An Enriched ^{40}K Source for Atomic Cooling *

WEI Dong(卫栋), XIONG De-Zhi(熊德智), CHEN Hai-Xia(陈海霞), ZHANG Jing(张靖)**

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006

(Received 12 October 2006)

We have developed an enriched ^{40}K source used in ^{40}K–^{87}Rb atomic mixture cooling experiment. The enriched ^{40}K source is a home-made dispenser which releases ^{40}K atoms by the redox reaction between ^{40}K enriched KCl and calcium. It is efficient and easy to be made and used. We collect 10^7 ∼10^8 ^{40}K atoms in collection magneto-optical trap. With this dispenser, we perform a quantum degenerate Fermi gas experiment.

PACS: 32. 80. Pj, 39. 10. +j, 03. 75. Ss

In the field of atomic physics, experimental and theoretical studies on quantum degenerate Fermi gas (DFG) and quantum degenerate boson-fermion mixtures (BFM) have attracted much attention in recent years. DFG and BFM present a new path for understanding high-T_c superconductivity and strong interaction, producing ultracold molecules as well as investigating BEC–BCS crossover regime. Because of the Pauli exclusion principle, the S-wave collisions between fermions are prevented in a spin polarized Fermi gas, while higher order partial waves are suppressed at low temperature. Evaporative cooling which is successfully used in achieving BEC cannot be utilized in cooling fermions into quantum degeneracy. In order to circumvent this limitation, two methods have been developed. One is to cool fermions by collisions between different spin polarized states. Two states, $\langle 9/2, 7/2\rangle$ and $\langle 9/2, 9/2\rangle$, of ^{40}K atoms were used in the first achieved DFG.[1] The other is called the sympathetic cooling in which fermions are sympathetically cooled by inter-species collisions between boson and fermion. Boson and fermion may be two different isotopes of the same chemical element or two different chemical elements. Until now, many studies on DFG and BFM have been realized in several combinations of boson and fermion: ^{40}K–^{87}Rb,[2,3] ^{6}Li–^{7}Li,[4−9] ^{6}Li–^{23}Na,[10] ^{6}Li–^{87}Rb.[11] ^{40}K and ^{87} Rb mixtures are selected in our laboratory. The goal of our experiment is to sympathetically cool a gas of fermions ^{40}K down below its Fermi temperature by bosons ^{87}Rb in order to obtain a DFG.

Laser cooling and trapping atoms[12] in a vapour cell is popularly used with magneto-optical traps (MOT) because of its relatively simple apparatus. In the MOT apparatus, the atomic source usually is a reservoir containing a small amount of alkali metal or a dispenser releasing alkali metal by redox reaction. The alkali atom vapour pressure can be controlled by heating or cooling the reservoir or by controlling the passing current through the dispenser. In our experimental apparatus, the rubidium source is a reservoir containing 5 g pure rubidium metal (natural abundance 72.2% ^{85}Rb, 27.8% ^{87}Rb), which was sealed in a vacuum system and separated from the MOT chamber by a valve. The natural potassium source is unacceptable for the experiments because the low abundance of the isotope ^{40}K (natural abundance is 93.26% ^{39}K, 0.012% ^{40}K, 6.73% ^{41}K) limits the collected atom number in MOT. Using a natural source, only 10^3 ^{40}K atoms were trapped in MOT in the past.[13,14] Enriched ^{40}K is available in the form of potassium chloride (KCl) rather than pure metal. The enriched ^{40}K dispensers are not available commercially (the naturally available potassium dispensers may be obtained from SAES Getters[15]). Thus, it was necessary to construct a ^{40}K source in house. In the first DFG experiment, DeMarco *et al.*[16] developed an enriched potassium source using the dispenser and collect 10^8 ^{40}K atoms in a vapour cell MOT. This method has been popularly used in many groups. In this study, we build an enriched ^{40}K dispenser based on SAES getters and Refs. [16,17]. Enriched ^{40}K in the form of KCl is very expensive, so it is important to build an efficient dispenser.

The dispensers use a redox reaction between an alkali metal chromate and a reducing agent to deliver pure alkali metal. The alkali metal is released by passing current through the dispenser and thus heating it by Ohmic heat. In our experiment, we use ^{40}K enriched KCl plus calcium (Ca) to generate potassium by redox reaction. The react equation can be written as

$$2\mathrm{KCl} + \mathrm{Ca} \xrightarrow{\mathrm{heat}} 2\mathrm{K} + \mathrm{CaCl_2}. \quad (1)$$

The condition of this reaction is under the certainly high temperature inside a vacuum chamber. The

* Supported in part by the National Basic Research Programme of China under Grant No 2006CB911101, the National Natural Science Foundation of China under Grant No 60678029, the Programme for New Century Excellent Talents in University under Grant No NCET-04-0256, and the Doctoral Foundation of the Ministry of Education of China (No 20050108007).

