Manipulating atoms with light

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BRIDGES
Dialogue towards a culture of peace
Thailand, December 2004

Outline

1. **What is light?**

   - From light waves to photons

2. **How does it interact with atoms?**

   - Quantum mechanics

   - Emission and absorption of photons by an atom

3. **Can one use and master these interactions?**

   - Light : a source of information on atoms

   - Light : a tool for acting on atoms

     Optical pumping ; Laser cooling

4. **What are the new perspetives opened by these methods?**

   - New research fields

   - New applications

Light waves

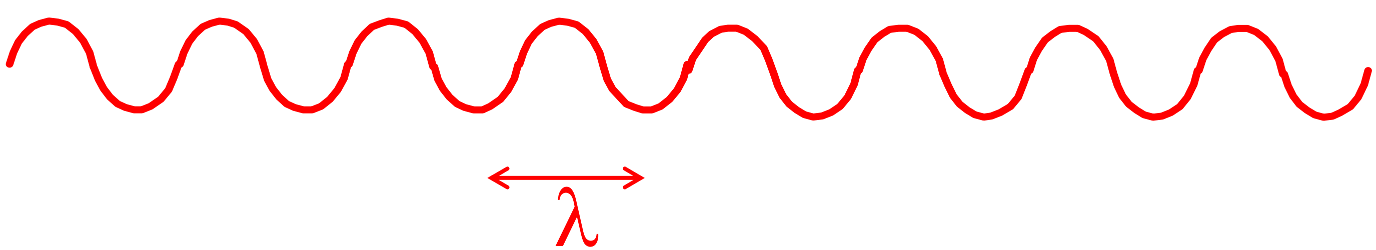
Frequency : ν

Period : $1 / \nu$

Speed of propagation : $c = 3 \times 10^8$ m/s

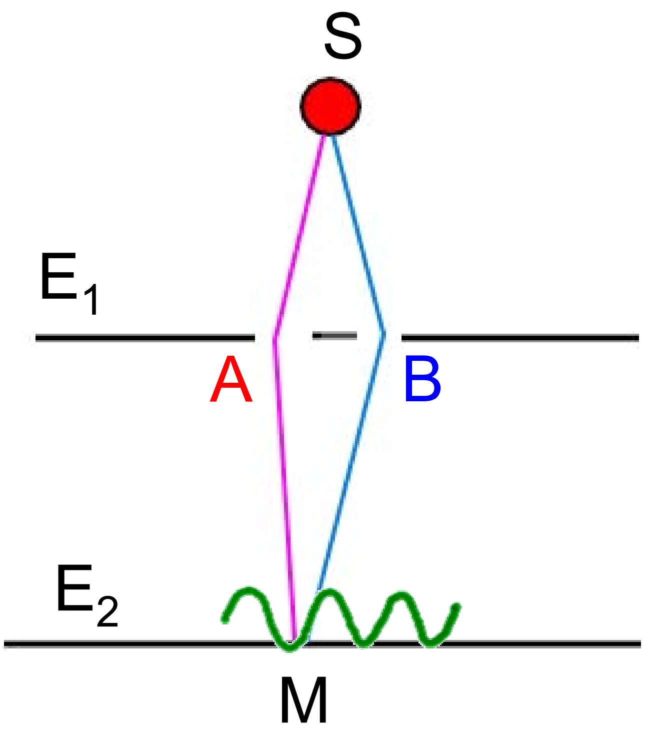
Wavelength : $\lambda = c / \nu$

At a given time, sinusoidal wave with a period λ



Interferences Diffraction

Light interferences



S : point light source
E_1: screen with 2 slits
A and B
E_2:observation screen

- To go from S to M, light can follow 2 paths
  SAM and SBM
- Depending on the position of M on E_2, the 2 waves arriving in M can be
  - in phase (constructive interferences)
  - out of phase (destructive interferences)
- The light intensity observed on the observation screen is spatially modulated

Photons

Light is also a beam of particles called « photons », with an energy E and a linear momentum p.

Planck-Einstein relations

The photons associated with a light wave with frequency ν have an energy E and a linear momentum p given by :

$$\boxed{E = h\,\nu \qquad p = h\,\nu / c}$$

h : Planck's constant = 6.36 $\times$ 10^{-34} J.s

Wave-particle duality

Atoms

Planetary model

Electrons, light particles with a negative charge, orbiting around a nucleus, particle with a much heavier mass and with a positive charge

Failure of these models

They predict that electrons should radiate energy because of their accelerated motion around the nucleus. They thus should fall into the nucleus

- Atoms should thus be instable
- The emitted spectrum should be continuous

2 predictions in contradiction with experiment

- Atoms are stable
- The emitted spectrum consists of discrete lines

Quantum mechanics

Wave- particle duality extended to matter

With every matter particle of mass M and velocity v is associated a wave with a wavelength λ_{dB} given by :

$$\lambda_{dB} = \frac{h}{M\,v}$$

Louis de Broglie 1924

More generally,

The state of a matter particle is described by a wave function obeying the Schrödinger equation

Only certain solutions of this equation are physically acceptable (analogy with the resonance frequencies of a music instrument)

Quantization of physical quantities

Quantization of the energy of an atom

The various possible oscillation frequencies of the wave function correspond to well defined energies of the atom

E_3 2nd excited state

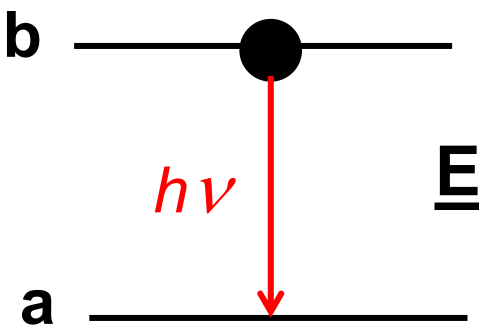
The internal energy of an atom can only take discrete values

E_2 1st excited state

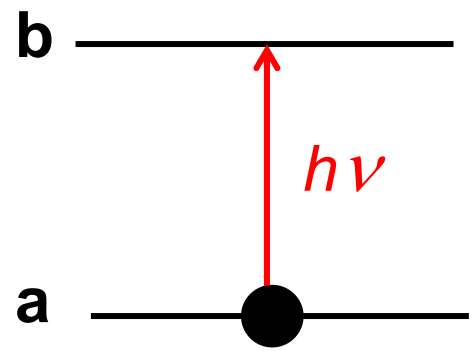
E_1 Ground state

Spectrum of energy levels

Elementary interaction processes between atoms and photons



Emission



Absorption

$E_b - E_a = h\nu$

Conservation of energy

Principle of spectroscopy

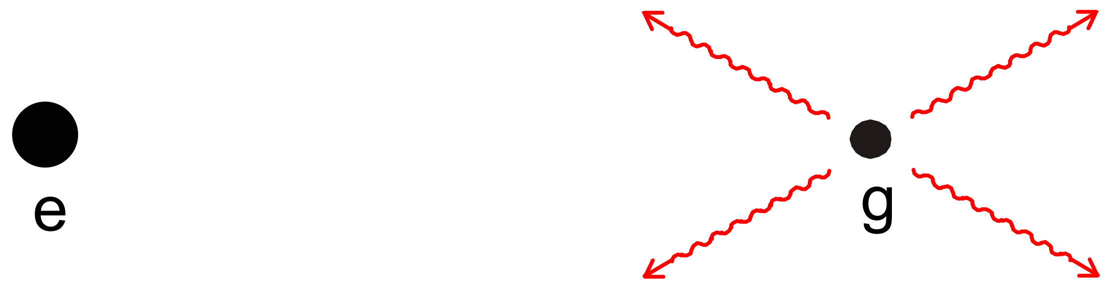
Measuring ν with a spectrometer gives $E_b - E_a$

Light is a source of information
on the structure of atoms and a probe
for detecting their presence in a medium

Spontaneous emission of a photon

An atom does not remain indefinitely in the excited state e. After a finite time τ_R, it falls back to the ground state g by spontaneously emitting a photon in <u>all possible directions</u>.

τ_R : <u>Radiative lifetime of</u> e, on the order of 10^{-8} s

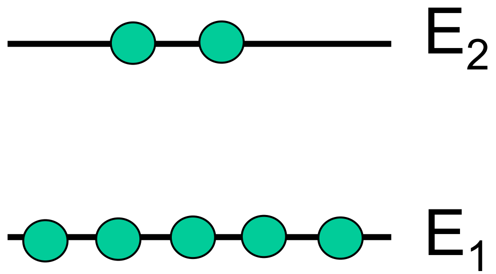


Induced emission of a photon (Einstein 1917)

A photon with energy $h\nu = E_e - E_f$, impinging on an atom in the excited state e induces (or stimulates) this atom to emit a photon exactly identical to the impinging photon (same energy, same direction of propagation, same polarization)

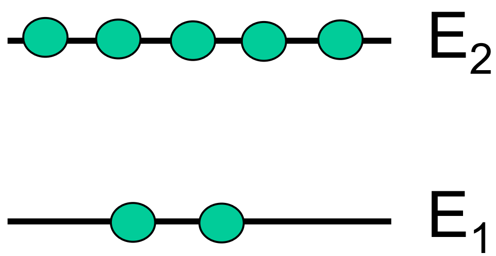
Amplification of light

Thermodynamic equilibrium



In an ensemble of atoms in equilibrium, a lower lever E_1 is always more populated than an upper level E_2.

