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Thermodynamics of non ideal trapped quantum gases: some new quantitative experimental studies

3rd Windsor Summer School on Condensed Matter Theory

Groupe d’Optique Atomique

Laboratoire Charles Fabry de l’Institut d’Optique - Orsay

http://atomoptic.iota.u-psud.fr

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Thermodynamics of non ideal trapped bosonic gases: some new quantitative experimental studies

- “Standard” method for alkalis revisited
- New methods with metastable Helium BEC

Non-ideal behavior in the thermodynamics of a trapped Bose gas

Atomic interactions: definite influence on the dynamics (modes) of a trapped Bose gas (Cornell-Wieman, Ketterle, Foot: scissor modes)

What about thermodynamics?

- Critical temperature T_c *vs.* Atom number N
- Condensed fraction N_0 / N *vs.* T / T_c
- Interaction energy, equilibrium shape of each component…

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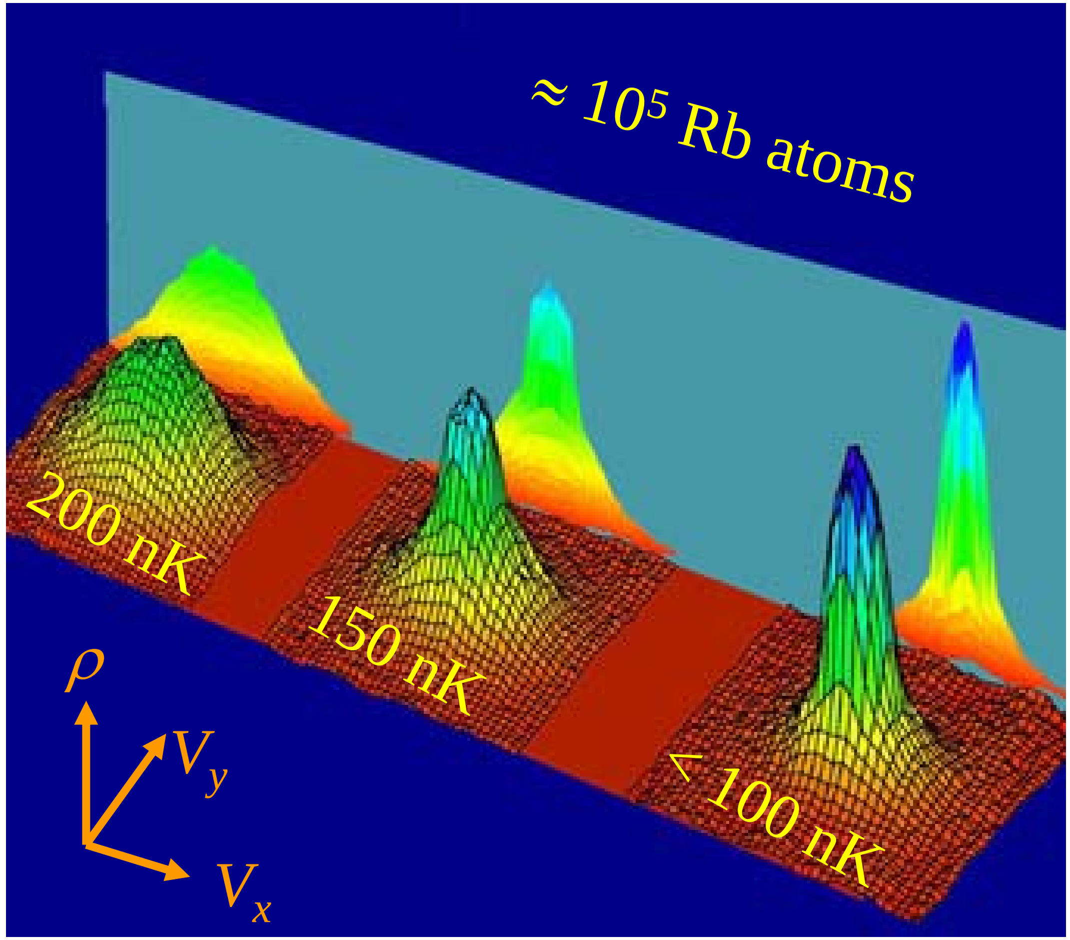
Thermodynamics of non ideal trapped bosonic gases: some new quantitative experimental studies

1. “Standard” method for alkalis revisited

- Critical temperature (F. Gerbier et al., PRL 92, 030405, 2004)
- Condensed fraction, interaction energy, equilibrium shape of a mixed profile… (F. Gerbier et al., PRA 70, 013607, 2004)

Trapped BEC: standard analysis

- Turn off the trap at $t = 0$
- Ballistic expansion, duration τ
- Absorption imaging
  - *Thermal component (Bose function, Gaussian wings): mostly velocity
  - *Condensate (Thomas Fermi profile, inverted parabola): mostly interaction energy



- Measurements difficult at a few percent level
- Theoretical issue: expansion of an interacting mixed cloud?

Critical temperature of a trapped Bose gas

Ideal (non-interacting) trapped Bose gas

$$T_c^{\text{ideal}} = T_c^0 - \frac{\zeta(2)}{\zeta(3)} \frac{\hbar(\omega_z + 2\omega_\perp)}{6k_B}$$

Thermodynamics limit

$$n\Lambda_T{}^3 = 2.612$$

« Finite size » effects

2% with our parameters

$$\omega_\perp / 2\pi = 413 \text{ Hz}$$

$$\omega_z / 2\pi = 8.69 \text{ Hz}$$

Critical temperature of a non ideal Bose gas

Effect of interactions?

Uniform case (box)

- Theory: T_c □ because of density fluctuations (a hot topics)
- Observed with dilute LHe on Vycor

Harmonic trap

- Theory: T_c □ for repulsive interaction because of density decrease at the trap center (Einstein criterium unchanged):

  W. Krauth; Giorgini et al. (1996)

$$\frac{T_c - T_c^{\text{ideal}}}{T_c^0} \approx -1.33 \frac{a}{a_{\text{HO}}}$$

- Observation?

