Trapping and cooling of potassium isotopes in a double-magneto-optical-trap apparatus

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We report on the efficient operation of a double-magneto-optical-trap (MOT) apparatus for potassium isotopes. Mechanisms for the cooling and the transfer between the two MOTs are studied. A magnetic quadrupole trap has been loaded from the second MOT; density and temperature appear to be promising for starting runaway evaporative cooling. [S1050-2947(99)03201-1]

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Experiments on cooling and trapping of potassium isotopes are strongly motivated by the occurrence in nature of three isotopes (^{39}K, ^{40}K, ^{41}K with a relative abundance of 93.26%, 0.012%, and 6.73%, respectively). Two of them, ^{39}K and ^{41}K, are bosons while ^{40}K is a fermion. Potassium therefore offers the opportunity to investigate the properties of different bosonic isotopes and eventually could allow the study of Bose condensates, a degenerate Fermi gas, or both. Unlike other alkali-metal atoms, potassium has not been widely investigated. Magneto-optical traps (MOTs) for the most abundant isotopes do not have a long history [1–5] and only recently was trapping reported for the rare fermion from a natural abundance sample [6,7] and for unstable isotopes from an on-line isotope separator [8]. Theoretical predictions for the collisional behavior at ultralow temperature reported so far are contradictory [9,10]. As a consequence, experimental investigations on potassium are challenging but also stimulating because of the large amount of original information which they are likely to provide.

With the final goal of cooling atoms at high densities starting from rare or expensive enriched isotopes, we have developed a double-MOT apparatus [11] which allows efficient loading and long trapping lifetime. An alternative to this approach is a MOT loaded by a slow beam generated in an atomic funnel [7]. In view of a possible future sympathetic cooling of ^{40}K by evaporatively cooled bosons, it is necessary to start working with the bosonic isotopes of potassium. However, the physics of laser cooling and the transfer process between the two MOTs for ^{39}K and ^{41}K are different than for alkali-metal atoms such as Rb. Similar to ^{7}Li, the hyperfine level spacing in the upper state is comparable to the homogeneous broadening and it is not possible to isolate a single cooling transition. For potassium further complications arise from the noninverted hyperfine structure in the excited level. Hence, two laser frequencies ν_1 and ν_2 red detuned with respect to the $F_g=1\rightarrow F_e=2$ and $F_g=2\rightarrow F_e=3$ transitions are necessary [1]. The optimal loading rate and number of atoms in MOTs of ^{39}K or ^{41}K are achieved when both laser fields are detuned with respect to the whole hyperfine structure of the $4\,^2P_{3/2}$ state using relatively high intensity. With this configuration, atoms are trapped at low density and high temperature (>1 mK) because sub-Doppler forces are suppressed. Recently we have found that by reducing intensities and detunings we can recover some of the usual characteristics of cooling other alkali-metal atoms [5].

We demonstrate that the double-MOT scheme is successful for potassium and we report on a systematic study of the transfer of atoms between the two MOTs and the loading of the second MOT, with either ^{39}K or ^{41}K. The atoms were also transferred to a quadrupole magnetic trap with a lifetime in the trap of about 30 s.

Laser light requirements for ^{39}K and ^{41}K double MOTs are somewhat complicated since intense radiation at two different frequencies is necessary for the two MOTs. Two frequencies are also necessary for the transfer. As is schematically shown in Fig. 1, all the laser light used in our experiment is provided by a cw Ti:sapphire laser (Coherent model 899-21) with an output power of up to 1 W. The laser frequency is offset locked using an acousto-optic modulator (AOM1) in double pass configuration to a saturated absorption signal obtained in a potassium vapor cell. Using six different AOMs we obtain independent beams for the two

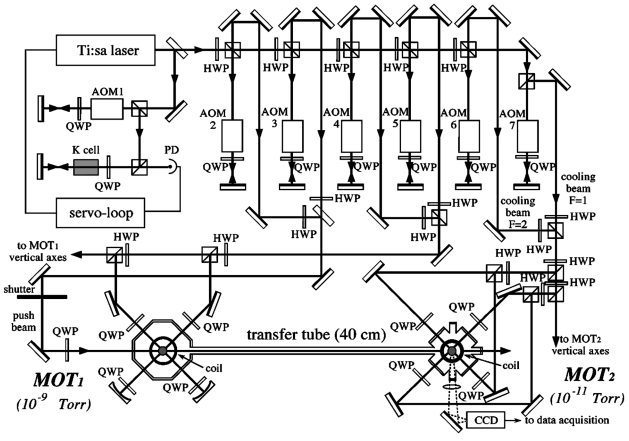

FIG. 1. Experimental apparatus of the double-MOT system for potassium isotopes. Ti:sa, titanium sapphire laser; QWP, quarter wave plate; HWP, half wave plate; AOM, acousto-optic modulator; PD, photodiode. Lenses are not shown for clarity.

