Spin distillation cooling of ultracold Bose gases

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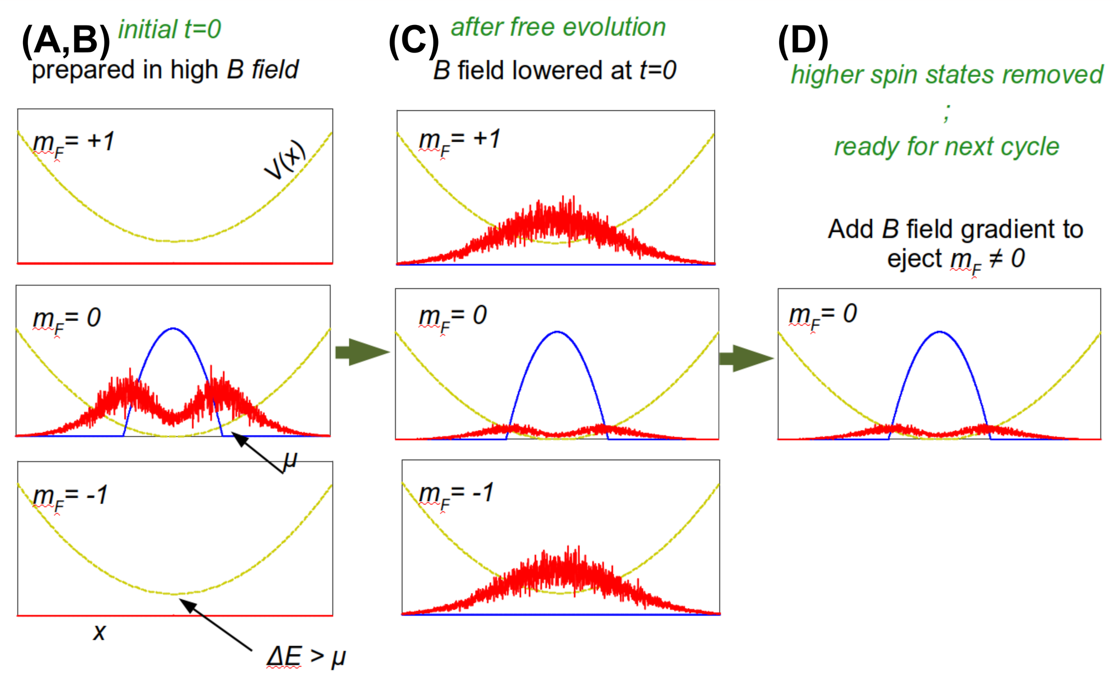
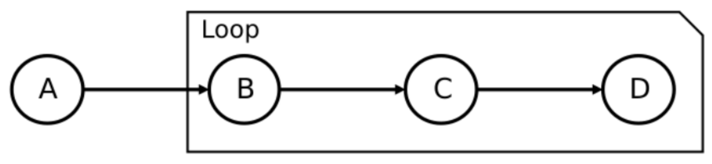
Conclusions: repeated cooling cycles check out in realistic simulations; two mechanisms, both allowing $k_B T \ll \mu$

