From Optical Pumping to Quantum Gases

Claude Cohen-Tannoudji

22nd International Conference on Atomic Physics

Cairns, Australia, 26 July 2010

1530
Collège de France

Recherche sur les Atomes Froids
Institut Francilien de
IFRAF

2010 : three anniversaries

60th anniversary of of optical pumping (1950)

50th anniversary of of the first laser (1960)

15th anniversary of BEC in a gas (1995)

Description of a few advances realized by Atomic Physics during this period

Description of a few trends and perspectives

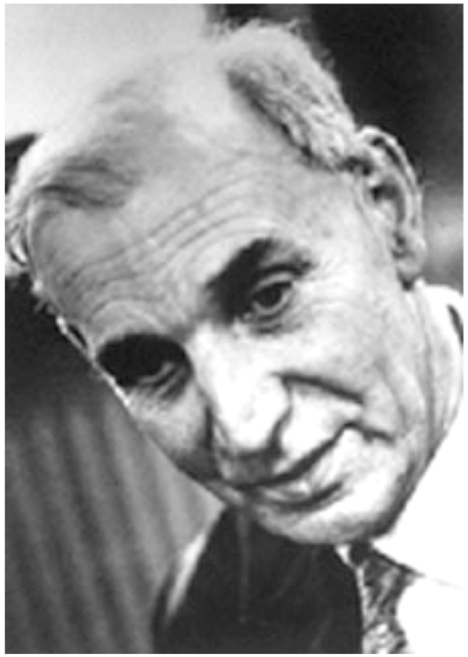
LE JOURNAL DE PHYSIQUE ET LE RADIUM

TOME 11, JUIN 1930, PAGE 255.

QUELQUES SUGGESTIONS CONCERNANT LA PRODUCTION OPTIQUE ET LA DÉTECTION OPTIQUE D'UNE INÉGALITÉ DE POPULATION DES NIVEAUX DE QUANTIFICATION SPATIALE DES ATOMES. APPLICATION A L'EXPÉRIENCE DE STERN ET GERLACH ET A LA RÉSONANCE MAGNÉTIQUE (1)

Par ALFRED KASTLER.

Laboratoire de Physique de l'École Normale Supérieure, Paris.



Alfred Kastler

Jean Brossel

Important features of optical pumping

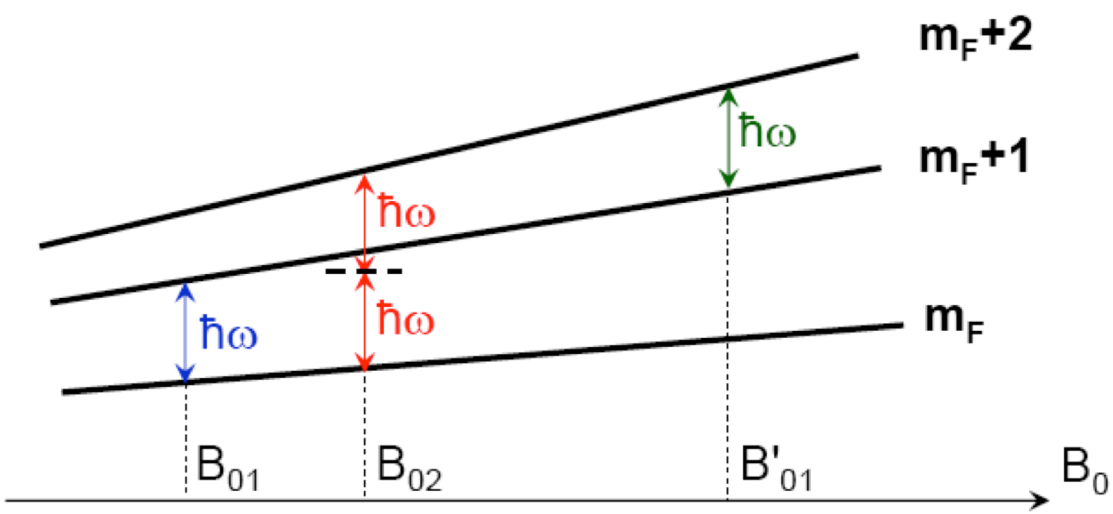
- **Achievement of high degrees of spin polarization (up to 90%)**
  First example of manipulation of atoms by light
- **Very sensitive optical detection of magnetic resonance in dilute atomic vapors where atom-atom interactions are small**
- **High resolution RF and microwave spectroscopy**

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

First experimental observation of RF multiphoton resonances



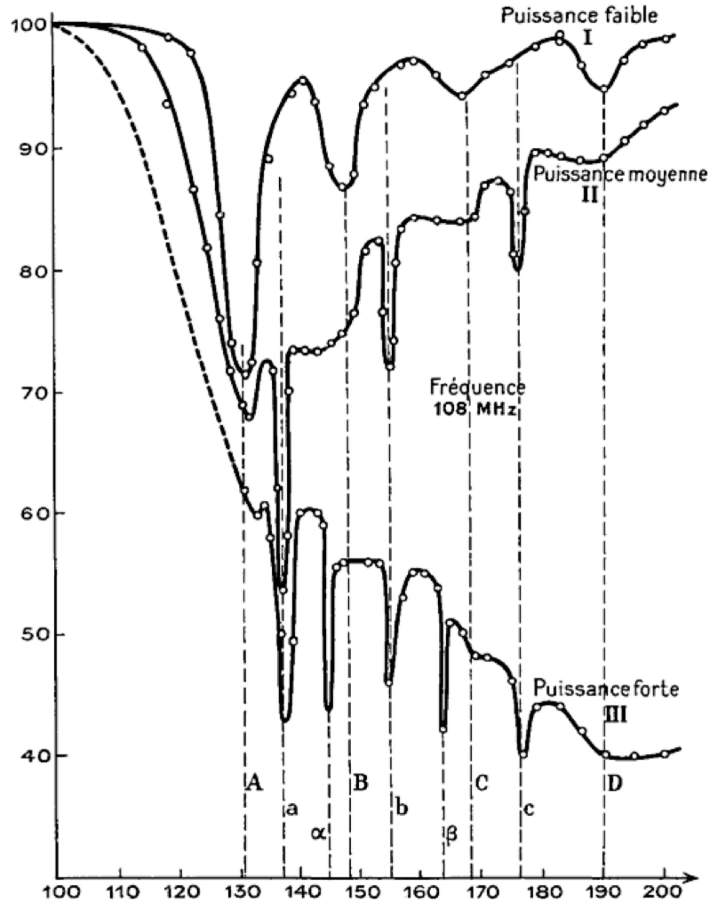
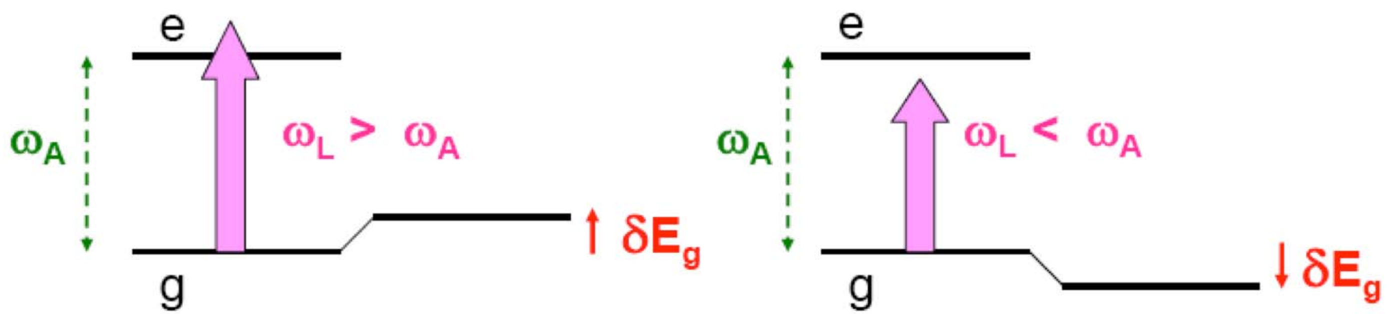


