All-optical production of chromium Bose-Einstein condensates

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We report on the production of ^{52}Cr Bose-Einstein condensates with an all-optical method. We first load 5×10^6 metastable chromium atoms in a one-dimensional (1D) far-off-resonance optical trap (FORT) from a magneto-optical trap, by combining the use of radio-frequency sweeps and depumping toward the $^5S_2$ state. The atoms are then pumped to the absolute ground state, and transferred into a crossed FORT in which they are evaporated. The fast loading of the 1D FORT (35 ms $1/e$ time) and the use of relatively fast evaporative ramps allow us to obtain in 20 s about 15 000 atoms in an almost pure condensate.

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The study of the degenerate quantum phases of chromium is especially appealing for two main reasons. First, the atomic magnetic moment of $6\mu_B$ (Bohr magneton) leads to large anisotropic long-range dipole-dipole interactions, which are non-negligible compared to the contact interaction [1], and can even become the dominant interaction close to a Feshbach resonance [2]. In this regime, the stability and excitation properties of dipolar Bose-Einstein condensates (BECs) are completely modified by dipole-dipole interactions [3]. In addition, the large $S=3$ spin in the ground state makes Cr a unique element for spinor physics [4]. Second, the existence of a fermionic isotope (^{53}Cr, 10% natural abundance) opens the way to obtain a degenerate dipolar Fermi sea, and to study the interesting stability properties of a dipolar boson-fermion mixture [5].

The historic [6] and still conventional way to produce quantum degenerate gases is evaporation inside a magnetic trap (MT). Another possibility, demonstrated first for Rb [7], is evaporative cooling in an optical trap created by a far red detuned laser. These traps offer an interesting experimental alternative as the highly confining MTs required to evaporate efficiently demand either large currents or the use of integrated structures [8]. For some atoms, the winning strategy to obtain condensation has been to use a far-off-resonance optical trap (FORT), either because of high inelastic collision rates (for Cs [9] and Cr [10,11]), or because of the absence of a permanent magnetic moment (for Yb [12]). In the first case, optically pumping the atoms to the lowest-energy Zeeman substate suppresses all two-body inelastic collisions at low temperature, but these high field seeking states cannot be trapped magnetically: the use of optical traps is necessary. The evaporation is then performed in a crossed FORT with a standard procedure, for which the evaporation dynamics is well understood [13].

However, efficiently loading a FORT is not straightforward in general, especially for Cr. In particular, in our experiment, a direct loading of a Cr optical trap in the ground $^7S_3$ state from a magneto-optical trap (MOT) leads to a small number of atoms, presumably because of a high light-assisted inelastic collision rate [14,15]. The loading procedure used to obtain the first Cr BEC [11] was to accumulate the atoms in metastable D states inside a MT, before transferring them first into an elongated Ioffe Pritchard MT, and then in a 1D FORT (produced by one beam). Our strategy is quite different, as we directly load a 1D FORT of metastable atoms from our MOT. In this Rapid Communication, we first describe our original method to rapidly load a 1D FORT (in less than 100 ms, to be compared to about 20 s in [11]). We then describe the evaporation procedure and show the evidence for the production of a BEC.

We produce an atomic Cr beam from an oven running at 1500 °C. After being decelerated in a one-meter-long Zeeman Slower atoms are captured in a standard MOT, with a few 10^6 atoms and an initial phase-space density of 5 $\times 10^{-7}$. A horizontal retroreflected 35 W ir laser beam (produced by a 50 W fiber laser, at 1075 nm) is focused at the MOT center (with a waist of 42 μm). The 425.5 nm cooling transition from the ground $^7S_3$ to the excited $^7P_4$ state has leaks toward metastable D states. When atoms decay into these D states in the low field seeking substates, they remain trapped due to the strong confinement of the ir laser along two transverse directions, and to the magnetic gradient created by the MOT coils along the ir beam propagation axis. We reported in [16] how we could obtain about one million metastable atoms in this continuous FORT loading procedure. However encouraging, this result turned out to be insufficient to reach quantum degeneracy: we obtained a final phase-space density in the 5×10^{-4} range after evaporation in a crossed FORT. Nevertheless, as the dependence of the evaporation process with the initial number of atoms is highly nonlinear, we estimated using [13] that a gain of a factor about 5 in the 1D FORT loading could be enough to reach degeneracy.

