Piégeage et refroidissement laser d'atomes et d'ions appliqués à la spectroscopie haute résolution

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Littérature

- W. Demtröder, "Laser Spectroscopy", Springer Verlag, Berlin
- Steven Chu, "The manipulation of neutral particles", Reviews of Modern Physics **70**, 685 (1998).
- Claude N. Cohen-Tannoudji, "Manipulating atoms with photons", Reviews of Modern Physics **70**, 707 (1998).
- William D. Phillips, "Laser cooling and trapping of neutral atoms", Reviews of Modern Physics **70**, 721 (1998).
- Claude N. CohenTannoudji and William D. Phillips, "New Mechanisms for Laser Cooling »; Phys. Today 43(10), 33 (1990); doi: 10.1063/1.881239
- http://www.nobel.se

Plan

1. Refroidissement laser

2.piège à atomes (mélasses, MOT, fontaines, …)

3.réseaux atomiques, pièges dipolaires

4.pièges à ions (Paul, Penning, ..)

5.BEC

Refroidissement laser

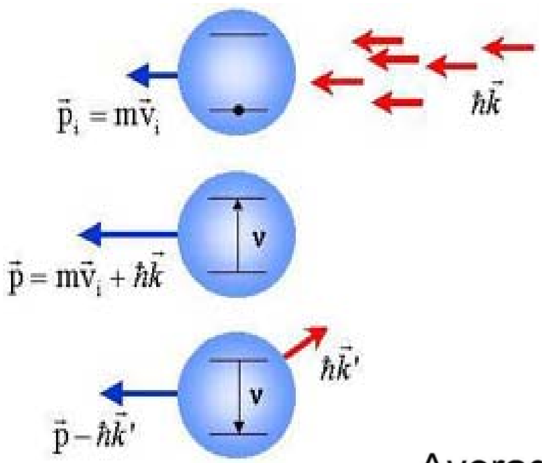
Depuis 1975…

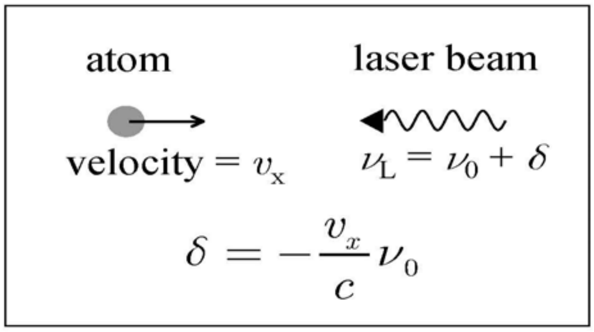
- **1975 Hänsch/Schawlow** and **Wineland/Dehmelt** : possibility of laser cooling
- **1978 First demonstration of laser cooling** for trapped ions (Neuhauser et al.; Wineland et al.)
- 1982 First stopping of a thermal beam (Philips & Metcalf)
- **1985 First 3-D cooling (Chu, Hollberg et al.)** ▯ 240 μK
- 1987 theory of magneto-optical trap (MOT) (Dalibard et al.)
- 1988 Sub-Doppler cooling (Cohen-Tannoudji et al.) ▯ 40 nK
- 1995 Laser + evaporative cooling (Anderson, Cornell et al.) ▯ 20 nK
-

Nobel Prizes

1989 Paul Dehmelt ion-trap
1997 Chu, Cohen-Tannoudji, Philips laser cooling & trapping
2001 Cornell, Ketterle, Wieman BEC
2005 Glauber, Hall, Hänsch laser-based precision spectroscopy
2012 Haroche, Wineland manipulation of individual quantum systems

Refroidissement laser



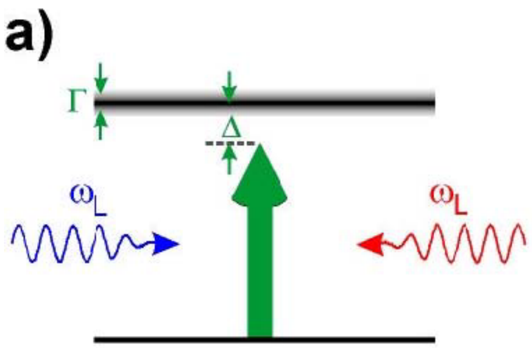


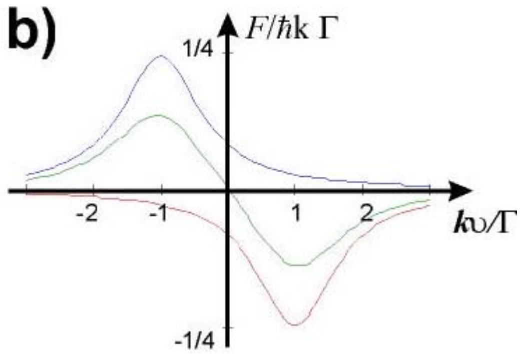
Average momentum kick of $(-h/\lambda)$ in time τ

$$F_x = \frac{dp_x}{dt} \sim \frac{\Delta p_x}{\tau} = -\frac{h}{\lambda\tau}$$

http://archive.nrc-cnrc.gc.ca/eng/projects/inms/fountain-clock.html

Refroidissement Doppler





$\omega_L < \omega_A$

Force de friction F = - αV

$$F(V) = \frac{\hbar k \Gamma}{2} \frac{s_0}{1 + s_0 + 4\left[\omega_{at} - \omega_L + k_L \cdot V\right]^2 / \Gamma^2}$$

Refroidissement Doppler - *limites*

- Nombre de cycle absoprtion-émission afin de freiner l'atome

$$N_{stop} \approx \frac{initial p_x}{\Delta p_x percycle} \approx \frac{mu_x}{h/\lambda}$$