Population inversion



Non equilibrium situation where an upper level E_2 is more populated than a lower level E_1.

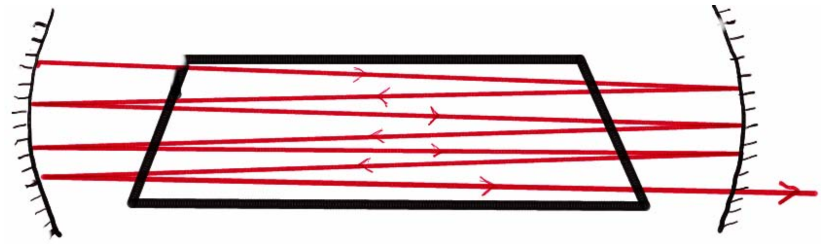
If a light beam with frequency ν passes through a medium where populations are inverted, the new photons which appear by induced emission are in a greater number than the photons which disappear by absorption.

The incident light beam is thus amplified

New light sources : lasers

C. Townes, A. Schawlow

Amplifying atomic medium put between two mirrors



Light can make several round trips between the 2 mirrors and be amplified several times.

If the cavity is « tuned », and if the gain is larger than the losses, one gets an « oscillator » for light.

« Laser » source with completely new characteristics as compared to usual thermal light sources (intensity, directivity, coherence, monochromaticity …)

- Emergence of new research fields
- A huge number of applications

Light is also a tool for acting on atoms

By using resonant or quasi-resonant interactions between atoms and photons, one can control the various degrees of freedom of an atom (spin, energy, velocity, position)

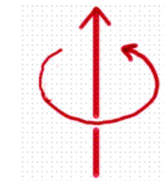
Resonant exchanges of energy, angular momentum, linear momentum between atoms and photons

Using the basic <u>conservation laws</u>
for manipulating atoms

TRANSFER OF ANGULAR MOMENTUM FROM PHOTONS TO ATOMS

Optical pumping

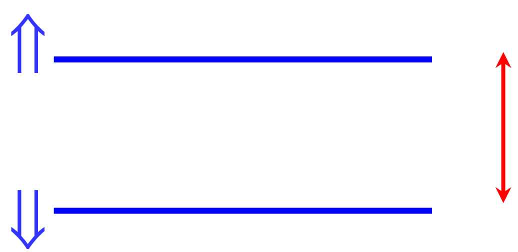
Atomic angular momentum



Atoms are « spinning tops »
They have an internal angular momentum **J**

The projection J_z of **J** along the z-axis is quantized
For example, for a « spin 1/2 » atom, there are two possible values of J_z : **Spin up** $\Uparrow$ **Spin down** $\Downarrow$

Atoms have also a magnetic moment M_z proportional to J_z
In a static magnetic field B, the 2 spin states have opposite magnetic energies proportional to B



Energy splitting ΔE proportional to B

$$\Delta E = h\,\nu_z$$

Magnetic resonance : transitions between the 2 spin states induced by a radiofrequency wave with frequency ν_z

Optical pumping (A. Kastler, J. Brossel)

At room temperatures and in low magnetic fields both spin states are nearly equally populated.
Very weak spin polarization

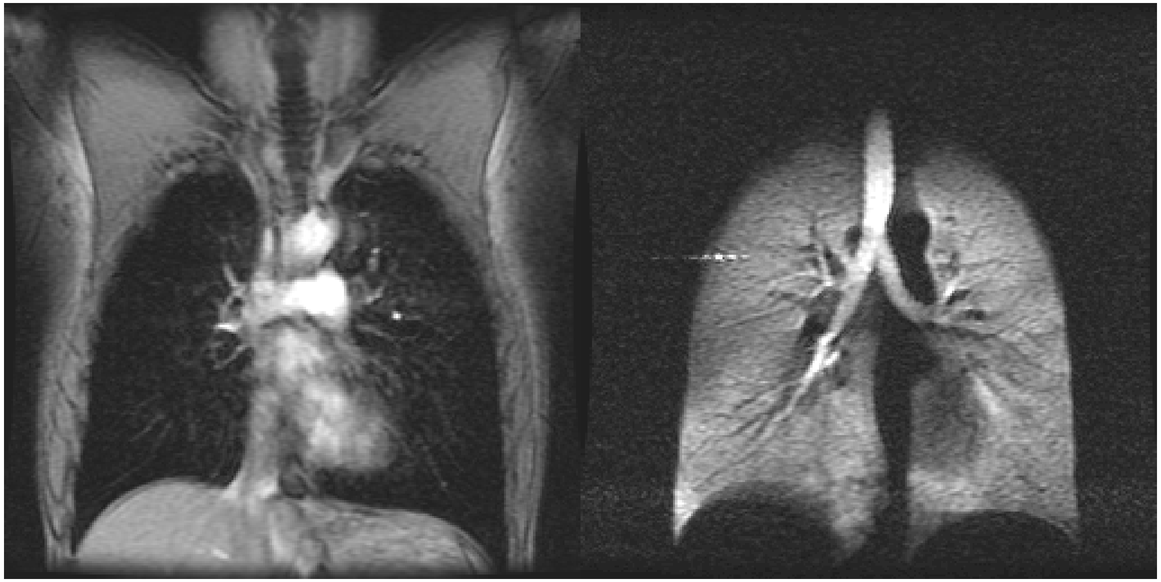
Magnetic resonance signals are proportional to the difference of populations between the 2 spin states.
Easy to observe only in dense systems (solids or liquids)

Polarized photons have also an angular momentum and it is easier to polarize light than atoms

By absorbing polarized photons, atoms can gain the angular momentum of these photons and become polarized.
Gaseous samples with large spin polarization

One can easily obtain in this way large signals of magnetic resonance with dilute gaseous samples

Images de résonance magnétique du poumon humain (IRM)



IRM-Proton IRM-^{3}He

Duke Univ., CAMRD
http://camrd4.mc.duke.edu/ (1997)

Centres IRM pour le poumon

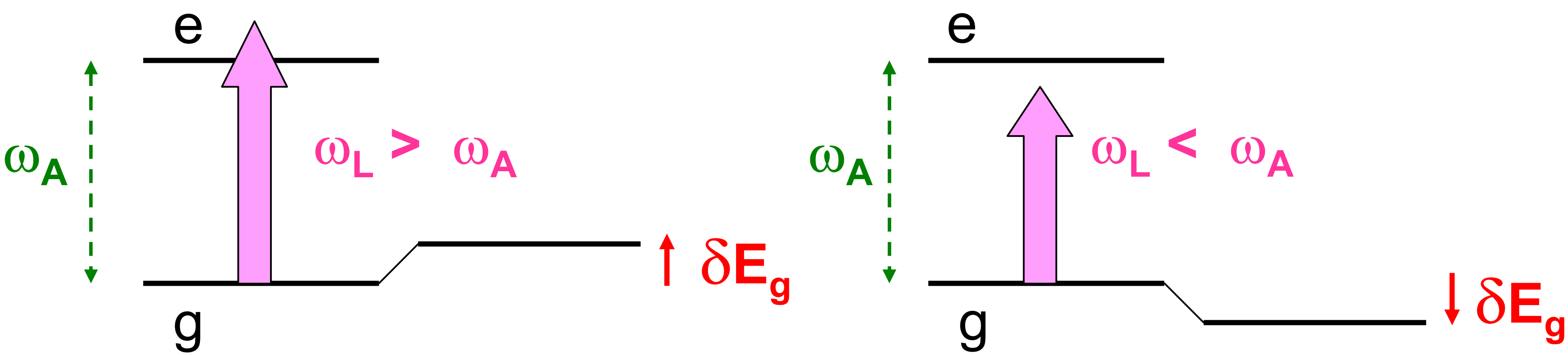
- Princeton
- Boston B&W H., St Louis
- Mainz U., Paris-Orsay, Nottingham U
- Duke U., U. of Virginia, U. of Pennsylvania.

Plusieurs autres centres en cours de création

LIGHT SHIFTS

Light shifts (or ac-Stark shifts)

A <u>non resonant</u> light excitation displaces the ground state g



- δE_g is proportional to the light intensity
- δE_g has the same sign as $\omega_L - \omega_A$

Two Zeeman sublevels g_1 and g_2 have in general different light shifts depending on the light polarization.

