Helium atom
From optical pumping to B.E.C.

Claude Cohen-Tannoudji

Inauguration meeting and Celebration of
Lev Pitaevskii's 70th birthday

Trento, 14/03/03

Helium atom

- A simple atom, the simplest one after Hydrogen

  High resolution sectroscopy. Tests of QED
- Two isotopes

  He_3 Fermion I = ½ He_4 Boson I = 0
- Small mass $\rightarrow$ Large de Broglie wavelength

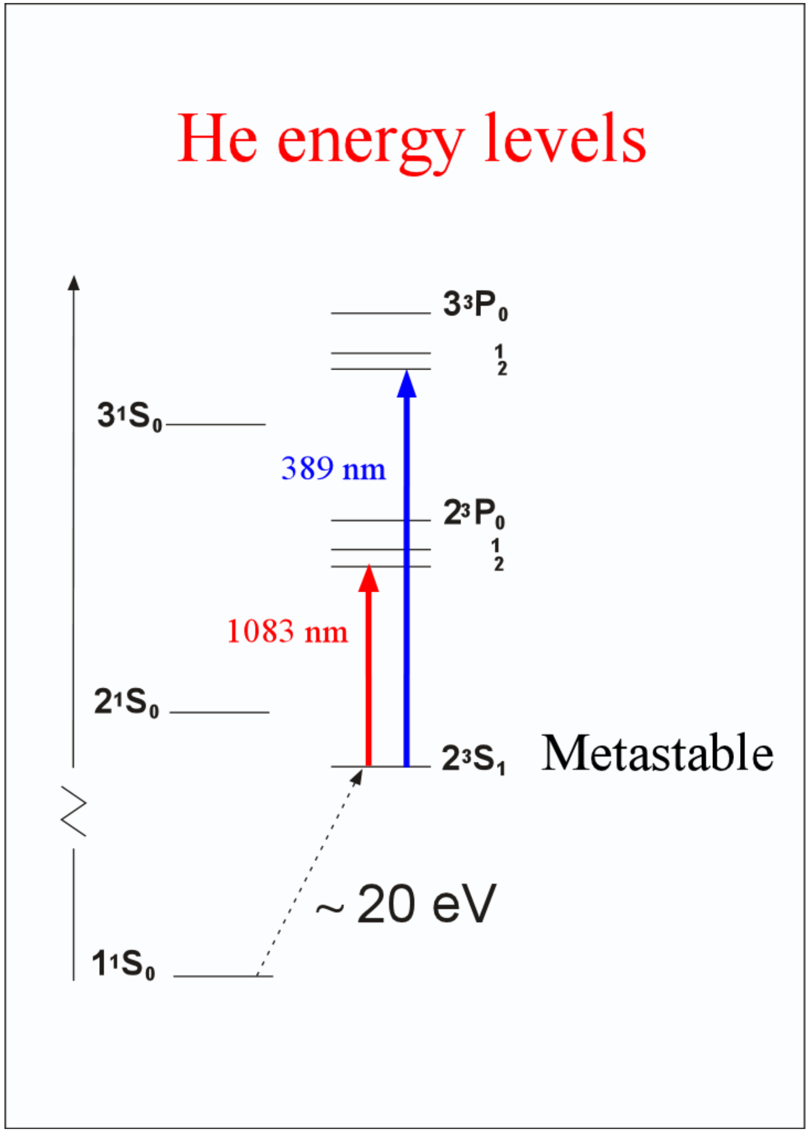
  Large zero-point energy

Purpose of this lecture

Present a brief survey of studies performed on Helium atoms, starting from optical pumping of He_3 and ending with B.E.C. of He_4 in the metastable triplet state

NUCLEAR POLARIZATION OF ^3He BY OPTICAL PUMPING

Laser manipulation of Helium



Not easy because the first excited state is the metastable state 2 $^3S_1$ lying 20 eV above the ground state 1 $^1S_0$

It is however possible to populate the long lived 2 $^3S_1$ state by a discharge and to use the 2 $^3S_1 \rightarrow 2\ ^3P_{0,1,2}$ transition at 1083 nm for manipulating both isotopes of Helium

Polarizing the nuclear spins of He_3 by optical pumping

Possibility to optically pump the long lived 2 $^3S_1$ state by using the 2 $^3S_1 \rightarrow$ 2 $^3P_{0,1,2}$ transitions at 1080 nm

In this state, the nuclei become polarized by interacting with the polarized electrons (through hyperfine coupling)

In a collision between two Helium atoms, one in 2 $^3S_1$, one in 1 $^1S_0$, the metastability can be transferred from the first atom to the second one

The collision time is so short that the nuclear magnetic moment does not evolve during the collision and remains polarized while the electronic cloud jumps from 2 $^3S_1$ to 1 $^1S_0$ (F. Colegrove, L. Shearer, K. Walters 1963)

A. Kastler was considering this method as an « Extension of Franck-Condon principle to nuclear spins »

High degrees of nuclear polarization (up to 85%)

Nuclear relaxation times

Nuclear magnetic moments are small

$\rightarrow$ Weak magnetic couplings

The He_3 nucleus has a spin ½

$\rightarrow$ No quadrupole moment

$\rightarrow$ No electric coupling with the electric field gradients

As a consequence, nuclear relaxation times are very long

The T_1 relaxation time can reach 5 days

in a glass cell with a Cesium coating!

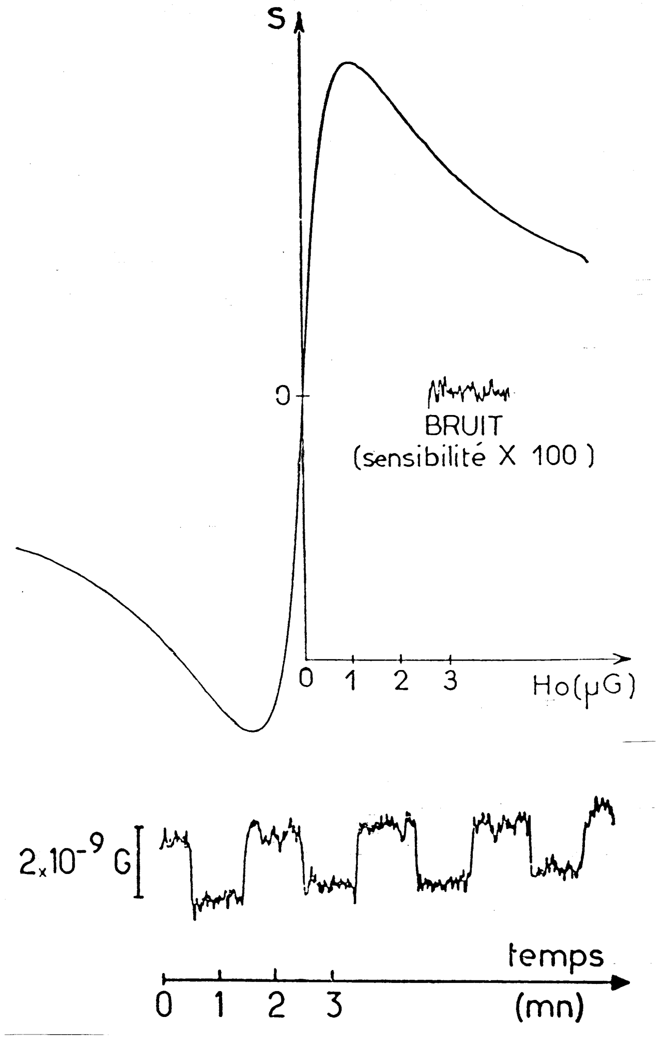
Example of earlier studies

Detection of the static magnetic field produced at a macroscopic distance by polarized He_3 nuclei using the « Hanle effect » in the ground state of Rb_{87}

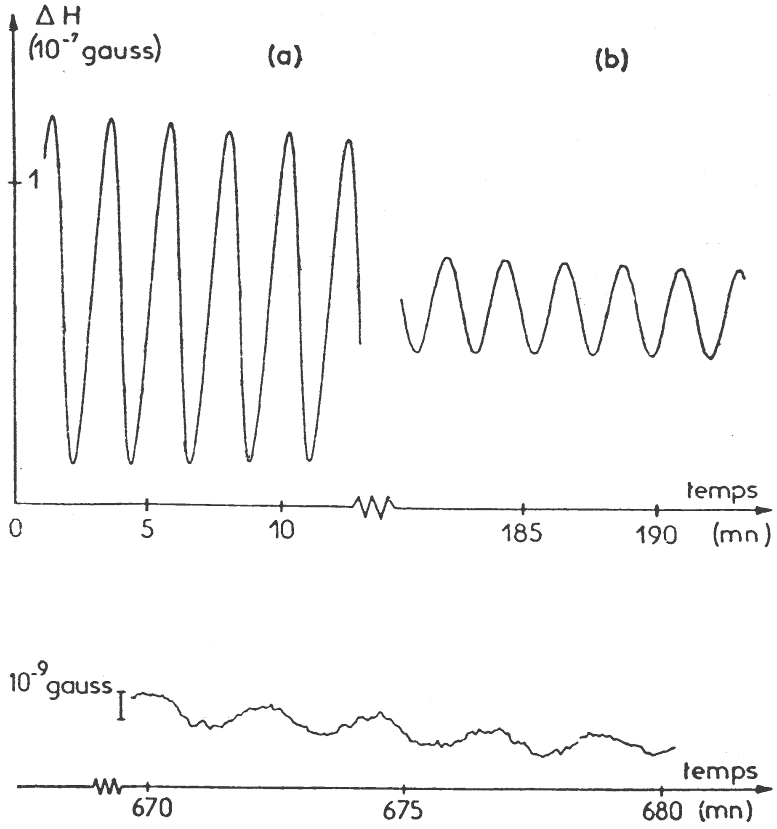
Hanle zero-field level crossing resonance in the ground state of Rb_{87}

