Photoassociative frequency shifts and atom-molecule dark states in ultracold metastable helium

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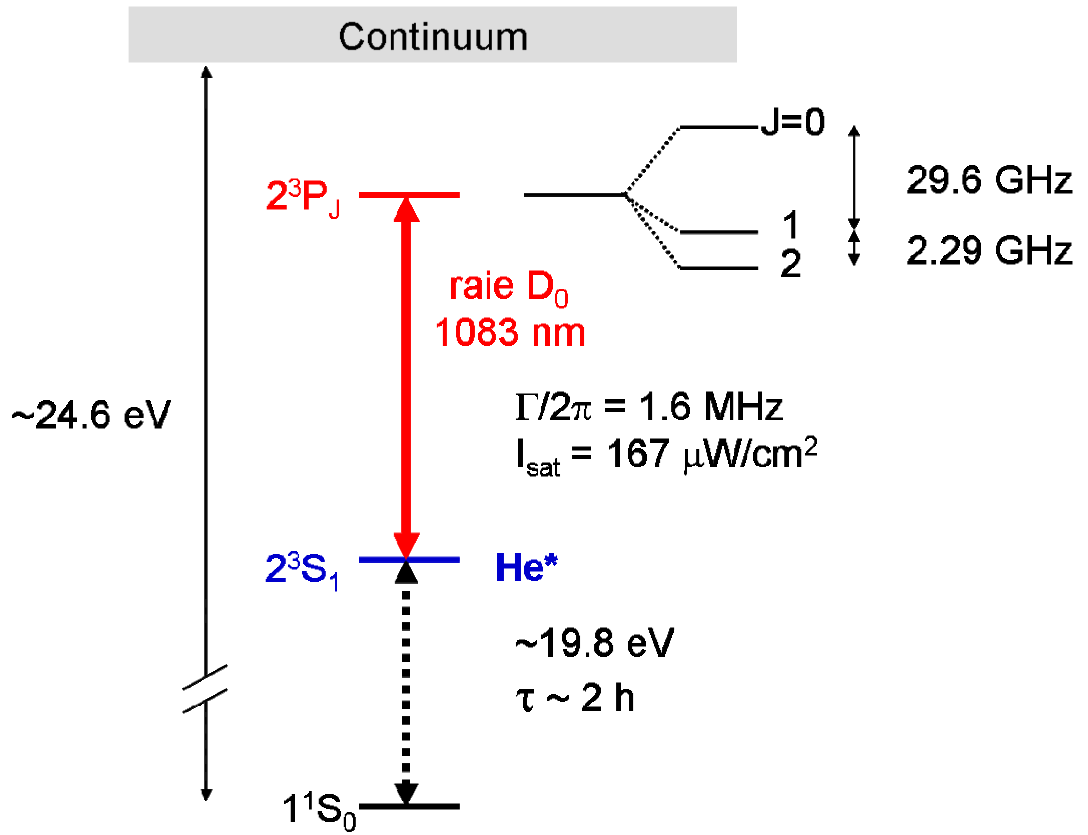
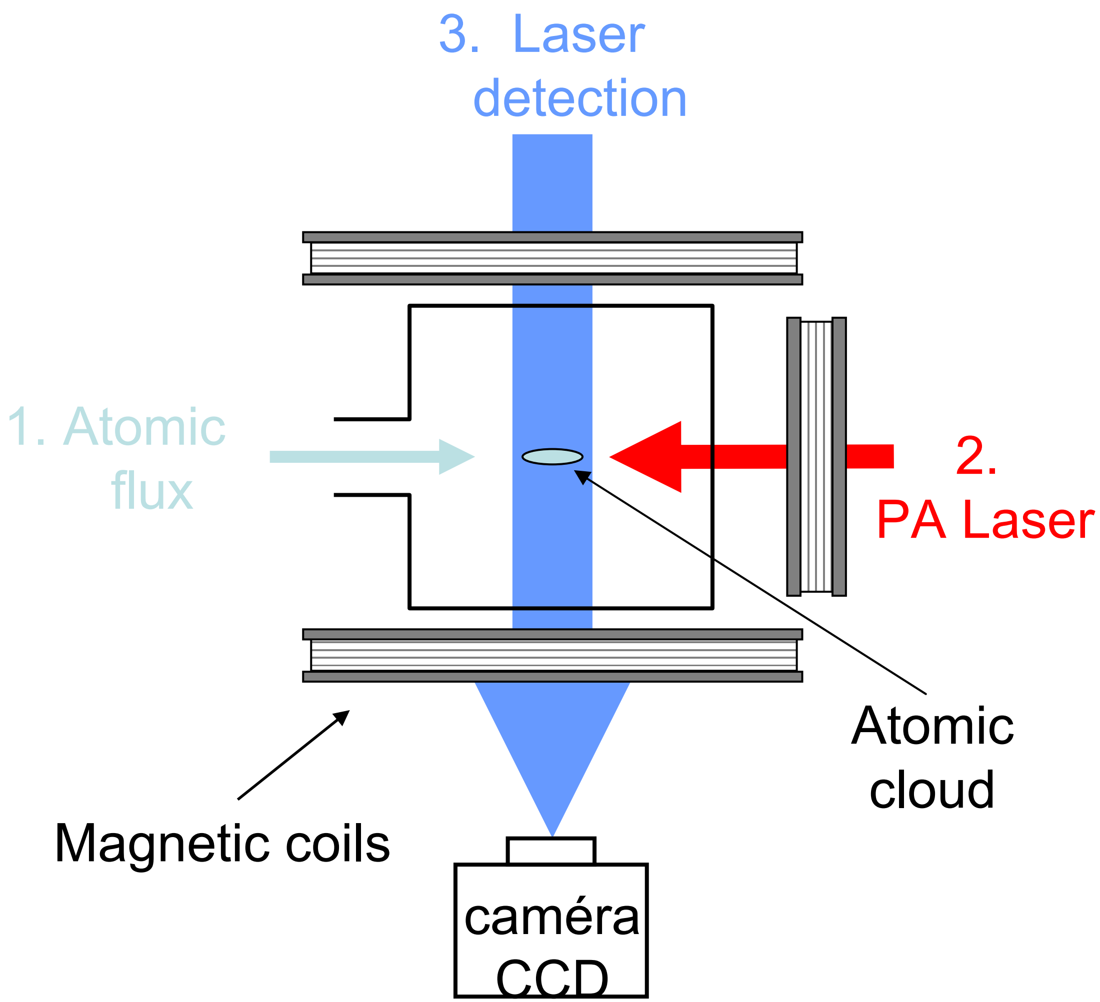
The metastable helium atom



Penning ionization :

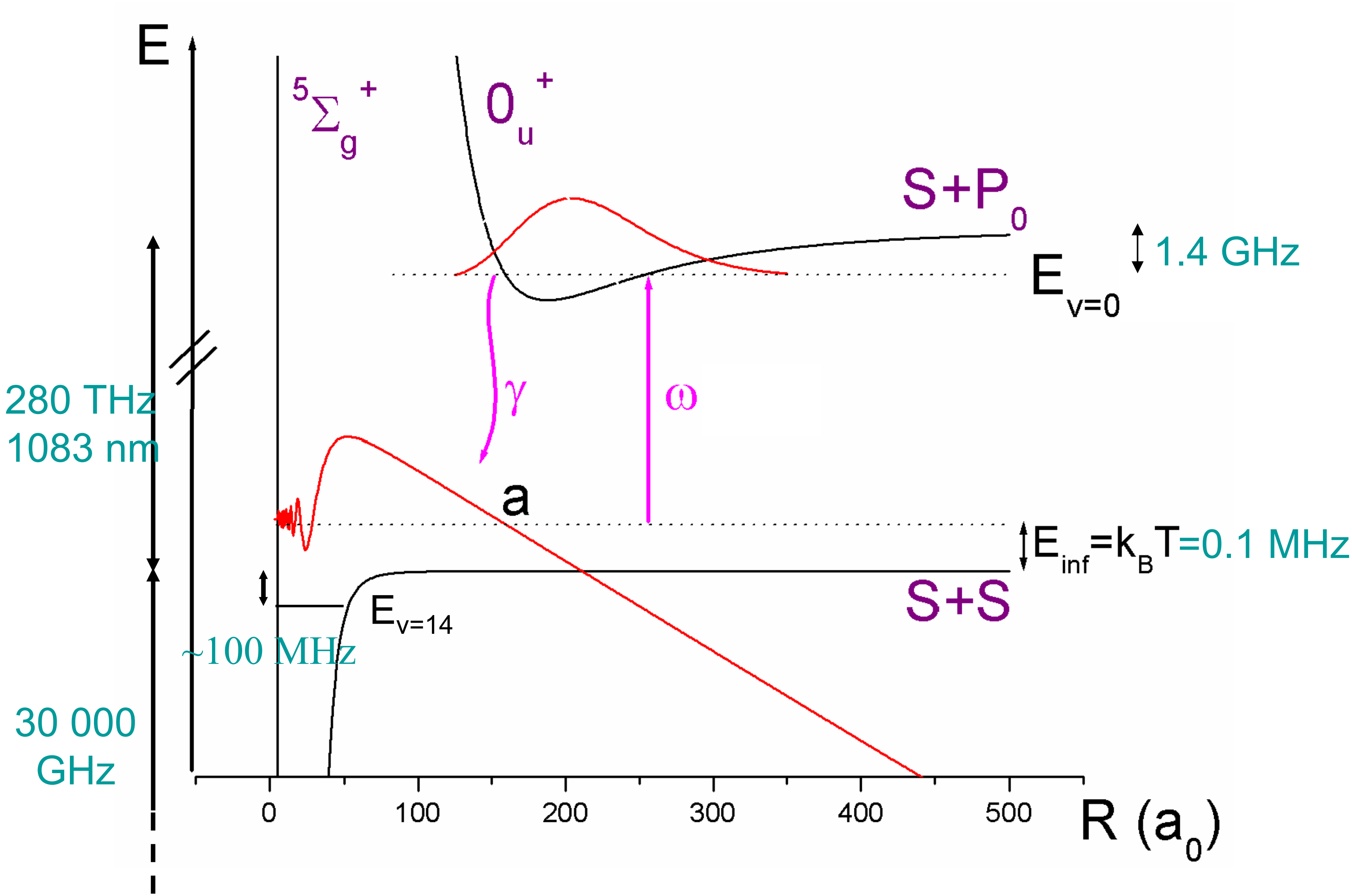
$$\mathrm{He}(2^3S)\uparrow + \mathrm{He}(2^3S)\uparrow \rightarrow \begin{cases} \mathrm{He}^+ + \mathrm{He}(1S) + e^- \\ \mathrm{He}_2^+ + e^- \end{cases}$$

