Atomic mirrors, atom lasers, and Bose-Einstein condensation of He*: from incoherent to quantum atom optics

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Atomic mirrors, atom lasers, and BECs

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   Ray Optics, Wave optics, Quantum Optics
2. Atomic mirrors: incoherent and coherent atom optics
   1. Classical reflection: a probe of the atom wall interaction
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   3. Why coherent optics with a coherent source (a laser) ?
3. Bose-Einstein Condensates and Atom lasers
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   2. Magnetic trapping
   3. Forced evaporation
   4. Observation
   5. Non ideal BEC
   6. Interference of BECs
   7. A gravity driven atom laser
4. Bose Einstein Condensation of metastable Helium
   1. He* and single atom detection
   2. The route to He* BEC
   3. A highly metastable system
   4. Towards quantum atom optics

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Atom Optics

Do with atoms what standard optics does with photons :

- Reflection, refraction, focusing: geometrical optics (incoherent)
  - Trajectories ⟷ Rays
- Interference, diffraction: wave optics (coherent)
  - Matter Waves ⟷ Electromagnetic Waves
- Wave/particle, squeezing, entanglement: quantum optics
  - Atoms (as quanta of matter waves) ⟷ Photons (quanta…)

Possible because of progress in control of atomic motion

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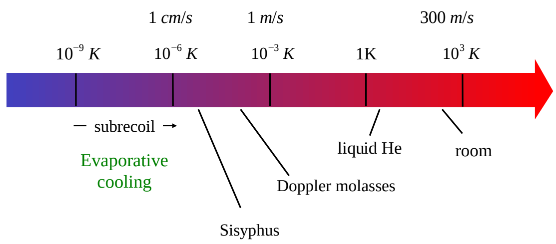
LASER COOLING OF ATOMS



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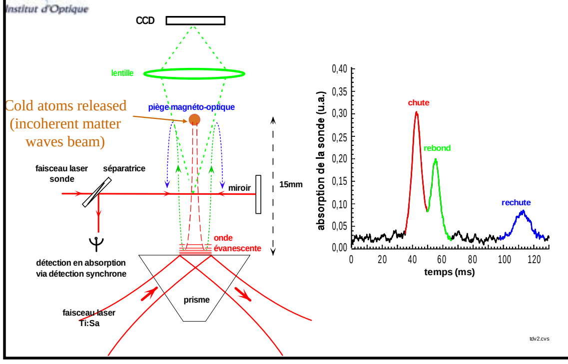
Evanescent wave atomic mirror



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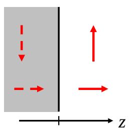
Interaction atome paroi à courte distance

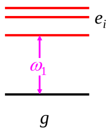


Dipôle électrostatique interagissant avec son image dans un conduc diélectrique

$$U(z) = -\frac{1}{64\pi\varepsilon_0}\frac{d_x^2 + d_y^2 + 2d_z^2}{z^3}\frac{\varepsilon - 1}{\varepsilon + 1}$$

Lennard-Jones : atome dans son état fondamental

$$d^2 \rightarrow \langle g|\hat{D}^2|g\rangle = \sum_i |\langle g|\hat{D}|e_i\rangle|^2 \neq 0$$



Fluctuations du dipôle atomique dominées par la première transition de résonance ω_1

$\Rightarrow$ Effets de retard négligeables si $z << \frac{c}{\omega_1} \approx 100\,\text{nm}$

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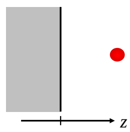
Potentiel de Casimir-Polder (atome-métal)



Calcul d'électrodynamique quantique valable à toute distance

$$U_{CP}(z) \xrightarrow[z\to\infty]{} -\frac{3}{32\pi^2\varepsilon_0}\frac{\hbar c\,\alpha}{z^4}$$

α : polarisabilité statique, dominée par ω_1

Interprétation (analogue Casimir entre conducteurs [10]: Haroche)

- déplacement du niveau fondamental (Lamb shift) dû aux fluctuations du vide
- valeur dépend de la structure des modes autour de l'atome
- modes affectés par le conducteur $\omega_\ell < \frac{c}{z}$