$\rightarrow$ Light shift of the magnetic resonance curve in g

C. Cohen-Tannoudji, C.R.Acad.Sci. **252**, 394 (1961)

TRANSFER OF LINEAR MOMENTUM FROM PHOTONS TO ATOMS

Radiation pressure force

Recoil of an atom absorbing a photon

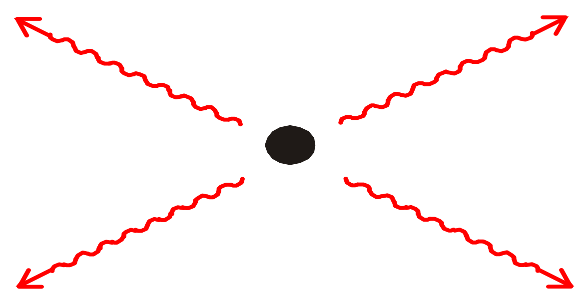
The atom, in the ground state g, absorbs a photon with momentum $h\nu/c$.

It jumps to the excited state e and gains this momentum $h\nu/c$.
It recoils with a velocity $v_{rec} = h\nu / Mc$.

Spontaneous emission of a photon

After a mean time τ_R (radiative lifetime of e, of the order of 10^{-8} sec), the atom falls down in g by spontaneous emission of a photon, with equal probabilities in 2 opposite directions

On the average, the loss of momentum in the spontaneous emission process is equal to zero.



Mean velocity change δv in a fluorescence cycle

Absorption followed by spontaneous emission.

$\delta v = v_{rec} = h\nu / Mc$ on the order of $10^{-2}\, m/s$

Atom in a resonant laser beam

Mean number of cycles per second : W

$W \approx 1/\tau_R \approx 10^8\ s^{-1}$

Mean acceleration a (or deceleration) of the atom

a = velocity change per second
= velocity change δv per fluorescence cycle
x number of cycles per second W
= $v_{rec} \times (1/\tau_R)$

$a = 10^{-2} \times 10^8\ m/s^2 = 10^6\ m/s^2 = 10^5\ g$

Huge radiation pressure force!

SLOWING DOWN
AND COOLING ATOMS

Slowing down and cooling atoms with lasers

The forces exerted by laser beams on atoms allow one

- to reduce their mean velocity

Slowing down atoms

- to reduce the velocity spread around the mean value, *i.e.* to reduce the disordered motion of the atoms

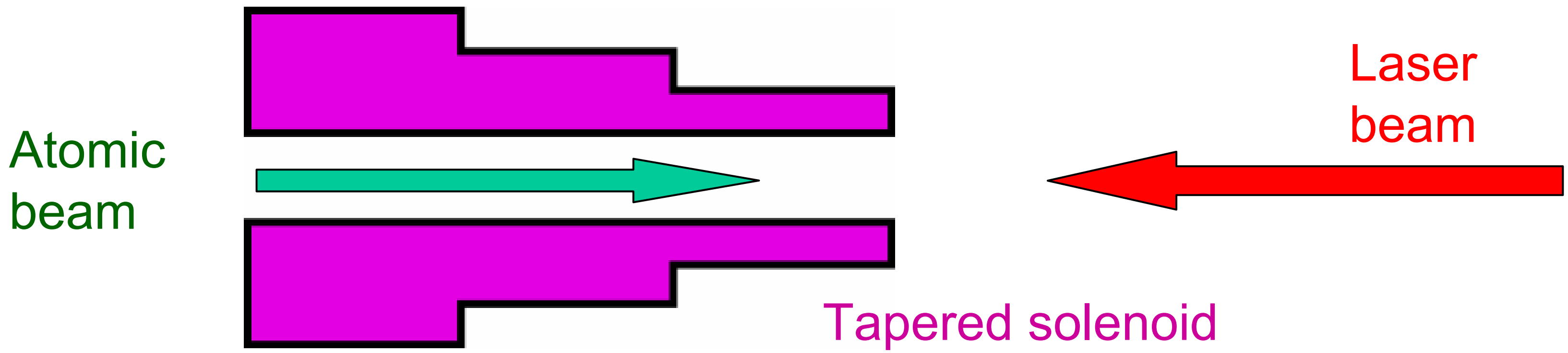
Cooling atoms

Several cooling mechanisms have been demonstrated (Doppler cooling, « Sisyphus cooling », subrecoil cooling)

Obtention of temperatures on the order of a few 10^{-6} K and of atomic velocities on the order of 1 cm/s

At room temperatures (T = 300 K), atomic velocities are on the order of 1 km/s

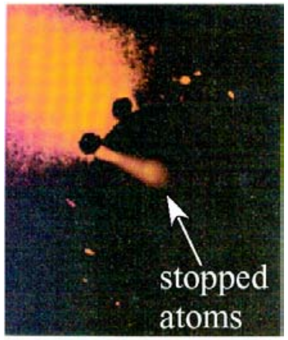
Stopping an atomic beam



Atoms coming from an oven with a velocity $v_0=10^3$ m/s are decelerated by the radiation pressure force exerted by the laser and stop after a time $t= v_0/a = 10^3/10^6 = 10^{-3}$s . They travel over a distance $L = v_0^2 / 2a = 0.5$ m

<u>Zeeman slower</u> J. Prodan, W. Phillips, H. Metcalf, P.R.L. <u>49</u>, 1149 (1982)

The Doppler detuning due to the deceleration of the atoms is compensated by a spatially dependent Zeeman shift



<u>Another solution</u> : chirp of the laser frequency

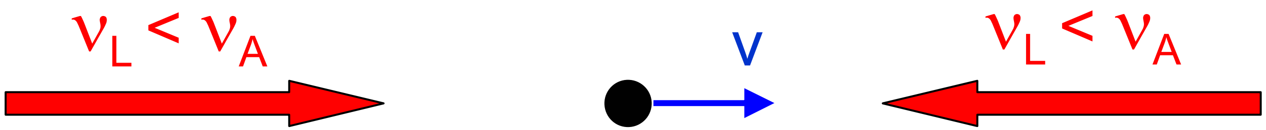
Laser Doppler cooling

T. Hansch, A. Schawlow, D. Wineland, H. Dehmelt

Theory : V. Letokhov, V. Minogin, D. Wineland, W. Itano

2 counterpropagating laser beams

Same intensity Same frequency ν_L ($\nu_L < \nu_A$)



Atom at rest (v=0)

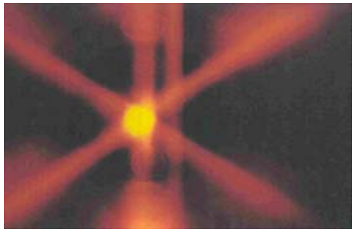
The two radiation pressure forces cancel each other out

Atom moving with a velocity v

Because of the Doppler effect, the counterpropagating wave gets closer to resonance and exerts a stronger force than the copropagating wave which gets farther

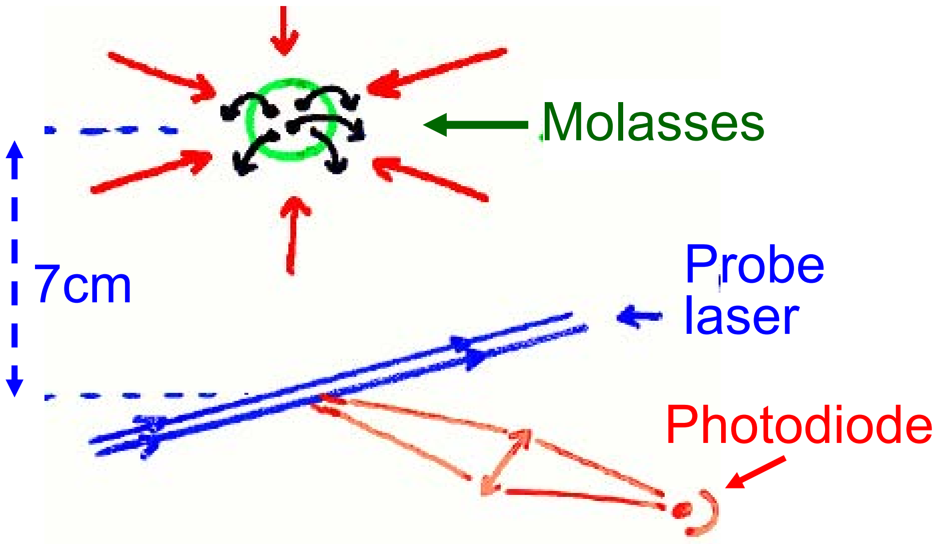
Net force opposite to v and proportional to v for v small

Friction force “Optical molasses”



Measurement of the temperature

Time of flight method



The time of flight signal depends on:

- the acceleration due to gravity
- the initial position distribution (which can be deduced from a photo of the molasses)
- the initial velocity distribution (which is determined by the temperature)

Experimental results

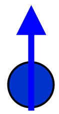
They don't agree with the predictions deduced from the theory of Doppler cooling and they are about 100 times lower than the lowest possible temperatures predicted by such a theory!

