Manipulating Atoms with Light

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Light and Matter

A few questions

- What is light and how is it produced?
- How does it interact with matter, *i.e.* with atoms?
- Can one control and use these interactions?

Characteristics of this research field

At the origin of conceptual and technological revolutions:

- relativistic revolution
- quantum revolution
- laser revolution

A constant interplay between:

- fundamental interrogations about the mechanisms
- new possibilities and new applications resulting from a better understanding of the mechanisms

Outline

1 – Wave-particle duality for light and atoms

First established for light before being extended to electrons and atoms

Quantum physics is essential for describing light, atoms and their interactions

2 - Light emitted or absorbed by atoms is a source of information on the world around us

Spectroscopy

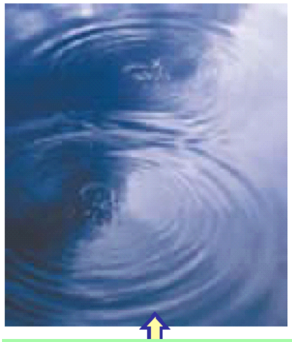
3 - Light-atom interactions can also be used for manipulating atoms

Optical pumping Laser cooling and trapping

4 - These advances in our understanding of atoms and light open new research fields, and give rise to new applications

Light

Light is an electromagnetic wave



Interferences in water

Frequency v characterizing the color

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

Interferences Diffraction

Light is also a beam of particles called photons

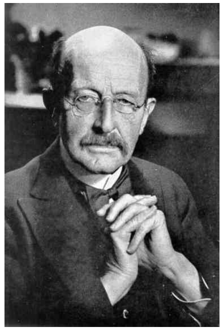
The energy exchanges between atoms and light are quantized in units of hv (Max Planck 1900)

$h = 6.36 \times 10^{-34}$ J.s

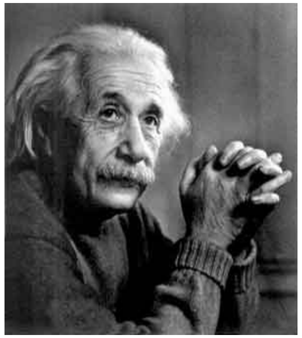
Light itself consists of energy quanta (Albert Einstein 1905)

Energy : $E = h\nu$

Momentum : $p = h\nu / c$



Max Planck



Albert Einstein

Both wave and particle aspects are essential

Wave-particle duality

Wave-Particle Duality Extended to Matter (1924)

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

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

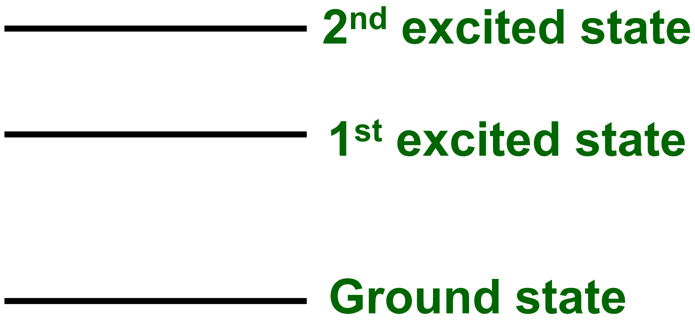
Louis de Broglie

More generally,

The state of a matter particle is described by a <u>wave function</u> obeying the <u>Schrödinger equation</u>

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

The energy of an atom cannot take any value. It is <u>quantized</u>



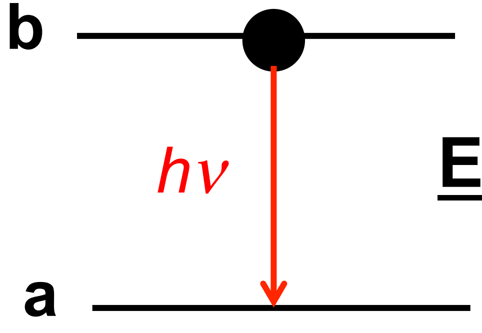
2nd excited state

1st excited state

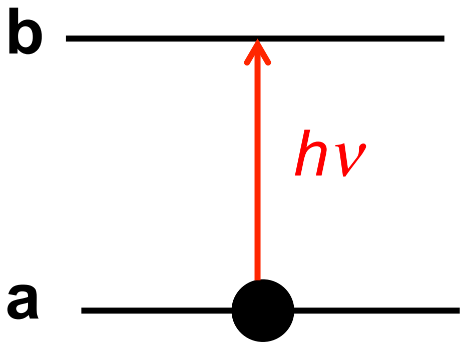
Ground state

Energy spectrum

Elementary interaction processes between atoms and photons



Emission



Absorption

$E_b - E_a = h\nu$

Conservation of energy

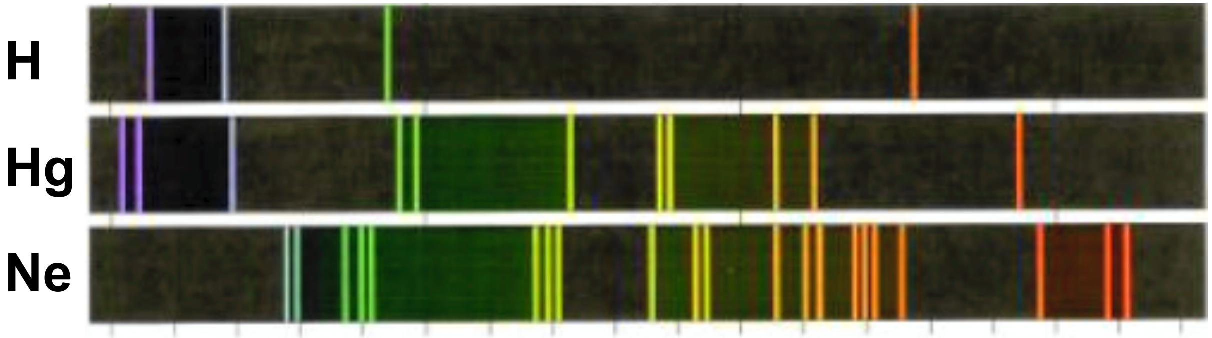
Measuring ν with a spectrometer gives $E_b - E_a$

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

Spectroscopy in all frequency ranges
RF, Microwave, Infrared, Visible, UV, X-ray, Gamma-Ray

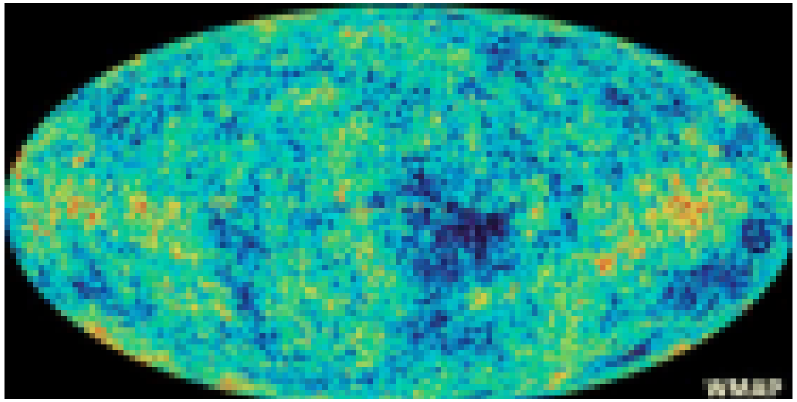
Light : a source of information From atoms to the cosmos

Examples of spectra of 3 different atoms



A spectrum of lines characterizes an atom.
It’s a « finger print » of this atom

Microwave background radiation: Information on the universe as it was 13.7 billions years ago!