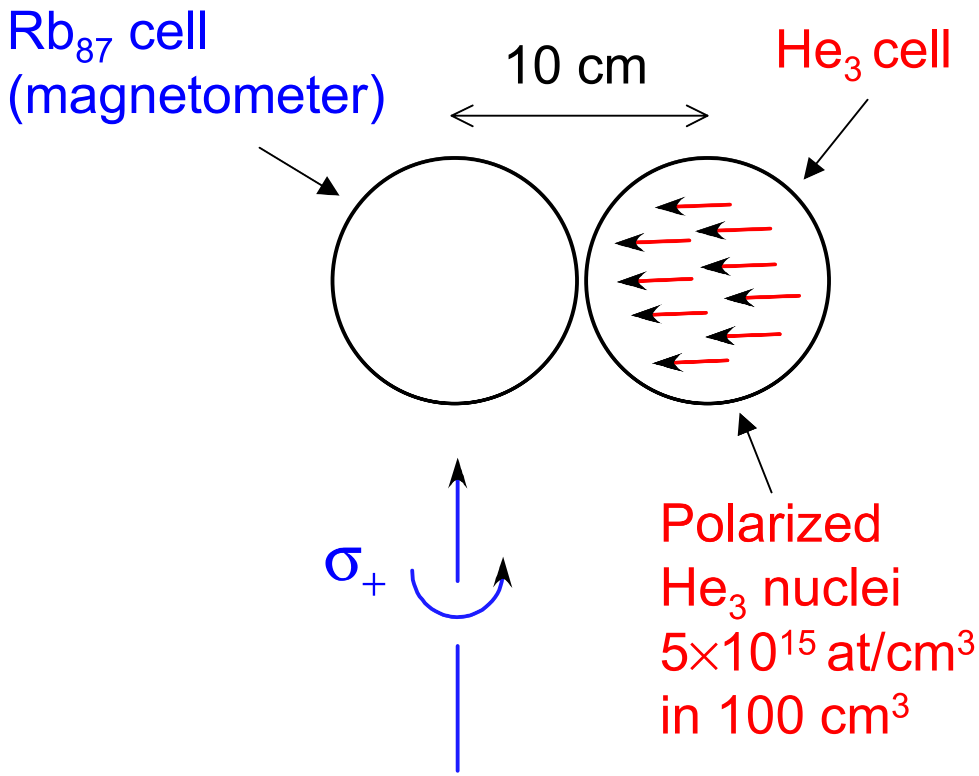
Magnetometer
with a sensitivity
of 5×10^{-10} Gauss

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



Magnetostatic detection of the static magnetic field produced by polarized He_3 nuclei

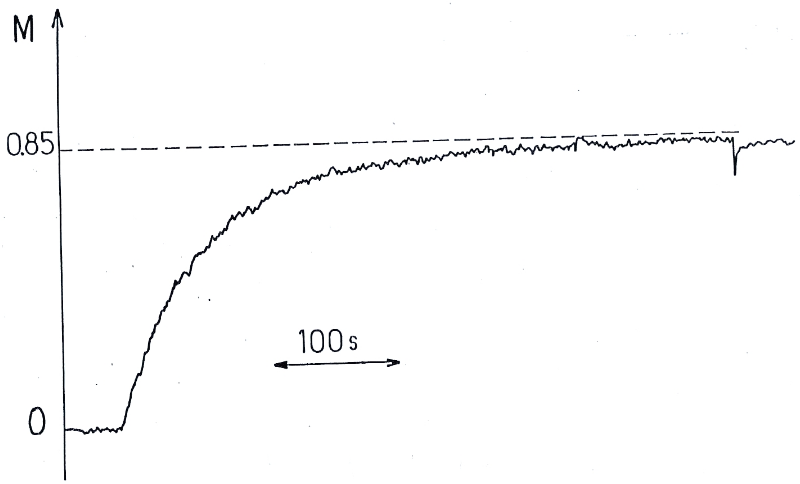




C. Cohen-Tannoudji, J. Dupont-Roc, S. Haroche, F. Laloë
Phys. Rev. Lett. 22, 758 (1971)

Present state of the art

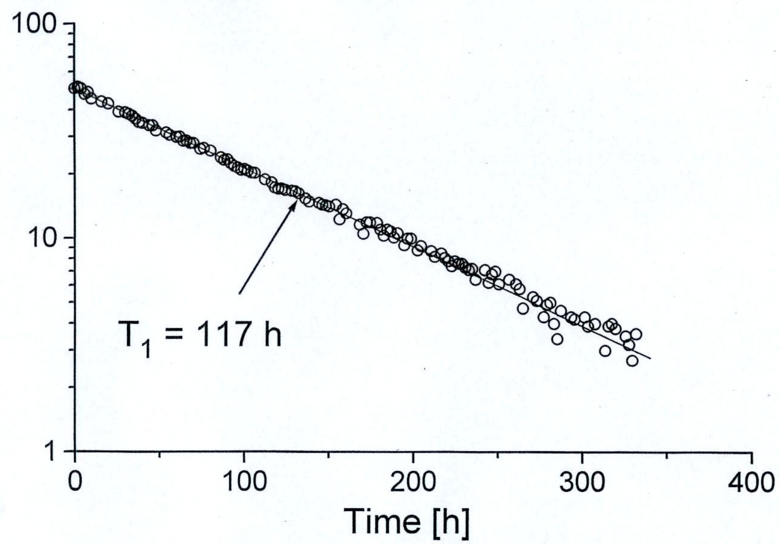
Nuclear polarization



N. Bigelow, P- J. Nacher, M. Leduc
J. de Physique,II 2, 2159 (1992)

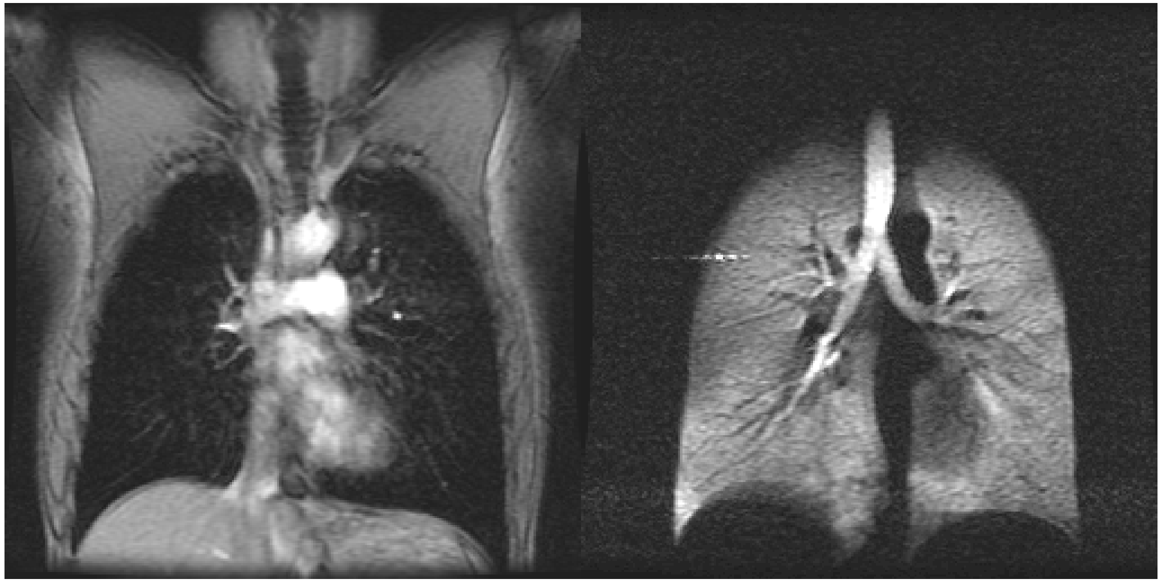
Relaxation time

(Cs coated glass cell)



W. Heil, H. Humblot, E. Otten,
M. Schafer, R. Surkau, M. Leduc
Phys. Lett. A201, 337 (1995)

MRI Images of the Human Chest



Proton-MRI ^{3}He-MRI

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

Human lung MRI centres :