** To whom correspondence should be addressed. Email: jzhang74@yahoo.com or jzhang74@sxu.edu.cn

reservoir of our dispenser is made of 0.125 mm thin nichrome (80% nickel, 20% chrome). The nichrome is chemically inert and behaves well at high temperatures, which was successfully used in Refs. [16,17] and commercial dispensers. The design of the reservoir in our experiment shown in Fig. 1 is quite different from the dispensers described in Refs. [16,17]. Two trenches are made symmetrically in the two sides of line1 and fold over line1, then fold back two sides of the trench and spot weld. Spot welding is a popular method used for joining sheet metal parts. The material to be welded is clamped between two copper electrodes of spot welding machine, a small 'spot' that is quickly heated to the melting point after the current is flowed, forming a nugget of welded metal. In this design, the reservoir has not only more space to contain enough reactants, but also a slit on the top of the two trenches for loading reactants and releasing atoms. The slit is upward for preventing escape of the reactants and big enough for the releasing ^{40}K atoms. The leads are cut directly from the sheet of nichrome. On the end of the lead, a hole is made to be used to combine the dispenser with the electrode. The two dispensers are spot welded on a common cathode and can be used one after another. The two dispensers are placed on a CF35 flange electrical feedthroughs, as shown in Fig. 2.

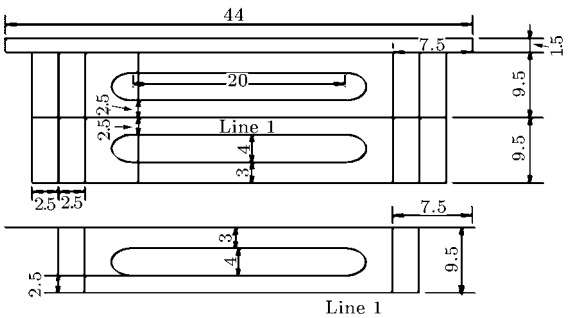

Fig. 1. Schematic of the enriched ^{40}K dispenser. The top drawing is dispenser planning sketch. Two trenches are made symmetrically in the two sides of line1 and folded over line 1, then fold back two sides of the trench and spot welded. Note that the unit of length is millimetre and the depth of the two trenches is approximately 2 mm. The lower drawing is dispenser in side view.

The reaction materials used in this chemical reaction, Ca and KCl, need powder form and are mixed uniformly. The high purity Ca is in the dendritic form and the KCl is in small granular form. The works that convert reaction material into powder form and mix them are accomplished in a glove box which is pumped by a turbo and then filled with high purity argon. The reason is that Ca reacts strongly with the oxygen and humidity in air to produce calcium hydroxide. Ca is filed using the metal file and then sieved through a copper mesh (100 mesh). Creating powdered Ca is a difficult work. On the one hand, Ca is soft and ductile. It becomes more soft and does not flake off easily because heat is created during the filing process. On the other hand, a piece of dendritic Ca is easily split into several small pieces. We use the tweezers to hold a piece and file it once by once instead of a to and fro movement so as to reduce the heat due to friction. KCl crystals are crushed in a mortar with a pestle. The ^{40}K enriched KCl[18] contains 6.2% ^{40}K, 64.47% ^{39}K and 29.33% ^{41}K. KCl is easy to be crushed into very thin powder so it does not need to be sieved through a mesh. We take out the required amount of Ca powder and put it into the mortar according to 2:1 volume ratio of Ca to KCl, then mix them uniformly. We carefully take some mixtures using a measuring spoon and load the reactants into the reservoir from the top slit of the dispenser. When the dispenser is fully filled, we use the tweezers to reduce the slit until it is small enough to prevent the escape of the solid reactants.

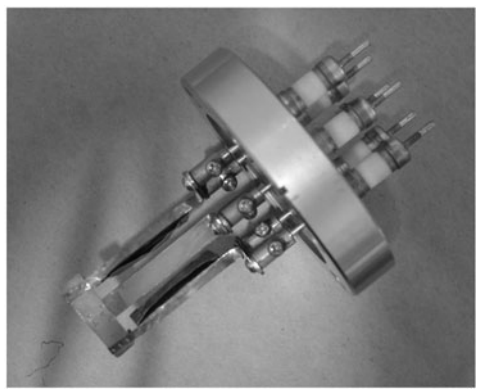

Fig. 2. Two dispensers with a common cathode on a vacuum flange.