Remarque : z grand $\Rightarrow$ $\omega_\ell << \omega_1$ $\Rightarrow$ polarisabilité statique

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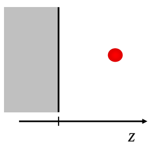
Potentiel de Lifshitz (atome-diélectrique)



$$U_L(z) \xrightarrow[z\to\infty]{} U_{CP}^{\infty}(z)\,\frac{\varepsilon(\omega_1)-1}{\varepsilon(\omega_1)+1}\phi(\varepsilon)$$

$\phi(\varepsilon) \simeq 0.77$ pour $1 < \sqrt{\varepsilon} < 2$

$\phi(\varepsilon) \simeq 1$ pour $\varepsilon \to \infty$ (métal)

A courte distance: Lennard Jones avec indice

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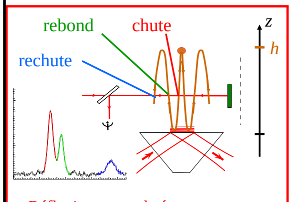
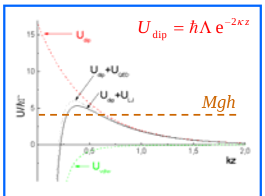
Interaction atome – diélectrique dans un miroir atomique (Orsay, 1996)



Réflexion sur onde évanescente



Potentiel réflecteur

Potentiel réflecteur contrôlé par les paramètres du laser onde évanescente (intensité, désaccord à résonance) :

$\Rightarrow$ seuil de réflexion pour énergie incidente *Mgh* définie (atomes froids)

$\Rightarrow$ potentiel de van der Waals au seuil de réflexion

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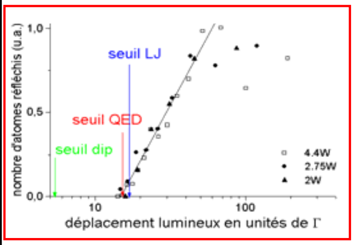
Seuil de réflexion sur un miroir atomique à onde évanescente



Rôle crucial de l'interaction de van der Waals

Accord marginal avec théorie si on prend

$U_{vdW}(z) = U_{LJ}(z)$

Meilleur accord pour

$U_{vdW}(z) = U_{CP}(z)$

Evidence of Casimir Polder

Profil gaussien du faisceau laser : droite en fonction de $\log\left(\frac{I_L}{\omega_L - \omega_1}\right)$

Mesure à une distance *z* = 48 *nm* de la paroi

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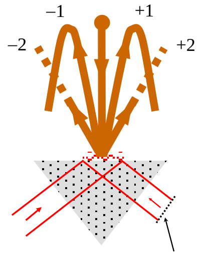
One can do coherent optics with incoherent sources

Atomic diffraction on a standing evanescent wave atomic mirror (reflection grating):

If the incoherent source is narrow enough, one can observe diffraction peaks

Spatial coherence increases when the source size decreases (Zernicke)



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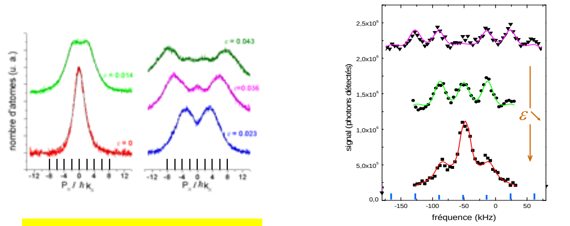
Atomic diffraction on a corrugated evanescent wave mirror

Limited collimation (5 mrad)

Better collimation (1 mrad)



Diffraction peaks not separated

Diffraction peaks well separated

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Specular vs rough mirror

Diffraction peaks as $J_n(m)$

Specular reflection: roughness small compared to wavelength : $m \ll 1$

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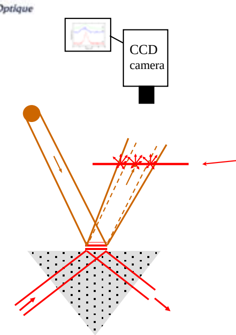
Atomic mirror specularity



- crude collimation: trap size, and mirror size (increases transverse coherence)
- bounced atomic cloud imaged when crossing the probing resonant light (only a few fluorescent photons permitted)
- Delay between bounce and analysis can be changed:
  - probe height;
  - Probe turned on just after bounce or at fall back