- le temps nécessaire

$$t_{min} \approx N_{stop} \times 2\tau \approx \frac{mu_x \lambda \tau}{h}$$

- la distance parcourue

$$d_{min} \approx \frac{m\lambda u_x^2}{h}$$

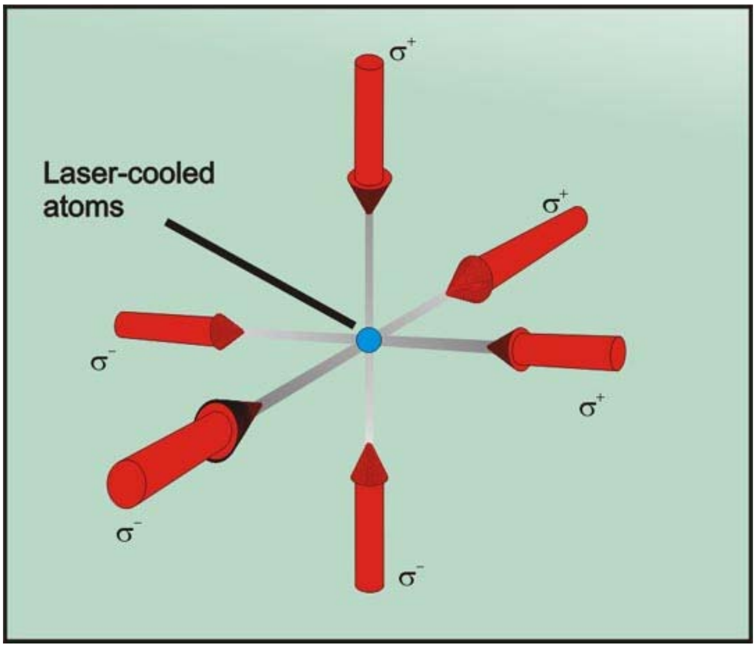
$$k_B T_{min} \sim h\Delta\nu$$

$$T_{min} \approx \frac{\hbar}{2k_B \tau}$$

Température limite Doppler
définie par la largeur naturelle de raie

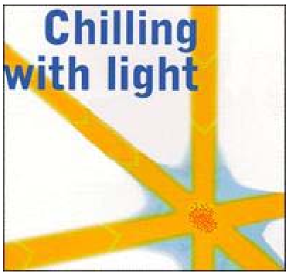
Facteur 2 de l'émission stimulée

Refroidissement Doppler - 3D



Mélasse optique

2. Pièges à atomes



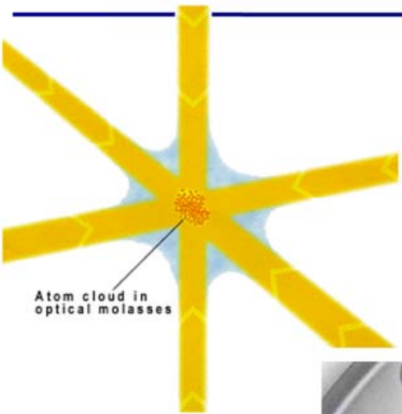
The Nobel Prize in Physics 1997

The Royal Swedish Academy of Sciences has awarded the 1997 Nobel Prize in Physics jointly to

Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**

for their developments of methods to cool and trap atoms with laser light.

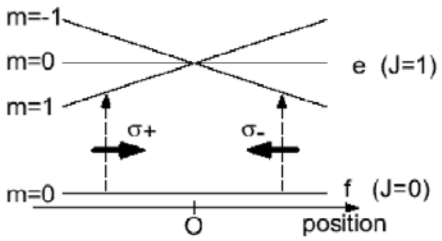
2. Pièges à atomes – *mélasses optiques*

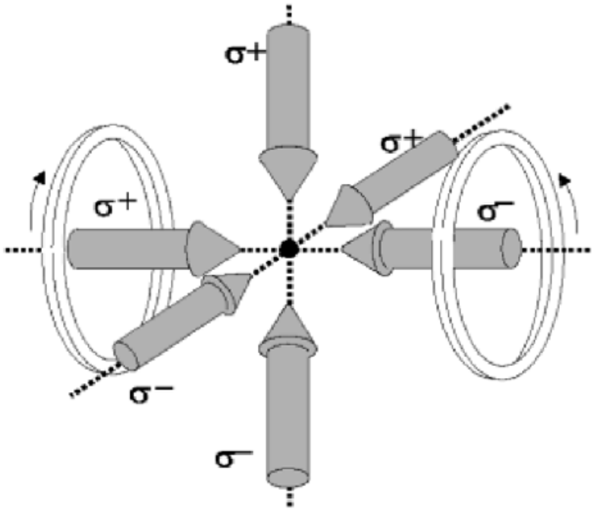


S. Chu, Scientific American, 174, 1992

- refroidissement Doppler (Hänsch et Schawlow 1975, Wineland et Dehmelt 1975)
- une force visqueuse
- ralentissement et confinement
- V ~ cm³ , fraction de seconde (100ms)
- T $\approx$ 200 μK

2. Pièges à atomes - *MOT*





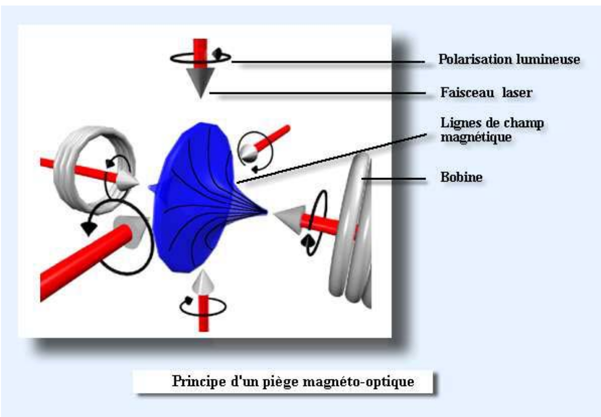
$$\mathbf{F} = - \alpha \mathbf{v} - k\,\mathbf{r}$$

mélasse 3D
effet Doppler

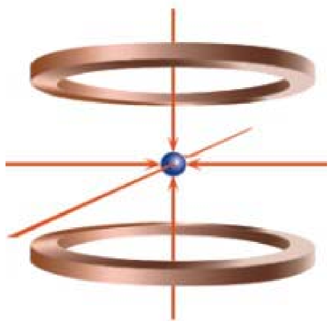
confinement
effet Zeeman

b' = 10 Gauss / cm
I = qq mW par faisceau

2. Pièges à atomes - *MOT*



Principe d'un piège magnéto-optique



2. Pièges à atomes - *MOT*

TOF

mesure de la température

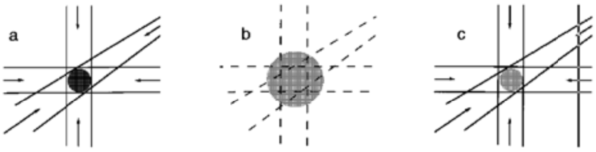
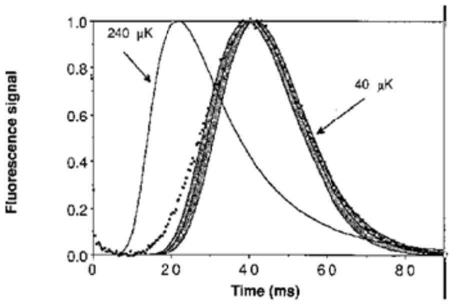
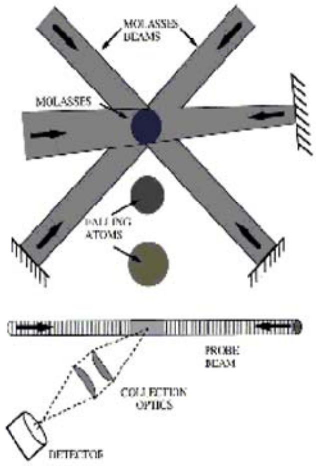
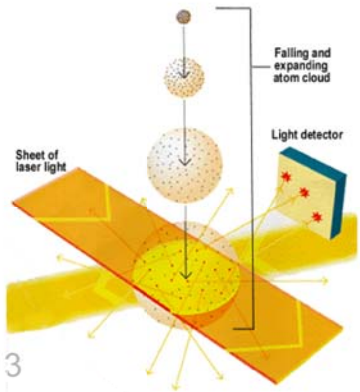


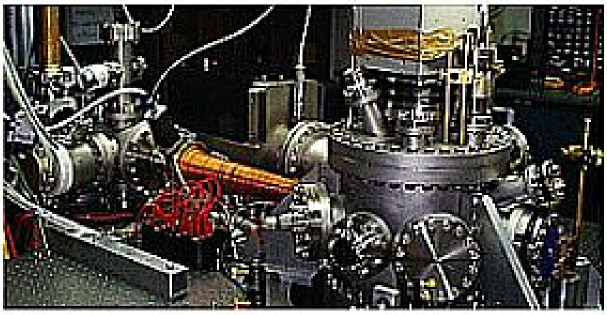
FIG. 13. Release-and-recapture method for temperature measurement.

