Weakly-bound molecules obtained by laser-association of cold atoms, and the analysis by the Vibrational quantum defect

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Outline

1. Brief presentation
2. Cold and ultra colds Atoms
3. Weakly bound molecules and motivations
4. Photoassociation spectroscopy
5. Atomic Clock in Tunisia! It's possible!
6. Collaboration opportunities

Presentation

- Last name: JELASSI
- Given name: Haikel
- Born June 05th 1980 in Tunis
- Position: Associate Professor Atomic physics in the National Center for Nuclear Sciences and Technologies (CNSTN), Tunisia.
- Experiment and theories of atomic and molecular physics.

- Diplomas:
  - PhD in Atomic Physics (dir. L. Pruvost), Laboratoire Aimé Cotton-CNRS- University of Paris-Sud FRANCE, Photo-associative spectroscopy of weakly bound molecules of rubidium. Lu-Fano analysis. Study of an atomic lens realization. (2007).
  - Master in Atomic and Molecular Physics and Optics ”DEA Lasers-Matière” Lieu : University of Paris-Sud FRANCE, (2003).
  - Master’s degree in Fundamental Physics (Tunis), (2002).

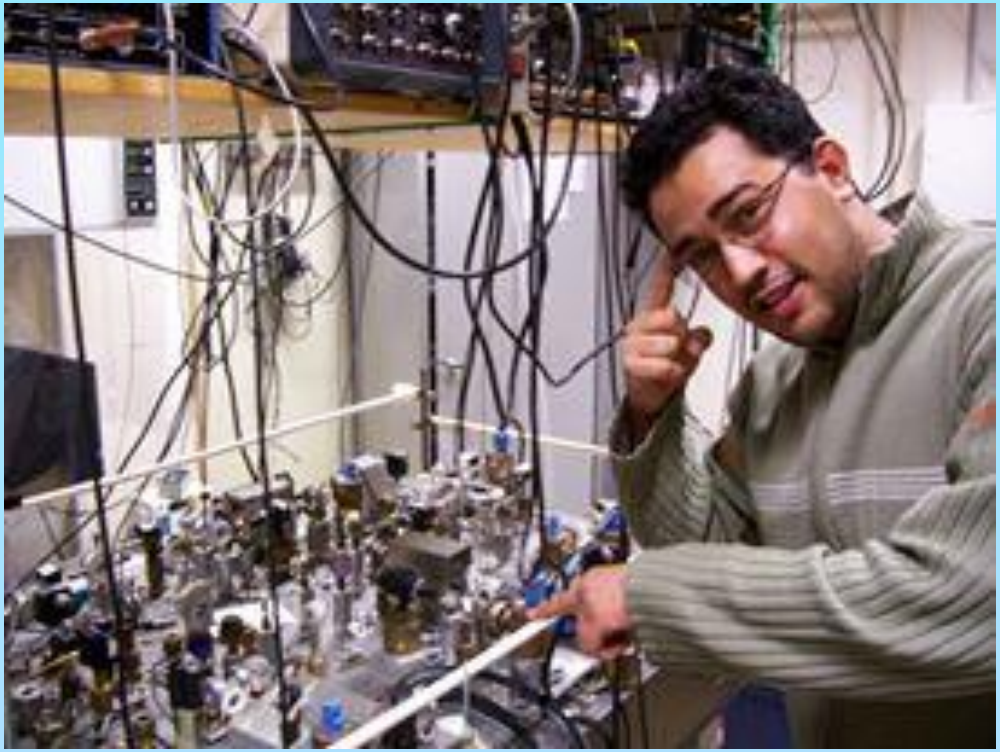
- Main research activities:
  - ✓ Cold Atoms
  - ✓ Atom optics : realization of atomic optics elements
  - ✓ Photoassociation spectroscopy
  - ✓ Caesium atomic beam and atomic clocks.
  - ✓ Atomic interferometry
  - ✓ Recently : Atomic processes in fusion plasma
  - ✓ Few work in Dosimetry
- Awards:

Tunisian physical society's prize : award to the first range student (2 times : 2001 and 2002)

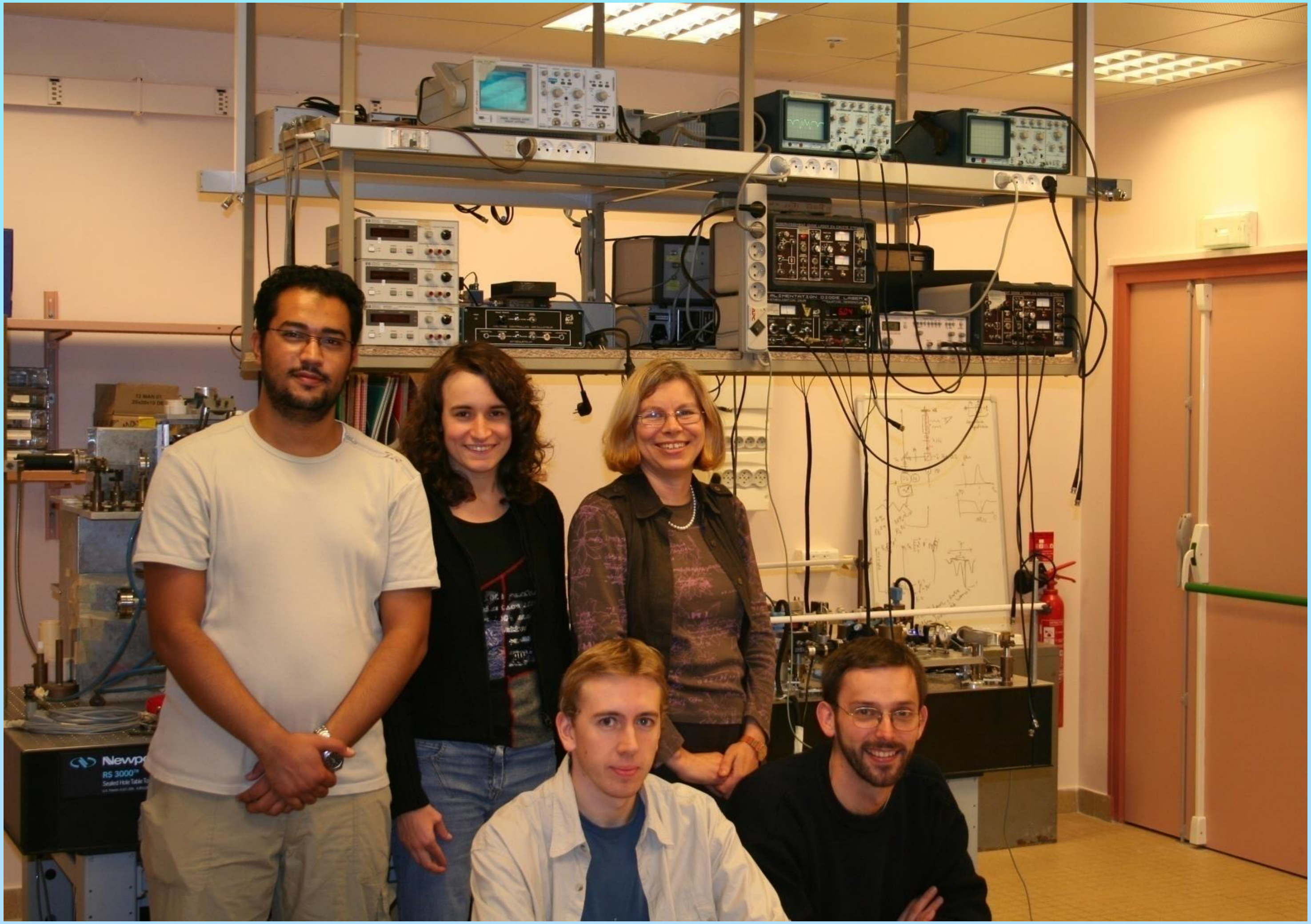
Member of the Steering Committee of the Quantum Africa conference Series

- Publications:
  - ✓ 17 papers in peer-reviewed international journals especially in APS (8 first authors)
  - ✓ 1 patent
  - ✓ H-index: 8, number of citations: more then100 (According to Web Of Science)

