective coherent population trapping"

i) cooling is not due to a <u>friction force</u> but to a <u>diffusion</u>.

ii) for cooled atoms no interaction with light

iii) $$|\Psi_{NC}(0)\rangle = \frac{1}{\sqrt{2}}\left\{ |g_{-1}, -\hbar k\rangle + |g_{+1}, +\hbar k\rangle \right\}$$

in He experiment $\lambda_B = 1.4\,\mu m$

has coherence on <u>external</u> degrees

iv) extension to other level configurations and geometries.

Applications of very cold atoms:

- Spectroscopy
- Metrology
- Bose- Einstein condensation
- Collisions with atoms or surfaces

In collisions of very cold atoms it results:

→ $\lambda_B = \dfrac{h}{M v_{at}}$ >> range of interaction potential

→ only few partial waves contribute to cross- section

→ dynamic of collision dominated by weak potentials at large distances