Critical temperature of a trapped non ideal Bose gas

Inconclusive experiments, except for a pioneering observation (1 standard deviation) by Ensher et al. (1996).

work	measured $\Delta T_c/T_c^{ideal}$
Mewes 1996	(assumed 0.0)
Ensher 1996	-0.06 ± 0.05
Han 1998	-0.04 ± 0.15
Shreck 2001	0.0 ± 0.2
Maragò 2001	0.00 ± 0.03

Two experiments in Orsay

- He*, with use of Penning ion rate measurements: team of Chris Westbrook
- Rb with standard analysis (revisited): team of Philippe Bouyer

Critical temperature of a trapped ^{87}Rb Bose gas: experimental tips

Fight shape oscillations ocurring at condensation in an elongated trap

- Slow down evaporation near condensation (200 kHz / s)
- Hold time (1 s) with RF knife on

Excellent control of the evaporating knife position above trap bottom

- Reference checked every 5 evaporations (emptying the trap)
- Temperature reproducibility: 20 nK

Critical temperature of a trapped ^{87}Rb Bose gas: atom number measurement

Standard absorption imaging after 22 ms TOF

- Condensed number N_c from Thomas-Fermi profile fit
- Total atom number N (thermal cloud + condensate) from integration

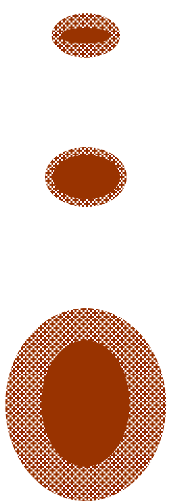
Absolute calibration of absorption cross section for our particular set up (polarisation, repumper, etc…):

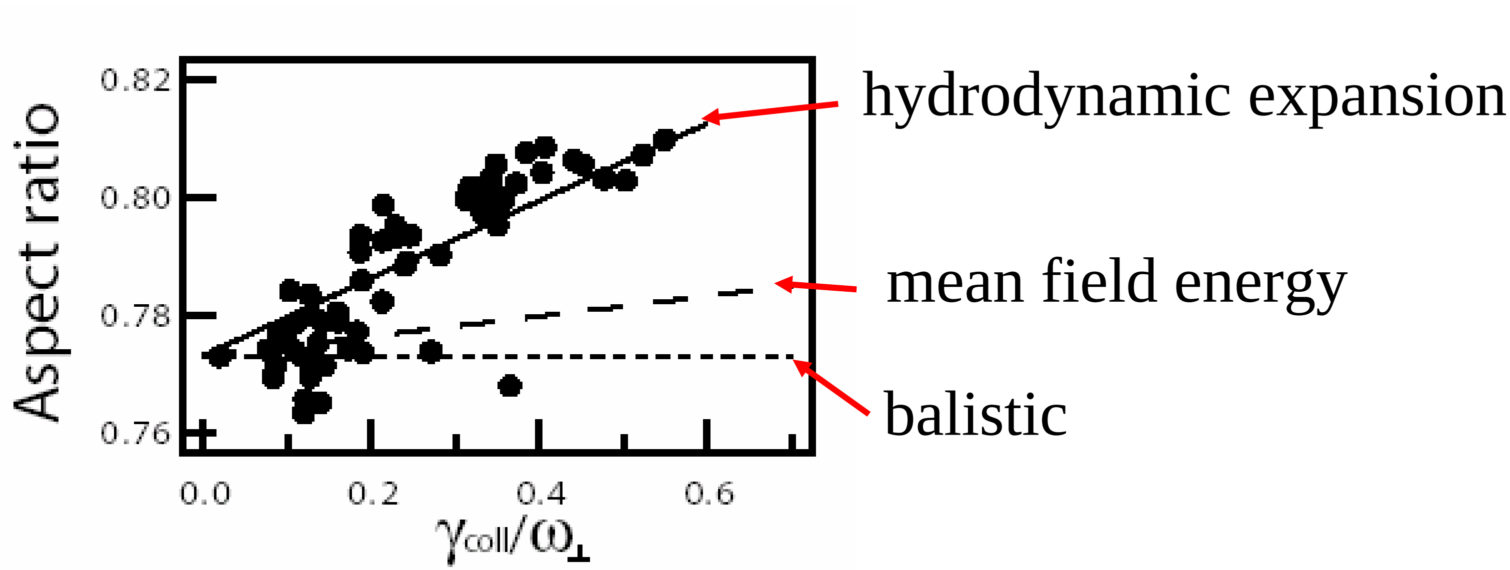
- Absolute atom number inferred from expansion energy of a pure BEC and compared to integrated absorption signal: relies on the value of the scattering length (accurately known from spectroscopy)

Critical temperature of a trapped ^{87}Rb Bose gas: temperature measurement revisited

Standard procedure of fitting a Bose profile to the wings of the TOF of the almost pure thermal cloud.

Necessary to compensate for hydrodynamics effect for large and dense thermal clouds (elongated trap $\omega_z / \omega_\perp \approx 45$). Also in Amsterdam.

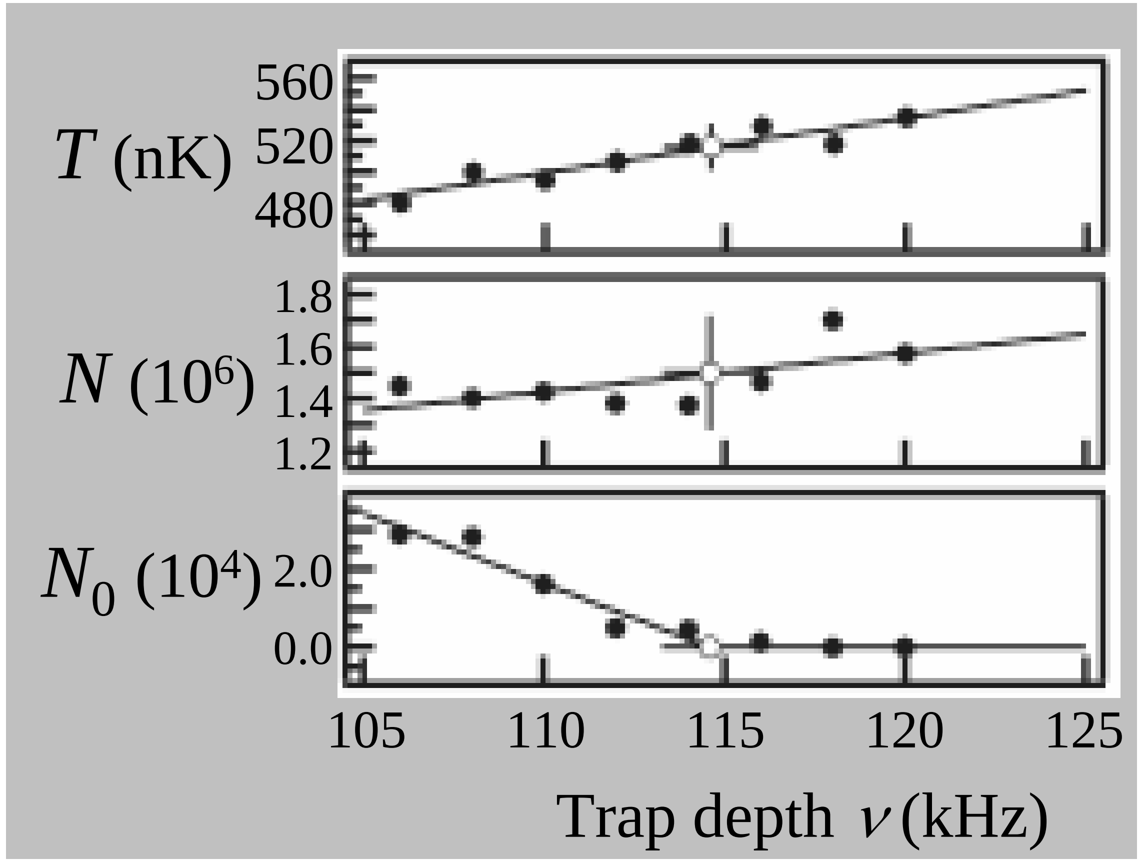




Critical temperature of a trapped ^{87}Rb Bose gas: determination of critical values N_c and T_c

