Enhanced Loading of ^{40}K from Natural Abundance Potassium Source with a High Performance 2D$^+$ MOT *

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^{40}K is one of the most important atomic species for ultra-cold atomic physics. Due to the extremely low concentration (0.012%) of ^{40}K in natural abundance of potassium, most experiments use 4–10% enriched potassium source, which have greatly suffered from the extremely low annual production and significant price hikes in recent years. Using naturally abundant potassium source, we capture 5.4×10^6 cold ^{40}K atoms with the help of a high performance of two-dimensional magneto-optical trap (2D$^+$ MOT), which is almost three orders of magnitude greater than previous results without the 2D$^+$ MOT. The number of the ^{40}K atoms is sufficient for most ultra-cold ^{40}K experiments, and our approach provides an ideal alternative for the field.

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Laser cooling[1–3] has become the foundational technology of cold atomic physics, which leads to the first realization of Bose–Einstein condensation (BEC)[4–6] of the bosonic atomic isotopes, and the first realization of quantum degeneracy[7] of fermionic atomic species. In recent years, ultra-cold fermionic alkaline atoms has become a highly successful research field. The existence of the long lived and highly controllable magnetic Feshbach resonances[8] allows us to study the BEC-BCS crossover of the fermionic superfluid[9–12] and the Efimov effect in the few-body physics.[13] Even more exciting, the ultra-cold ground states of ^{87}Rb^{40}K[14–16] and ^{23}Na^{40}K[17] molecules were also successfully created from the high rovibrational excited states of Feshbach molecules, and this creation is extremely promising to lead to new discoveries of dipolar quantum gases[18] and new enabling technologies for universal quantum computers.[19]

As one of the only two stable fermionic alkaline isotopes, ^{40}K is a very important kind of atom for cold atom research. Natural potassium is composed of three isotopes: ^{39}K (93.26%), ^{41}K (6.73%), and ^{40}K (0.012%). Due to the extremely low concentration of ^{40}K, an experiment of Tino's group only captured approximately 8000 ^{40}K atoms[20] in the MOT loaded directly from the background vapor pressure of the natural K source, which is not enough for most cold ^{40}K experiments. Huge background pressure of the other potassium isotopes also causes a very large scattering loss of the cold ^{40}K atoms, limiting the trap lifetime of the ^{40}K. Consequently, most of the current ultra-cold ^{40}K experiments are using the isotope enriched ^{40}K source. In these experiments, typically a 4–10% enriched ^{40}KCl is heated to 1400℃ together with metallic calcium in an electrically heated dispenser, and potassium atoms are released from the chemical reaction $2KCl+Ca \xrightarrow{heat} CaCl_2+2K\uparrow$.[21,22] However, the isotope enriched ^{40}K source suffers significantly from the low worldwide production capacity and will be out of stock for years. In the past two years, the price of isotope enriched potassium also increased by a factor of 10. Great success was achieved by using a high-performance Zeeman slower to capture cold ^{40}K in the MIT group, where 5×10^7 cold ^{40}K atoms in the MOT are from natural potassium resource.[23] However, in a Zeeman slower, more than 99% atoms flying out of the oven are wasted before they can be slowed and captured by the 3D MOT. Therefore, it is impossible to use an enriched source in the Zeeman slower, leading to the waste of the potentiality of improving the number of atoms by 3 orders of magnitude.

In this Letter, we report on the trapping of 5×10^6 ^{40}K MOT from a natural potassium source with a high performance 2D$^+$ MOT, which provides a high flux of slow ^{40}K source for the ^{40}K 3D MOT. The number of ^{40}K atoms we captured is larger or comparable with most of the ultra-cold ^{40}K experiments using the sympathetic cooling technology, thus our setup can be used in most future ultra-cold ^{40}K experiments.

The experimental setup is part of our experimental effort in pursuing the ultra-cold NaK molecules. Our setup consists of a 2D$^+$ MOT for potassium, a Zeeman slower for sodium and a long distance magnetic transport belt transferring cold ^{23}Na and ^{40}K from the MOT chamber to the science chamber for evaporative cooling. The slowed ^{23}Na and ^{40}K atomic beams can be simultaneously trapped in the MOT chamber. In our previous work, after magnetic transporting and evaporating in a hybrid trap[24] we have produced more than 1×10^7 ^{23}Na BEC atoms[25] on this machine.