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

About 10 more centres getting started

SPIN POLARIZED ^3He
A DILUTE QUANTUM FLUID

Spin-polarized He_3
A dilute quantum gas

Two spin-polarized He_3 atoms in the ground state cannot collide in a s-wave

Their minimum distance of approach is given by the de Broglie wavelength $\lambda_{dB} = h / mv$

This is not due to spin-spin interactions (which are extremely small), but this is a consequence of Fermi statistics

At low enough temperatures, λ_{dB} becomes larger than the range of the atom-atom interaction potential, and the polarized gas behaves as a perfect gas

Theoretical investigation of these effects

C. Lhuillier, F. Laloë

J. de Physique, 40, 239 (1979)

J. de Physique, 43, 127 and 225 (1982)

SPOQS meetings

Prediction of a modification of the transport properties of the polarized gas (thermal conductivity, viscosity)

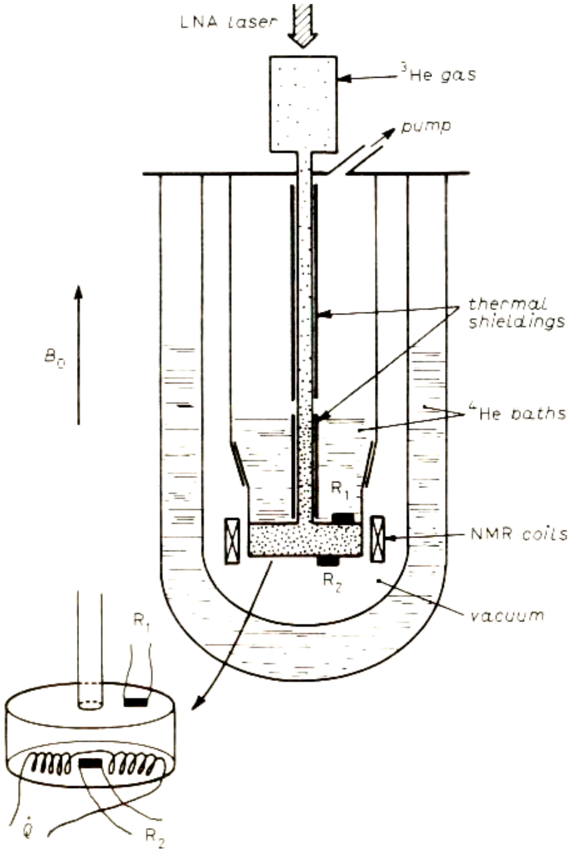
Collective oscillatory modes for the spin degrees of freedom (spin waves)

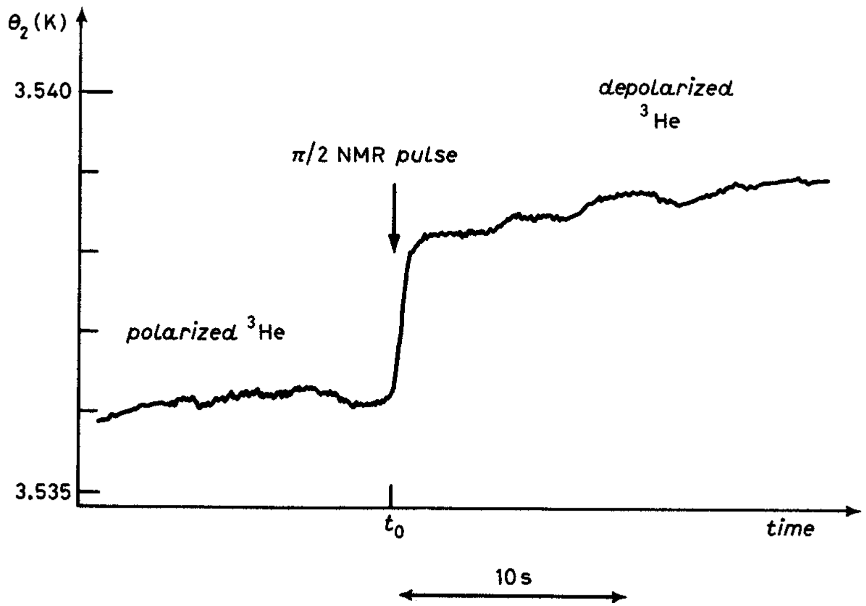
More recent development

Inefficiency of evaporative cooling for laser cooled, magnetically trapped Fermionic gases

Example of experimental investigation

Modification of the thermal conductivity of a spin-polarized He_3 gas

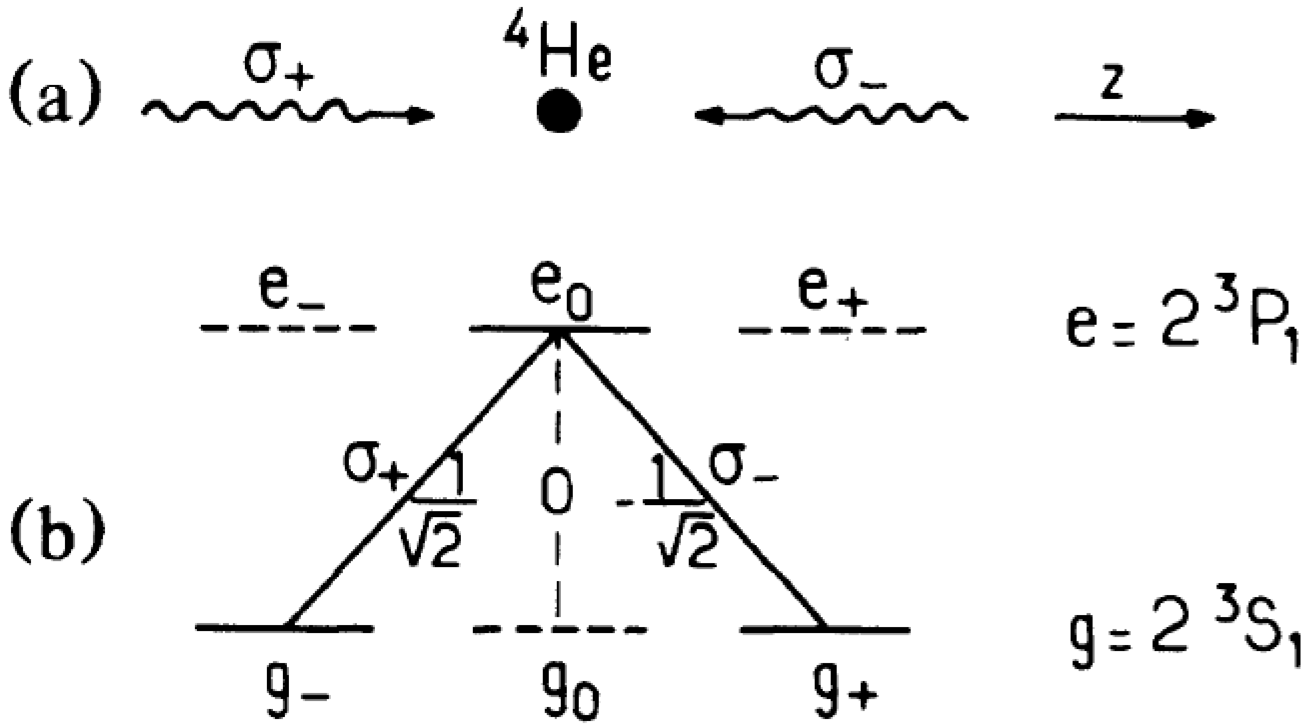




M. Leduc, P-J. Nacher, D. Betts, J. Daniels, G. Tastevin, F. Laloë
Europhys. Lett. 4, 59 (1987)

SUBRECOIL LASER COOLING OF ^4He

Laser cooling of He_4



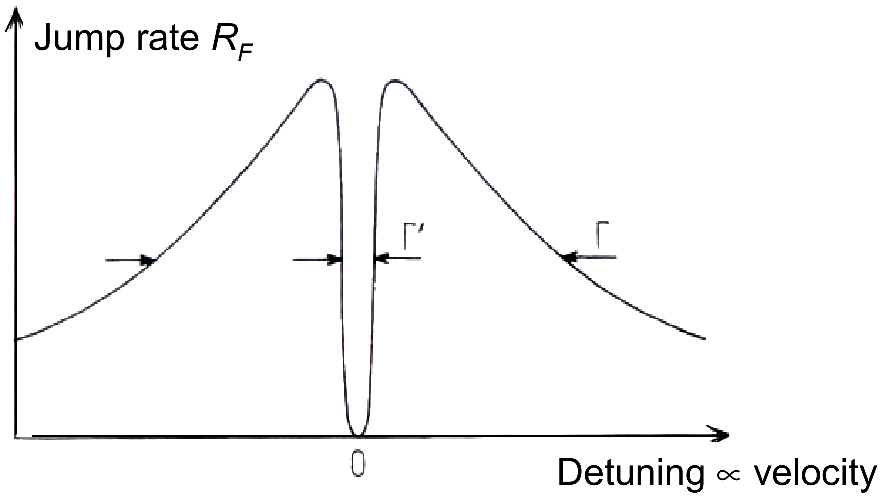
Pure 3-level Λ-system leading to coherent population trapping