FIG. 10. — Orientation produite par de la lumière circulaire gauche σ^-. En abscisse, champ magnétique H en Gs ; en ordonnée, variation relative ρ du signal d'orientation.

J. Brossel, B.Cagnac, A.Kastler
Compt. Rend. Acad. Sci.
237,984 (1953)
J.Phys.Rad. 15,6 (1954)

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.

Position-dependent light-shifts (focused light beam or standing wave)

have several interesting applications:

- **Sisyphus cooling**
- **Laser traps**
- **Optical lattices**

George W. Series

Adriano Gozzini

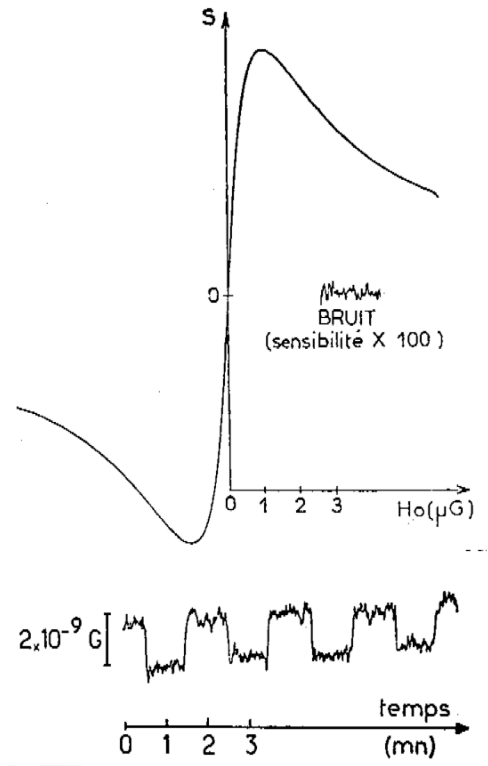
Wilhelm Hanle

Hanle effect in atomic ground states g

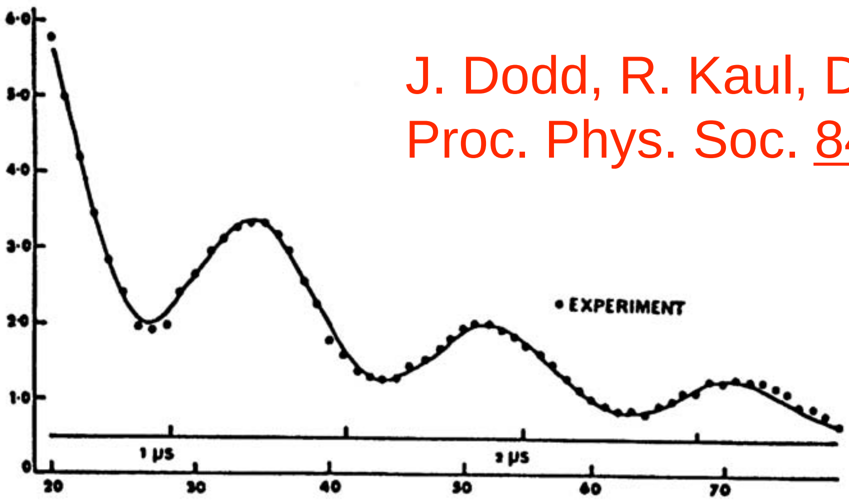
Very narrow level crossing resonances if relaxation times in g are long

Magnetometer with a sensitivity of 5×10^{-10} Gauss

J. Dupont-Roc, S. Haroche, C. C-T, Phys. Lett. 28A, 638 (1969)



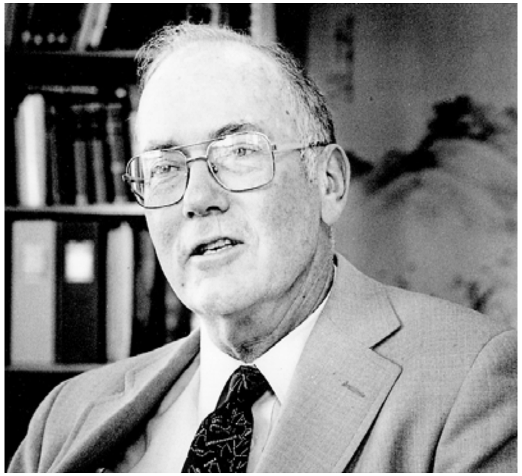
First observation of quantum beats



J. Dodd, R. Kaul, D. Warrington, Proc. Phys. Soc. 84, 176 (1964)

See also E. Aleksandrov Optics and Spectroscopy 17, 522 (1964)

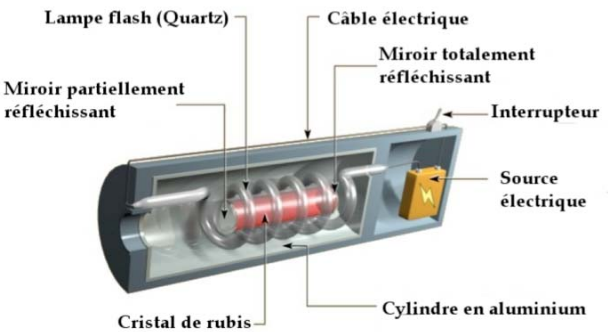
First proposal of "optical masers" (1958)



Charles Townes

Arthur Schawlow

The first laser (1960)