Very reproducible evap. ramps, stopped at different values of trap depth ν:

- plot T, N, N_0 vs. ν
- linear fits
- find ν_c
- derive N_c and T_c



See estimated error bars

Critical temperature of a trapped ^{87}Rb Bose gas: results

- Non ideal behavior (effect of interactions) observed at the level of $2\,\sigma$

- Good agreement with mean field theory: fit of ΔT by $\alpha N^{1/6}$ yields:

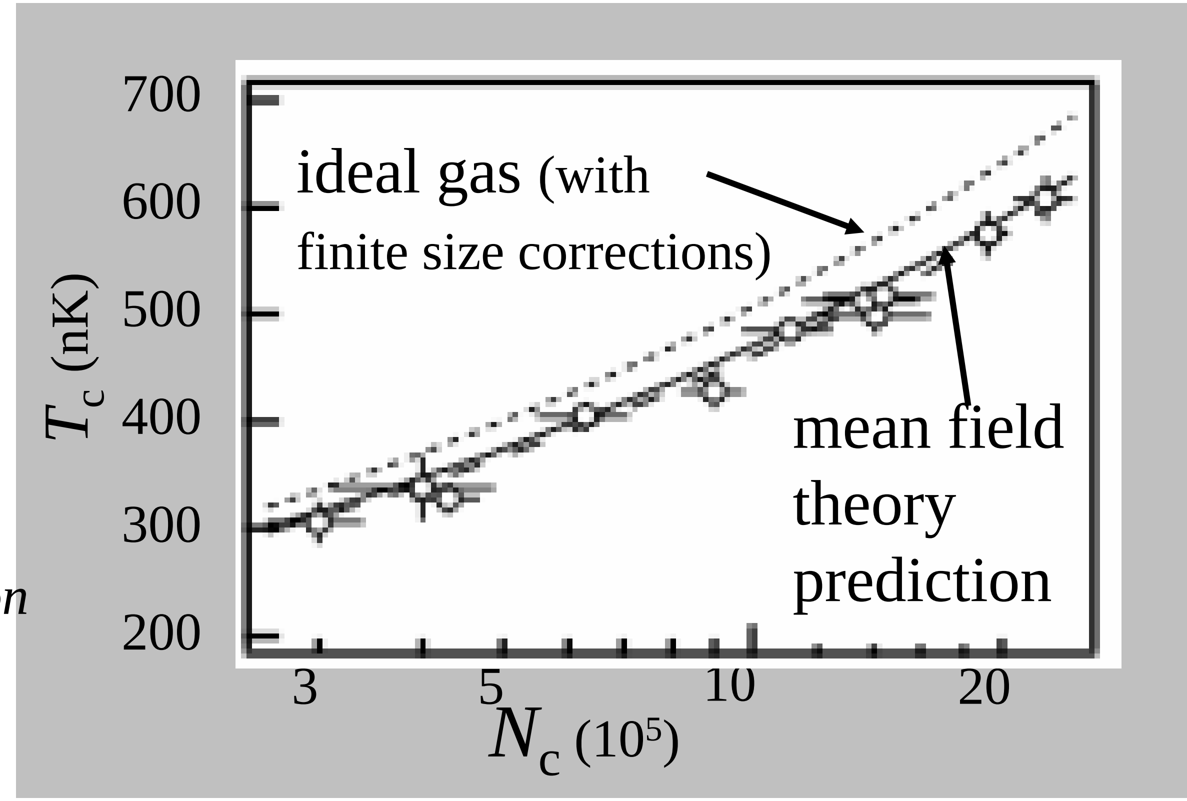
$$\alpha = -0.009(1)^{+0.003}_{-0.002}$$