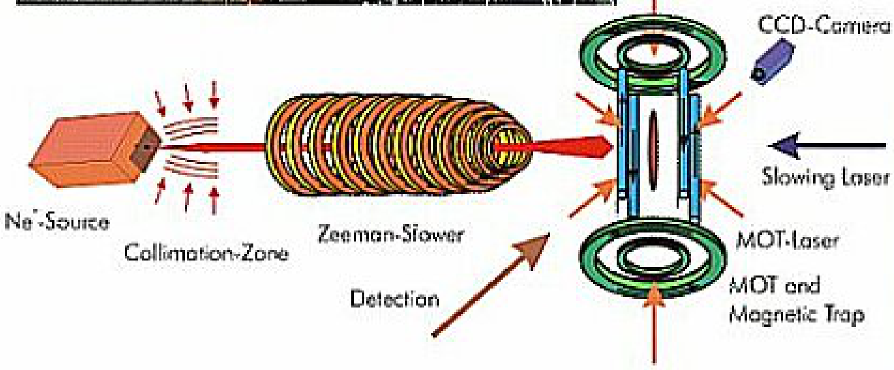


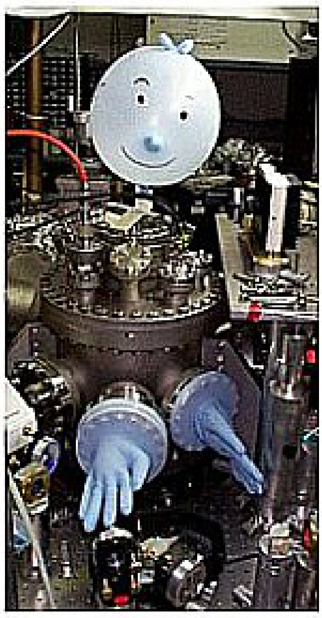




2. Pièges à atomes - *MOT*



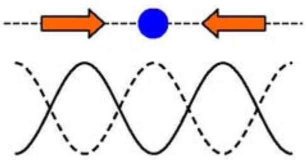




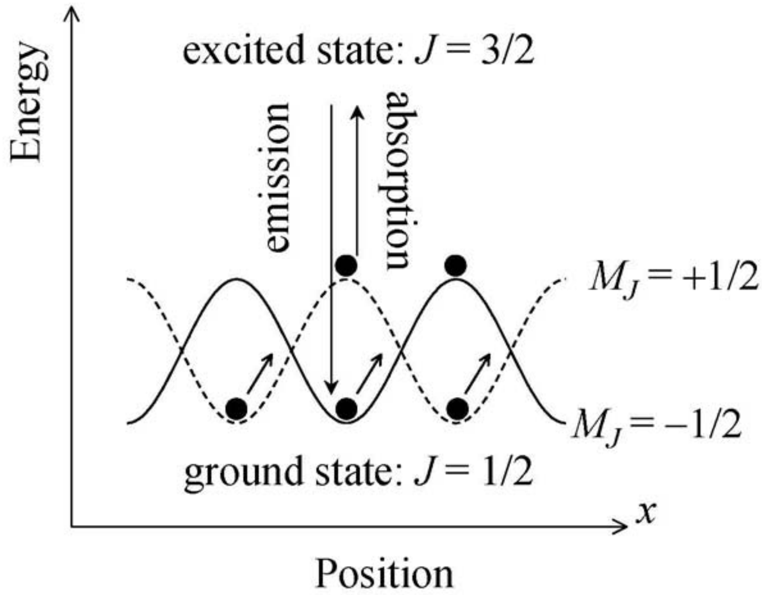
MOT néon, IQO, Hannover

2. Pièges à atomes – *polarization gradient cooling*

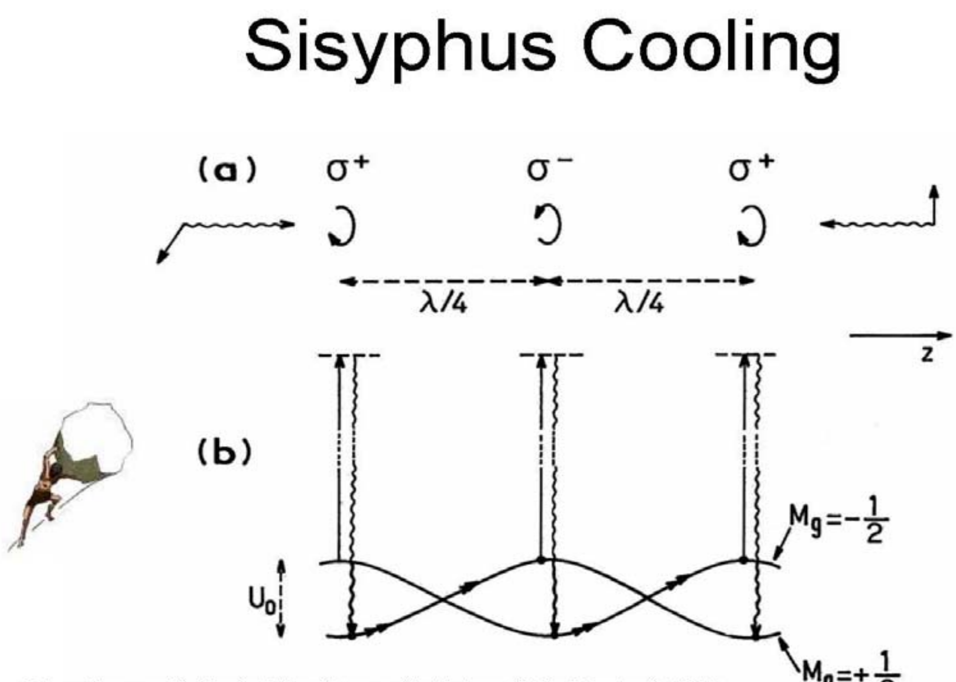
Refroidissement Sysiphe



- counter-propagating beams create interference pattern
- Atomic levels shifted by the AC-Stark effect