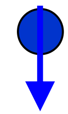
P. Lett, R. Watt, C. Westbrook, W. Phillips, P. Gould, H. Metcalf
Phys. Rev. Lett. 61, 169 (1988)

Sisyphus cooling

(J. Dalibard, C. Cohen-Tannoudji)

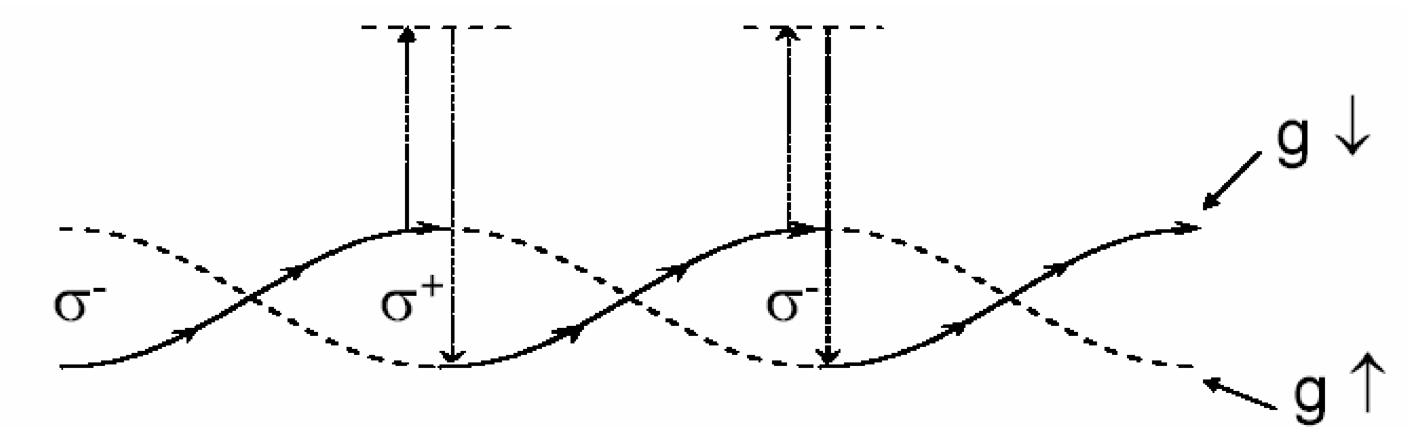
Several ground state sublevels

 Spin up

 Spin down

In a laser standing wave, spatial modulation of the laser intensity and of the laser polarization

- Spatially modulated light shifts of g↑ and g↓ due to the laser light
- Correlated spatial modulations of optical pumping rates g↑ ↔ g↓

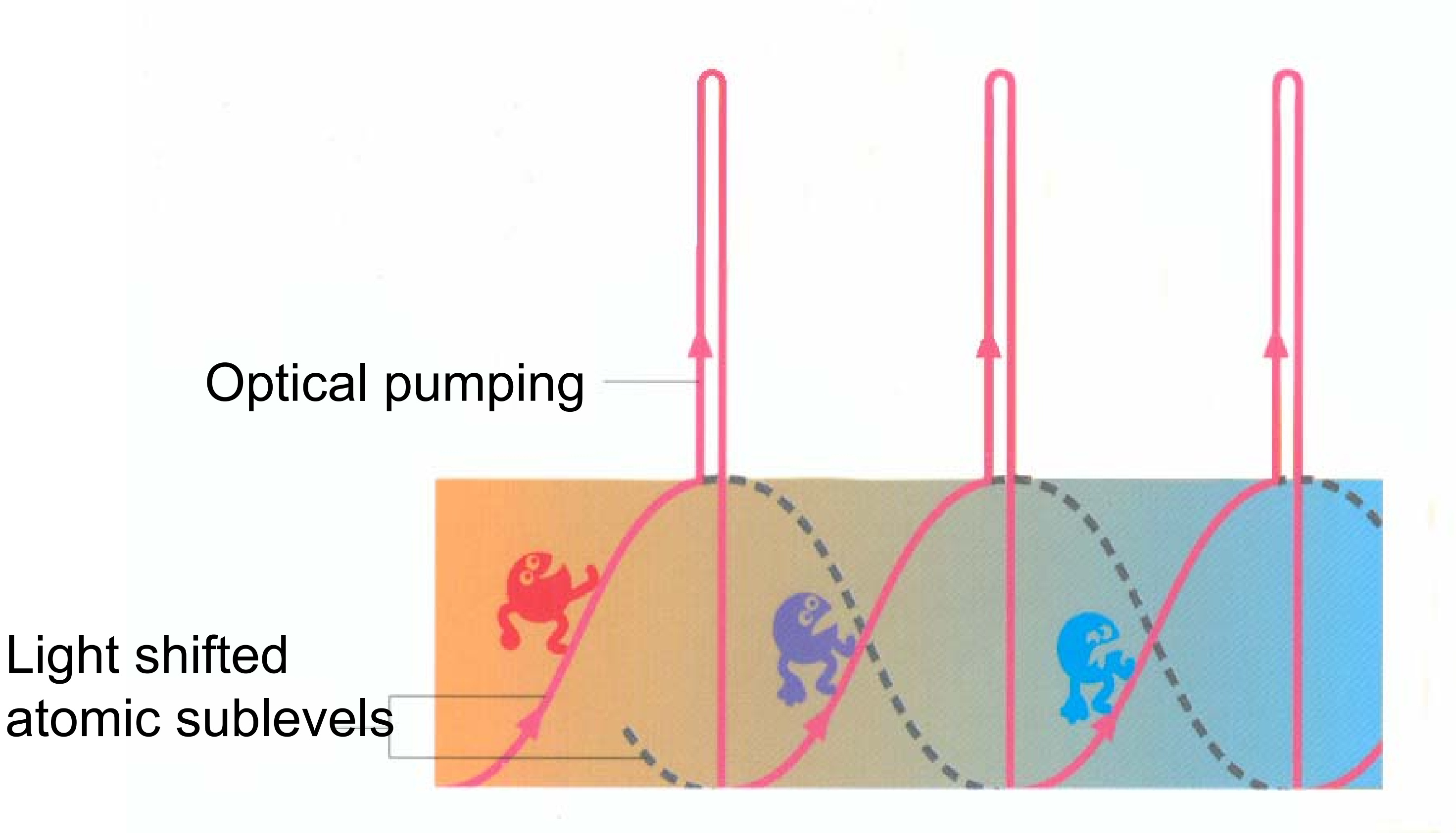


The moving atom is always running up potential hills (like Sisyphus)!

Very efficient cooling scheme leading to temperatures in the μK range

Sisyphus cooling

J. Dalibard, C. Cohen-Tannoudji

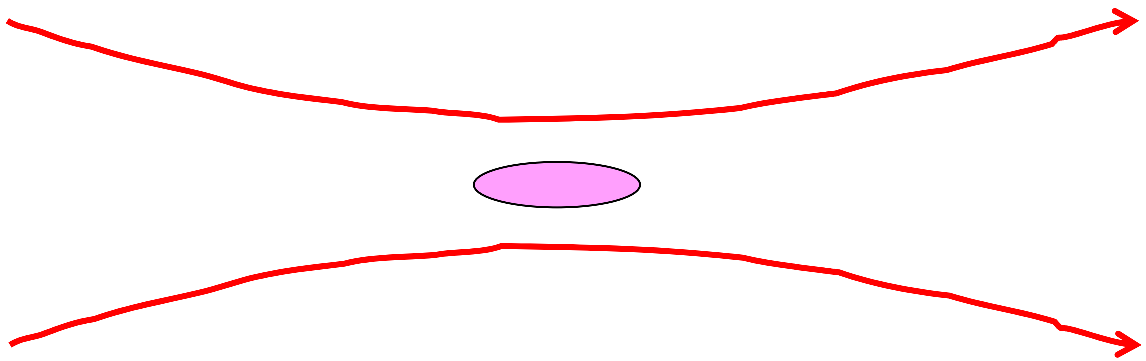


TRAPS FOR NEUTRAL ATOMS

Laser traps

Laser traps

Spatial gradients of light shifts



Focused laser beam with a red detuning ($\omega_L < \omega_A$)

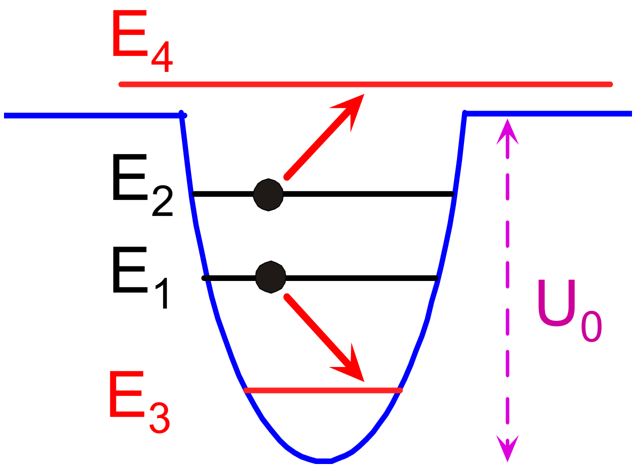
The light shift δE_g of the ground state g is negative and its absolute value is maximum at the focus

