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SMR 1302 - 3

WINTER SCHOOL ON LASER SPECTROSCOPY AND APPLICATIONS

19 February - 2 March 2001

SPECTROSCOPY OF COLLIDING COLD ATOMS

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These are preliminary lecture notes, intended only for distribution to participants.

Spectroscopy of colliding cold Atoms

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Program:

Lect. I - Basic Concepts
- General Introduction
- Cooling atoms with laser beams
- Trapping atoms
- Examples of applications

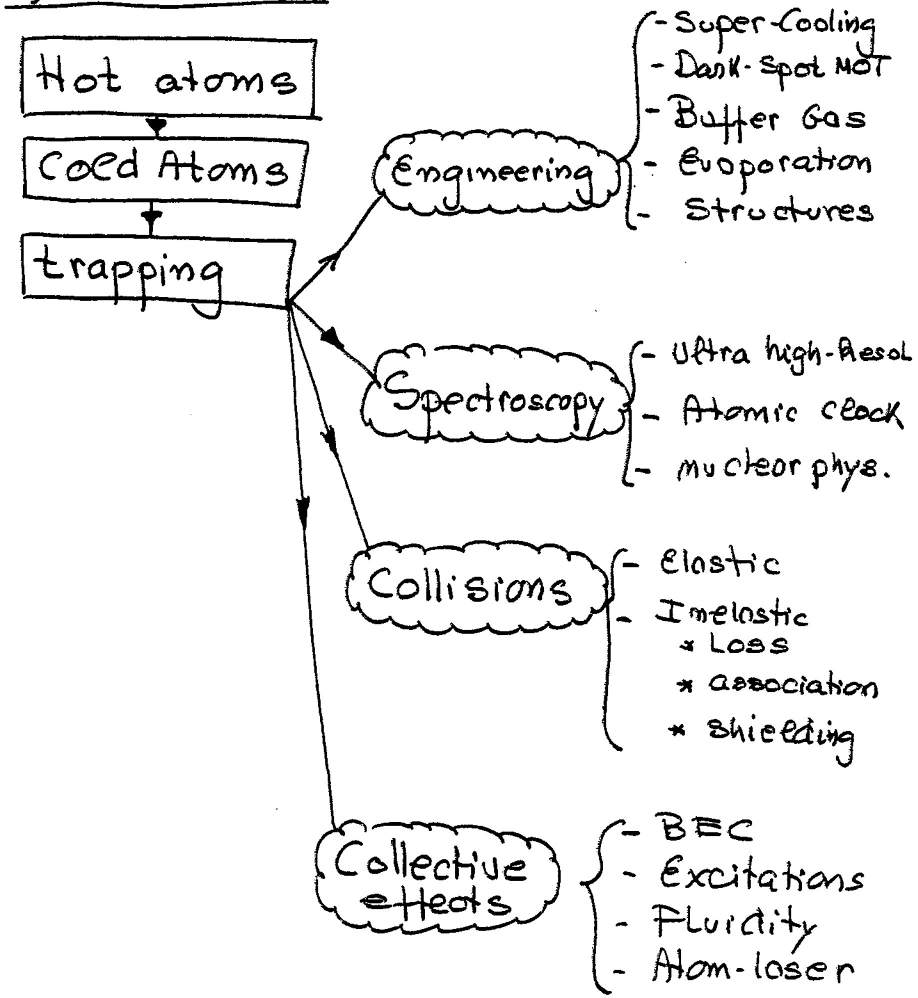
Lect. II - Cold collisions in the presence of light
- Exoergic collisions: homonuclear
- Exoergic collisions: heteronuclear
- New model at low intensity limit

Lect. III - Cold collisions and chemical reaction
- Photoassociative spectroscopy
- Photoassociative ionization
- Shielding collisions with photons
- New ideas

Extra - Bose Einstein-Condensation

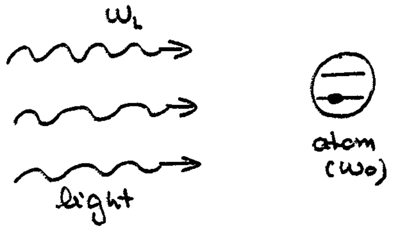
I- Basic Concepts

I.1) Introduction



⇒ *Cold atoms have expanded the frontiers of atomic and molecular physics*

* Radiation Pressure



Dipole Interaction

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

* Spontaneous force
- absorption $\quad \Delta\vec{p} = \hbar\vec{K}$
- emission $\quad \langle\vec{p}\rangle = 0$

$$\vec{F}_s = \left(\begin{array}{c}\text{absorption}\\ \text{rate}\end{array}\right)\hbar\vec{K} = \hbar\vec{K}\,\frac{\Gamma}{2}\left(\frac{s}{s+1}\right)$$

$s \equiv$ saturation parameter

* Dipole force

- Induced dipole interacting with field gradient

$$\vec{F}_d = -\frac{1}{2\Omega^2}(\vec{\nabla}\Omega^2)\hbar\Delta\,\omega_L\left(\frac{S}{1+S}\right)$$

$\Delta = \omega_L - \omega_0$ (detuning)

$\vec{F}_d$ is conservative; $\vec{F}_s$ is not

$\Longrightarrow$ $\vec{F}_s$ can be used to cool atoms

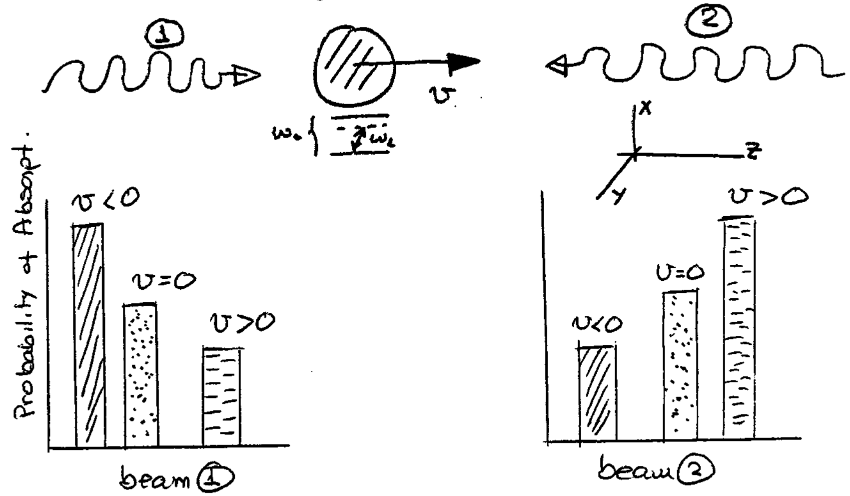
$\vec{F}_d$ can confine atoms

How to cool?