As a first main step, we were able to lower the magnetic forces applied to the atoms during the loading in order to (i) allow the capture of metastable atoms produced in any magnetic substate, and (ii) increase the volume of the trap. We report in [17] how we use fast radio-frequency (rf) ramps to spin flip the atoms in the trap at a high rate: we excite the atoms with a rf produced by a 150 W amplifier that we send to an 8-turn, 8-cm-diam coil located 5 cm from the MOT center, and we continuously sweep the rf frequency while loading the FORT. Magnetic forces are thus averaged out, and we can trap in a pure 1D FORT 80% more atoms than without rf.

In a second decisive step, we investigated the possibility to accumulate atoms in a different metastable state. The $^5S_2$ state is easier to load due to the larger branching ratio to this
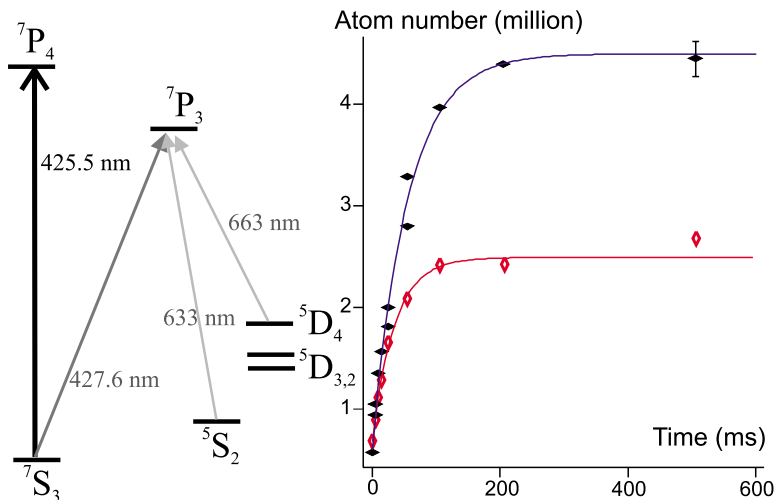
FIG. 1. (Color online) Loading of the 1D horizontal FORT (right). We plot the number of metastable atoms after a given accumulation duration. The presence of rf frequency ramps during the accumulation almost doubles the final number of atoms (top curve versus bottom). The solid lines are exponential fits. The error bar gives (as in the other figures) the typical statistical uncertainty. We show (left) the atomic levels and transitions of interest.

level from $^7P_3$ than to the D states from $^7P_4$ (a gain of about 100 is expected [18]). Besides, our study in [16] proved that one of the main limiting processes for the continuous loading in the FORT in metastable D states comes from inelastic collisions, and the absence of spin-orbit interaction at first order for $^5S_2$ is thus favorable. Finally, calculations of the light shifts show that optical trap depths are expected to be almost twice as large in the $^5S_2$ state than in the D states.

To depump toward $^5S_2$, we apply during the loading process a weak beam at 427.6 nm (35 μW, 3 mm $1/e^2$ diameter), at resonance with the $^7S_3 \rightarrow {}^7P_3$ transition. In order to guarantee that the MOT capture efficiency is not reduced by this new beam, and to repump any atom in the $^5S_2$ state outside of the FORT, we add a "dark spot" repumper at 633 nm: we shine on the atoms a 0.4 mW beam going across a horizontal wire imaged on the MOT center, with an image size of 400 μm. The depumping effect of the 427.6 nm beam is thus counterbalanced in most of the MOT capture volume by the 633 nm beam (the MOT beams have a $1/e^2$ diameter of 7 mm), but the atoms that accumulate in the 1D optical trap in the $^5S_2$ state do not get repumped back to the ground state. The use of this dark spot during the loading increases the final number of atoms by 20%. A similar technique is used in [19] to reduce the amount of inelastic collisions in a Na cloud.