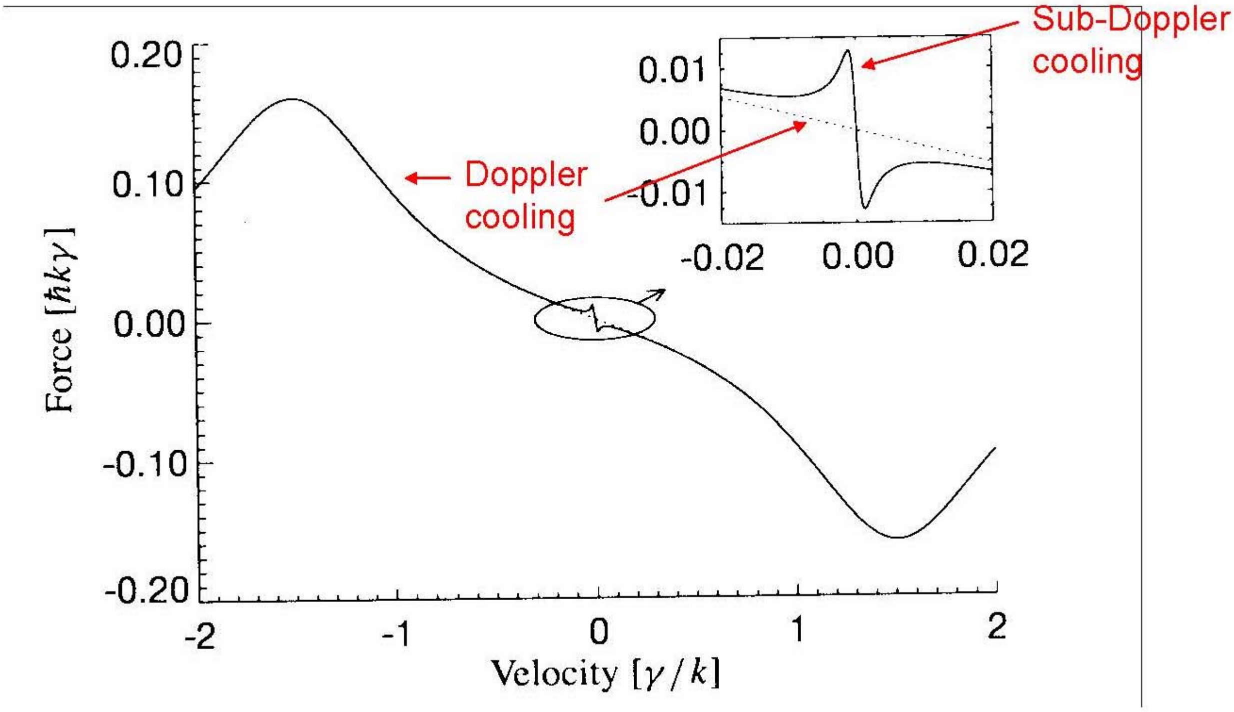
2. Pièges à atomes – *polarization gradient cooling*



Cohen-Tannoudji, Manipulating Atoms with Photons (Nobel Lecture), 1997

Sous l'effet d'un light shift oscillant

2. Pièges à atomes – *polarization gradient cooling*



H.J. Metcalf, P. van der Straten, Laser Cooling and Trapping, Springer, 1999

3. Réseaux atomiques, pièges dipolaires

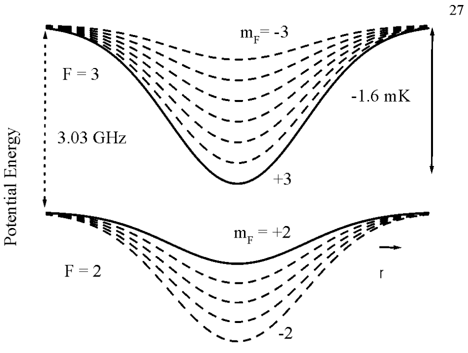


Figure 4.2: AC Stark shift in the focus of a circularly polarized Gaussian laser beam for both hyperne levels in the Rb 5 2 ground state ( ) under typical experimental parameters, for P = 240 mW. Solid lines indicate the spin states toward which the atoms are driven by absorption of the trapping light.

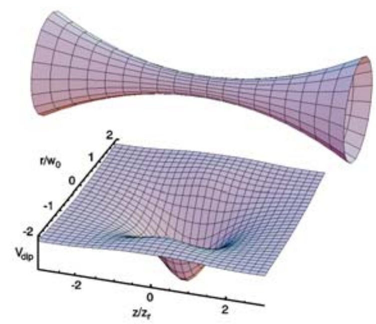


Abbildung 2.9.: Räumliche Verlauf des Dipolpotentials aufgrund des fokussierten Laserstrahls mit $\omega_0 = 3,5\,\mu$m und $\lambda = 850$ nm.

croisement de deux ondes stationnaires

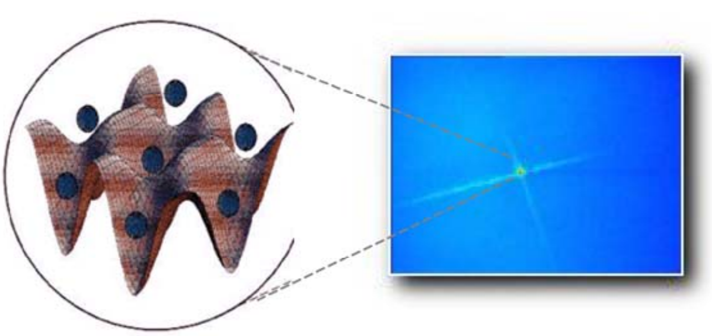
loin de résonance (FORT)

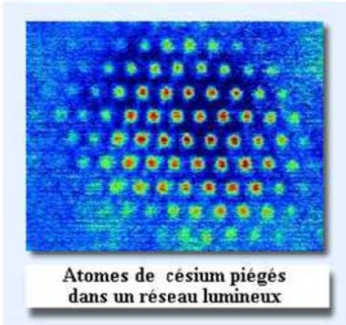
potentiel

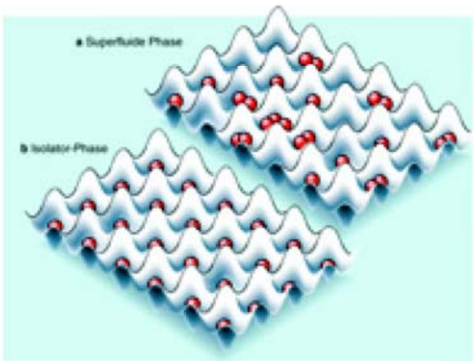
$$U(\rho,z,t) = U_0 \frac{w_{0^2}}{w(z)^2} \exp^{-\frac{2\rho^2}{w(z)^2}} \cos^2(\pi \Delta\upsilon t - kz)$$

$$\text{avec} \quad \lambda = \frac{2\pi}{k},\ w(z)^2 = w_{0^2}\left(1 + \frac{z^2}{z_{0^2}}\right),\ \text{et} \quad \Delta\upsilon = \upsilon_1 - \upsilon_2$$

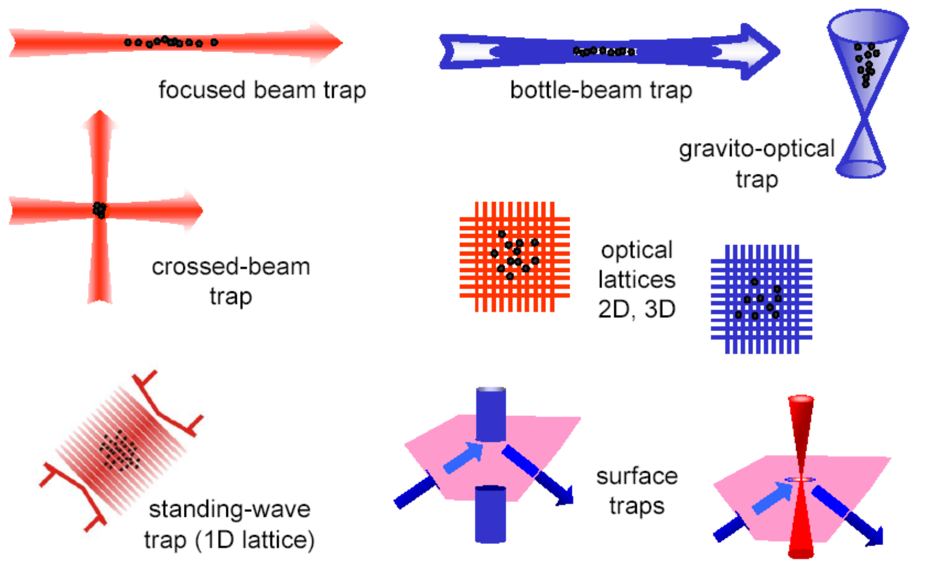
3. Réseaux atomiques, pièges dipolaires







3. Réseaux atomiques, pièges dipolaires



extremely versatile tools → many interesting applications !!!