PA setup

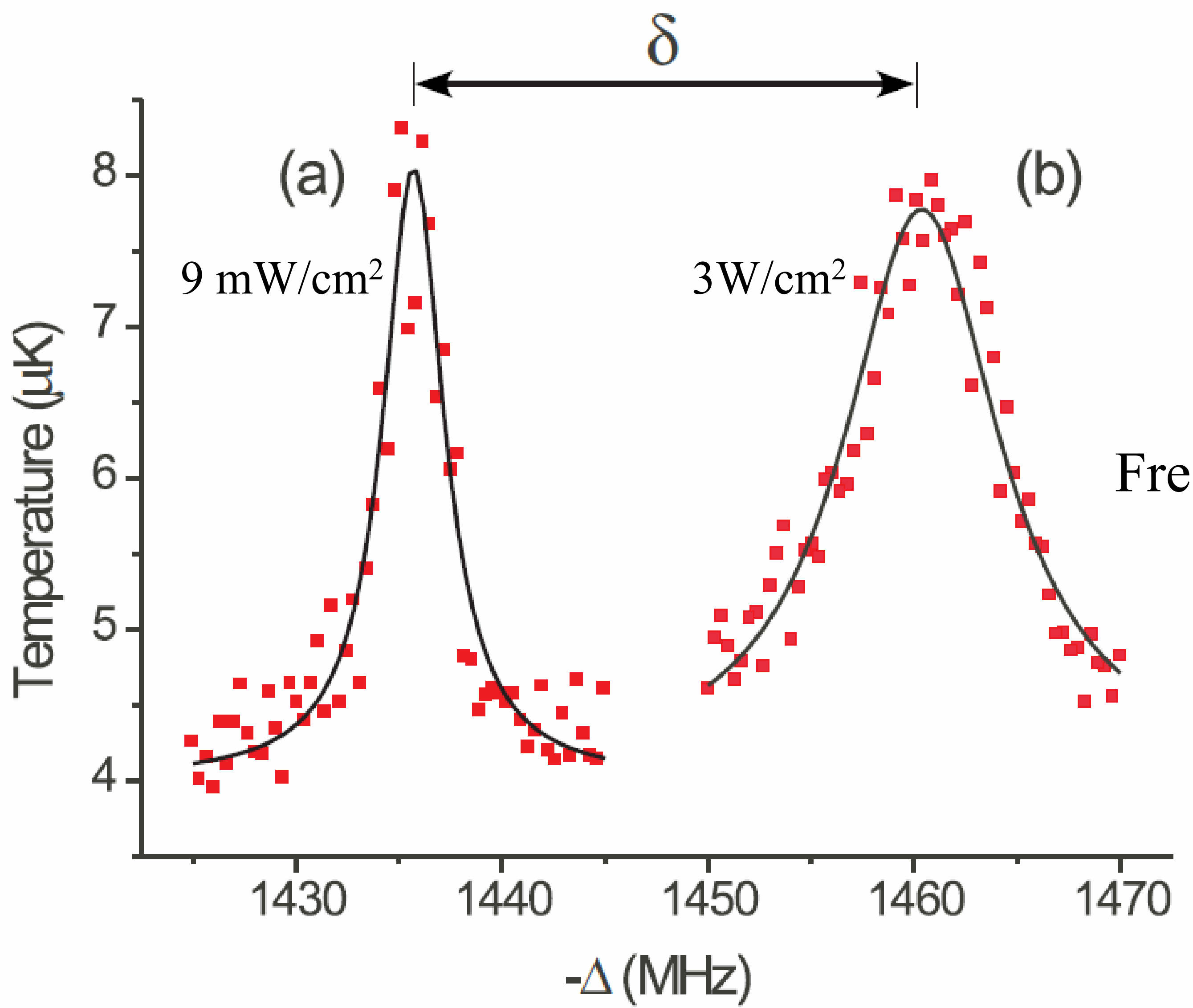


3. Laser detection
1. Atomic flux
2. PA Laser
Atomic cloud
Magnetic coils
caméra CCD

Photoassociation in the purely long-range 0_u^+ potential

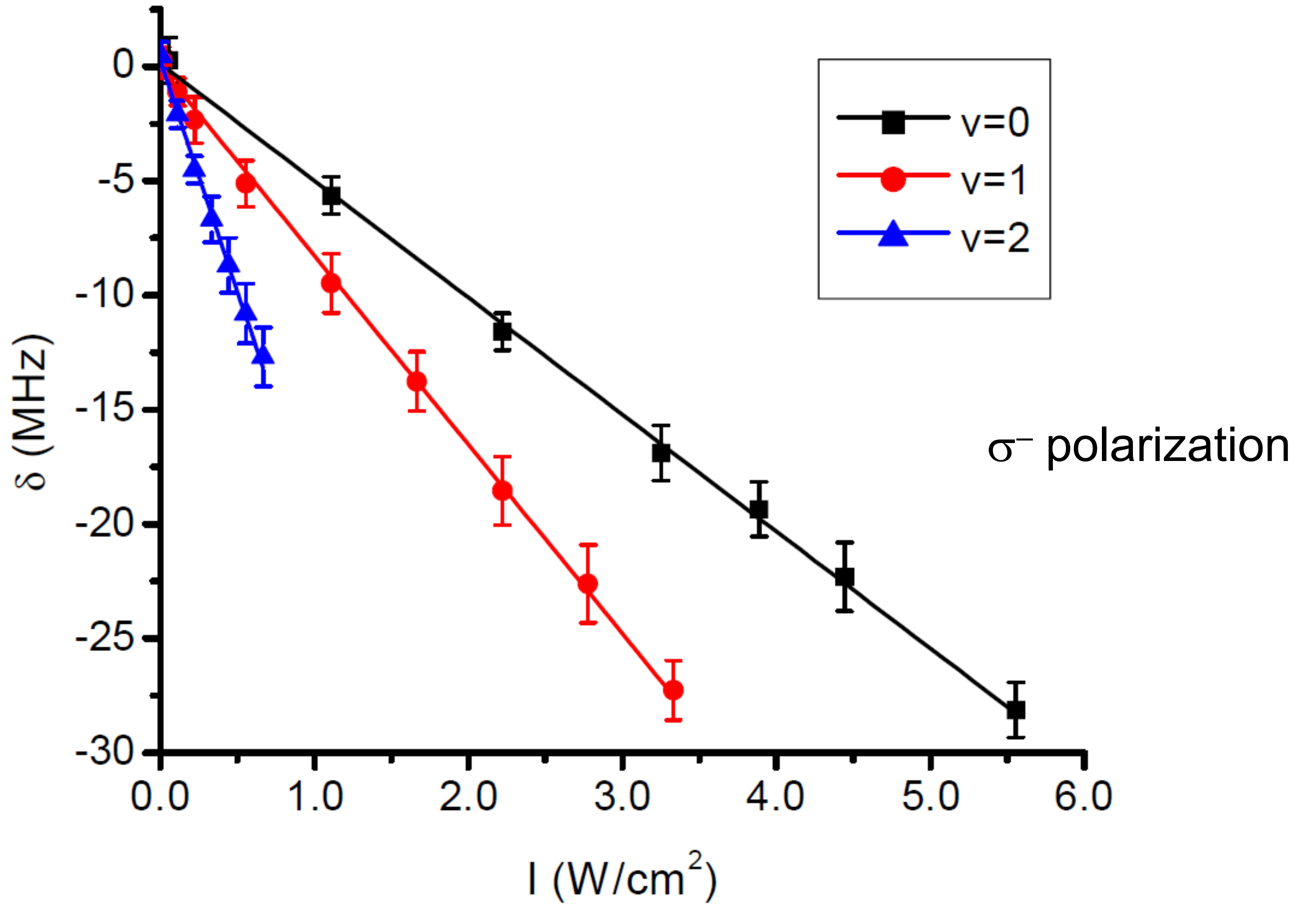


Light-shift of the molecular line



Free-bound transition
to 0_u^+, $v = 0$

Measured light-induced frequency shifts of PA lines

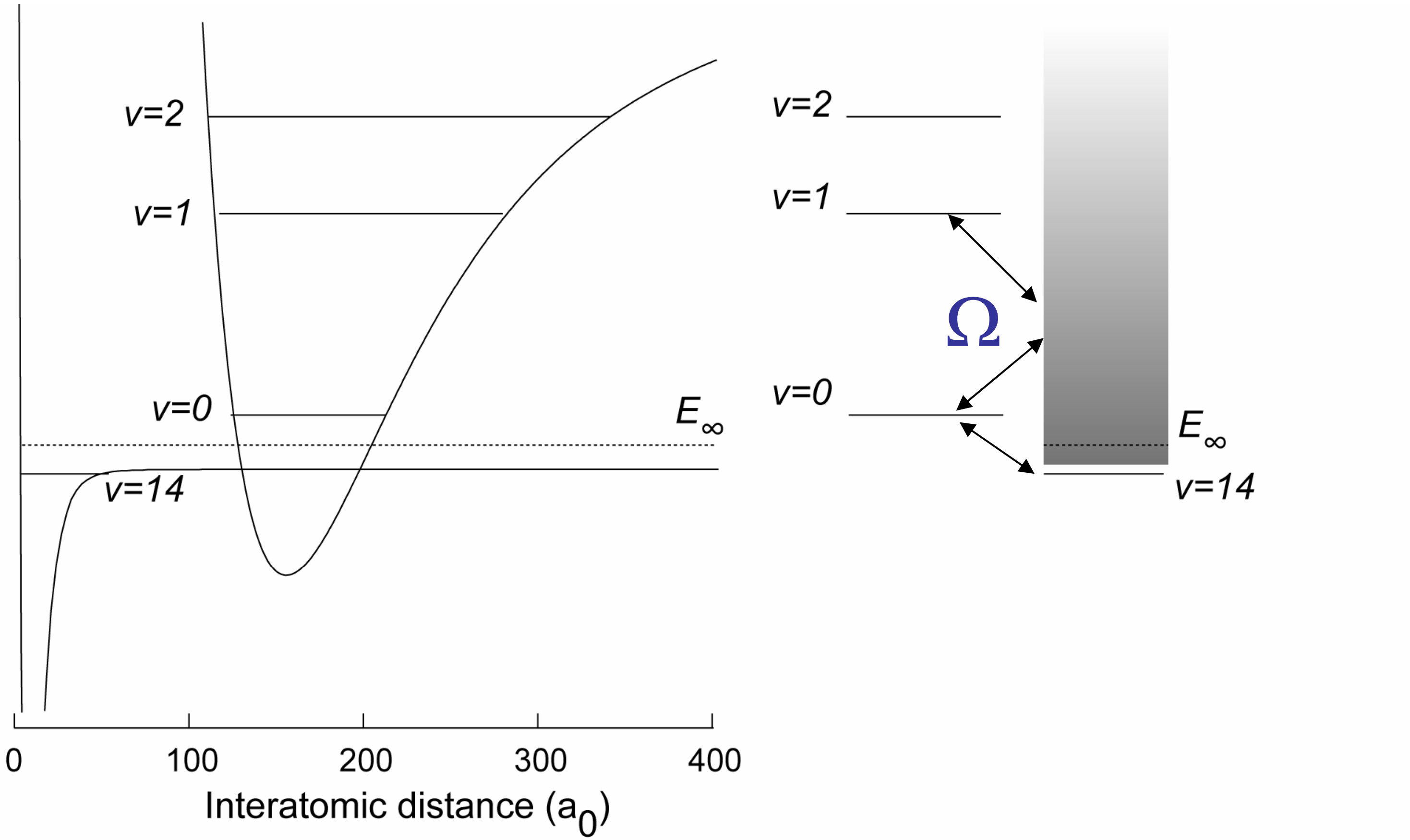


Large uncertainties on actual laser intensity focused on the atomic cloud :Measurement of slope ratios

Experimental dependance on light polarization

Physical origin of the shift

In the dressed-atom picture



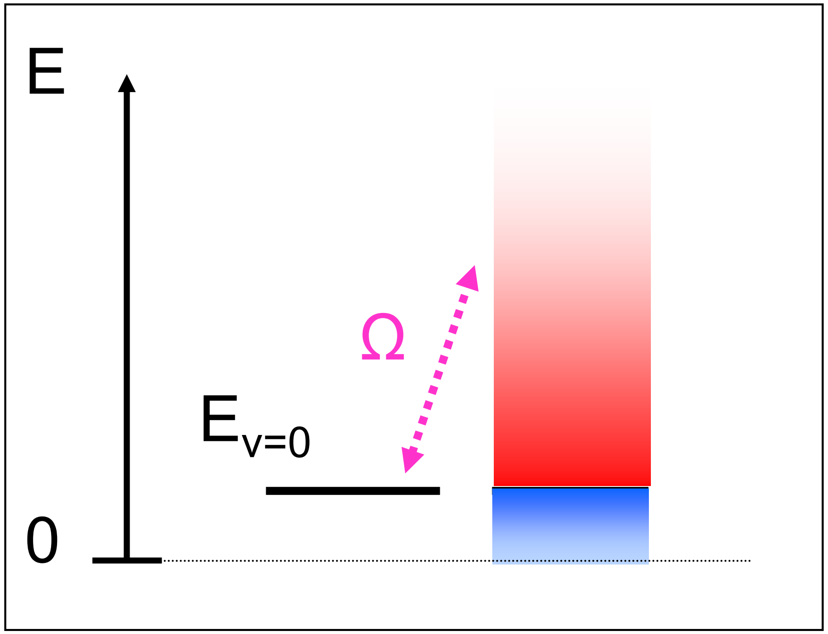
- shifts of discrete states embedded in a continuum

  $\hbar\Omega$ << *excited level spacing : isolated level approximation*

- $E_\infty \rightarrow 0$ and $E_{v=14} \rightarrow 0$: influence of *v=14* on the shift