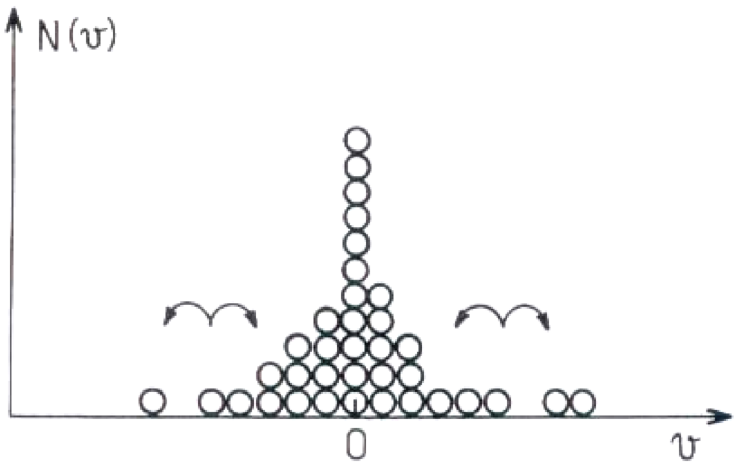
The detuning from Raman resonance is provided by the Doppler effect which is opposite for the 2 counterpropagating waves « Velocity Selective Coherent Population Trapping » (VSCPT)

Subrecoil laser cooling by VSCPT

Inhomogeneous random walk in velocity space with a jump rate R_F vanishing at zero velocity where atoms pile up

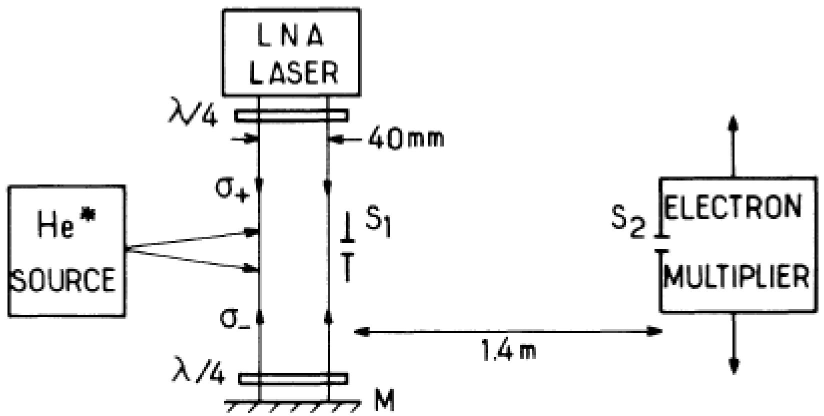
No lower limit to the velocity spread which can be achieved

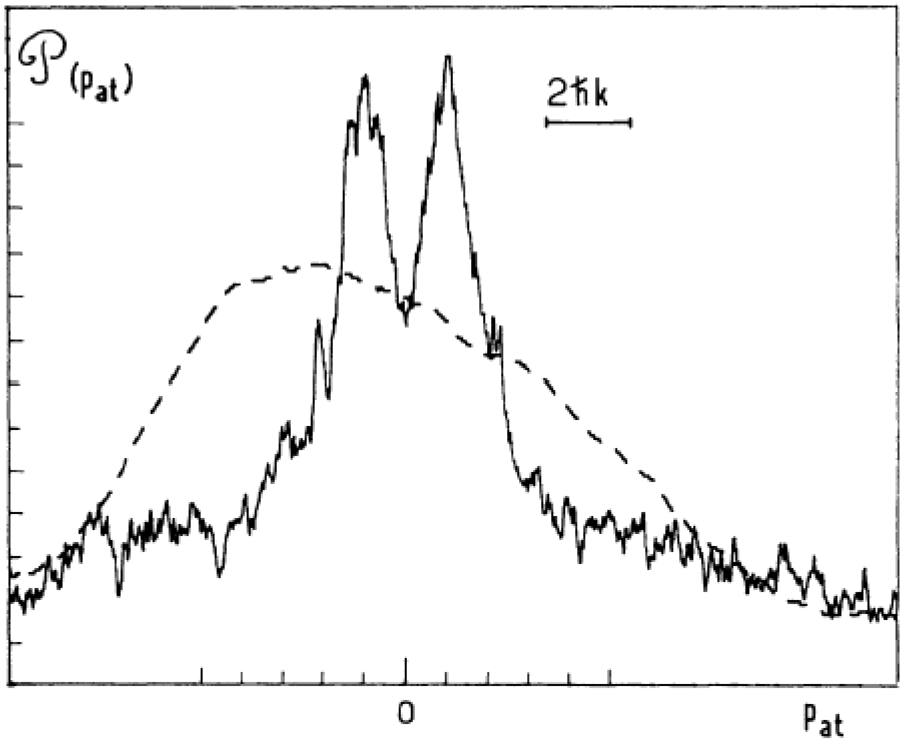




A.Aspect, E.Arimondo, R.Kaiser, N.Vansteenkiste, C.Cohen-Tannoudji, Phys.Rev.Lett. 61, 826 (1988)

First experimental observation of subrecoil cooling

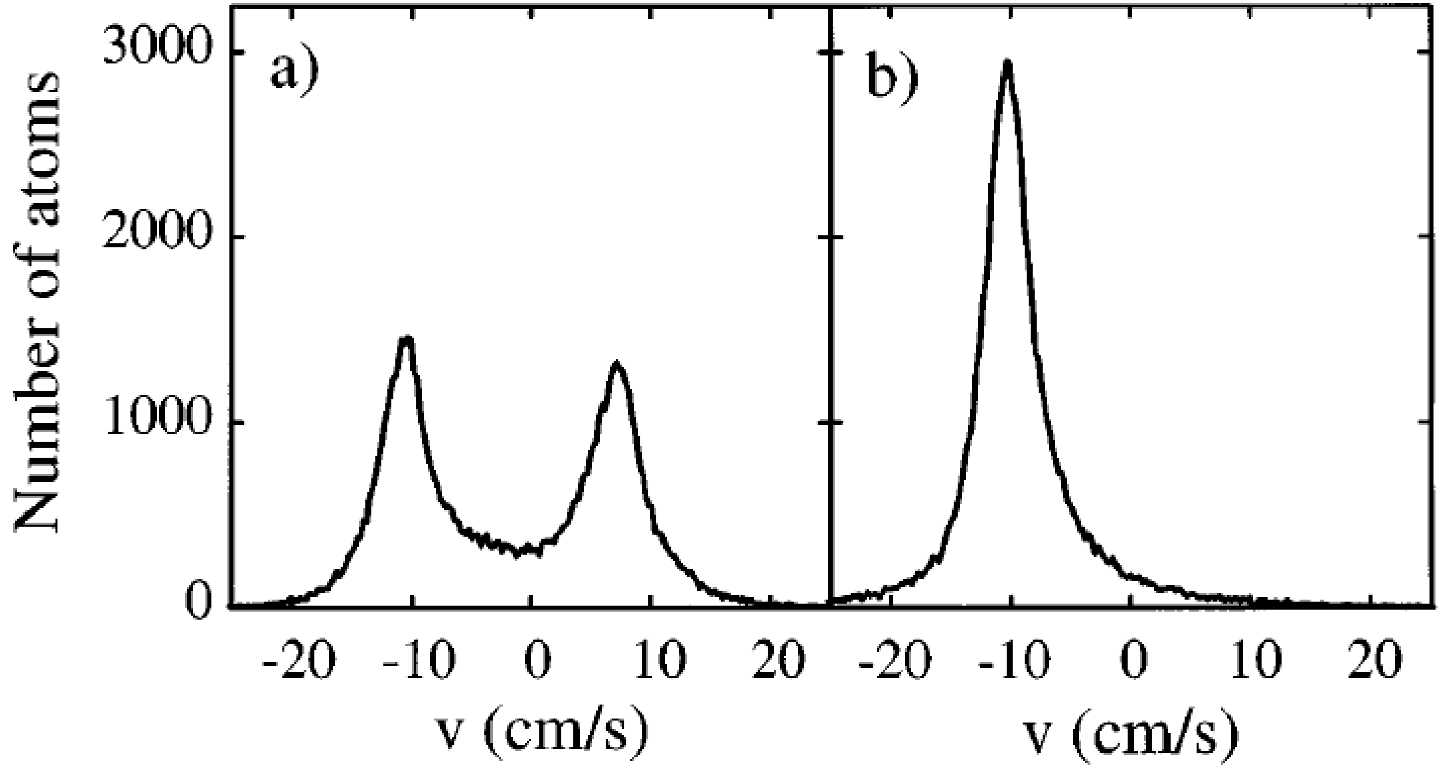




A.Aspect, E.Arimondo, R.Kaiser, N.Vansteenkiste, C.Cohen-Tannoudji, Phys.Rev.Lett. 61, 826 (1988)