Attractive potential well in which neutral atoms can be trapped

Other types of traps using radiation pressure forces of polarized waves and magnetic field gradients

Magneto-optical traps (MOT) J. Dalibard

Evaporative cooling



Atoms trapped in a potential well with a finite depth U_0

2 atoms with energies E_1 et E_2 undergo an elastic collision

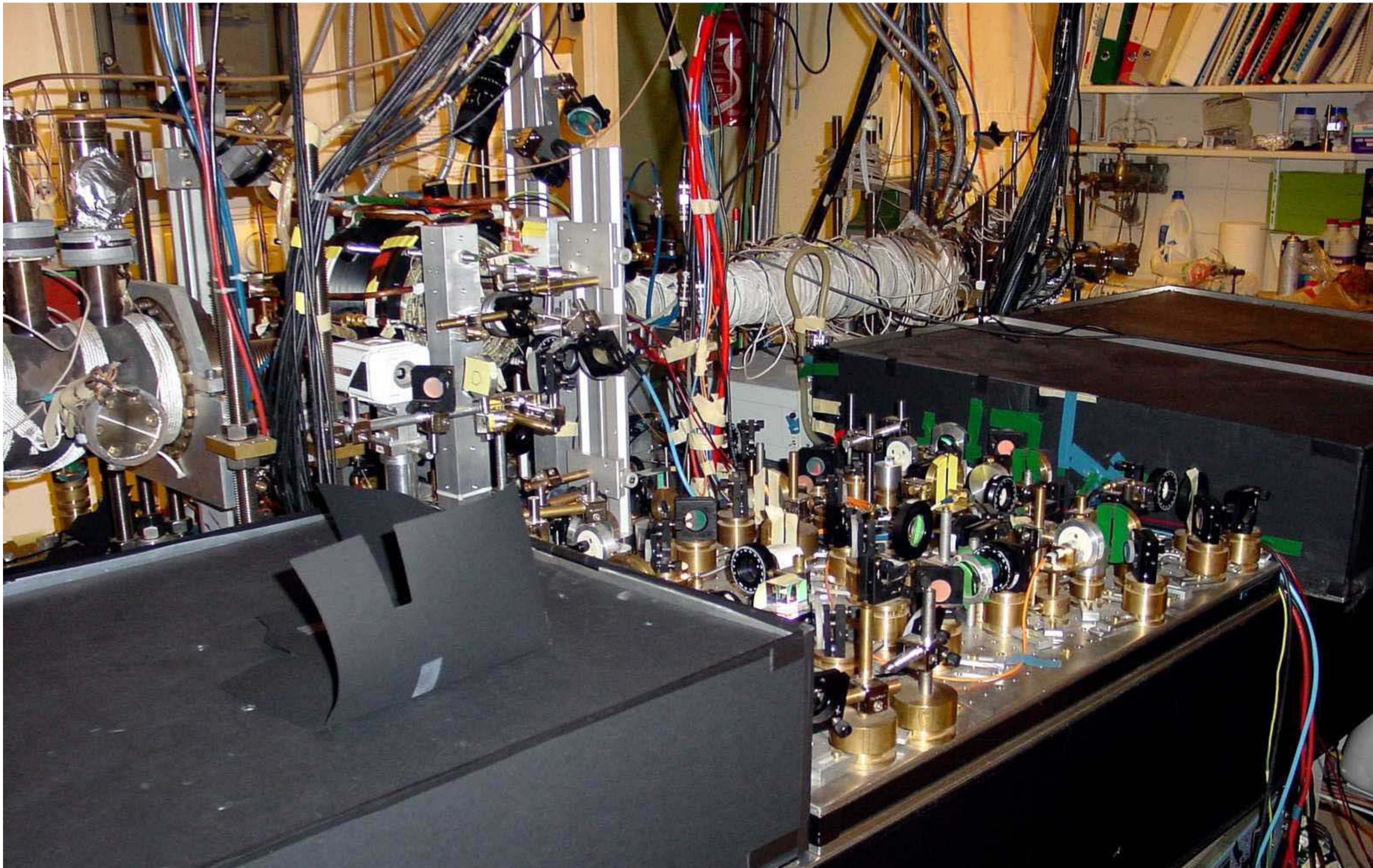
After the collision, the 2 atoms have energies E_3 et E_4, with

$$E_1 + E_2 = E_3 + E_4$$

If $E_4 > U_0$, the atom with energy E_4 leaves the well

The remaining atom has a much lower energy E_3. After rethermalization of the atoms remaining trapped, the temperature of the sample decreases


500m



Applications of ultracold atoms

1- Long observation times

Better atomic clocks

2- Long de Broglie wavelengths

Atomic interferometry

3- High phase space densities

Bose-Einstein Condensation
Atom lasers and matter waves

ATOMIC CLOCKS

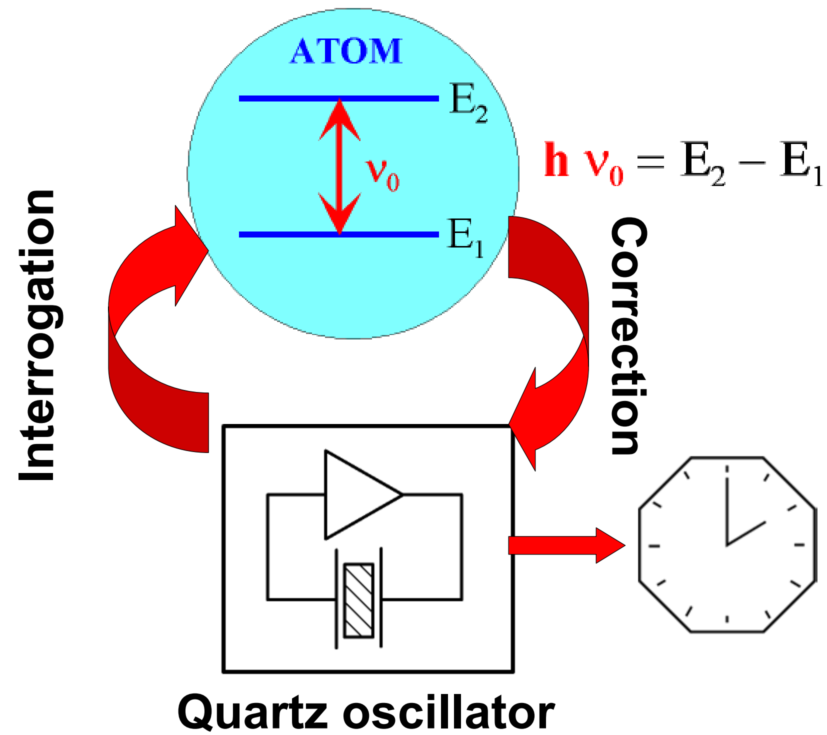
Principle of an atomic clock

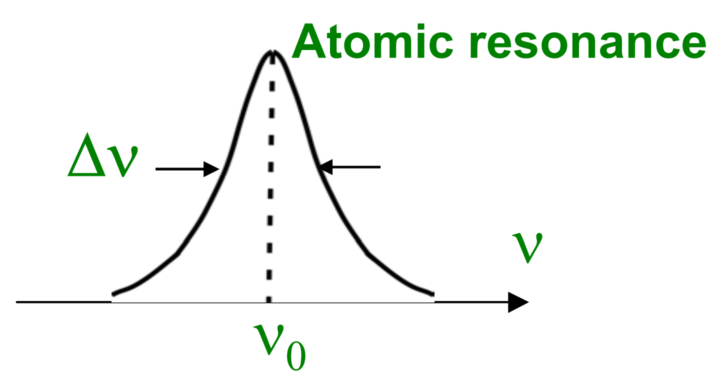
Quartz oscillator
whose frequency is
maintained at the center
ν_o of an atomic resonance

The narrower the
atomic resonance,
the better the accuracy
of the clock

The width $\Delta\nu$ of the
atomic resonance is
inversely proportional
to the observation time T

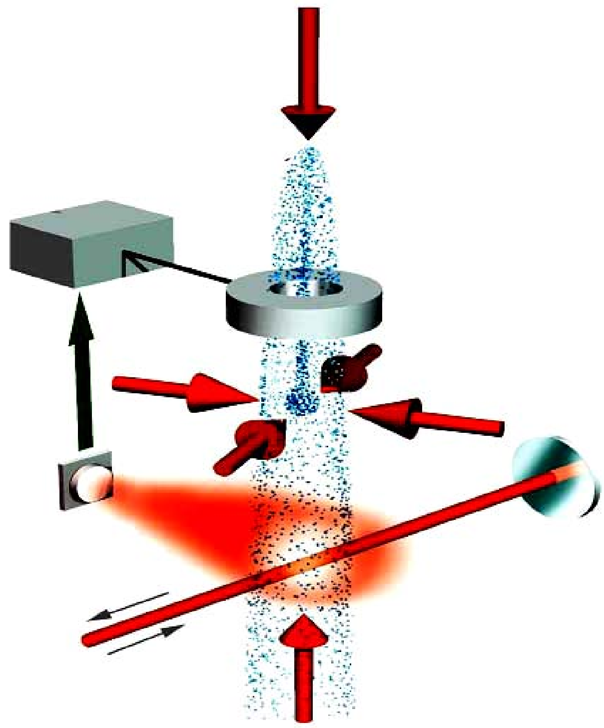
Ultracold atoms move
slowly and provide
long observation times