Spin distillation cooling



Cooling cycle



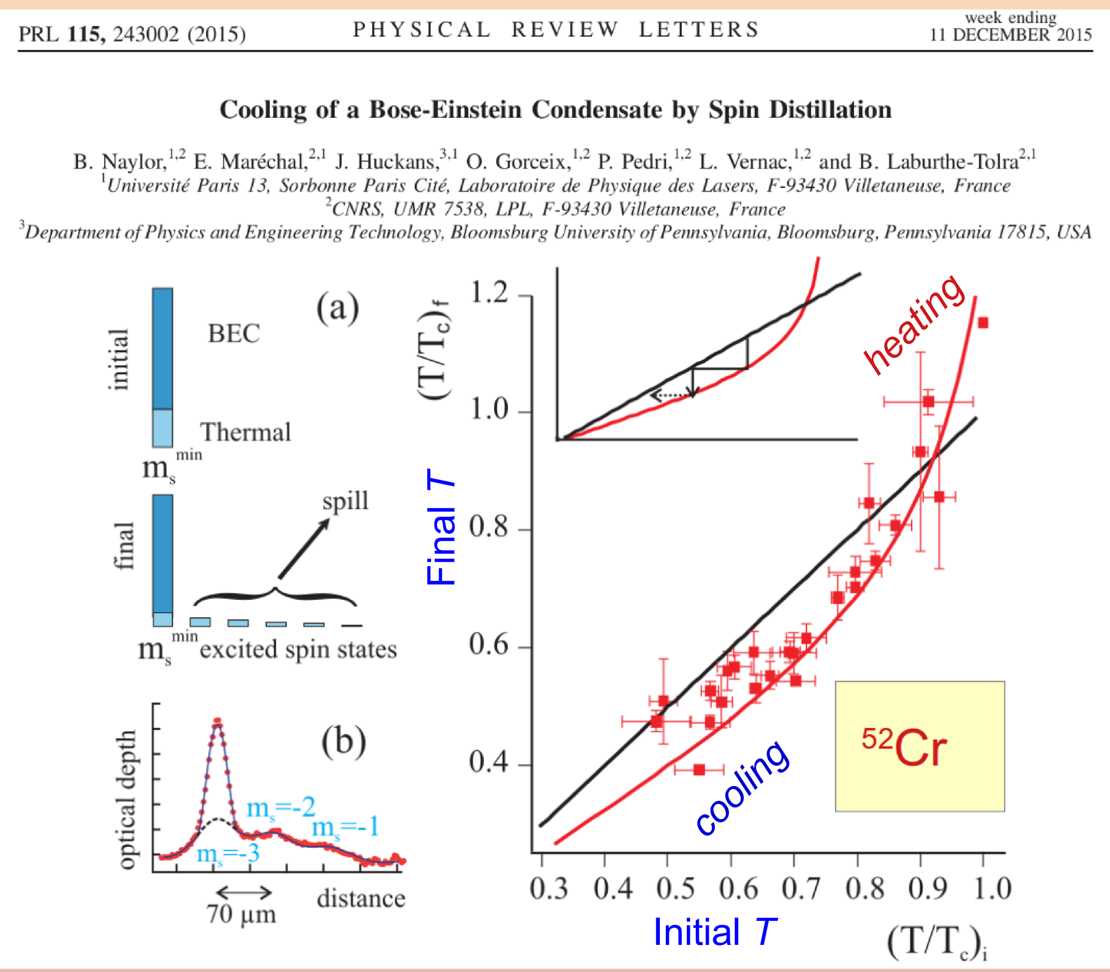
Schematic diagram of time sequence of cooling event: (**A**)—a thermal sample of atoms is prepared, (**B**)—active cooling begins, (**C**)—active coolings stops, (**D**)—unwanted atoms are removed.

- (A) Stochastic Gross Pitaevskii Euation (SGPE) for initial state generation
- (B) plain nonlinear Schrodinger equation (GPE) for dynamical evolution

$$i\hbar\frac{\partial}{\partial t}\boldsymbol{\psi}(\mathbf{r}) = (H_{sp} + H_c + H_d)\boldsymbol{\psi}(\mathbf{r})$$

$$H_{sp} = -\frac{\hbar^2}{2m}\nabla^2 + V_{trap}(\mathbf{r}) - \boldsymbol{\mu}\cdot\mathbf{B}$$

Initial experiments – 1 cycle



PRL **115**, 243002 (2015) PHYSICAL REVIEW LETTERS week ending 11 DECEMBER 2015

Cooling of a Bose-Einstein Condensate by Spin Distillation

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Simulation method – classical field

Bose field — semiclassical replacement

$$\hat\Psi(\mathbf{x}) = \sum_j \hat a_j \psi_j(\mathbf{x}) \longrightarrow \phi(\mathbf{x}) = \left\{\sum_{j\in C}\alpha_j\psi_j(\mathbf{x})\right\}$$

so-called "classical fields"