Adiabatic transfer of atoms into a single peak

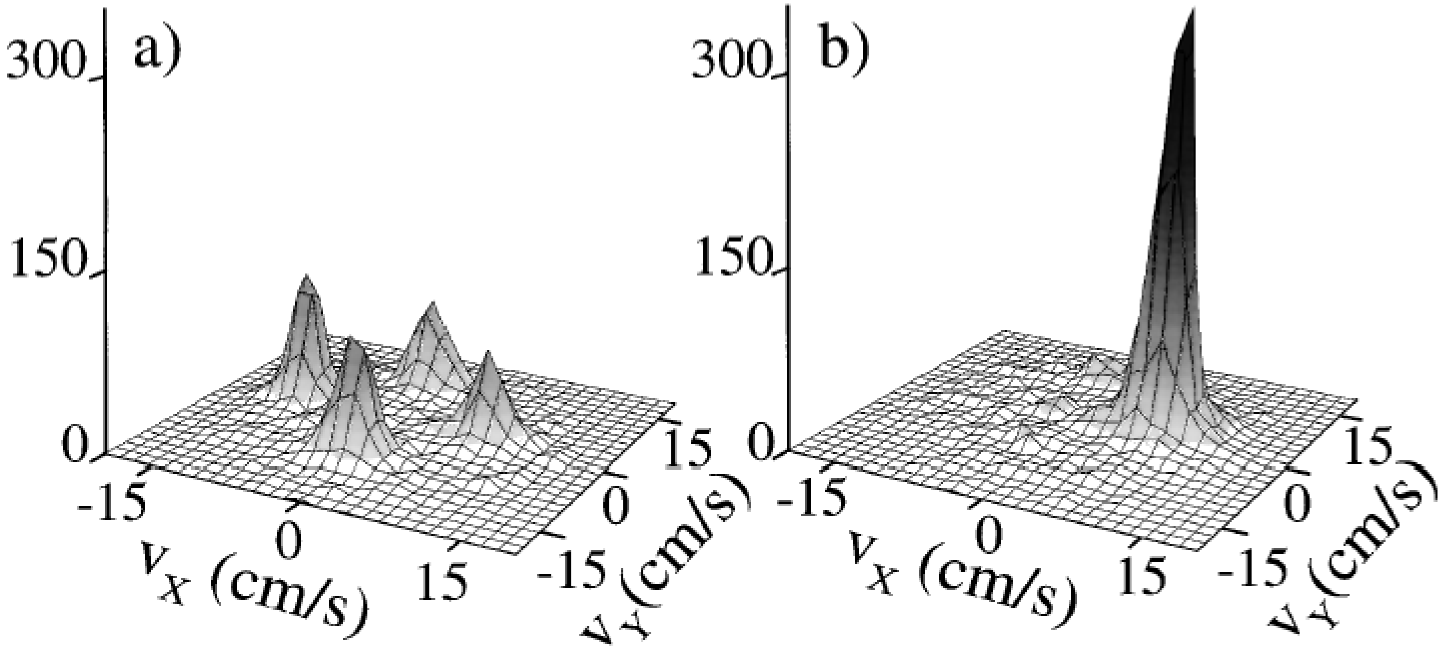
Switching off adiabatically one of the laser beams



Analogy with STIRAP

Extension to 2 dimensions

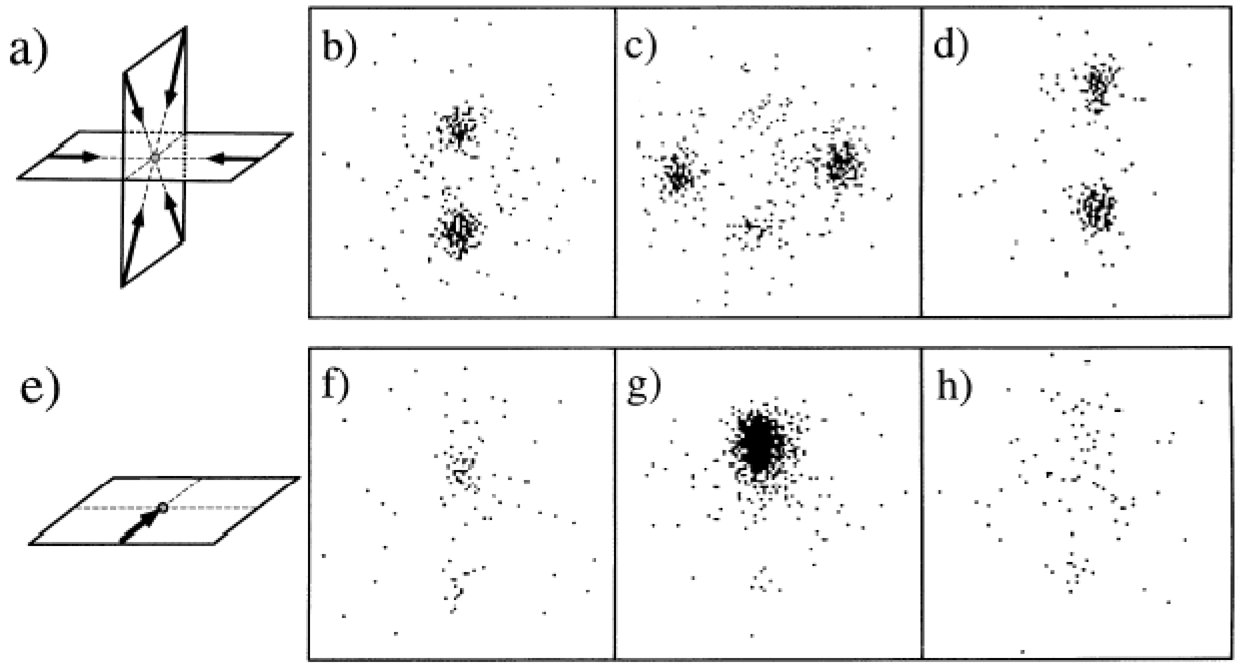
Theory : M. Olshanii



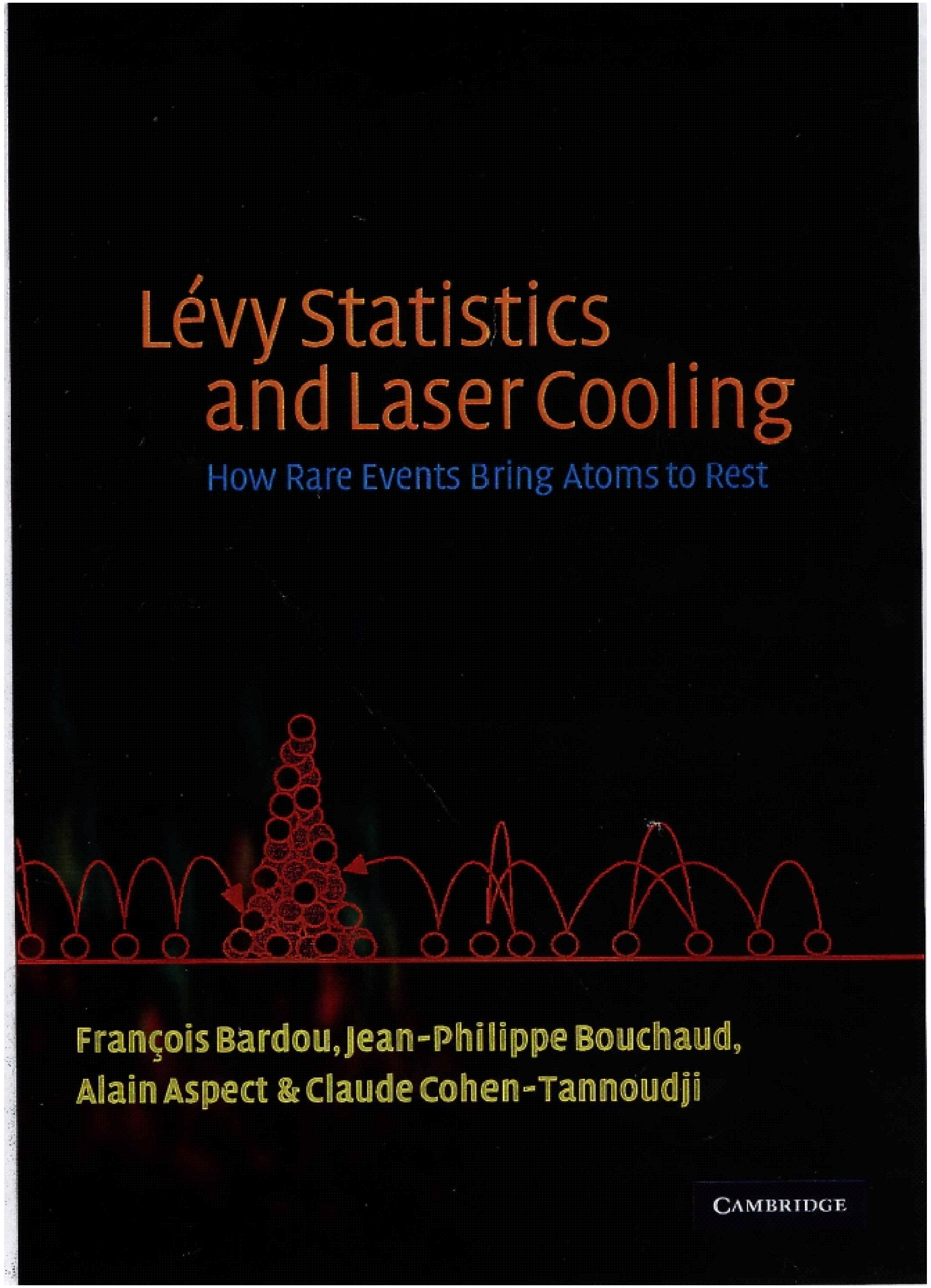
S.Kulin, B.Saubamea, E.Peik, J.Lawall, T.Hijmans, M.Leduc, C.Cohen-Tannoudji, Phys.Rev.Lett. 78, 4185 (1997)