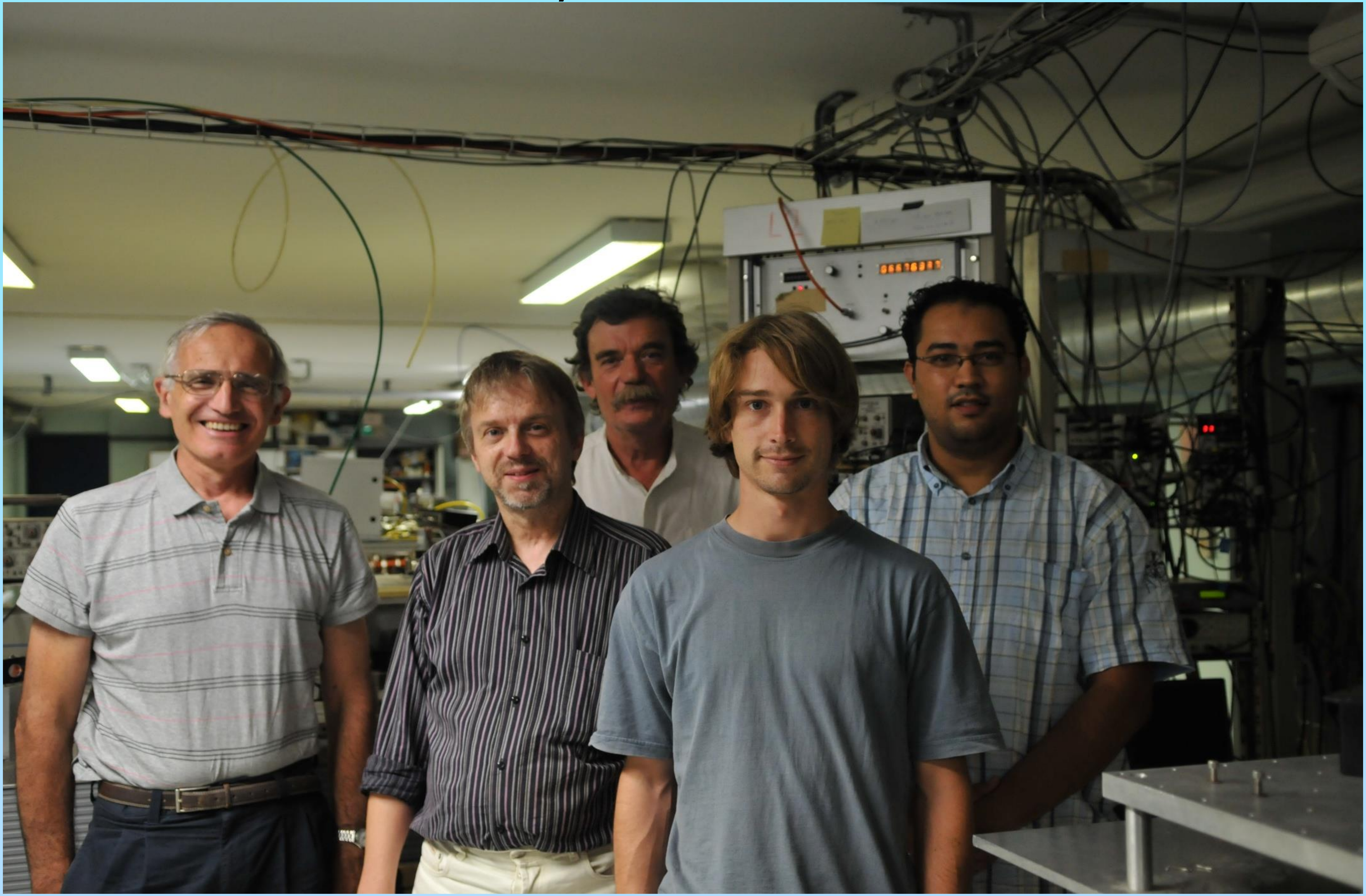
In 2005, Paris



In 2007, Paris



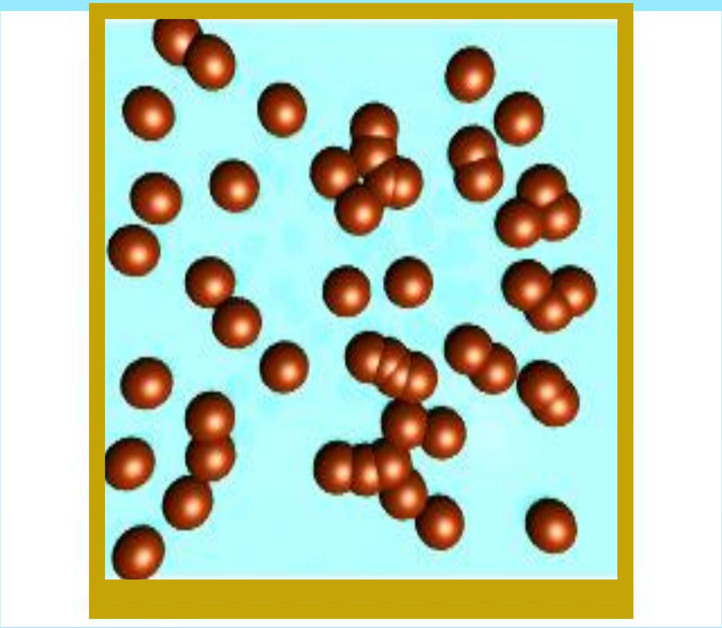
In 2008, Toulouse France

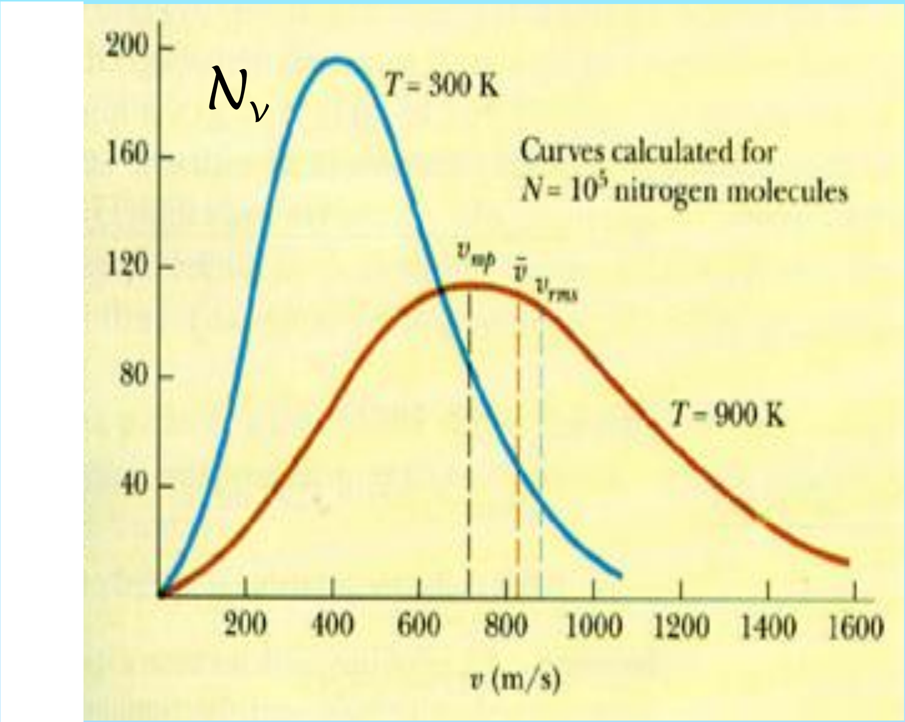


Cold atoms

Laser cooling

Temperature against agitation





V = 700 m/s

T → Thermal Agitation → Velocity Dispersion

How cool down atoms ?

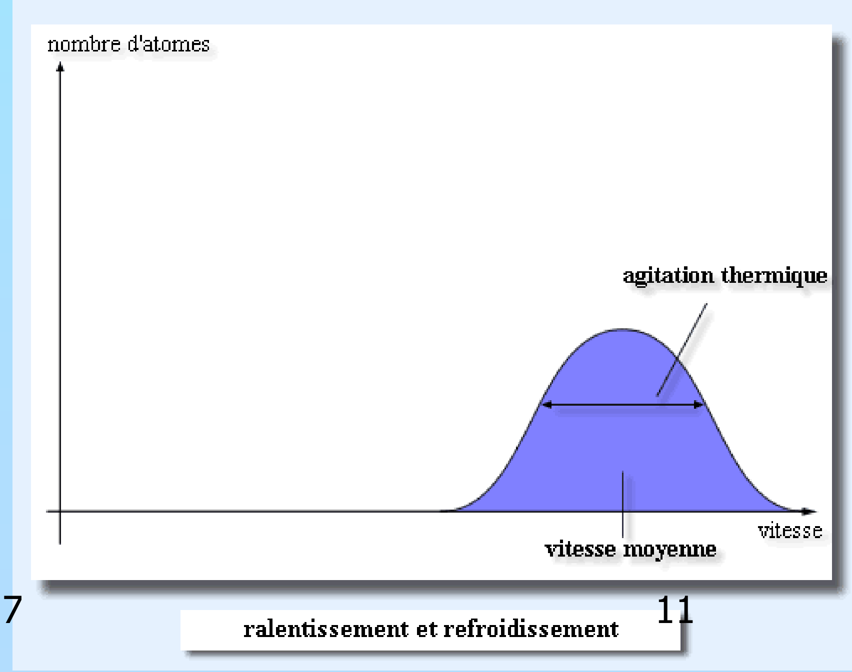
$$\frac{1}{2}mv^2 = \frac{3}{2}kT$$

⟶ @ T = 300 K   v ≈ 300 m/s

T:	1 nK	1 µK	10 µK	1 mK	4K	96K	300K
v:	0,5 mm/s	2 cm/s	5 cm/s	0,5 m/s	35 m/s	170 m/s	300 m/s
λ_{dB}:	8 µm	250 nm	80 nm	8 nm	0,1 nm	25 pm	14 pm

(for ^{85}Rb)