Ruby laser

Theodor Maiman

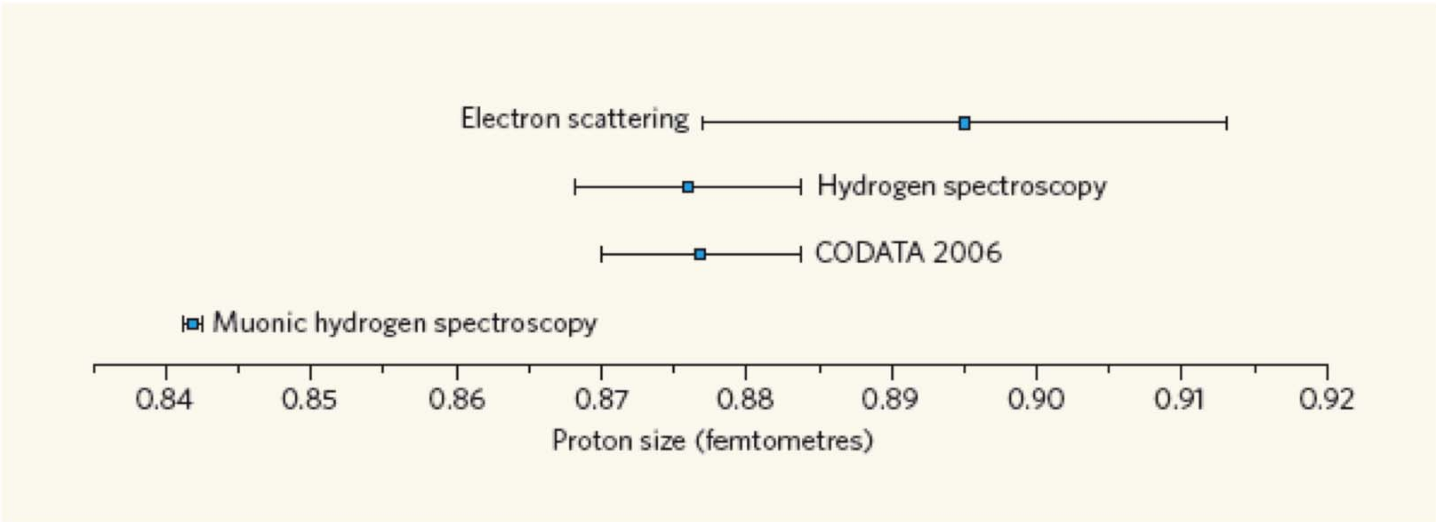
The impact of lasers for fundamental physics

- High resolution spectroscopy
  Saturated absorption. Doppler-free two-photon
- Nonlinear optics. Quantum optics
- Fundamental tests
  Parity violation in atoms. Tests of QED
- Atoms in intense laser fields
  Multiphoton ionization
  High harmonic generation
- Ultrashort laser pulses
  Femtoseconds. Motion of atoms in a molecule
  Attoseconds. Motion of electrons in an atom
- Control of atomic motion by laser light
  Laser cooling and trapping
  Quantum degenerate gases
- Quantum information with ions and atoms…….

466, 213 (2010)

The Lamb shift of muonic atoms falls in the optical domain and is very sensitive to the size of the nucleus because of the small size of the muon orbits compared to electron orbit

A recent laser spectroscopy experiment performed by an international collaboration at the Paul Scherrer institute on muonic hydrogen has given a value of the proton size significantly smaller than the one given by other methods. This discrepancy is not yet explained!



One of the first meetings on cold atoms

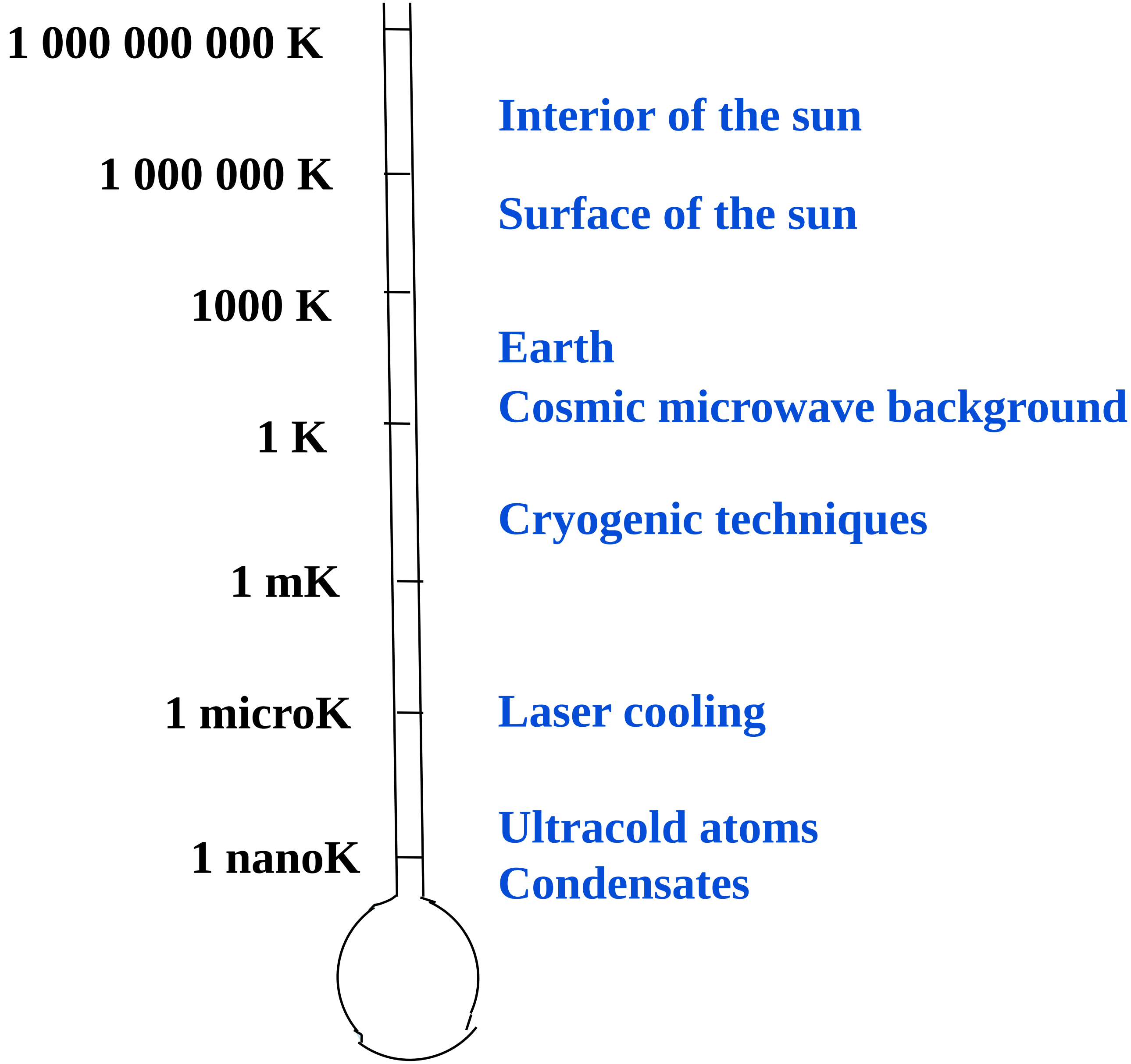
International meeting on laser cooling
Tvärminne, Finland, March 1984

