Observation of
Bose-Einstein condensation of ^{4}He*

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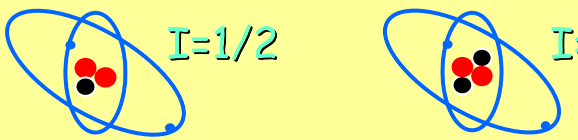
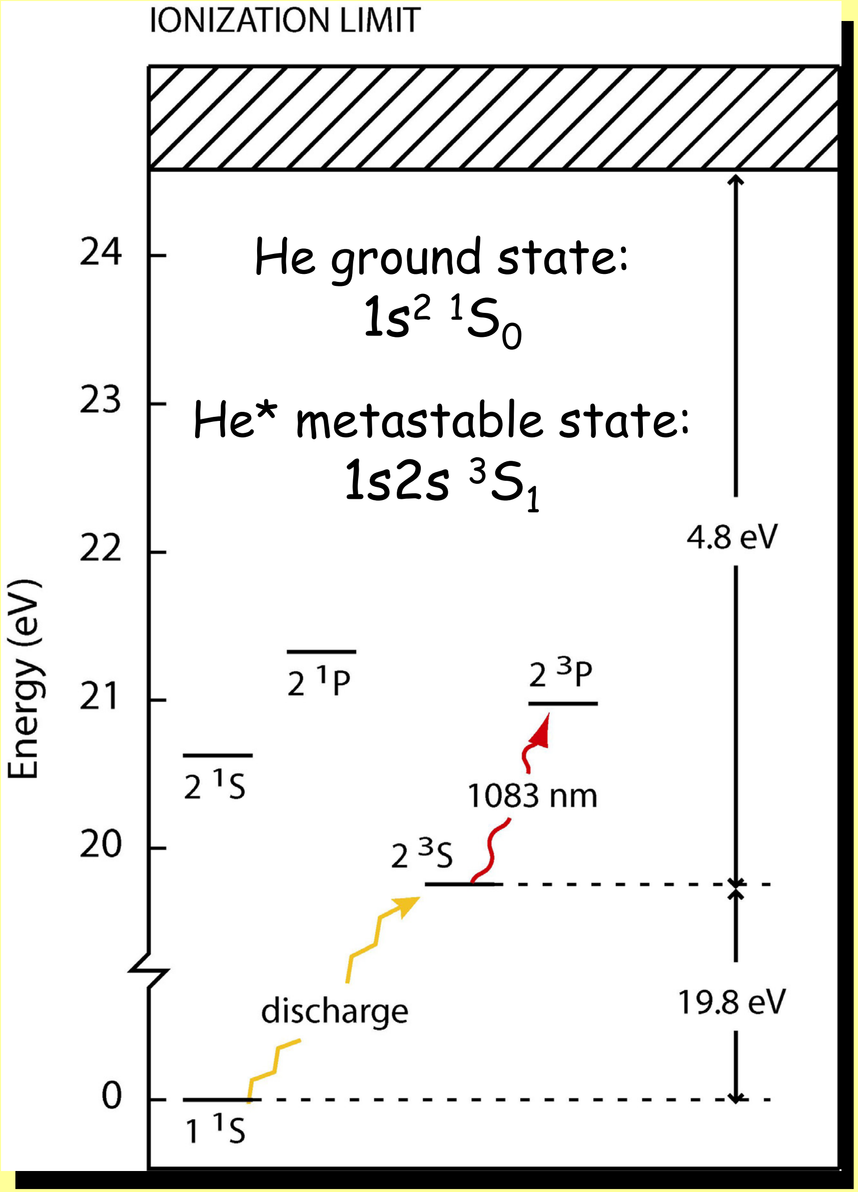
Laser Centre vrije Universiteit amsterdam