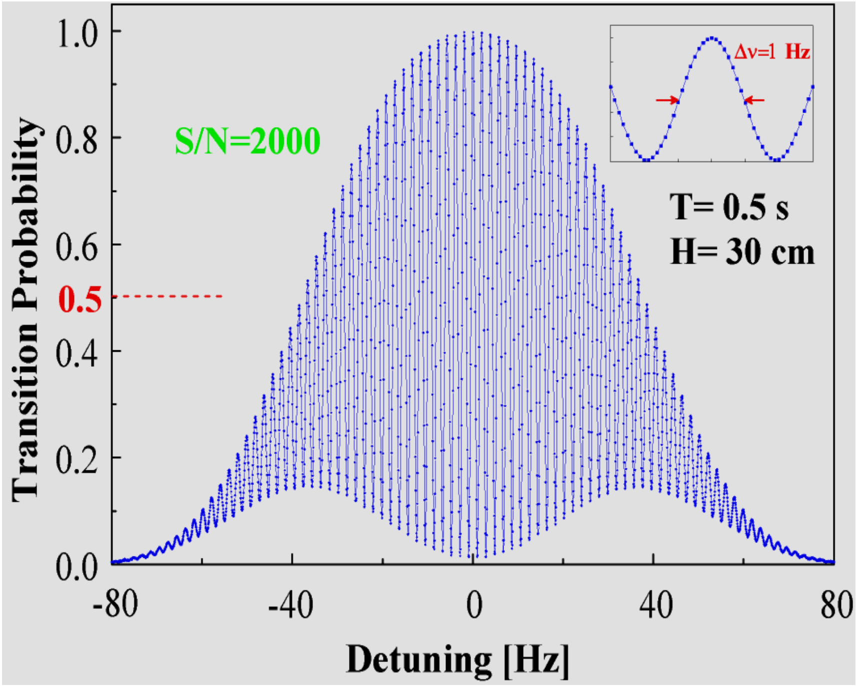




Atomic fountains

- Sodium fountains : Stanford S. Chu
- Cesium fountains : BNM/SYRTE C. Salomon, A. Clairon





Stability : 1.6 x 10^{-16} for an integration time 5 x 10^{4} s

Accuracy : 7 x 10^{-16}

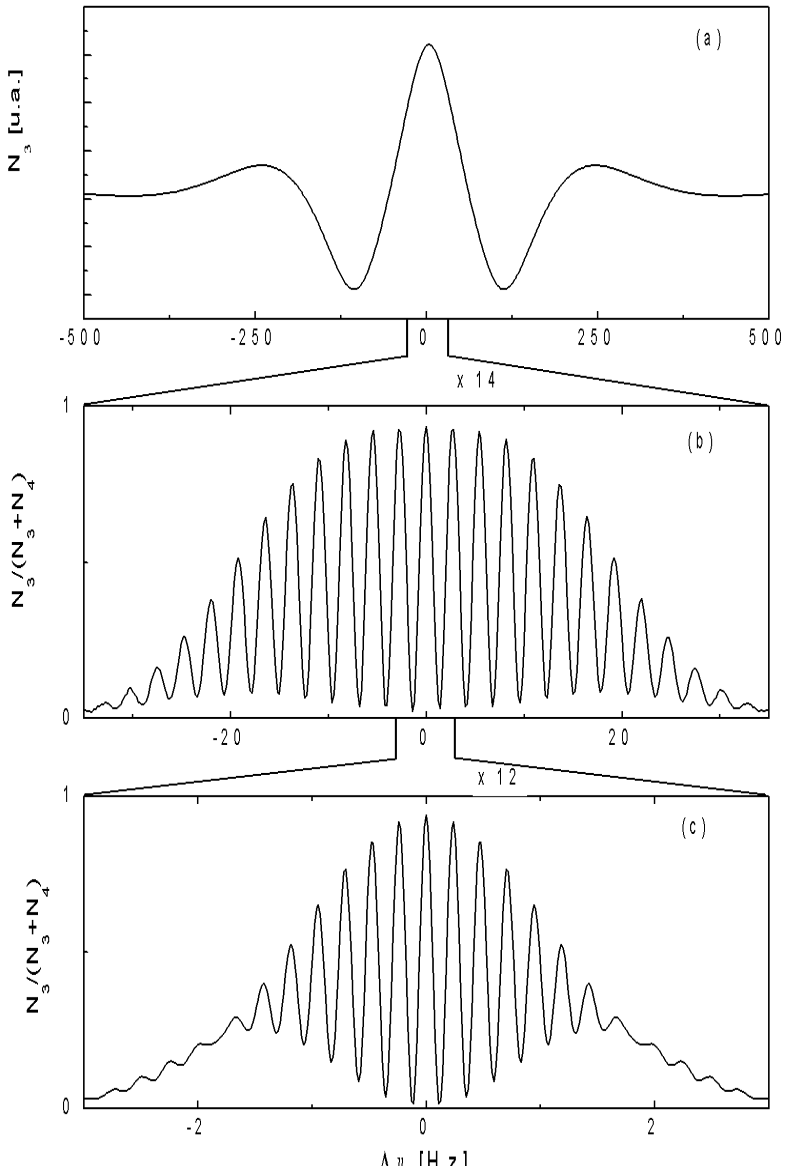
Transportable fountains

Parabolic flights

Tests of PHARAO with parabolic flights

Atomic clocks with cold atoms

A.Clairon, C.Salomon (B.N.M./L.P.T.F.)



- Thermal beam :
  v = 100 m/s, T = 5 ms
  $\Delta\nu$ = 100 Hz
- Fountain :
  v = 4 m/s, T = 0.5 s
  $\Delta\nu$ = 1 Hz
- PHARAO :
  v = 0.05 m/s, T = 5 s
  $\Delta\nu$ = 0.1 Hz

ACES (Atomic Clock Ensemble in Space)

