Evaporative Cooling

by Eunhwa Jeong

1. Introduction

Laser cooling
Buffer gas cooling } → Evaporative cooling → BEC

- Limitations of Laser cooling
- Magnetic traps
  - quadrupole trap
  - TOP (Time-averaged, Orbiting Potential)
- Evaporative Cooling

2. Limitations of Laser cooling

- collisions between laser and cooled atoms

a) photon recoil limit $k_B T_{rec} = \frac{P^2}{2M_{atom}} = \frac{(\hbar k)^2}{2M_{atom}}$

b) Doppler limit for temperature $T_D = \frac{\hbar \gamma_0}{2}$

c) reabsorption of light that is emitted by other atoms

$\sim$ net repulsive force

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Collective Behavior of Optically Trapped Neutral Atoms

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$\nabla \cdot \vec{F}_A = -6\sigma_L^2 I_\infty \frac{n}{c}$, σ_L : cross section for absorption of the laser light

$\nabla \cdot \vec{F}_R = 6\sigma_L \sigma_R I_\infty \frac{n}{c}$, σ_R : " of scattered light

$\vec{F} = \vec{F}_A + \vec{F}_R \sim \left(\frac{\sigma_R}{\sigma_L} - 1\right)$, $\sigma_R > \sigma_L$

$\vec{F}_A$: attraction due to intensity gradient