calibration

statistical

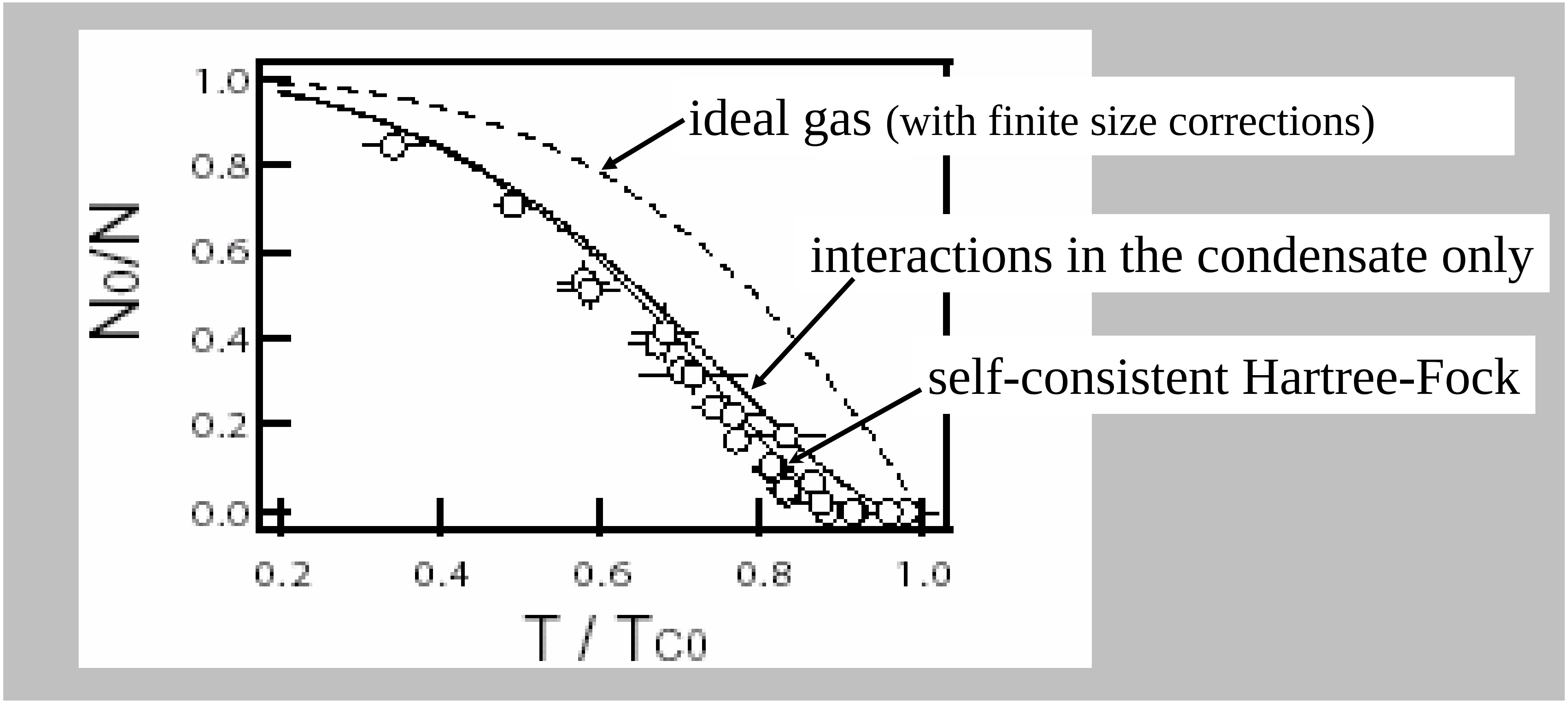
to be compared to

$$\alpha_{th} = -0.007$$



- No upwards shift due to density fluctuations as predicted for homogeneous case: in agreement with predicted suppression for trapped Bose gases (Giorgini, Pitaevski, Stringari; Arnold and Tomasik)

Trapped ^{87}Rb Bose gas: condensed fraction



Reasonable agreement but experiment systematically below theory

Error in temperature measurement due to interaction between thermal cloud and BEC during expansion? Theory is missing for expansion of a mixed cloud!

Trapped interacting Bose gas: conclusions

Deviation from ideal gas clearly observed

Agreement with mean field theory

- Shift of critical temperature
- Self consistent Hartree Fock modeling of the mixed cloud profile

Observation of hydrodynamics effects in TOF of dense thermal cloud

Theory needed to better understand TOF of mixed sample (condensate and thermal cloud)

No effect observed beyond mean field: likely to be difficult

Thermodynamics of non ideal trapped bosonic gases: some new quantitative experimental studies

1. “Standard” method for alkalis revisited
2. New methods with metastable Helium BEC

A. Browaeys et al., Phys. Rev. A **64**, 34703 (2001).

A. Robert et al., Science **292**, 461 (2001).

O. Sirjean et al., PRL 89(22): 220406 (2002)

S. Seidelin et al., PRL in print

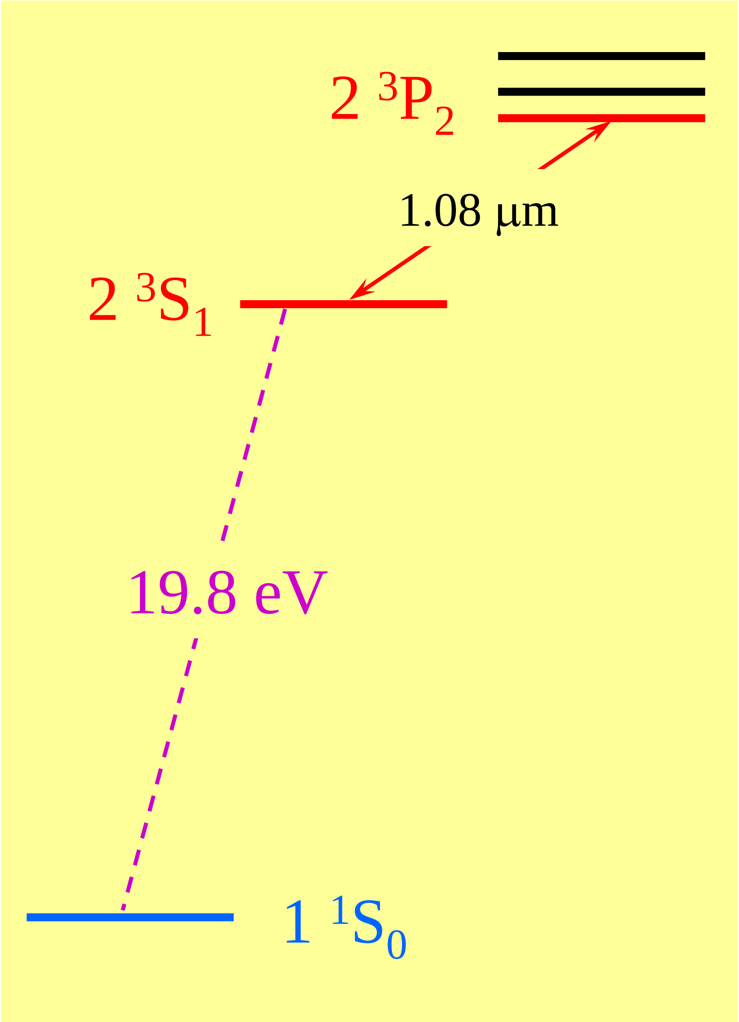
Metastable Helium $2\ ^3S_1$

- Triplet (↑↑) $2\ ^3S_1$ cannot *radiatively* decay to singlet (↑↓) $1\ ^1S_0$ (lifetime 9000 s)
- Laser manipulation on closed transition $2\ ^3S_1 \rightarrow 2\ ^3P_2$ at 1.08 μm (lifetime 100 ns)