The 2D$^+$ MOT setup for potassium is shown in

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Fig. 1. The main chamber is a $200 \times 60 \times 60\,\mathrm{mm}^3$ cuboid-shaped steel chamber with four large rectangular glass windows ($40 \times 160\,\mathrm{mm}^2$) sealed to the steel chamber by metal indium. To the best of our knowledge, it is the largest window size of 2D$^+$ cooling setup for ^{40}K in the world, allowing us to use a large cooling beam to achieve high performance. The main chamber is connected to a standard CF35 four-way cross, which connects to a 50 L/s diode ion pump (SANJING: 2SP-50 CF63, not shown in Fig. 1), 5 g of natural potassium metal and a CF35 anti-reflective coated viewport. On the other side of this chamber, a 45-degree polished stainless-steel mirror with an elliptical surface (diameters 34 mm and 48 mm) and a hole in the middle is attached to a differential pumping tube. The mirror has a reflectivity of only 70%, but does not react with potassium. The tube intercepts the mirror at its center and has a diameter of 2 mm over a distance of 14 mm, which then widens to 5 mm over a total distance of 13 cm. An all metal inline UHV valve (MIV-150-V) connects the 2D chamber to the 3D MOT chamber, which allows separated baking and trouble shooting.

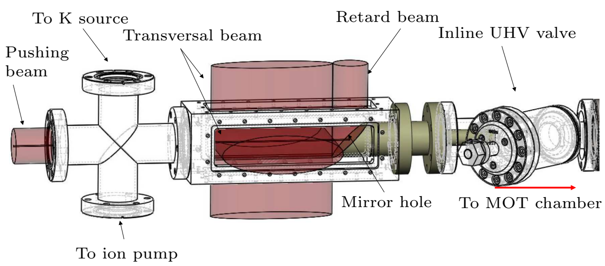

Fig. 1. The sketch of ^{40}K 2D$^+$ MOT. A standard CF35 four-way cross, the main 2D chamber, the differential pumping tube, the polished stainless-steel mirror with a hole in the center, and the all metal inline UHV valve are shown above. Pushing and retarding beams are helpful for pushing the atoms from 2D$^+$ MOT to the octagonal chamber.

Four rectangular shaped coils ($160 \times 60\,\mathrm{mm}^2$, 200 turns) are placed around the rectangular windows to produce the 2D quadrupole field for the 2D$^+$ MOT, generating a maximum transverse gradient magnetic field of 15 Gauss/cm. The current of these four coils can be independently controlled to adjust the transverse zero field position of the magnetic field. In the radial direction, ^{40}K atoms are magneto-optically trapped in the horizontal line of zero magnetic field. Along the axial direction, the mirror has a hole in its center and creates a dark cylindrical region in the retarding beams. Outside the dark cylindrical region, pushing the retarding beam slows down the atoms one way, while inside the region, the only pushing beam pushes the atoms to the 3D MOT chamber.

The natural abundant metal potassium source is placed at 75 cm away from the chamber. The atom source is heated to 100℃, and the temperature of the 2D$^+$ cooling chamber is 70℃. The vapor pressure is also monitored by the Doppler broadened absorption signal of potassium. Because the split of ground state hyperfine energy level of ^{39}K is smaller than the Doppler broadening and the dominant concentration of potassium isotopes is ^{39}K, and therefore the majority of the absorption is contributed from ^{39}K atoms. The potassium vapor pressure (all isotopes) is 2×10^{-7} mbar.

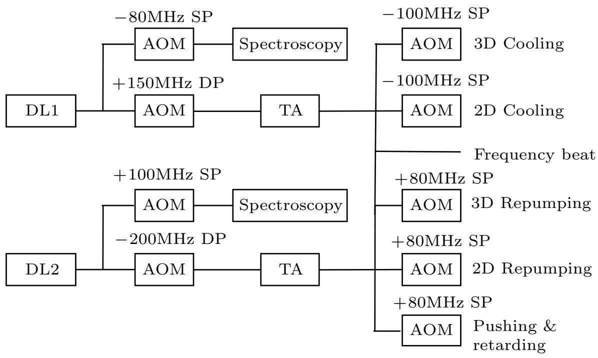

Fig. 2. Laser systems for ^{40}K. The frequency and amplitude of all the beams are controlled by the acousto-optic modulator (AOM) in single pass (SP) and double pass (DP) configuration. TA represents the tapered amplifier. The 2D cooling, 2D repumping and 3D cooling, 3D repumping are lasers for 2D and 3D MOT, respectively (2D Cooling and 2D Repumping are lasers for 2D MOT, while 3D Cooling and 3D Repumping are lasers for 3D MOT). All the beams are coupled into the single mode polarization maintaining fibers.