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MOTs and for the pushing beams necessary for transferring atoms from the first to the second cell. Each beam is frequency and intensity controlled by an AOM in double pass configuration. By changing the lock position and the AOM frequencies, we are able to switch from one isotope to the other. The first MOT (MOT_1) was operated with a total laser power of ~ 150 mW for ^{41}K and ~ 500 mW for ^{39}K divided between the two laser frequencies ν_1 and ν_2 with 60% of the power in the beam at frequency ν_2. The $1/e$ diameter of the beams is 2 cm and the MOT magnetic field has an axial gradient of 15 G/cm. The second MOT (MOT_2) operates at a slightly lower power (~ 100 mW) and the beams have a diameter of 1 cm, limited by the cell windows. The typical axial magnetic field gradient is 10 G/cm and can be increased up to 80 G/cm for purely magnetic trapping. Additional coils are necessary in both MOTs to compensate for residual magnetic fields. In MOT_1 the trapping beams are retroreflected using curved mirrors. This compensates for the intensity imbalance due to the uncoated cell windows. In the second cell we use a six-independent-beam configuration avoiding also the intensity unbalance due to the absorption from the trapped atoms. A photodiode and a charge-coupled device (CCD) camera monitor the number of atoms and the size of the atom cloud in each trap.

The vacuum system consists of two cells joined in the horizontal plane by a 40 cm long transfer tube with an inner diameter of 1.1 cm. The first cell (MOT_1) is made of stainless steel. It is connected to an ion pump (25 l/s) and a valve connects this cell with the potassium reservoir. The vapor pressure in the cell is controlled by adjusting the temperature of the reservoir. The second cell (MOT_2), made of Pyrex, is maintained at a much lower pressure ($<10^{-11}$ Torr) using a second ion pump (55 l/s) in conjunction with a titanium-sublimation pump. Six strips of uniformly magnetized rubber surrounding the transfer tube create a hexapole field that gives a radially confining potential for spin-polarized ''low-field seeking'' atoms [11].

The working temperature of potassium in the reservoir is around 50 °C for ^{41}K and 40 °C for ^{39}K. The maximum number of atoms collected in MOT_1 is 3×10^8 for ^{41}K and 3×10^9 for ^{39}K, with a loading time of 3–4 s depending on the potassium reservoir temperature.

The procedure to transfer atoms from MOT_1 to MOT_2 starts with the loading of MOT_1 for 1 s. High-power fields detuned with respect to the whole hyperfine structure of the D_2 transition are used to maximize the number of atoms loaded into MOT_1: for ^{41}K the laser fields are detuned by -24 MHz and -36 MHz with respect to the $F_g=1\rightarrow F_e=2$ and $F_g=2\rightarrow F_e=3$ transitions, while for ^{39}K the detunings are -30 MHz and -50 MHz, respectively. Next the atoms trapped in the first cell are further cooled for 5–10 ms by changing the laser field parameters. As expected from the results of a previous work on the cooling mechanisms in ^{39}K [5], we observed a strong temperature reduction (from a few mK down to less than 200 μK) for both isotopes by decreasing the detuning of the ν_2 beams and the intensity of the ν_1 beams. Then, the laser beams of MOT_1 are turned off and the pushing beams are flashed on for 1 ms to accelerate the atoms into the transfer tube. In contrast to double MOTs of ^{87}Rb [11], potassium requires two frequencies for efficient transfer. One push beam consists of light blue detuned by 10 MHz with respect to the $F_g=2\rightarrow F_e=3$ transition that is circularly polarized to apply a strong optical force to the atoms and to optically pump them into the ''low-field seeking'' $F_g=2$, $M_F=1,2$ Zeeman sublevels that are radially confined by the transfer tube's hexapole magnetic field. However, strong optical pumping to near resonant states makes repumping light desirable for transfer. The repumping push beam is resonant with the $F_g=1\rightarrow F_e=2$ transition. The transfer efficiency is optimized when the first push beam has σ^+ polarization and the repump push beam uses σ^+ or π polarization. The two pushing beams, with a power of ~ 2 mW each, are superimposed and weakly focused to a point near the center of MOT_2. After ~ 15 ms the atoms reach the second cell, where they are captured in MOT_2. MOT_1 is turned on again and the cycle is repeated. By optimizing all the parameters, we were able to obtain a maximum single-shot transfer efficiency of 30%. We note that the single-shot efficiency drops to 10% if the cooling phase in the first MOT is omitted. A similar reduction is observed if the magnetic guide is removed.

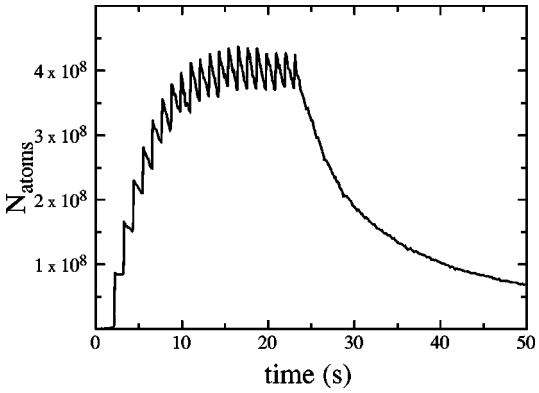

FIG. 2. Fluorescence from MOT_2 as a function of time monitored with a photodiode. Every second during the first 25 s atoms are transferred from MOT_1 and accumulated. For the last 25 s the transfer is stopped and the fluorescence decays following a double exponential.