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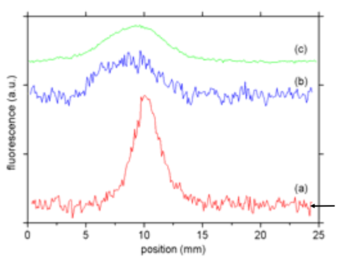
Specularity of the reflection vs prism roughness

Transverse profile after reflection from different prisms



« standard » polish $\sigma \sim 0.25$ nm

« superpolish » $\sigma \sim 0.1$ nm

Specular reflection !

$\theta_{diff} = 0 \pm 5$ mrad

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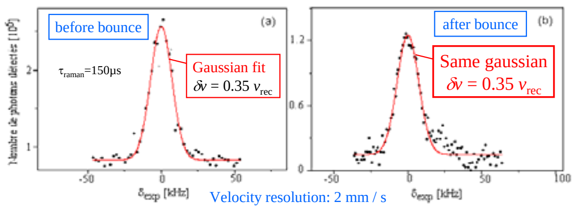
High resolution specularity study on a superpolished prism

(velocity selective Raman transfer)



- Specular peak without supplementary angular spread: $\theta_{diff} = 0 \pm 1$ mrad
- Broader pedestal, that vanishes when bouncing laser detuning increases: diffuse reflection

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Specular reflection on imperfect mirrors?

How can a real mirror, with some unavoidable residual roughness, behave as an ideally flat reflector?

Because it reflects waves

If wavelength λ >> roughness σ

$\Rightarrow$ Diffuse reflection vanishes as $1-\exp\left(-\frac{\sigma^2}{2\pi^2\lambda^2}\right)$

$\Rightarrow$ Specular reflection: preserves coherence

Analogous to Debye-Waller, Mössbauer, Lamb-Dicke effects

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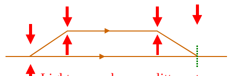
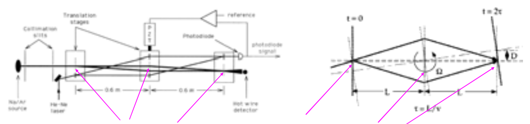
Interferometry with large incoherent sources

As in photon optics, large size incoherent sources can yield high visibility fringes in Michelson-like (or Mach-Zehnder like) atom interferometers :

- Field amplitude division (beam splitters)
- Fringe « localized » in a particular plane





Nanofabricated grating beam splitters

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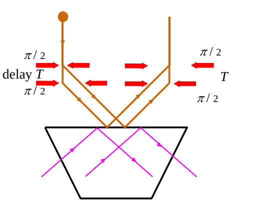
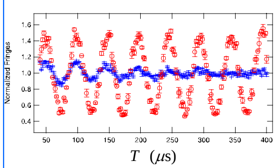
An atomic mirror interferometer with a large incoherent source



Evanescent wave atomic mirror

Fringe visibility *vs.* separation at atomic reflection

$\Delta = 2V_R T \quad (1.2\ \mu\text{m for } T = 10^{-4}\ \text{s})$



Study of transverse coherence destruction at reflection on a mirror (roughness, shape defects)

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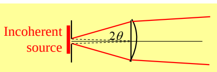
The limits of optics with incoherent source

Incoherent optics can achieve high precision measurements of position, direction…



- Requires filtering (for instance collimation)
  $\Rightarrow$ coherence increases
- Ultimately: selection of a single mode: $\Delta x.\Delta\theta = 1$ (coherence)

Filtering $\Rightarrow$ weak signal. Much less than one photon per mode

Analogous problem in atom optics : cooling and trapping typically yields 10^{-6} atom per phase space elementary cell $\Delta^3 r.\Delta^3 p = \hbar^3$

THE solution in photon optics: LASER
many photons per mode (> 10^{10} for a simple He-Ne laser)

In atom optics: Atom laser ? Many atoms in $\hbar^3$?

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How to have many atoms in the same mode ?