Metastable helium

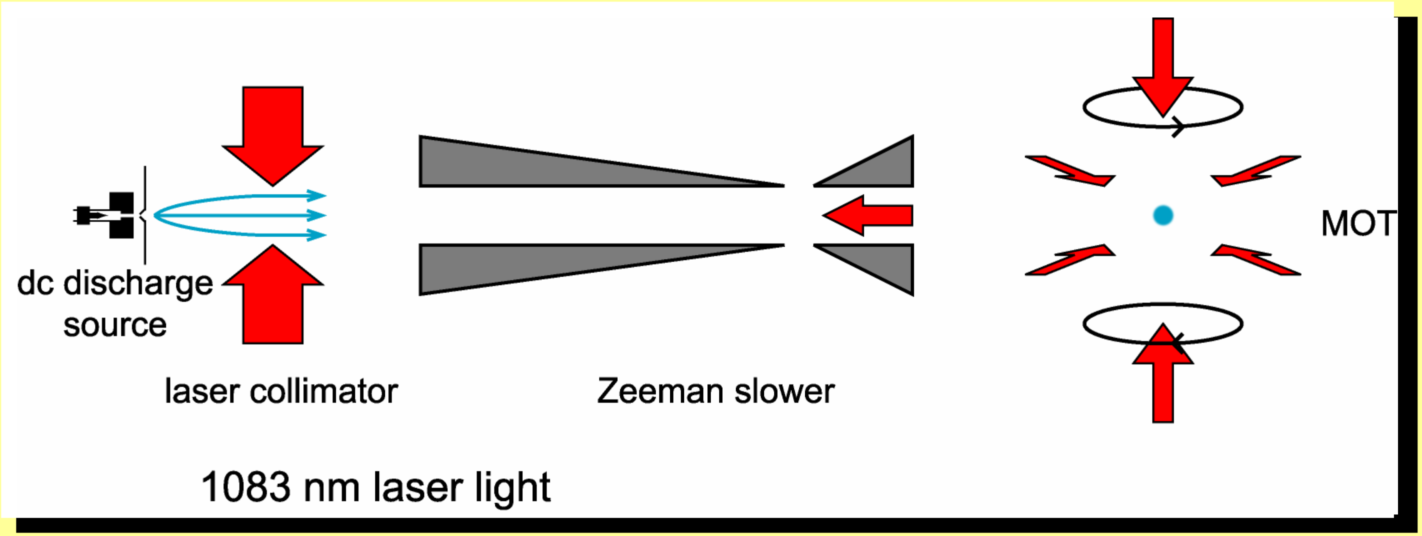
- $2\ ^3S_1$ state: τ = 8000 s,
  Laser cooling: λ=1083 nm
- 20 eV internal energy: single **He*** atom detection
- Penning ionization: **He⁺**
  ($He^* + He^* \rightarrow He + He^+ + e^-$)
- $^3He^*$ *fermion* and $^4He^*$ *boson*



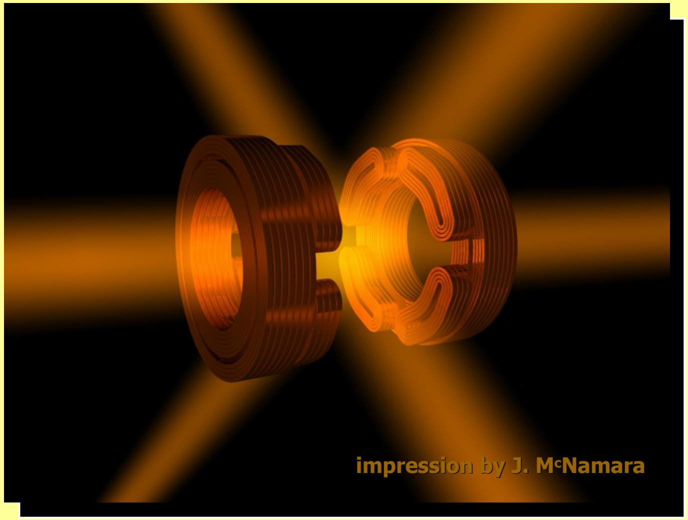
- Scattering lengths large and positive!
  a_{44}=+7.512 nm ; a_{34}=+28.8 nm



Magneto-optical trap (MOT) setup



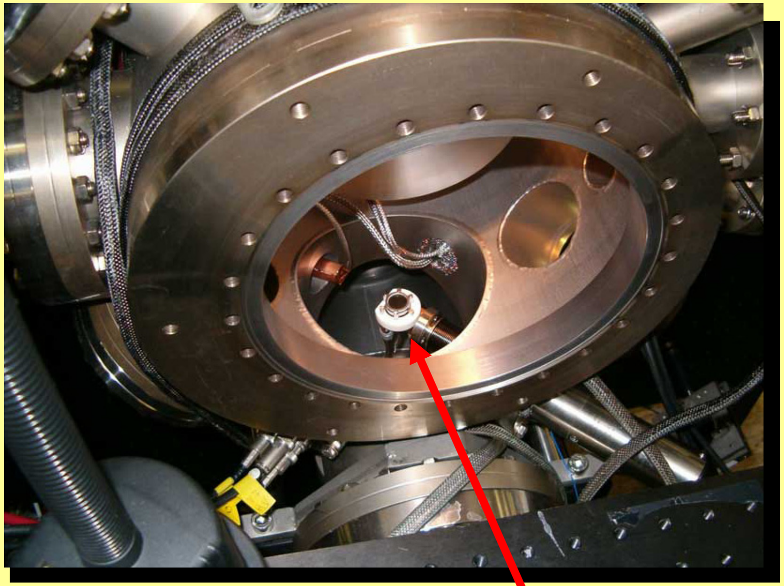
Loading and cooling of ~2×10^9 $^4He^*$ atoms in ~1 second at T ~ 1 mK (phase-space density ~10^{-7})