D. Guéry-Odelin

4. Pièges à ions

The Nobel Prize in Physics 1989

The Royal Swedish Academy of Sciences has awarded this year's Nobel Prize in Physics for contributions of importance for the development of atomic precision spectroscopy

Hans Dehmelt
University of Washington
Seattle, USA

Wolfgang Paul
Universität Bonn
Federal Republic of Germany

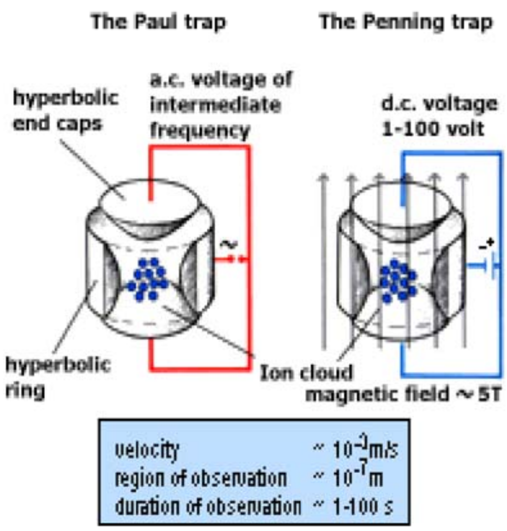
Norman F. Ramsey
Harvard University
Cambridge, USA

for the development of the ion trap technique

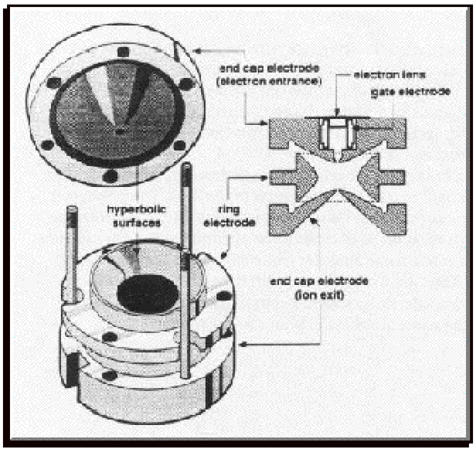
for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks

4. Pièges à ions

- électrodes métalliques avec application d'un champ
- confinement pendant des durées très longues (*des heures…*)
- permettant des études de grande précision (*temps d'interactions très grands*)
- sélectivité en *e*/m



Le piège de Paul



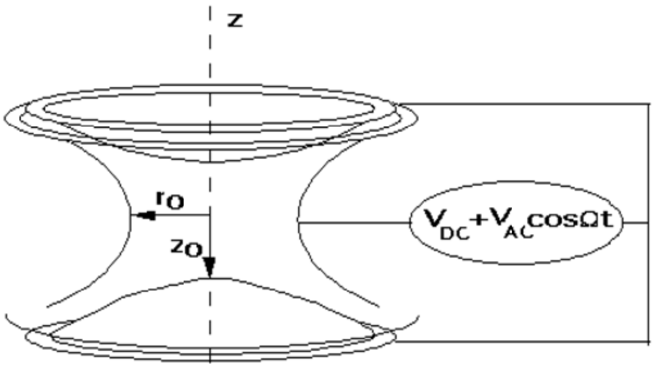
spectroscopie haute résolution et métrologie
mesures des durées de vie de niveaux atomiques

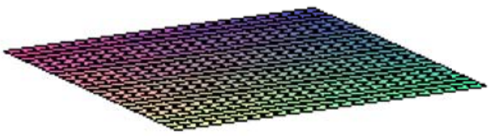
ion unique
sauts quantiques
lumière non classique
transition de phase, cristaux coulombiens et chaînes d'ions
Interférences de deux atomes
états non classiques
portes logiques
mesures de fréquences optiques
sonde nanomètrique
. ..

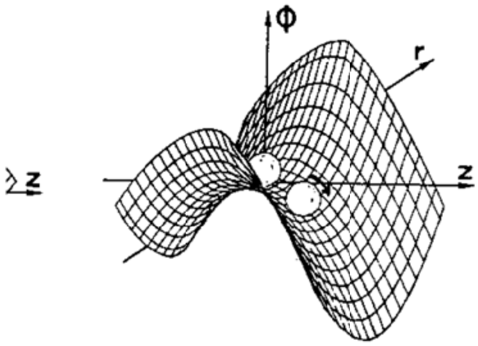
spectrométrie de masse
- **outil en chimie structurale**
- **collisions réactives lentes et rapides**
- **analyse qualitative et quantitative et ses applications**

Le piège de Paul

$$\varphi(x,y,z,t)=(V_{DC}+V_{AC}\cos\%OMEGAt)\frac{x^2+y^2+2z^2}{2r_{0^2}}$$

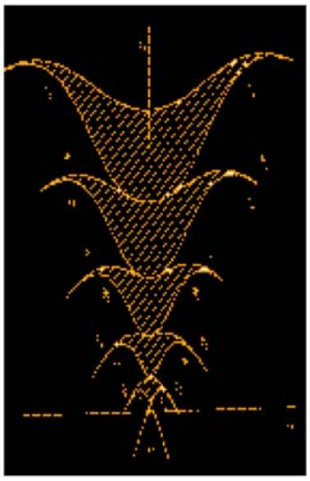






Le piège de Paul

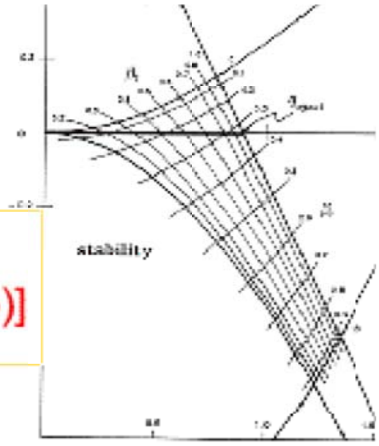
Mouvement d'une particule chargée régi par un système d'*équations de Mathieu*
(sans interactions avec les autres)



$u=x,y,z$

$$\frac{d^2u}{dt^2}+\frac{\Omega^2}{4}(a_u-2q_u\cos\Omega t)u=0$$

$$a_x=-\frac{a_z}{2}=\frac{8eU_{dc}}{2r_o^2m\Omega^2},\quad q_x=-\frac{q_z}{2}=\frac{4eV_{ac}}{2r_o^2m\Omega^2}$$



Les solutions *stables* sont données par

$$u(t)=u_o[A_u(t)\cos(\omega_u t+\varphi)+B_u(t)\sin(\omega_u t+\varphi)]$$
$$v_u(t)=u_o\omega_u[C_u(t)\cos(\omega_u t+\varphi)+D_u(t)\sin(\omega_u t+\varphi)]$$