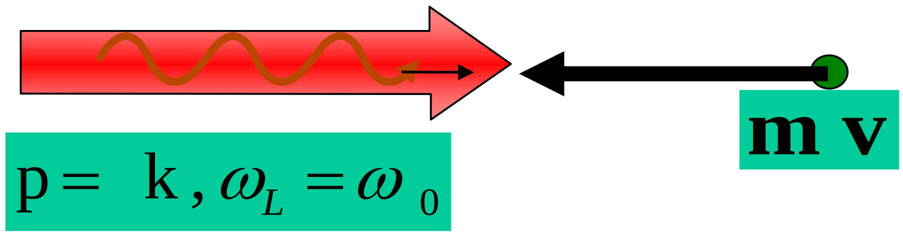
$$\lambda = \frac{h}{\sqrt{2\pi mkT}}$$



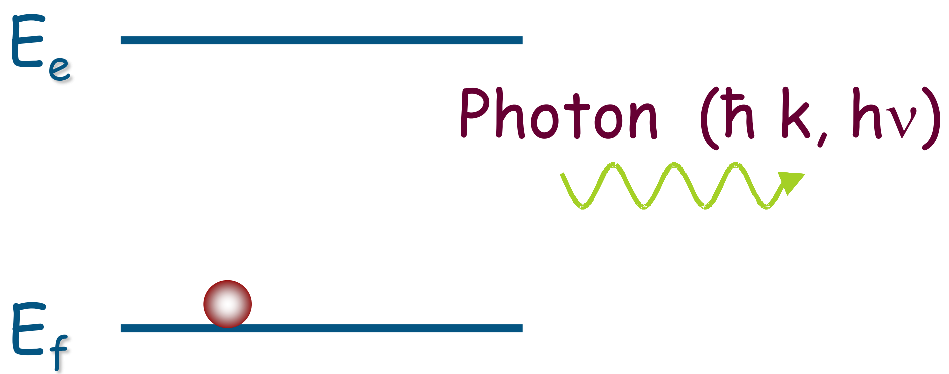
Solution : Use lasers

T. W. Hänsch and Schawlow, Opt. Comm. 13, 68 (1975)
D. Wineland and H. Dehmelt, Bul. Am. Phys. Soc. 20, 637 (1975)

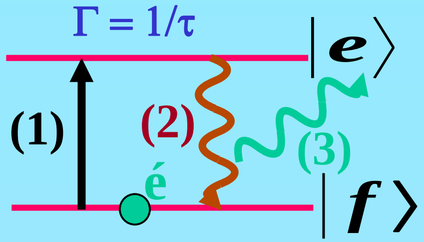
Mechnical effect of light on atoms



Absorption + spontaneous emission



Radiation pressure force



(1) : absorption

(2) :deexcitation

(3) Spontaneous emission

After absorption/spontaneous emission cycle : linear momentum exchange between atom-photon

After **n** cycles :

Σspontaneous emission **= 0** (Random behavior)

The atom acquires in total: $\boldsymbol{n \quad k}$

Radiation force : $\boldsymbol{F = n \quad K}$

^{85}Rb
λ = 780 nm
m = 85 uma ≈ 10^{-25} kg
δv = recoil velocity= 6 mm/s
v_0 = 300 m/s
Stop with 50 000 photons

1 photon / 60 ns = 3 ms
a = 300 / 3.10^{-3} = 10^5 m/s² ☹
10^4 g

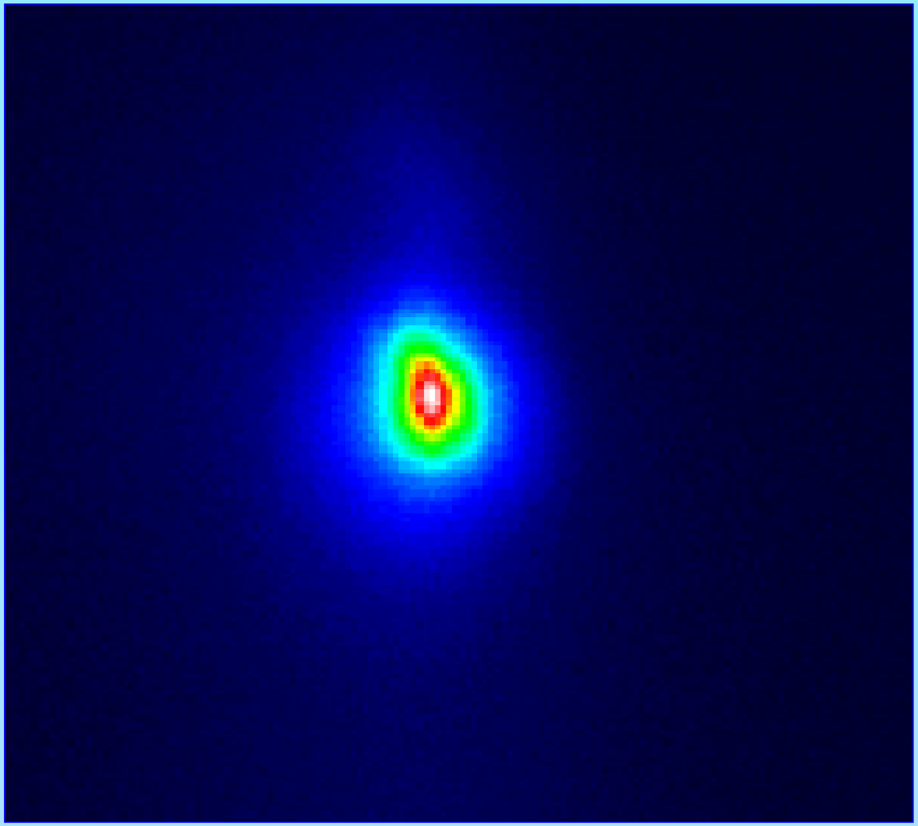
Colling atoms

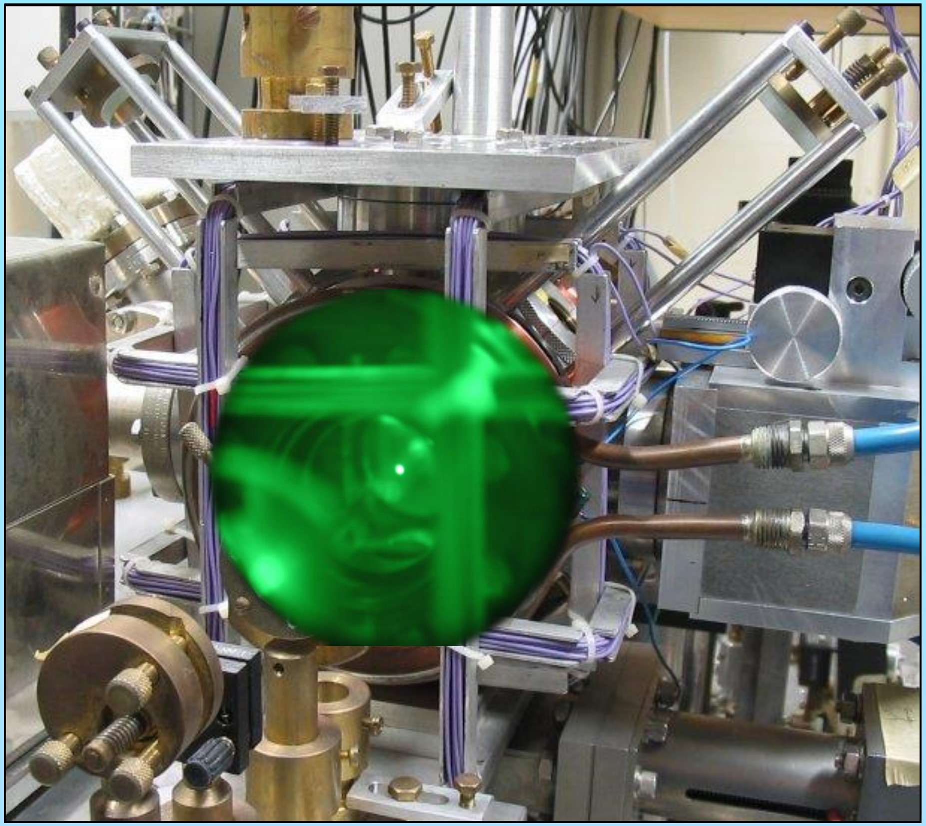
Prix Nobel de physique 1997 attribué à
W. Phillips, S. Chu et C. Cohen-Tannoudji

"for development of methods to cool and trap atoms with laser light"

Magneto optical trap for cold atoms





CCD Camera

Infra-rouge observer

vacuum: 10^{-8}...10^{-10} mbar

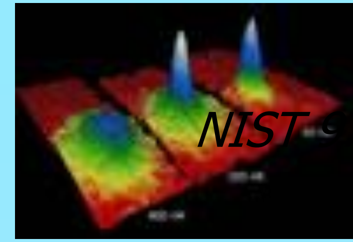
laser diode P = several mW

N ≈ 10^7 atoms de ^{87}Rb, V ≈ 0,5 mm x 0,5 mm x 0,5 mm

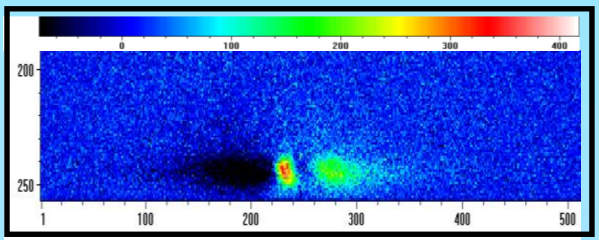
→ density ≈ n ≈ 10^{11}atoms/cm^3 T ≈ 30 μK

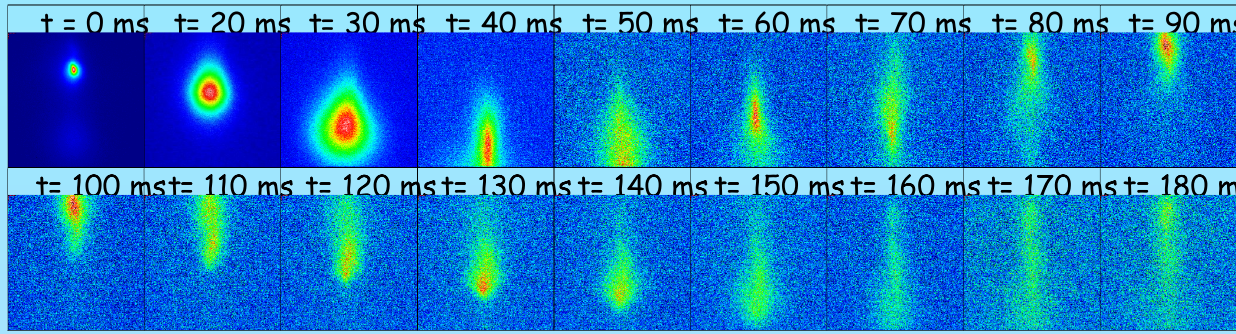
What we can made with an ensemble of cold atoms?