Detection methods

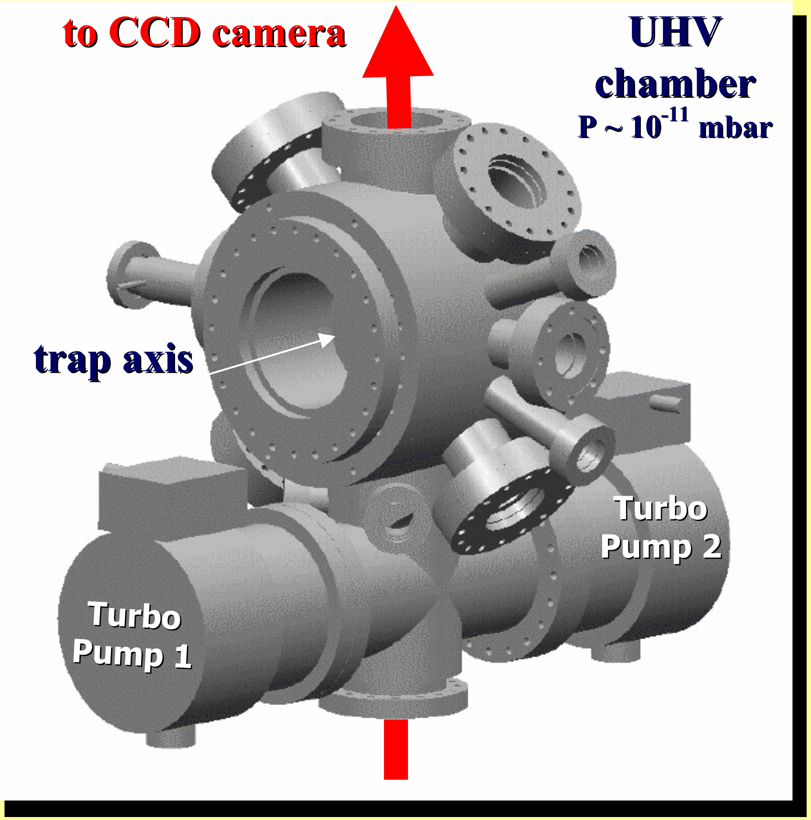
He*, He⁺, absorption imaging

He⁺ MCP (not visible)



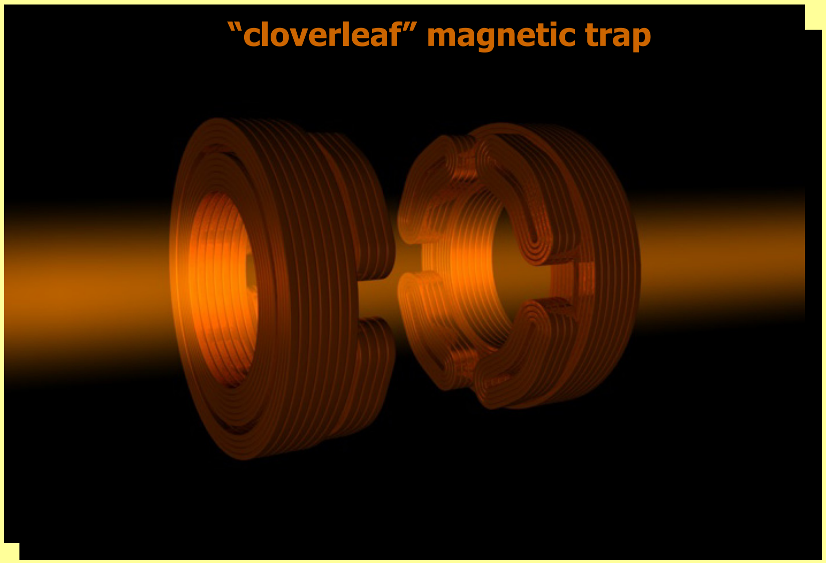
He* MCP

on translation stage



1-D Doppler cooling in magnetic trap

$$V_{ext}(r) = \frac{m}{2}\omega_x^2 x^2 + \frac{m}{2}\omega_y^2 y^2 + \frac{m}{2}\omega_z^2 z^2 \qquad (\omega_x = \omega_y >> \omega_z)$$



Circularly polarized laser beam along the z-axis at high (24 G) B_0

Laser cooling in **axial** (z) direction: (σ^+- cycling transition)

Cooling in **radial** direction: **reabsorption of spontaneously emitted red-detuned photons** (collisions, anharmonic mixing)

Successfully used to cool spin-polarized ^{3}He* fermions ($>1\times10^9$)

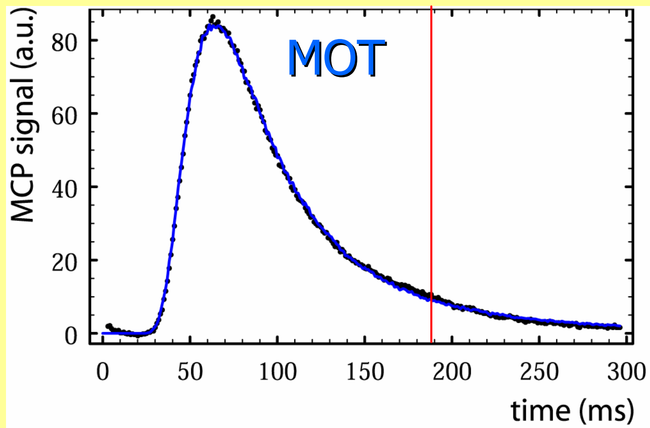
s-wave collisions are forbidden – Pauli principle
Cooling in radial direction – reabsorption of scattered photons