- deceleration z-axis
- diffusion x, y,
- Doppler effect can select absorption

Ex: Laser deceleration of an atomic beam

* Two light beams ($\Delta<0$) + One atom



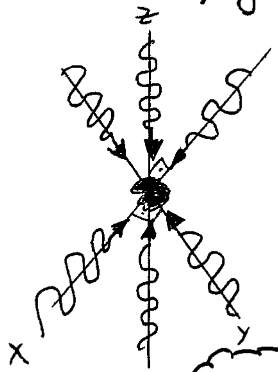
Net result:

* force opposed to velocity

$$m\frac{dv}{dt} = -\alpha v$$

* Viscous force $\Delta<0$; Energy remove $\Longrightarrow$ Optical Molasses

- 3D configuration:



* 6 laser beams create a 3D viscous medium
* No confinement
* Atoms cool down

$$\boxed{m\frac{d\vec{v}}{dt} = -\alpha\vec{v}}$$ $\alpha = \alpha(\Delta, \Omega)$

Damping comes from spontaneous force
→ depends on spontaneous emission
→ Random motion
→ Heating

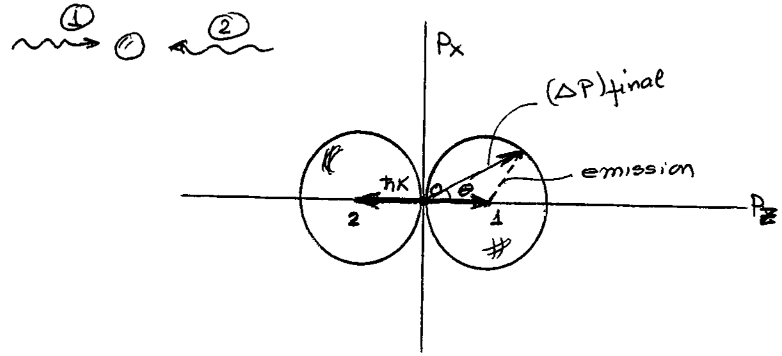
Balance between cooling and heating takes to a limit ⟹ Doppler Temperature

* Equation for atom Kinetic Energy

$$\frac{dK_i}{dt} = v_i F_i + H_i$$

$$K_i = \frac{1}{2} m v_i^2 \qquad i = x, y, z$$

2 laser beams in z-direction



* After one cycle of absorption-emission atom can end up in any point of a surface in p-space composed of two spheres of radius $\hbar K$

* Averaged momentum variation

$$\langle(\Delta P_x)^2\rangle = \langle(\Delta P_y)^2\rangle = \frac{(\hbar K)^2}{3}$$

$$\langle(\Delta P_z)^2\rangle = \frac{4}{3}(\hbar K)^2$$

* Absorption - Emission rate $= \frac{\Gamma}{2} \cdot S$ (per beam)

$$S = \frac{\frac{1}{2}\Omega^2}{\Delta^2 + \frac{1}{4}\Gamma^2}$$

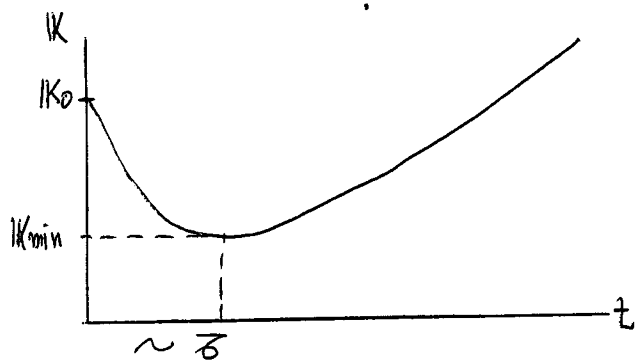
* Heating rate

$$H_i = \underset{\substack{\uparrow \\ \text{2 beams}}}{2}\, \frac{\Gamma}{2} S \frac{\langle(\Delta p_i)^2\rangle}{2m}$$

$$\frac{dK_i}{dt} = v_i F_i + H_i = +v_i^2\alpha + H_i = +2\frac{\alpha K_i}{m} + H_i$$

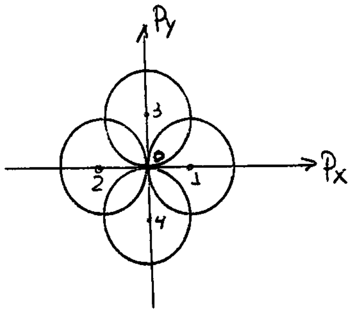
$$K(t) = \sum K_i = K_0 + (e^{-t/\tau}-1)K_{0z} + \beta[t-\tau(e^{-t/\tau}-1)]$$

$$\tau = \frac{(\Delta^2+\frac{1}{4}\Gamma^2)m}{4\Gamma\hbar k^2 s|\Delta|}$$



Heating dominates $\Longrightarrow$ needs to cool all directions

6 laser beams

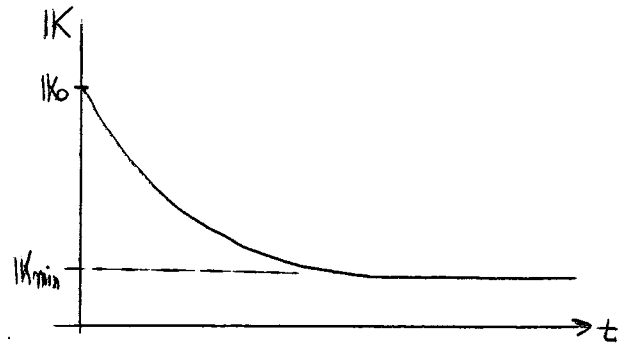


$$\langle(\Delta p_i)^2\rangle = \frac{2}{3}(\hbar k)^2$$

$$\frac{dK}{dt} = 2\Gamma\hbar k^2 s\frac{2\Delta}{(\Delta^2+\frac{1}{4}\Gamma^2)}\frac{K}{m} + 3\Gamma s\frac{(\hbar k)^2}{m}$$

$(\Delta<0)$

$$K(t) = (K_0 - K_{min})e^{-t/\tau} + K_{min}$$



$$K_{min} = \frac{3\hbar(\Delta^2+\frac{1}{4}\Gamma^2)}{4|\Delta|}$$ (Doppler Limit)