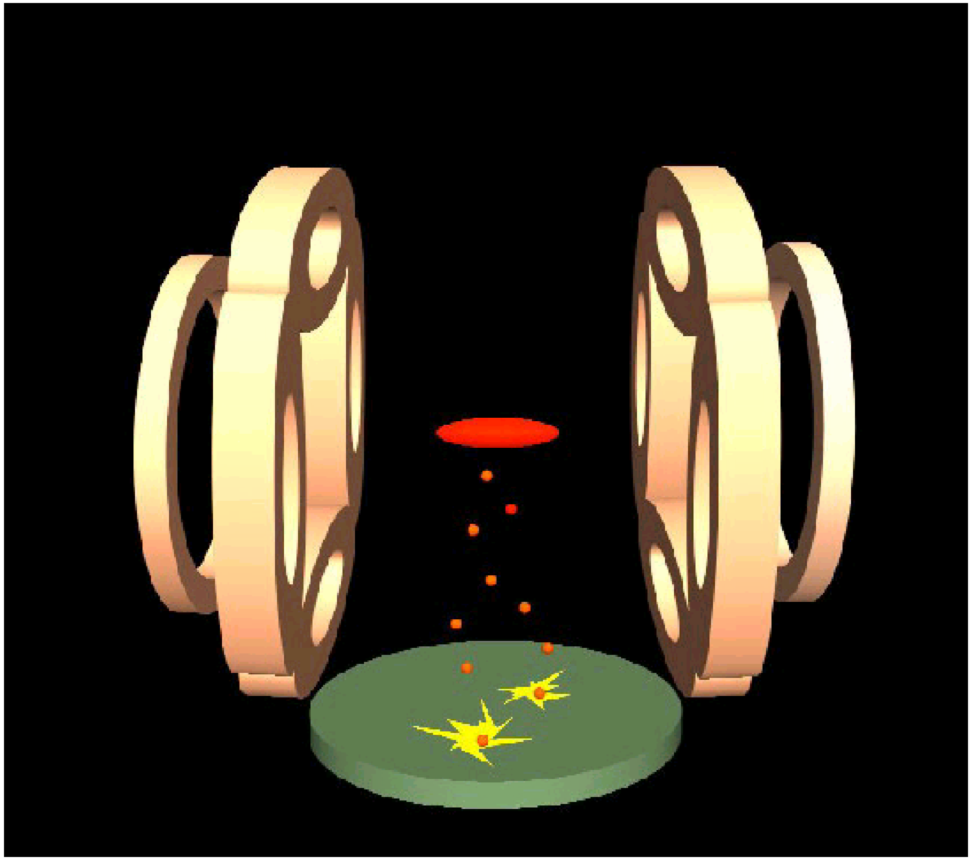
- Large electronic energy stored in He*

  ⇒ ionization of colliding atoms or molecules

  ⇒ extraction of electron from metal: single atom detection with Micro Channel Plate detector



He* trap and MCP detection



Clover leaf trap

@ 240 A : B_0 : 0.3 to 200 G ;

B' = 90 G / cm ; B''= 200 G / cm^2

$\omega_z / 2\pi$ = 50 Hz ; $\omega_\perp / 2\pi$ = 1800 Hz (1200 Hz)

He* on the Micro Channel Plate detector:

⇒ an electron is extracted

⇒ multiplication

⇒ observable pulse

Single atom detection of He*

The route to He* BEC: not such an easy way

Pros:

- Strong magnetic trap (2 Bohr magnetons)
- Ultrasensitive detection scheme
- Very rapid release scheme

$\Rightarrow$ Excellent TOF diagnostic

Cons:

- Source of cold He* not as simple as alkalis'; vacuum challenges
- Elastic cross section *a priori* unknown at low temperature

  Direct measurement of rethermalization of the energy distribution after RF knife disturbance (A. Browaeys et al., PRA…): $a \approx 20$ nm (as predicted by Shlyapnikov 95, Venturi …)
- Penning ionization

Penning ionization of He*

$$He^{*} + He^{*} \rightarrow He(1\,^{1}S_{0}) + He^{+} + e^{-}$$

Reaction constant ≈ 5×10^{-10} $cm^{3}.s^{-1}$ @ 1 mK

Impossible to obtain a sample dense enough for fast thermalization?

Solution (theory, Shlyapnikov et al., 1994; Leo el al.):

Penning ionization strongly suppressed (10^{-5} predicted!) in spin polarized He* because of spin conservation:

$$m = 1 \; + \; m = 1 \; \not\rightarrow \; s = 0 \; + \; s = 1/2 \; + \; s = 1/2$$

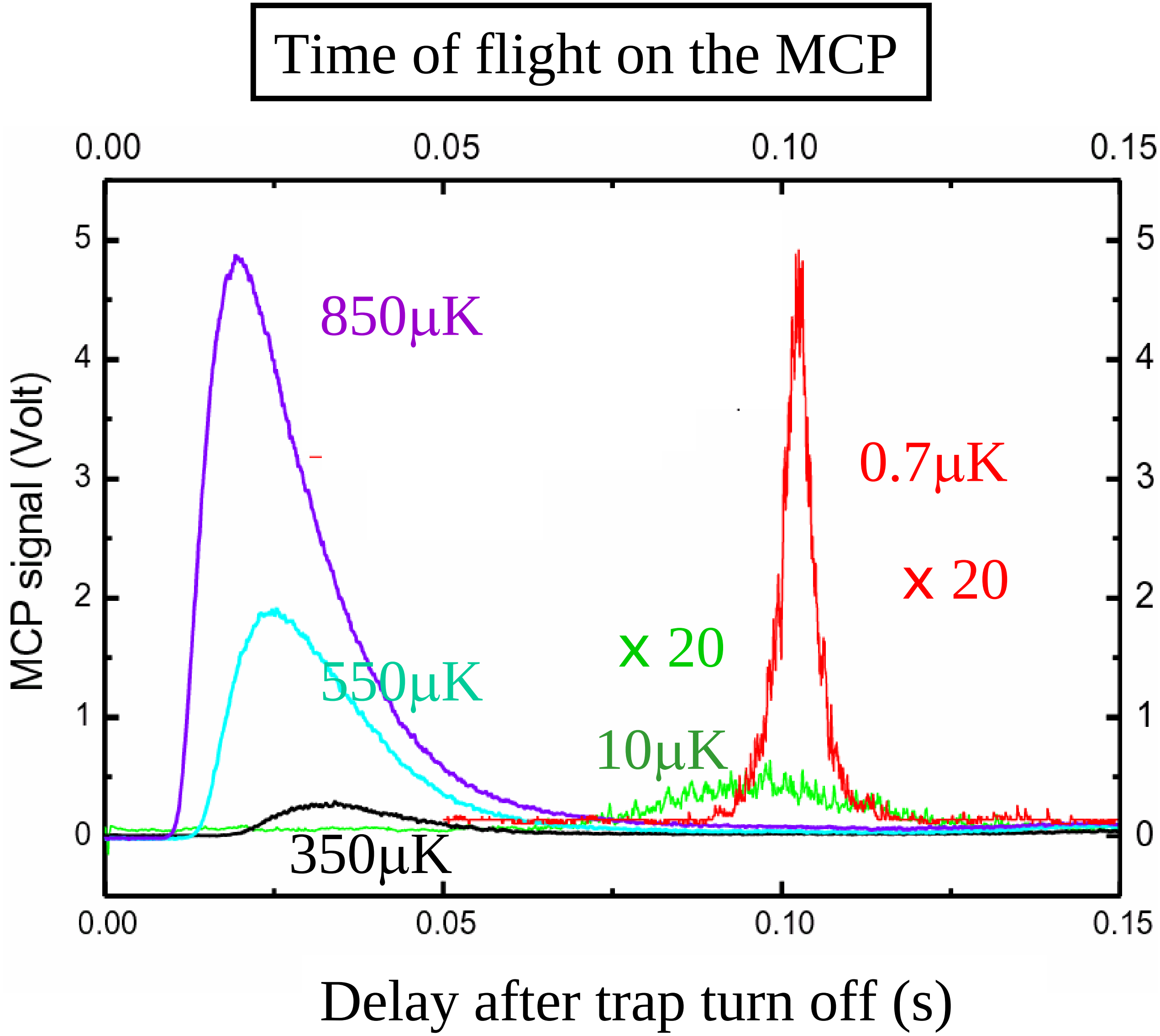
Magnetically trapped He* ***is*** spin polarized