Contribution of the continuum states

Fano *(Phys. Rev. 124, p1866, 1961)*
Simoni et Julienne *(PRA 66, 063406, 2002)*



$$\delta = \frac{1}{2\pi} vp \int_0^{+\infty} \frac{\Gamma(E)}{E_{v=0} - E} dE$$

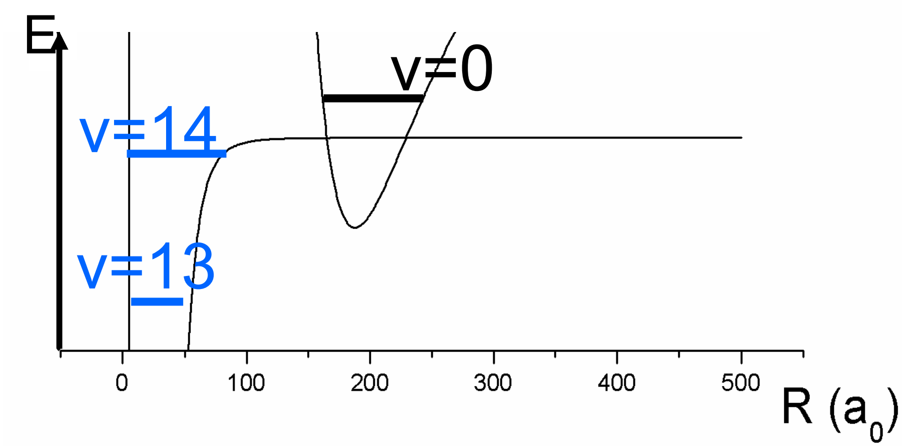
$$\Gamma(E) = 2\pi \left| \langle \phi^e_{v=0} | \Omega | \psi^g_E \rangle \right|^2$$

Contribution to the integral :
- blue if $E<E_{v=0}$
- red if $E>E_{v=0}$

Red contribution in the limit $E \rightarrow 0$
Proportional to laser intensity

The Franck-Condon overlaps depend on *a*

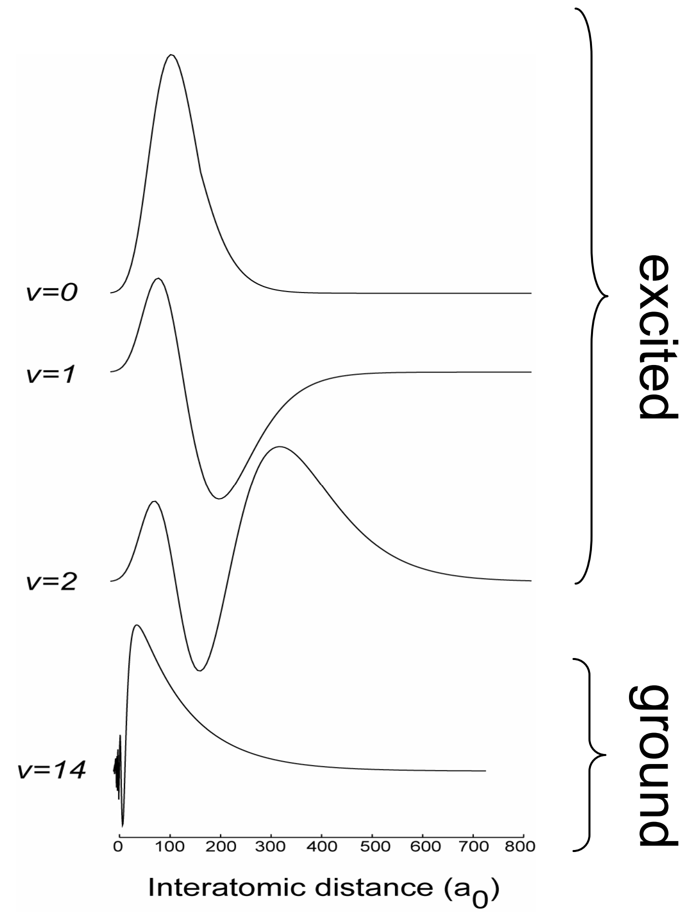
Contribution of the bound states



$$\delta = \sum_{i=0}^{14} \frac{|\langle \phi^e_{v=0}|\Omega|\phi^g_{v=i}\rangle|^2}{E^e_{v=0} - E^g_{v=i}} \approx \frac{|\langle \phi^e_{v=0}|\Omega|\phi^g_{v=14}\rangle|^2}{E^e_{v=0} - E^g_{v=14}}$$

