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Evaporation of an atomic beam on a material surface

G. Reinaudi, T. Lahaye, A. Couvert, Z. Wang, and D. Guéry-Odelin
Laboratoire Kastler Brossel*, 24 rue Lhomond, F-75231 Paris Cedex 05, France
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We report on the implementation of evaporative cooling of a magnetically guided beam by adsorption on a ceramic surface. We use a transverse magnetic field to shift locally the beam towards the surface, where atoms are selectively evaporated. With a 5 mm long ceramic piece, we gain a factor 1.5 ± 0.2 on the phase space density. Our results are consistent with a 100% efficiency of this evaporation process. The flexible implementation that we have demonstrated, combined with the very local action of the evaporation zone, makes this method particularly suited for the evaporative cooling of a beam.

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Since its first demonstration for magnetically trapped atomic hydrogen [1], evaporative cooling has proven to be a powerful technique to increase the phase-space density of trapped gases. It was used, in the case of alkali vapors, to reach the Bose-Einstein condensation (BEC) threshold [2]. This cooling technique plays a central role in the rapidly expanding field of ultracold quantum degenerate gases. Evaporative cooling occurs when energetic atoms are removed from the cloud as a result of elastic collisions. Since these atoms belong to the high energy tail of the thermal distribution, the remaining trapped atoms collisionally equilibrate to a lower temperature.

As initially proposed and studied theoretically in Ref. [3], if a non-degenerate, but already slow and cold beam of particles, is injected into a magnetic guide where transverse evaporation takes place, quantum degeneracy can be achieved at the exit of the guide. Such a scheme transposes in the space domain what is usually done for trapped atoms in time, so that all operations leading to condensation are performed in parallel, resulting in a much larger expected output flux.

In recent experiments, evaporative cooling of a beam has been implemented by driving transitions to an untrapped state with radio-frequency [4] or/microwave [5] fields. The drawback of these two methods lies in the range over which a radio-frequency (rf) spectroscopy technique [6] permits to accommodate the four copper tube (outer diameter 6 mm, inner diameter 4 mm). Atoms propagate through a cylindrical hole of radius \( R = 1.5 \) mm. The currents run are chosen with opposite sign for adjacent tubes in order to generate a two-dimensional quadrupole magnetic field configuration characterized by a transverse gradient \( b = 800 \) G/cm, with a current of 320 A per tube. In addition we superimpose a longitudinal bias field \( B_0 = 1 \) G to avoid Majorana spin-flips losses [6].

The resulting semi-linear confining potential reads:

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

where \( \mu = \mu_B/2 \) is the magnetic moment of an atom, and \( r = (x^2 + y^2)^{1/2} \) is the distance from the guide axis.

For a given transverse confinement, the beam is completely characterized by its flux \( \Phi \), its temperature \( T \) and its mean longitudinal velocity \( v \). The flux is on the order of \( 5 \times 10^9 \) atoms/s. The temperature of the guided beam is deduced from a radio-frequency (rf) spectroscopy technique [6]. This technique allows for the determination of the temperature with an accuracy of typically 3% [6]. For our parameters, we find \( T = 640 \) \( \mu \)K. With this flux, temperature and mean longitudinal velocity, the beam is clearly in the collisional regime [6].

To demonstrate the implementation of evaporation by using a ceramic surface, we have to remove atoms from the beam selectively in position. This is accomplished by the application of a transverse magnetic field \( B_\perp \) that
of the beam is at most of the order of the radius
the flux and temperature of the beam remain constant
and the mean longitudinal velocity of the atoms. Indeed,
potential, the temperature, the radius
shifts the minimum of the transverse confinement towards the cylindrical edge of the ceramic surface (see Fig. (b)). This magnetic field is generated by a pair of coils with a mean radius 45 mm and separated by a distance of 100 mm. Such a two-coils configuration is particularly well suited for our demonstration since it essentially results in a field perpendicular to the guide axis over the whole range of interest, the longitudinal component being negligible around the guide axis.

In presence of the coils field, the atoms are transversally shifted by $\delta = B_\perp / b$. The confinement strength essentially remains unaffected in the range of parameters where the method has been used. We have checked that, in a zone without a ceramic piece, the application of the transverse magnetic field only results in a shift of the atomic beam. Indeed, even for $\delta$ as large as 2 mm, the flux and temperature of the beam remain constant within the accuracy of our measurements. This is indeed the first prerequisite to validate our protocol.

Qualitatively, as the measured thermal transverse size of the beam is at most of the order of the radius $R$, we expect that when the line of minimum of energy has been shifted by the diameter of the hole in the ceramic ($\delta \gtrsim 2R$), no atoms remain. For a given displacement $\delta$, the fraction of remaining atoms depends on the confining potential, the temperature, the radius $R$ of the ceramic and the mean longitudinal velocity of the atoms. Indeed, an atom with a low longitudinal velocity spends more time in the evaporation zone and increases its probability of being evaporated.

We have depicted on Fig. the fraction of remaining atomic flux $\varphi$ as a function of the displacement $\delta$. Even after a shift by $\delta = R$, no atoms remain. To understand quantitatively the shape of this evaporation curve, we have developed a Monte-Carlo numerical simulation. The initial positions and velocities of the particles are randomly chosen according to the thermal equilibrium distribution in the semi-linear potential $\mathcal{U}$. We use the experimental values for the bias field $B_0$, the gradient $b$, the mean velocity $v$ of the beam and the temperature $T$. The motion of each atom is governed by the Hamiltonian $H = p^2 / 2m + U(x)$, and calculated with a symplectic fourth-order algorithm, interatomic collisions are not taken into account. The surface of evaporation is a cylinder of radius $R$ and length $\ell = 5$ mm. To account for the relative displacement between the atoms and the surface, the cylinder is shifted off axis by a quantity $\delta$. Consequently, the evaporation criterium reads $(x-\delta)^2 + y^2 \gtrsim R^2$. In the numerical simulation, we assume a 100% efficiency of evaporation. This assumption is strongly supported by the excellent agreement between the simulation (Fig. solid line) and the experimental points (squares). The only adjustable parameter in the simulated curve is a global shift on $\delta$, which reveals that the ceramic piece is, in absence of transverse field, out-of-center by approximately 60 $\mu$m.

For a displacement $\delta = 1$ mm and an upstream temperature of 640 $\mu$K, we have measured the temperature 3 m downstream the ceramic piece. After such a distance the beam has completely rethermalized to the lower temperature 500 $\mu$K. In combination with the measured 40% flux reduction (Fig. 2), we deduce a gain in phase space density of 1.5 $\pm$ 0.2. This result is in good agreement with the prediction of our numerical simulation (see Fig. 3).
FIG. 3: Gain in phase space density resulting from the evaporation on a ceramic surface after rethermalization. Dashed lines: $D'/D$ deduced from the Monte-Carlo numerical simulation for a surface length $\ell = 0.01$ mm (a), 5 mm (b), 10 mm (c) and 50 mm (d). Solid line: two-dimensional evaporation where all atoms with a maximum distance from the center axis above the radius $R - \delta$ are evaporated. One then realizes a true two-dimensional evaporation where all atoms above a given radius are evaporated (solid line on Fig. 3).

With a succession of ceramic pieces, it is possible in principle to adjust in a very flexible way, using external magnetic fields, the degree of evaporation by deflecting locally the atom trajectories towards the surface. An alternative way would consist in decreasing the radius of the successive pieces placed in the ultra-high vacuum chamber which accommodates the magnetic guide. This technique is particularly well suited for experiments aiming at achieving a cw atom laser.

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