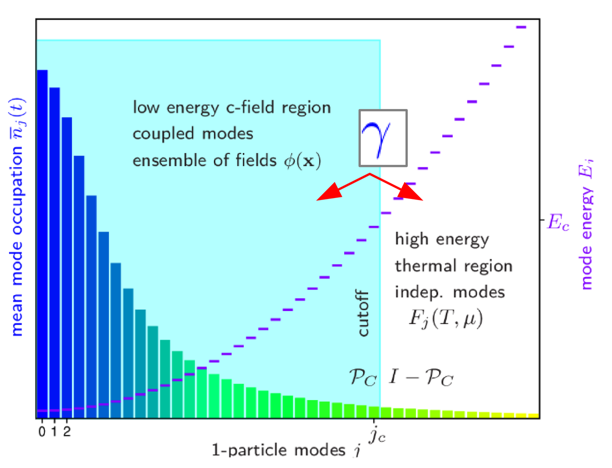
$$\left[\hat a_j, \hat a_k^\dagger\right] = \delta_{jk}$$

$$\hat a_j \gg 1 \rightarrow \hat a_j \approx \alpha_j$$

Assuming high occupation:

This method is essential because exact quantum mechanics of 10^5 atoms in 10^6 states is not feasible

Remarkably: the main physics is captured well



Developed by many authors: M. Brewczyk, M. Gajda, M. Davis, K. Rzążewski, A. Sinatra, R. Burnett, E. Witkowska, ... (no priority implied)
Useful Reviews: M. Brewczyk et al. J. Phys B **40**, R1 (2007); P. Blakie et al. Adv. Phys. **57**, 363 (2008)

Initial states - Stochastic GPE

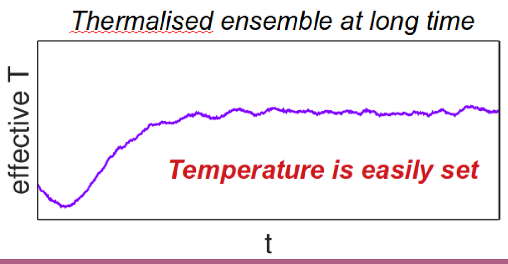
$$i\hbar\frac{\partial\Psi(\mathbf{r},\tau)}{\partial\tau} = (1-i\gamma)\left[-\frac{\hbar^2}{2m}\nabla^2 + \frac{1}{2}m\sum_j\omega_j^2 r_j^2 + \mathcal{H}_I(\Psi) - \mu\right]\Psi(\mathbf{r},\tau) + \sqrt{2\hbar\gamma k_B T}\,\eta(\mathbf{r},\tau)$$

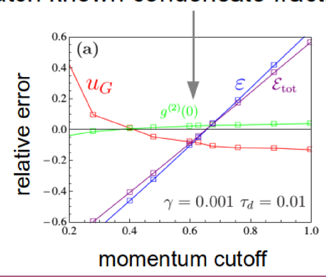
$$\mathcal{H}_I(\Psi) = g|\Psi(\mathbf{r},\tau)|^2 + H_d(\Psi)$$

loss of particles to tails (dissipation); Hamiltonian dynamics; chempot sets N; trap, etc; gain of particles from tails (complex noise, fluctuation)

Cutoff and numerical lattice:
- k^{max} : optimised for several variables according to Pietraszewicz, PD, PRA **92**, 063620 (2015); **98**, 023622 (2018)
- volume: chosen to match known condensate fraction

Thermalised ensemble at long time





The case of ^{52}Cr S=3

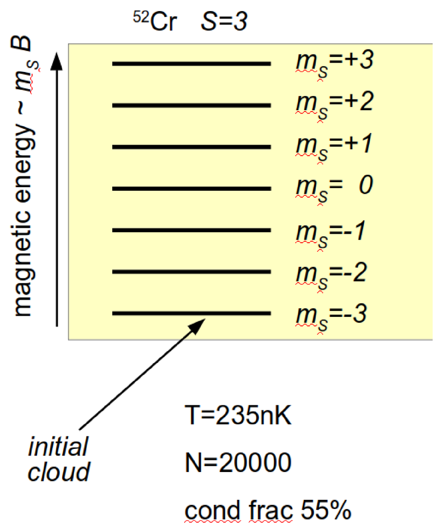
Dipolar interactions, 7 components
Linear Zeeman effect