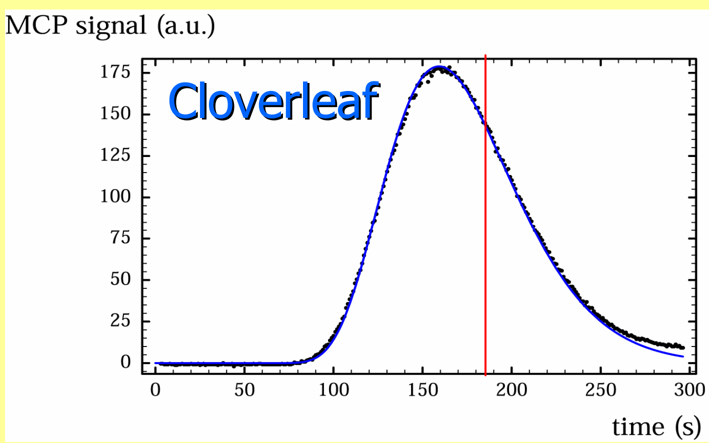
Characterization trapped He* cloud

Time-of-flight on microchannel plate detector (MCP)

$$s = s_o - \tfrac{1}{2} g t^2$$

$t_{T=0} = 190$ ms





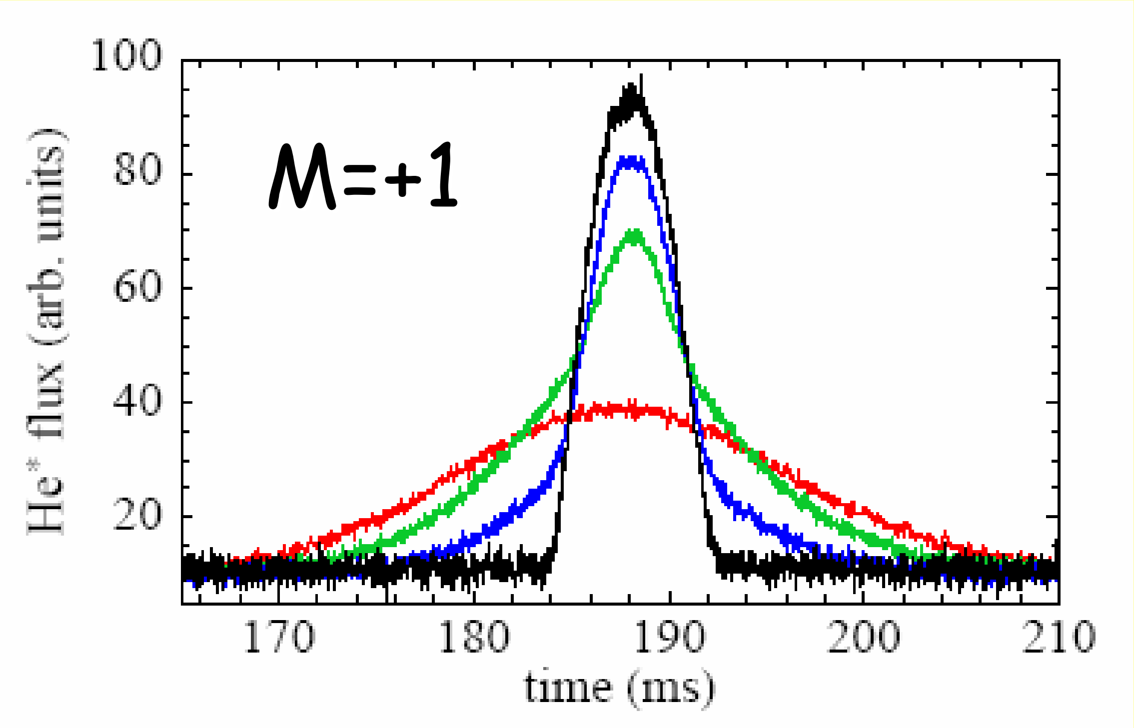
- **MOT :**
  $T = 1$ mK, $N = 1.0 \times 10^9$
- **Cloverleaf**, after **1D Doppler cooling:**
  $T = 0.15$ mK, $N = 6 \times 10^8$