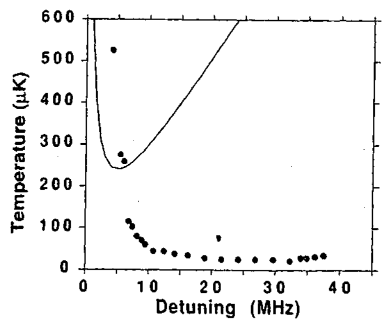
$$\tau = \frac{(\Delta^2+\Gamma^2/4)m}{4\Gamma\hbar k^2|\Delta|s}$$

Since K_{min} depends on Δ → optimization

$$\frac{dK_{min}}{d\Delta}=0 \Longrightarrow (K_{min})_{min} = \frac{3}{4}\hbar\Gamma, \quad \Delta = -\Gamma/2$$

System	Na	Cs	K	Rb	Li
Doppler Limit	237μK	125	137	141	140

* Measurements of $T_{min}(\Delta)$



→ Much lower value can be obtained

Explanation: Multi-level nature of the atoms together with optical pumping

Consider a $J=\frac{1}{2} \longrightarrow J'=\frac{3}{2}$ cooling transition

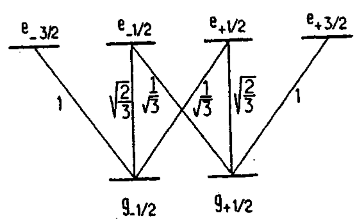
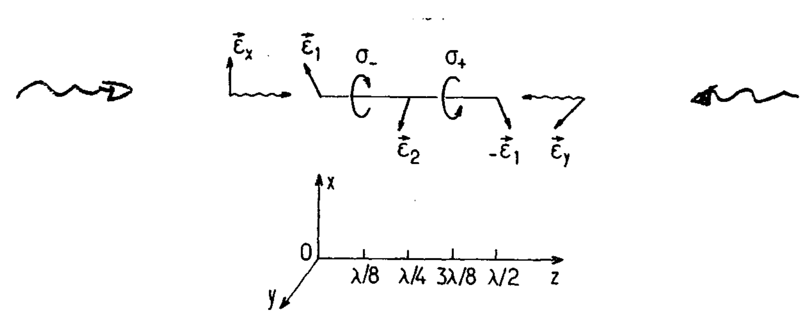


Fig. 2. Atomic level scheme and Clebsh-Gordan coefficients for a $J_g = 1/2 \leftrightarrow J_e = 3/2$ transition.

→ Light polarization can accumulate population in a certain level

→ Consider polarization as follow:



* There is polarization variation as a function of position

→ $g_{-1/2}$ state higher population when σ^-

→ $g_{+1/2}$ state higher populated when σ^+

* Since interaction is also dependent of polarization → Stark shift of levels $\left(\sim \frac{\hbar \Omega^2}{\Delta}\right)$ oscillates with position.

Combination of light shift and population

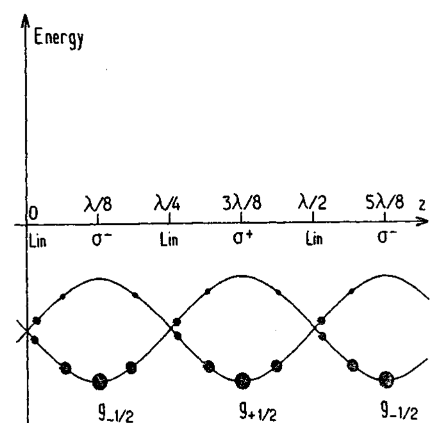
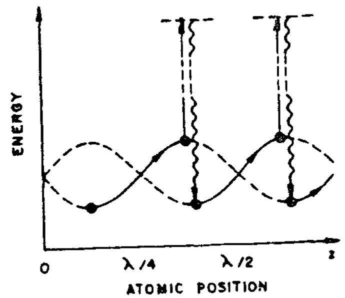


Fig. 3. Light-shifted energies and steady-state populations (represented by filled circles) for a $J_g = 1/2$ ground state in the lin ⊥ lin configuration and for negative detuning. The lowest sublevel, having the largest negative light shift, is also the most populated one.

→ Atoms moving in this system will suffer the effects of both: light-shift and optical pumping

$\Longrightarrow$ Sisyphus Cooling



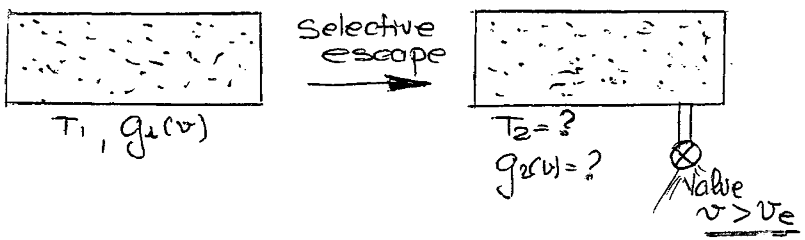
* New limit $\Longrightarrow$ $(KT)_{min} \sim \dfrac{\hbar\,\Omega^2}{\Delta}$

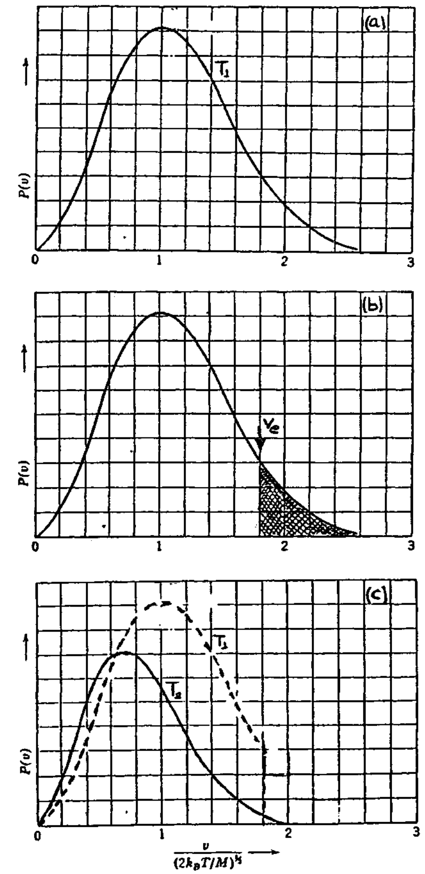
→ good agreement with experim.