Light is also a tool for manipulating atoms

When an atom absorbs and reemits a photon, it acquires some properties of the absorbed photon (energy, momentum, polarization)

One can thus modify the properties of an atom by exciting it with conveniently prepared light beams

First example : Optical pumping

The absorption of polarized light can polarize atoms: all the atomic magnetic moments point along the same direction

Detection of magnetic resonance in dilute atomic gases

Second example : Laser cooling

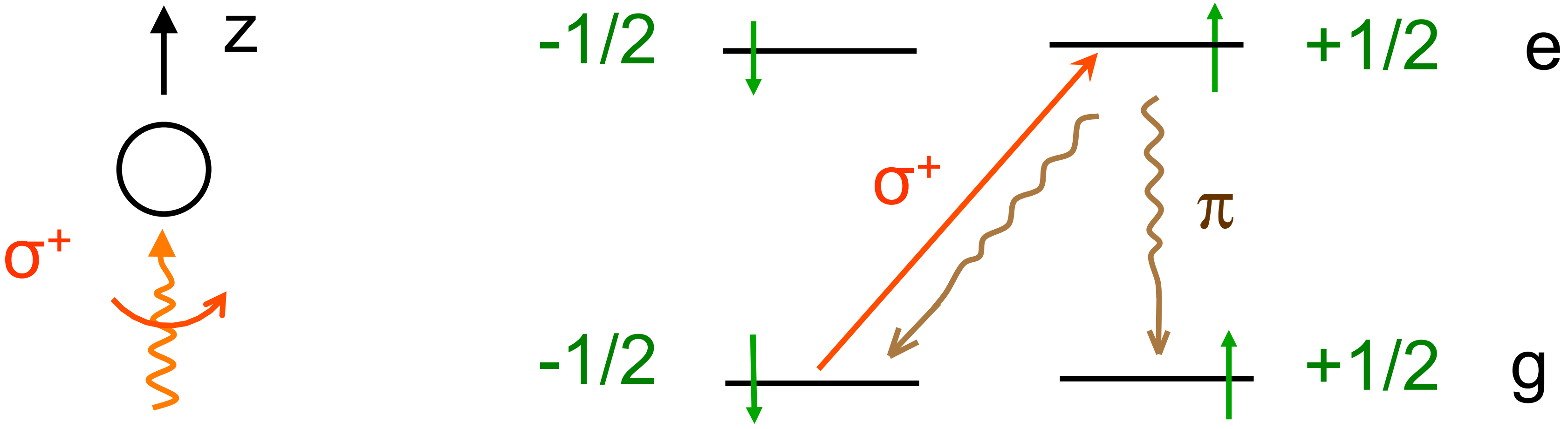
The absorption of photons coming all in the same direction can give rise to a radiation pressure force which changes their velocities

Ultracold atoms

POLARIZING ATOMS

Transfer of angular momentum from polarized photons to atoms

Optical pumping



σ_+ photons have an angular momentum +1 along Oz in units of ħ. Consequently, the excitation with polarization σ_+ excites selectively the transition g, - 1 / 2 → e, + 1 / 2

The atom then falls back, either in g, -1 / 2, in which case it can start a new cycle, or in g, +1 / 2, by spontaneous emission of a photon π, in which case it remains trapped in this state

Optical detection of any transfer g, - 1 / 2 ↔ g, + 1 / 2 due to collisions or to magnetic resonance transitions

Important features of optical pumping

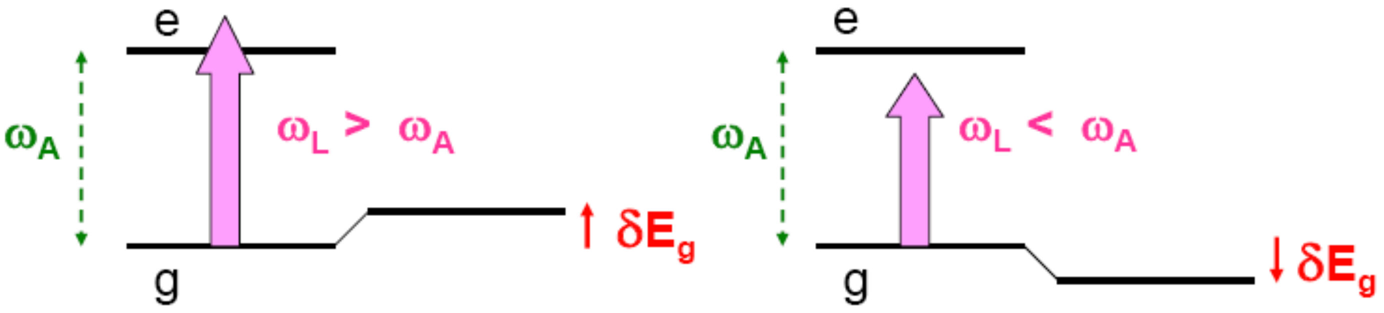
- Achievement of high degrees of spin polarization (up to 90%)
  First example of manipulation of atoms by light
- Very sensitive optical detection of magnetic resonance in dilute atomic vapors where atom-atom interactions are small
- High resolution RF and microwave spectroscopy

A few discoveries made with optical pumping

- Multiphoton RF transitions.
- Displacement of energy levels by light (Light shifts)
- Importance of linear superposition of Zeeman sublevels
  - Coherent multiple scattering
  - Hanle effect
  - Quantum beats
  - Dark resonances
- Practical applications
  - Atomic clocks Masers MRI

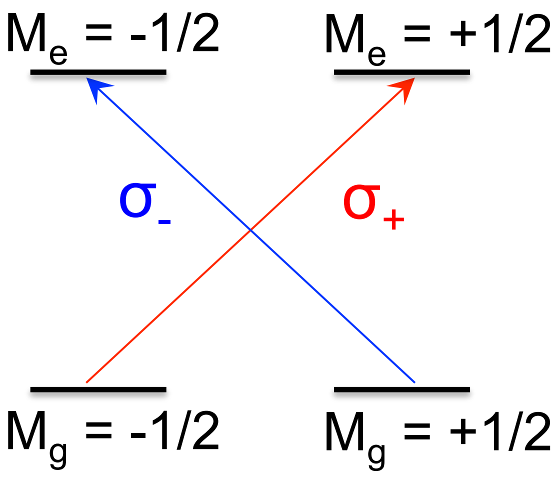
Light shifts (or ac-Stark shifts)

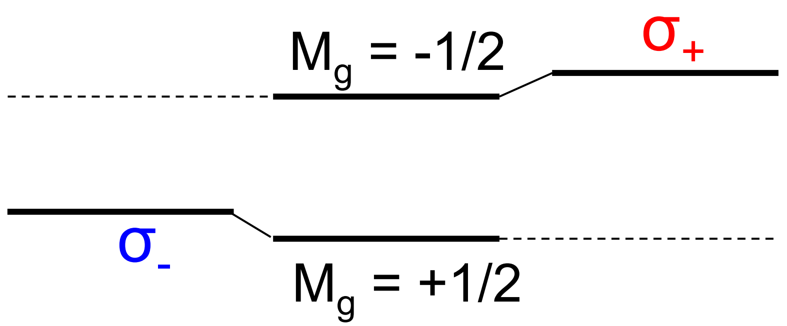
A non resonant light excitation displaces the ground state g



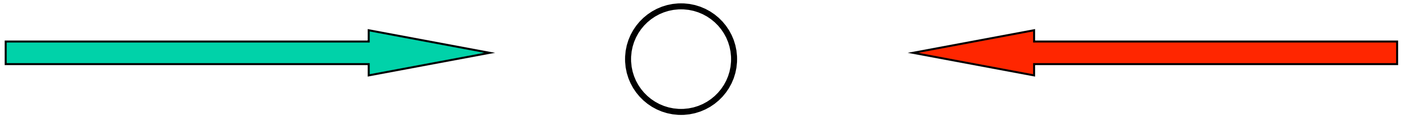
- δE_g is proportional to the light intensity
- δE_g has the same sign as $\omega_L - \omega_A$

