1. Introduction

Laser cooling \{ \rightarrow \text{Evaporative cooling} \rightarrow \text{BEC}

Buffer gas cooling

- Limitations of Laser cooling

- Magnetic traps
  \{ \text{quadrupole trap}
  \quad \{ \text{TOP (Time-averaged, Orbiting Potential)}

- Evaporative Cooling
2. Limitations of Laser cooling
   - collisions between laser and cooled atoms
     a) photon recoil limit \( k_B T_{\text{rec}} = \frac{p^2}{2M_{\text{atom}}} = \frac{(\hbar k)^2}{2M_{\text{atom}}} \)
     b) Doppler limit for temperature \( T_D = \frac{k_B T}{\frac{c}{v}} \)
     c) reabsorption of light that is emitted by other atoms

\[ \nabla \cdot \mathbf{F}_A = -6 \sigma_L I_0 \frac{n}{C}, \quad \sigma_L : \text{cross section for absorption} \]
\[ \nabla \cdot \mathbf{F}_R = 6 \sigma_R \sigma_L I_0 \frac{n}{C}, \quad \sigma_R : \text{of scattered light} \]
\[ \mathbf{F} = \mathbf{F}_A + \mathbf{F}_R \sim \left( \frac{\sigma_R}{\sigma_L} - 1 \right), \quad \sigma_R > \sigma_L \]
\[ \mathbf{F}_A : \text{attraction due to intensity gradient} \]
\[ \mathbf{F}_R : \text{repulsion due to multiple scattering of photons by atoms} \]
FIG. 1. Spatial distributions of trapped atoms. (a) Below 10⁸ 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 (e) it is 0.8 cm.
3. magnetic traps

choices as trapping mechanism other than laser

- electric field - too small polarizibility of ground state atom
- magnetic field - \( \mu \)'s for alkali atoms are large enough
  \( \text{Alkali} \sim \mu_B, B \sim 10-100 \text{mT} \)

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

\[J = \frac{1}{2}, I = \frac{3}{2}\]

trappable states:

- \( F = 2, m_F = 2, 1, 0 \)
- \( F = 1, m_F = -1 \)

Zeeman splitting
First Observation of Magnetically Trapped Neutral Atoms

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FIG. 1. Equipotentials (equal field magnitudes in millite- ses) 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: $\sim 1.25 R \sim 3.4$ cm, $R =$ radius of ring

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

$V < 3.5$ m/s atoms are trappable.
\( N(t) \sim e^{t / \tau_0} \), \( \tau_0 \approx 0.83(7) \text{s} \).

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

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

  **Nonadiabatic spin flip**

  *Adiabaticity condition:* \( \omega_L \gg \omega_t \), \( \omega_L \): Larmor frequency

\( \omega_t \): Angular frequency of orbital motion in trap

Loss occurs at \( \omega_L \left( = \frac{m_b B^2}{h} \right) < \omega_t \left( \sim \frac{v^2}{b} \right) \), \( b \): minimum distance from path to center

\( \rightarrow b \sim \left( \frac{m_b B^2}{\hbar} \right)^{1/2} \), radius of ellipsoid in which non-adiabatic spin flips occur.

- This ellipsoid includes bottom of the potential.
2) **TOP** (Time-averaged, Orbiting Potential)

\[ \mathbf{B} = (xB_q + B_b \cos \omega_b t, yB_q + B_b \sin \omega_b t) \hat{r} - 2x \mathbf{B}_q \hat{k} \]

\[ U(r, \mathbf{v}) = \mu |\mathbf{B}| \]

\[ U_{\text{TOP}} (r, \mathbf{v}) = \frac{\omega_b}{2\pi} \int_0^{2\pi} U(r, \mathbf{v}) \, dt \]

\[ \approx \mu B_0 + \frac{\mu B^2}{4B_0} (r^2 + 8z^2) + \ldots \]
The radius of the trajectory of the field is zero: $R_0 = \frac{B_0}{B_g}$.

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.

$$U_{\text{top}}(r=R_0) = \frac{\mu B_b^2}{4B_b} R_0^2 = \frac{\mu B_b^2}{4B_b} \left(\frac{B_b}{B_g}\right)^2 = \frac{\mu B_b}{4}$$

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

$B_b \uparrow \rightarrow \frac{\mu B_b^2}{4B_b} \sim k$ (spring constant) $\uparrow \rightarrow$ density $\uparrow$
adiabatic condition \( \omega_t \ll \omega_b \ll \omega_n \)

\[ \frac{\omega}{\Delta \nu} \sim 100 \text{kHz}, \quad 7.5 \text{kHz} \sim 7 \text{MHz} \]

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

\[ 87^{\text{Rb}} \]
\[ F = 1, m_F = -1 \]

radial trap depth \( \sim 100 \mu \text{K} \).

With \( B_b \) fixed, \( \omega_t \) ramping down over a period of about 150s.

\[ n = 3.3 \times 10^{10} \text{cm}^{-3} \]

\[ T = 16 \mu \text{K} \]

\[ 7.5 \times 10^6 \text{ atoms} \]

\[ n' = 2 \times 10^4 \text{ atoms} \]

\[ T = 200 \text{ nK} \]

\[ n = 6.2 \times 10^6 \text{ cm}^{-3} \]

\[ n' = 6 \times 10^4 \text{ cm}^{-3} \]

change in phase-space density

\[ \frac{p_{\rho}^{'2}}{p_{\rho}^{2}} = \frac{n' x^3}{n x^3} = \frac{n'}{n} \left( \frac{T}{T} \right)^{3/2} \sim 10^3 \]

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**FIG. 2.** The average time of \(^{87}\text{Rb}\) 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 suppresses this and provides tight confinement.
- $10^3$ magnitude increase in phase-space density, final temperature 200nK after cryo cooling.