Evaporative Cooling

* Does not involve laser but is very important

* Imagine a confined gas

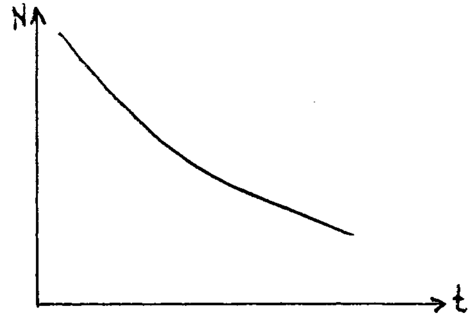


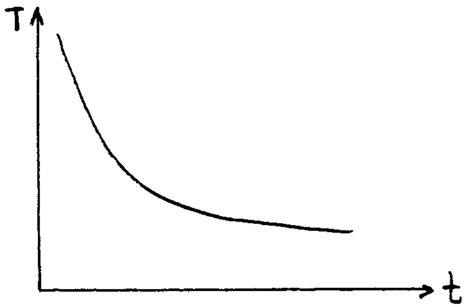


$$\int_0^{v_e} g_1(v,T_1)\,dv = \int_0^{\infty} g_2(v,T_2)\,dv$$

$T_2 < T_1$

⋮





⇒ Ultra-low temperatures can be obtained

$T \sim 10^{-9}\,K$ is possible

Trapping

* To trap is necessary first to cool

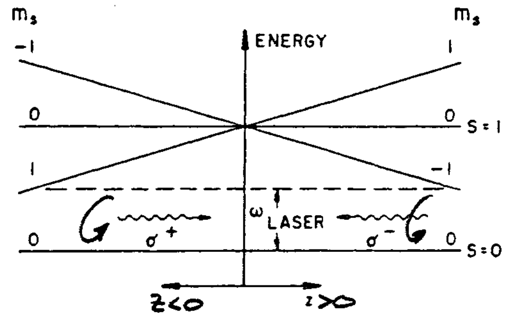
* Trapping → restoring force to equilibrium position

force ⇒
- * From light
- * static B-field
- * Oscillating fields

Magneto-Optical Trap (MOT)

* Use of internal structure of atoms to produce a spatial selection rule

* Consider:
  → Atom with ground state $S=0$
  → Excite state $S=1$
  → Magnetic field with linear gradient (profile)
  → Counter propogating lasers with circular polarization of opposite helicity. ($\Delta<0$)



* Selection rules
$$\begin{cases} \sigma^+ \to \Delta m_s = +1 \\ \sigma^- \to \Delta m_s = -1 \end{cases}$$

* Atom moving $z>0$; transition $0\to -1$ closer to resonance
σ^- stronger ⇒ $\boxed{\text{Force to the left}}$

* Atom moving $z<0$; transition $0 \to +1$ closer resonant,
→ σ^+ stronger ⇒ $\boxed{\text{Force to the right.}}$

* Atom at $z=0$, both transitions are equal → $\boxed{\text{No net force}}$

$\Delta < 0$ → damping force
$B(z)$ → restoring force

⇓

$$\boxed{m\frac{d\vec{v}}{dt} = -\alpha\vec{v} - K\vec{r}}$$

* Using radiative force

$$\frac{\alpha}{2\pi} = \frac{16\,\Omega_0^2\,|\Delta|\,(K/4\pi)}{(1+2\Omega_0^2)^2\left[1+\frac{4\Delta^2}{1+2\Omega_0^2}\right]^2}$$

$$\frac{\mathbb{K}}{2\pi} = \frac{16\,\Omega_0^2\,|\Delta|}{(1+2\Omega_0^2)^2\left[1+\frac{4\Delta^2}{1+2\Omega_0^2}\right]^2}\,\frac{d\omega}{dz}$$

→ System is normally over damped
Good!!!!

→ Capture velocity is small
BAD!!!!

$v_c \sim 12\text{-}20\ m/s$

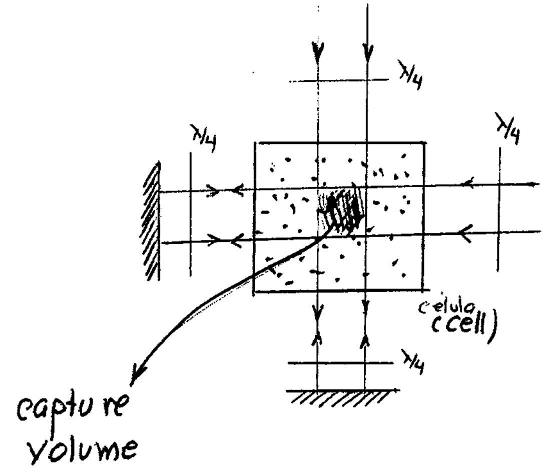
Room temperature ($v_{mp} \sim 500\,m/s$)
only very low tail of Maxwell distribution can be captured

* First demonstration of MOT was done with decelerated atomic beam

* Would be possible to capture from vapor (Hot) phase?

YES, if you can accumulate the atoms for long time

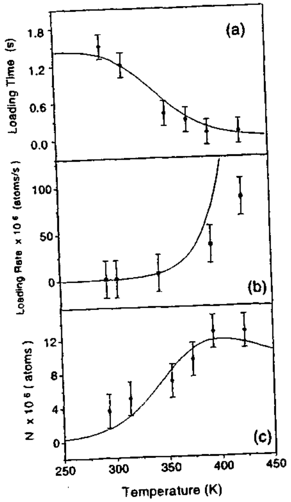
Capture → thermalize → Capture → ......

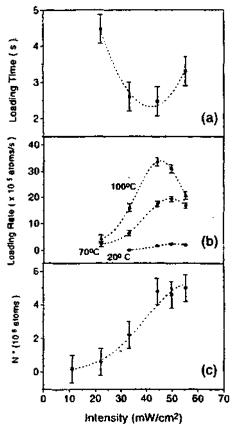


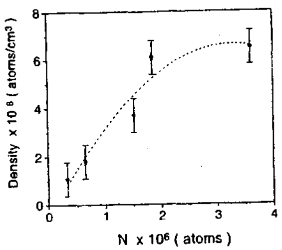
How it looks like?