Proportional to laser intensity

$E^e_{v=0} - E^g_{v=i} > 0$: blue contribution

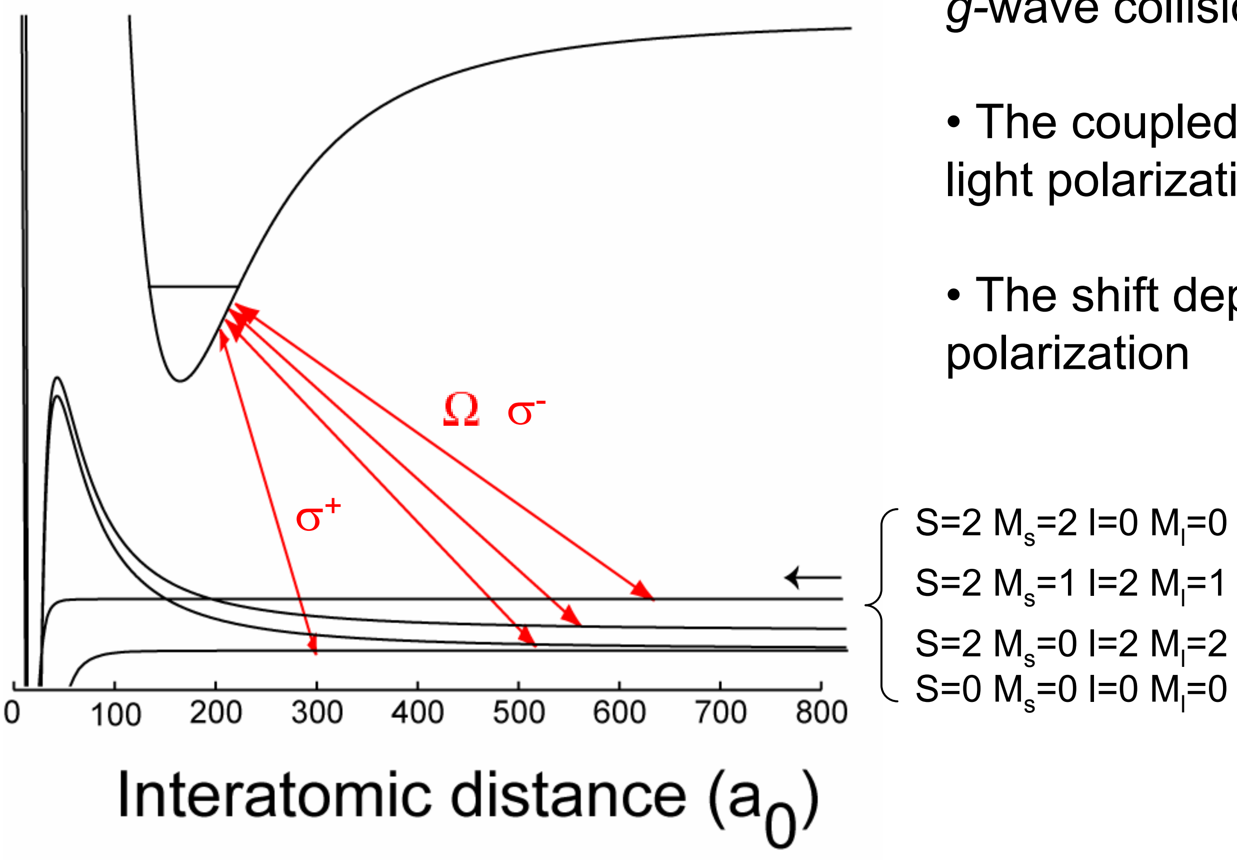


<u>dependance on *a* in :</u>

- the Franck Condon overlaps
- the position of $E_{v=14} \sim -h^2/2\mu a^2$

Vanishing overlap for odd vibrational numbers in the excited state

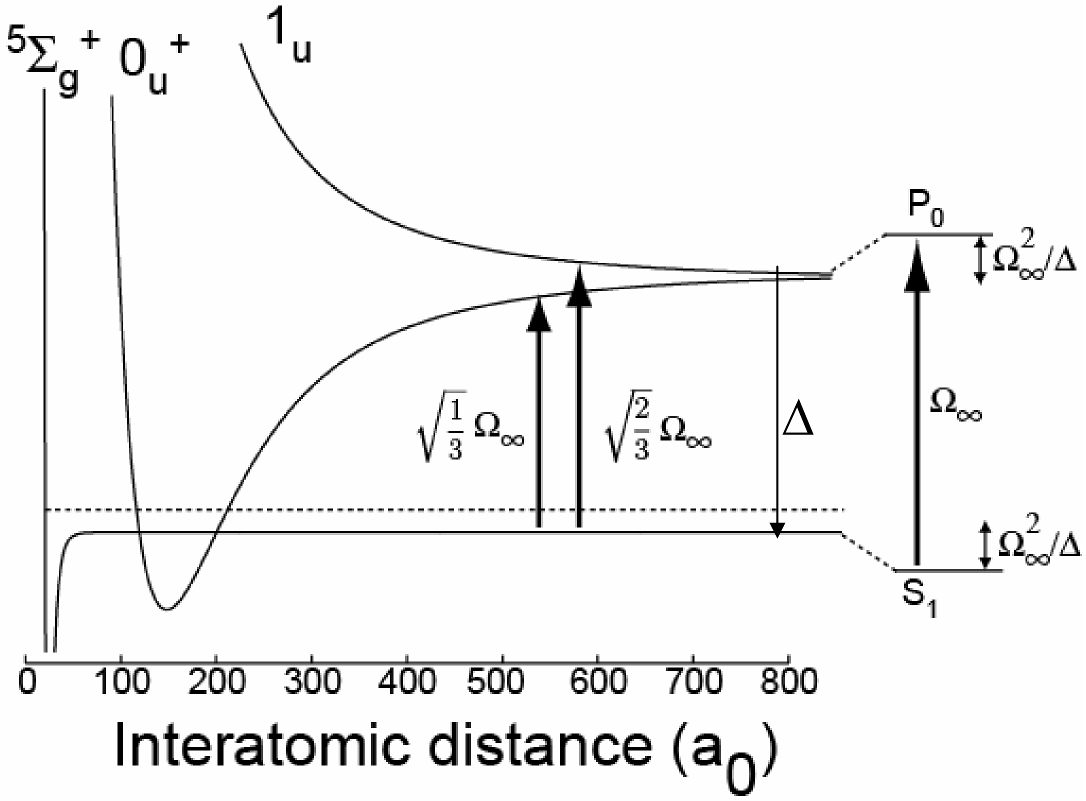
Dependance on light polarization



- The excited state is coupled to other collisional channels than the incoming one (non polarized spin states, *d*- and *g*-wave collisions)
- The coupled channels depend on light polarization
- The shift depends on light polarization

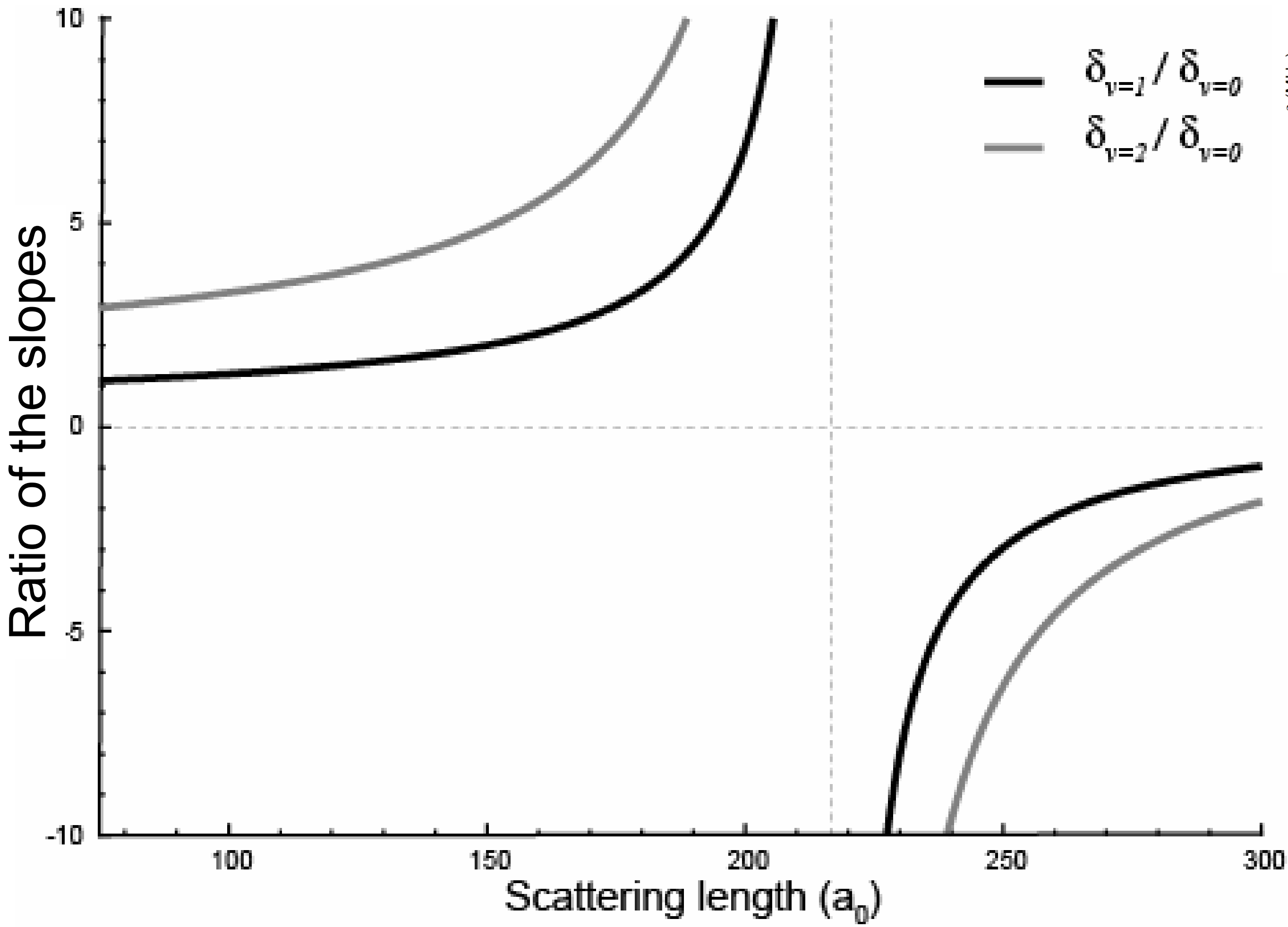
Are there any other light shifts ?