$\vec{F}_B$: repulsion due to multiple scattering of photons by atoms

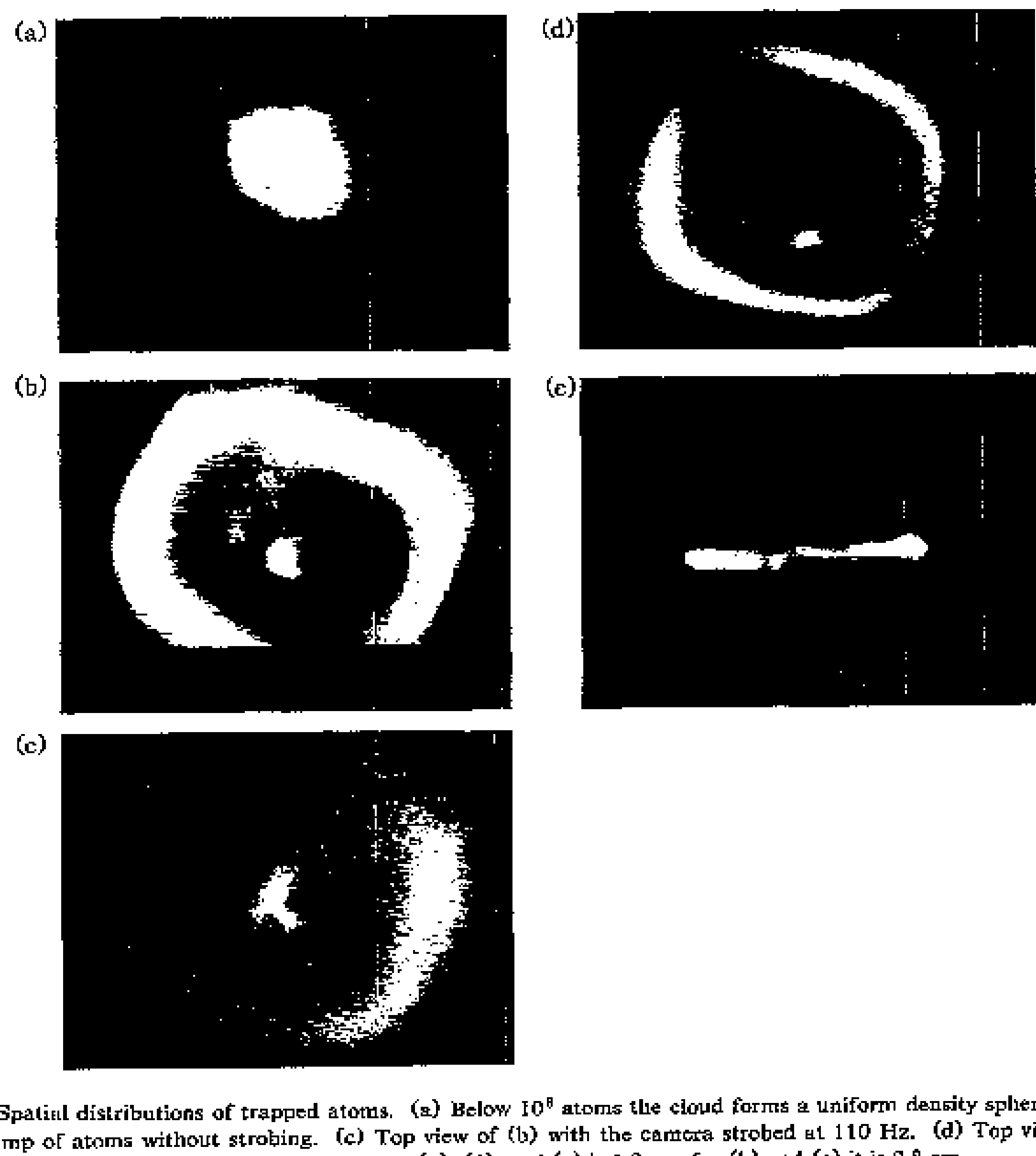


FIG. 1. Spatial distributions of trapped atoms. (a) Below 10^8 atoms the cloud forms a uniform density sphere. (b) Top view of rotating clump of atoms without strobing. (c) Top view of (b) with the camera strobed at 110 Hz. (d) Top view of a continuous ring. (e) Side view of (d). Horizontal full scale for (a), (d), and (e) is 1.0 cm; for (b) and (c) it is 0.8 cm.

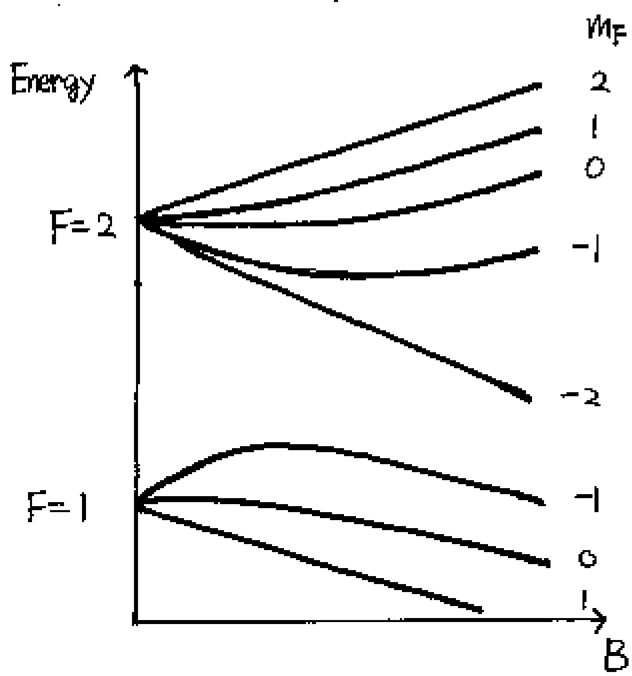
3. magnetic traps

choices as trapping mechanism other than laser

- electric field – too small polarizability of ground state atom
- magnetic field – μ's for alkali atoms are large enough

$\mu_{alkali} \sim \mu_B$, $B \sim 10-100\,mT$

$$\vec{F} = \vec{\mu}\cdot\nabla|\vec{B}|$$
$$= m_F g_J \mu_B \nabla|\vec{B}|$$



$J = 1/2$, $I = 3/2$

trappable states:

F=2 , m_F = 2, 1, 0

F=1 , m_F = −1

Zeeman splitting

1) quadrupole trap

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First Observation of Magnetically Trapped Neutral Atoms

