Peculiarities and applications of narrow-line magneto optical traps for neutral atoms

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Low energy physics seminar 35th cycle
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Contents

History

1925	Bose and Einstein predicted a new state of matter
1975	Hänsch and Schawlow and Wineland and Dehmelt proposed the optical molasses
1982	Phillips and Metcalf realized the Zeeman slower
1989	Chu realized the first magneto optical trap;
1997	Chu, Cohen-Tannoudji and Phillips received the Nobel Prize;
2001	Cornell, Wieman, and Ketterle received the Nobel Prize

Why are MOT cool

Mot characteristics:

- Low temperatures
- high densities
- relatively simple and robust
- are the workhorse of most cold atom experiments.

Application:

- Degenerate quantum gases
  Lanthanides: Er, Dy, Yb...
- Atomic clocks
  bosonic alkaline earth elements ^{88}Sr...

The scattering rate

The rate at witch an atom at rest absorbs photons is given by:

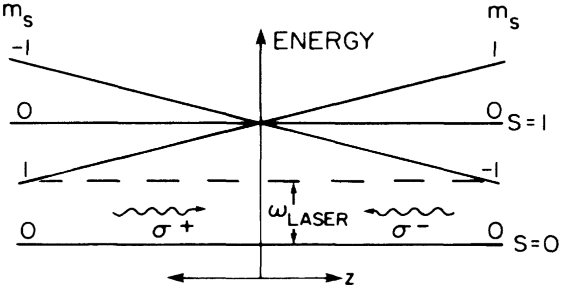
$$R_s = \frac{\gamma}{2}\frac{s}{1 + s + 4\delta^2/\gamma^2}$$

where $\delta = \omega_\mathrm{L} - \omega_\mathrm{A}$, γ is the transition linewidth and s is the saturation parameter

- an atom absorbs a photon with $\hbar\omega_L$ energy
- emits a photon with $\hbar\omega_A$ energy
- the atom momentum changes by $\vec{p} = \hbar\vec{k}$
- the atom is subjected to a force $\vec{F}_\mathrm{s} = \hbar\vec{k}R_\mathrm{s}$

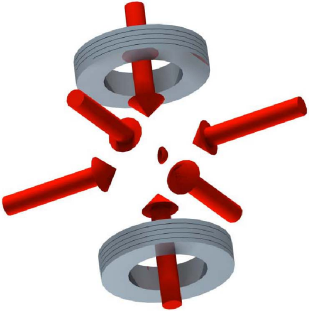
Principles of operation

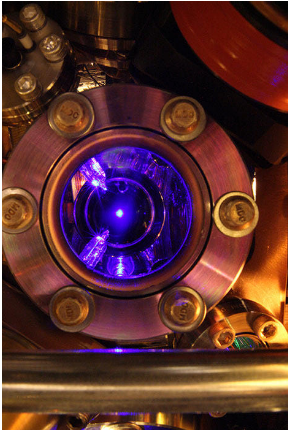
The detuning δ is velocity dependent via the Doppler effect:
$\omega'_{\mathrm{L}} = \omega_{\mathrm{L}} - \vec{k} \cdot \vec{v} \rightarrow \vec{F} = -\alpha \vec{v}$
The detuning can be made position dependent using a magnetic field gradient:
$\omega'_{\mathrm{A}} = \omega_{\mathrm{A}} + \frac{\mu \nabla B\, z}{\hbar}$



Credit: E. L. Raab et al Phys. Rev. Lett. 59, 2631 (1987)

Optical Scheme

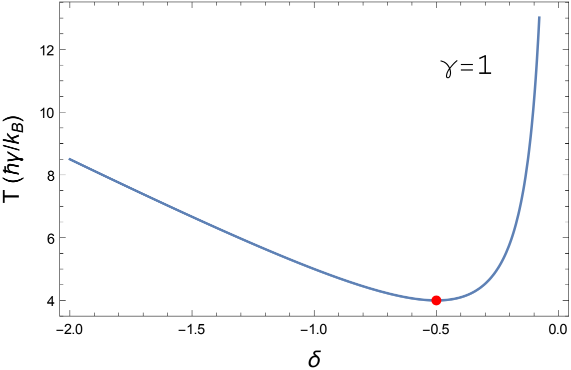




Credit: Dreon et. al. J. Phys. B: At. Mol. Opt. Phys. 50 (2017)
Credit: The Ye group and Brad Baxley, JILA