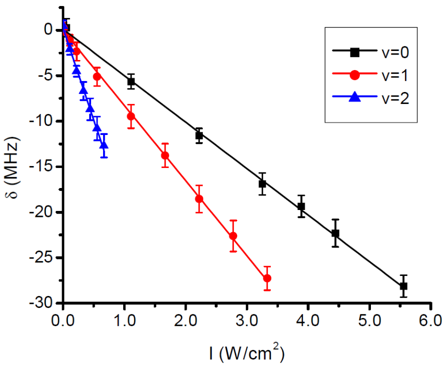
Influence of dressing effects



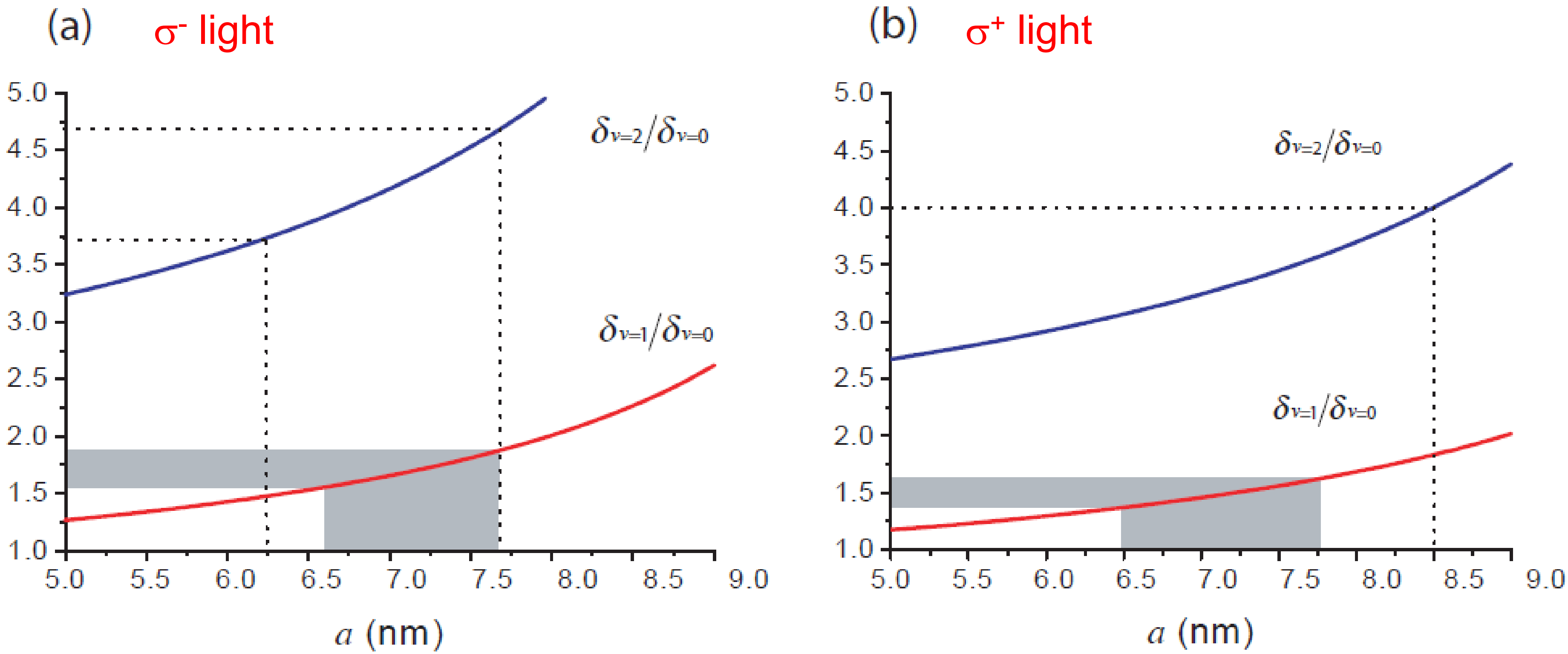
- at infinite separation, the atoms still interact with light
- additional shifts of the order of Ω^2/Δ
- overall effect found to be negligible

Comparison between theory and experiment





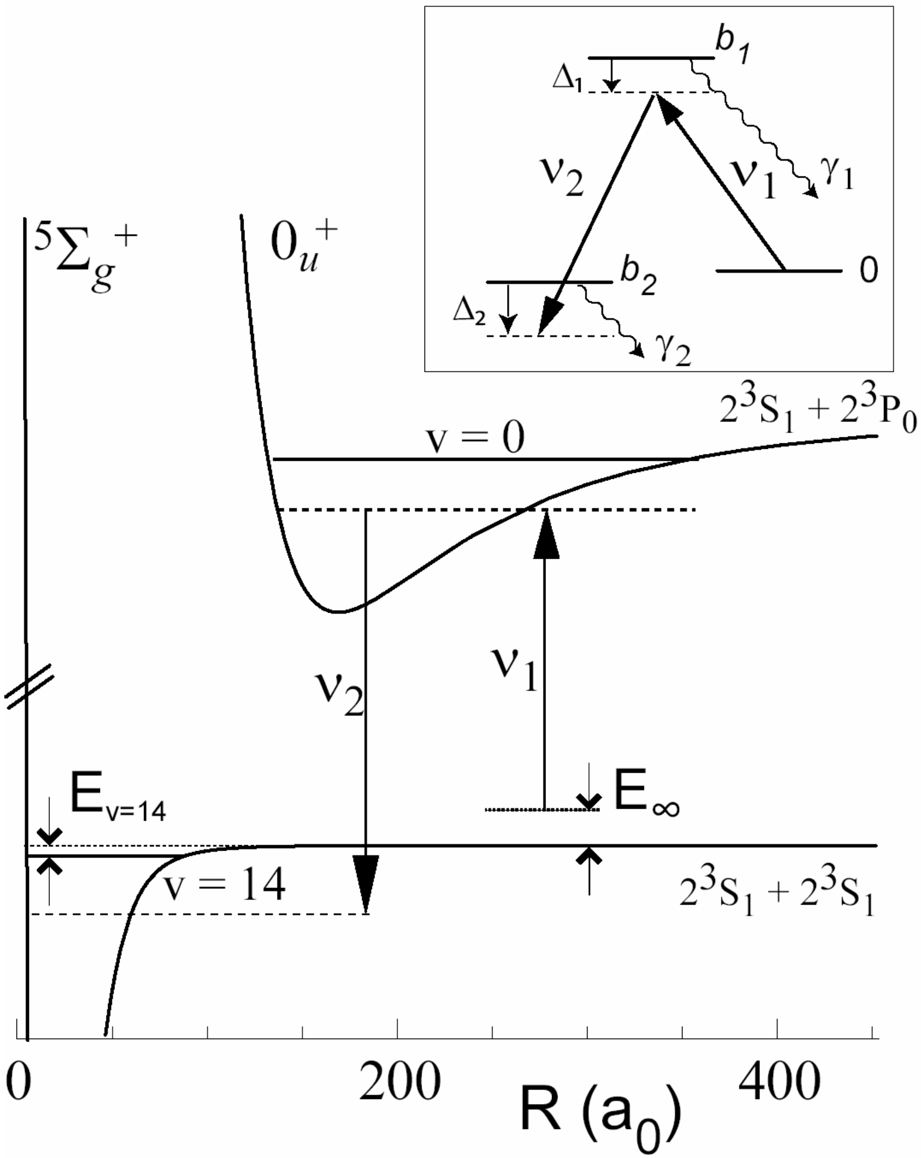
Comparison between theory and experiment