Mouvement des particules

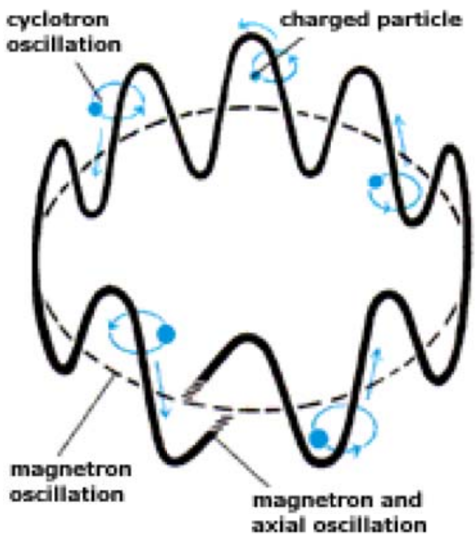
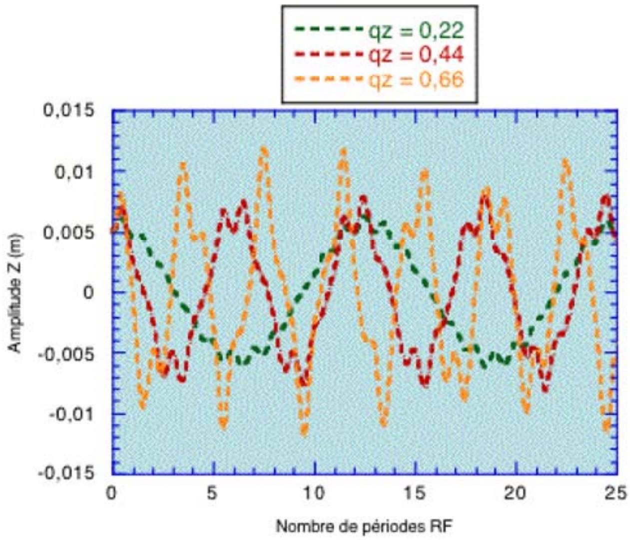
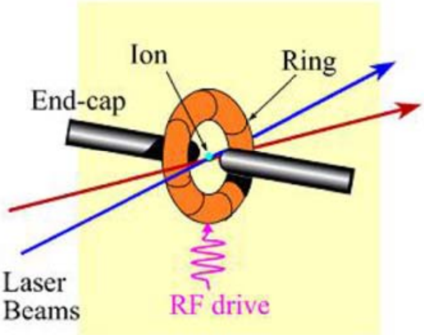