In order to characterize the 1D FORT loading, and for evaporation, we then prepare the atomic sample in the $^7S_3$, $m_J = -3$ absolute ground state. We switch off the MOT beams and magnetic gradients, as well as the rf, and we repump the atoms in $^5S_2$ and $^5D_4$ to the ground state. We do not have yet the possibility to repump atoms in the $^5D_2$ and $^5D_3$ states, which may cause some inelastic collisions during evaporation. Finally, the atoms are transferred to $m_J = -3$: after the 20 ms necessary for the eddy currents generated by switching off the MOT coils to disappear, we apply with the 427.6 nm laser a 50 μs, 0.25 mW retro-reflected pulse of circular polarization, in the presence of a 2.3 G magnetic field. The field direction during optical pumping is finely aligned with the polarization beam propagation axis, so that we can send ms long pulses without losing many atoms, proving that indeed a dark state has been obtained on this optical $J \rightarrow J$ transition. We image atoms in this state using a

dark ground absorption imaging system with a resonant circularly polarized beam on the trapping transition.

Results shown in Fig. 1 have been obtained by first forming a stationary MOT (in about 50 ms) in the presence of the depumping and dark spot beams, and then switching on the horizontal ir beam for a given duration. The number of atoms trapped typically reaches 2.5 million when no rf ramps are applied, and about 4.5 million with rf ramps. In this case, the $1/e$ loading time is about 35 ms, and from the slope at $t=0$, we infer a loading rate equal to 1.3×10^8 atoms/s, which is only a factor about 4 smaller than the MOT one. We have thus realized a very efficient loading procedure from a MOT into a 1D FORT, with a final temperature of 100 μK, a phase-space density of 5×10^{-6}, and an elastic collision rate of 50 s^{-1}. Compared to typical starting parameters for alkali-metal atoms in FORTs before evaporation (see, for example, [7]), this phase-space density is relatively small (presumably due to large inelastic losses), which will lead to substantially longer evaporation durations.

To reach degeneracy, we start to form a crossed FORT just after preparing the atoms in the $^7S_3$, $m_J = -3$ state, thus creating a "dimple" [20]: we transfer some laser power from the horizontal beams to a second ir beam, which is almost vertical, and has a 56 μm waist. The power dispatching is controlled via a half-wave plate on a computer-controlled rotation stage, in front of a polarizing beam splitter cube: we proceed to a 9.1-s-long linear rotation of this plate by an angle equal to 32°. We stress that the relative polarization of the three ir beams does matter. The dimple loading efficiency is optimal when the polarizations of the three ir beams are orthogonal to better than about 20°. When the vertical beam polarization is parallel to one of the horizontal beam polarizations, we observe a strong reduction of the loading efficiency of the crossed trap (see Fig. 2), which prevents reaching BEC [21]. Yet the path differences between the ir beams are much larger than the expected coherence length of our ir laser, assuming a 5 nm full width at half-maximum continuous emitting spectrum. Our observations may be related to the intensity noise spectrum of the ir laser (see the inset in Fig. 2), which points toward a regular structure in its frequency spectrum.

During the dimple formation, we start to lower the total ir laser power using an acousto-optic modulator (AOM): 6 s
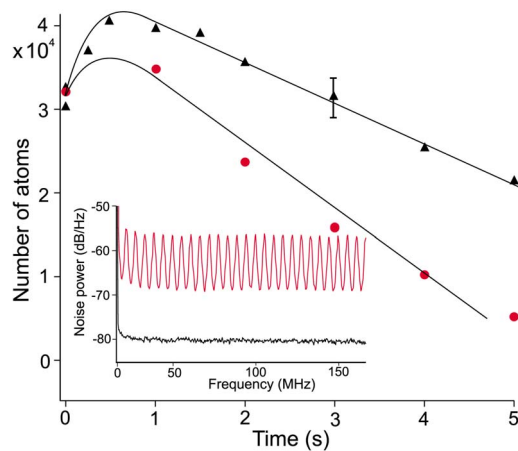
FIG. 2. (Color online) Top: Experimental evidence for the importance of the relative polarizations of the different ir beams creating the crossed FORT. After a dimple has been formed by transferring half of the ir power to the vertical beam, the number of atoms in the dimple is plotted versus time. When the three ir beams (the two horizontal ones and the vertical) have a linear polarization along three orthogonal axes (triangles), the loading from the horizontal FORT is more efficient than when two have parallel polarizations (circles). Besides, the losses are reduced. Solid lines are guides for the eye. Bottom: Intensity noise spectrum of the ir laser observed with a 1 GHz bandwidth photodetector (top curve); the noise spectrum obtained with no light is shown below.