$T = 3 \times T_D$,

Phase-space density increase ~ 600

No atoms lost during Doppler cooling

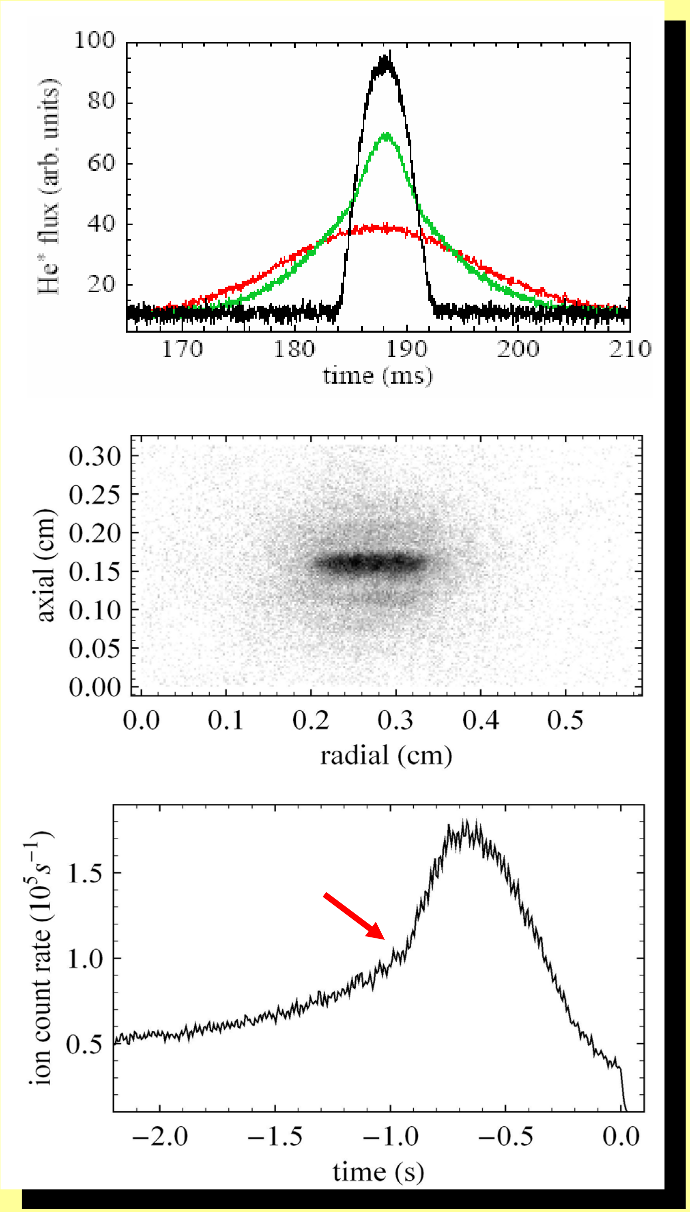
BEC reached after 15 s rf (50 – 8 MHz) evaporative cooling ramp



BEC also observed after 2 s rf ramp (with less atoms)

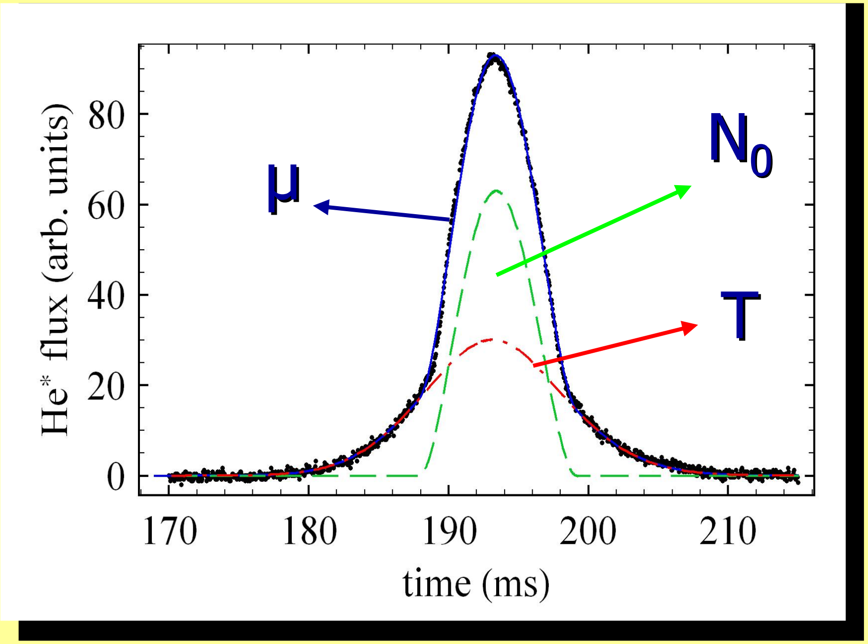
Observation of BEC

- Time-of-flight:
  - Number of atoms, N_0(BEC), N_{th}
  - Temperature, T
  - Expansion in x-direction (vertical)
- Absorption imaging:
  - MCP calibration (MOT)
  - Expansion in y,z plane
- He^+ ions: non-destructive
  - Loss processes
  - BEC formation and decay



from fit noncondensed part: T_c~2 μK and N_T

N_0 via μ or integral



Method 1:

N_0 = integral of green curve times MCP calibration (20% accuracy)