❖Bose-Einstein Condensat (BEC): T→ few nK



❖Quantum optics and quantum atomic: atom laser, lenses,



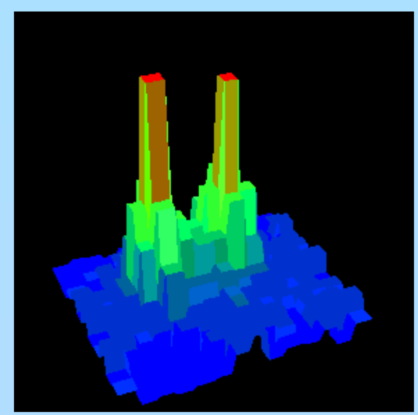


❖ photoassociation (cold molecules creation)

❖ Gaz of Rydberg & cold Plasma

❖ Quantum information

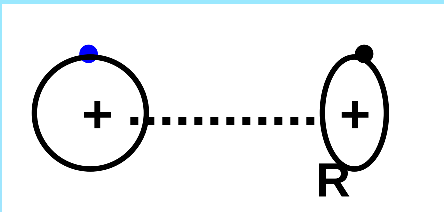
❖ Metrology : atomic clock & Gyro-meter, accelerometer

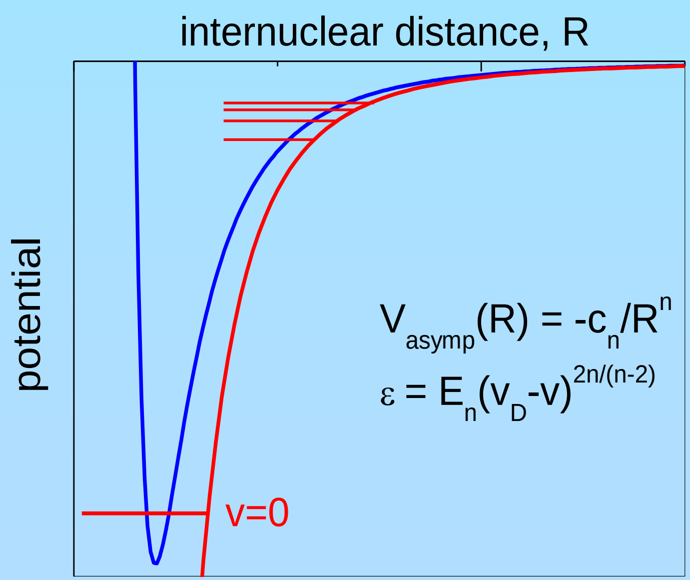


Weakly bound molecules

Weakly bound molecules. Long range potential

The molecule is large : the internuclear distance is 30-100 a_0. The binding energy is weak, about 0-30 cm^{-1}





Dipole-dipole interaction

Because the large internuclear distances, the binding energy is due to the dipole-dipole interaction.

For homonuclear molecules, depending on the symmetry, the asymptotic potential is

$$V(R) = -c_3/R^3$$

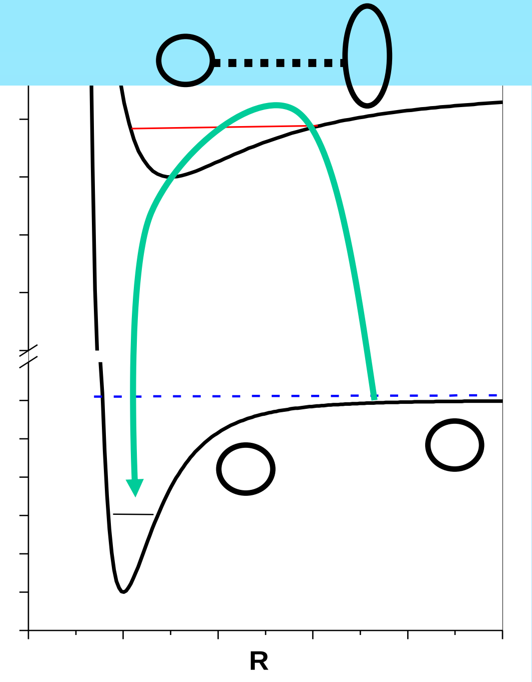
$$V(R) = -c_6/R^6$$

Or sum of them...

c_3, c_6 are coefficients including atomic constants and radial atomic elements <ns|r|n’p>. They are known, either from atomic spectroscopic data, or, by accurate calculations.

Weakly bound molecules, PA spectroscopy analysis, motivation

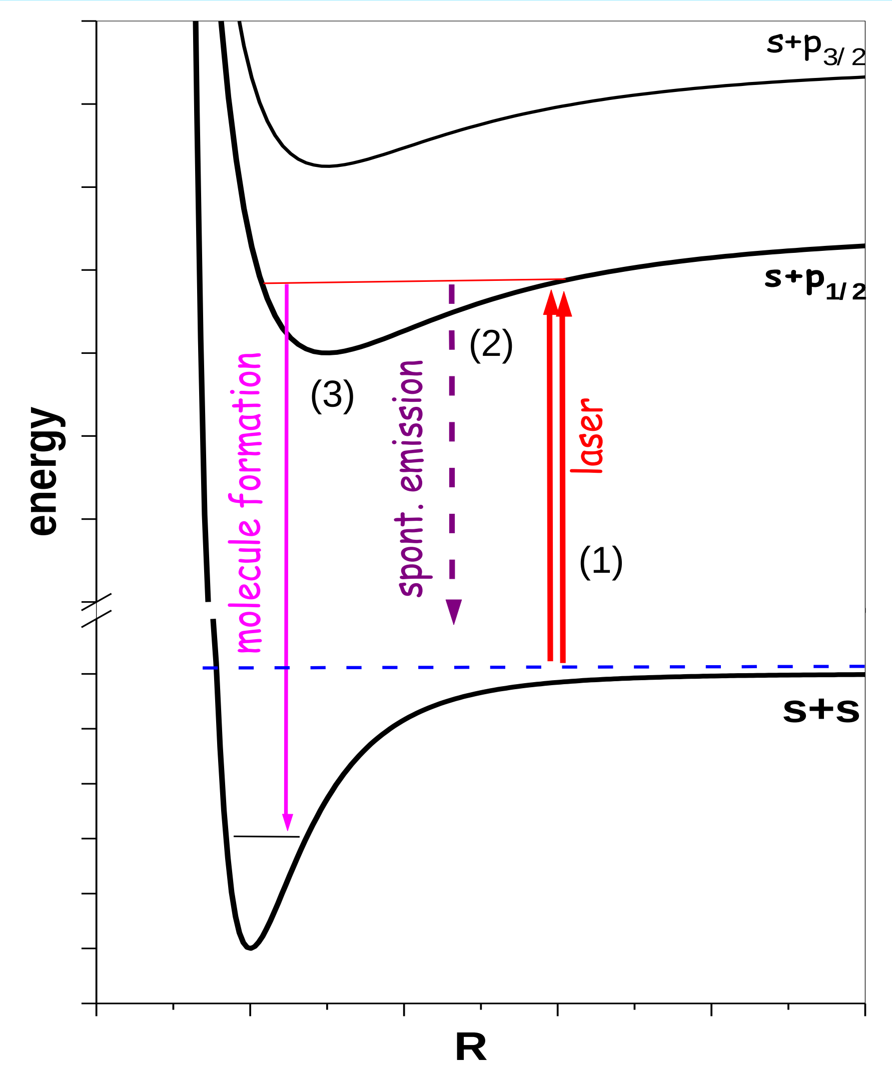
- Present in the atmosphere and the interstellar medium
- Involved in processes like collisions at small energy transfer
- A key element for cold molecule formation starting from cold atoms
- In the context of cold molecule formation starting from cold atoms, the challenge is to find efficient excitation schemes to produce molecules in a ground state.
- Very often, the first step of the route to cold molecules is the photo-association process : 2 atoms are associated via a photon excitation, to give a molecule in an excited level.



$$Rb(5s) + Rb(5s) + h\nu \rightarrow Rb_2^*$$

Others processes : Raman excitation , STIRAP , Magneto-association using a magnetic Feshbach resonances, Optical Feshbach resonances …