The adventure of cold atoms. The first period

- Trapping of electrons, ions
- Theory of radiative forces
- Proposal of Doppler cooling
- Laser cooling of ions
- Slowing down of atomic beams
- Optical molasses
- Traps for neutral atoms
- Sisyphus cooling, Subrecoil cooling, Evaporative cooling
- Atom optics, atom interferometry
- Atomic fountains

A lot of good surprises!
Cooling works better than expected

Temperature scale (in Kelvin units)

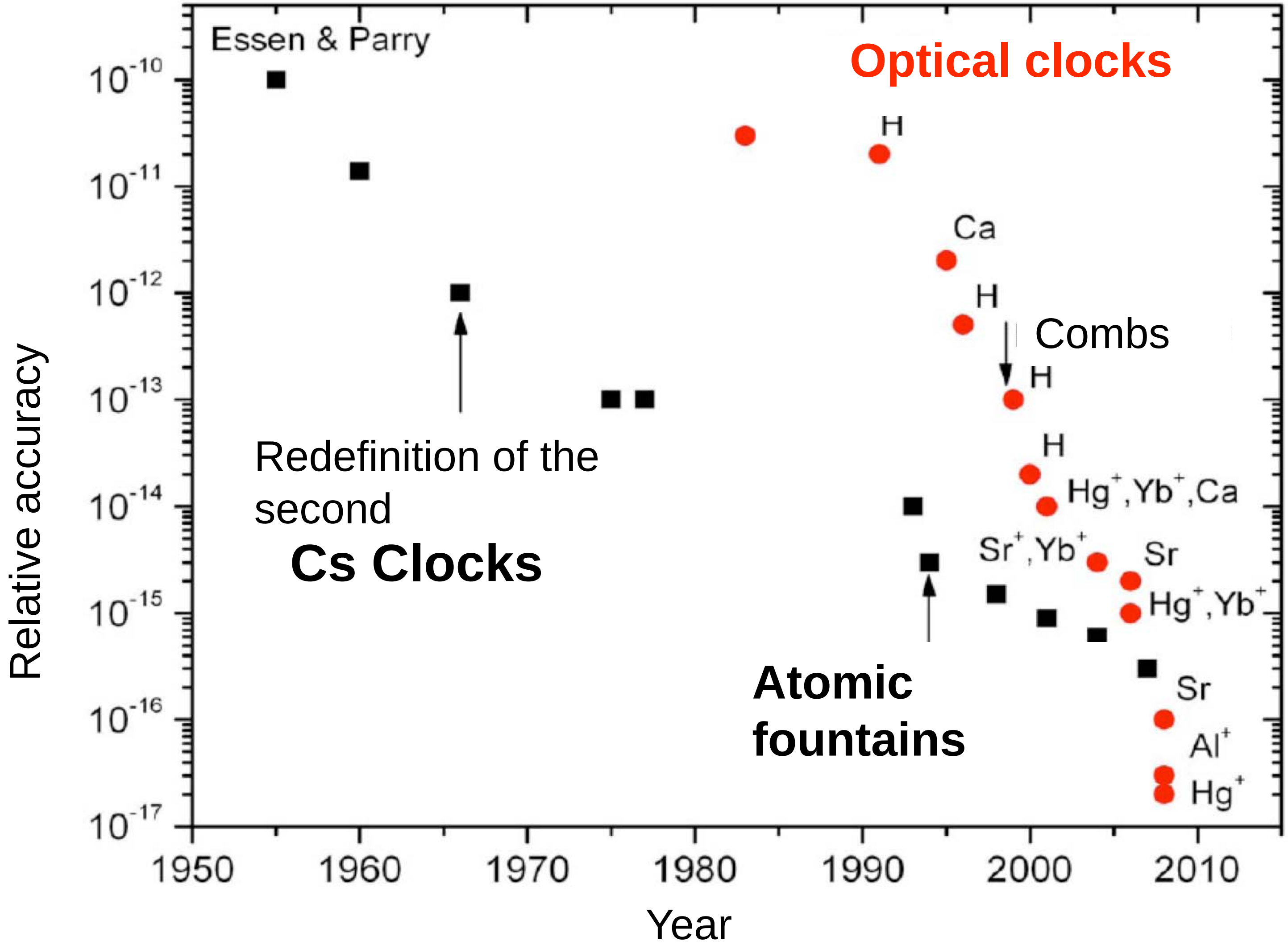


From terrestrial clocks to space clocks

ACES project

Test of Einstein's gravitational shift
$\Delta\omega / \omega = \Delta U / c^2$

C. Salomon
A. Clairon



A stability of $3x10^{-17}$ corresponds to

- an error smaller than 1 second in 1 billion years

- to a sensitivity of 30 cm for the gravitational red shift

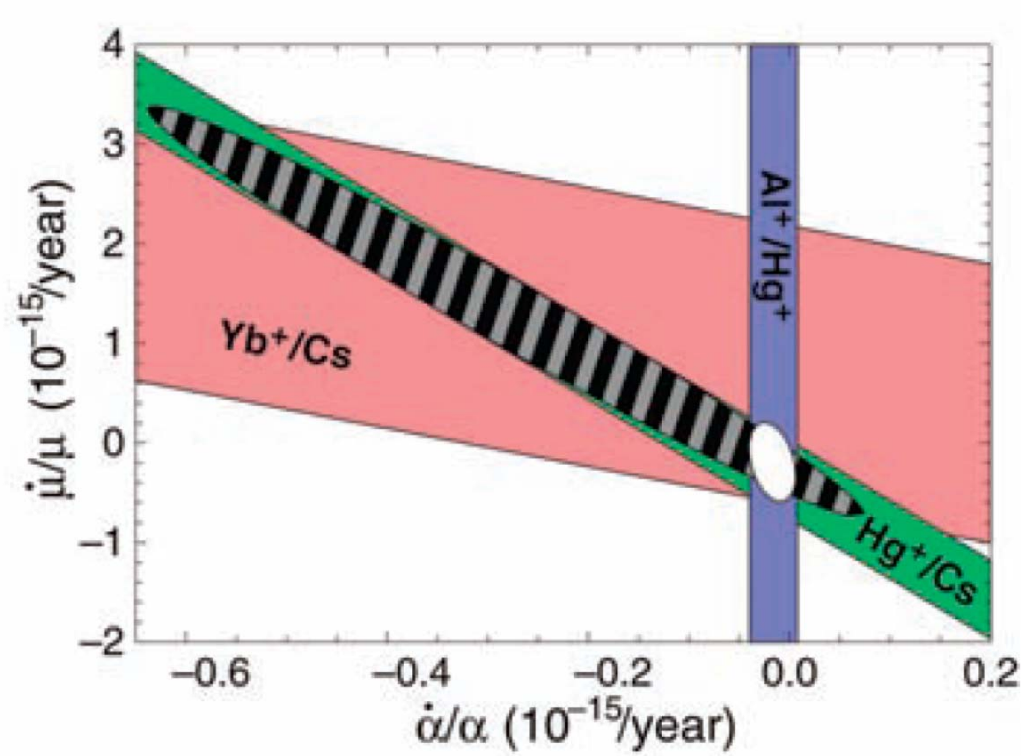
Recent results obtained by the NIST-Boulder group