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





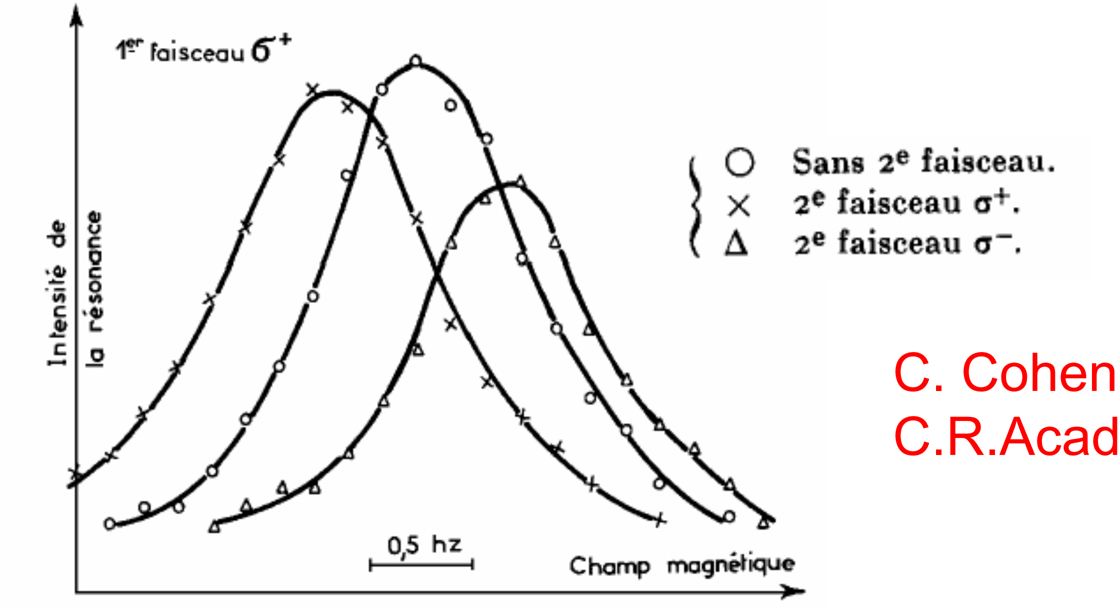
Experimental observation



First beam
Pumping beam σ_+

Atoms

Second perturbing beam
σ_+ or σ_- polarized

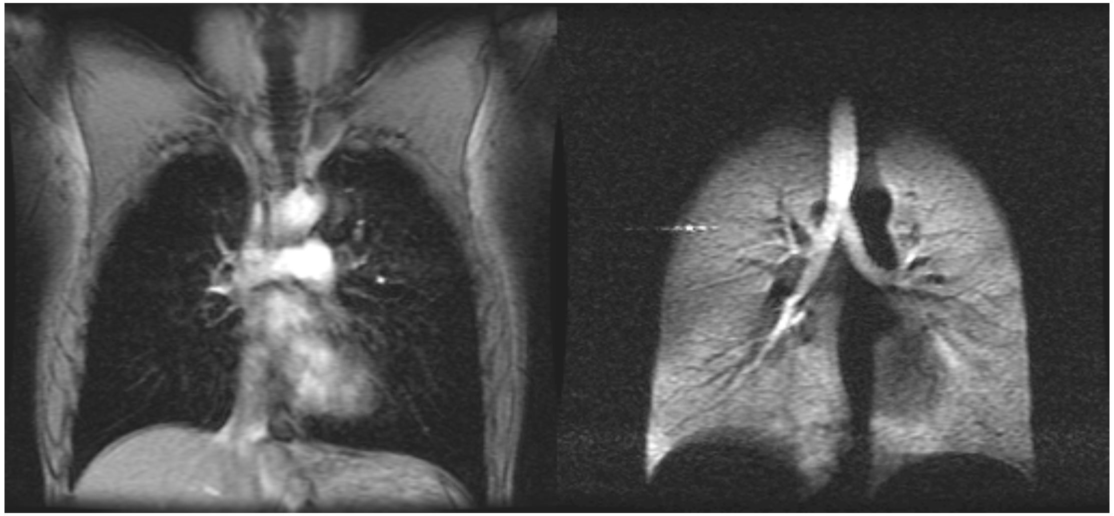


C. Cohen-Tannoudji,
C.R.Acad.Sci. 252, 394 (1961)

Two ways of considering light-shifts

- **Perturbation for high resolution spectroscopy**
- **A tool for manipulating the internal energy of atoms**
  Important applications for laser cooling and trapping

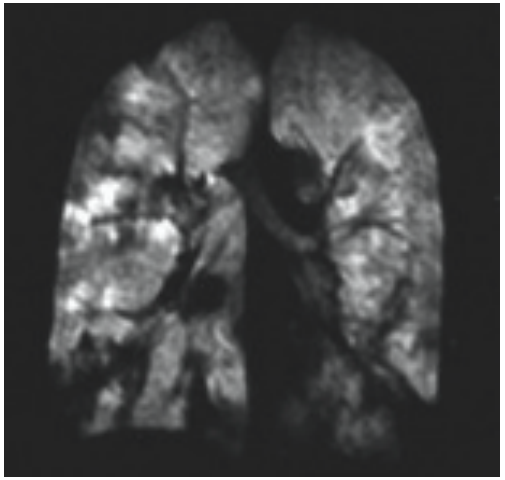
MRI Images of the Human Chest



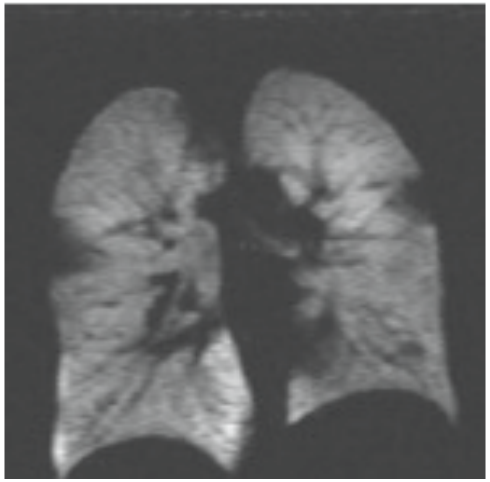
Proton-MRI

^{3}He-MRI

G.A.Johnson, L. Hedlund, J. MacFall Physics World, November 1998



Asthma



Smoker

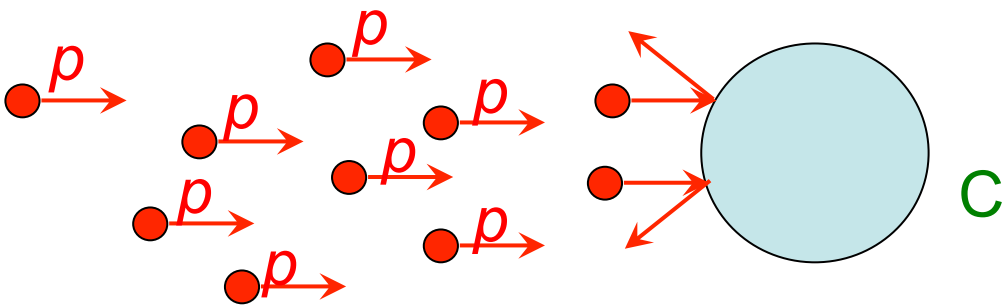
LASER COOLING AND TRAPPING

Transfer of linear momentum from photons to atoms

Forces exerted by light on atoms

A simple example

Target C bombarded by projectiles *p* coming all along the same direction

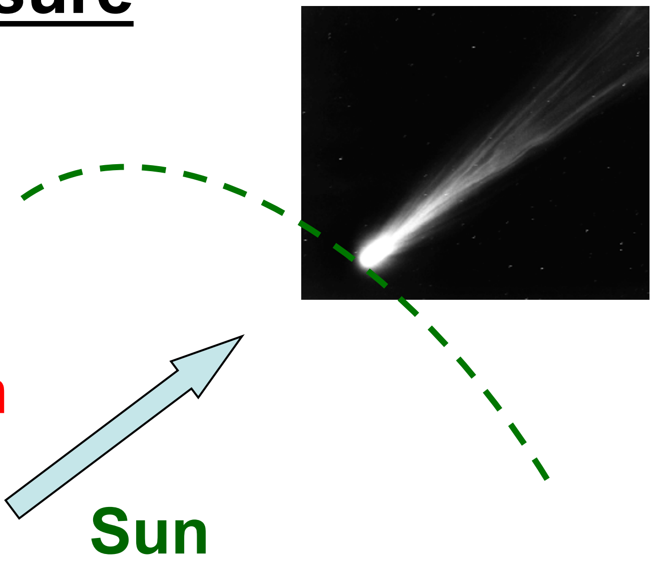


As a result of the transfer of linear momentum from the projectiles to the target C, the target C is pushed

Atom in a light beam: radiation pressure

Analogous situation, the incoming photons, scattered by the atom C playing the role of the projectiles p

