A new cooling device for the sympathetic cooling of molecules

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Sympathetic cooling - ingredients

1. whiskey → 1. „hot“ atoms / molecules
2. ice cubes → 2. already cold atoms
3. glass → 3. trapping potential

[Eric Hudson (UCLA) - KITP Conference 2013]
Advantages

• **Smpathetic cooling**
  – does not rely on laser cooling → no level structure needed
  – dramatically expands the palette of atoms and molecules accessible for study in the ultracold regime

• What’s already possible?
First Sympathetic Cooling of atoms to BEC

Production of Two Overlapping Bose-Einstein Condensates by Sympathetic Cooling

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- two 3D-MOTs loaded several times to collect $\sim 10^9$ rubidium atoms
- preparation of two different spin states possible $|1,-1\rangle$ or $|2,2\rangle$
- can be cooled independently by rf evaporation to BEC

FIG. 1. The glass lower vacuum chamber is connected to the upper chamber through a narrow transfer tube and to sublimation and ion pumps as noted. It is surrounded by the three coils that comprise the magnetic trap. Small additional windows (not shown) allow the cloud to be viewed along some of the diagonals. The trapping laser beams go through the six perpendicular 2.5 cm diam windows, four of which are visible in the figure.
First Sympathetic Cooling of *atoms* to BEC

- preparation of mixture possible $|1,-1\rangle$ and $|2,2\rangle$
- $|1,-1\rangle$ has smaller magnetic moment than $|2,2\rangle$
  $\rightarrow$ extends to larger magnetic fields in the same trap
- during rf evaporation mostly $|1,-1\rangle$ is evaporated
  $\rightarrow$ $|2,2\rangle$ is evaporatively cooled to BEC

FIG. 4. Number of $|1,-1\rangle$ and $|2,2\rangle$ atoms in a two-species cloud as a function of the temperature during the sympathetic evaporative cooling. The cloud is being cooled from the initial magnetic trap temperature to just above the condensation temperature.
First Sympathetic Cooling of *atoms* to BEC

- Results
  - sympathetic cooling of different spin states is possible
  - different species?

FIG. 4. Number of $|1, -1\rangle$ and $|2, 2\rangle$ atoms in a two-species cloud as a function of the temperature during the sympathetic evaporative cooling. The cloud is being cooled from the initial magnetic trap temperature to just above the condensation temperature.
Inter-species sympathetic cooling

**Reports**

Bose-Einstein Condensation of Potassium Atoms by Sympathetic Cooling

G. Modugno, G. Ferrari, G. Roati, R. J. Brecha, A. Simoni, M. Inguscio

We report on the Bose-Einstein condensation of potassium atoms, whereby quantum degeneracy is achieved by sympathetic cooling with evaporatively cooled rubidium. Because of the rapid thermalization of the two different atoms, the efficiency of the cooling process is high. The ability to achieve condensation by sympathetic cooling with a different species may provide a route to the production of degenerate systems with a larger choice of components.

- two 3D-MOT system for potassium and rubidium
- start
  - \(2 \times 10^8\) \(^{87}\)Rb and \(2 \times 10^6\) \(^{41}\)K atoms in QUIC trap @300\(\mu\)K
- \(\rightarrow\) microwave evaporation of Rubidium
Inter-species sympathetic cooling

**Fig. 1.** Evolution of the number of atoms (A) and temperature (B) of the two atomic samples in the magnetic trap as a function of the microwave evaporation threshold of Rb. The solid circles correspond to $^{87}$Rb and the open circles to $^{41}$K.

**Fig. 2.** False color absorption images of Rb (left) and K (right) at four different stages of the sympathetic cooling. The density of the K sample increases by more than two orders of magnitude, going from $4 \times 10^9$ cm$^{-3}$ to $6 \times 10^{11}$ cm$^{-3}$, when the temperature is lowered from 40 to 0.9 μK. The density of the Rb sample is instead approximately constant during the evaporation.

very efficient interspecies thermalization $\rightarrow$ BEC
Inter-species sympathetic cooling

• Results
  – inter-species sympathetic cooling possible
  – still uses light and level structure
  – dark cooling?