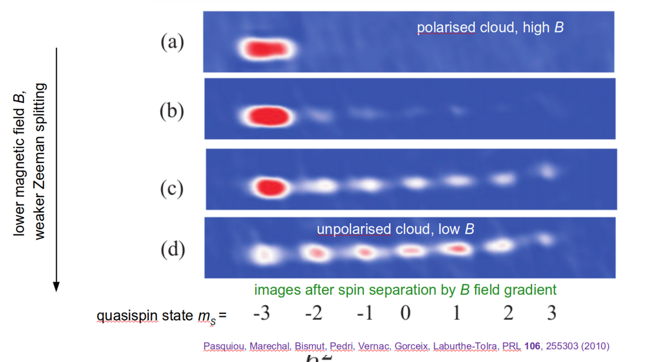
Parameters as in experiment

Seven spinor components

$$\boldsymbol{\psi}(\mathbf{r}) = (\psi_3(\mathbf{r}),\psi_2(\mathbf{r}),\psi_1(\mathbf{r}),\psi_0(\mathbf{r}),\psi_{-1}(\mathbf{r}),\psi_{-2}(\mathbf{r}),\psi_{-3}(\mathbf{r}))$$

- Several hyperfine species of the same atom
- Atoms can change their species





T=235nK
N=20000
cond frac 55%

$$H_{sp} = -\frac{\hbar^2}{2m}\nabla^2 + V_{trap}(\mathbf{r}) - \boldsymbol{\mu}\cdot\mathbf{B}$$

$$\boldsymbol{\mu} = g_L\mu_B m_s$$

Trap frequencies $(250, 300, 215)$ Hz — Linear Zeeman effect

$$i\hbar\frac{\partial}{\partial t}\boldsymbol{\psi}(\mathbf{r}) = (H_{sp} + H_c + H_d)\,\boldsymbol{\psi}(\mathbf{r})$$

$$\boldsymbol{\psi}(\mathbf{r}) = (\psi_3(\mathbf{r}),\psi_2(\mathbf{r}),\psi_1(\mathbf{r}),\psi_0(\mathbf{r}),\psi_{-1}(\mathbf{r}),\psi_{-2}(\mathbf{r}),\psi_{-3}(\mathbf{r}))$$

$$H_{sp} = -\frac{\hbar^2}{2m}\nabla^2 + V_{trap}(\mathbf{r}) - \boldsymbol{\mu}\cdot\mathbf{B}$$

H_c is a 7×7 matrix in spinor components

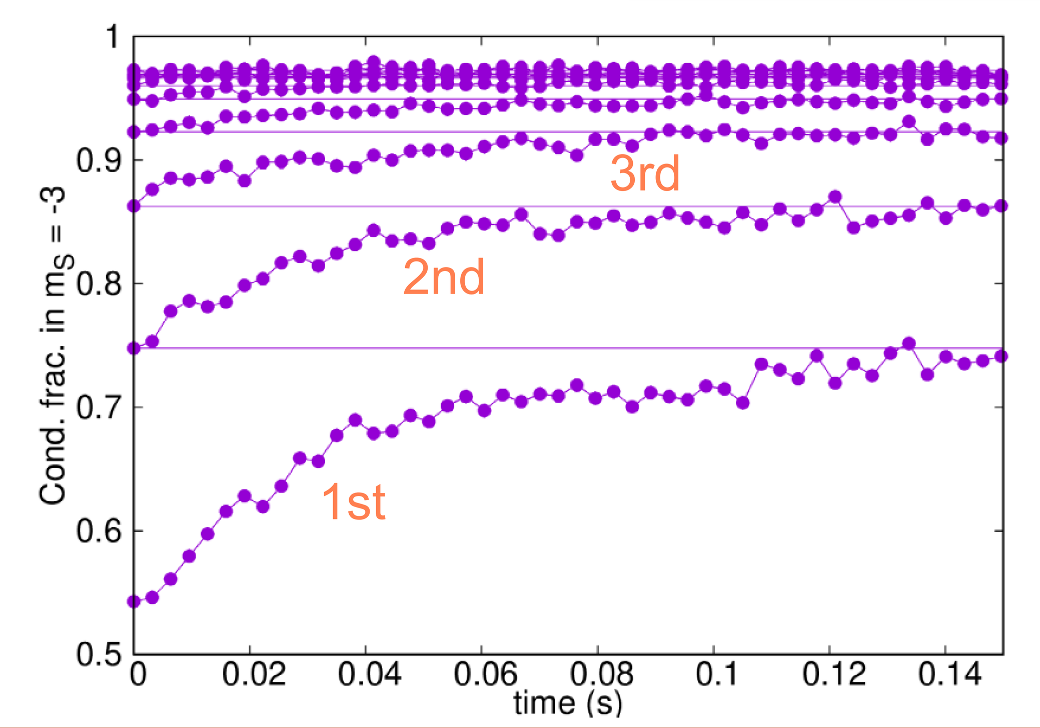
H_d is the dipolar interaction term. It will not be written down today.