Explanation of the tail of the comets



In a resonant laser beam, the radiation pressure force can be very large

Accelerations (or decelerations) on the order of 100.000 g

Atom in a resonant laser beam

Fluorescence cycles (absorption + spontaneous emission) lasting a time τ (radiative lifetime of the excited state) of the order of 10^{-8} s

Mean number of fluorescence cycles per sec : $W \sim 1/\tau \sim 10^{8}\ \mathrm{sec}^{-1}$

In each cycle, the mean velocity change of the atom is equal to:

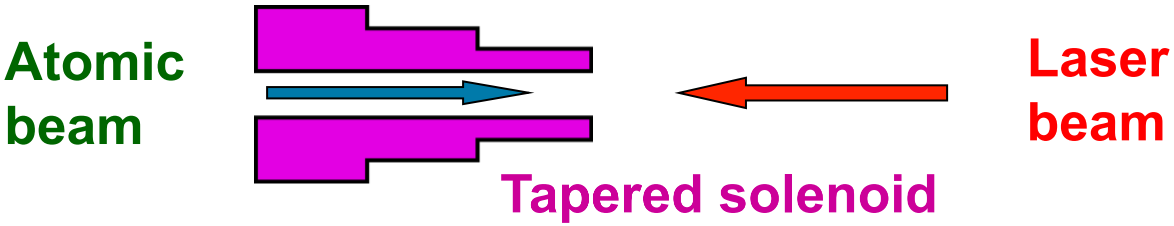
$$\delta v = v_{rec} = h\nu/Mc \sim 10^{-2}\ \mathrm{m/s}$$

Mean acceleration a (or deceleration) of the atom

$$\begin{aligned} a &= \text{velocity change /sec} \\ &= \text{velocity change } \delta v \text{ / cycle x number of cycles / sec } W \\ &= v_{rec} \times (1/\tau) = 10^{-2} \times 10^{8}\ \mathrm{m/s^2} = 10^{6}\ \mathrm{m/s^2} = 10^{5}\ g \end{aligned}$$

Huge radiation pressure force!

Stopping an atomic beam



J. Prodan
W. Phillips
H. Metcalf

Zeeman slower

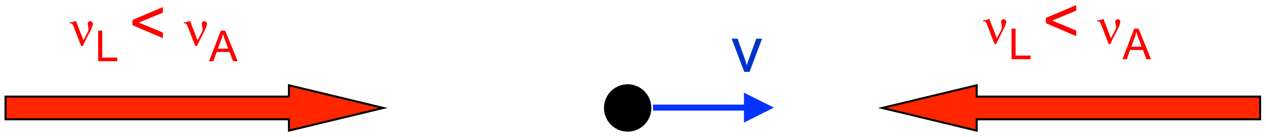
Laser Doppler cooling

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

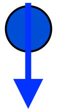
Friction force “Optical molasses”

Measured temperatures 100 times lower than expected!

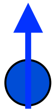
“Sisyphus” cooling

J. Dalibard
C. Cohen-Tannoudji

Several ground state sublevels



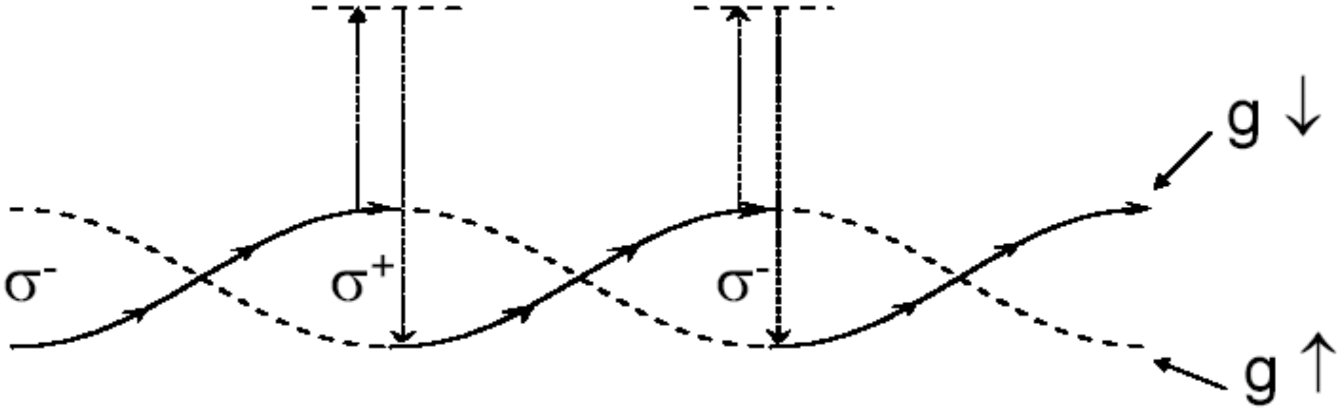
Spin down



Spin up

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↑**

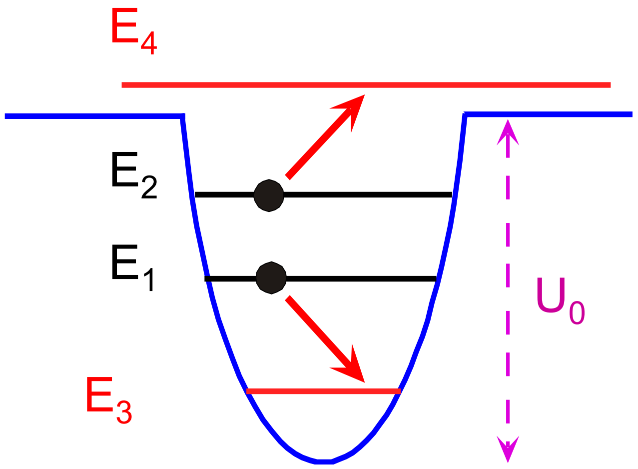


The atom is always running up potential hills (like Sisyphus)!

Very efficient cooling leading to temperatures in the mK range

Evaporative cooling

H. Hess, J.M. Doyle MIT



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

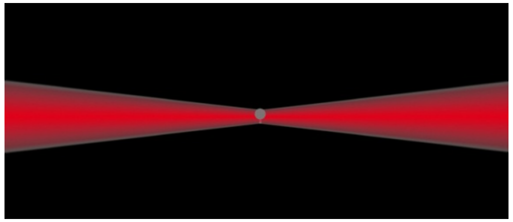
$$E_1 + E_2 = E_3 + E_4$$

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 decreases

Traps for neutral atoms

“Optical Tweezers”



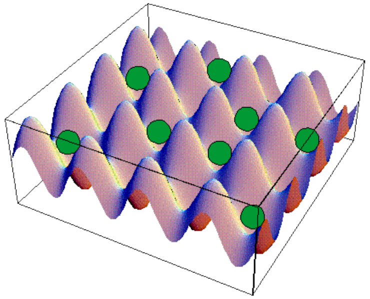
Spatial gradients of laser intensity

Focused laser beam. Red detuning ($\omega_L < \omega_A$)

The light shift δE_g of the ground state g is negative and reaches its largest value at the focus. Attractive potential well in which neutral atoms can be trapped if they are slow enough