Doppler temperature

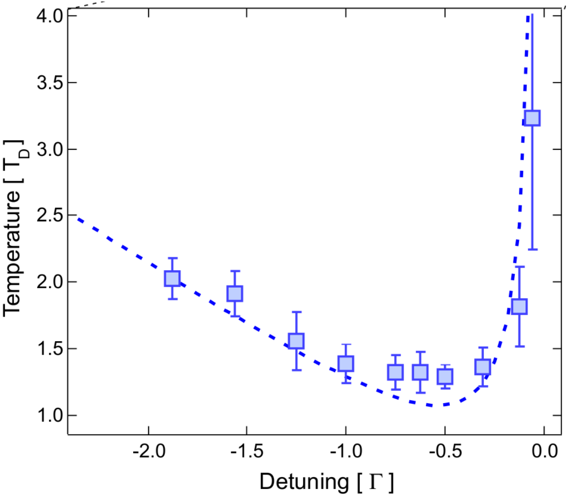
$$T = \frac{\hbar\gamma}{8k_\mathrm{B}}\left(\frac{\gamma}{|\delta|} + 4\frac{|\delta|}{\gamma}\right) \qquad T_\mathrm{min} \propto \frac{\gamma}{2} \quad \text{for} \quad \delta = -\frac{\gamma}{2}$$



Experimental data in 3D

^{4}He*

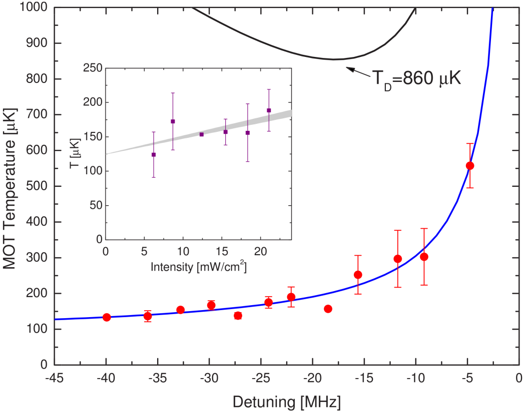
T_D 35.75 µK



Credit: R. Chang et. al. Phys. Rev. A 90 (6), pp.063407 (2014)

Sub-Doppler cooling of Er

- $\gamma \simeq 36\,\text{MHz}$
- $T_{\text{D}} = 860\,\mu\text{K}$
- $T \simeq 100\mu\text{K}$
- 10^4 atoms



Credit: A. J. Berglund et. al. Phys. Rev. A 76, 053418 (2007)

Time scales

$$E_{\mathrm{r}} = \frac{\hbar^2 k^2}{2m} \qquad \Rightarrow \qquad \omega_{\mathrm{r}} = \frac{\hbar k^2}{2m}$$

Atom internal state evolve according to γ:

$$t_{\mathrm{int}} = 1/\gamma$$

Atom external time:

$$kv = \gamma \quad \text{and} \quad a = v_{\mathrm{r}}\gamma \implies t_{\mathrm{ext}} = 1/kv_{\mathrm{rec}} = \hbar/2E_{\mathrm{r}}$$

Broadband

$t_{\mathrm{ext}} \gg t_{\mathrm{int}}$

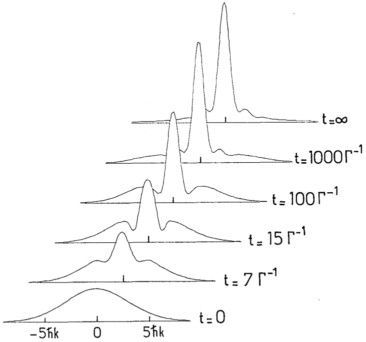
$\gamma \gg 2\omega_{\mathrm{r}}$

Narrow line

$t_{\mathrm{ext}} \simeq t_{\mathrm{int}}$

$\gamma \simeq 2\omega_{\mathrm{r}}$

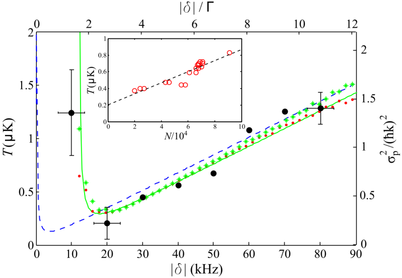
Narrow line MOT

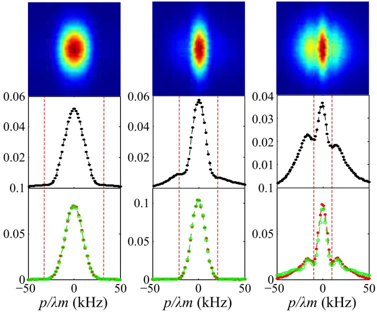


- Optimal detuning $\delta \simeq 3\omega_{\mathrm{r}}$
- Predicted final temperature $\simeq 1.5 E_{\mathrm{r}}/k_{\mathrm{B}}$
- Semiclassical theory is no longer valid
- velocity distribution is a power law $P(v) \propto |v|^{-2\frac{|\delta|}{\omega_{\mathrm{r}}}}$
- small capture velocity
- gravity can't be neglected: $R = \frac{\hbar\gamma k}{2}\frac{1}{mg} \simeq 1$