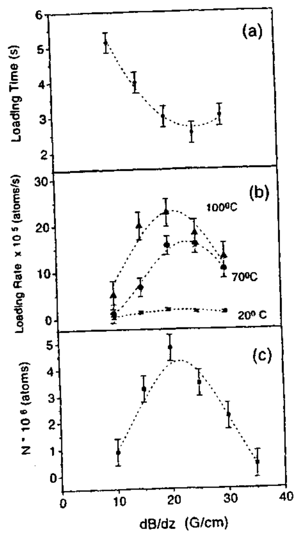
* MOT operation depends of several parameters ⟶ needs optimization

* MOT always produce a mixture of atoms in both states (background and excited)



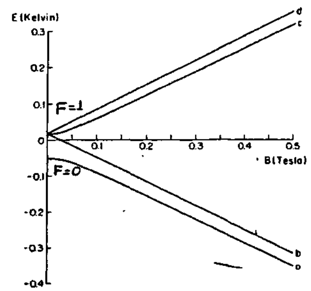






Magnetic Trapping

* Possible due to spin-field interaction

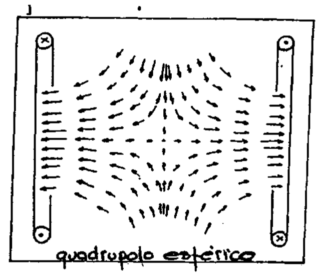


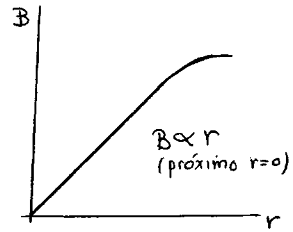
} weak field seekers

$U = -\vec{\mu} \cdot \vec{B}$

} Strong field seekers

* Producing minimum of B-field ⟹ confinement of atoms





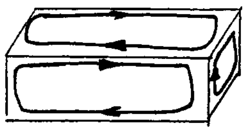
⟹ Atoms can escape near B=0

trapping states $\xrightarrow{\text{to}}$ untrapping states

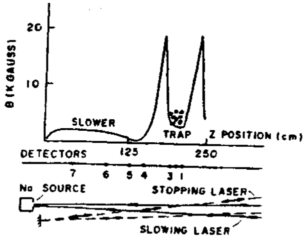
"Majorana Flops"

rate $\sim \frac{10^{-3}}{R^2}$ (mm²/s)

* Minimum of B-field with $B \neq 0$

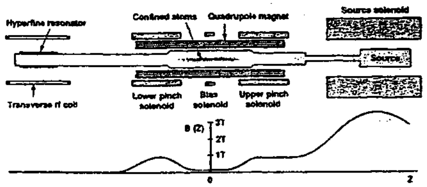


transversal ⇒ quadrupolo
longitudinal ⇒ dois baneiros

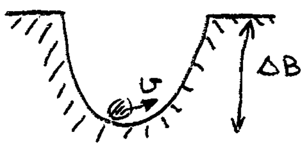


* Solution at MIT (1987)

* Experiments with hydrogen



* Pure magnetic trap are not very deep. Atoms must be already cold.



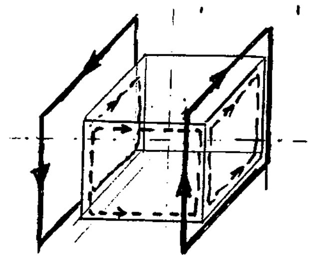
(1000 K) $v = 1000\, m/s \rightarrow \Delta B = 2\,10^{7}\, G$

(10 K) $v = 100\, m/s \rightarrow \Delta B = 2\,10^{5}\, G$

(10^{-1} K) $v = 10\, m/s \rightarrow \Delta B = 2\,10^{3}\, G$

(10^{-3} K) $v = 1\, m/s \rightarrow \Delta B = 2\,10^{-3}\, G$

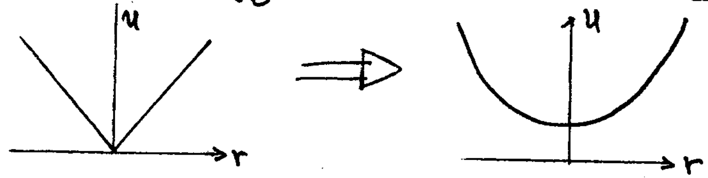
* TOP (time Orbiting Potential)
(avoide escape $B = 0$)
- Composition of spherical quadrupole with oscillating field

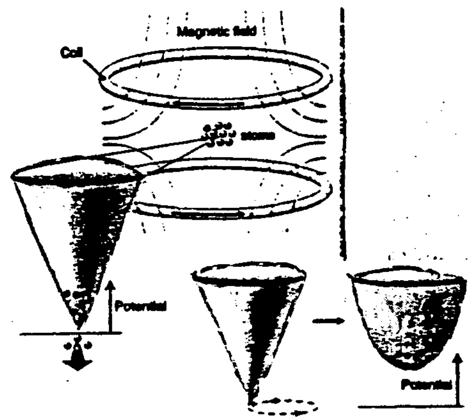


$$\mathcal{U} = \mu[xB' + B_0 \cos\omega_0 t]\hat{x} + \mu[yB' + B_0 \operatorname{sen}\omega_0 t]\hat{y} - 2yB'\hat{z}$$

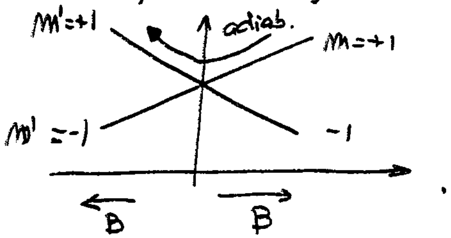
For $\omega_t < \omega_b$
(oscillation of atoms < oscill. field)

$$\bar{\mathcal{U}} = \frac{\omega_b}{2\pi}\int_0^{2\pi/\omega_b} \mathcal{U}(t)\,dt = -\mu B_0 - \frac{\mu B'}{4B_0}(r^2 + 8z^2)$$





* Loss of atoms by "Majorana Flop"
  — take place when spin does not follow field adiabatically



* This occur when rate of change in the field (seen by the atom) is bigger than Larmor freq.

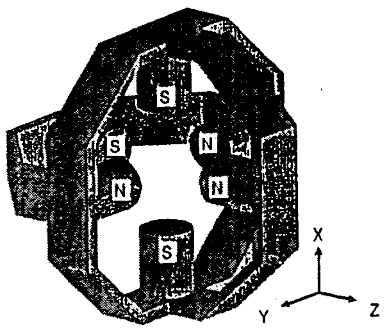
* Consider atom travelling at R from the center $(B=0)$. At this position

$$\left.\begin{aligned} \omega_L &= \frac{\mu\,(RB')}{\hbar} \\ \text{Rate of field Variation} &= \frac{v}{R} \end{aligned}\right\} \quad \frac{v}{R} > \frac{\mu RB'}{\hbar}$$

transition Region $\quad R < \sqrt{\dfrac{v\hbar}{\mu B'}}$

Rate of loss = flux of atoms at this region

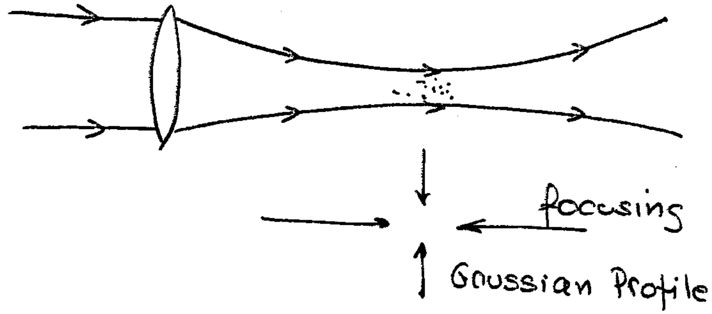
<u>Others</u>:

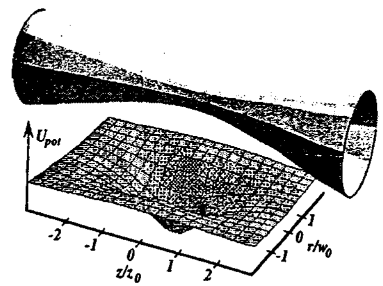


FORT : Use dipolar force

$$F_d \propto -\Delta \cdot \nabla \Omega^2$$

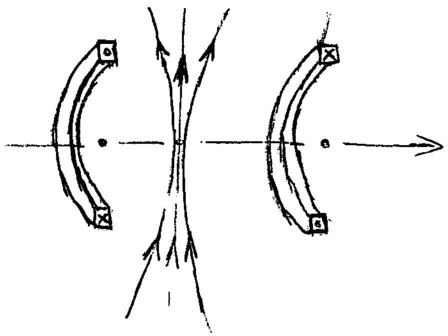
$\Delta < 0 \longrightarrow$ attraction towards maximum intensity

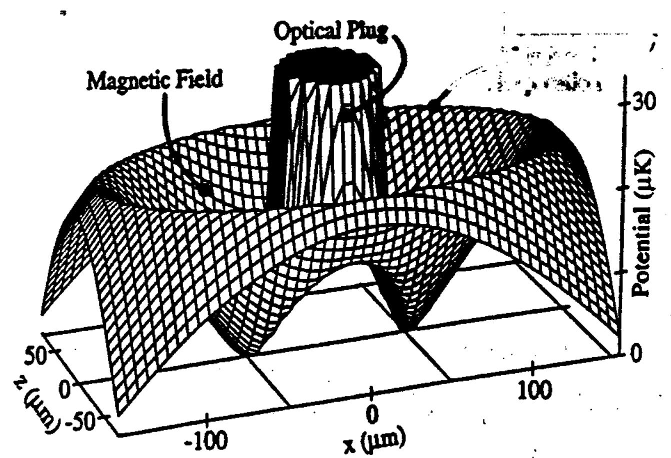




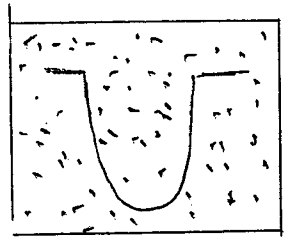
"Optical Plug"

* Another alternative to avoide B=0
* Dipole force to creat a repulsive barrier around B=0
  $\Delta > 0$, repel atoms

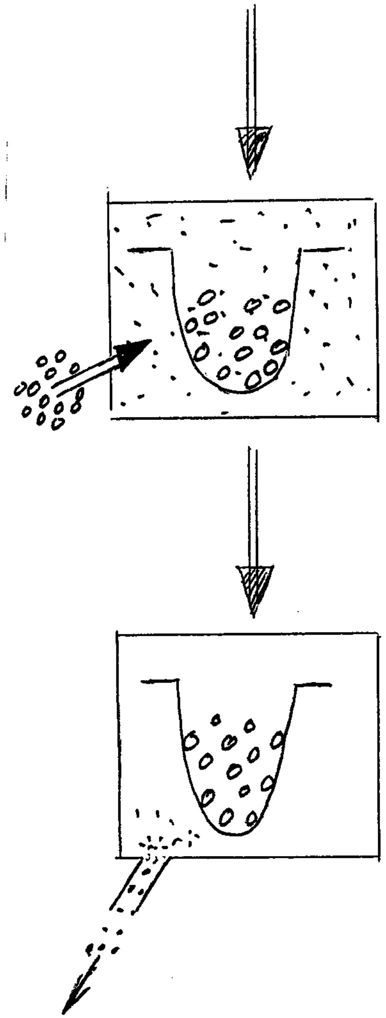




Cooling by a buffer-Gas



Magnetic trap
+
untrapped cold gas (He)



Injection of trapable specie → thermalizing → trapping

[Ni, Co, Er, Eu, Ho, Gd... CaH]

Remotion of buffer

$$\Delta T = \frac{T_{buffer} - T_0}{(M+m)^2 / 2Mm}$$

A few applications

Ultra-high resolution laser spectroscopy

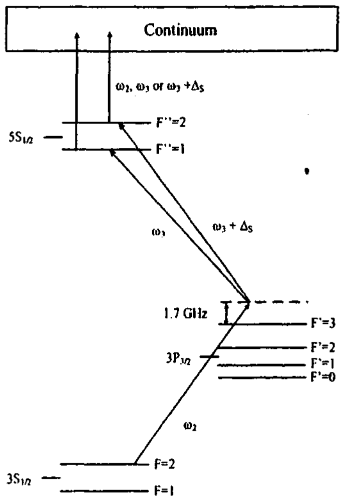


Fig. 2. Energy levels diagram of sodium, showing the transitions relevant for the measurement.

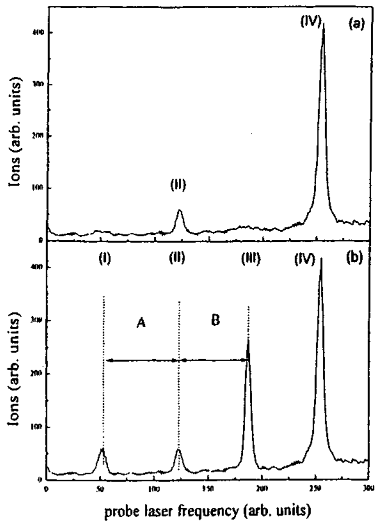


Fig. 3. Ion spectrum obtained during the "probe cycle" (a) without and (b) with the sideband in the probe laser frequency. See text for details.