after the atomic polarization, a decreasing nonlinear ir laser power ramp is triggered. This ramp corresponds to a linear ramp of the voltage sent to the power input of the voltage-controlled oscillator driving the AOM. The resulting theoretical depths of the traps created by the horizontal and vertical FORT beams are shown in Fig. 3. We show as well the evolution of the experimental classical phase-space density $N_{\mathrm{at}}(\frac{\hbar\bar{\omega}}{k_B T})^3$, where $\bar{\omega}$ is the geometric means of the dimple trap
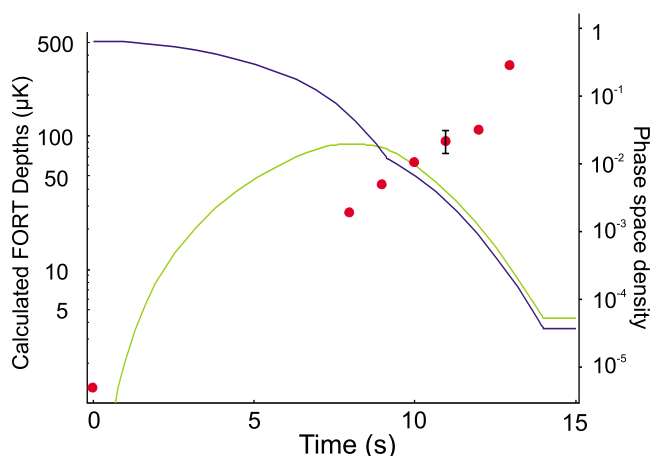

FIG. 3. (Color online) Calculated potential depths created by the horizontal and vertical (bell shape) FORT beams (log scale) during the transfer in the crossed FORT and the evaporation. We show as well the classical phase-space density (dots) in the initial 1D FORT (at $t=0$), and after all the atoms are transferred into the dimple. At the very end of the ramp, the cloud reaches degeneracy, and the classical phase-space density (exceeding 1) is therefore not shown.
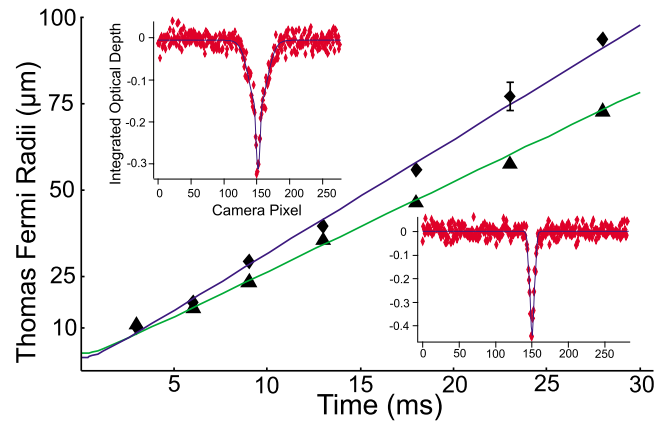

FIG. 4. (Color online) Analysis of the experimental free expansion of an almost pure BEC. The Thomas-Fermi radii along y (diamonds) and z (triangles) are deduced from absorption pictures. The solid lines are results of numerical simulations using the measured trap frequencies, with the *in situ* radii giving the best agreements with the experimental data. Insets: integrated optical density of the atomic cloud after 4 ms of free expansion, when T_c is reached (left), and well below T_c (right); one pixel corresponds to 2.2 μm.

angular frequencies and T is the temperature of the cloud containing N_{at} atoms.