We fabricate several dispensers according to the above process and test them for obtaining detailed information. First, we determine the relationship between the temperature of the dispenser and the passing current. A thermocouple is attached to a dispenser and they are required to contact well each other. The thermocouple is connected to the CF35 flange electrical feedthroughs. This can help us determine the dispenser temperature inside the vacuum. The dispenser is sealed in a simple vacuum system with pressure less than 10^{-4} Pa by a turbo pump. Figure 3 shows the temperature versus current. Then, we fabricate a natural abundance K dispenser for practicing the entire constructing process and testing the efficiency of dispensers. For unenriched dispenser, Ca, purity 99.5% and KCl, ultra-dry, purity 99.998% are used. The unenriched dispenser is placed in a simple vacuum system which is a CF four-way crosses as shown in Fig. 4. A pair of windows provide access for the laser beam. The vacuum pressure reaches less than 10^{-4} Pa by a turbo pump. We use the saturated absorption spectroscopy (SAS) apparatus to detect the released K atoms. An external cavity diode

laser (ECDL) (Toptica DL100) is used with the wavelength near 767 nm. We adopt a counter-propagating scheme. The forward laser beam serves as the pump field and the retro-reflected laser beam as probe is focused into the photodiode. The frequency of the laser is scanned across the ^{39}K atomic D_2 transition line. The four-way crosses is heated to 50°C using thermocoax for preventing the released K atom condensation on the wall. The valve is opened and the vacuum system is pumped continuously by the turbo. With a 6 A current passing the dispenser, a natural abundance K SAS is observed as shown in Fig. 5. The SAS signal drops to half the amplitude of the beginning after four hours with the dispenser burning for 10 min. With the successful experience, an ^{40}K enriched dispenser is constructed and installed in the experimental vacuum system. In order to make the ^{40}K enriched dispenser having a good efficiency, Ca with the purity 99.99% is used. Each dispenser contains about 15 mg KCl. The two CF35 flanges with dispensers are installed onto a CF tees. When all of work has been carried out, we open the glove box and take out the CF Tees. The following work is to install the CF Tees in the vacuum system. In order to prevent reactant contact with

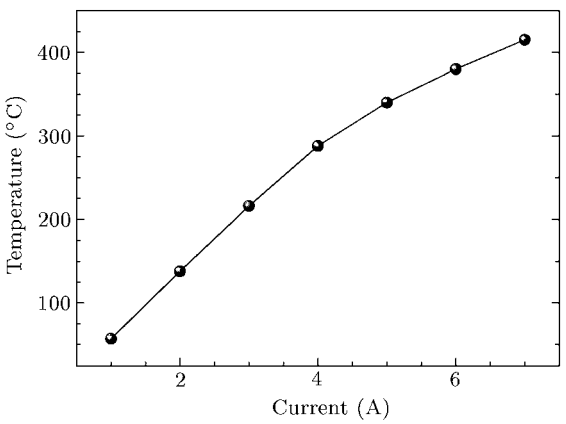

Fig. 3. The relationship between the dispenser's temperature via the passing current.

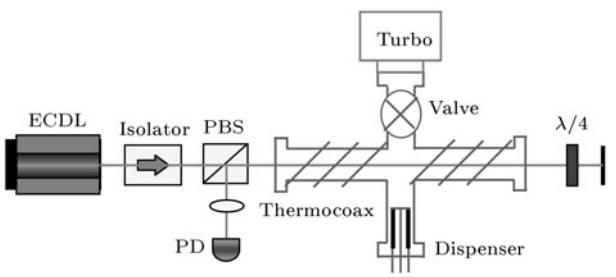

Fig. 4. Experimental setup for saturated absorption spectroscopy in vapour cell with dispenser.

air, an operation plastic bag is used. We place all required tools and CF tees with dispensers into the plastic bag, then connect the plastic bag with the vacuum system. Letting the argon gas pump the bag continuously, until the air is exhausted and the argon is full filled, we remove the covered flange and install the CF Tees into the vacuum system. We fire one of our enriched sources in the vacuum system and observe the SAS, in which ^{40}K transition lines can be seen clearly as shown in Fig. 6.