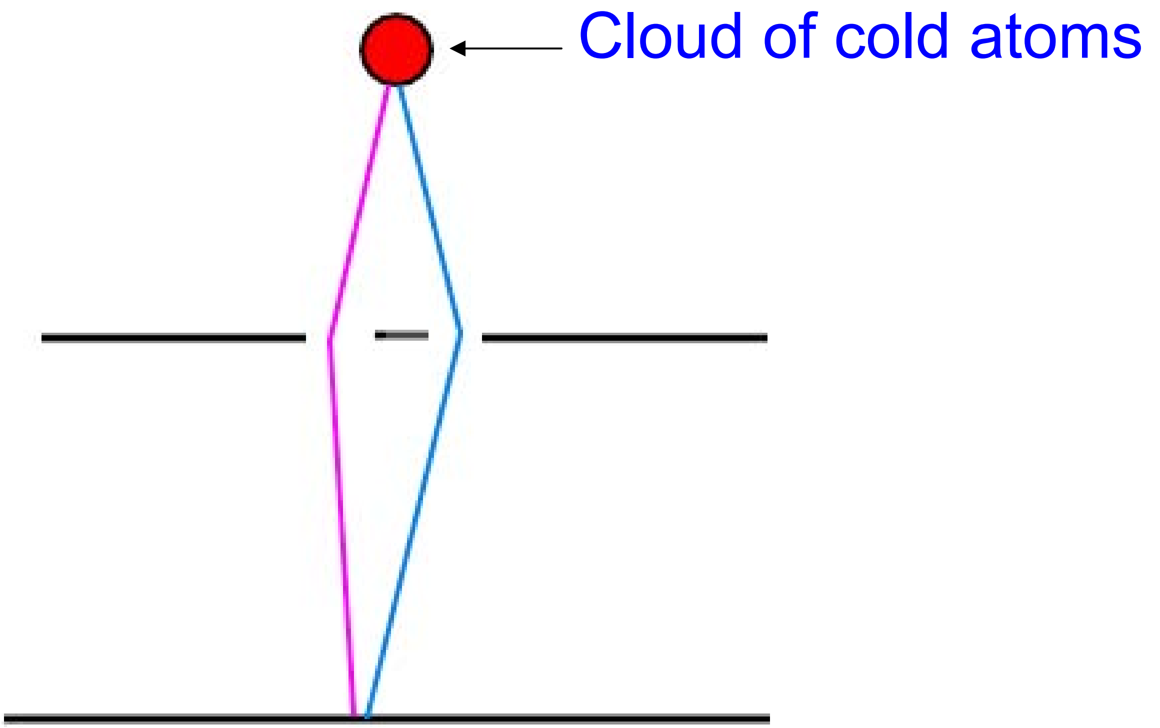
cnes
esa

- Time reference
- Validation of space clocks
- Tests of fundamental theories

C. Salomon *et al* , C. R. Acad. Sci. Paris, t.2, Série IV, p. 1313-1330 (2001)

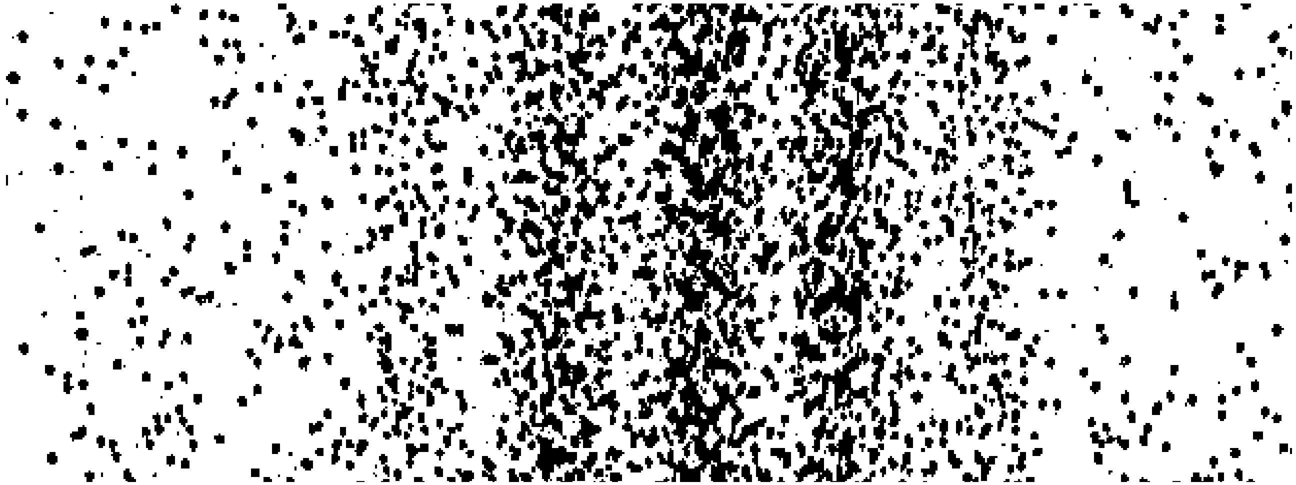
INTERFERENCES BETWEEN DE BROGLIE WAVES

Interference fringes obtained with the de Broglie waves associated with metastable laser cooled Neon atoms



F.Shimizu, K.Shimizu, H.Takuma Phys.Rev. **A46**, R17 (1992)

Experimental results

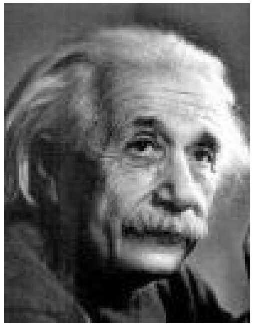


Each atom gives rise to a localized impact on the detector
The spatial repartition of the impacts is spatially modulated

Wave-particle duality for atoms

The wave associated with the atom allows one to calculate the probability to find the atom at a given point

Bose-Einstein condensation



Bose-Einstein condensation (BEC)

At low enough temperatures and high enough densities, the de Broglie wavelength of the atoms becomes larger than the mean distance between atoms

Identical bosons in a trap are then predicted to condense in the ground state of the trap
Macroscopic number of atoms in the same quantum state
Macroscopic matter waves

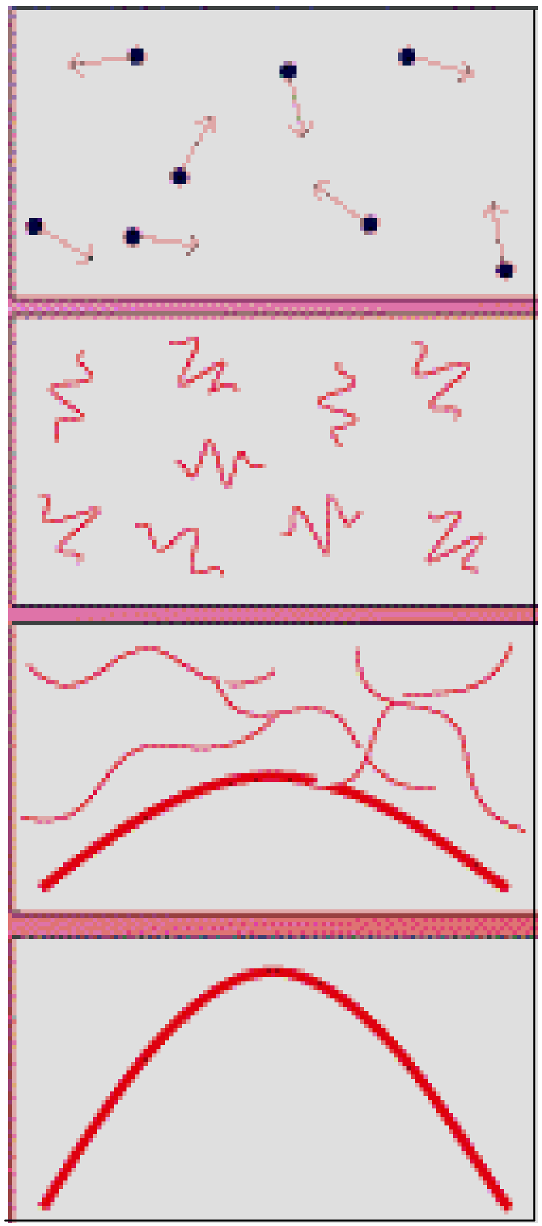
Combination of laser cooling and trapping with previously developed methods for studying spin-polarized Hydrogen (magnetic trapping, evaporative cooling) have led to the observation of BEC in alkali gases

Boulder, MIT, Houston (1995)

BEC has been also observed in Hydrogen (MIT, 1998) and in metastable Helium (Orsay, ENS, 2001).
Very recent observation of molecular condensates.

Sketch of the waves associated with the trapped atoms

Evolution of these waves when T decreases from a value much higher than T_C to a value much lower