Credit: Castin et. al. J. Opt. Soc. Am. B/Vol. 6, No. 11 (1989)

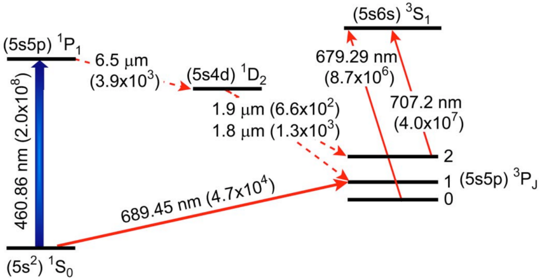
Narrow line ^{88}Sr MOT





Credit: Chalony et. al. PRL 107, 243002 (2011)

Narrow line ^{88}Sr MOT



461 nm: $^1\mathrm{S}_0 \rightarrow {}^1\mathrm{P}_1$

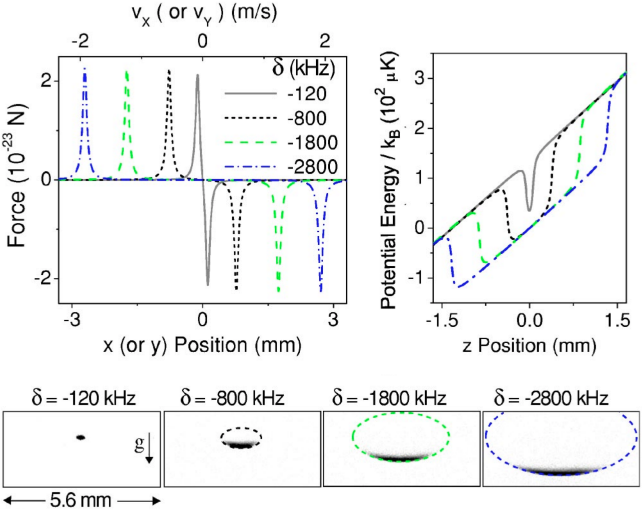
- $\gamma = 32$ MHz
- $\omega_\mathrm{r}/2\pi = 10.7$ kHz
- $T_\mathrm{D} = 768\,\mu$K
- $\frac{\hbar\gamma k}{2mg} = 43 \times 10^3$

689 nm: $^1\mathrm{S}_0 \rightarrow {}^3\mathrm{P}_1$

- $\gamma = 7.5$ kHz
- $\omega_\mathrm{r}/2\pi = 4.7$ kHz
- $T_\mathrm{D} = 0.3\,\mu$K
- $\frac{\hbar\gamma k}{2mg} = 16$

Credit: Loftus et. al. Phys. Rev. Lett. 93, 073003 (2004)

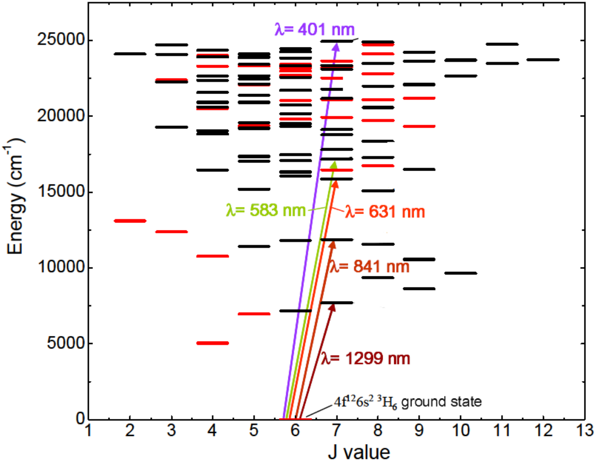
Narrow line ^{88}Sr MOT



Credit: Loftus et. al. PRA 70, 063413 (2004)

Lanthanides

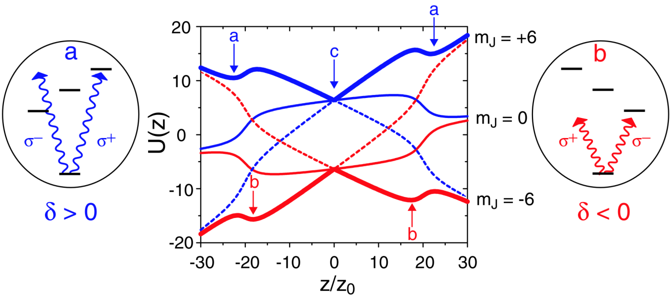
λ (nm)	401	583	841
γ (kHz)	36	190	8
T_D (µK)	660	4.8	0.19