Single ion optical clocks with Al^+ and Hg^+

Laboratory tests of a possible variation of fundamental constants

$$\nu_{Al^+} / \nu_{Hg^+} = 1.052871833148990438(55)$$

$$\dot{\alpha} / \alpha = (-1.6 \pm 2.3) \times 10^{-17} / \text{year}$$



Science, **319**, 1808 (2008)

Most recent reported accuracy for Al^+ : 8.6×10^{-18}

The quest for quantum effects in a gas

3 characteristic lengths in a gas

$d = n^{-1/3}$ = mean distance between atoms (n : spatial density)

λ_{dB} = thermal de Broglie wavelength

r_0 = range of atom-atom interactions

When T decreases, λ_{dB} increases. Various regimes appear

Regime of quantum transport : $r_0 \ll \lambda_{\mathrm{dB}} \ll d$

The gas is non degenerate since $\lambda_{\mathrm{dB}} < d$.

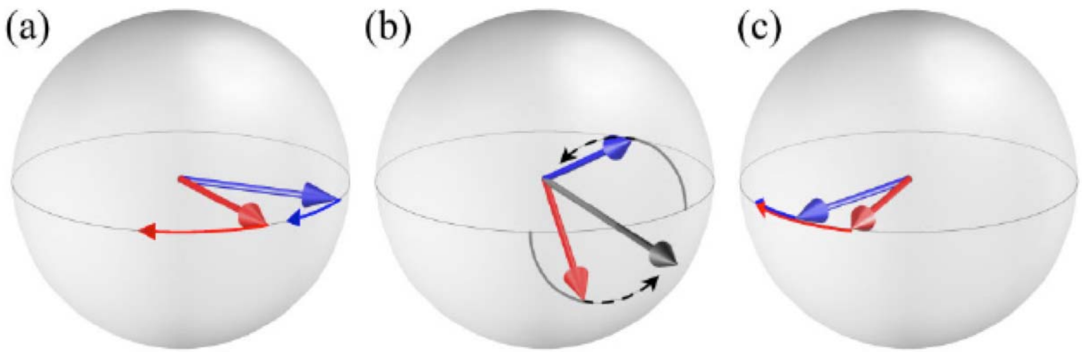
On the other hand, collisions between identical atoms must be described quantum mechanically since $r_0 < \lambda_{\mathrm{dB}}$.

Classical gas with quantum transport properties due a modification of collisions (quantum indiscernability).

In particular, 2 spins undergoing a collision rotate around their vector sum, even in absence of spin-spin interactions

Effect called “Identical Spin Rotation Effect (ISRE)

A recent observation of spectacular effect due to ISRE



C.Deutsch et al
Phys.Rev.Lett. 105, 020401 (2010), 9 July 2010

87Rb atoms trapped in a chip

Simple reasoning considering 2 classes of spins
- fast spins sampling large regions of the trapping field
- slow spins sampling smaller regions ➔ slower spin precession

Collision between a slow spin and a fast spin
- the 2 spins rotate around their vector sum
- if the rotation angle is equal to π, the slow spin which was delayed becomes in advance, so that the 2 classes of spin can be rephased when the fast spins catch up the slow spins

A certain analogy with spin echoes

Observation of coherence times increased by a factor 20

Regime of quantum degeneracy : $r_0 \ll d \ll \lambda_{dB}$

Quantum degenerate gas since $\lambda_{dB} > d$.
Classical Maxwell Boltzmann statistics is no longer valid.

Attempts to observe BEC on spin polarized Hydrogen

- The only atoms to remain in the gas phase at T=0°K (Hecht, Stwalley, Nosanow)
- Experiments starting at MIT, Amsterdam (Kleppner, Greytak, Walraven, Silvera)
- Theoretical calculations of the effect of collisions (Kagan)
- Stimulation for new experimental methods
  Wall free confinement   Evaporative cooling

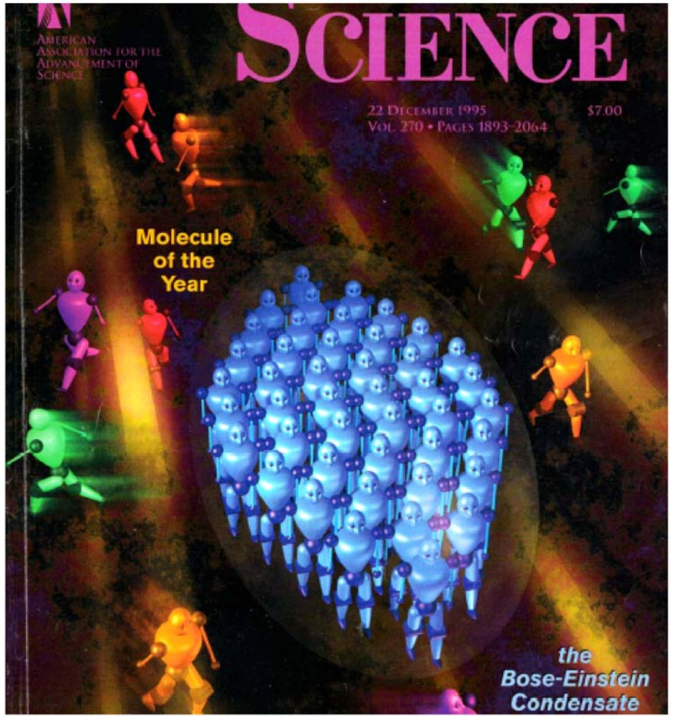
Attempts to observe BEC on alkali atoms

- Lower temperatures achievable (laser cooling)
- Easier evaporation (larger elastic cross sections)
- Easier optical detection
- Weak inelastic processes: the condensate is metastable, but it lives a time long enough to be observed