Extension to 3 dimensions

Coherent manipulation of atomic wave packets
in the nK range

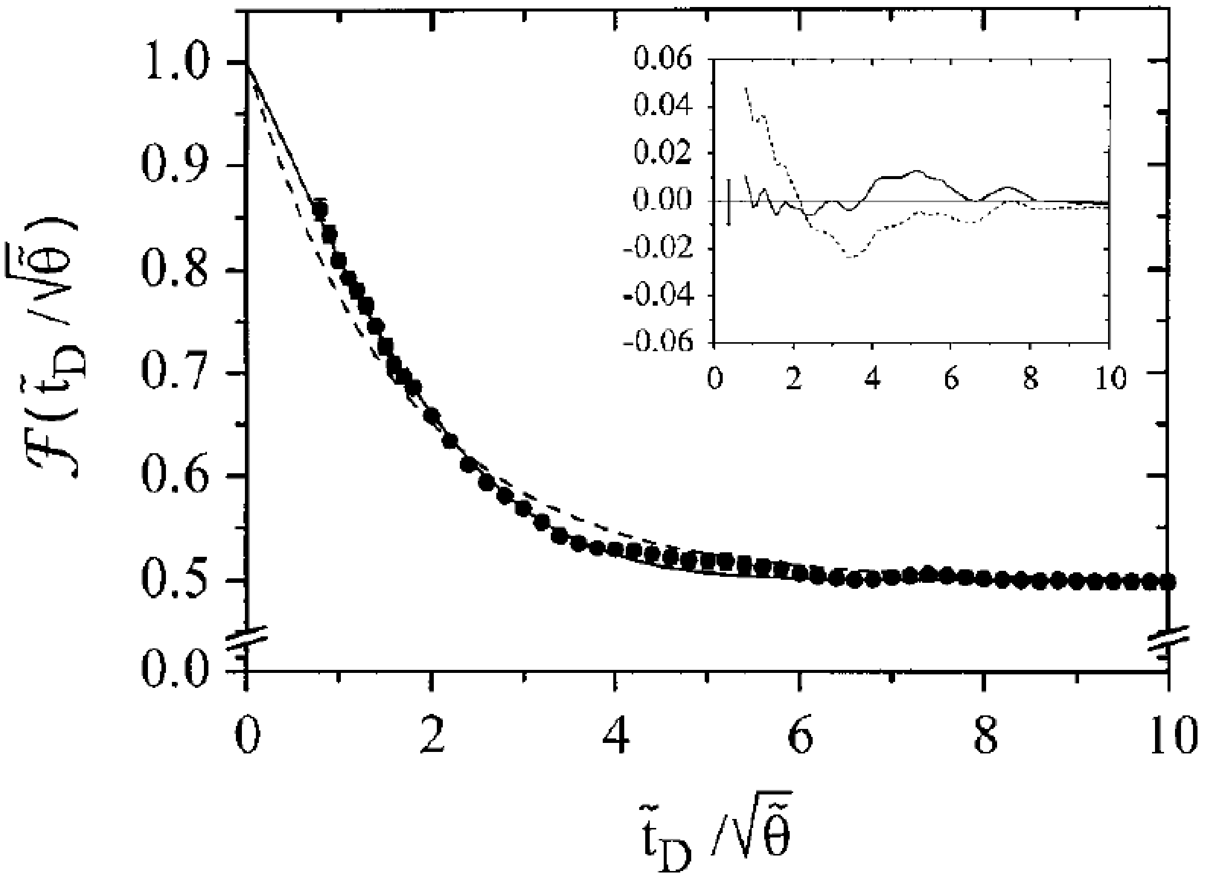


S.Kulin, B.Saubamea, E.Peik, J.Lawall, T.Hijmans, M.Leduc, C.Cohen-Tannoudji, Phys.Rev.Lett. 78, 4185 (1997)


Lévy Statistics
and Laser Cooling
How Rare Events Bring Atoms to Rest
François Bardou, Jean-Philippe Bouchaud,
Alain Aspect & Claude Cohen-Tannoudji
CAMBRIDGE

Momentum distribution of He_4 atoms cooled in the nK range

Comparison with theoretical calculations based on Lévy statistics and predicting non ergodic effects



B.Saubamea, M.Leduc, C.Cohen-Tannoudji
Phys.Rev.Lett. 83, 3796 (1999)

BOSE-EINSTEIN CONDENSATION OF METASTABLE ^4He

Penning collisions for He*

$$He^*(2\ ^3S_1) + He^*(2\ ^3S_1) \rightarrow He\ (1\ ^1S_O) + He^+ + e^-$$

$$\rightarrow (He_2)^+ + e^-$$

The energy of the 2 $^3S_1$ state is about 20 eV above the ground state

Penning cross-sections have huge cross-sections which, at first sight, should prevent any Bose-Einstein condensation in this state

But, He* atoms are spin-polarized in a magnetic trap, and the conservation of the total spin is expected to dramatically reduce the Penning cross-section

Quenching of Penning collisions in a spin-polarized sample

$He^*(2\,^3S_1) + He^*(2\,^3S_1) \rightarrow He\,(1\,^1S_O) + He^+ + e^-$

S=1, M=1 S=1, M=1 S=0 S=1/2 S=1/2

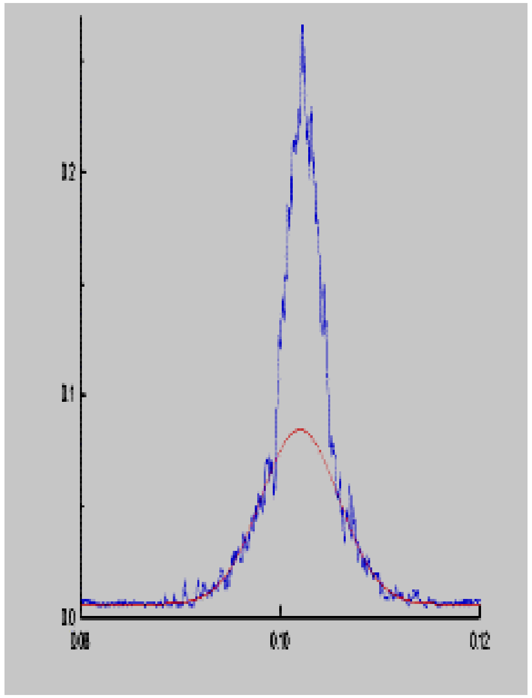
The total spin is equal to 2 before the collision and to 1 or 0 after the collision. It cannot be conserved.