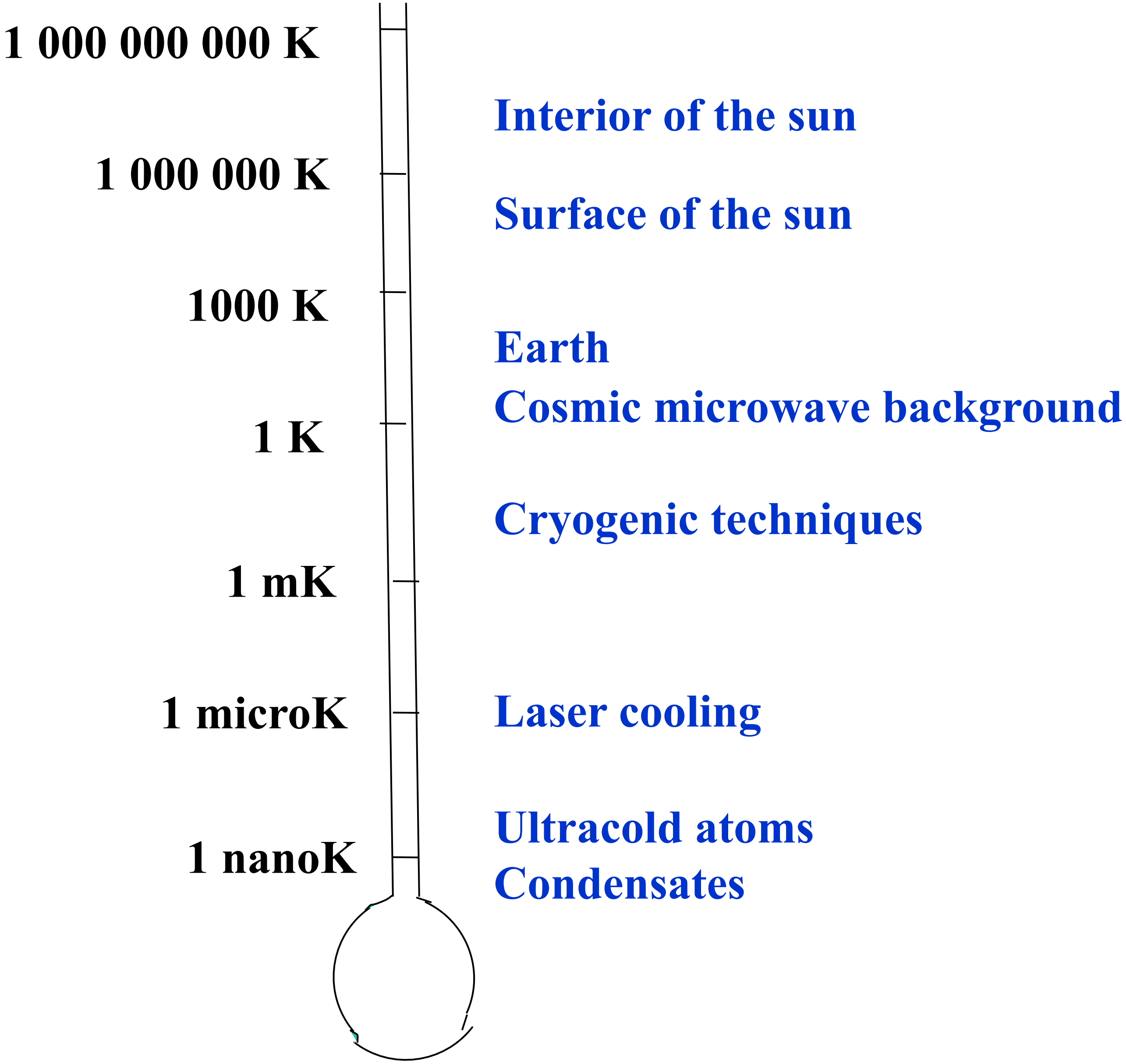
“Optical lattice”

Spatially periodic array of potential wells associated with the light shifts of a detuned laser standing wave



The dynamics of an atom in a periodic optical potential, called “optical lattice”, shares many features with the dynamics of an electron in a crystal. But optical lattices offer new possibilities!

Temperature scale (in Kelvin units)



1 000 000 000 K

Interior of the sun

1 000 000 K

Surface of the sun

1000 K

Earth

Cosmic microwave background

1 K

Cryogenic techniques

1 mK

1 microK

Laser cooling

Ultracold atoms

1 nanoK

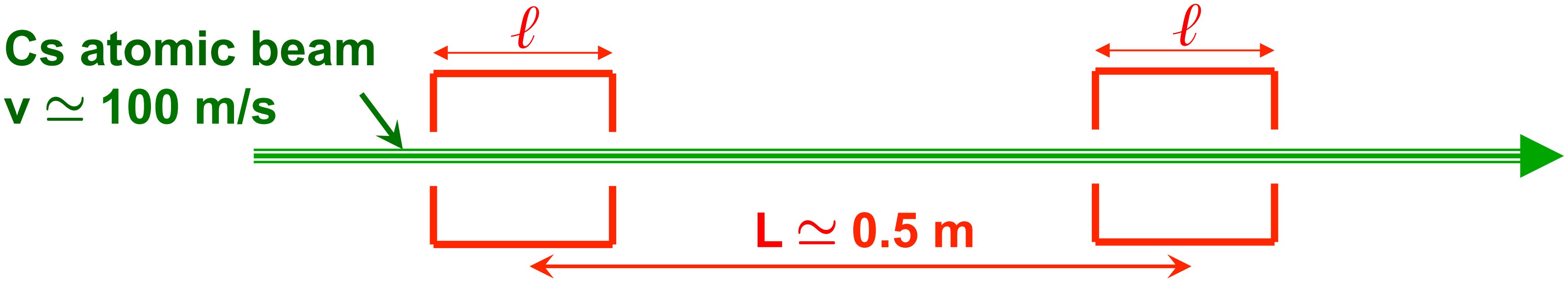
Condensates

A FEW APPLICATIONS OF ULTRACOLD ATOMS

- Long interaction times → High precision measurements
  More precise atomic clocks
- Large de Broglie wavelengths
  Atomic interferometry   Quantum degenerate gases

Improving atomic clocks with ultracold atoms

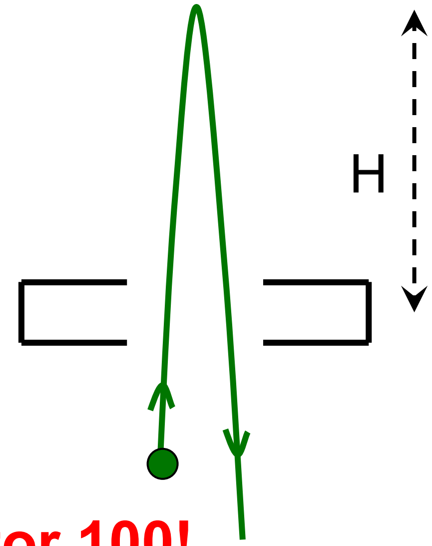
Usual clocks using thermal Cs atoms



Appearance in the resonance of Ramsey fringes having a width determined by the time $T = L / v \simeq 0.005$ s

Fountains of ultracold atoms

Throwing a cloud of ultracold atoms upwards with a laser pulse to have them crossing the same cavity twice, once in the way up, once in the way down, and obtaining in this way 2 interactions separated by a time interval T



$$g(T/2)^2/2 = H \quad \rightarrow \quad T = 2\sqrt{2H/g}$$

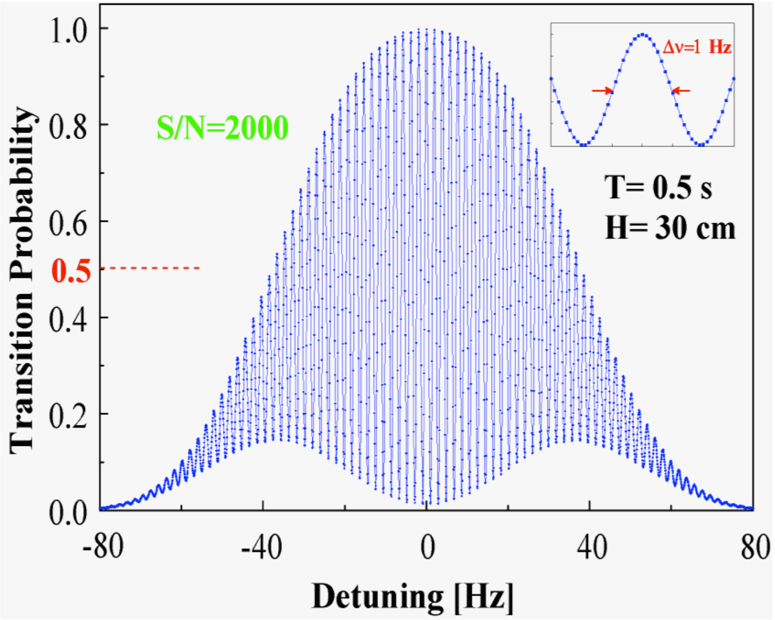
H = 30 cm ➔ T = 0.5 s Improvement by a factor 100!