Bose-Einstein Condensation:

$\Rightarrow$ happens when atomic wave packets overlap $\quad n\Lambda_T^3 \geq 1$

$\Rightarrow$ increase of density usually leads to molecule (or cluster) formation (except liquid Helium: superfluidity)

$\Rightarrow$ At temperature below 1 µK, BEC with dilute atomic medium

First demonstration in 1995 : evaporative cooling of magnetically trapped alkali atoms (Rb, Na, Li) : Boulder, MIT, Rice

Nobel 2001

BEC of spin polarized hydrogen (MIT, 1998)

BEC of metastable helium (Institut d'Optique, ENS, 2001)

BEC in an optical trap (Georgiatech, 2001)

More alkali: K (Florence 2001).

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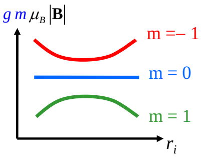
Recipe for BEC with a dilute atomic sample

$n\Lambda_T^3 \geq 1 \quad \Longrightarrow$ decrease temperature and/or increase density (moderately)

- Laser cooling and trapping $\Rightarrow \; n\Lambda_T^3 \leq 10^{-6}$ (start from 10^{-15})
- Turn off lasers (avoid rescattering, light induced inelastic collisions..)
- Turn on a magnetic trap, with a non nul (bias) minimum magnetic field (avoid Majorana non adiabatic losses)
  $n\Lambda_T^3 < 10^{-6}$

$U = g\,m\,\mu_B\,|\mathbf{B}|$



Low field seekers ($g\,m > 0$) trapped at minimum of $|\mathbf{B}|$
Demands large gradients

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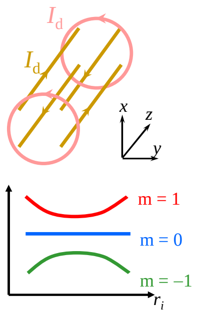
Magnetic Trapping of paramagnetic atoms



Energy $U = g\,m\,\mu_B\,|\mathbf{B}|$

Low field seekers ($g\,m > 0$) trapped at minimum of $|\mathbf{B}|$

- Transverse confinement (*x*, *y*): quadrupole (usually stiff)
- Longitudinal (weak) confinement: dipole beyond Hemholtz configuration; also provides bias guiding field

$$|\mathbf{B}| \sim B_0 + \frac{B''}{2}z^2 + \left(\frac{B'^2}{2B_0} - \frac{B''}{4}\right)^2 (x^2+y^2)$$

Large gradients required

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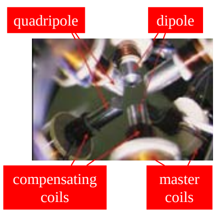
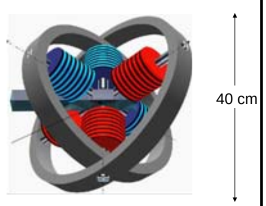
The Orsay Rb BEC special: iron core electromagnet

Institut d'Optique

- Low electric power (80 W)
- Strong gradient
- Shielding of the ambient magnetic field





- Car battery operated BEC
- 1 D regime
- Stability good enough to allow for quasi CW atom laser

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Recipe for BEC with a dilute atomic sample

$n\Lambda_T^3 \geq 1 \quad \Longrightarrow$ decrease temperature and/or increase density (moderately)

- Laser cooling and trapping $\Rightarrow \; n\Lambda_T^3 \approx 10^{-6}$ (start from 10^{-15})
- Turn off lasers (avoid rescattering, light induced inelastic collisions..)
- Turn on a magnetic trap, with a non nul (bias) minimum magnetic field minimizing entropy increase (match potential) $\quad n\Lambda_T^3 < 10^{-6}$
- Forced (RF transition) evaporative cooling

  $\Rightarrow$ T decreases and $n\Lambda_T^3$ increases to 2.6…

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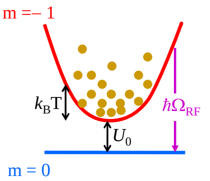
Forced evaporative cooling



RF eliminates atoms with energy > $\eta\, k_B T$ (typically $\eta \approx 6$)

After rethermalization (elastic collisions)

- T ↘ ⇒ Λ_T ↗
- n ↗ (although N ↘, because T ↘)