Fig. 2. False color absorption images of Rb (left) and K (right) at four different stages of the sympathetic cooling. The density of the K sample increases by more than two orders of magnitude, going from $4 \times 10^9$ cm$^{-3}$ to $6 \times 10^{11}$ cm$^{-3}$, when the temperature is lowered from 40 to 0.9 μK. The density of the Rb sample is instead approximately constant during the evaporation.
Dark cooling of *atoms*

**Buffer-Gas Cooled Bose-Einstein Condensate**

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We report the creation of a Bose-Einstein condensate using buffer-gas cooling, the first realization of Bose-Einstein condensation using a broadly general method which relies neither on laser cooling nor unique atom-surface properties. Metastable helium (⁴He*) is buffer-gas cooled, magnetically trapped, and evaporatively cooled to quantum degeneracy. 10¹¹ atoms are initially trapped, leading to Bose-Einstein condensation at a critical temperature of 5 μK and threshold atom number of 1.1 × 10⁶. This method is applicable to a wide array of paramagnetic atoms and molecules, many of which are impractical to laser cool and impossible to surface cool.

Bose-Einstein condensation without laser cooling
Buffer-Gas Cooled Bose-Einstein Condensate

- plastic container @ 200mK (Eddy currents) with thin film of Helium on the walls
- anti-Helmholtz coils → 5K magnetic trap depth
- desorption of Helium with pulsed laser
- rf discharge produces trappable metastable helium $^4\text{He}^*$ ($|S=1, m_s=+1>$)
Buffer-Gas Cooled Bose-Einstein Condensate

- $^4\text{He}^*$ is cooled to $\sim 500\text{mK}$ with $^4\text{He}$ buffer gas
- forced evaporation $\rightarrow 2\text{mK}$ skimming transfer in QUIC-trap $\rightarrow 500\mu\text{K}$ rf-induced evaporation $\rightarrow T_c \sim 4,5\mu\text{K}$

FIG. 1 (color). Schematic of the experimental apparatus.
Buffer-Gas Cooled Bose-Einstein Condensate

• **Summary**
  - buffer-gas cooling as starting point with 500mK
  - **completely dark** cooling method
  - potentially applicable to a wide range of atom

FIG. 1 (color). Schematic of the experimental apparatus.
What about sympathetically cooling molecules?

- not as successful as atoms yet
- atom molecule interaction
  - ratio of elastic collision to inelastic collision unfavorable
  - rule of thumb: ratio of cross sections >100
- two ways
  - look for suitable molecules
  - change interaction
Suitable molecules

Prospects for sympathetic cooling of polar molecules: NH with alkali-metal and alkaline-earth atoms – a new hope

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Beryllium and Magnesium are promising coolants for sympathetic cooling of NH molecules

Ultracold Hydrogen Atoms: A Versatile Coolant to Produce Ultracold Molecules

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Hydrogen has good collisional properties to sympathetically cool NH to 1K and OH to 250mK
Influencing interactions

Large Effects of Electric Fields on Atom-Molecule Collisions at Millikelvin Temperatures

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Controlling interactions between cold molecules using external fields can elucidate the role of quantum mechanics in molecular collisions. We create a new experimental platform in which ultracold rubidium atoms and cold ammonia molecules are separately trapped by magnetic and electric fields and then combined to study collisions. We observe inelastic processes that are faster than expected from earlier field-free calculations. We use quantum scattering calculations to show that electric fields can have a major effect on collision outcomes, even in the absence of dipole-dipole interactions.

- polar molecule with high anisotropy
- study collisions with rubidium
  
  deuterated ammonia ND$_3$
Influencing interactions

• without electric field
  – ND₃ orients smoothly along the inermolecular axis

• with electric field
  – orientation of ND₃ becomes confused when the potential anisotropy is similar to the electric Stark energy

• → increases probability of inelastic collisions
Sympathetically cooling molecules?

- rich internal structure
  - rotational and vibrational degrees of freedom
- basically every photon can be absorbed
- → „dark“ cold bath
The ultimate fridge ...
The ultimate **atomic fridge**...