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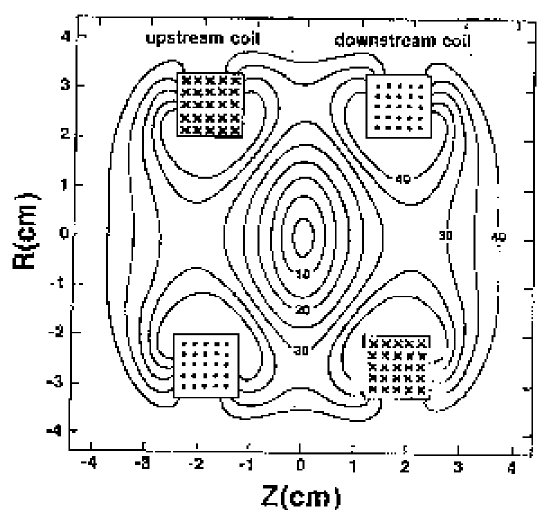


FIG. 1. Equipotentials (equal field magnitudes in millitesla) of our quadrupole trap in a plane containing the axis of symmetry (z axis).

- Na $3^2S_{1/2}$, $F=2$, $m_F=2$ state used.
- Zeeman energy increases linearly.
- coil separation : $\sim 1.25R \sim 3.4$ cm , R : radius of ring

  $B \sim 0.025$T , potential depth ~ 17mK

  $v < 3.5$ m/s atoms are trappable.

semilogarithmic scale

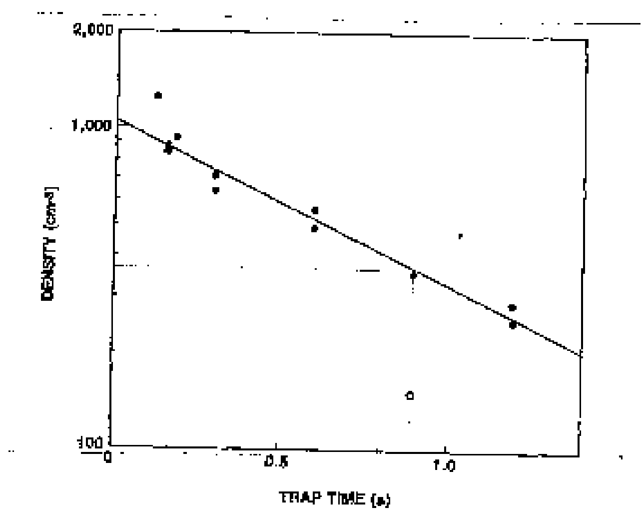


FIG. 4. Atomic density vs trapping time. A fit to all the filled points yields a decay time of 0.83(7) s. The filled points were taken at a measured background pressure of $\sim 1\times10^{-8}$ Torr; the open point was taken at $\sim 2\times10^{-8}$ Torr. Its decreased density reflects the fact that the pressure limits the lifetime.

- time constant for the decay of the trapped atom population:

$N(t) \sim e^{-t/\tau_0}$, $\tau_0 \simeq 0.83(7)\,s$.

- fundamental limit to the storage time for atoms in the trap:

  nonadiabatic spin flip

  adiabaticity condition: $\omega_L \gg \omega_t$, ω_L : Larmor frequency

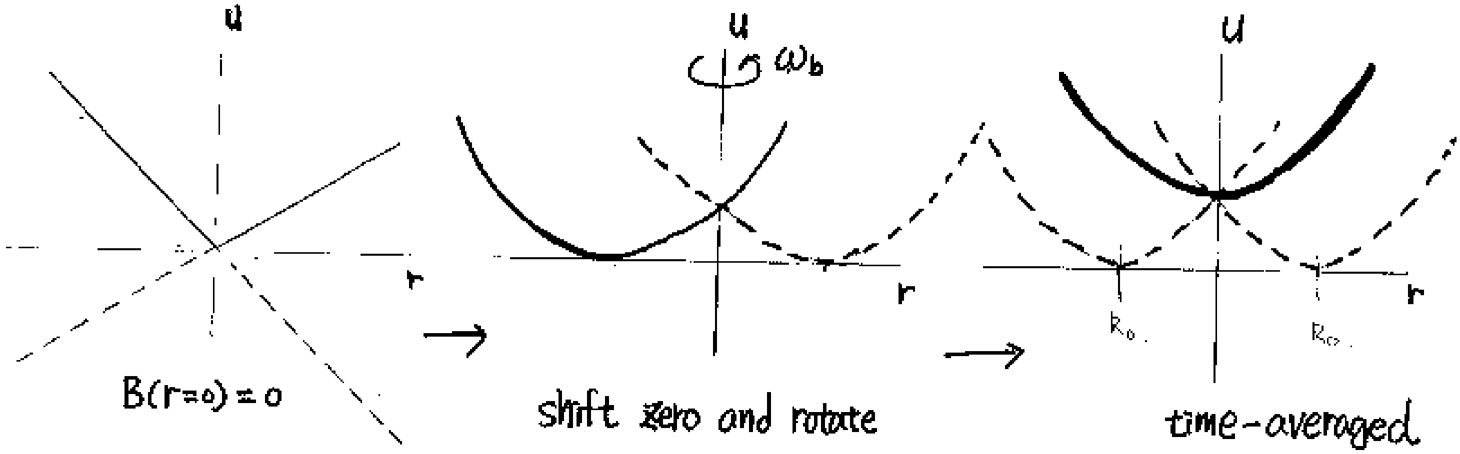
  ω_t : angular frequency of orbital motion in trap

Loss occurs at $\omega_L \left(= \frac{\mu b B_q'}{\hbar}\right) < \omega_t \left(\sim \frac{v}{b}\right)$, b: minimum distance from path to center

$\rightarrow b_0 \sim \left(\frac{v\hbar}{\mu B_q'}\right)^{1/2}$, radius of ellipsoid in which non-adiabatic spin flips occur.

- this ellipsoid includes bottom of the potential.

2) TOP (Time-averaged, Orbiting Potential)



$$\vec{B} = (xB_q' + B_b\cos(\omega_b t))\hat{i} + (yB_q' + B_b\sin(\omega_b t))\hat{j} - 2zB_q'\hat{k}$$

$$U(\vec{r},t) = \mu|\vec{B}|$$

$$U_{TOP}(r,z) = \frac{\omega_b}{2\pi}\int_0^{\frac{2\pi}{\omega_b}} U(t)\,dt$$

$$\simeq \mu B_b + \frac{\mu B_q'^2}{4B_b}(r^2 + 8z^2) + \cdots$$

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Stable, Tightly Confining Magnetic Trap for Evaporative Cooling of Neutral Atoms

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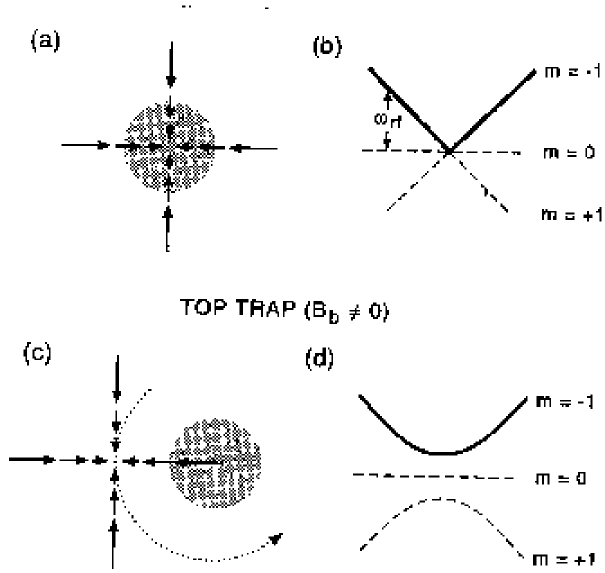

FIG. 1. The magnetic field configuration (a) and the cylindrically symmetric potential (b) of a quadrupole trap. The magnetic field at ω_{rf} for evaporation is shown schematically (b). The instantaneous horizontal field configuration of the TOP trap (c) is displayed together with the time-averaged, orbiting potential (d) of this new type of trap. In both the quadrupole potential and the TOP potential, an atom like ^{87}Rb is considered, which is trapped in a state with the total angular momentum quantum number $F = 1$ and the magnetic quantum number $m = -1$.