The parameters characterizing the magnetic field around the trap center turned out to be critical to obtain a BEC. We need to compensate for a magnetic potential curvature along the weak axis of the 1D FORT (Ox) due to the coil producing the polarization field, by using a 4 cm radius coil located 10 cm above the MOT center, in a horizontal plane. The 1D FORT lifetime is thus significantly increased. This new coil creates as well a gradient b_z along the vertical axis, which induces a force opposed to gravity. We do not obtain the most efficient evaporation when the two forces compensate as expected according to [22], but for $6\mu_B b_z = -0.8 m_{52} g$, where m_{52} is the atom mass and g is the gravity acceleration. This effect can be interpreted by the fact that it is better if the atoms evaporated out of the dimple into the wings of the crossed FORT do not come back to collide with atoms remaining in the dimple [23]. A leak along these wings is thus favorable, and we found indeed that it is better to have as well a small gradient along Ox (0.1 G cm^{-1}) once the dimple is formed.

Phase transition to BEC is observed with the appearance of a very narrow feature at the center of the velocity distribution, as measured by the cloud's profile after some free expansion. A bimodal velocity distribution (see the left inset of Fig. 4) is observed below $T = 150$ nK, consistent with a predicted degeneracy temperature of 170 nK [24]. We estimate the trap frequencies at the critical point by scaling the experimental frequencies ($f_1 = f_2 = 110 \pm 2$ Hz, $f_3 = 150 \pm 2.5$ Hz) measured through parametric excitation at the very end of the evaporation ramp, where we obtain an almost pure condensate of up to $N_{\mathrm{BEC}} = 15\,000$ atoms (right inset of Fig. 4).

In order to characterize the pure BEC, we analyzed the absorption pictures along the two axes (Oy and Oz) of the CCD camera during free expansions as long as 30 ms. We

obtain the two radii $R_y(t)$ and $R_z(t)$ by standard analysis, assuming the Thomas-Fermi (TF) regime [24]. The corresponding results in Fig. 4 demonstrate a clear anisotropic expansion. A comparison with a numerical resolution of the Gross-Pitaevskii equation [25] provides the following *in situ* TF radii: $R_{z\mathrm{TF}}=5\pm0.25$ μm ($=R_{x\mathrm{TF}}$), $R_{y\mathrm{TF}}=3.75\pm0.25$ μm, and the chemical potential $\mu/h=m_{52}\bar{\omega}^2\bar{R}_{\mathrm{TF}}^2/2=790\pm90$ Hz ($\gg f_3$, which justifies the TF approximation), $\bar{R}_{\mathrm{TF}}$ being the geometric means of the TF radii. The value of μ is consistent with the expected chemical potential ($\mu_{\mathrm{TF}}/h=865\pm40$ Hz), given N_{BEC}, $\bar{\omega}$, and the value of the scattering length reported in [26]. The peak density in the BEC is $(6.4\pm0.75)\times10^{13}$ cm^{-3}.

We want to emphasize the relative simplicity of our setup and of the experimental procedure we use to reach BEC with chromium. First, the total duty cycle for producing a BEC is about 20 s (while it is more than 35 s in [11]). It could be as small as 14 s since the 1D FORT loading takes about 100 ms, but we need some time at the end of a cycle to recover the starting parameters. Thanks to the relatively short evaporation duration, vacuum requirements to reach degeneracy are easier to fulfill than in many BEC experiments: the pressure in our experimental chamber is in the 5×10^{-11} mbar range, which induces a limited $1/e$ lifetime of 25 s for the 1D FORT. In addition, we run our oven at a temperature limited to 1500 °C (1600 °C in [11]), increasing thus both the robustness of our setup and its capacity to deliver a Cr beam over a long period of time.

In conclusion, we have obtained a Cr BEC with an different strategy. The key point was to load from a MOT a 1D FORT with a sufficient atom number, which could not be obtained by running the oven at a higher temperature. Reaching degeneracy thus required the development of two accumulation techniques described in this paper. They could also be instrumental for achieving BEC with other atoms, such as calcium, which can be optically trapped in metastable states [27]. Besides, we point out that the nonperfect compensation of gravity and the orthogonality of the polarizations of the ir beams involved in the crossed FORT are necessary for a successful evaporation in optical traps.

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