⇒ $n\,\Lambda_T^{\;3}$ ↗

Ω_{RF} ramped down to BEC

$n\,\Lambda_T^{\;3} > 2.612$

Strong demands

- large elastic cross section
- small losses (< 1/300 el.)
  - background pressure ultra low
  - no inelastic processes

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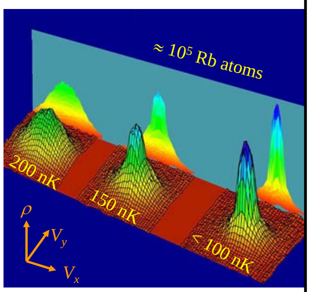
Optical observation of Rb condensation

- Turn off the trap at $t = 0$
- Ballistic expansion, duration τ
- Absorption imaging

⇒Velocity distribution

- * Thermal component (Gaussian wings)
- * Condensate (inverted parabola)



Measurement difficult for less than 10^4 atoms

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Non ideal (interacting) BEC

Non linear Schrödinger equation (Gross Pitaevskii equ.)

$$-\frac{\hbar^2}{2M}\Delta u_0(\mathbf{r}) + V(\mathbf{r})u_0(\mathbf{r}) + Ng|u_0(\mathbf{r})|^2 u_0(\mathbf{r}) = \mu\, u_0(\mathbf{r})$$

Mean field interaction

Thomas Fermi approximation

$$-\frac{\hbar^2}{2M}\Delta u_0(\mathbf{r}) + V(\mathbf{r})u_0(\mathbf{r}) + Ng|u_0(\mathbf{r})|^2 u_0(\mathbf{r}) = \mu\, u_0(\mathbf{r})$$

Inverted parabola in a harmonic trap

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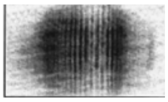
Interferences between BECs

Observation of Interference Between Two Bose Condensates

M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, W. Ketterle

Interference between two freely expanding Bose-Einstein condensates has been observed. Two condensates separated by ~40 micrometers were created by evaporatively cooling sodium atoms in a double-well potential formed by magnetic and optical forces. High-contrast matter-wave interference fringes with a period of ~15 micrometers were observed after switching off the potential and letting the condensates expand for 40 milliseconds and overlap. This demonstrates that Bose condensed atoms are "laser-like"; that is, they are coherent and show long-range correlations. These results have direct implications for the atom laser and the Josephson effect for atoms.



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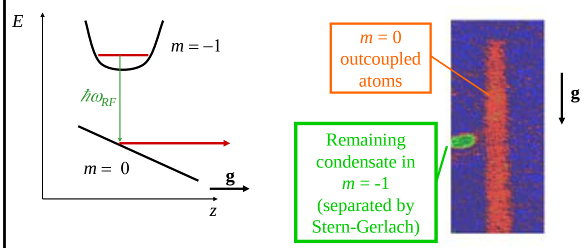
Rb quasi CW gravity driven atom laser



RF (weak) outcoupler from BEC: falling single mode matter wave

cf. Esslinger et al.;

for a simple analytical 3D theory including gravity see Gerbier et al., PRL 2001

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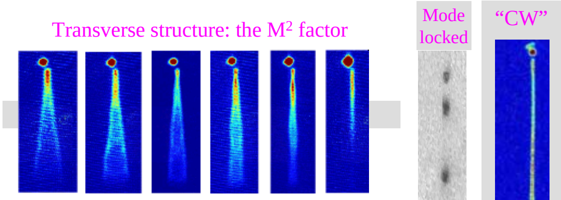
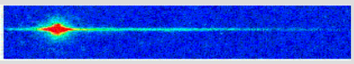
Atom lasers

Transverse structure: the M^2 factor

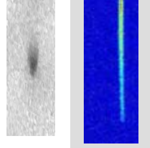


J.-F. Riou et al., 2005

A guided atom laser



W. Guérin et al., 2006



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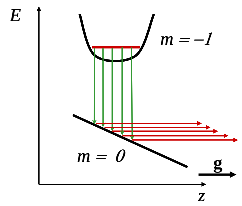
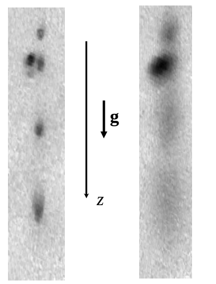
Mode locked atom laser

• Comb of coherent RF outcouplers





Interference between coherent lasers at different frequencies: analogy to mode locked laser (cf Kasevich et al.)