maximum number deduced: **N_0=1 x 10^7**

However: saturation of MCP for N_0 > 1 x 10^6

N_0 too small

<u>Method 2</u> : N_0 via chemical potential

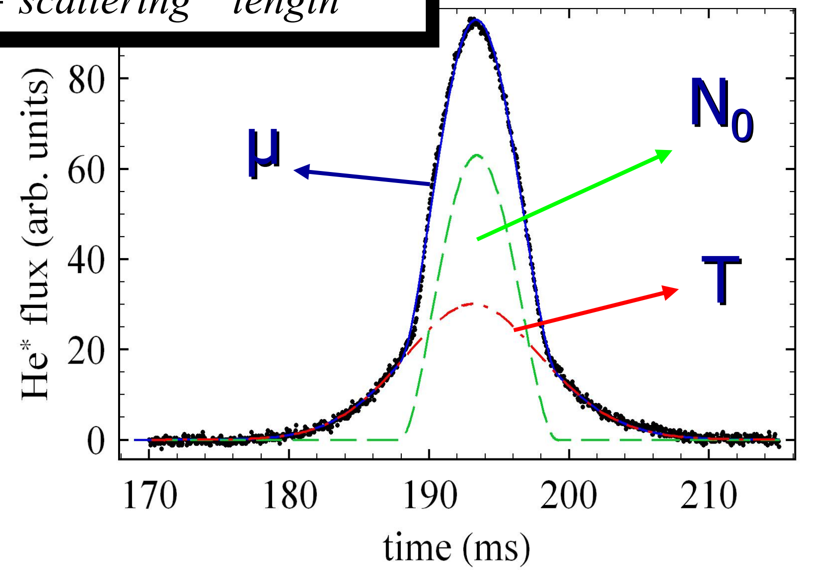
$$\mu_{TF} = \frac{\hbar\omega_{ho}}{2}\left(\frac{15 N_0 a}{\sqrt{\hbar/(m\omega_{ho})}}\right)^{2/5}$$

μ extracted from width of TOF signal (radial expansion only!) gives $\mathbf{N_0 = 5 \times 10^7}$

$$\omega_{ho} = \sqrt[3]{\omega_x \omega_y \omega_z}$$

μ – *chemical potential*

a – *scattering length*



However: Absorption imaging reveals anomalous expansion of the BEC as a result of too slow trap switch-off: stretching in radial direction.

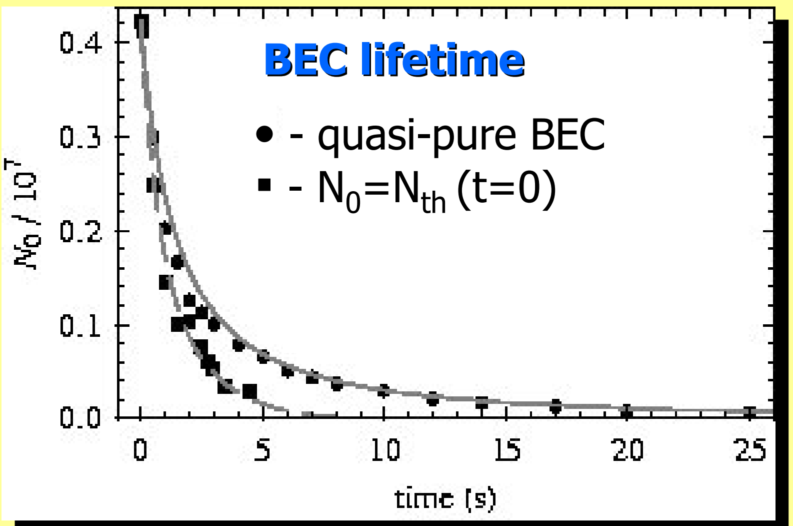
N_0 too large

$1.5 \times 10^7 < N_0 < 4 \times 10^7$

Decay of the condensate:
the effect of atomic transfer

BEC is detected up to t=75 s

(Cloud lifetime τ ~ 3 min)



Model :

P. Zin, A. Dragan, S. Charzynski, N. Herschbach, P. Tol, W. Hogervorst, W. Vassen, J. Phys. B**36,** L149 (2003)

Assumption:

BEC + thermal cloud remain in thermodynamic equilibrium during decay

- Output: $N_0(t)$, $N_{th}(t)$, $T(t)$
- Input: $N_0(0)$, $N_{th}(0)$, τ - lifetime, β (two-), L (three-body loss rate constant)

Decay of the condensate:
the effect of atomic transfer

- Atoms lost from a condensate are lost from the trap, or transferred to the thermal cloud.
- The presence of a thermal cloud reduces the lifetime of a BEC

Assumption:

only background gas collisions

$$\dot{N}_C = -\frac{1}{\tau}\left(N_C + \frac{1}{4} N_T \right)$$

Atomic transfer

simplest case: non-interacting bosons & only background collisions

Only background gas collisions cause trap loss

$$N_T = g_3(1)\left(\frac{kT}{\hbar\omega}\right)^3$$

$$E_T = \hbar\omega\frac{\pi^4}{30}\left(\frac{kT}{\hbar\omega}\right)^4 = \alpha N_T^{4/3}$$

$$\dot{N} = -\frac{1}{\tau}N = \dot{N}_C + \dot{N}_T = -\frac{1}{\tau}(N_C + N_T)$$

$$\dot{E} = -\frac{1}{\tau}E = \dot{E}_C + \dot{E}_T = -\frac{1}{\tau}(E_C + E_T)$$

$$\dot{N}_T = -\frac{1}{\tau}N_T\frac{1-\varepsilon_0 N_T/E_T}{4/3-\varepsilon_0 N_T/E_T} \simeq -\frac{3}{4\tau}N_T$$

$$\dot{N}_C = -\frac{1}{\tau}\left(N_C + \frac{1}{4}N_T\right)$$

$$\varepsilon_0 = \tfrac{1}{2}\hbar\left(\omega_x + \omega_y + \omega_z\right)$$

BEC decay depends on N_T

including two- and three-body losses

$$-\dot{N} = \frac{1}{\tau}N + 2\chi\int \mathrm{d}^3r\,\left(\frac{1}{2!}n_C^2 + 2n_C n_T + n_T^2\right) + 3\xi\int \mathrm{d}^3r\,\left(\frac{1}{3!}n_C^3 + \frac{3}{2!}n_C^2 n_T + 3n_C n_T^2 + n_T^3\right)$$