But this conservation law is not strict. Spin-spin dipole couplings during the collision can slightly mix states with different values of the total spin

The net effect is that Penning collisions are expected to be reduced by 5 orders of magnitude when the sample is spin-polarized

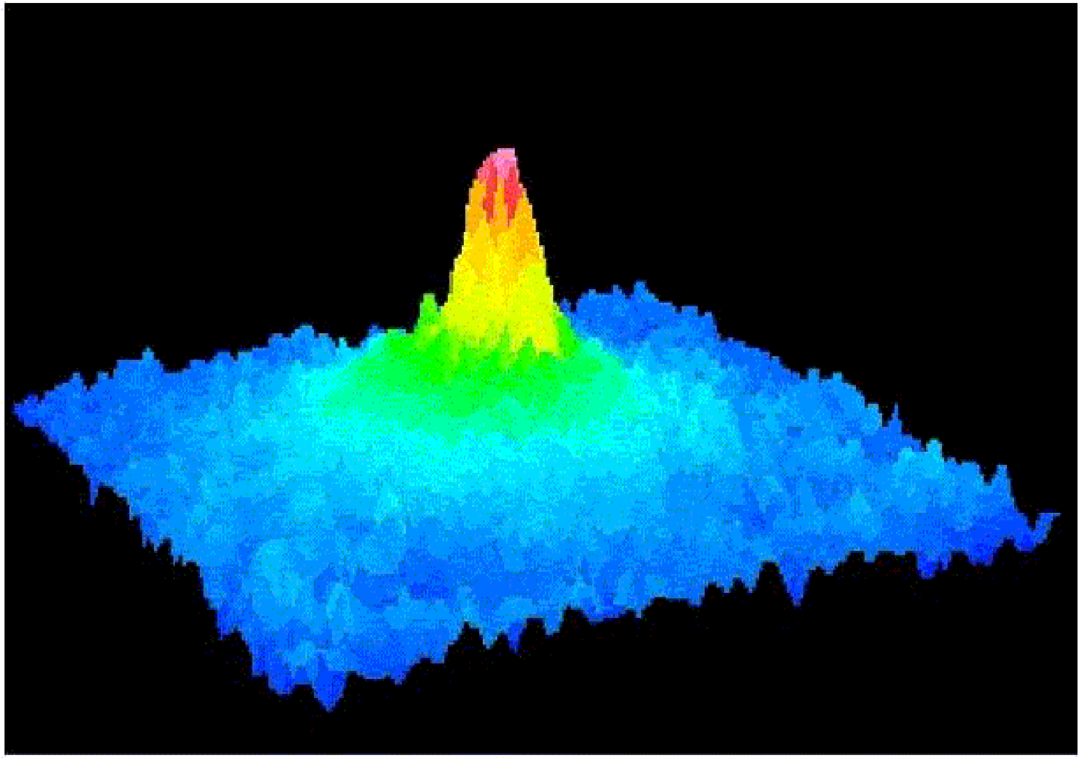
G. Shlyapnikov, J. Walraven, U. Rahmanov, W. Reynolds, Phys. Rev. Lett. 73, 3247 (1994)

Bose-Einstein condensation of metastable helium
IOTA - Orsay



A. Robert, O. Sirjean, A. Browaeys, J. Poupard,
S. Nowak, D. Boiron, C. Westbrook, A. Aspect,
Science, 292, 461 (2001)

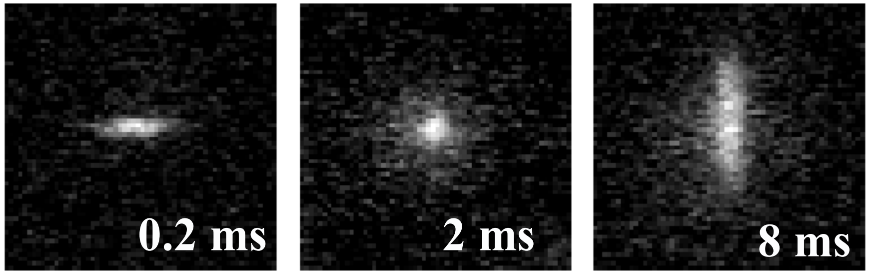
Bose-Einstein condensation of metastable helium
ENS -Paris

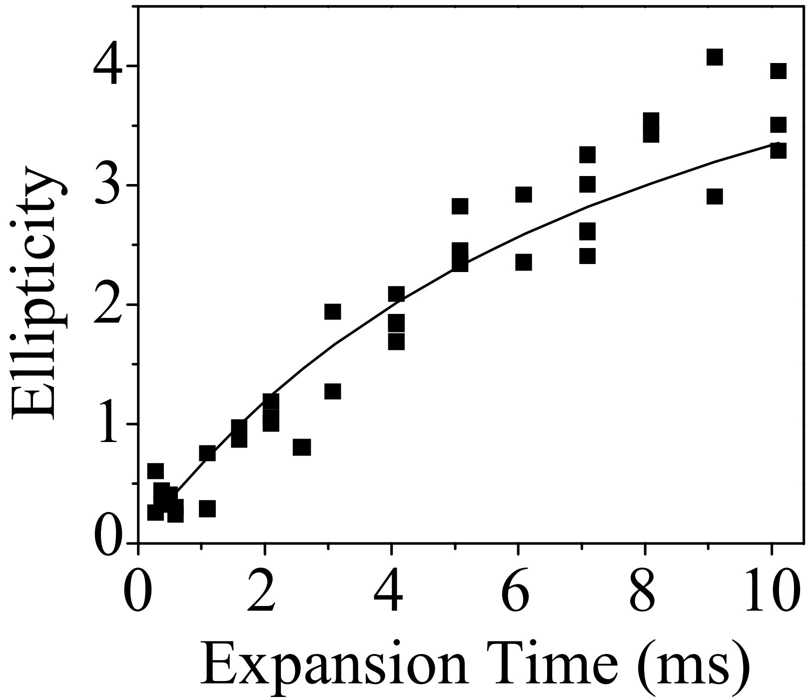


F. Pereira Dos Santos, J. Léonard, J. Wang, C. Barrelet,
F. Perales, E. Rasel, C. Unnikrishnan, M. Leduc,
C. Cohen-Tannoudji, Phys. Rev. Lett. 86, 3459 (2001)

Ballistic expansion of the condensate

Inversion of the ellipticity
Clear signature of the condensation





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F. Perales, E. Rasel, C. Unnikrishnan, M. Leduc,
C. Cohen-Tannoudji, Phys. Rev. Lett. 86, 3459 (2001)

A few perspectives

-Condensate of atoms having a high internal energy

Atom lasers

Atom lithography

- Possibility to detect the atoms one by one

Atom statistics

Higher order correlation functions

- Large collision cross-sections

Investigation of collisional processes (2-body, 3-body)

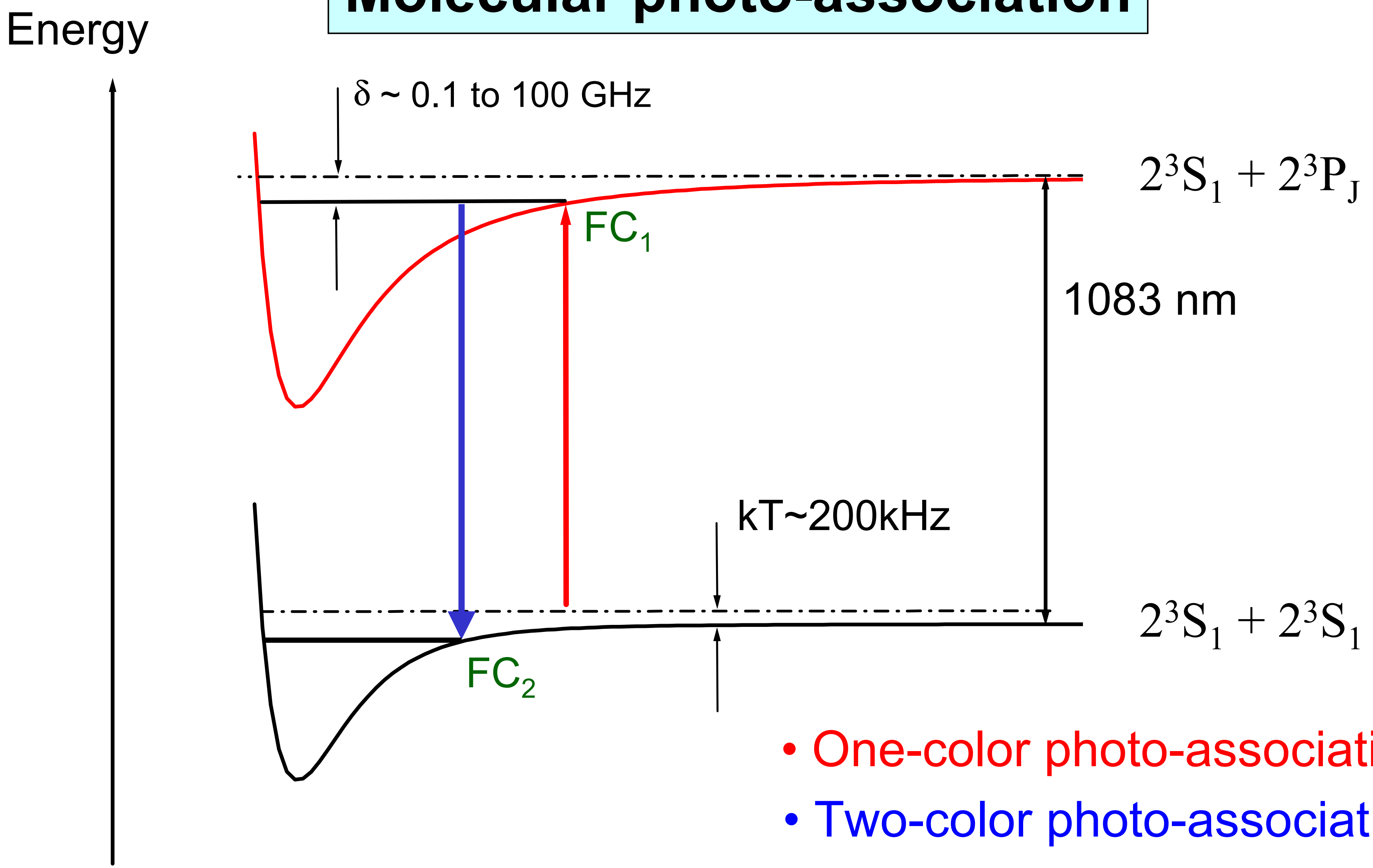
Hydrodynamic regime

- Photo-association

Molecules with 2 metastable atoms?

