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Magneto-optical trapping of Fermionic potassium atoms

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We have trapped ^{40}K in a vapor-cell magneto-optical trap starting from a natural abundance sample. This rare, weakly radioactive atom is a fermion. The number of trapped atoms is approximately 8000, with a density of $\sim 10^8$ atoms/cm^3. Contrary to what is observed for the other isotopes of potassium, our data indicate that temperatures lower than the Doppler-cooling limit can be reached for ^{40}K. We discuss the interest of these results in view of possible experiments to study a degenerate Fermi gas. [S1050-2947(98)05601-7]

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The observation of Bose-Einstein condensation (BEC) in ^{87}Rb [1], ^{7}Li, [2] and ^{23}Na [3] opened the way to the study of the effects of quantum statistics in dilute gases. One of the most interesting prospects in this field is now to investigate the properties of an ultracold gas of fermionic atoms. At phase-space densities similar to the ones achieved in BEC experiments, the behavior of a degenerate Fermi gas may be studied and, at still lower temperatures, the superfluid phase-transition could be observed [4,5]. The choice of the fermionic atom is, however, more restricted because the number of naturally occurring fermionic species is much smaller than the number of bosonic ones [6]. In particular, among the alkali-metal atoms only lithium and potassium have fermionic isotopes. In recent experiments, trapping of ^{6}Li was demonstrated [7]; no result has previously been reported for the fermionic isotope of potassium, namely, ^{40}K.

We report herein on trapping of ^{40}K in a magneto-optical trap (MOT) from an unenriched (natural abundance) sample. Ordinary potassium is composed of three isotopes: ^{39}K (93.26%), ^{41}K (6.73%), and ^{40}K (0.012%). The bosonic atoms ^{39}K and ^{41}K are stable. ^{40}K is weakly radioactive, with a half-life of 1.28×10^9 years. Therefore potassium offers the opportunity of investigating the properties of different bosonic isotopes, for which different signs of the scattering length and the possibility of observing Feshbach resonances were predicted [8], and eventually will allow the comparison of a Bose condensate with a degenerate Fermi gas.

Magneto-optical trapping of ^{39}K and ^{41}K was demonstrated considerably later than the other alkali-metal atoms [9–11]. Recently, trapping of β-decaying ^{38}K^m (with a half-life of 0.925 s) and ^{37}K (half-life 1.226 s), produced using an on-line isotope separator, was reported [12].

A major difference of ^{39}K and ^{41}K MOT's with respect to most other alkali-metal atoms comes from the small hyperfine splitting of the $4P_{3/2}$ excited state [13]. The values of laser detuning typically used to trap other atoms result in strong optical pumping. In order to overcome this problem, in the experiments performed so far, two sets of laser beams were used, one exciting the atoms from the lower $F=1$ hyperfine level, the other interacting mostly with the atoms in the $F=2$ level. For optimum operation of the trap, both beams were detuned to the red by an amount larger than the whole hyperfine structure of the excited state; a relatively high laser power was needed for trapping. As described in detail in the following, trapping of ^{40}K proved, in this respect, to be simpler than for the other isotopes. The hyperfine structure in ^{40}K is indeed slightly larger with respect to the other isotopes and, more important, the structure is inverted (see Fig. 1). It is possible in this case to trap the atoms with the trapping laser tuned on the red side of the $F=\frac{9}{2}\rightarrow F'=\frac{11}{2}$ cycling transition and the optical repumping light tuned to the $F=\frac{7}{2}\rightarrow F'=\frac{9}{2}$ transition.