+ similar equation for total energy loss rate

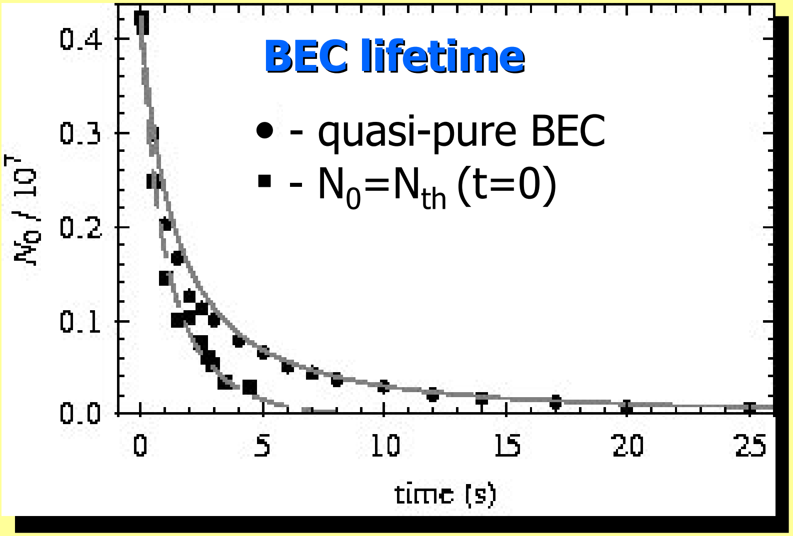
τ - lifetime
χ - two-body loss rate
ξ - three-body loss rate

Expressions for condensate and thermal (noncondensate) part density are related!

Decay of the condensate:
the effect of atomic transfer

BEC is detected up to t=75 s

(Cloud lifetime τ ~ 3 min)



For quasi-pure BEC the model gives decay without atomic transfer (upper curve)

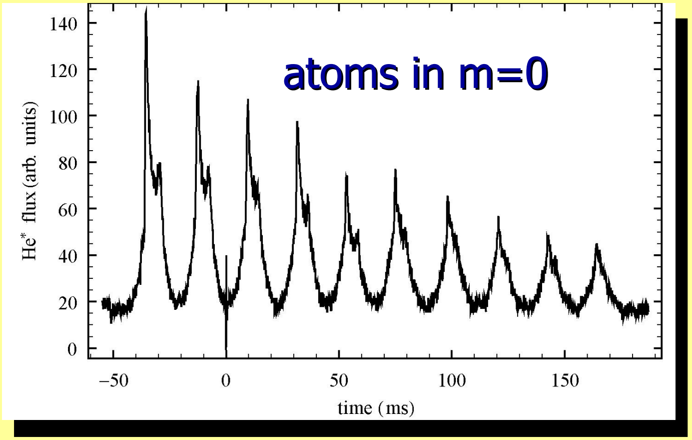
Estimated loss rate constants:
β=2(1) $\times10^{-14}$ cm^3/s
L=9(3) $\times10^{-27}$ cm^6/s

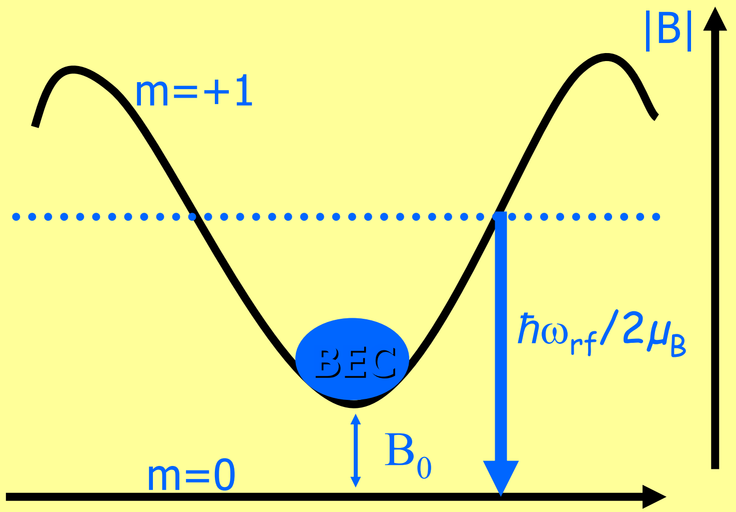
Theoretical predictions:
$\beta=1\times10^{-14}$ cm^3/s
$L=2\times10^{-27}$ cm^6/s