Open questions

- Can successive cycles lead to more cooling?
- What are the limitations / conditions needed?
  - how should magnetic field be changed in successive cycles?
- does it also work for ^{23}Na (suggested in the paper)

Cooling cycles confirmed

Adapting B after every cycle $\quad B = k_B T / 6\mu_B$



Cooling mechanism in ^{52}Cr

- Dipolar interactions populate the $m_s = -2$ state via the nonequilibrium process

$$\psi^c_{-3}\,\&\,\psi^{th}_{-3} \rightleftharpoons \psi^c_{-3}\,\&\,\psi^{th}_{-2}$$

provided the Zeeman energy gap between spin states is sufficiently small

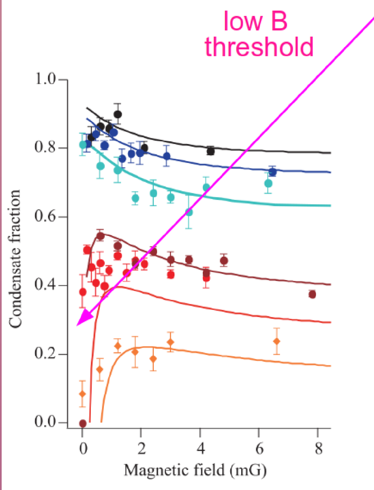
- No condensates appear in components $m_s = -2, -1, \ldots, 3$ because thermal clouds are not saturated.
- Higher spin components are removed by reshaping the trap and increasing B
- Cycle repeats, possibly with a modified B field

Limitations in ^{52}Cr ; minimum B

1) Thermal energy should be sufficient to overcome the magnetic energy barrier

$$2\mu_B B \lesssim k_B T.$$

2) The magnetic field should be high enough that the condensate ground state remains polarised and **cannot** overcome the magnetic energy barrier



$$B > B_{th} = 0.68\frac{2\pi\hbar^2(a_6 - a_4)}{2m\mu_B}n$$

Santos, Pfau, PRL **96**, 190404 (2006)
Diener, Ho, PRL **96**, 190405 (2006)

scattering lengths in the total spin 6 and 4 channels

Combining conditions leads to

$$k_B T \gtrsim 0.34\left(\frac{a_6 - a_4}{a_6}\right)\mu$$

for our system this gives $0.05T_c$, $0.13\,\mu$ --- very low

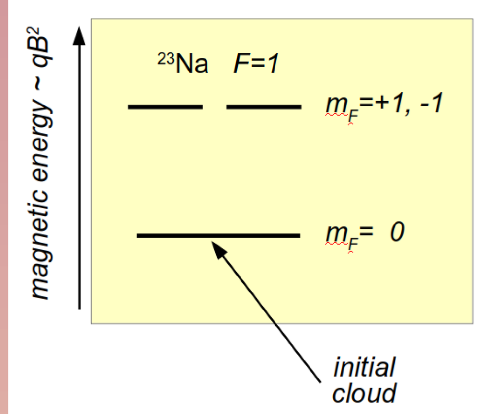
The case of ^{23}Na F=1

Contact interactions, 3 components
Quadratic Zeeman effect

Was conjectured to also allow cooling via the quadratic Zeeman effect, purely through contact spin-dependent interactions
Naylor, Marechal, Hackens, Gorceix, Pedri, Vernac, Laburthe-Tolra, PRL **115**, 243002 (2015)

