Evaporative cooling of a magnetically guided beam

David Guéry-Odelin

Kastler Brossel Laboratory

Jean Dalibard, Gaël Reinaudi (poster session), DGO, Antoine Couvert, Zhaoying Wang, Thierry Lahaye
Overview of the experimental setup

7 \cdot 10^9 \text{ atoms/s at 1 m/s}

Step 1: Cold atoms packet production

Step 2: 4.5 meter long Magnetic Guide

Step 3: Evaporative cooling

2 \cdot 10^9 \text{ atoms}
The potential experienced by the atoms

Evidence for Majorana losses

4 copper tubes in quadrupolar configuration

Longitudinal Bias field

\[ U(r) = \mu \sqrt{B_0^2 + b' r^2} \]

Harmonic

Linear

\[ k_B T \ll \mu B_0 \]

\[ U(r) \approx \mu B_0 + \frac{\mu b'^2 r^2}{2B_0} \]

\[ k_B T \gg \mu B_0 \]

\[ U(r) \approx \mu b' r \]

1 Gauss “=” 33 μK
Radio-frequency filtering = temperature measurement

\[ h\nu_{RF} = U_{\perp}(R) \]

Fraction of remaining atoms

\[ \frac{\phi'}{\phi} \]

Probe

T = 380 μK

b = 600 G/cm

\[ \nu_{RF} \text{ (MHz)} \]
Influence of the shape of the confining potential on the thermalization time

Thermalization in a box versus thermalization in a trap

\[
\frac{dT_i}{dt} = -\frac{T_i - T_j}{N_i \tau}, \quad i \neq j
\]

\[
\tau = \frac{n_c}{\gamma}
\]

\[
n_c = \frac{3}{2}
\]

\[
n_c = 3
\]

harmonic potential
Thermalization in the multiple partial wave regime

Total cross section

\[ \sigma = \sigma_s + \sigma_d + \sigma_g + \ldots \]

Collision rate \( \propto \sigma \)

\[ \frac{1}{\tau} \propto \frac{1}{T^4} \sum_{l \leq l' \in \{0, 2, 4, \ldots\}} \alpha_{ll'} \int_0^\infty \sin \delta_l \sin \delta_{l'} \cos(\delta_l - \delta_{l'}) v^3 e^{-mv^2/2k_BT} dv \]

Interference terms

Thermalisation time is not proportional to the collision rate because of partial wave interferences

M. Anderlini and DGO, cond-mat 0507681, to appear in PRA
A concrete example

$^{87}\text{Rb}$  \[ |F = 1, m_F = -1\rangle \quad \text{and} \quad |F = 2, m_F = 1\rangle \]
Thermalization experiments in a guide

Maximum gain in phase space density with one antenna = 1.9
Thermalization experiments after a microwave evaporation

Maximum gain in phase space density = 2.6

PRA 72, 033411 (2005)
Increasing the phase space density of the beam

\[ T_{i} = 574 \pm 10 \ \mu K \]
\[ T_{f} = 164 \pm 6 \ \mu K \]
\[ \Phi_{f}/\Phi_{i} = 0.13 \pm 0.02 \]

\[ \rho_{f}/\rho_{i} = 10.4^{+4.1}_{-3.0} \]

PRA 72, 033411 (2005)
Increasing the phase space density of the beam

90 cm/s  65 cm/s

Measured range of a RF antenna = 20 cm
Measured range of a MW horn = 20 cm

The performance in terms of gain on phase space density and collision rate of a RF antenna or of a MW horn strongly depends on their efficiency

Experimentally if is very difficult to ensure a perfect efficiency
Local evaporation on dielectric surface

The shift of the beam trajectory by a transverse magnetic field does not lead to any detectable heating of the beam downstream.

\[ b = 800 \text{ G/cm} \]

Thickness = 5 mm

Fraction of remaining atoms

100 % efficiency
The dimensionality of evaporation depends on the time spent close to the surface.

1) Low velocity

2) Large thickness of the ceramic

Trajectory in a linear confinement
Dimensionality of the evaporation

Gaël Reinaudi et al., submitted to Phys. Rev. A
What is the best parameter to evaluate the distance to quantum degeneracy?

The gain in space density is dictated by the number $N_c$ of collisions that a given atom will undergo in average.

For our best parameters $N_c \sim 25$

- Evaporation dynamics
  - Rethermalization kinetics depends on the shape of the confining potential
  - Runaway on the collision rate only possible in a linear confinement, because of the 2D character of the evaporation

\[
\begin{align*}
\partial_z (n v) &= -\Gamma_1 n , \\
\partial_z (n v^2 + n v_{th}^2) &= -\Gamma_1 n v , \\
\partial_z \left[ n v \left( \frac{5}{2} v_{th}^2 + \frac{v^2}{2} + \frac{\langle U \rangle}{m} \right) \right] &= -n \left( \frac{\Gamma_1 v^2}{2} + \Gamma_2 v_{th}^2 \right)
\end{align*}
\]

\[v_{th} = \sqrt{k_B T / m}\]

This set of equations is valid in the supersonic regime \(v > 3v_{th}\).

T. Lahaye and DGO, submitted to PRA
Results deduced from the HD equations

Trade off between the runaway and the kinetics

\[ L_{ev} \sim L_0 \frac{T_i^{3/2}}{\Phi_i} \]

\( N_c \sim 200 \)

needed to reach degeneracy on 4 m

These predictions can be decreased if one reduces the mean velocity while keeping the supersonic condition
How to implement a 3D evaporation?
Coupling atoms into the « magnet train »

No detectable heating occurs in the coupling on the whole range of injection velocity.
Conclusion

We have implemented evaporation on an atomic beam in 3 different manners: Radio-frequency, Microwave, Adsorption on a surface

We have gained one order of magnitude on the phase space density

To increase the number of collisions undergone by an atom during its propagation

Conveyor belt

Coupling compressed magneto-optical trap

http://www.lkb.ens.fr/recherche/atfroids/welcome.html