a = 7.2 ± 0.6 nm

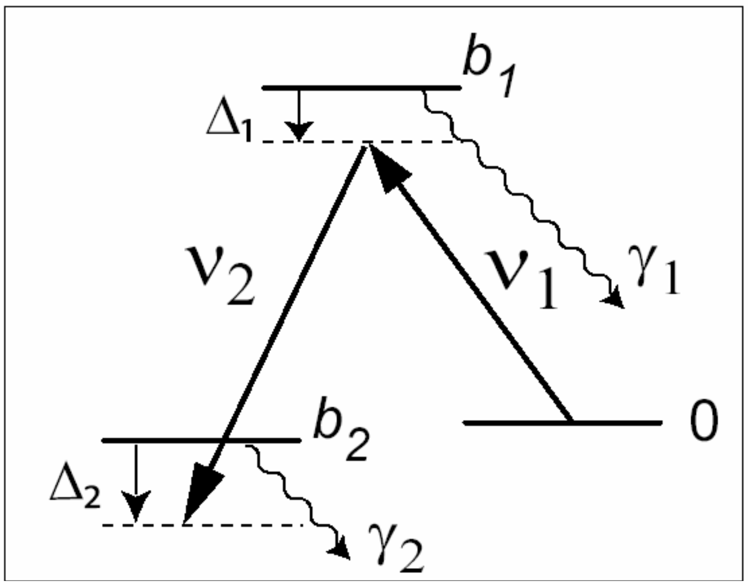
Eur. Phys. Lett. ***72*** *548 (2005)*

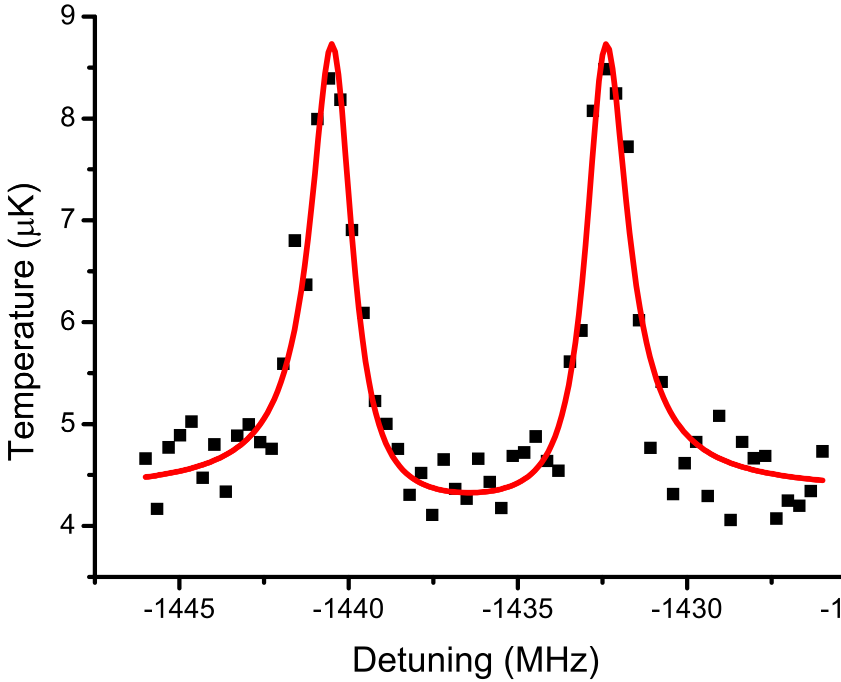
2-photon photoassociation and stimulated Raman process



Measuring the energy of the highest bound state provides an even more precise determination of a

Autler-Townes splitting

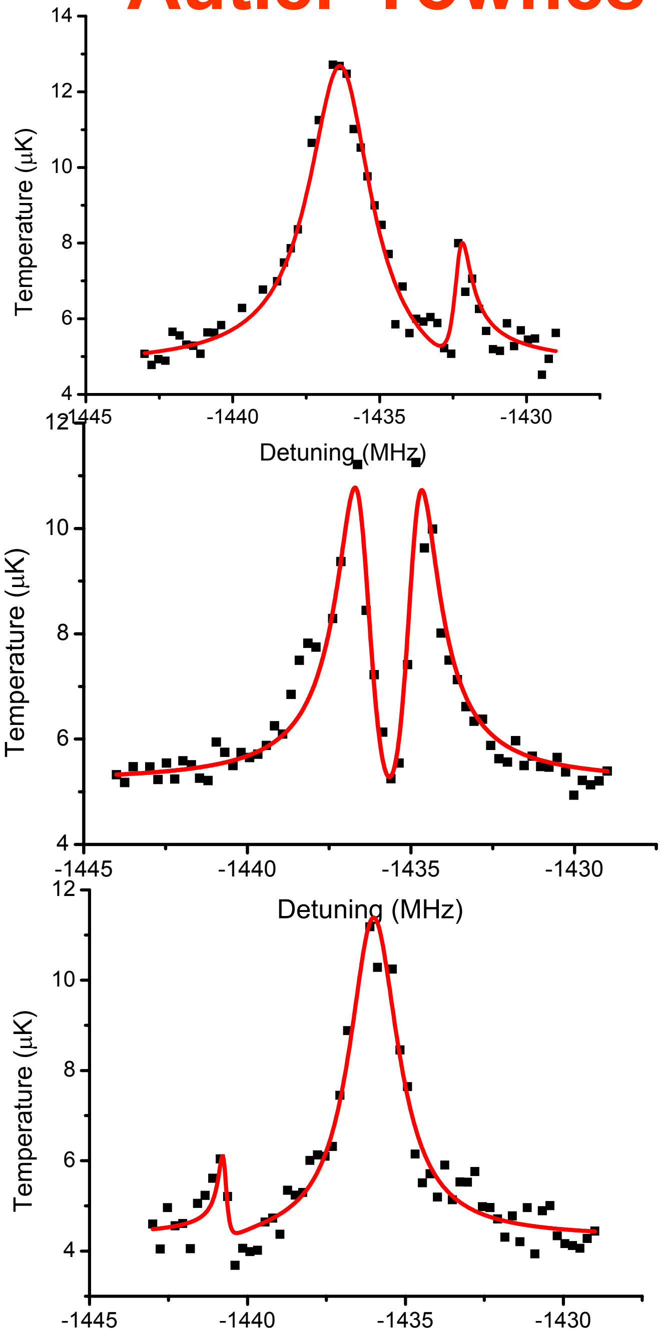




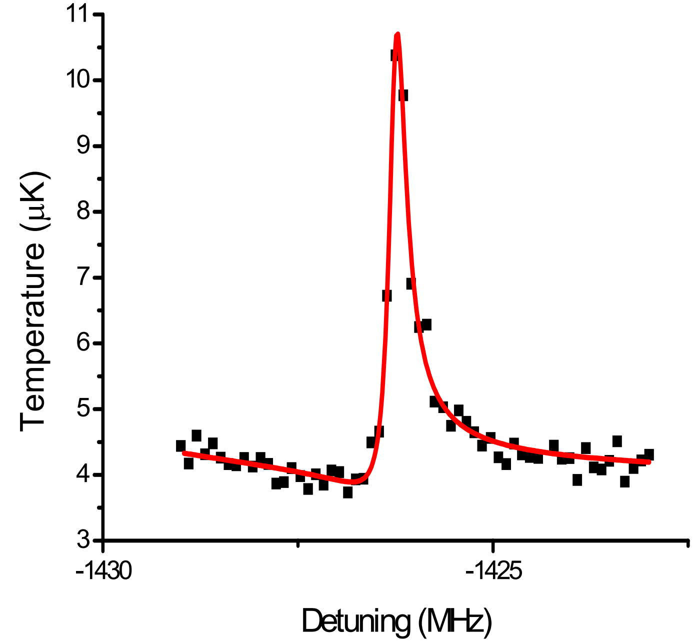
Laser 2 : at resonance on b1 – b2 transition