Cold molecule formation (a scheme to summarize)



Cold atoms @T=10 μK

Laser photo-association (1)

$Rb(5s) + Rb(5s) + h\nu \rightarrow Rb_2^*$

Desexcitation

(2) : spontaneous emission

$Rb_2^* \rightarrow h\nu' + Rb + Rb$

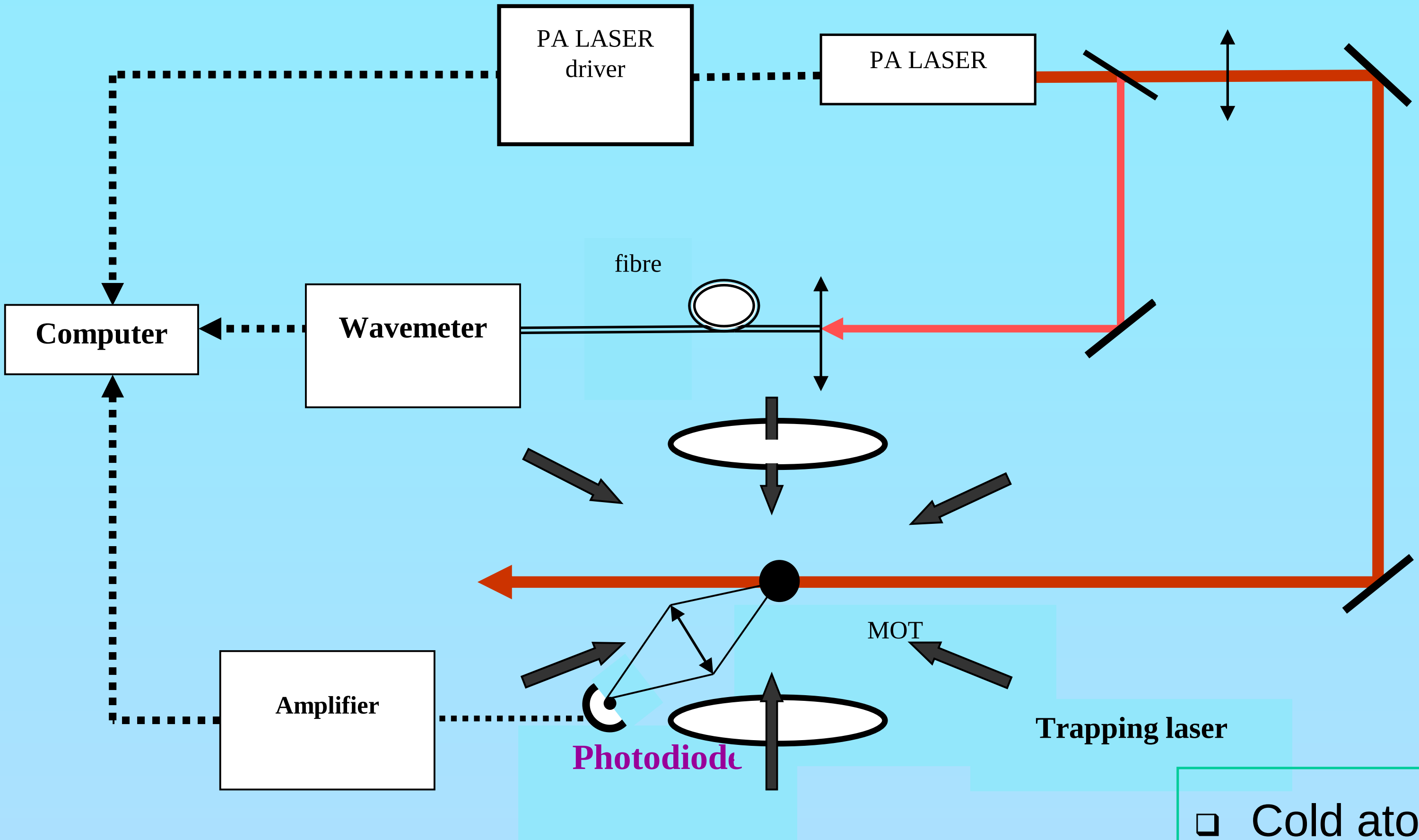
(3) : **decay to molecule.**

$Rb_2^* \rightarrow h\nu'' + Rb_2$

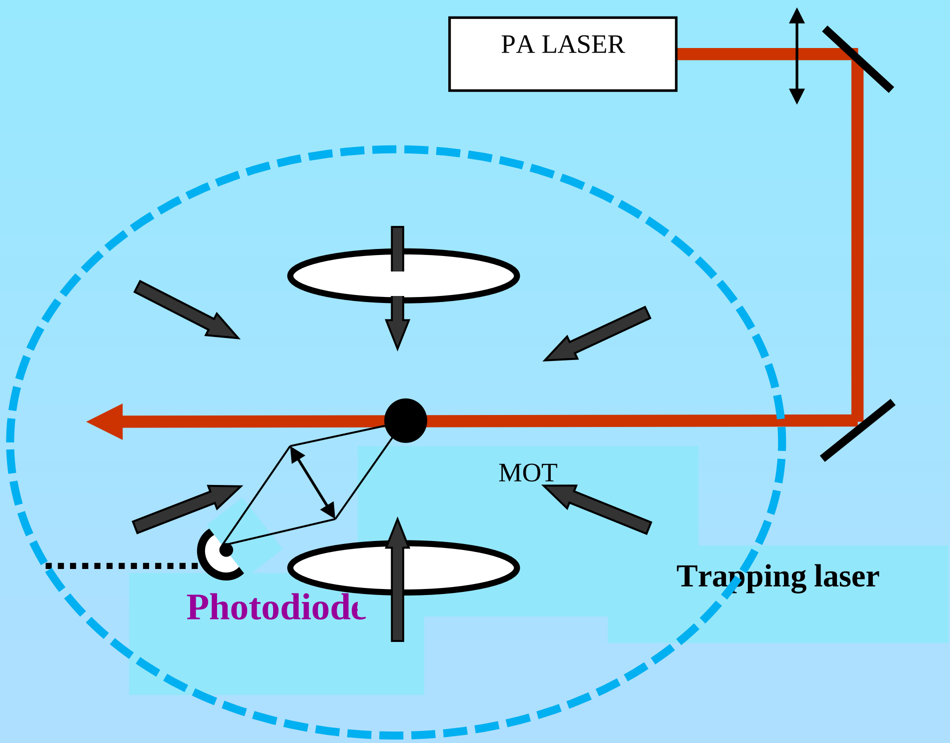
Spectroscopy of long range molecule is an important issue : detect levels with mixing in the wavefunction

Spectroscopy of weakly bound molecules

Analysis methods



- Cold atoms : laser-trapped and **cooled down to T=10 µK** (v~cm/s range)
  - A low T to accurately define the initial state and to get **HR spectroscopy**



- A tunable laser **photoassociates** the atoms

$$Rb(5s) + Rb(5s) + h\nu \rightarrow Rb_2^*$$

- The Rb_2^* molecule desexcition induces the **loss of 2 atoms**

spontaneous emission

$Rb_2^* \rightarrow h\nu' + Rb + Rb$ gives hot atoms.

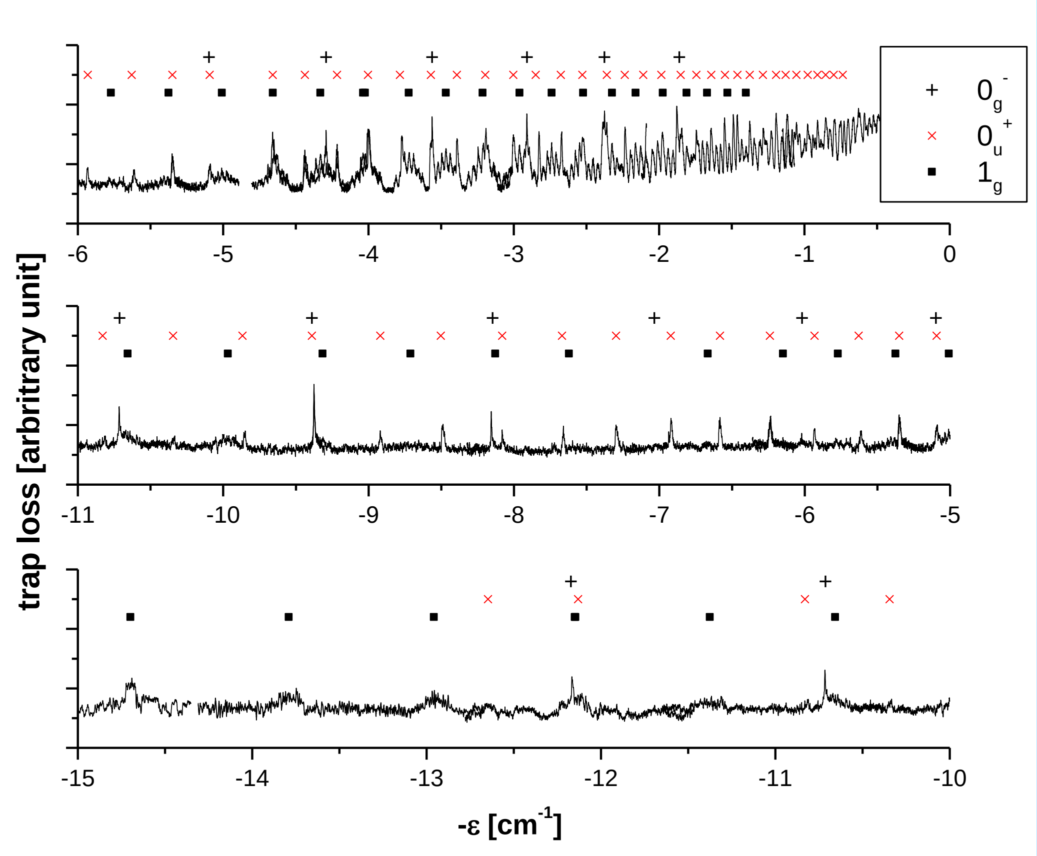
decay to molecule.