$T >> T_C$

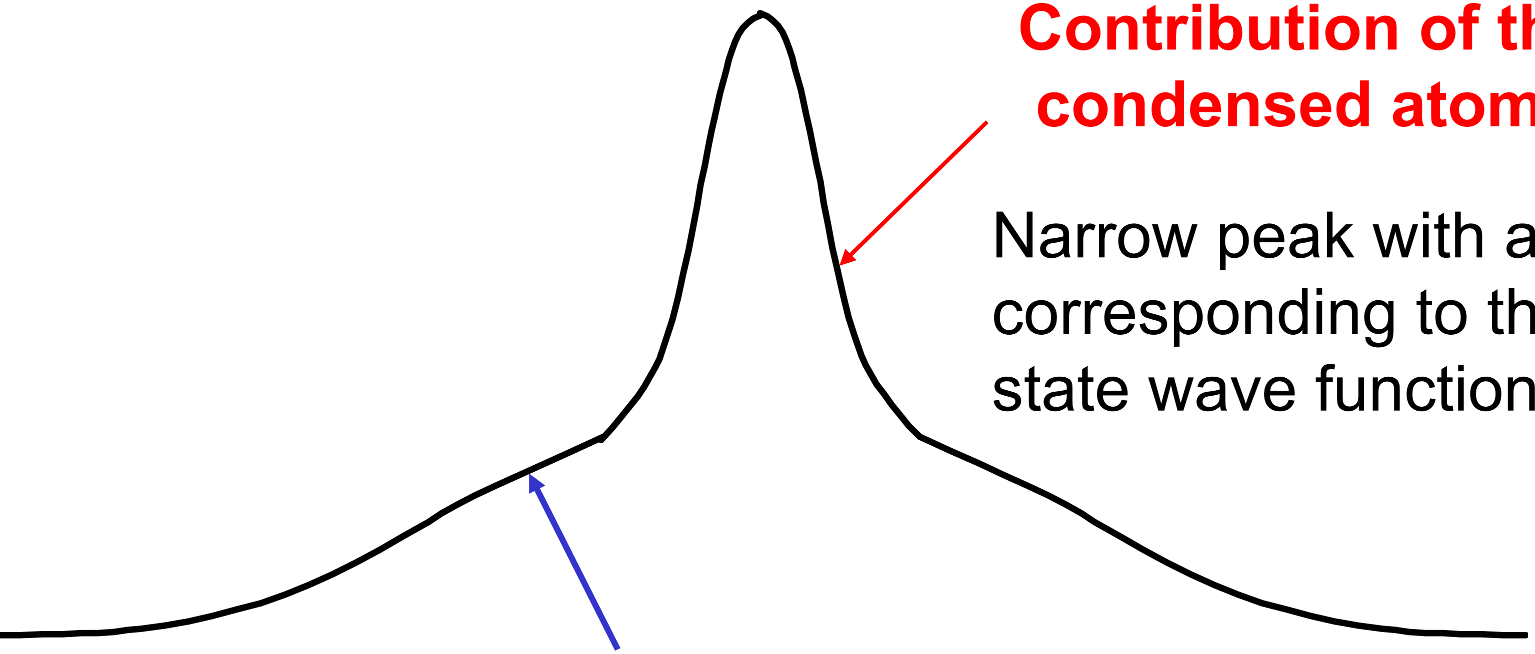
$T > T_C$

$T \sim T_C$

$T < T_C$

W. Ketterle

Bimodal structure of the spatial distribution of bosons



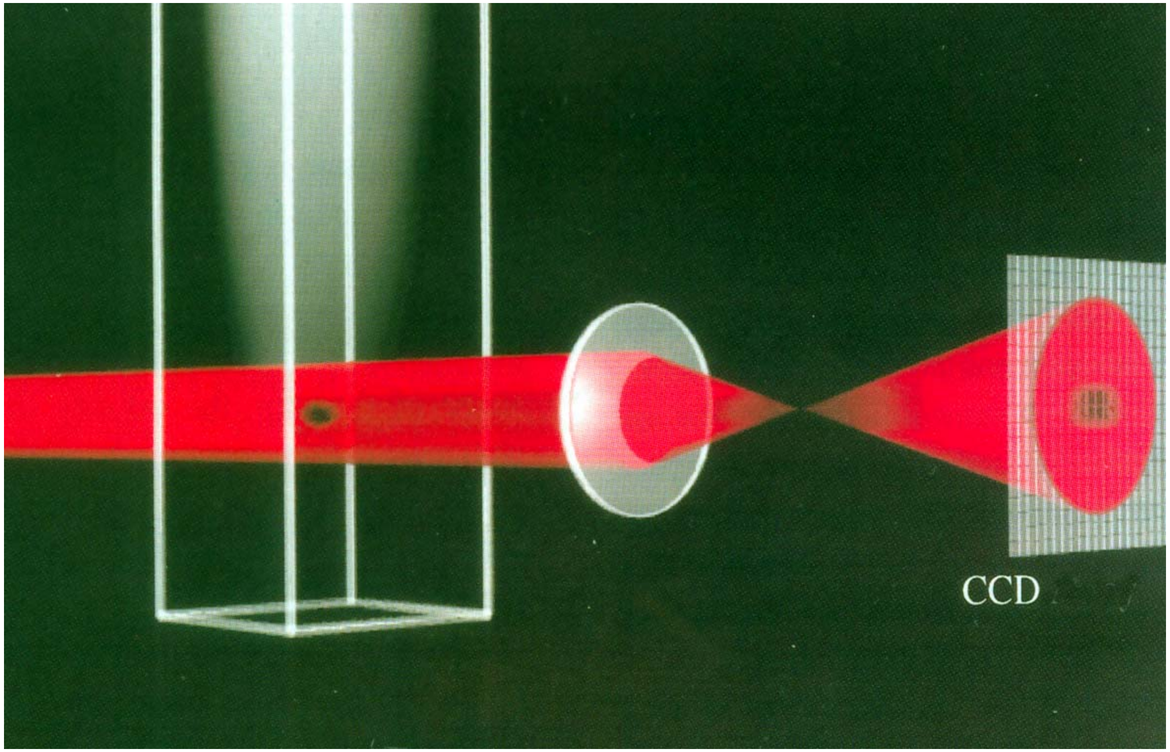
Contribution of the condensed atoms

Narrow peak with a width corresponding to the ground state wave function of the well

Contribution of the non condensed atoms

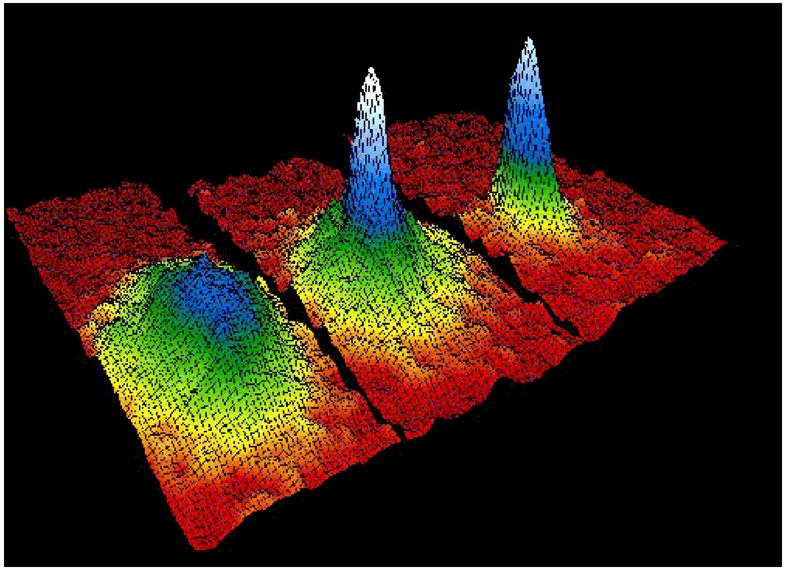
Broad piedestal coming from atoms occupying excited states ot the well described by wave functions with a larger width

Visualization of the atomic cloud



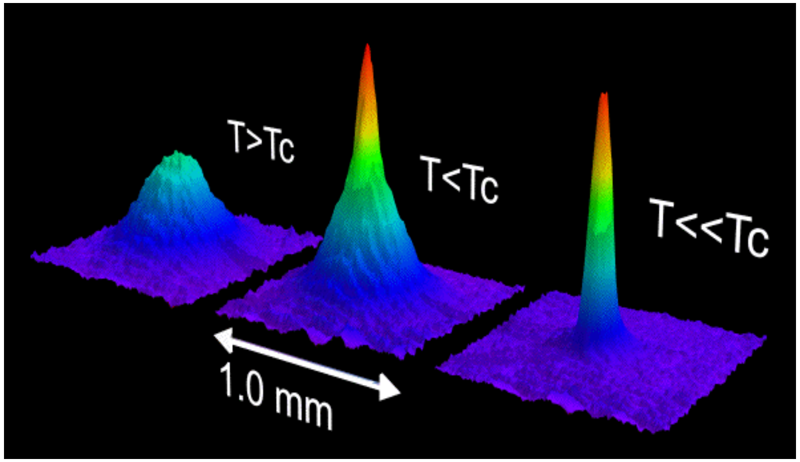
Spatial dependence of the absorption
of a laser beam by the cloud

JILA



Science, 269, 198 (1995)

MIT



Phys. Rev. Lett. 75, 3969 (1995)

^{87}Rb	Boulder
^{23}Na	MIT
^{7}Li	Rice
^{1}H	MIT
^{4}He*	Orsay, LKB
^{41}K	Florence
^{133}Cs	Innsbruck
^{174}Yb	Kyoto

Molecular condensates
Boulder, Innsbruck,
MIT, LKB

Importance of gaseous Bose Eintein condensates

Matter waves have very original properties (superfluidity, coherence,…) which make them very similar to other systems only found, up to now,in condensed matter (superfluid He, superconductors)

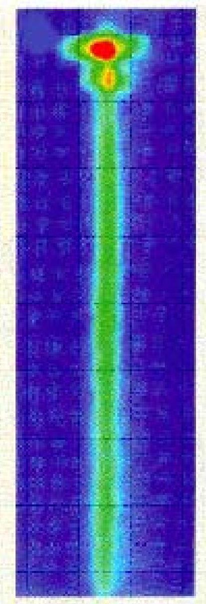
The new feature is that these properties appear here on very dilute systems, about 100000 times more dilute than air. Atom-atom interactions have then a much smaller effect which can be calculated more precisely

Furthermore, these interactions can be modified at will, in magnitude and in sign (attraction or repulsion), using « Feshbach resonances » obtained by sweeping a static magnetic field

A great stimulation for basic research!

Examples of applications

- Magnetometers and masers with optically pumped atoms
- MRI of the lung with optically pumped He^3 atoms
- Atomic clocks with ultracold atoms reaching a relative frequency stability and an accuracy of a few 10^{-16}
- Atom lithography
- Atomic gradiometers and gyrometers with de Broglie waves
- Atom lasers : coherent beams of atomis de Broglie waves extracted from a Bose Einstein condensate
- Quantum information using a Bose Einstein condensate trapped in an optical lattice



Most of these applications were not planned in advance and introduce discontinuous changes in the technology

Conclusion

Our ability to control and to manipulate quantum systems (atoms, ions, electrons) has considerably increased during the last few decades

This is opening completely new research fields and allows us to ask new questions and to investigate new systems, new states of matter.

One can reasonably expect that this will lead us to a better understanding of the world and to interesting new applications

Importance of basic research

- for improving our vision of the world
- for solving the various problems (energy, environment, health) that mankind has to face
- for improving, by scientific education, our ability to fight against intolerance, fundamentalism, and for promoting in this way the establishment of peace between nations