A simplified scheme of the apparatus we used is shown in Fig. 2. It was designed to allow trapping of any of the three K isotopes. As can be seen from the saturation spectrum in Fig. 3, the frequencies of all the relevant transitions are within ~ 1.3 GHz. Therefore, all of the laser beams required for trapping are derived from a Ti:sapphire laser pumped by

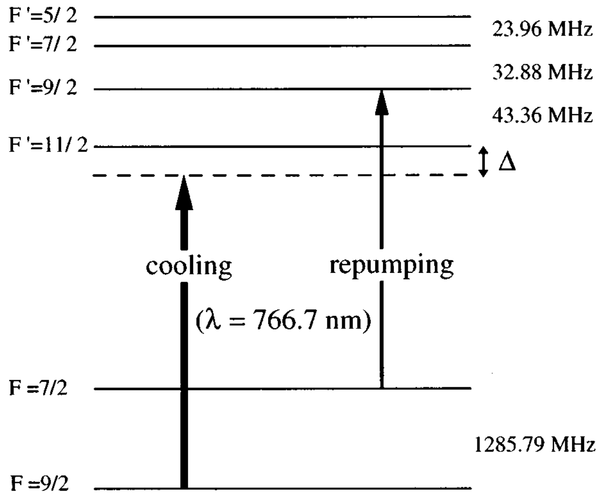

FIG. 1. Simplified energy-level scheme (not to scale), showing the hyperfine structure of the $4^2S_{1/2}$ and $4^2P_{3/2}$ states of ^{40}K, and the laser frequencies used for magneto-optical trapping of this atom.

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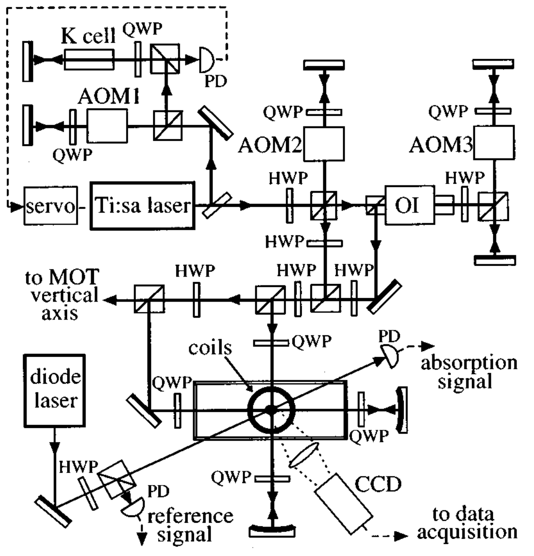

FIG. 2. Scheme of the experimental apparatus. AOM, acousto-optic modulator; PD, photodiode; HWP, half-wave plate; QWP, quarter-wave plate; Ti:sa, titanium:sapphire laser. Lenses are not shown for clarity.

a 15-W Ar-ion laser. In addition, in this experiment we used an external-grating-stabilized diode laser that provided a probe beam. Using an acousto-optic modulator (AOM1) in a double-pass configuration, the Ti:sapphire laser frequency is offset locked to a sub-Doppler feature of the saturation spectrum in a potassium cell. The two frequencies required for the MOT are then obtained using acousto-optic modulators (AOM2 and AOM3). In particular, for ^{40}K trapping, the frequency of AOM1 was modulated around 85 MHz. Using phase-sensitive detection, the laser frequency was locked 170 MHz blue of the $(F=1\rightarrow F'=0,1,2\text{–}F=2\rightarrow F'=1,2,3)$ crossover signal of ^{39}K. Trapping light with a red detuning $\Delta\sim 18$ MHz below the $F=\frac{9}{2}\text{–}F'=\frac{11}{2}$ transition was generated by double passing through the AOM2 acousto-optic modulator driven at a frequency around 208 MHz. The optical-repumping light was obtained by passing four times through a 202-MHz acousto-optic modulator (AOM3). The maximum total power at the trapping region was 200 mW for the trapping light, and 40 mW for the repumping light. The output beams from AOM2 and AOM3 were combined on a polarizing cube, and then split into three beams that were sent in orthogonal directions into the trapping cell. The diameter of the beams was 1.5 cm for the trapping beams and for the repumping beams. After passing the cell, the beams were retroreflected using curved mirrors to compensate for losses on the uncoated cell windows. Two coils in the anti-Helmholtz configuration produced the magnetic field for the magneto-optical trap, with a maximum gradient at the trap region of ~ 18 G/cm. The trapping chamber is a glass cell connected to an ion pump. Potassium was introduced in the cell from a reservoir containing natural-abundance metallic potassium at a temperature of 40 °C. The pressure of K vapor in the trapping chamber, kept at room temperature, was $\sim 3\times 10^{-9}$ Torr. The fluorescence of the trapped atoms was detected with a calibrated, triggerable charge coupled device (CCD) camera.