- The radius of the trajectory of the field zero $R_0 = \frac{B_b}{B_q'}$.
- Loss by nonadiabatic spin flip occurs in a toroidal volume lying in the x-y plane distance R_0 from bottom.

  $\rightarrow$ atoms with radial energy $\geq \frac{\mu B_b}{4}$ removed.

$$U_{TOP}(r=R_0) = \frac{\mu B_q'^2}{4B_b} R_0^2 = \frac{\mu B_q'^2}{4B_b} \cdot \left(\frac{B_b}{B_q'}\right)^2 = \frac{\mu B_b}{4}$$

- By reducing the bias field B_b adiabatically, we can cool the atom cloud.

  $B_b \downarrow \rightarrow \frac{\mu B_q'^2}{4B_b} \sim k$ (spring constant) $\uparrow \rightarrow$ density $\uparrow$

- adiabatic condition $\omega_t \ll \omega_b \ll \omega_L$

$\frac{\omega}{2\pi} \sim 100\,\text{Hz}$ $\quad 7.5\,\text{kHz}$ $\quad 7\,\text{MHz}$

Experiment: $B_b = 10\,\text{G}$, $\frac{\partial B}{\partial r} = 120\,\text{G/cm}$, $\frac{\partial B}{\partial z} = 240\,\text{G/cm}$

^{87}Rb $F=1, m_F=-1$

$\omega_b = 2\pi \times 7.5\,\text{kHz}$,

radial trap depth $\sim 100\,\mu\text{K}$.

With B_b fixed, ω_{rf} ramping down over a period of about 150s.

$$\left.\begin{array}{l} 7.5\times10^{6}\ \text{atoms} \\ T = 16\,\mu\text{K} \\ n = 3.3\times10^{10}\,\text{cm}^{-3} \end{array}\right\} \longrightarrow \left\{\begin{array}{l} 2\times10^{4}\ \text{atoms} \\ T = 200\,\text{nK} \\ n = 6.2\times10^{10}\,\text{cm}^{-3} \end{array}\right.$$

change in phase-space density

$$\frac{\rho'_{ph}}{\rho_{ph}} = \frac{n'\lambda'^3}{n\lambda^3} = \frac{n'}{n}\left(\frac{T'}{T}\right)^{-3/2} \sim 10^3$$

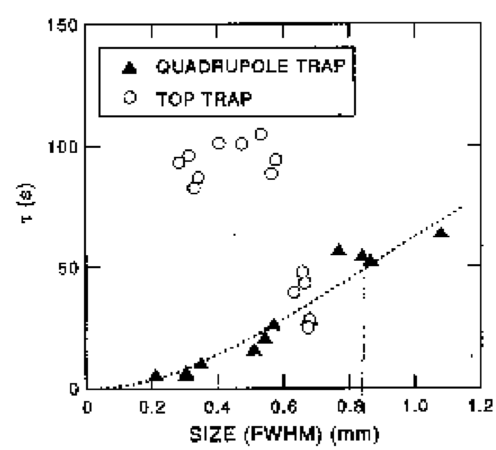

FIG. 2. The storage time of [87]Rb atoms as a function of trapped cloud size in the quadrupole and TOP traps. The fit to the quadrupole data (dashed line) indicates the scaling law expected from losses due to collisions with background gas and due to nonadiabatic spin flips in the center of the quadrupole trap.

4. Conclusion

- Lifetime of small clouds in the TOP trap is independent of size.
- Major loss mechanism : non-adiabatic spin flips
- TOP trap supresses this and provides tight confinement.
- 10^3 magnitude increase in phase-space density, final temperature 200 nK after ω_{rf} cooling.