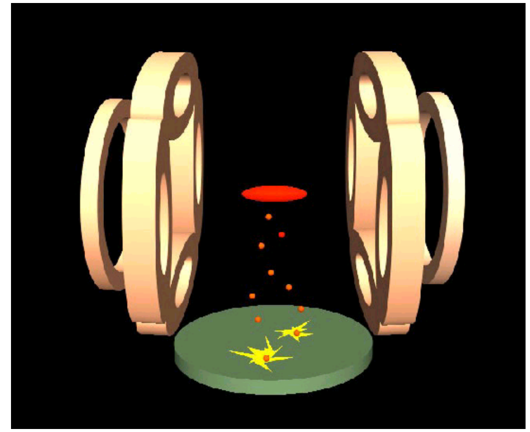
Preliminary experimental evidence (Amsterdam, Orsay, 1999): suppr. < 10^{-2}

Definitive evidence of supression (> 10^{-4}) :
BEC of He* observed (Orsay, Paris, 2001)

$a = 20 \pm 10$ nm

Evaporative Cooling to BEC





- RF ramped down from 130 MHz to ~ 1 MHz in 70 s (exponential 17 s)

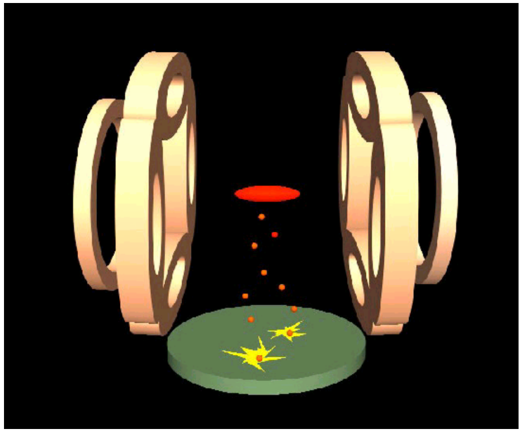
  ⇒ less atoms, colder

- Small enough temp. (about 2µK): all atoms fall on the detector, better detectivity

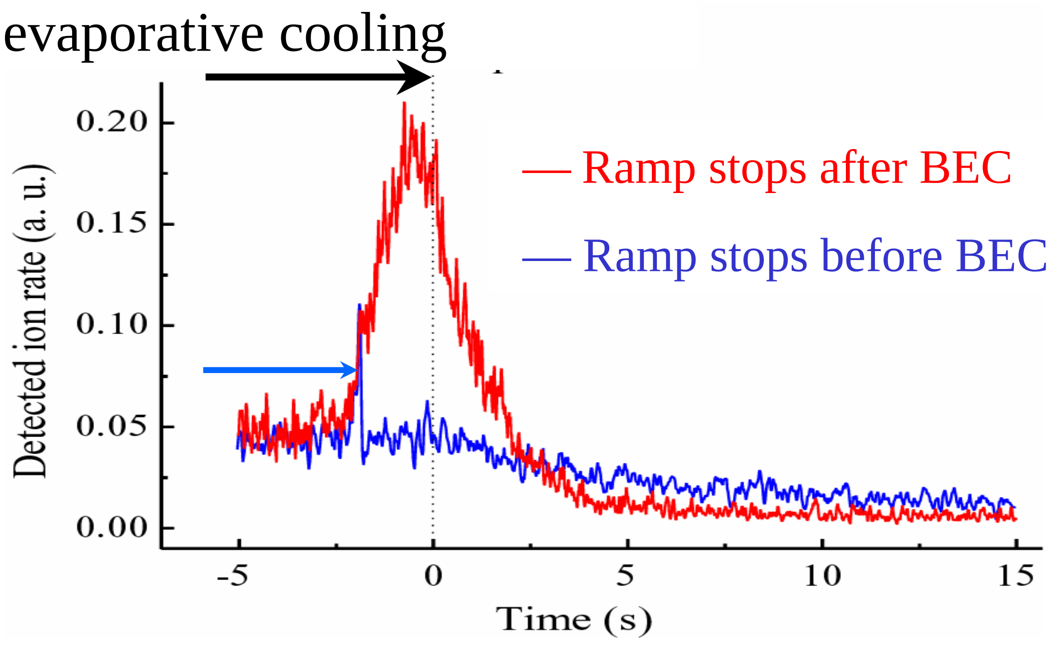
- At 0.7µK: narrow peak, BEC

Residual ionization of trapped He*

A new tool for monitoring a BEC



- Residual ionization (He+): detected with negatively biased grid (2keV) in front of MCP in counting mode (from 10^2 to $10^3\ s^{-1}$)



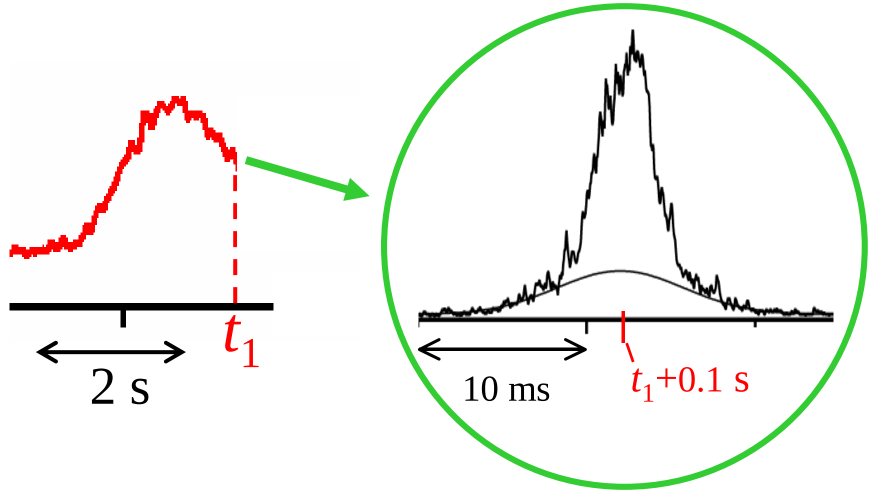
Real time observation of BEC birth and death on a single sample!

Interpretation: ionization increases with density (2 and 3 body ionization)

Quantitative?