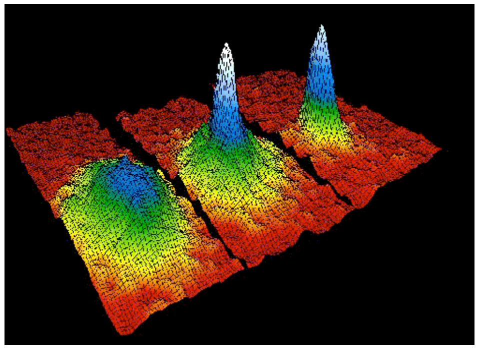
Gaseous Bose Einstein Condensation (1995)

Eric A. Cornell   Wolfgang Ketterle   Carl E. Wieman

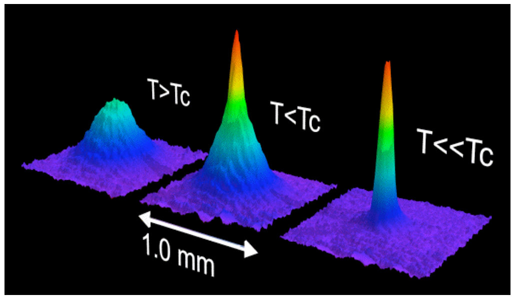
All atoms are in
the same quantum state



They form a macroscopic matter wave



JILA ^{87}Rb



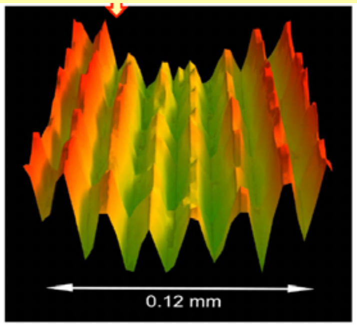
MIT ^{23}Na

Macroscopic matter waves of bosonic atoms

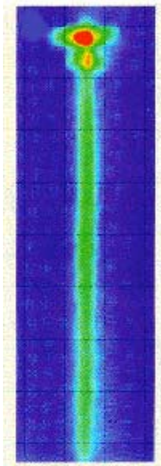
Coherence

Interferences between 2 condensates

MIT



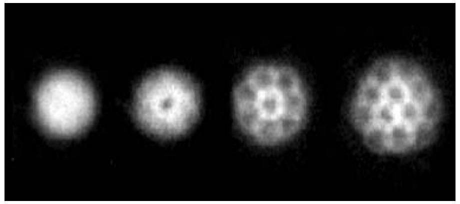
Munich



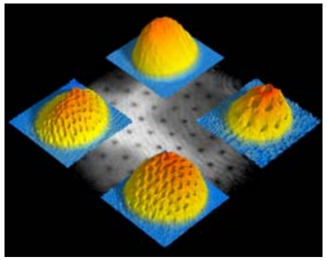
Atom lasers

Coherent beam of atomic de Broglie waves extracted from a condensate

Superfluidity

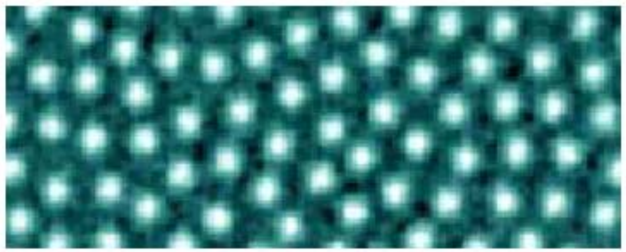


ENS



MIT

Quantized vortices



Abrikosov lattice in a type II superconductor

Mean-field description (Gross Pitaevskii equation): each atom evolves in the mean field created by the other atoms

Ultracold quantum gases

Evolution of this research field during the last few years

Emphasis is put on the study of strongly correlated systems, for which mean field approaches are no longer sufficient

Stronger connections with other fields of physics become possible because ultracold quantum gases can be used

- as fully controllable model systems for getting a better understanding of many body and few body physics
- as benchmarks for validating or eliminating theoretical models
- as box tools for exploring new situations

How to get strongly correlated quantum gases

- Feshbach resonances
- Atoms in optical lattices
- Low dimension systems

Optical lattices

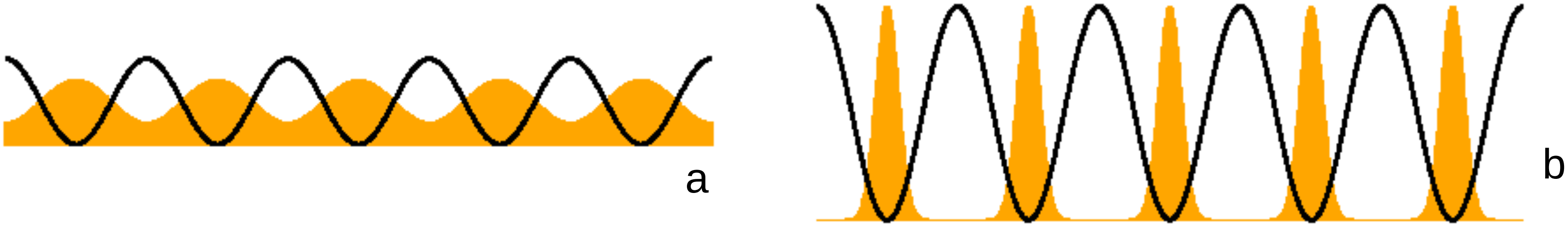
Early studies at ENS (G. Grynberg), Gaithersburg, Munich

The dynamics of an atom in a periodic optical potential, called "optical lattice" and associated with the light shifts produced by a non resonant standing wave, shares many features with the dynamics of an electron in a crystal. But it offers new possibilities!

- **Possibility to switch off suddenly the optical potential**
- **Possibility to vary the depth of the periodic potential well by changing the laser intensity**
- **Possibility to change the spatial period of the potential by changing the angle between the 2 running laser waves**
- **Possibility to change the frequency of one of the 2 waves and to obtain a moving standing wave**
- **Possibility to change the dimensionality (1D, 2D, 3D) and the symmetry (triangular lattice, cubic lattice)**