Examples of atomic fountains

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

Christophe
Salomon

André
Clairon

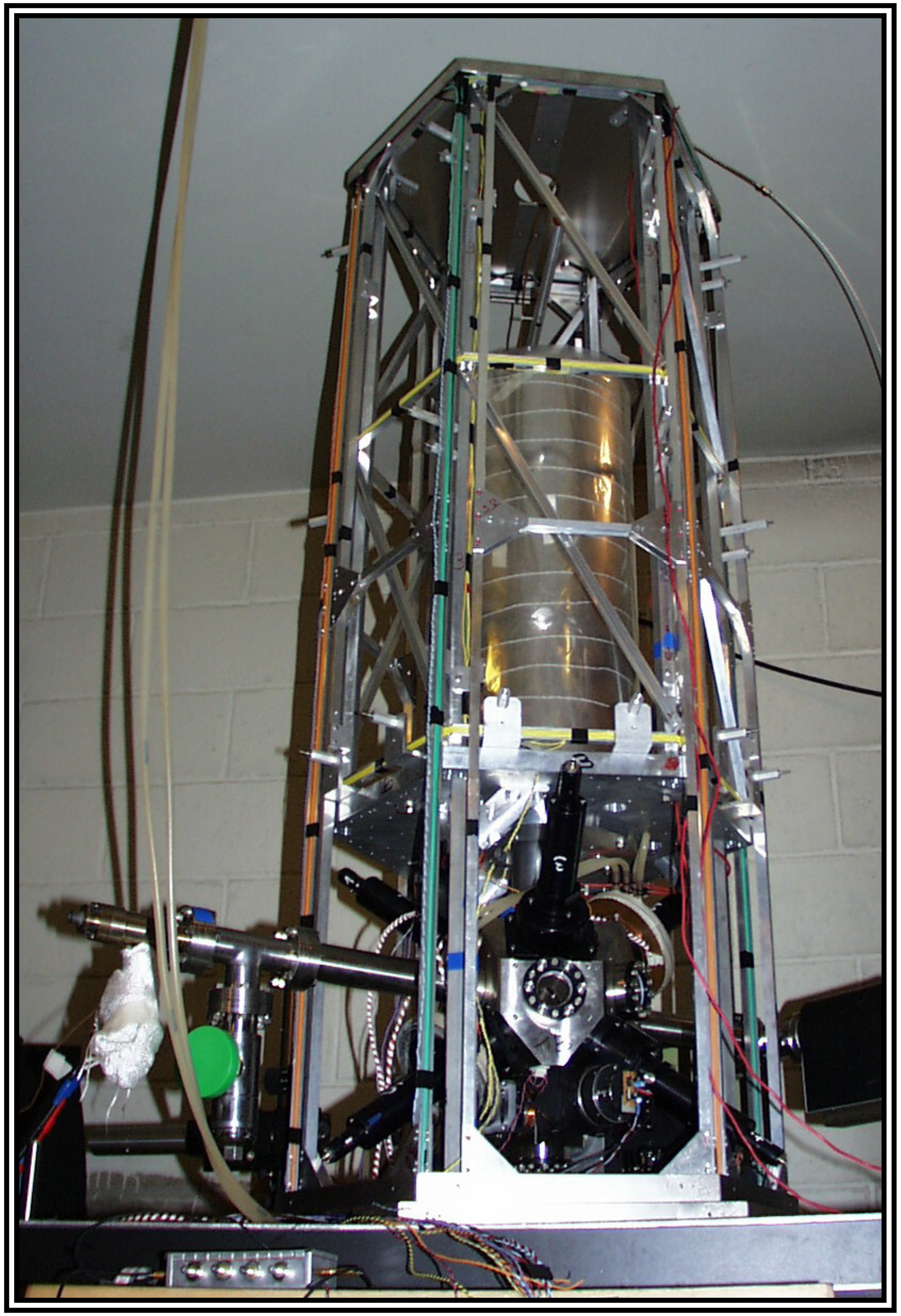


Stability : 1.6 x 10^{-16} for an integration time 5 x 10^{4} s

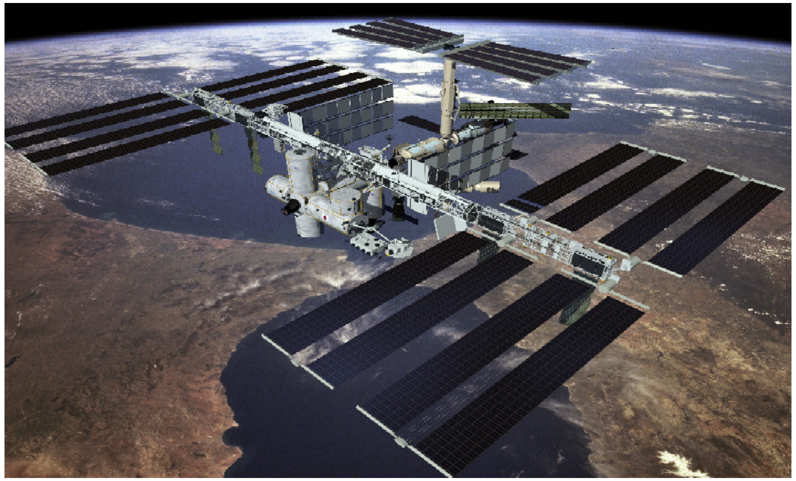
Accuracy : 3 x 10^{-16}

A stability of 10^{-16} corresponds to an error smaller than 1 second in 300 millions years

Atomic
Fountain
BNM-SYRTE



From terrestrial clocks to space clocks



ACES project

Gravitational shift of the frequency of a clock

An observer at an altitude *z* receives the signal of a clock located at the altitude $z+\delta z$ and measures a frequency $\omega_A(z+\delta z)$ different from the frequency, $\omega_A(z)$, of his own clock

$$\frac{\omega_A(z+\delta z)-\omega_A(z)}{\omega_A(z)}=\frac{\delta\,\omega_A}{\omega_A}=\frac{g\,\delta z}{c^2}$$

$$g=10\,\mathrm{m/s^2}\quad \delta z=1\,\mathrm{m}\quad \mathrm{c}=3\times 10^8\,\mathrm{m/s}\quad \rightarrow\quad \delta\omega/\omega=10^{-16}$$

2 clocks at altitudes differing by 1 meter have apparent frequencies which differ in relative value by 10^{-16}.

A space clock at an altitude of 400 kms differs from a terrestrial clock by 4×10^{-11} . Possibility with ACES to check this effect with a precision 70 times better than all previous tests

New perspectives

Relativistic geodesy with 1-10 cm accuracy

Ground ground gravitational potential comparison with optical clocks

Optical clocks

Quality factor of the resonance

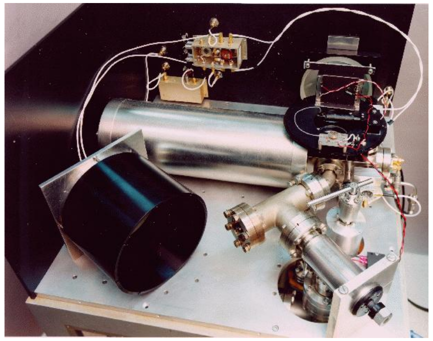
$$Q = \nu T$$

Q increases considerably when the frequency n is changed from microwave to optical, by a factor on the order of 10^5.