Laser 1 : scanned probe

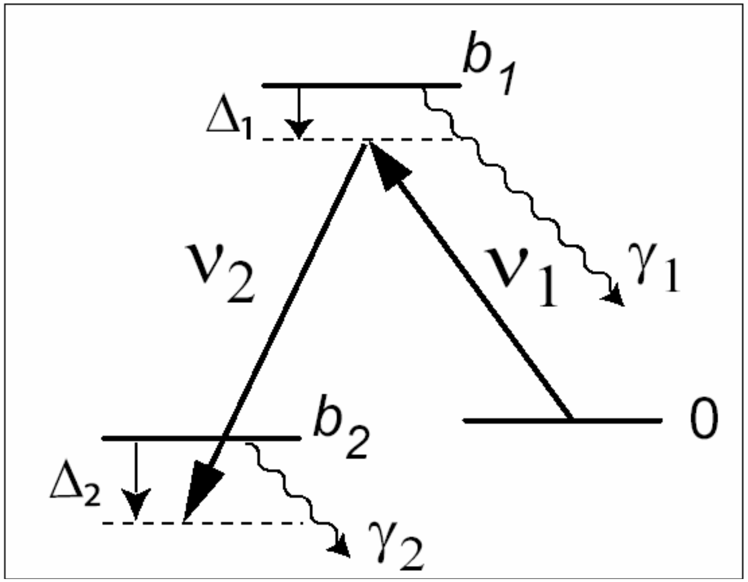
Autler-Townes doublet and Raman peak

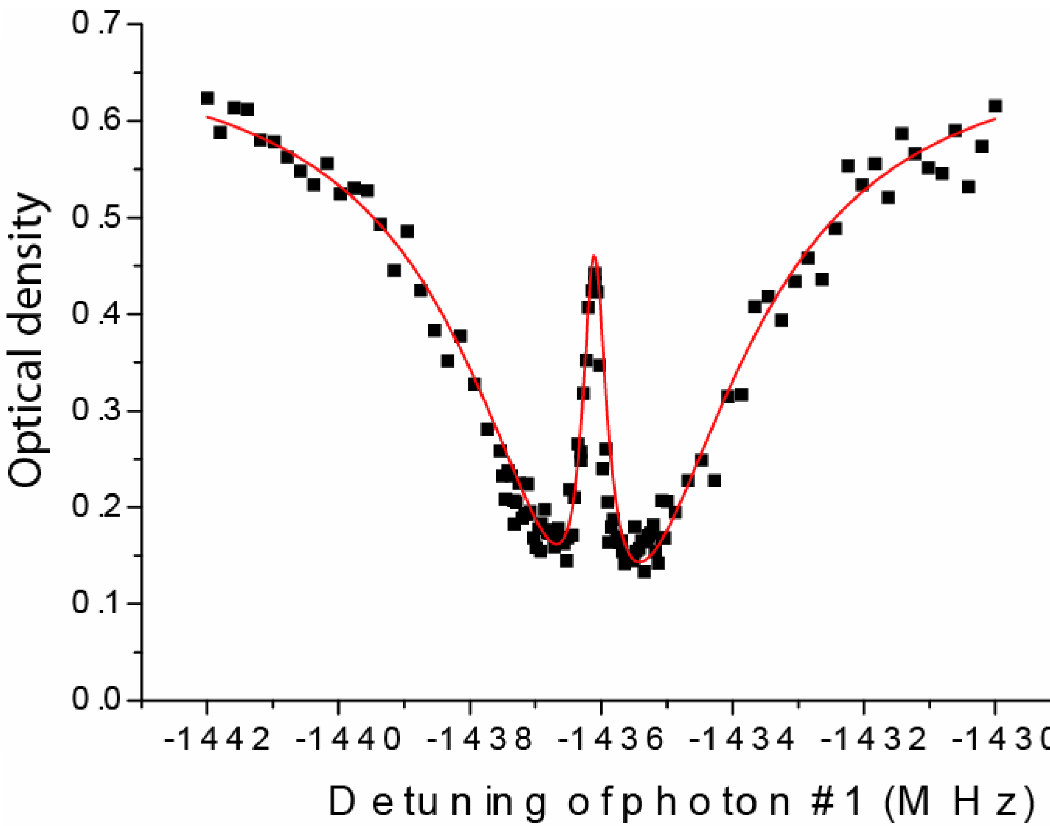


Fano profile



Dark resonance



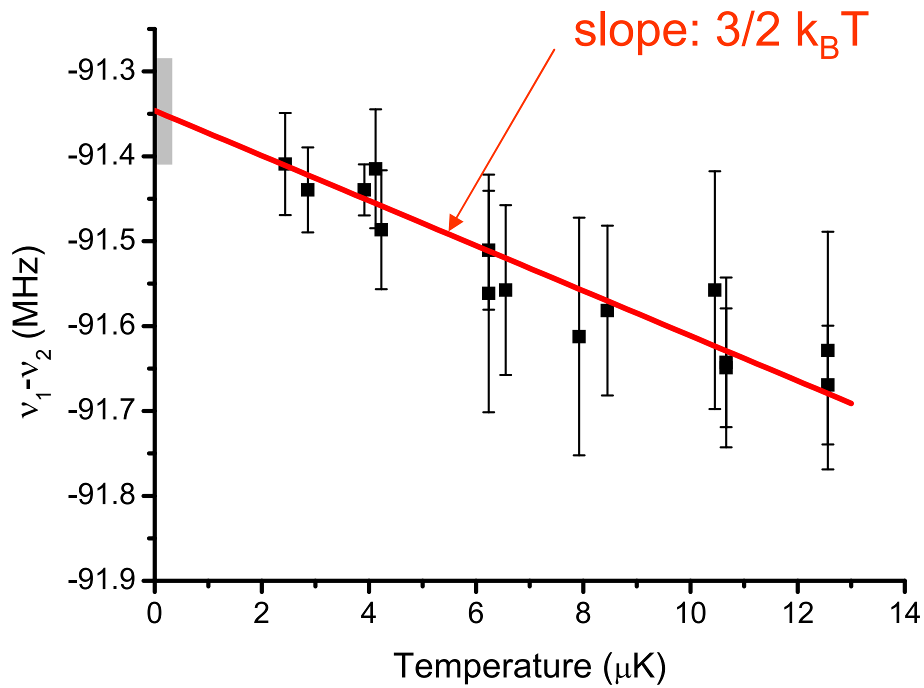


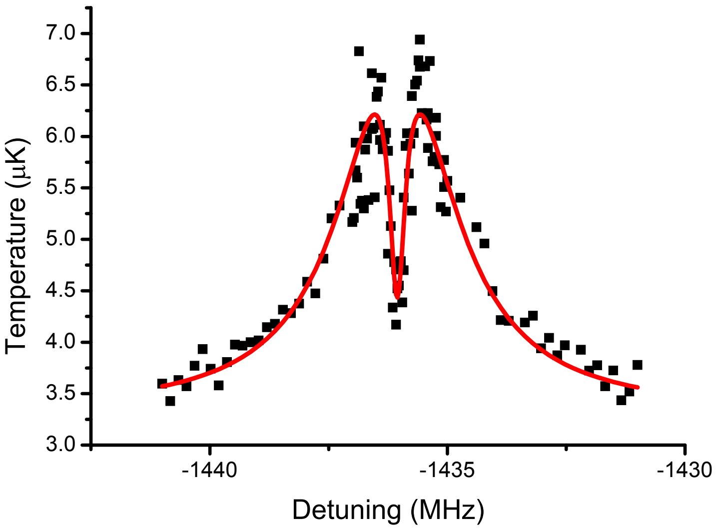
Laser 2 : at resonance on b1 – b2 transition, low intensity

Laser 1 : scanned probe

Destructive interference between amplitudes of atom-bound (0-b_1) and bound-bound (b_1-b_2) transitions

Measuring the position of the dark resonance



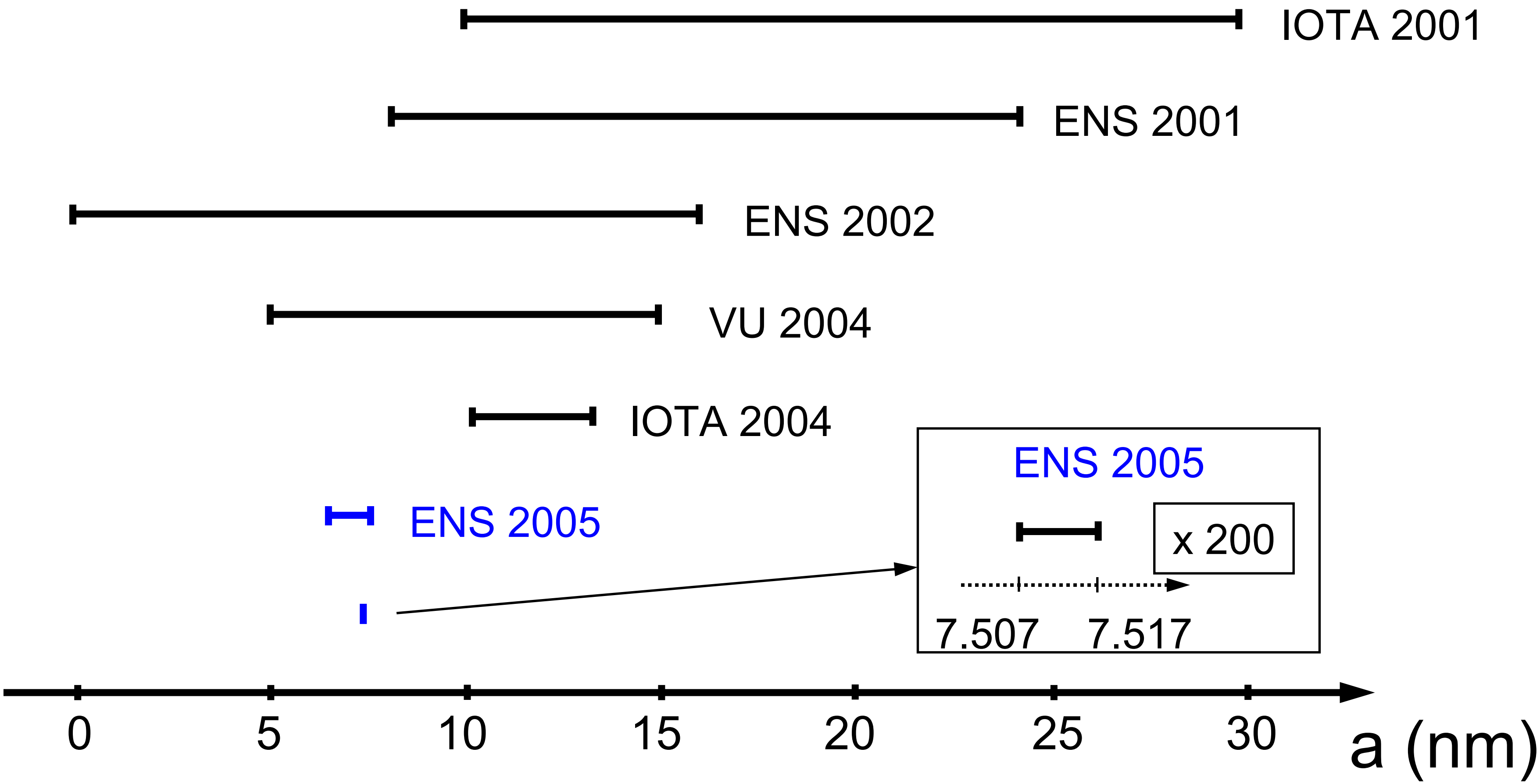


$$E_{v=14} = -91.35 \pm 0.06 \text{ MHz}$$

Using *ab initio* potentials from Przybytek and Jeziorski, J. Chem. Phys. **123**, 134315 (2005)

$$a = 7.512 \pm 0.005 \text{ nm}$$

S-wave scattering length of spin-polarized metastable helium



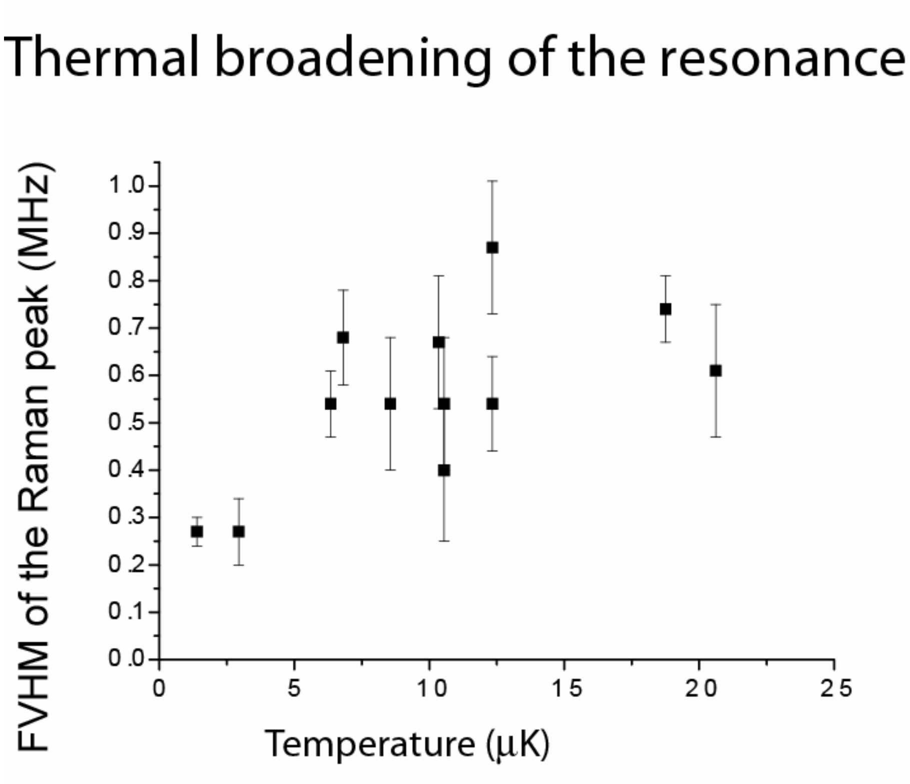
a = 7.512 ± 0.005 nm *(PRL* ***96*** *023203, (2006))*