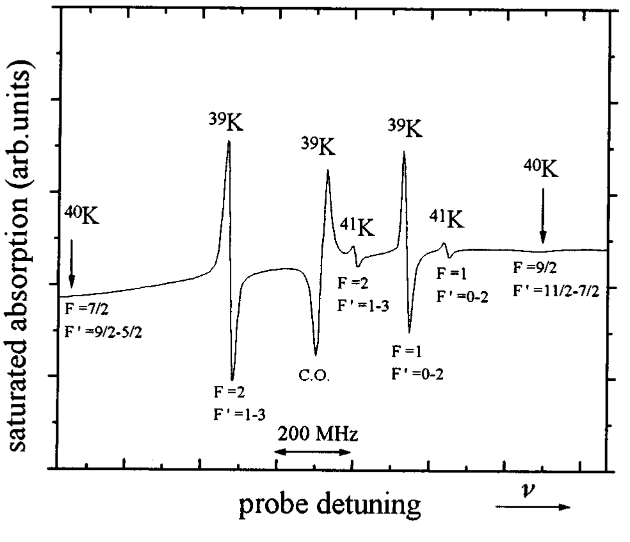

FIG. 3. Derivative of the saturated absorption signal recorded in a potassium cell. The weak signal of ^{40}K, which cannot be seen on this scale, was observed with an enlarged vertical scale. c.o., crossover resonance.

The main constraint in the study of the ^{40}K trap was the intense background due to the fluorescence from the other more abundant isotopes. With the trap operating under optimum conditions, the intensity of the fluorescence from the trapped atoms was only ~ 2.5 times larger than the fluorescence light from the background atoms. This made it difficult to use a photodiode to detect the light scattered from the trapped ^{40}K atoms. Therefore, the usual methods to study magneto-optical traps, such as time-of-flight measurement of the temperature, could not be applied. We used a CCD camera which gave a better spatial discrimination and, by using image-subtraction methods, a significant reduction of the background signal. This allowed us to estimate the number of trapped atoms and to measure the diameter of the trap. The number of atoms in the trap measured with this method was $N\sim 3\times 10^3$ for a laser intensity of 10 mW/cm^2 per beam and a detuning $\Delta\sim 18$ MHz $(\sim 3\Gamma_{\text{nat}})$ with respect to resonance. The trap shape was spherical with a diameter of 1 mm. It did not show a critical dependence on the beam alignment. The loading time in these conditions was 3 s. A more accurate value for the number of trapped atoms was obtained by measuring the absorption of a weak probe laser beam interacting with the trapped atoms. Light from the diode laser was sent through the trap and detected with a low-noise photodiode. The laser frequency was modulated at 20 kHz to allow lock-in detection. The absorption spectrum in Fig. 4 shows the three hyperfine components $F=\frac{9}{2}\rightarrow F'=\frac{11}{2},\frac{9}{2},\frac{7}{2}$. The peak absorption is 5×10^{-5}. This corresponds to $N=8\times 10^3$ for the number of atoms in the trap, in fairly good agreement with the value estimated from the measurement of the fluorescence intensity. The number of trapped atoms is limited by the low abundance of ^{40}K in the vapor. Indeed, using the same apparatus, we trapped 5×10^7 atoms of ^{39}K [14]. The trap-loading time, essentially determined by collisions with ^{39}K and ^{41}K background gas in the cell, was ~ 3 s in both cases. The ratio in the number of trapped atoms is therefore given by the ratio of the loading rates. From our data, this is consistent with the ratio of the densities of the two species in the vapor.