^{166}Er MOT

$$\mu = 7\mu_{\rm B} \implies F = F_{\rm s} - \mu|\nabla B| - mg, \qquad \mu = g m_{\rm j}\mu_{\rm B}$$

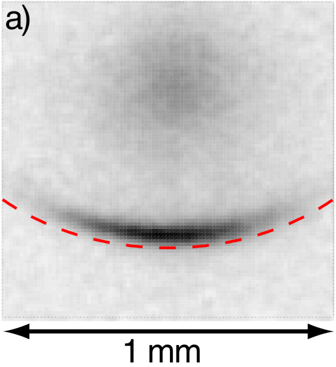
$$\omega_{\rm r}/2\pi = 1.7\text{kHz} \text{ , } \hbar\gamma k/2mg = 7$$



- the $m_{\rm j} = j$ state is a “low field seeking state”
- For $|\nabla B| \neq 0 \qquad F \to F_{\rm s} + g m_{\rm j}|\nabla B|$

Credit: Berglund et. al. PRL 100, 113002 (2008)

^{166}Er MOT

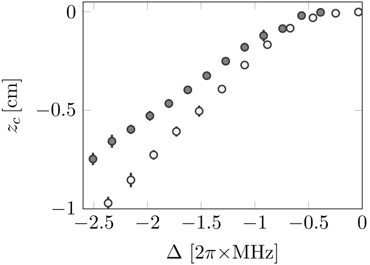


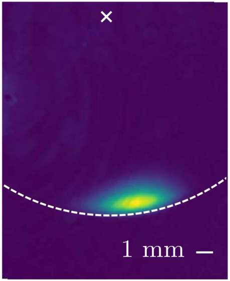
$T = 2\mu K$
Atoms are polarized in the $J = 6$ $m_{\text{j}} = 6$ state

Credit: Berglund et. al. PRL 100, 113002 (2008)

^{162}Dy MOT

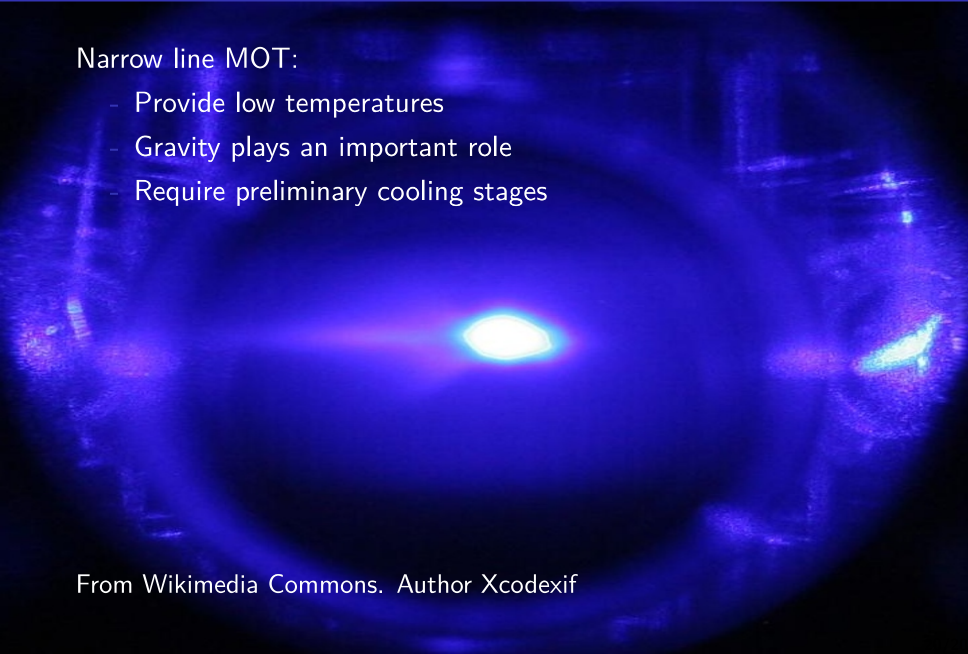
- 626 nm 136 kHz transition
- $\omega_{\mathrm{r}}/2\pi = 3.1\mathrm{kHz}$, $\hbar\gamma k/2mg = 171$
- $\delta = 30\gamma$
- 3×10^8 atoms at $T = 20\mu K$
- Mot vertical position self-adjust for $F_{\mathrm{s}} = mg$





Credit: Dreon et. al. J. Phys. B: At. Mol. Opt. Phys. 50 (2017)

Conclusions



Narrow line MOT:

- Provide low temperatures
- Gravity plays an important role
- Require preliminary cooling stages

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