Cooling of a Bose Einstein Condensate by Spin distillation

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Cooling Mechanisms

Evaporation:

Lose most energetic atoms, Then system rethermalises

Very Efficient up to $k_B T \approx \mu$

Very recent result, beat most limitations

Demagnetization cooling:

Transfer of kinetic energy into magnetic energy

Why do we need new cooling mechanisms? Colder gases?
Quantum magnetism

Spin \( \frac{1}{2} \) interacting Fermions or Bosons
Super-exchange interaction
Esslinger: short range anti-correlations
I. Bloch, T. Porto, W. Ketterle, R.G. Hulet…

Magnetic correlations appear when

\[
\frac{S}{N} < S_{\text{Magnetic}} < k_B \log(2s + 1)
\]

A condensed atom carries no entropy

Entropy of a saturated cloud:

\[
\frac{S}{N} \approx 3.6k_B \left( \frac{T}{T_c} \right)^3 = 3.6k_B f_{th}
\]

For a fully saturated gas, the entropy is given by the thermal fraction

Removing entropy \( \iff \) removing thermal atoms
Chromium

Large electronic Spin: $S=3$

**Optical dipole traps** equally trap all Zeeman state of a same atom

Linear Zeeman effect \[ E(m_S) = m_S g \mu_B B \]

**Stern-Gerlach separation:**
(magnetic field gradient)
Feature introduced by dipolar interactions:

Free Magnetization

\[ \hbar \Gamma \approx V_{dd} \]
Spontaneous magnetization due to BEC

BEC only in $m_s=-3$ (lowest energy state)

Pasquio et al. PRL 108, 045307 (2012)
Spin Cooling: Principle of the Experiment

Step 1:

\[ g\mu_B B \gg k_B T \]
Spin Cooling: Principle of the Experiment

**Step 1:**
\[ g\mu_B B >> k_B T \]

**Step 2:**
\[ g\mu_B B \approx k_B T \]

Linear Zeeman
Spin Cooling: Principle of the Experiment

Step 1:

BEC

\[ g\mu_B B \gg k_B T \]

Thermal

\[ g\mu_B B \approx k_B T \]

Step 2:

excited spin states

Step 3:

With RF pulse or Magnetic field gradient
A competition between two mechanisms

(i) Thermal cloud depolarizes

(ii) BEC melts to resaturate $m_s = -3$ thermal gas (and cools it)

(iii) Kill spin-excited states
A competition between two mechanisms

(i) Thermal cloud depolarizes

(ii) BEC melts to re-saturate $m_s=-3$ thermal gas (and cools it)

(iii) Kill spin-excited states

Who Wins?

Losses in thermal cloud due to depolarization
A competition between two mechanisms

(i) Thermal cloud depolarizes
(ii) BEC melts to resaturate $m_s=-3$ thermal gas (and cools it)
(iii) Kill spin-excited states

Who Wins?

Losses in thermal cloud due to depolarization

BEC melts (a little)
A competition between two mechanisms

At high $T/T_c$, BEC melts (too few atoms in the BEC to cool the thermal gas back to saturation)

At low $T/T_c$, spin filtering of excited thermal atoms efficiently cools the gas

Theoretical model: rate equation based on the thermodynamics of Bosons with free magnetization. Interactions are included within Bogoliubov approximation
Summary of the experimental results as a function of B

(large field, no effect)
Theoretical limits for cooling

There does not seem to be any limit other than practical. In principle, cooling is efficient as long as depolarization is efficient.

Process can be repeated. At each spiling, a factor 2 in entropy is gained.
Extension to ultra-low temperatures for non-dipolar gases

In our scheme, limitation around 25 nK, limited by \( k_B T \approx g_J \mu_B B \)
(difficult to control below 100 \( \mu G \))

Proposal: use Na or Rb at zero magnetization.

Spin dynamics occurs at constant magnetization

\[
\begin{align*}
F=1, m_F=-1, & \quad 0, \quad 1 \\
(0 0) \rightarrow (-1 1)
\end{align*}
\]

\( g_J \mu_B B = 2.8 kHz / G \)

\( q \approx 70 Hz / G^2 \)


We estimate that temperatures in the pK regime may be reached

Nota: the spin degrees of freedom may also be used to measure temperature
Shock Cooling

Preliminary Results

Initial conditions: Thermal Gas at $1 \mu K$ in every spin state

$m_s = -3$ -2 -1 0 1 2 3
Shock Cooling

Preliminary Results

Collaboration with M. Gajda et M. Brewczyk

Initial conditions: Thermal Gas at 1μK in every spin state

\[ m_s = -3, -2, -1, 0, 1, 2, 3 \]

Then Evaporation while monitoring Spin distribution and momentum distribution

What happens?

Magnetic Order? Bose order?
Shock Cooling

Initial conditions: Thermal Gas at 1μK in every spin state

Then Evaporation while monitoring Spin distribution and momentum distribution

BEC forms only in $m_s = -3$ and $m_s = -2$ gas is saturated but never forms a BEC!
**Shock Cooling**

**Preliminary Results**

- Preliminary results suggest good agreement

- Simulations give a BEC in $m_s=-3$ and a saturated thermal gas in $m_s=-2$ with no BEC

**Interpretation?**

Favorable fast dynamics (-2 -2) $\longrightarrow$ (-3 -1)
New cooling mechanism to reach very low entropies (in bulk):
Use spin to store and remove entropy

Should be applicable to non-dipolar species, with pK regime possible

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Thank you

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P. Pedri (Theory), L. Santos (Theory, Hannover)
Thanks! – Come and Visit