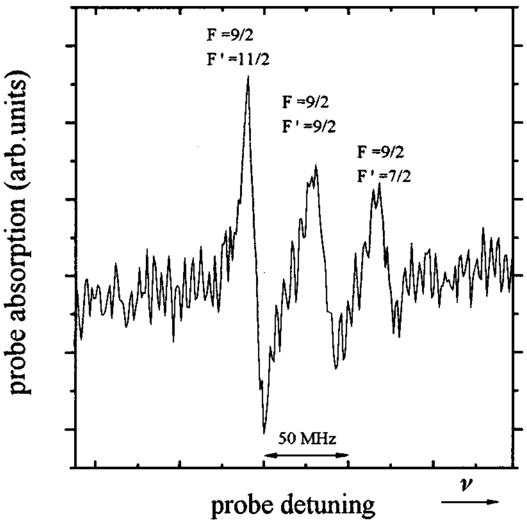

FIG. 4. Derivative of the $F=\frac{9}{2}\rightarrow F'=\frac{11}{2},\frac{9}{2},\frac{7}{2}$ absorption signals from the cold ^{40}K atoms in the MOT.

In order to estimate the temperature of the trapped atoms, we used a release-and-recapture method [15]. After loading the trap, the trapping beams and the magnetic field were switched off, and the number of atoms remaining in the observation region for different values of the dark time was measured using the CCD camera. With this method, we measured temperatures down to ~ 50 μK. This would indicate a temperature lower than the Doppler cooling limit $T_D = 150$ μK. It is interesting to note that the temperature measured in ^{39}K and ^{41}K MOT's is always above the Doppler limit. The minimum temperature we measured for ^{39}K was 180 μK [14]. This is due to the small hyperfine structure in the excited state that prevents sub-Doppler cooling mechanisms from working. In ^{40}K, the hyperfine structure is slightly larger, and it is inverted. It therefore represents a much simpler system where sub-Doppler cooling can be effective. Also, our experiment involved a low number of atoms in the trap, so that heating mechanisms that become important for high numbers of trapped atoms are negligible in this case. It is clear, however, that because of the poor signal-to-noise ratio in our data, and the well-known limitations of the release-and-recapture method due to the presence of gravity, this result should be considered only as an indication to be further investigated.

In conclusion, we have captured ^{40}K atoms in a MOT starting from a natural abundance sample. This is a demonstration of the potentialities of laser trapping as a method to study extremely rare isotopes in the presence of other more abundant species. In an optimized trap, we collected $\sim 8\times 10^3$ atoms with a density of about 10^8 atoms/cm^3. The estimated minimum temperature is ~ 50 μK.

The possibility of collecting rare atoms from a natural abundance vapor is of particular interest considering the recently demonstrated methods to trap the atoms in a higher-pressure cell and transfer them into a lower-pressure cell where they can be accumulated [16,17]. We are presently setting up an apparatus based on a double-MOT scheme [18]. ^{40}K atoms will be collected in a first MOT, similar to the one realized in this work, and transferred into a second chamber where they can be accumulated; this will allow us to obtain a larger number of trapped ^{40}K atoms with essentially no background atoms, and eventually to load them into a magnetic trap.

The results of this work can be considered as a first step toward the study of a quantum degenerate gas of fermionic atoms. As already proposed for Li [19], further cooling can be achieved by simultaneously trapping ^{40}K and either ^{39}K or ^{41}K in a magnetic trap and using sympathetic cooling [18], or by producing coexisting ^{40}K subsystems in different hyperfine states. The choice of the right procedure requires, however, the knowledge of collision parameters; some of them have been calculated for ^{39}K and ^{41}K [8] but they are so far unknown for ^{40}K. Another possibility is sympathetic cooling of ^{40}K with a different atomic species, such as rubidium, for which efficient evaporative cooling down to quantum degeneracy conditions is now a well-developed method.

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