Two types of optical clocks are being studied

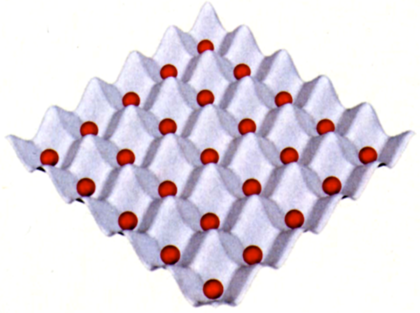
1 – Single ion optical clocks

A single ion is trapped, cooled and a very narrow optical transition connecting the ground state to a long lived excited state is used as the clock transition

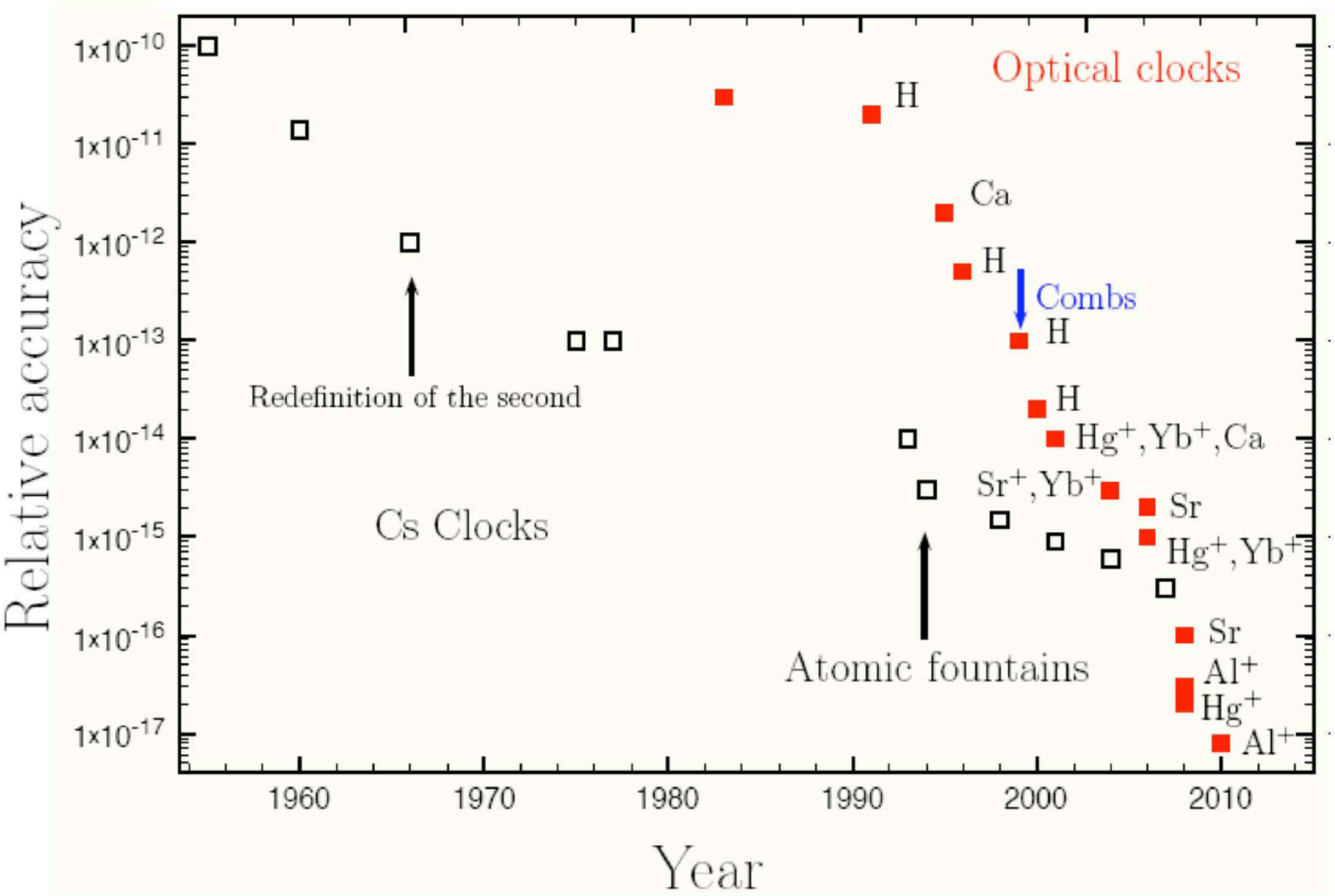


2 – Neutral atoms in an optical lattice

The frequency of the light producing the lattice is such that the light shifts ot the 2 states of the clock transition are equal (Katori)



The two types of clocks could be miniaturized and put in space

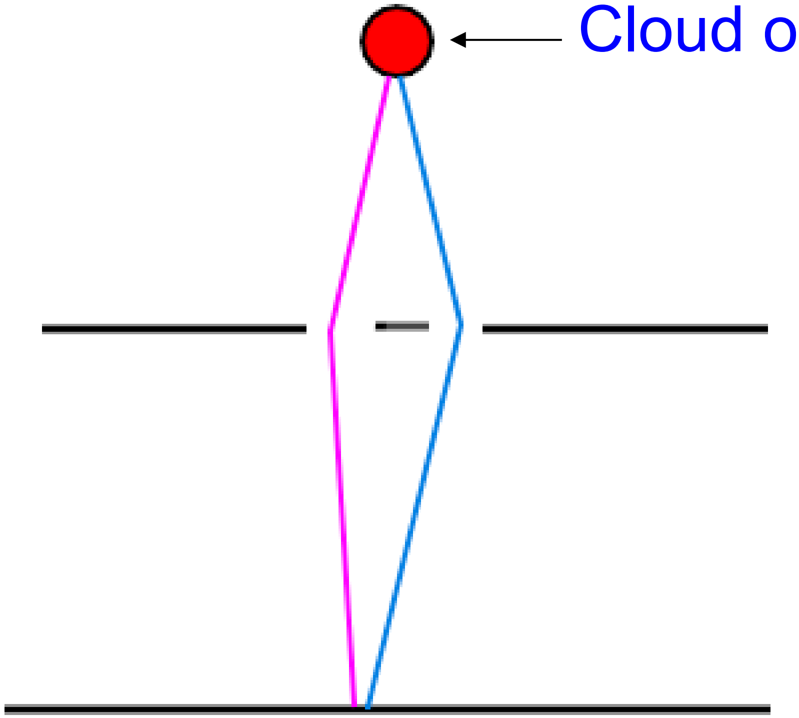


A relative accuracy of 10^{-17} corresponds to
- an error smaller than 1 second in 3 billion years
- to a sensitivity of 10 cm for the gravitational red shift

Looking for variations of the fundamental constants

ATOMIC DE BROGLIE WAVES

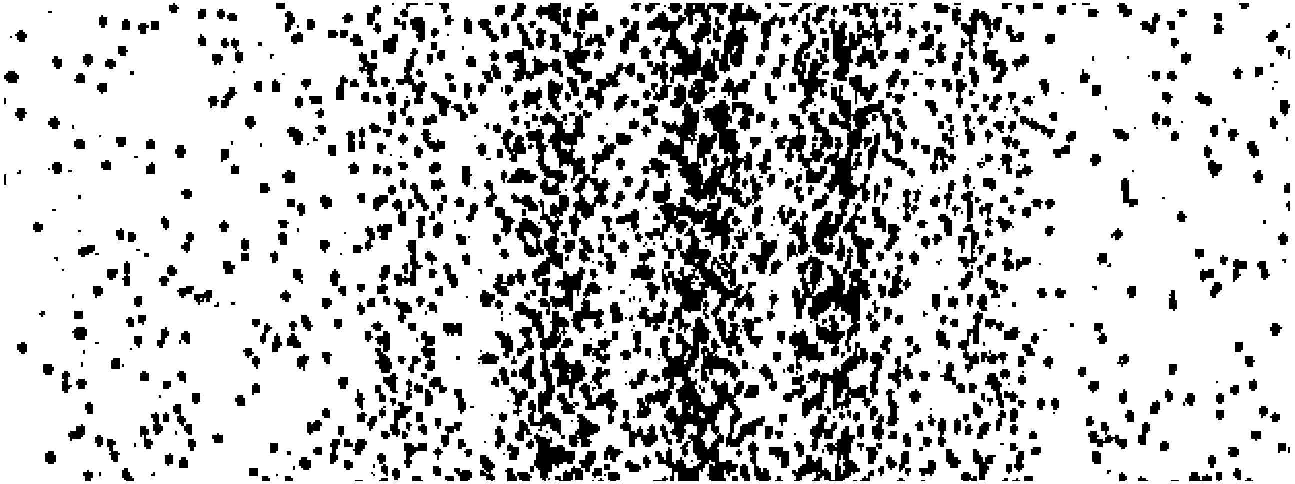
Interference fringes obtained with the de Broglie waves associated with metastable laser cooled Neon atoms