FM = 200 Hz

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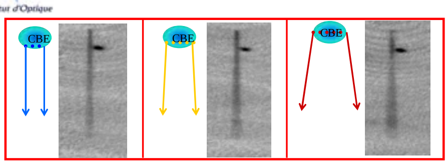
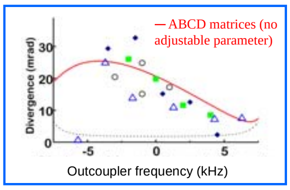
Divergence of a cw atom laser



Divergence clearly increases with height z_{out} of the RF knife

Divergence due to a lensing effect (interaction with the condensate)

Quantitatively interpreted with a straightforward extension of the ABCD matrices treatment of the propagation of usual (photon) laser beams



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Coherent Atom Optics has much to learn from Coherent Photon Optics

- Do not forget your Optics classes
- There is a whole host of useful concepts, models, approximations…

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Atomic mirrors, atom lasers, and BECs

1. Atom Optics
   Ray Optics, Wave optics, Quantum Optics
2. Atomic mirrors: incoherent and coherent atom optics
   1. Classical reflection: a probe of the atom wall interaction
   2. Coherent atom optics with incoherent atom sources: matter wave diffraction
   3. Why coherent optics with a coherent source (a laser) ?
3. Bose-Einstein Condensates and Atom lasers
   1. Critical phase space density
   2. Magnetic trapping
   3. Forced evaporation
   4. Observation
   5. Non ideal BEC
   6. Interference of BECs
   7. A gravity driven atom laser
4. Bose Einstein Condensation of metastable Helium
   1. He* and single atom detection
   2. The route to He* BEC
   3. A highly metastable system
   4. Towards quantum atom optics

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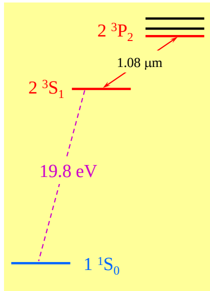
Metastable Helium $2\,^3S_1$

- 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



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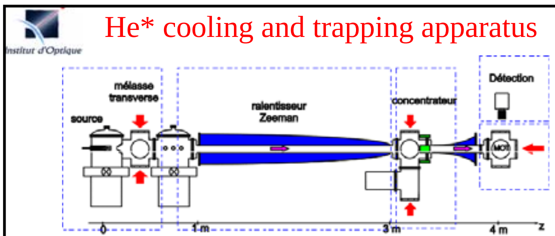
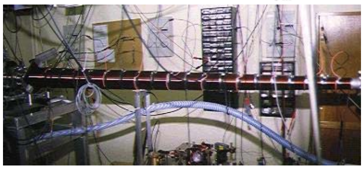
He* cooling and trapping apparatus





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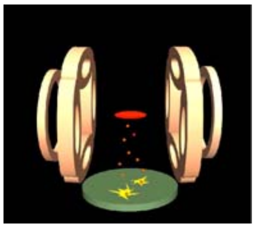
He* trap and MCP detection



Clover leaf trap

@ 240 A : B_0 : 0.3 to 200 G ;

B' = 90 G / cm ; B''= 200 G / cm²

$\omega_z / 2\pi$ = 50 Hz ; $\omega_\perp / 2\pi$ = 1300 Hz

He* on the Micro Channel Plate detector:
- ⇒ an electron is extracted
- ⇒ multiplication
- ⇒ observable pulse

Single atom detection of He*

Ions (X^+) detection also possible (He* atoms still in the trap) by negatively biasing the detector

Continuous (non destructive) monitoring of trapped He*

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

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

⇒ Excellent TOF diagnostic

Cons:
- Source of cold He* not as simple as alkalis'; vacuum challenges
- Penning ionization
- Elastic cross section unknown at low temperature