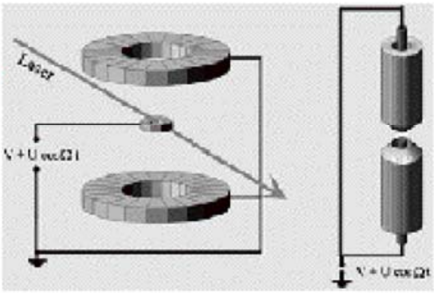
Fig. 9

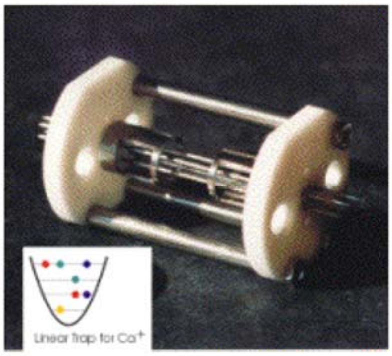


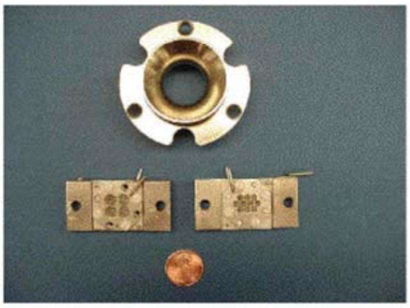
Le piège de Paul



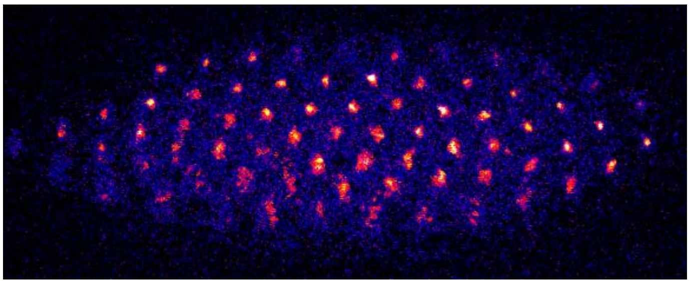
An Ion Trap

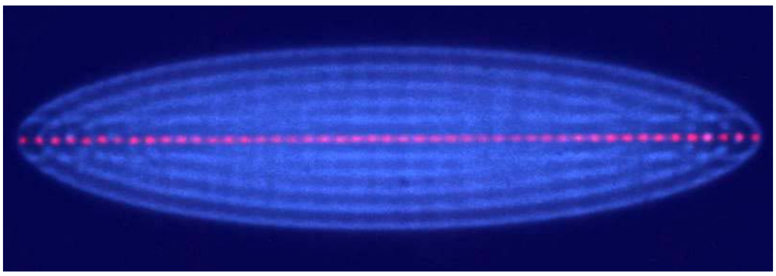


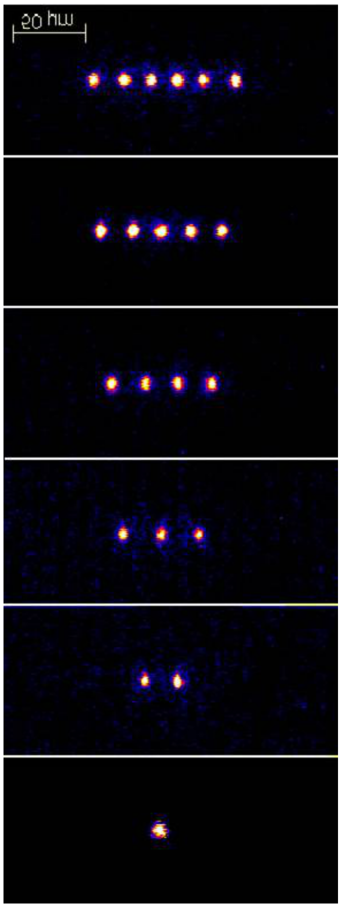




Des chaînes

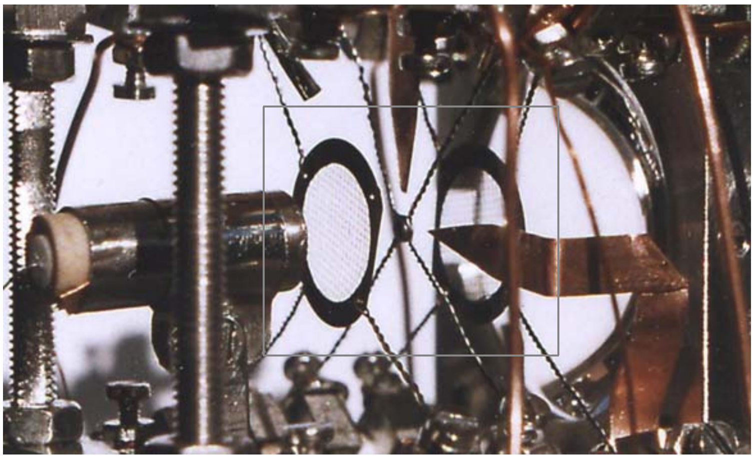


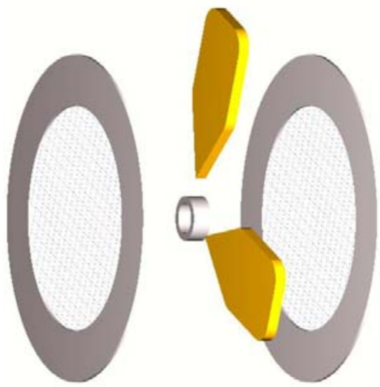




vers un ion unique

Le piège miniature





géométrie de *Paul-Straubel*

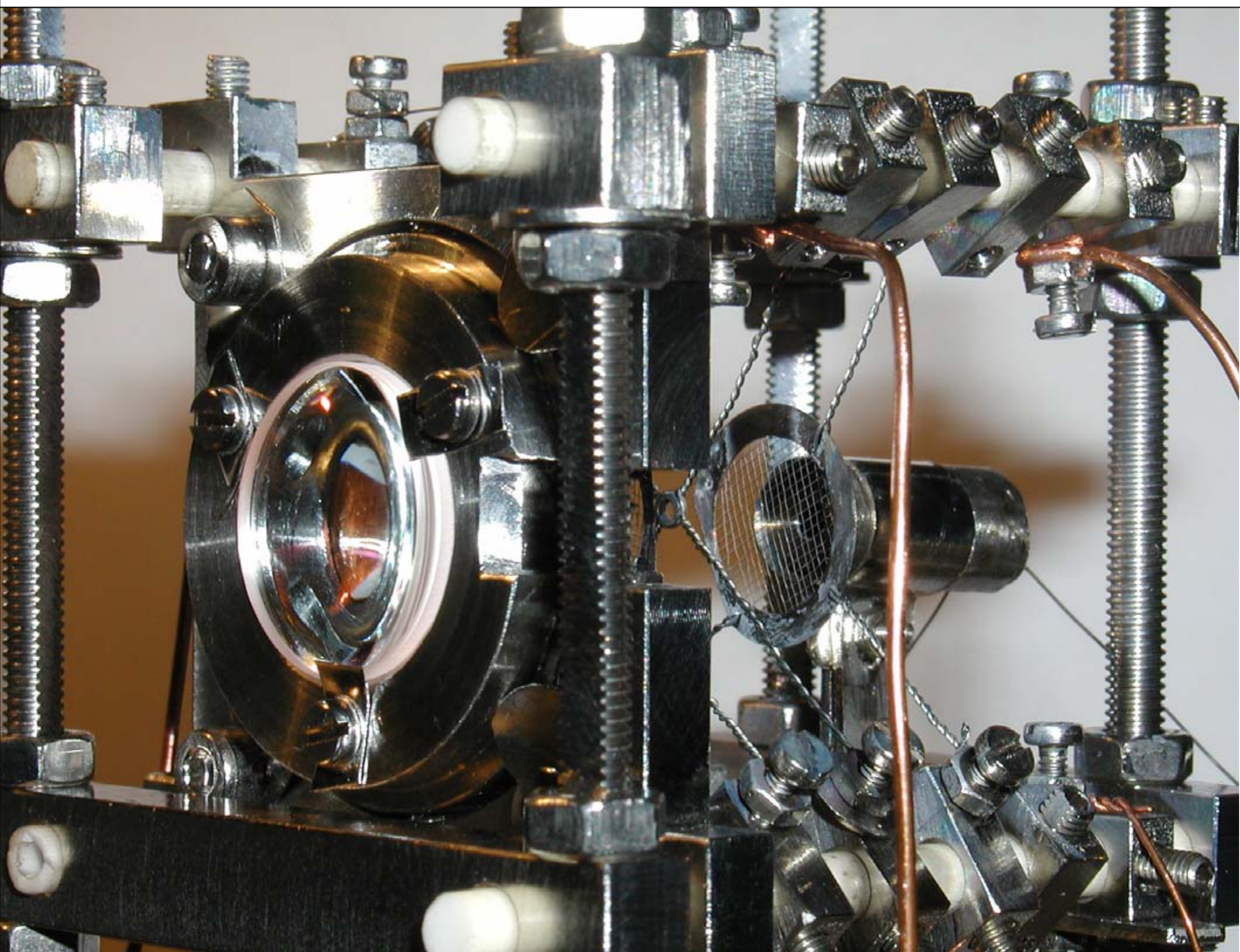
r_{int}=0.7mm, $2z_0$=0.85mm,

en molybdène

électrodes de compensation en x, y, z (2),

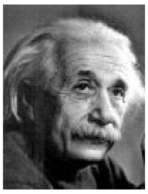
$\Omega \approx$11.7 MHz, $D_{tot} \approx$ qq eV

fréquences séculaires de 1 à 2 MHz.



5. Condensats de Bose-Einstein

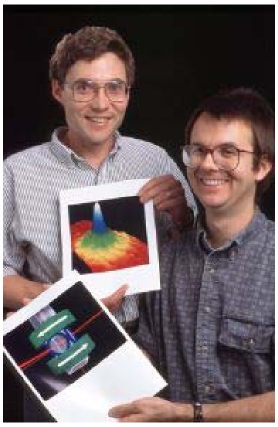
prédit en 1924 par



A. Einstein **S. Bose**

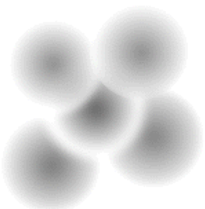
premier condensat (Rb) créé en 1995 au JILA, puis MIT

The Nobel Prize in Physics 2001

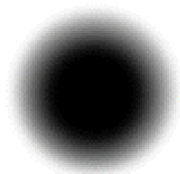


Eric A. Cornell, Carl E. Wieman, Wolfgang Ketterle

5. Condensats de Bose-Einstein



Some very cold atoms



Some atoms in a BEC condensate

le « principe d'exclusion de Pauli », interdit à deux fermions identiques d'occuper le même état.

longueur d'onde de Broglie $\lambda_{dB} = \frac{h}{mv} = \frac{h}{\sqrt{2\pi m k_B T}}$

seuil de condensation $n\lambda_{dB^3} = 2.612$

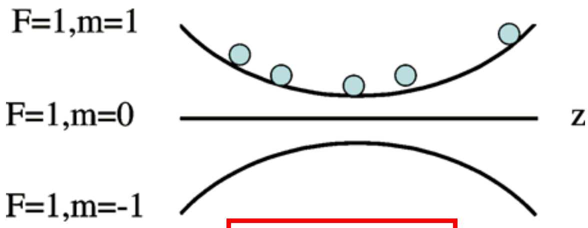
n densité de l'espace de phase *p.ex. piège dipolaire 0.001-0.005*

5. Condensats de Bose-Einstein

1ere étape : MOT T= 10μK, N= $n\lambda_{dB}$ = et énergie de recul !!