Ionization monitoring plus TOF: a quantitative tool

Complement ion curent measurement $i(t_1)$ by measurement of the spatial distribution of atoms at t_1



⇒ Switch off the trap at t_1 and observe Time of Flight of the released atoms:

⇒ Atom number in the condensate

⇒ Atom number and temperature in the thermal cloud

Applications:

- measurement of 2-body and 3-body ionization constants (quantum depletion correction important)
- BEC thermodynamics study for a non-ideal gas

2- and 3-body ionization in a quasi pure He* BEC

- 2-body $He^{*} + He^{*}$ ® $He^{+} + He(1S) + e^{-}$ 1 ion / 2 lost He* atoms

- 3-body $He^{*} + He^{*} + He^{*}$ ® $He^{*}_{2} + He^{*}(:\ 1mK)$

  ↳ $He^{+} + He(1S) + e^{-}$ 1 ion / 3 lost He*

Ion rate per atom

$$G = \frac{\text{ion rate}}{N_0} = \frac{2}{7}k_2 b\, n_0 + \frac{8}{63}k_3 L\, n_0^{2}$$

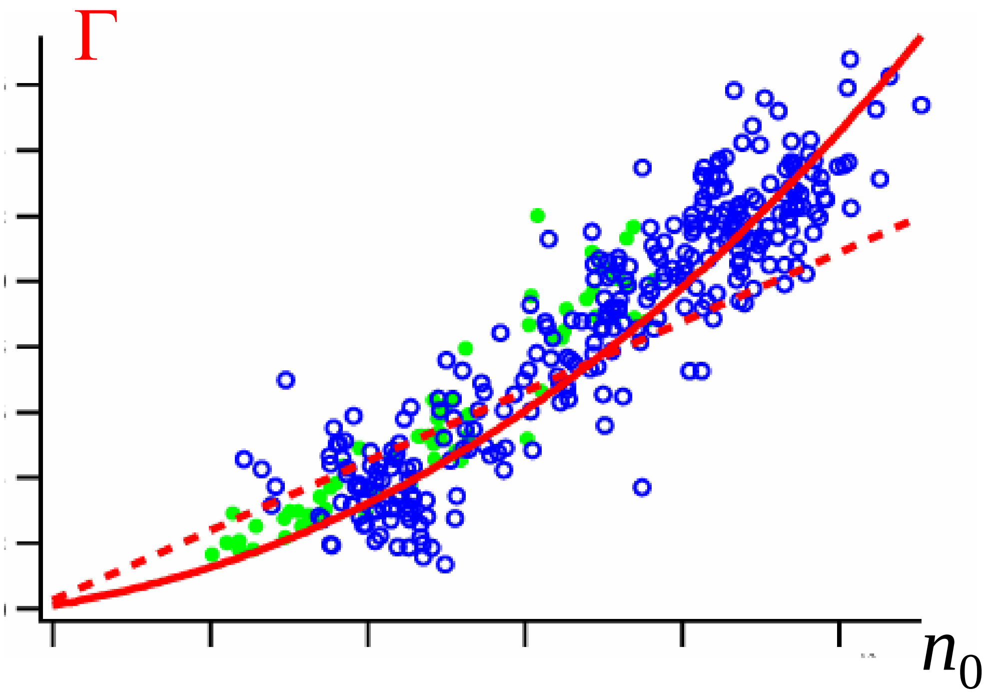
peak density

Number of condensed atoms

κ_2 and κ_3 : quantum degeneracy factors (1 / 2! and 1 / 3! for dilute BEC)

For a given ion rate, N_0 and n_0 measured by TOF $\Rightarrow$ Γ *vs.* n_0

Ion rate per atom *vs* peak density in a quasi pure BEC



For each ion rate, TOF:

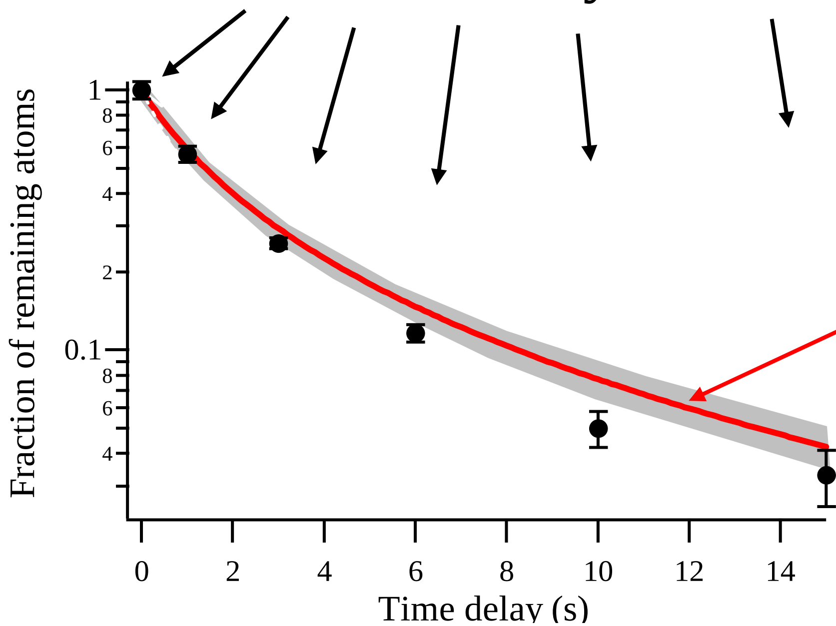
$\Rightarrow$ N_0 and n_0

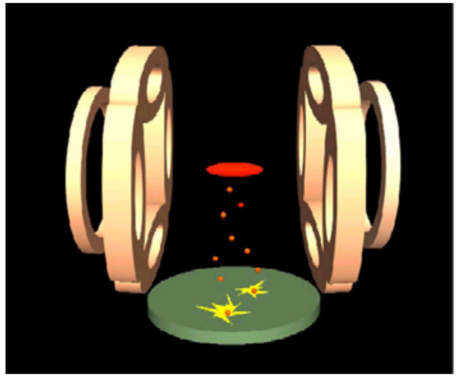
$\Rightarrow$ check pure BEC (thermal cloud not visible, i. e. < 10%)

Fit to $G = \frac{2}{7} k_2 b\, n_0 + \frac{8}{63} k_3 L\, n_0^2$ $\Rightarrow$ (β, L) : 3 body (L) important

Direct measurement of the decay of a quasi pure BEC: a consistency test

For identical samples, TOF measurement of atom number after delay t : standard method





Consistent with decay predicted for ionization only (β ,L)

⇒Non ionization processes negligible

⇒No avalanches (also: no correlations in ion detection)

No use of ion monitoring for this test?