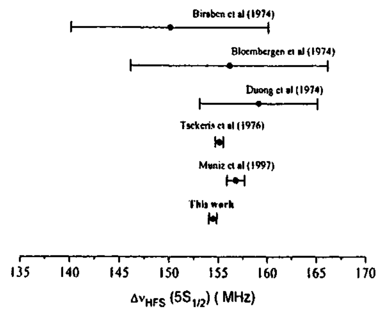
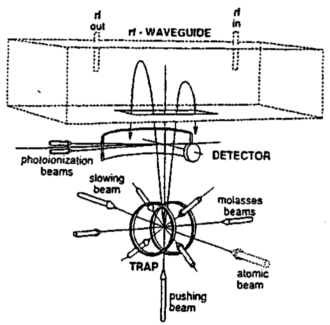
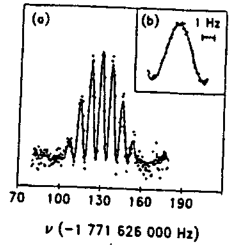


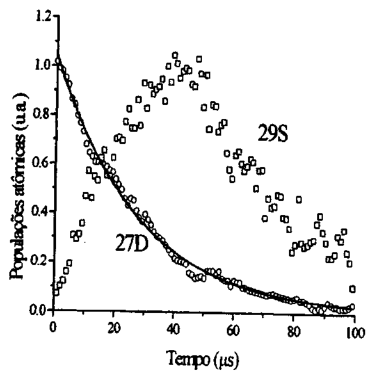
Fig. 5. Graphical comparison between our result and previous measurements for the hyperfine splitting of the Na 5S level. References are in the text.

* Atomic Clock "Fountain"

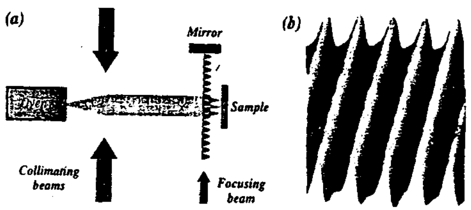


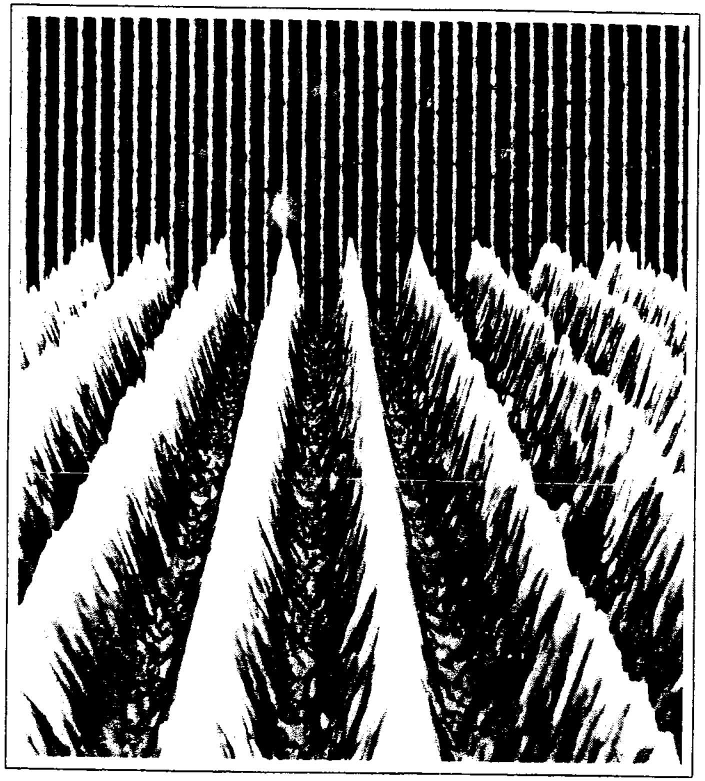


* Rydberg Atoms



Atomic Lithography





* Optical Lattices

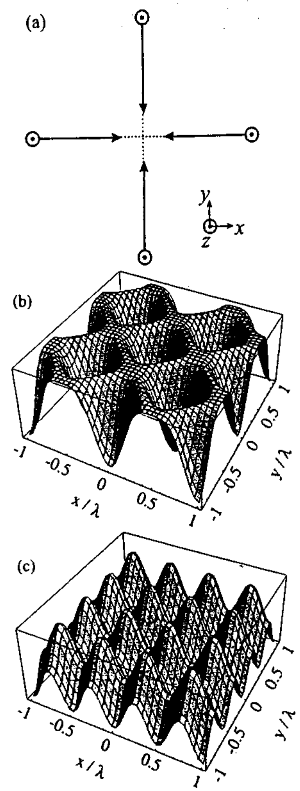
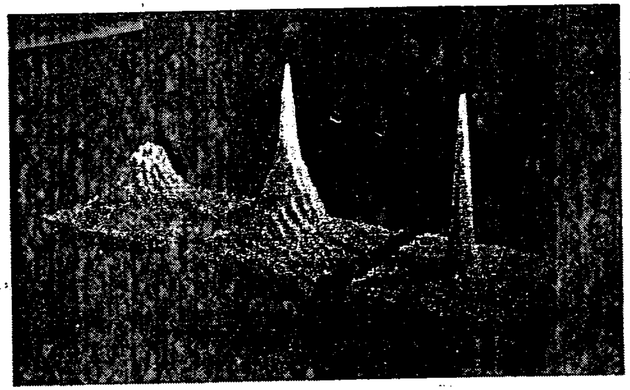


Fig. 3. (a) Beam configuration generating a phase-dependent 2D periodic lattice. The figure is drawn with $\mathbf{k}_1 \perp \mathbf{k}_2$. (b) Dipole potential for red detuned laser beams and $\phi_1 = \phi_2 = \phi_3 = \phi_4 = 0$. (c) Dipole potential for red detuned laser beams and $\phi_1 = \phi_3 = \pi/2$, $\phi_2 = \phi_4 = 0$.

Introduction to Bose-Einstein Condensation



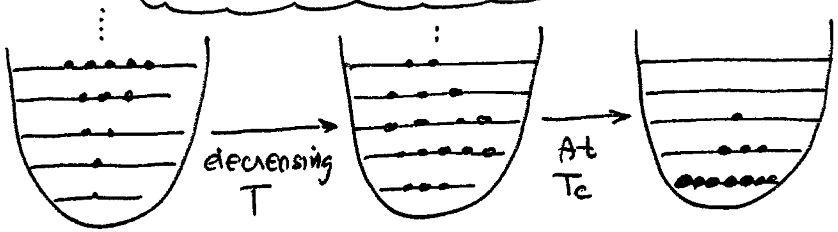
* Sistema where $\lambda_{DB} \sim n^{-1/3}$

$\longrightarrow$ coherence and special macroscopic properties

$$\boxed{\lambda_{DB} = \frac{h}{\sqrt{2\pi M K T}}} \longrightarrow$$

Cooling particles is possible to reach the quantum degenerated regim.