The cooling beam is generated by diode laser DL1 (Toptica DLC pro), providing 60 mW at 767.7 nm. The frequency stabilization is achieved by locking this laser using saturated absorption spectroscopy. A beam of 30 mW is split from the laser output and injected into a tapered amplifier (BoosTA: 780 L) that delivers 1 W. Similar to the cooling beam, the repumping laser DL2 (Toptica DL pro) provides 50 mW and the light is amplified from 20 mW to 530 mW by another TA (UniQuanta: TAL801). The laser system for ^{40}K is shown in Fig. 2. Cooling and repumping lights sending to 2D and 3D-MOT chambers are combined at the end of the polarization-maintaining single mode fiber, and then they are expanded by spherical and cylindrical telescopes to generate the retro-reflected transverse beams with elliptical cross section ($1/e^2$-diameters: 80 mm and 30 mm). The longitudinal pushing and retarding beams are linearly polarized and have a circular cross section ($1/e^2$-diameters: 15 mm) which is shown in Fig. 1. The power imbalance can be compensated by shifting the position of zero magnetic field.

For our purpose, the essential parameters which characterize the performance of 2D$^+$ MOT are the atom number and loading rate of the ^{40}K MOT. The optimized 2D cooling and repumping powers are 140 mW and 80 mW with the frequency detunings −18 MHz and −15 MHz, respectively. The intensity ratios between the pushing and retarding beam is 7:1, and gradient magnetic field is 4 G/cm.

The experimental sequence is realized by a LabVIEW program based on an NI analog and digital output device. The 8-bit fluorescent pictures are taken by an industry camera (DMK41BU02) triggered by digital signal, and then transferred back to the computer every second. The camera has been calibrated to measure the fluorescence signal precisely. Figure 3 shows the loading process of ^{40}K MOT. In contrast to switching off the 2D$^+$ MOT, the loading rate has been improved by 266 times and 5.4×10^6 atoms can be captured in 1 min when it is on.

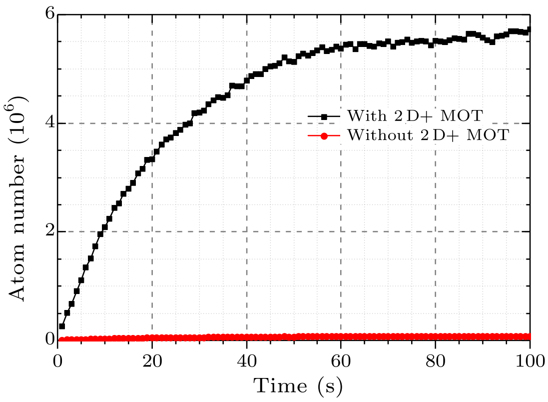

Fig. 3. The ^{40}K MOT atom number as a function of the loading time. The blue triangle line indicates the ^{40}K MOT loading curve with 2D$^+$ MOT working well, while the red star line shows the ^{40}K MOT loading with 2D$^+$ MOT switched off.

In conclusion, we have realized a high performance 2D$^+$ MOT of ^{40}K atoms with natural abundance potassium source, which significantly enhances the loading rate of the ^{40}K 3D MOT. The 2D$^+$ MOT design also separates the UHV MOT chamber from the 2D$^+$ MOT chamber where high density of background ^{39}K and ^{41}K vapor significantly limits the trap lifetime of the cold atoms. Both two advantages are important for ultra-cold ^{40}K experiments. Unlike the fermionic ^{6}Li which has a broad and stable Feshbach resonance to enable direct evaporative cooling in the optical dipole trap, most cooling apparatuses for ^{40}K use sympathetic cooling with another kind of Bosonic atom[26–29] during the cooling process, and the evaporation is carried out on the Bosonic atom and most of the ^{40}K atoms stay in the trap, thus the cooling starts with very few ^{40}K atoms. Here 5.4×10^6 is larger than most of the ^{40}K numbers in those experiments. For experiments which require an extremely large number of ^{40}K atoms, for example, the cold molecule experiment, the 2D$^+$ setup can work in a dual source mode: using a natural abundance source for the laser system testing, spectroscopy measurement etc., and using an enriched source[30] when making a large number of molecules. This is the major advantage of the 2D$^+$ MOT design compared with the Zeeman slower design. The dual source mode could significantly elongate the life span of an enriched source.

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