Yes: reproducibility of the sample checked by monitoring the ion current before TOF (not standard)

2- and 3- body ionization rate constants

Experimental issues:

- Ion detection efficiency : 100% assumed in the MCP active area
- Atom number calibration : from expansion energy, assuming a = 20 nm (scaling laws for different values of a : precise measurements needed)

Theoretical issues:

- Quantum depletion important for 3-body term:

$$k_3 = \frac{1}{3!}\left(1 + 34.1\sqrt{n_0 a^3}\right)$$

0.6 at largest n_0

- Residual thermal cloud (≈ 10%) : increases the quantum depletion term by ≈ 50%

$$b_{20} = 2.7(\pm 2) \times 10^{-14}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$
$$L_{20} = 9.2(\pm 6) \times 10^{-27}\,\mathrm{cm}^6\,\mathrm{s}^{-1}$$

Theory:

$$2 \times 10^{-14}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$
$$10^{-26}\,\mathrm{cm}^6\,\mathrm{s}^{-1}$$

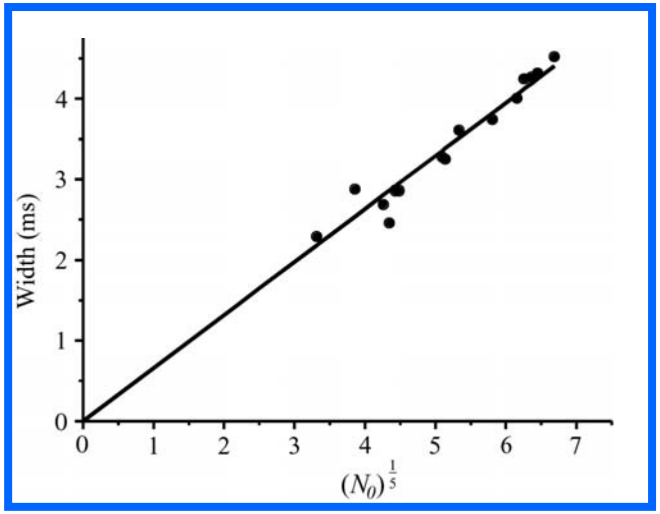
Error bars on (β, L) much smaller than on β or L separately

The scattering length issue

Scattering length a: unique parameter to describe the interaction energy.

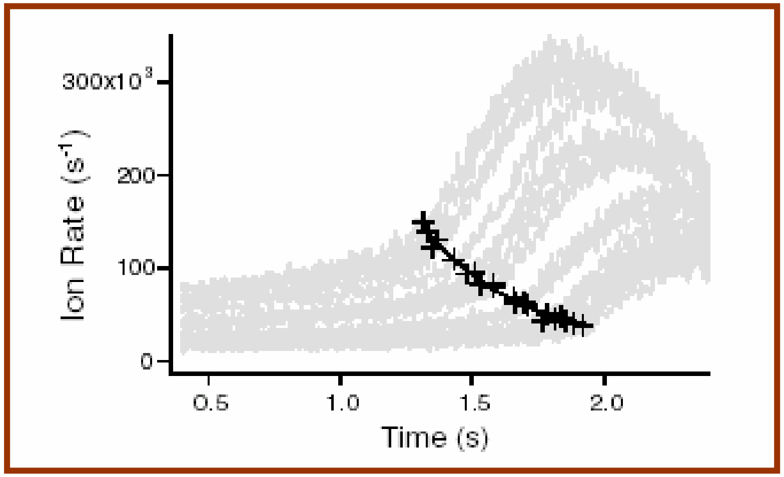
How to measure it?

Expansion velocity of a pure condensate scales as $\left(N_0 a\right)^{\frac{1}{5}}$



A serious difficulty: determining the absolute atom number

Our most recent solution: calibrating the atom number by observing the critical temperature



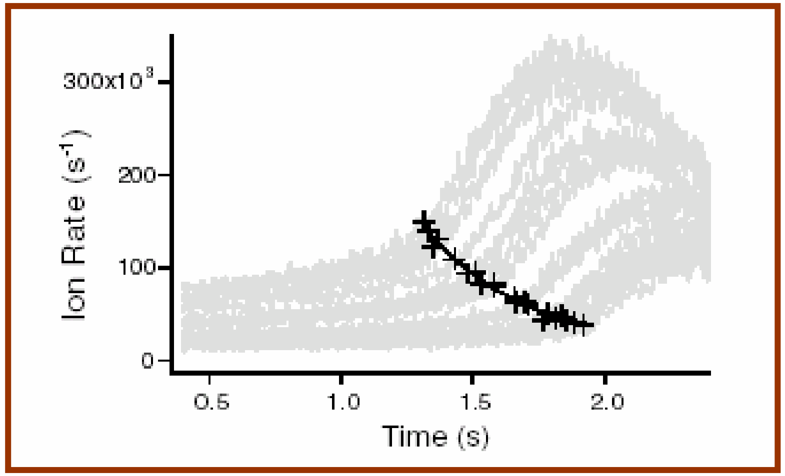
$$a = 11.3^{+2.5}_{-1.5}\ \text{nm}$$

Our first value: $a = 20 \pm 10\,\text{nm}$

The scattering length issue

A serious difficulty: determining the absolute atom number

Our most recent solution: calibrating the atom number by observing the critical temperature



But critical temperature correction depending on the value of *a*.

An independant measurement of *a* would allow us to reinterpret our results as a measurement of the shift of Tc, of the quantum depletion, etc…
Photoassociation spectroscopy measurements in progress at ENS.

Combining different methods: a great tool

He*: a new tool for quantum atom optics

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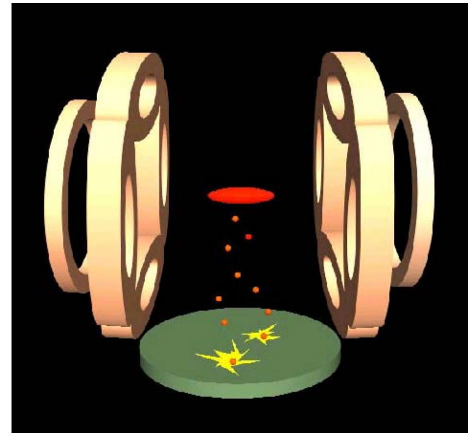
Penning ionization monitoring of a He* BEC combined with standard TOF: a powerful tool



Single He* detection, resolved in time and space

- Study of correlation functions of atomic field (*cf* photon counting as a trigger of photon quantum optics)
  - Hanburry-Brown & Twiss type experiments
  - Fluctuations of atom laser around BEC transition
  - Build up of interferences from independant BEC
  - Detection of entangled pairs; Bell's inequalities?
  - Luttinger liquid?

Suggestions welcome

Groupe d 'Optique Atomique du
Laboratoire Charles Fabry de l'Institut d'Optique

Electronics
André Villing
Frédéric Moron

Alain Aspect
Philippe Bouyer
Chris Westbrook

Denis Boiron
Isabelle Bouchoule
Nathalie Wesbrook

ATOM CHIP BEC
Jérome Estève
Torsten Schumm
Jean-Baptiste Trebia
Hai Nguyen

BEC VERSATILE SOURCE
Yann Le Coq
Marie Fauquembergue
Jean Felix Riou
William Guérin

He* BEC
Olivier Sirjean
Signe Seidelin
Jose Gomes
Rodolphe Hoppeler
M. Schellekens

Post doc applications encouraged

QUASI 1D Rb BEC
Fabrice Gerbier
Simon Richard
Mathilde Hugbart
Andres Varon
Joseph Thywissen
Jocelyn Retter