$Rb_2^* \rightarrow h\nu'' + Rb_2$ gives untrapable molecules

- At the resonance the loss of atoms is recorded via the trap fluorescence signal (= atom number).

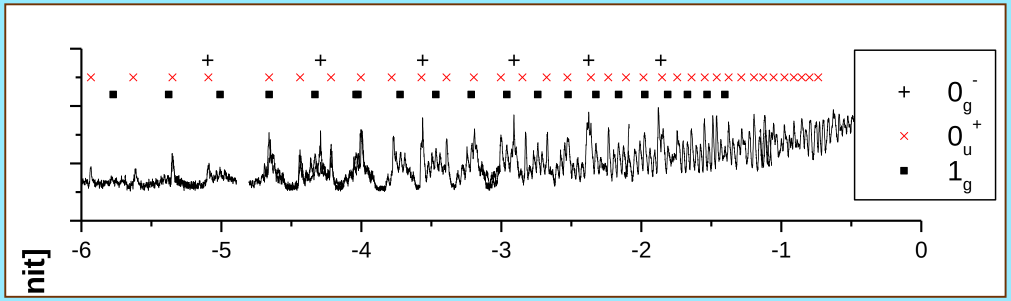
- The so called trap-loss spectroscopy

Trap loss PA spectroscopy of $^{87}Rb_2$, below the $5s_{1/2}+5p_{1/2}$ limit



- Close to the dissociation limit = weakly bound molecules
- 3 detected molecular series : 0_g^-, 0_u^+ and 1_g
- binding energy ε of each level measured with a 0.03 cm-1 resolution.

Data analysis



- DATA?
  - ❑ Line positions : the binding energies of detected levels
  - ❑ Amplitudes of lines : transition probability

$$|\langle initial|\boldsymbol{dE}|final\rangle|^2 = |\langle 5s|\boldsymbol{dE}|5d\rangle|^2 \times \left|\langle \Psi_i(R\middle|\Psi_f(R)\rangle\right|^2$$

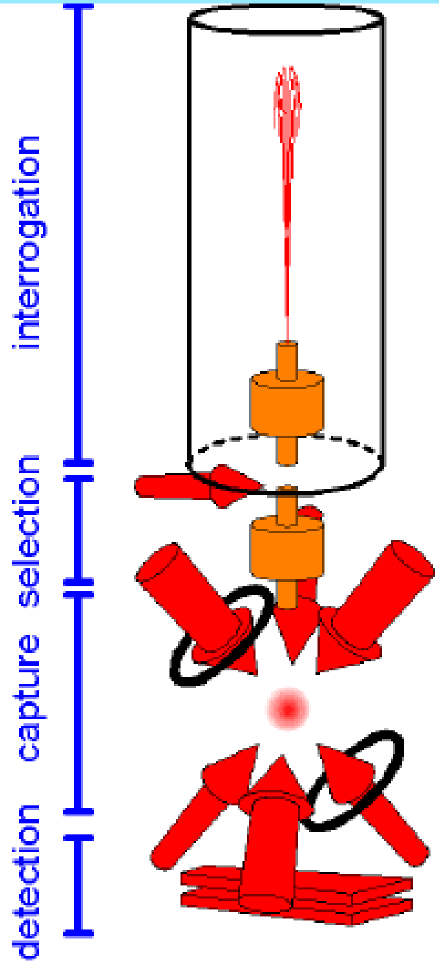
- ANALYSIS

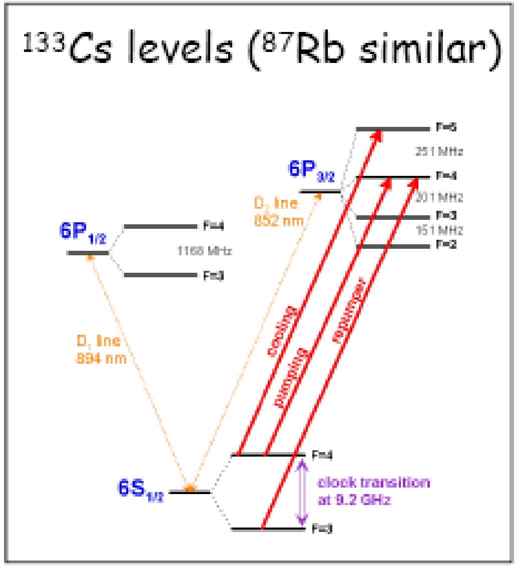
Many performing methods : RKR, potential model, ab-initio, semi-classical …

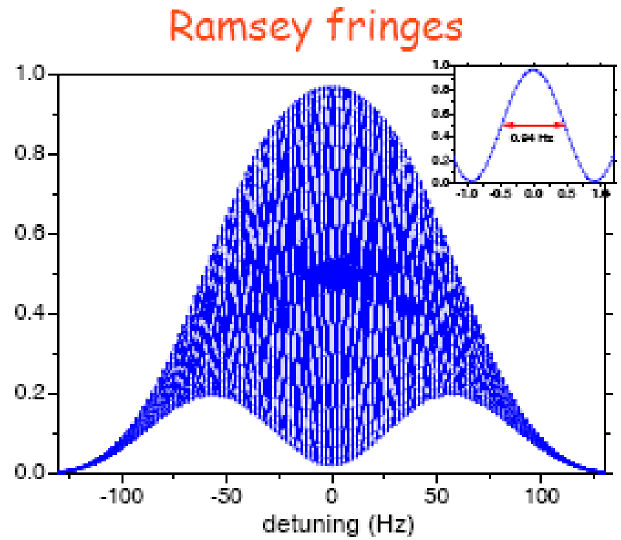
- ❑ Build a molecular potential curve
  - including assumptions for asymtotic form or for the barrier location
- ❑ *Numerically* solve to get the Eigen values (energies)
- ❑ Compare to the data and improve the molecular potential
- ❑ Add the coupling between the potentials

The **vibrational quantum defect** approach is not numerically. It proposes an analysis to detect and quantify the couplings.

Outstinding project :
The Tunisian Atomic Clock





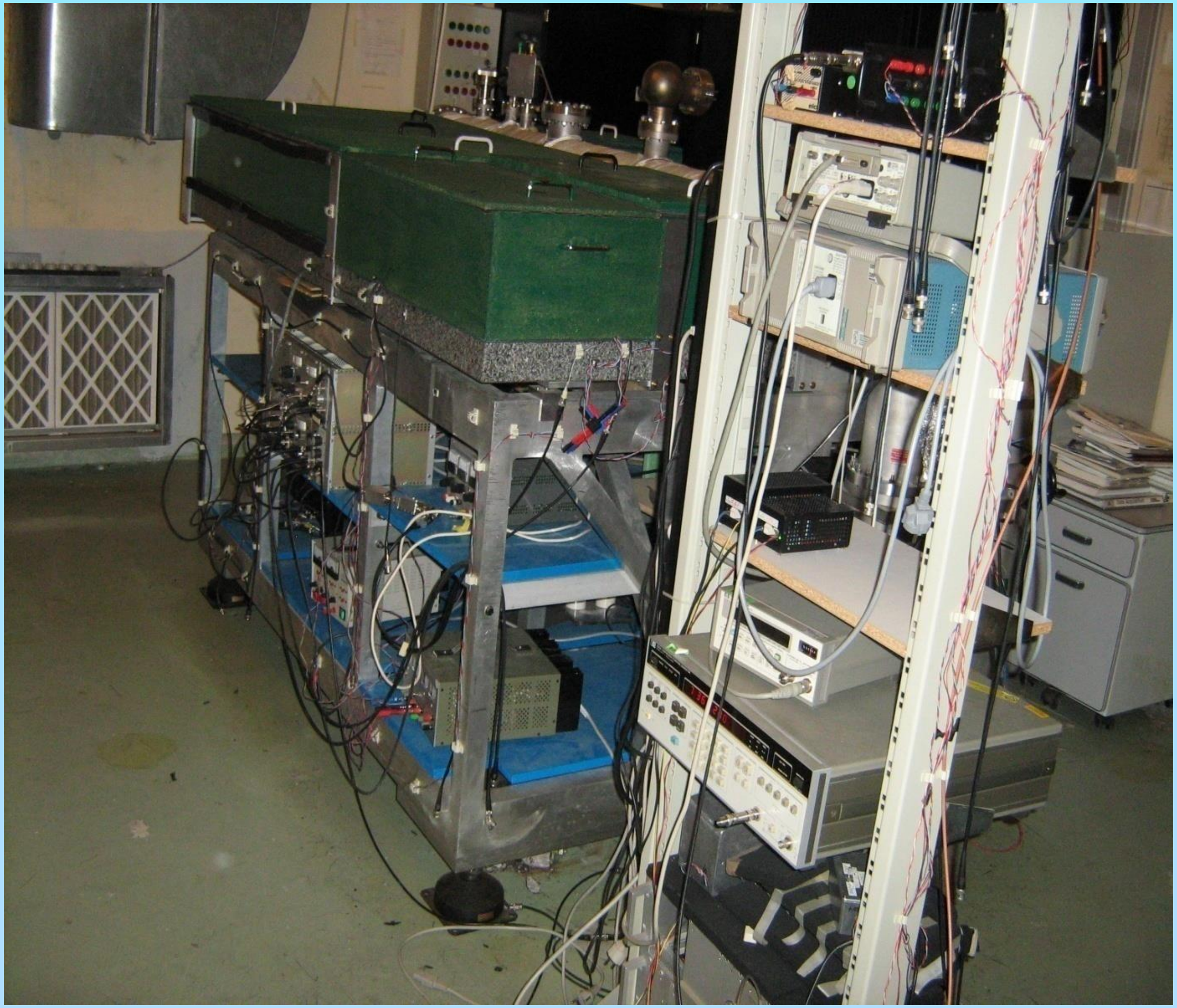


Atomic quality factor:

$$Q_{at} = \nu_{ef}/\Delta\nu \simeq 9.8 \times 10^9$$

Best frequency stability (~ Quantum Projection Noise limited): 1.6×10^{-14} @1s

Best accuracy: 2.4×10^{-16}




cnstn
Abstract
Introduction
The Local Oscillator
Examples of Local Oscillator
Specifications
Results of numerical simulations
Conclusion

Collaboration opportunities through TYAN Network

To invite TYAN members for a short stay in My centre, we could Seeking money from :

- IAEA (International Atomic Energy Agency),
- AAEA (for Arab countries),
- AUF (For francophone)
- IUPAP (The International Union of Pure and Applied Physics)
- ICTP
- Others…

For different fields :

Atomic process in Plasma

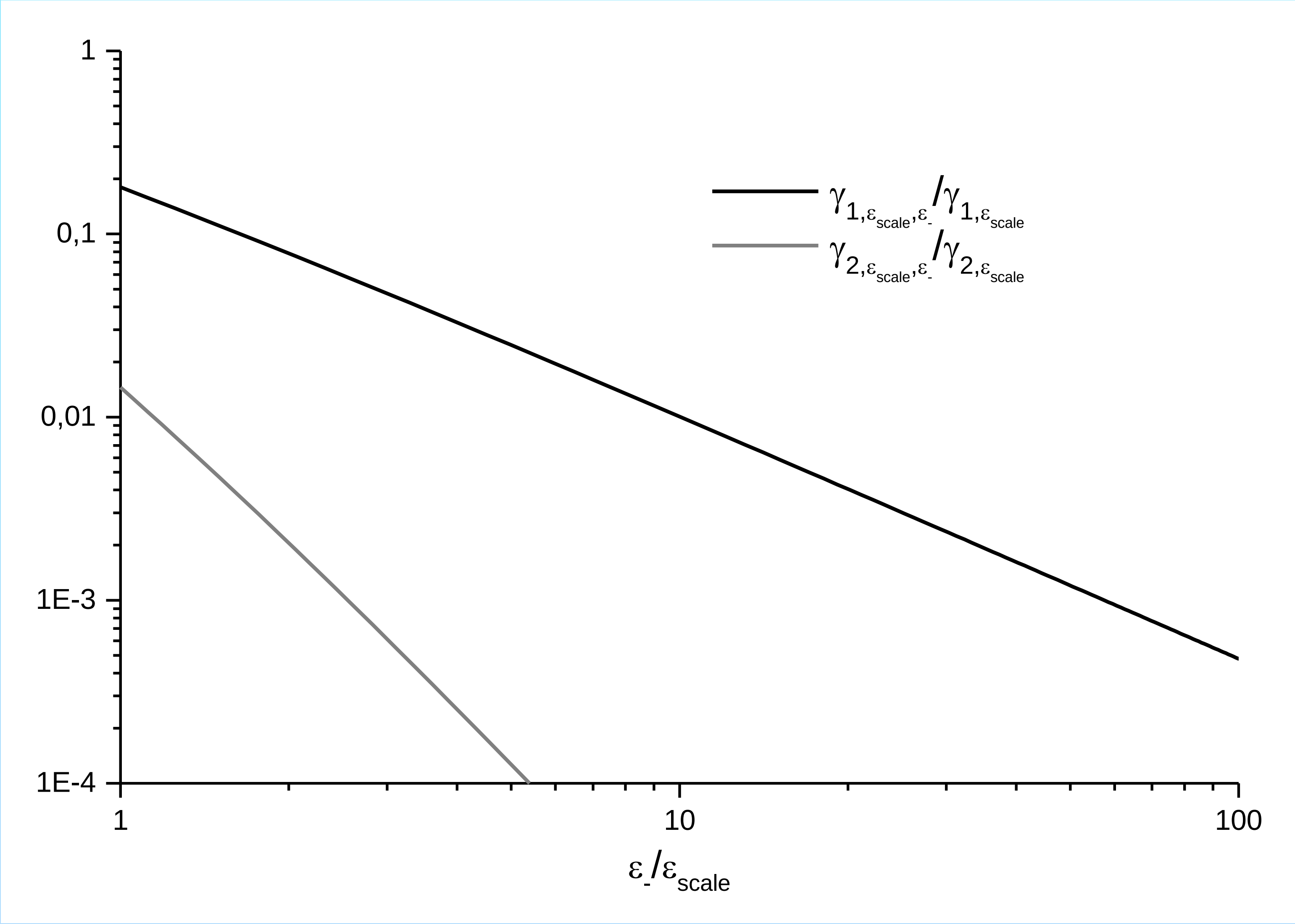
Use for Materials (poylmers, Dyes, Semi conductors, etc…) for Dosimetry Purpose regarding their Physical and Chemical properties

Merci pour votre Attention

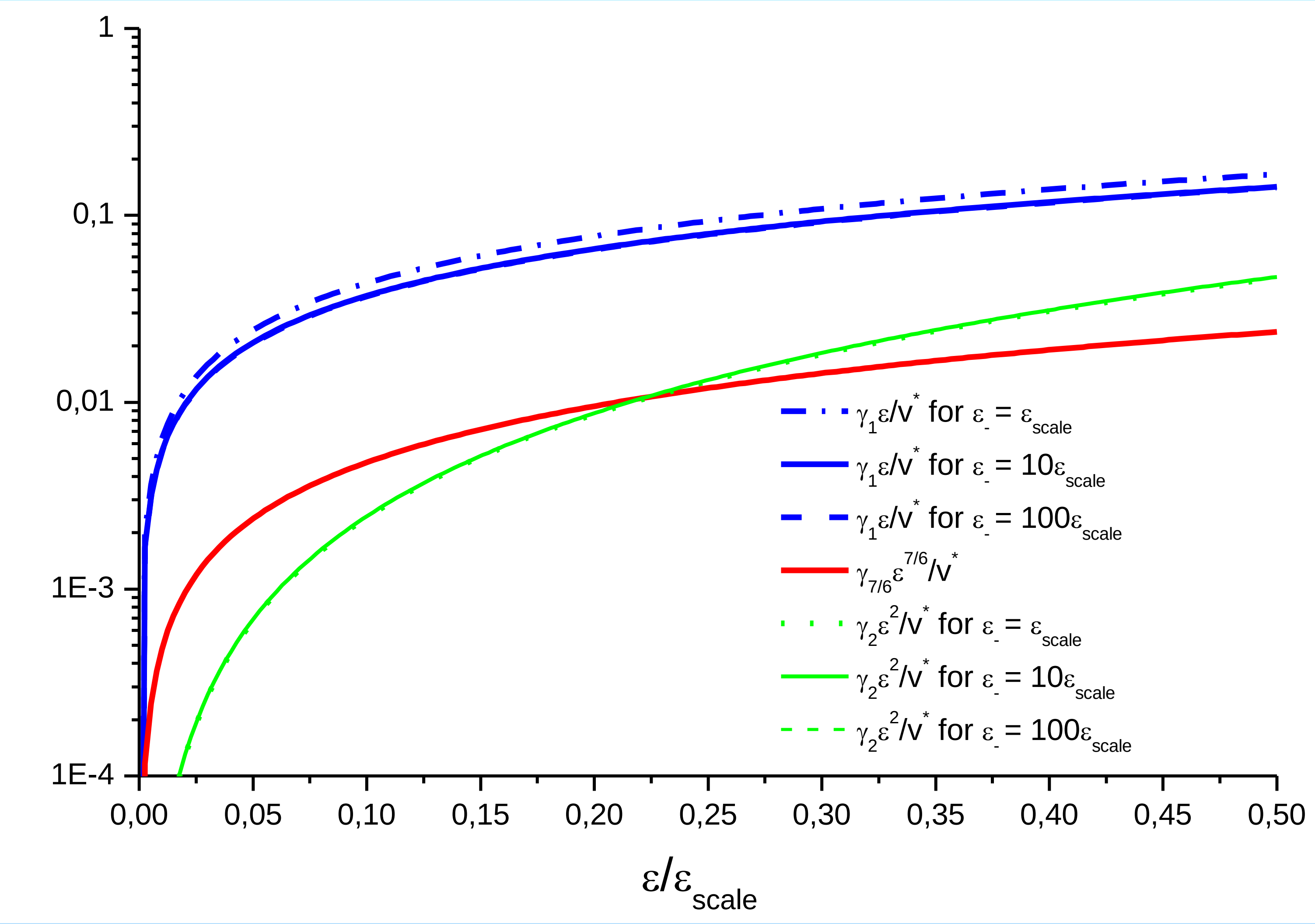
Thank you for your attention

Deuxième amélioration de LRB :