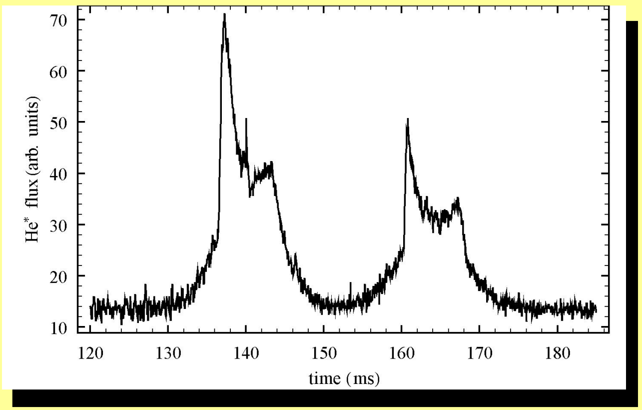
P.O. Fedichev *et al*., Phys. Rev. Lett. **77**, 2921 (1996)

Rf output coupler – pulsed atom laser

Repeating rf-sweeps
250 MHz/s

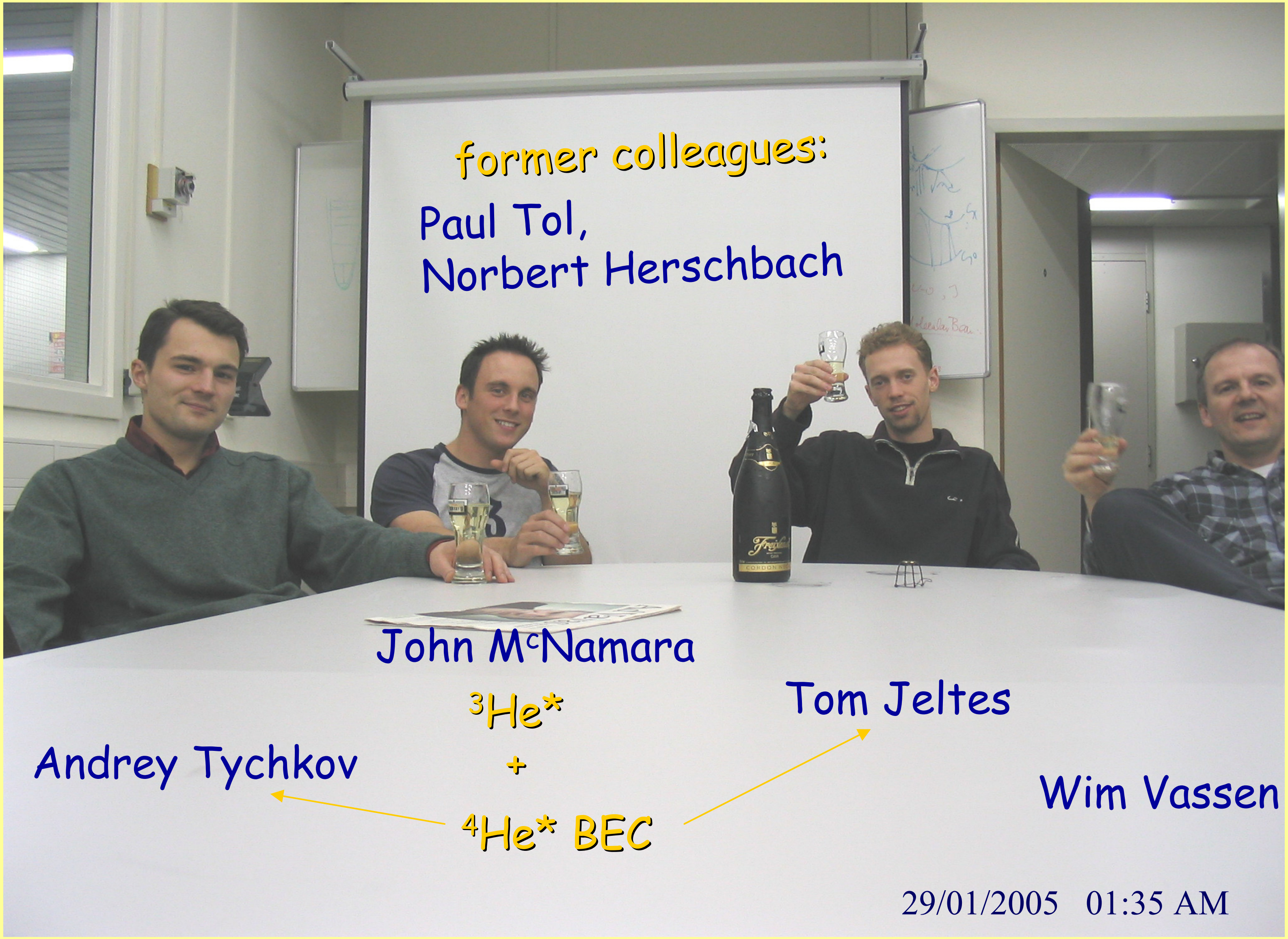






mean field interactions

determine pulse shape



former colleagues:
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Norbert Herschbach
John McNamara
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+
^{4}He* BEC
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Wim Vassen
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4 year PhD position available !!