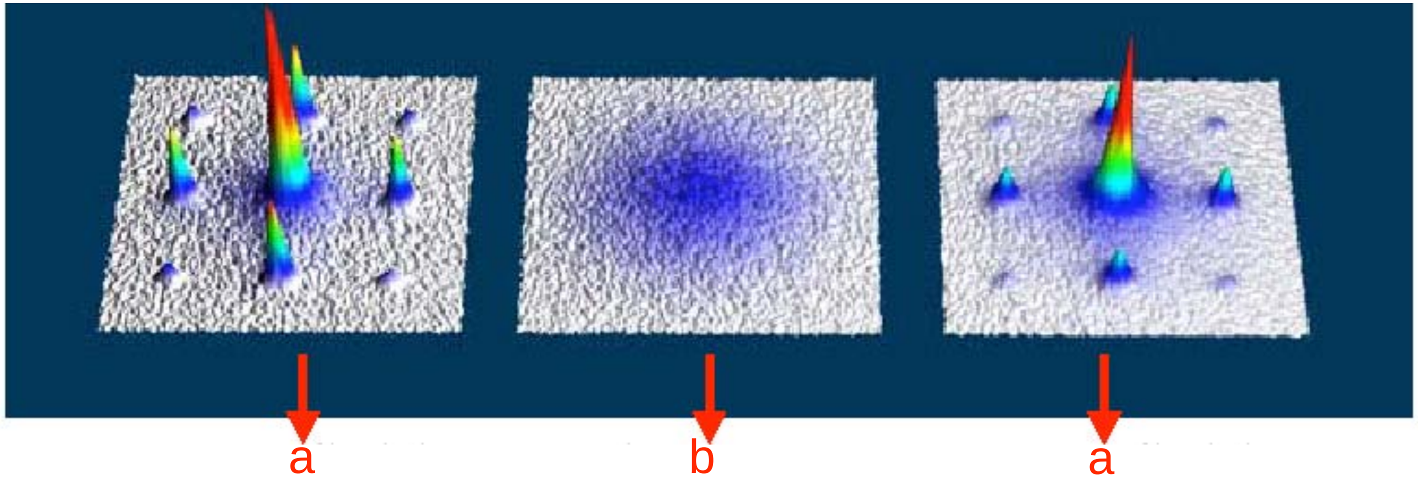
Furthermore, possibility to control atom-atom interactions, both in magnitude and sign, by using "Feshbach resonances"

Superfluid – Mott insulator transition



a – Small depth of the optical lattice potential wells.
Delocalized matter waves. Superfluid phase

b - Large depth of the wells. Localized waves. Insulator phase



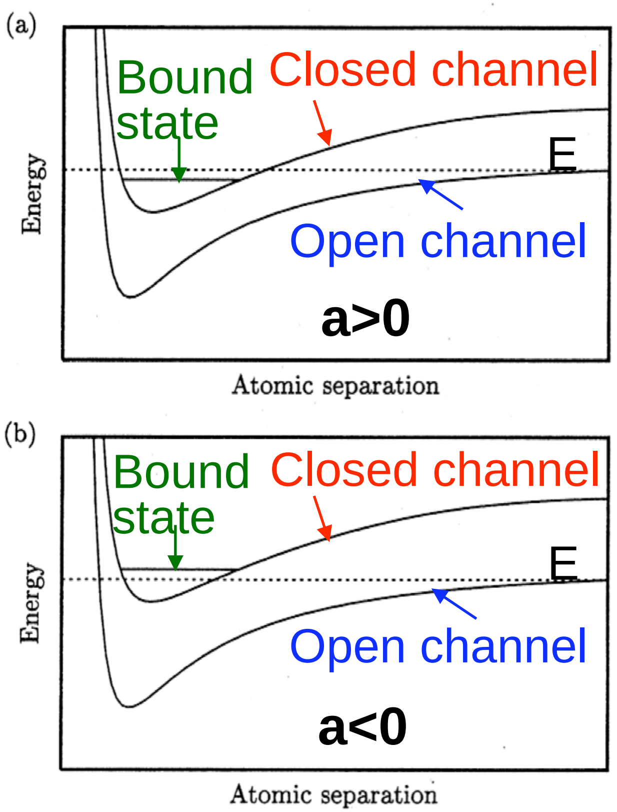
I. Bloch group in Munich Nature, 415, 39 (2002)

Appearance of correlations in the Mott insulator phase requiring a beyond mean-field description

Extension to fermionic gases

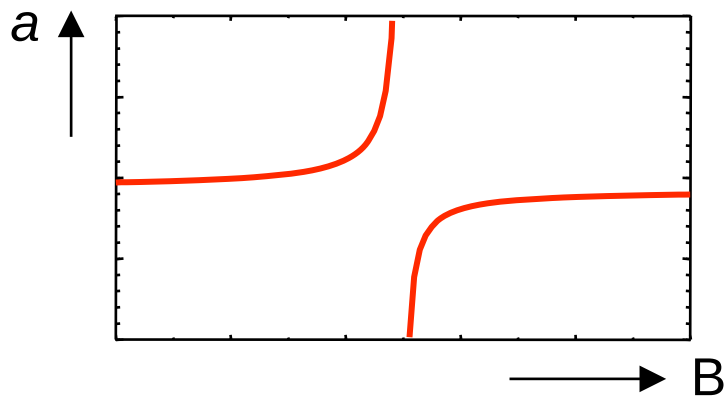
Fano - Feshbach Resonance

Resonance between a free colliding state of 2 atoms in an open channel and a bound state in another closed channel



The 2 channels correspond to 2 different relative orientations of the spins of the 2 atoms

Their energy difference can be varied by sweeping a magnetic field B, leading to resonant variations of the scattering length *a* which characterizes collisions at very low T