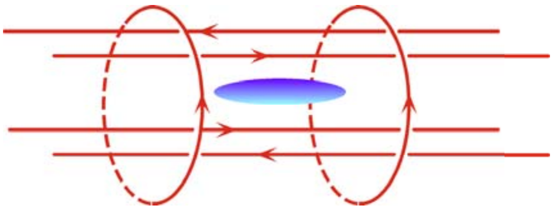
2ème étape: piège magnétique

minimum local de |***B***| + spin polarisation



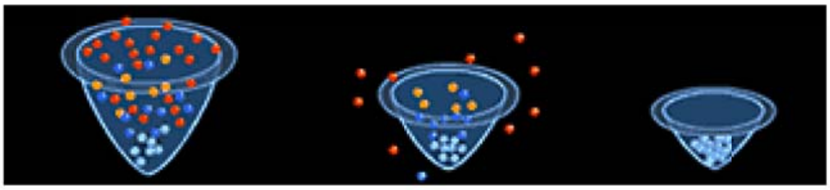
$V=|\boldsymbol{\mu}||\boldsymbol{B}|$

p.ex. Ioffe-Pritchard trap, profondeur 1 mK



5. Condensats de Bose-Einstein

3ème étape: refroidissement évaporatif



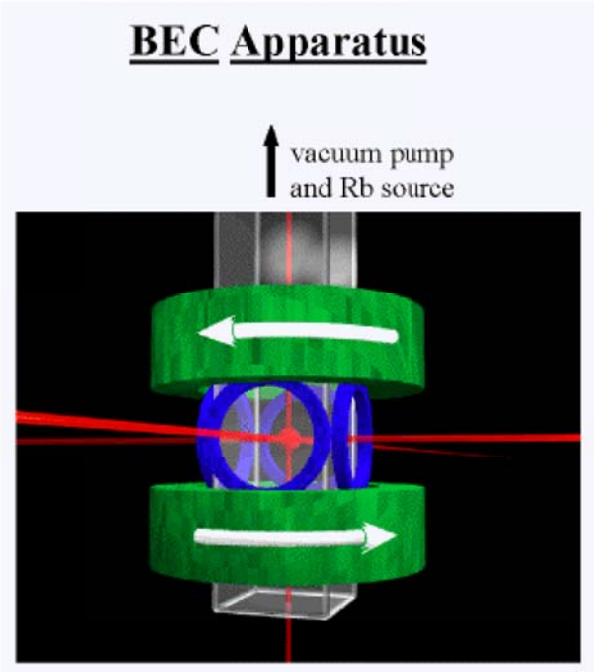
redistribution par collisions élastiques

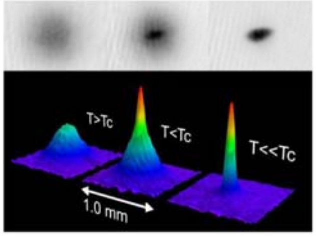
N_{in} ~ 10^9 at N_f ~ 10^5 – 10^7 at N_f= N_{in}/100

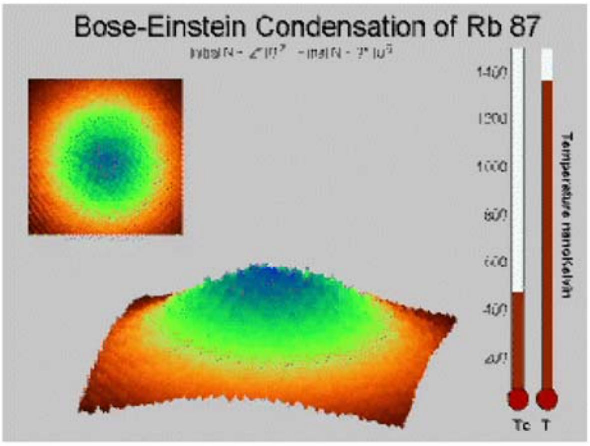
T_{in} ~ qq 100 μK T_f ~ 1 μK – 500pK T_f= T_{in}/ 1000

$\Rightarrow$ $n\lambda^3$ x 10^7 !!! quelques dizaines de secondes

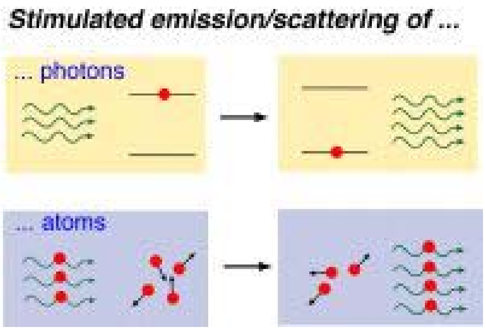
5. Condensats de Bose-Einstein



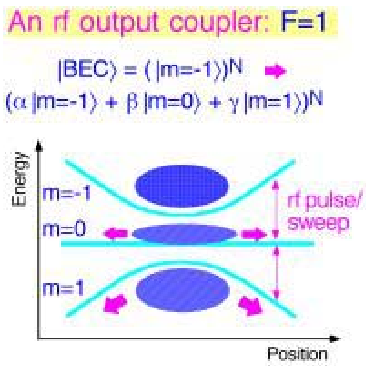


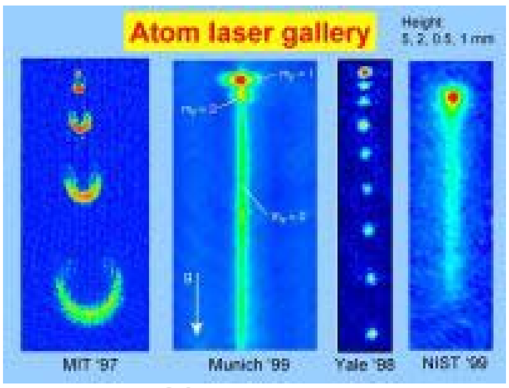


5. Condensats de Bose-Einstein

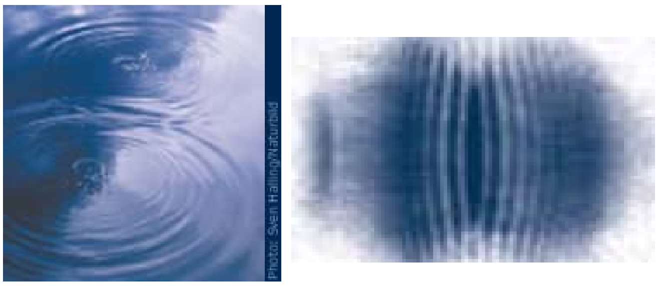


le laser à atomes





interférences



Applications

- horloges atomiques
- ondes cohérentes de matière (laser à atomes)
- recherche fondamentale

Synthèse

types	τ_{trap}	**N**	T_{limite}	$\delta\nu/\nu$
cellules		10^{19} m^{-3}	300K	10^{-8}
piège rf	> h	1	mK + LD	< 10^{-18}
Penning	> h		mK	10^{-6}
mélasses optiques	< 100 ms		qq 100μK	10^{-8}
MOT	qq s	10^{9}	10 μK	10^{-8}
fontaines	1s	10^{8}	100 μK	10^{-16}
réseaux atomiques	s	10^{8}	μK	<10^{-12}
BEC	s	3.10^{7}	500 pK	??