Cold Atoms are good candidates



macroscopic occupation of ground state $\Longrightarrow$ change in the macroscopic behavior

To understand BEC, let's review the basic concepts.

* Consider a gas of bosons confined by a potential $U(\vec{r})$

* The occupation of each state

$$n_\epsilon = \frac{1}{e^{(\epsilon-\mu)/KT} - 1}$$

$\mu \equiv$ chemical potential (function of N, T, U..)

$$N = \sum_{\text{states}} n_\epsilon$$

$$E = \sum_{\text{states}} \epsilon\, n_\epsilon$$

$\Longrightarrow$ Cont. approx. of states $\longrightarrow$ density of states

$$g(\epsilon) = \frac{2\pi (2M)^{3/2}}{h^3} \int_{V^*(\epsilon)} \sqrt{\epsilon - U(r)}\, d^3r$$

Equations:

$$N = N_0 + \int_0^\infty n_\epsilon\, g(\epsilon)\, d\epsilon$$

$$E(T) = \int_0^\infty \epsilon\, n_\epsilon\, g(\epsilon)\, d\epsilon$$

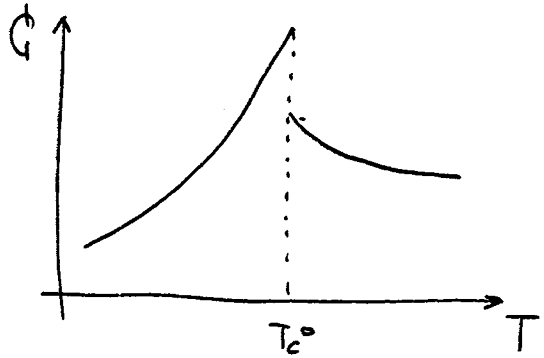
$\Longrightarrow$ $C = \left.\frac{\partial E}{\partial T}\right)_N$; $\frac{N_0}{N}$ = condensated fraction

Potential	T_c	$N_0/N \ (T<T_c)$	$C(T_c^-)/Nk$	$\Delta C(T_c)/Nk$
$U(z)=\begin{cases}\varepsilon_3(z/a), & z>0\\ \infty, & z<0\end{cases}$	$\left[\frac{h^3N}{1.4Sk^{5/2}(2\pi M)^{3/2}}\right]^{2/5}\left[\frac{\varepsilon_3}{a}\right]^{2/5}$	$1-\left[\frac{T}{T_c}\right]^{5/2}$	6.88	3.35
$U(z)=\varepsilon_3(z/a)^2$	$\left[\frac{3h^3N}{\sqrt{2}Sk^2\pi^4M^{3/2}}\right]^{1/2}\left[\frac{\varepsilon_3}{a^2}\right]^{1/4}$	$1-\left[\frac{T}{T_c}\right]^{2}$	4.38	0
3D box	$\left[\frac{h^3N}{2.612k^{3/2}(2M\pi)^{3/2}V}\right]^{2/3}$	$1-\left[\frac{T}{T_c}\right]^{3/2}$	1.92	0
$U(r)=\varepsilon_1(r/a)^2$	$\left[\frac{Nh^3}{1.202\pi^3k^3(2M)^{3/2}}\right]^{1/3}\left[\frac{\varepsilon_1}{a^2}\right]^{1/2}$	$1-\left[\frac{T}{T_c}\right]^{3}$	10.82	6.57
$U(z,\rho)=\varepsilon_1(z/a)^2+\varepsilon_2(\rho/b)^2$	$\left[\frac{Nh^3}{1.202\pi^3k^3(2M)^{3/2}}\right]^{1/3}\left[\frac{\varepsilon_1}{a^2}\right]^{1/6}\left[\frac{\varepsilon_2}{b^2}\right]^{1/3}$	$1-\left[\frac{T}{T_c}\right]^{3}$	10.82	6.57

Harmonic Oscillator:

$$KT_c^\circ = 0.941\,\hbar\omega N^{1/3}$$

$$\frac{N_0}{N} = 1 - \left(\frac{T}{T_c^\circ}\right)^3$$



* With interaction

$$H(1\text{ particle}) = \frac{P^2}{2M} + U(r) + \underbrace{\gamma\rho(\vec r)}_{\text{Interaction}}$$

* $$U_{eff}(r) = U(r) + \gamma\rho(\vec r)$$

$\rho(\vec r)$ = can be calculated in first approx.

$\gamma = \dfrac{4\pi\hbar^2 a}{M}$ a = scattering length

$$\rho(r) \cong \frac{1}{\lambda_D^3}\exp\left(-\frac{U(r)}{KT}\right)$$

Considering H.O. , $a>0$

$\Delta T_c \longrightarrow$ correction

$$\frac{N_0}{N} = 1 - \left(\frac{T}{T_c^\circ}\right)^3 - \frac{4a}{\lambda_D}\left(\frac{T}{T_c^\circ}\right)^{7/2} + \cdots$$

$\Rightarrow$ Interactions must be treated in a more appropriated way (Last lecture)

$$H = -\frac{\hbar^2}{2M}\nabla^2 + U(\vec r) + A|\varphi|^2$$

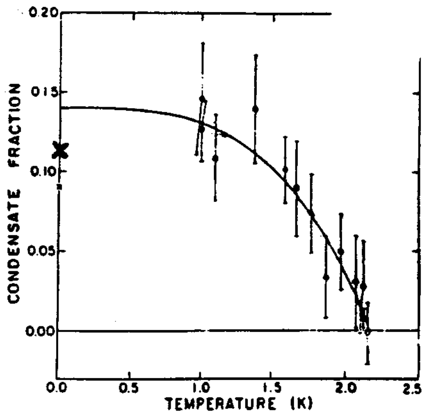
$$A = (N-1)\frac{4\pi\hbar^2}{M}a$$

Exemple (^4He)

Consider as ideal gas $T_c^\circ = 3.15K$

* Superfluidity at 2.17K.

* Measurement of $\bar{p} = 0$ population
  (Phys. Rev. Lett. 49, 279 (1982))



* Consider interaction
  $V = 27.6 \text{ cm}^3$
  $N = 6\ 10^{23}$
  $a = 1.9 Å$ (London - 1939) $\longrightarrow$ $\rho A = 1.26$

$$\boxed{T_c \cong 2.1K}$$

Lista publicações pelo Grupo de São Carlos em técnicas de aprisionamento e aplicações.
(não incluindo colisões frias)

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