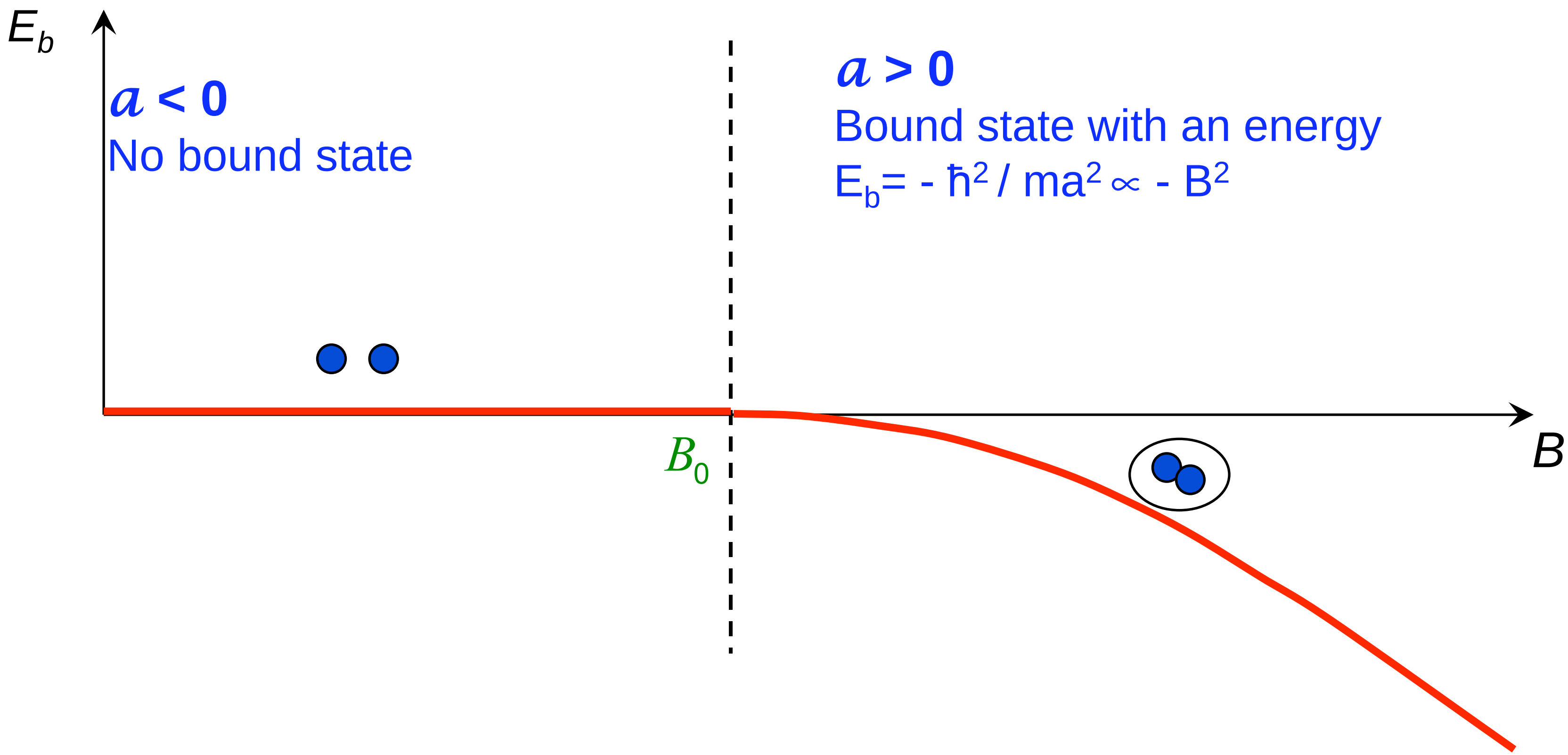


In the region of B where the scattering length a is positive and large, the 2 atoms can form a bound state with a weak binding energy.

In the region where a is negative, there is a long range attractive force

In the region a = ∞, strongly interacting system

Formation of a Feshbach molecule



If B_0 is swept through the Feshbach resonance from the region a < 0 to the region a > 0, a pair of colliding ultracold atoms can be transformed into a Feshbach molecule

Another interesting system: Efimov trimmers in the region a>0 (R. Grimm, M. Inguscio)

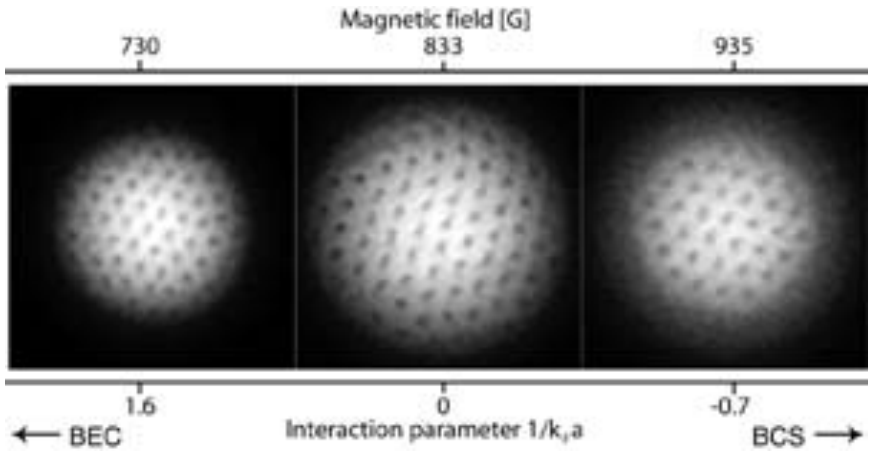
From 2-body to many body : BEC-BCS crossover

By varying the magnetic field around a Feshbach resonance, one can explore 3 regions for 2-component Fermi gases

- **Region a>0. There is a true bound state in the interaction potential where 2 fermions with different spin states can form molecules which can condense in a molecular BEC**
- **Region a<0. No molecular state, but long range attractive interactions giving rise to weakly bound Cooper pairs which can condense in a BCS superfluid phase (many body effect)**
- **Region a = ∞ (Very strong interactions) Strongly correlated system with universal properties.**

- **Observation at MIT of quantized vortices in the 3 zones demonstrating the superfluidity of the 3 phases**
  Science, 435, 1047 (2005)

- **Imbalanced mixtures of the 2 spin states**



a>0 a=∞ a<0

Low dimensional systems

Berezinskii-Kosterlitz-Thouless transition

Demonstration of the fact that this 2D transition is due to the unbinding of vortex-antivortex pairs. Direct detection of the appearance of free vortices when the transition occurs

(see for example J.Dalibard group)

Tonks-Girardeau gas

A 1D gas of interacting bosonic atoms exhibits certain features which make them similar to fermions

(see for example I.Bloch group)

Quantum gases as quantum simulators

A recent example

Experimental determination of the equation of state of a uniform Fermi gas

C.Salomon group, *Nature* 463, 1057 *Science* 328, 729 (2010)

In the limit of short-range interactions, the scattering length is sufficient for characterizing the interactions, and the equation of state should apply to all fermionic systems sharing the same property. Expressed in terms of dimensionless parameters, this equation is universal.

For example, when $a = \infty$, $\mu = (1+\beta)\, E_F$, with $\beta = -\,0.58$

The experimental equation of state is therefore useful

- not only for testing theoretical models
- but also for describing the properties of other systems with completely different orders of magnitude, like the outer crust of neutron stars

Conclusion
Current Trends in Atomic Physics

A more and more perfect control of atomic systems

- Control of internal degrees of freedom (spin polarization, internal energy)
  Optical pumping, Light-shifts

- Control of external degrees of freedom (velocity, position)
  Laser cooling and trapping
  Optical lattices

- Control of atom-atom interactions
  Feshbach resonances

Towards higher frequency and time resolutions

- High resolution laser spectroscopy

  Ultra-stable lasers Frequency combs

  Atomic clocks

  New tests of fundamental physics can be performed

  General relativity Quantum mechanics

  QED (example of the radius of the proton)

  Parity violation in atoms

  Compared to high energy experiments, the weakness of the energies involved in atomic physics is compensated by the high precision of the measurements

- Ultra-short laser pulses

  Femtosecond and attosecond pulses

  The dynamics of nuclei in a molecule and of electrons in an atom can now be investigated

Exploration of new states of matter

- The very large de Broglie wavelength λ_{dB} of ultracold atoms can be larger than the mean distance between atoms in a gas

  Achievement of gaseous Bose-Einstein condensates

- Better understanding of the quantum macroscopic properties of these systems

  Coherence Superfluidity

- Possibility with optical lattices and Feshbach resonances to achieve strongly correlated gaseous systems which can no longer be described by mean field approaches

  Superfluid- Mott insulator transition

  BEC-BCS crossover in Fermi gases

- Ultracold quantum gases can provide a better understanding of strongly correlated systems appearing in other fields

  Quantum simulators