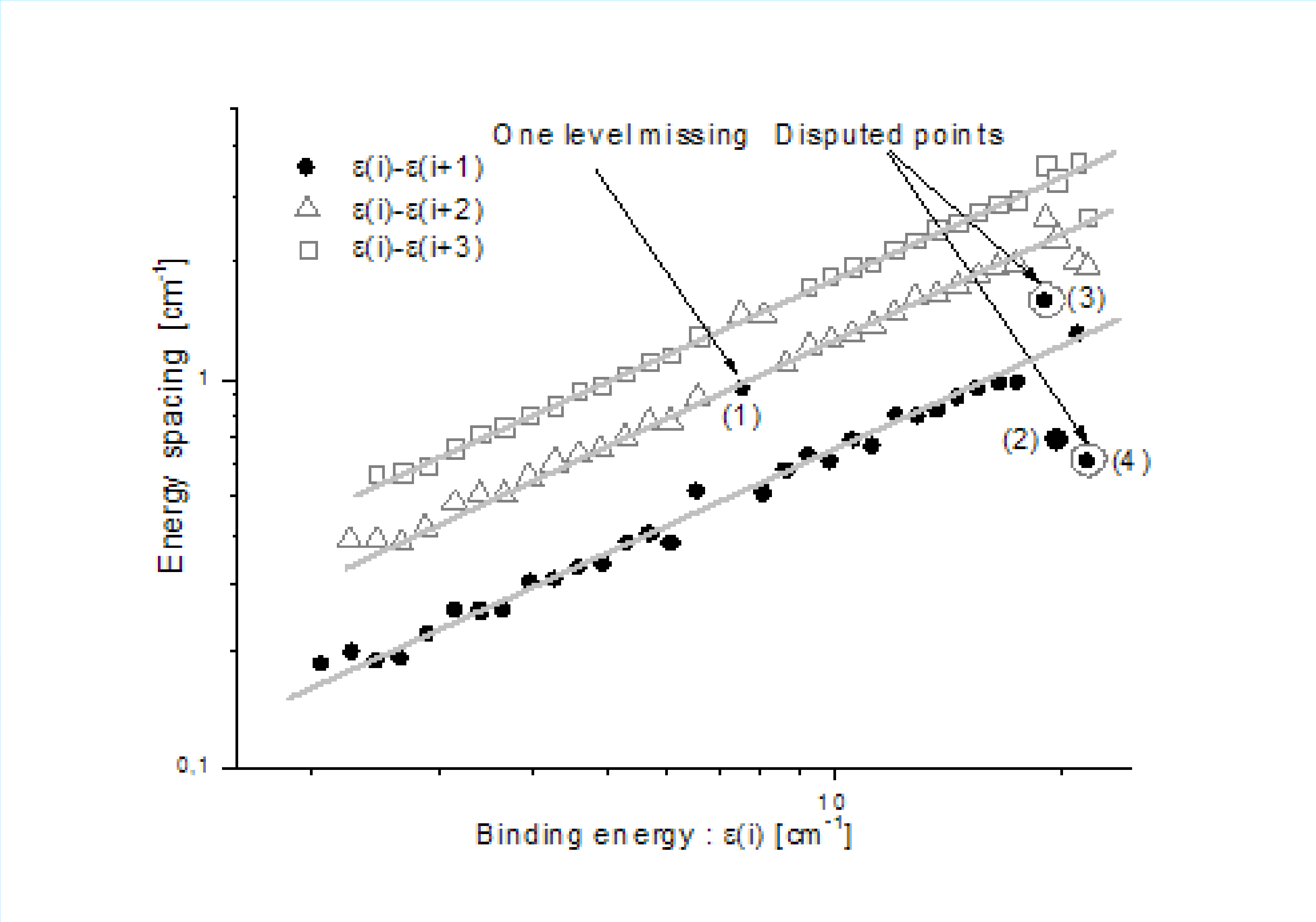
Case n=3, m=6.



Deuxième amélioration de LRB :
Case n=3, m=6.



Etude de la progression de la série vibrationnelle $^{87}Rb_2(5s_{1/2} + 5p_{1/2})1_g$



H. Jelassi and L. Pruvost, PHYSICAL REVIEW A 89, 032514 (2014).

Liste finale des niveaux détectés

i	Measured ϵ (cm^{-1})	Mean ϵ (cm^{-1})	Attributed $v_D - [v]$	N_T
1	21.750(2)	21.750(2)	not 1_g level	
2	21.130(2)	21.130(2)	110	0
3	19.816(2)	19.816(2)	109	0
4	19.122(2)	19.122(2)	not 1_g level	0
5	not detected		108	
6	17.522(2)	17.522(2)	107	0
7	16.538(2); 16.548(2)	16.542(2)	106	0
8	15.536(2); 15.538(2); 15.546(2) 15.546(2); 15.596(2)	15.552(2)	105	0
9	14.582(2); 14.602(2); 14.604(2) 14.610(2); 14.610(2)	14.602(2)	104	0
10	13.694(2)	13.694(2)	103	0
11	12.854(2); 12.862(2); 12.868(2)	12.862(2)	102	0
12	12.050(2); 12.054(2); 12.054(2) 12.056(2); 12.062(2)	12.056(2)	101	0
13	11.270(2); 11.280(2); 11.300(2); 11.132(2)	11.246(2)	100	0
14	10.546(2); 10.562(2); 10.582(2); 10.592(2)	10.570(2)	99	0
15	9.870(2); 9.870(2); 9.872(2); 9.888(2)	9.875(2)	98	0
16	9.220(2); 9.260(2); 9.260(2); 9.275(2)	9.254(2)	97	0
17	8.616(2)	8.616(2)	96	0
18	8.034(2)	8.034(2)	95	0
19	7.526(2)	7.526(2)	94	0
20	not detected		93	
21	6.570(2)	6.570(2)	92	0
22	6.054(2)	6.054(2)	91	0
23	5.676(2)	5.672(2)	90	0
24	5.274(2); 5.278(2)	5.276(2)	89	0
25	4.878(2); 4.912(2)	4.896(2)	88	0

H. Jelassi and L. Pruvost, PHYSICAL REVIEW A 89, 032514 (2014).

Liste finale des niveaux détectés : niveaux à structure hyperfine résolue

i	$\epsilon(\text{cm}^{-1})$	Attributed $v_D - [v]$	N_T	i	$\epsilon\ (\text{cm}^{-1})$	Attributed $v_D - [v]$	N_T	i	$\epsilon\ (\text{cm}^{-1})$	Attributed $v_D - [v]$	N_T
			−3		3.458(2)		−3		2.540(2)		−3
			−2		3.428(2)		−2		2.510(2)		−2
	4.596(2)		−1		−3.400(2)		−1		2.478(2)		−1
26	4.562(2)	87	0	30	3.372(2)	83	0	34	2.452(2)	79	0
	4.532(2)		+1		3.342(2)		+1		2.426(2)		+1
	4.496(2)		+2		3.308(2)		+2		2.388(2)		+2
	4.464(2)		+3		3.274(2)		+3		2.360(2)		+3
			−3		3.220(2)		−3		2.360(2)		−3
	4.296(2)		−2		3.184(2)		−2		2.322(2)		−2
	4.266(2)		−1		3.150(2)		−1		2.298(2)		−1
27	4.236(2)	86	0	31	3.118(2)	82	0	35	2.264(2)	78	0
	4.202(2)		+1		3.082(2)		+1		2.228(2)		+1
	4.170(2)		+2		3.044(2)		+2		2.192(2)		+2
	4.140(2)		+3		3.008(2)		+3		2.166(2)		+3
	4.016(2)		−3		2.972(2)		−3				−3
	3.984(2)		−2		2.936(2)		−2				−2
	3.956(2)		−1		2.904(2)		−1				−1
28	3.928(2)	85	0	32	2.864(2)	81	0	36	2.102(2)	77	0
	3.900(2)		+1		2.830(2)		+1		2.066(2)		+1
	3.860(2)		+2		2.796(2)		+2		2.032(2)		+2
	3.822(2)		+3		2.760(2)		+3		1.996(2)		+3
	3.716(2)		−3		2.730(2)		−3				−3
	3.688(2)		−2		2.700(2)		−2		1.950(2)		−2
	3.656(2)		−1		2.672(2)		−1		1.912(2)		−1
29	3.626(2)	84	0	33	2.644(2)	80	0	37		76	0
	3.596(2)		+1		2.612(2)		+1		1.880(2)		+1
	3.564(2)		+2		2.576(2)		+2		1.842(2)		+2
	3.534(2)		+3		2.544(2)		+3		1.806(2)		+3

H. Jelassi and L. Pruvost, PHYSICAL REVIEW A 89, 032514 (2014).