After a few loading cycles the number of trapped atoms in MOT_2 approaches a steady value (Fig. 2). The maximum number of atoms is limited mainly by two factors. The first is light assisted collisions between cold atoms which become more and more important as the density increases. The second is due to the finite dimensions of the trapping region. We optimized all the trap parameters to balance between these two effects. The importance of light assisted collisions can be extracted from the decay of the fluorescence coming from MOT_2 when the loading is stopped (Fig. 2). The fluorescence decay curve can be fitted by the sum of two exponentials with different time constants (the first of a few seconds, the second of the order of a hundred seconds) demonstrating the existence of two loss mechanisms, one dominating at high densities, the other limiting the MOT lifetime for low densities.

The operation of MOT_2 has been characterized by varying parameters of the trapping fields. The number of atoms recaptured in the second trap is independent from the intensity of the trapping laser fields over a wide range and can be optimized by using the same detunings as in MOT_1 during the loading phase. The maximum number of atoms we can

collect in MOT_2 is 1.5×10^8 for ^{41}K and 5×10^8 for ^{39}K, at a temperature of a few mK and a density $[\langle n\rangle = 1/N\int n^2(\mathbf{x})d^3x$, where N is the total number of atoms and $n(\mathbf{x})$ is the density at the space point $\mathbf{x}]$ of up to 10^8 atoms/cm^3 for both isotopes.

To compress the cloud of cold atoms and decrease the temperature we apply a ''cooling'' phase for 5–10 ms: for ^{41}K we change the detuning of the ν_1 field to -12 MHz and to -20 MHz for the ν_2 field. For ^{39}K optimum conditions are found when the detuning of the ν_1 field is -30 MHz and that of the ν_2 field is -12 MHz. In both cases the intensity of the ν_1 field is reduced to ~1.5 mW/cm^2. During ''cooling'' and ''loading'' phases the quadrupole magnetic field is the same. After this period we let the cloud expand in the dark for different times, then we flash the atoms with the ν_1 and ν_2 trapping beams, both shifted into resonance, for 100 μs and image the cloud fluorescence on a CCD camera. This allows us to measure both the temperature and the spatial distribution of the trapped atoms.

We obtain a minimum temperature of ~150 μK (Fig. 3) and a density of 5×10^8 atoms/cm^3 for ^{41}K and 1×10^9 atoms/cm^3 for ^{39}K. This leads to a transient increase of almost three orders of magnitude in the phase space density with respect to the uncompressed MOT.

The loading of a quadrupole magnetic trap from the MOT in the cooling phase is achieved by turning off the trapping light and by increasing the current in the anti-Helmholtz coils of MOT_2. The maximum axial gradient was 80 G/cm. Without any effort to pump all the atoms to a particular ''low-field seeking'' Zeeman state, but merely pumping the atoms to the trapped $F_g=2$ states, we transfer 30% of the atoms from MOT_2 to the magnetic trap. The lifetime in the magnetic trap is about 30 s and strongly depends on the pressure in the first cell. To evaluate the number of elastic collisions during this lifetime one should know the relevant cross section. If one assumes a value of the order of 10^{-15} m^2 with our densities and temperatures we should have about ten collisional processes during a lifetime. This could be promising for the next steps to be followed for Bose-Einstein condensation [12,13], such as, for instance, magnetic compression and evaporative cooling.

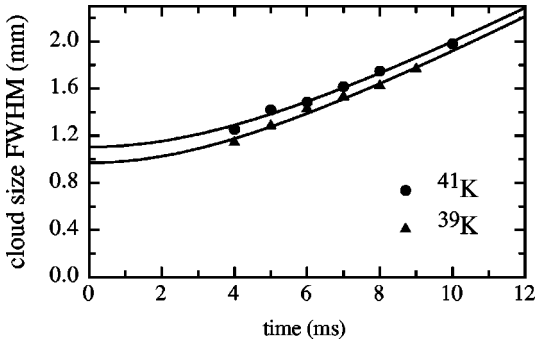

FIG. 3. Free expansion of a cloud of cold atoms after the release from the MOT_2 in the ''compressed'' phase. Data are taken imaging with a CCD camera the fluorescence of the atoms illuminated, during the expansion, for 100 μs with resonant laser light. The fitted curves give a temperature of 143 μK for ^{41}K and 136 μK for ^{39}K.

We demonstrated the operation of a double-MOT apparatus for ^{41}K and ^{39}K. The use of a double-MOT configuration is also particularly suited for trapping of the small abundance fermionic ^{40}K; indeed in this case, still better performances are expected because of the inverted hyperfine level structure that should allow efficient sub-Doppler cooling. We also loaded cold atoms into a quadrupole magnetic trap with a lifetime of 30 s. This is promising in view of evaporative cooling of the trapped atoms towards the achievement of quantum degeneracy in a gas of potassium atoms.

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