Cloud of cold atoms

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

Experimental results



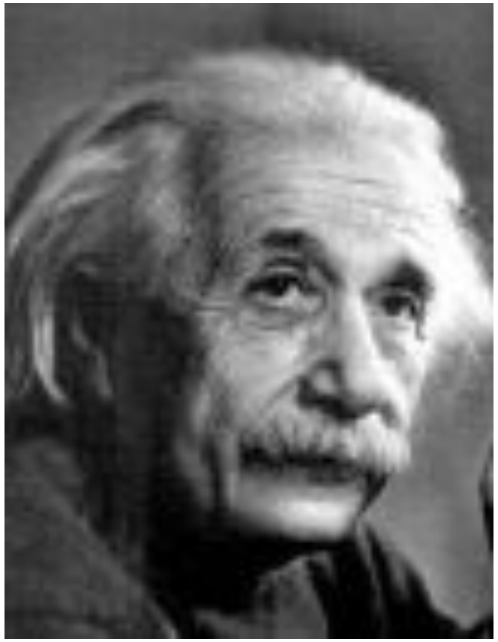
Each atom gives rise to a localized impact on the detector
The spatial repartition of the impacts is spatially modulated

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

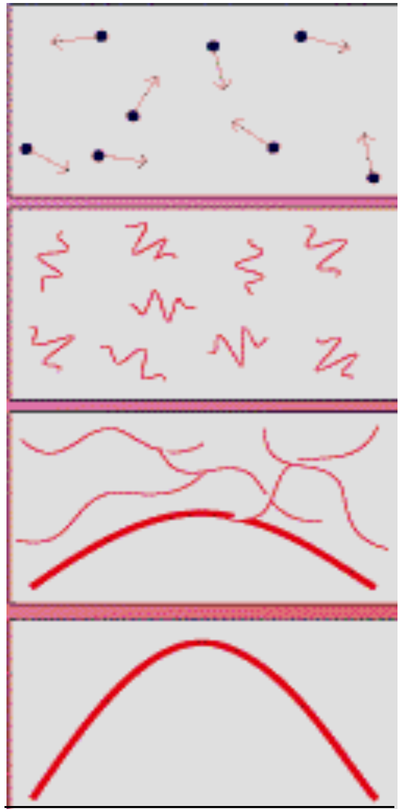
Bose-Einstein Condensation

Satyendra Nath Bose



Albert Einstein

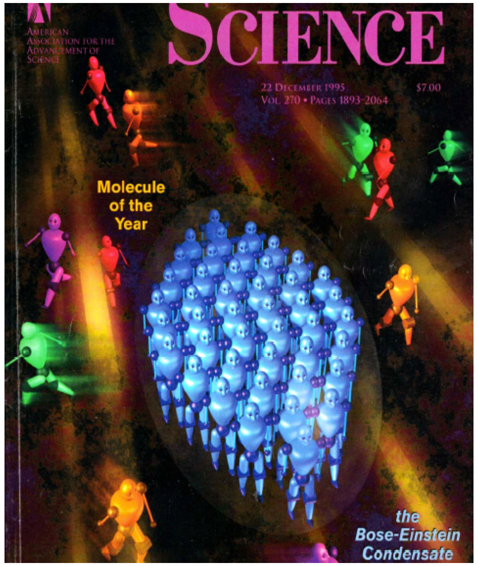
Bose Einstein condensation



When the temperature decreases, the de Broglie wavelength increases and the atomic wave packets become more and more extended.

When they overlap, they interfere and all atoms condense in the ground state of the trap which contains them.

They form a macroscopic matter wave

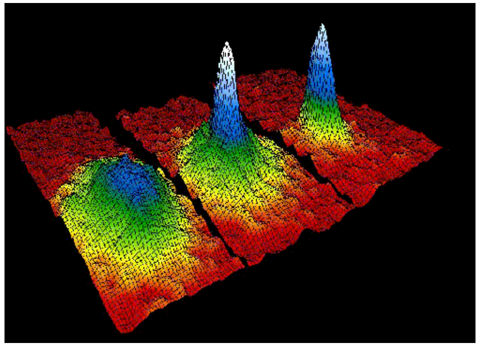


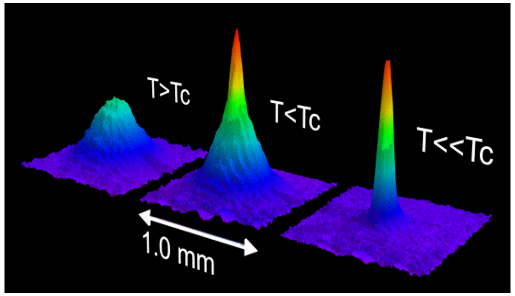
All atoms are in the same quantum state and they evolve in a coherent way like the soldiers of an army marching in lockstep

These gaseous condensates, discovered in 1995, are macroscopic quantum systems with properties (superfluidity, coherence) which make them very similar to other systems only found up to now in liquids or solids (liquid helium, superconductors)

Experimental observation (1995)


Eric A. Cornell **Wolfgang Ketterle** **Carl E. Wieman**


JILA ^{87}Rb



MIT ^{23}Na

Many others atoms have been condensed
^{7}Li, ^{1}H, ^{4}He*, ^{41}K, ^{133}Cs, ^{174}Yb, ^{52}Cr…

Extension to composite bosons formed by fermionic pairs

Importance of gaseous Bose Einstein 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 in very dilute systems, about 100000 times more dilute than air. Atom-atom interactions can then be described in terms of binary collisions and 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

Bose Einstein condensates thus appear as model systems for simulating more complex systems. Fruitful connections can thus be established with other fields (strongly interacting many body systems, astrophysics, quantum simulators)

Conclusion

The better understanding of light-matter interactions has allowed several important advances:

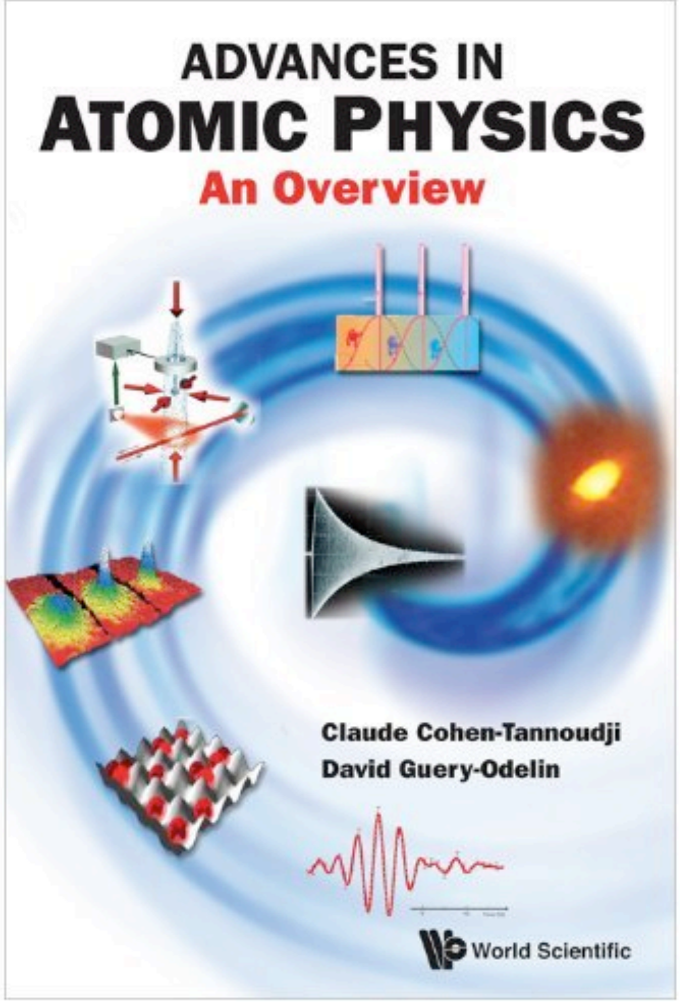
- **invention of new light sources, the lasers**
- **invention of new schemes (optical pumping, laser cooling) for manipulating atoms**

These advances are opening new research fields and allow us to ask new questions and to investigate new systems, new states of matter, like macroscopic matter waves which share many common features with light waves

The history of light and matter shows that basic research

- **changes our vision of the world by introducing conceptual revolutions (relativity, quantum physics)**
- **leads to a wealth of unexpected practical applications**

Claude
Cohen-Tannoudji



ADVANCES IN
ATOMIC PHYSICS
An Overview

Claude Cohen-Tannoudji
David Guery-Odelin

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