- Cools everything you put into it
  - Able to absorb a large amount of heat
- Is never empty
  - Sympathetic cooling with self-replenishable reservoir
- Is really, really cold
  - Reservoir is ultra cold itself
- Turns off the light once you shut the door
  - No cooling light causes disturbances

➢ Allows for sympathetic cooling of large ensembles to ultra cold regime
Continuous loading of a magnetic trap

EUROPHYSICS LETTERS


Continuous loading of a non-dissipative atom trap

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(received 3 July 2002; accepted in final form 4 November 2002)
Continuous loading of a magnetic trap

beam parameters: 
  flux: $\Phi = 10^7$ atoms/s 
  velocity: $v = 20$ cm/s

trap parameters: 
  transversal trap frequency: $\omega_\perp = 100\omega_z$ 
  longitudinal trap frequency: $\omega_z = 2\pi \times 10$ Hz

$\Rightarrow$ initial phase space density: $\mathcal{D} \sim 2 \times 10^{-5}$

resonance at $U_\perp \sim 270$ μK 
temperature $T \sim 24$ μK 
trapped atoms $N \sim 10^8$

$\Rightarrow$ phase space density: $\mathcal{D} \sim 10^{-2}$
Experimental concept

2D-MOT
↓
3D-MOT
↓
Transport in quadrupole guide to stray light protected region
↓
Final trap
Mesoscopic scale

- Mesoscopic chip trap
  - Fast cycle times
  - Versatile fields
  - Large trapping volume
Implementation

• Several non interacting traps at the same time
  – Without external fields

• Wire structures outside vacuum:
  – Easy exchange of wire structure
  – No vacuum feedthroughs
  – Better vacuum
  – Cooling of wire structures easy
Double MOT system

Optimization of magneto-optical wire trap:

- Loading with 2D⁺-MOT
- Large light beams with high power
- Optimized magnetic fields
- No external fields

Loads > $6 \times 10^{10}$ atoms/s
Final atom number ~ $2 \times 10^{10}$ atoms
Magnetic transport

2 \cdot 10^9 \text{ atoms}
F=2, m_F=2

Magnetic guide
Distance to surface: 1,6 mm
Beam velocity

number of atoms in stripe

arrival time [s]

25.7 cm/s
Loading of a static trap

- Static trap with constant currents
- Freely adjustable barrier height for incoming atoms
- Freely adjustable trap bottom
- Possible transverse evaporation with microwave

Trap characteristics:
- 5.6 Hz, 171.2 Hz, 167.8 Hz
- Depth: 747 µK
- Offset: 1.1 G
Challenges

• Operate MOT, do state preparation and launch the atoms while keeping atoms in static trap
  – Light
Lifetime

![Graph showing the lifetime of atoms with time in trap in seconds.](image)

- **No switching**

- Lifetime: 51s
Lifetime

![Graph showing the lifetime of atoms in a trap over time]

- **Lifetime**
  - **47s**
  - **51s**

- Number of atoms vs. time in trap (s)
- Black squares: no switching
- Red triangles: lights on
Challenges

- Operate MOT, do state preparation and launch the atoms while keeping atoms in static trap
  - Light
  - Magnetic fields
Different current paths

- Different magnetic field for both configurations even with same currents in the trapping area (simulation and trap offset measurement)

⇒ can be compensated
Lifetime

The graph shows the number of atoms as a function of time in the trap. The x-axis represents the time in the trap in seconds, ranging from 0 to 25. The y-axis represents the number of atoms, ranging from $3 \times 10^6$ to $10^7$.

There are three distinct trends indicated by different markers:
- **Filled squares** represent 'no switching'.
- **Triangles** represent 'lights on'.
- **Filled circles** indicate 'full reload sequence every ~1s'.

The time points for each trend are marked as follows:
- **51s** for 'no switching'.
- **47s** for 'lights on'.
- **31s** for 'full reload sequence every ~1s'.

This graph visually demonstrates the decay of the number of atoms over time for each condition.
Loading characteristics

![Graph showing loading characteristics with x times relocation.]
Reload several times
Loading characteristics

![Graph showing loading characteristics with number of atoms on the y-axis and number of reloads on the x-axis. The graph includes error bars indicating variability.](attachment:Slide38.png)
Temperature

![Graph showing temperature and number of atoms vs. number of reloads. The graph displays two curves: one blue curve for number of atoms and one red curve for temperature. The x-axis represents the number of reloads, ranging from 0 to 35, and the y-axis represents the number of atoms, ranging from $0 \times 10^6$ to $2 \times 10^7$. The temperature axis ranges from 250 µK to 770 µK.]
Summary and Outlook

• A lot of potential:
  – Trapping $\sim 2 \times 10^7$ atoms in a static trap
  – Temperature $\mu$K
  – Refillable and dark
  – Suitable device for sympathetic cooling

• Next steps:
  – Implementing new wire structure
    • Reduce eddy currents
    • Thus improve molasses
    • Even more freedom with magnetic fields
The Team

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Thank you for your attention!