- ^{4}He – ^{3}He mixtures

Molecular photo-association



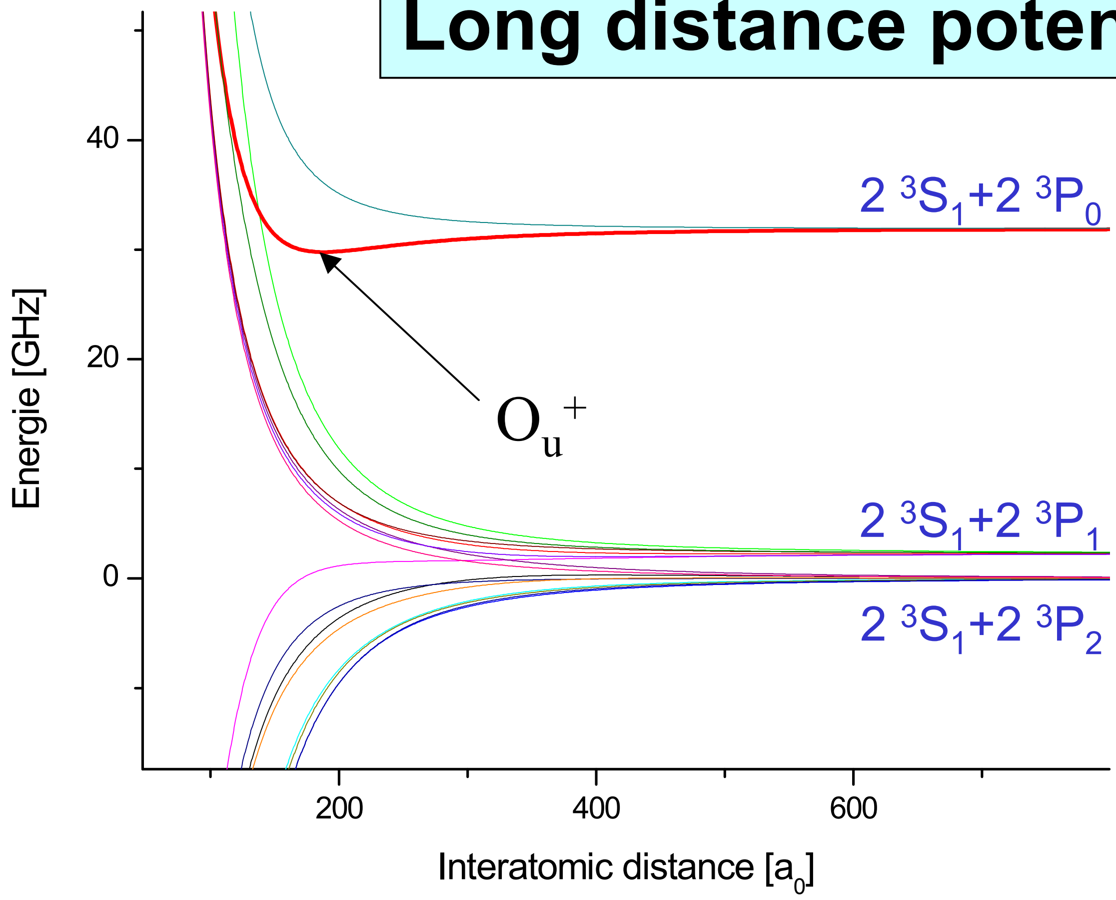
- One-color photo-association
- Two-color photo-association

FC_1 , FC_2 : Franck-Condon turning points

Extension to metastable Helium of experiments previously performed on ultracold alkali atoms

Long distance potential curves

A. Mosk



Investigation by the Amsterdam-Utrecht groups of a few molecular states formed by one-color photo-association below the frequency of the $2\ ^3S_1 \rightarrow 2\ ^3P_2$ transition
Ion detection
PRL 84 , 1874 (2000)

In Paris, we study the molecular states in the potential O_u^+ which depends only on long distance interactions

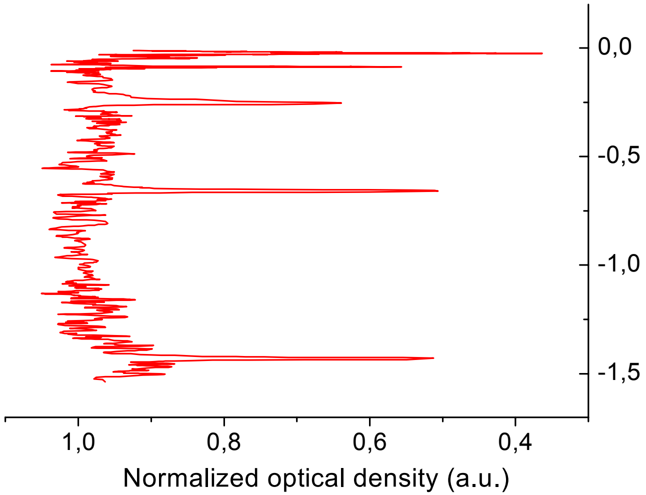
- Pure long range molecular potential
- Detection by the losses of the atomic cloud

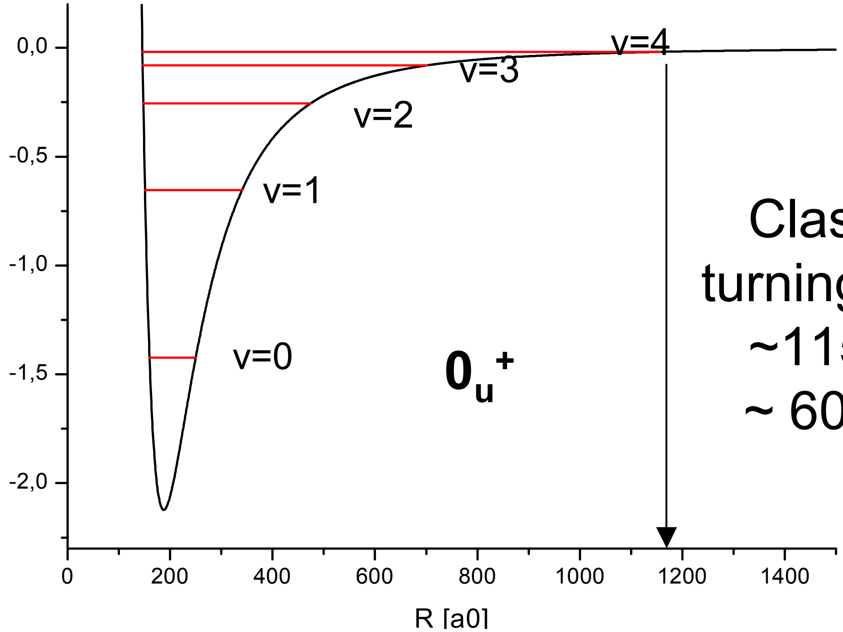
J. Leonard
A. Mosk
M. Walhout
T. Müller
M. Leduc
C. C-T

Pure long range molecules in the well O_u^+

Laser diode continuouly tuned over 3 nm with temperature

Experiment : **Detunings [GHz]** **(0 ⇔ $2^3S_1 - 2^3P_0$ line)** **Calculations :**





Classical turning point ~1150 a_0 ~ 60 nm !

	Born-Oppenheimer (MHz)	B.O. + Rotation	B.O. + Rot + Retardation	Experiment (±10 MHz)
v=4, J=1	21	16.8	18.4	25
v=3, J=1	88	77.7	80.4	85
v=2, J=1	271	254.4	255.3	255
v=1, J=1	683	648.4	653.5	655
v=0, J=1	1474	1423.6	1428.0	1430

2nd Generation of experiments
« Accurate » frequency measurement

- Instead of using a large frequency scan, we lock the PA laser on the atomic line and we detune it with AOM's
  <300 kHz absolute accuracy
- We correct for the Zeeman shift (magnetic trap) and for the temperature shift

Preliminary results

	tabulated C_3	1% change in C_3	Experiment
v=4, J=1	18.4	$\pm$ 0.5 MHz	18.4 $\pm$ 0.3
v=3, J=1	80.4	$\pm$ 1.4 MHz	80.1 $\pm$ 0.3
v=2, J=1	255.3	$\pm$ 2.5 MHz	soon
v=1, J=1	653.5	$\pm$ 3.3 MHz	soon
v=0, J=1	1428.0	$\pm$ 2.5 MHz	xxx

Hope to improve the determination of C_3