Three quasispin components $\quad \psi = (\psi_1, \psi_0, \psi_{-1})$

Quadratic Zeeman effect is relevant here



$$H_{QZE} = -q\int d\mathbf{r}\; n_0(\mathbf{r})$$

$$q = \alpha_q|\mathbf{B}|^2$$

$$\alpha_q/2\pi\hbar \approx 277\mathrm{Hz}/G^2$$

$$H_s = \int d\mathbf{r}\sum_{m_F=-1}^{1}\psi^*_{m_F}(\mathbf{r})\left(-\frac{\hbar^2}{2m}\nabla^2 + V_{trap}\right)\psi_{m_F}(\mathbf{r}) + \int d\mathbf{r}\left(\frac{c_0}{2}n(\mathbf{r})^2 + \frac{c_2}{2}\mathbf{F}(\mathbf{r})^2\right). \qquad (7)$$

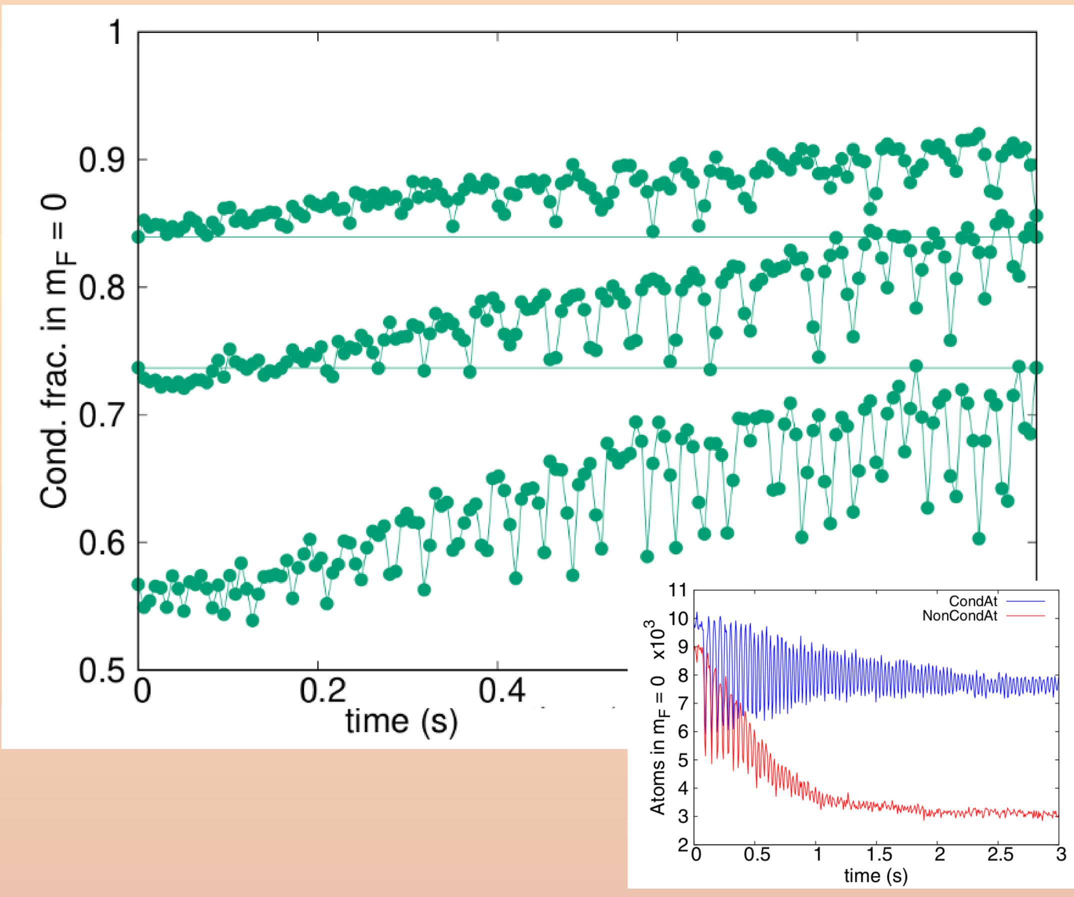
$$\mathbf{F} = (\psi^\dagger F_x\psi, \psi^\dagger F_y\psi, \psi^\dagger F_z\psi)$$