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Problem 1: Penning ionization of He*

$$He^* + He^* \rightarrow He(1\,^1S_0) + He^+ + e^-$$

Reaction constant ≈ 5 x 10^{-10} cm³.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} !) 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}

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Problem 2: thermalization

- Evaporative cooling requires a fast enough thermalization
- Initial density is small (large Penning ionization in Magneto-Optical Trap and optical molasses from which magnetic trap is loaded)

⇒ Fast thermalization demands large elastic collision cross section

Encouraging calculations (Shlyapnikov 95, NIST): $a \approx 10$ nm

Very encouraging measurements (Orsay, dec 2000, Browaeys et al, PRA)

- Direct measurement of thermalization of the energy distribution: $a \approx 20$ nm
- Magnetic trap lifetime ≈ 1 mn

$\Rightarrow \frac{elastic}{inelastic} > 300$ criterium for evaporative cooling fulfilled

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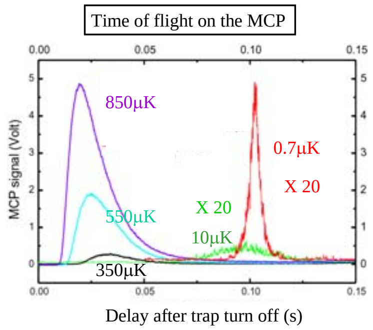
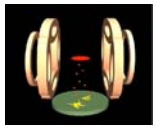
Evaporative Cooling to BEC





- 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

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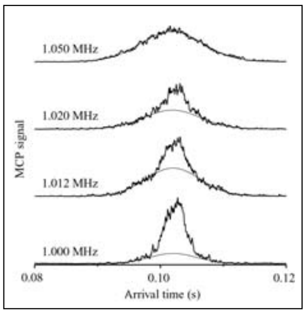
Data analysis



- Thermal distribution fitted to the wings:

⇒ temperature

⇒ thermal atom number N_{th}

- Inverted parabola (Thomas-Fermi) fitted to the remaining component:

⇒ BEC atom number N_0

⇒ BEC width W (Thomas-Fermi radius)

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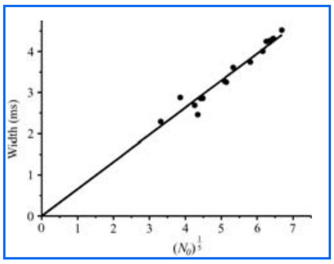
Condensate width *vs* Atoms number



Thomas-Fermi regime:

$$W \propto N^{1/5}$$

Absolute calibration of atom number by different methods

Slope ⇒ **scattering length** (trapping frequencies known)

$a = 20 \pm 10 nm$ @ 1 µK

ENS: $a = 16 \pm 8 nm$

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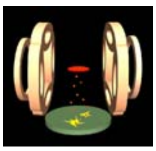
He* (or Ne*?) BEC with MCP detector: a new tool

- Continuous monitoring of the trapped atoms via ion current

⇒ Non destructive observation of a condensate



- Single He* detection, time and position resolved

⇒ A step analogous to the introduction of photon counting techniques in photon quantum optics?

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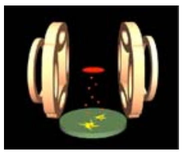
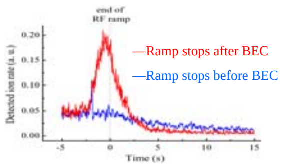
Birth and death of a condensate

- Trapped thermal cloud
- Ions monitoring (negatively biased detector)
- Forced evaporative cooling (RF ramp)





Real time observation of BE transition and of condensate decay on a single sample!

Increase of ion current at transition: density increase (residual Penning)

⇒ Study of B E Condensation dynamics (cf laser onset dynamics)

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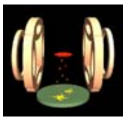
New studies in quantum atom optics

- A milestone in Photon Quantum Optics: the use of photon counters to measure photon statistics
- A similar step in Atom Optics: BEC of metastable atoms, single atom (or ion) detection resolved in space and time



- Study of correlation functions of atomic field
  - Hanburry-Brown &Twiss type experiments
  - Fluctuations of atom laser around BEC transition
  - Build up of interferences from independant BEC
- Quantum optics with a small number of quanta…

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