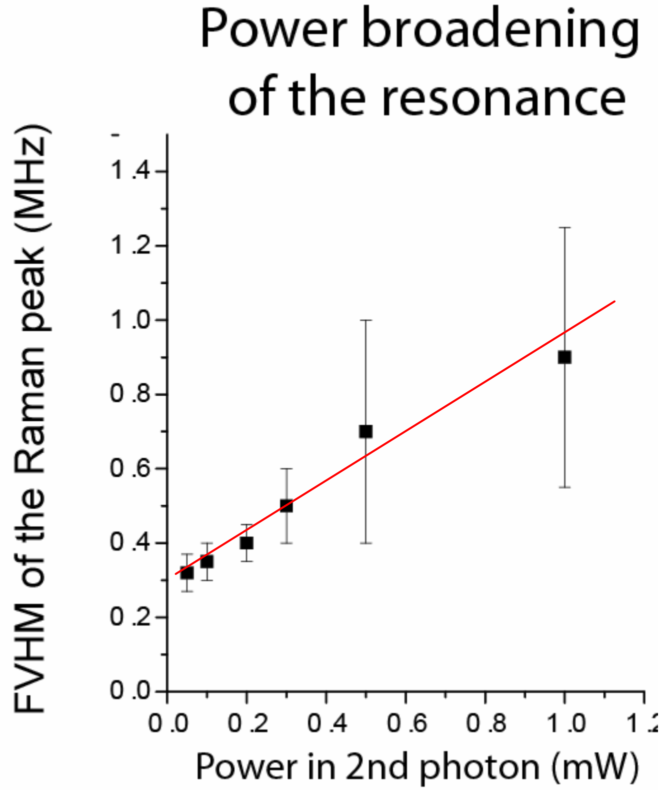
Theoretical value : a = 7.64 ± 0.2 nm

Measuring the lifetime of the molecular state *v*=14

Exotic molecule : two bound ^{4}He* atoms distant of about 5 nm

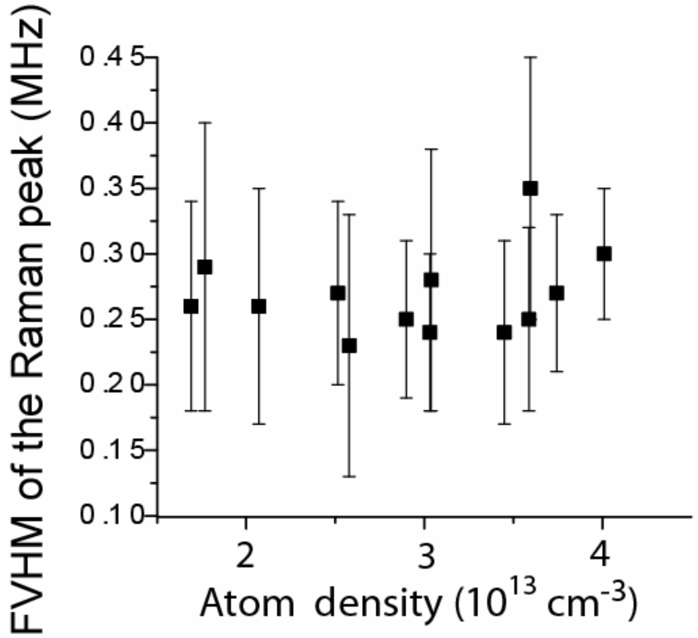
What is limiting the width of our signals ?





What is limiting the width of our signals ?

Do atom-molecule collisions limit the lifetime of *v=14* ?



No

Natural width of the order of 0.3 MHz
→
Lifetime of 3 μs

LIFETIME MOST LIKELY LIMITED BY PENNING PROCESSES

Inelastic decay between spin-polarized atoms in an ultracold gas previously investigated theoretically and Experimentally (Fedichev *et al.* PRA 53, 1447 (1996), Venturi *et al*. PRA 60, 4635 (1999)):

Rough estimate using r_0 *(~5nm)* the mean size of the dimer and the theoretical Penning collision rate in a spin-polarized gas K_{inel}

$$1/(K_{inel} r_o^{-3}) \sim 4\mu s$$

Good agreement

Prospects

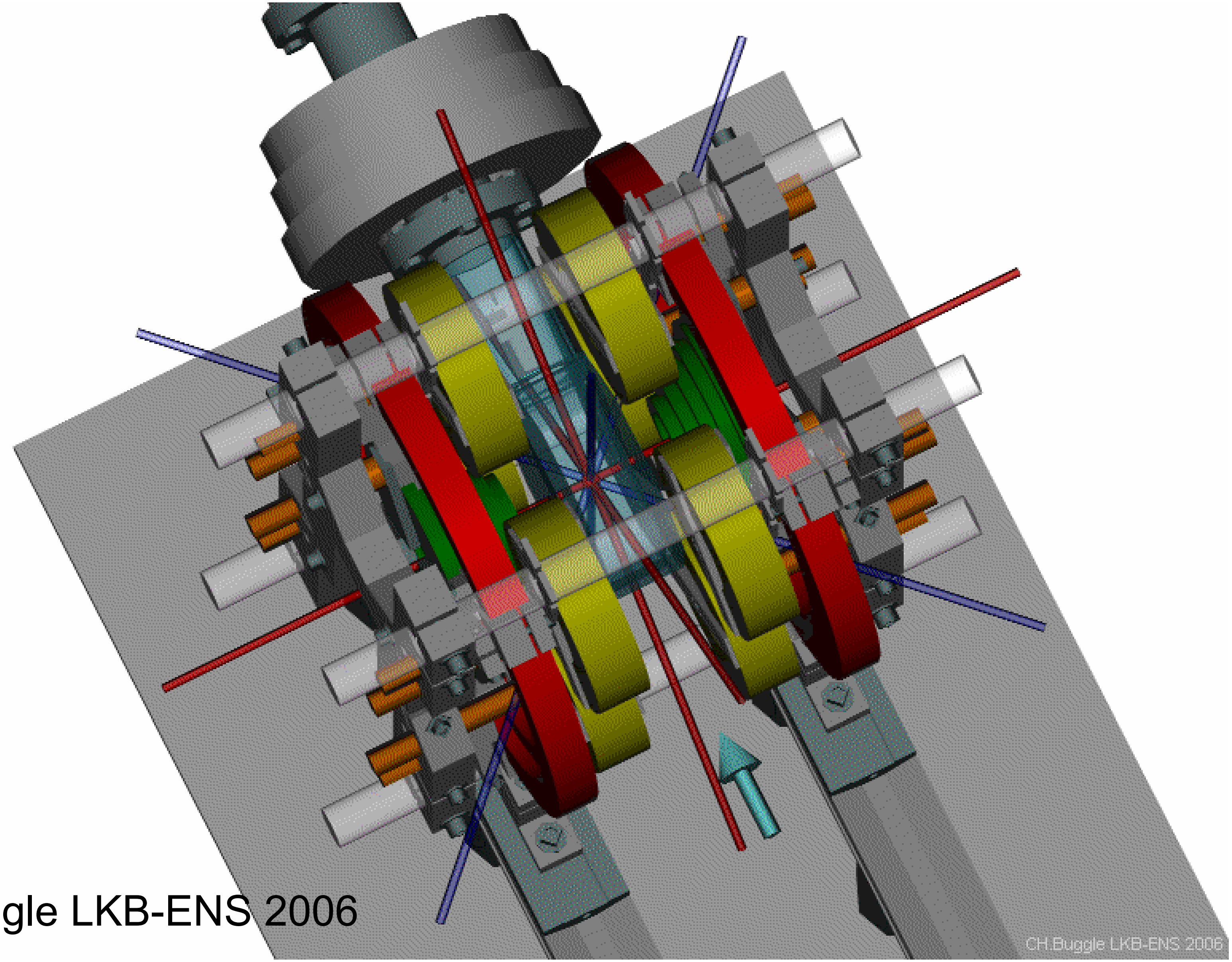
- Calculation of K_{inel} using potentials adjusted to the new determination of *a*

- Accurate estimation of the expected lifetime of the molecular state *v=14* due to Penning processes using close-coupled calculation

The present team

from left to right : Julien Dugué, Nassim Zahzam, Christian Buggle, Claude Cohen-Tannoudji, Maximilien Portier, Michèle Leduc, Steven Moal, C. S. Unnikrishnan

Soon : a new setup !



Ch. Buggle LKB-ENS 2006