$$n(\mathbf{r}) = \sum_{m_F} n_{m_F}(\mathbf{r}) = \sum_{m_F}|\psi_{m_F}(\mathbf{r})|^2$$

$c_0 = 4\pi\hbar^2(2a_2 + a_0)/3m$ — spin-independent; large

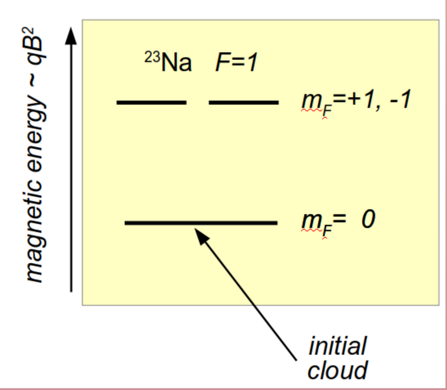
$c_2 = 4\pi\hbar^2(a_2 - a_0)/3m$ — spin-dependent; small

Cooling cycles



Cooling mechanism in ^{23}Na

- Low threshold for spin mixing allows Rabi oscillations between lowest and higher quasispin states. $\psi_0\,\&\,\psi_{\pm1} \rightleftharpoons \psi_0\,\&\,\psi_{\pm1}$
- The process $\psi^c_0\,\&\,\psi^{th}_{\pm1} \rightleftharpoons \psi^{th}_0\,\&\,\psi^c_{\pm1}$ is then essential to exchange condensate and thermal populations in a single spin component, and irreversibly degrade the reversible Rabi oscillations
- The thermal atoms redistribute, leaving only 1/3 of the original number in $m_F = 0$
- Higher energy spin components are removed.
- Cycle repeats, possibly with a modified B field

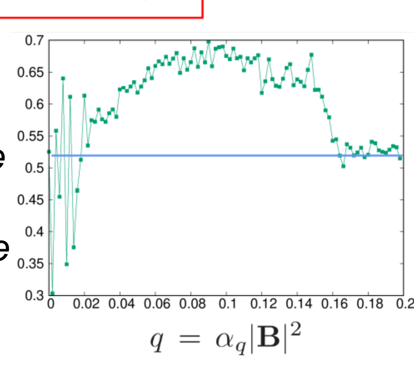


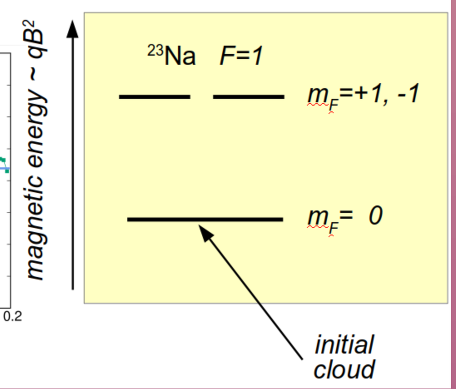
Limitations in ^{23}Na ; maximum B

- Spin mixing terms responsible for the transfer $2n_0 \rightleftharpoons n_{\pm1}$ and Rabi oscillation have energy of order $c_2 n$
- Therefore, amplitude of spin mixing process will decay rapidly once the energy difference exceeds $c_2 n$
- Under magnetic field, energy to take two atoms from $m_F = 0$ to $m_F = +1, -1$ is $2q$
- ---> One needs: $q \lesssim c_2 n_0^{max}$

plugging in, get $q \lesssim 0.16$

condensate fraction after 1 cycle





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