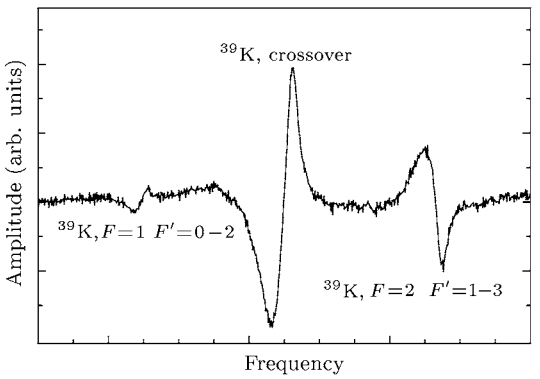

Fig. 5. The experimental results of saturated absorption spectroscopy for natural abundance K dispenser.

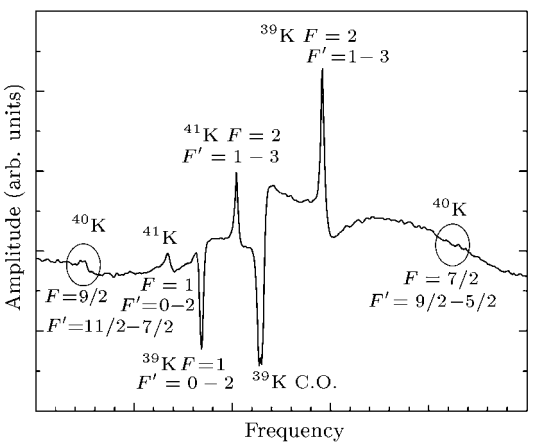

Fig. 6. The experimental results of saturated absorption spectroscopy for ^{40}K enriched dispenser. The places labelled by circles are two absorption lines for the fermion isotope ^{40}K.

In order to test our source efficiency, we cool and trap ^{40}K atoms in collection chamber from the background vapour released by our enriched dispenser. The vacuum pressure dropped to 2×10^{-6} Pa when the dispenser is fired. The trapping beams are red-detuned 14 MHz from $4^2S_{1/2}$ $F = 9/2 \rightarrow 4^2P_{3/2}$ $F' = 11/2$, and each beam is with the power 15 mW. The re-pump light is red-detuned 11.2 MHz from the $4^2S_{1/2}$ $F = 7/2 \rightarrow 4^2P_{3/2}$ $F' = 9/2$. All of beam diameter is 25 mm and the configuration of the MOT is three retro-reflected laser beams. More detailed information can be found in Ref. [19]. The magnetic field is 9 Gcm^{-1}. We have obtained the atom number of approximately 10^7–10^8. Figure 7 presents a photo of

^{40}K MOT.

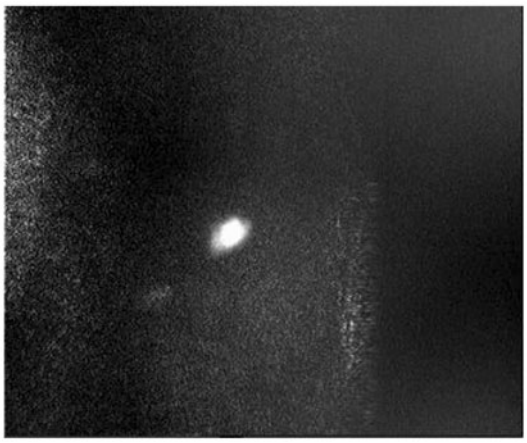

Fig. 7. The MOT performed using ^{40}K enriched dispenser. The atom numbers approximately $10^7 \sim 10^8$ are monitored by calibrated fluorescence detection.

In summary, we have constructed and installed an enriched ^{40}K source in a vacuum system. The dispenser is efficient and easy to be made and used. With this source, we can perform DFG and BFM experiments.

References

[1] DeMarco B and Jin D S 1999 *Science* **285** 1703
[2] Roati G, Riboli F, Modugno G et al 2002 *Phys. Rev. Lett.* **89** 150403
[3] Aubin S, Myrskog S, Extavour M H T et al 2006 *Nature Physics* **2** 384
[4] Schreck F, Khaykovich L, Corwin K L et al 2001 *Phys. Rev. Lett.* **87** 080403
[5] Bourdel T, Khaykovich L, Cubizolles J et al 2004 *Phys. Rev. Lett.* **93** 050401
[6] Zhang J, Van Kempenc E G M, Bourdel T et al 2004 *Phys. Rev.* A **70** 030702
[7] Truscott A G, Strecker K E, McAlexander W I et al 2001 *Science* **291** 2570
[8] Granade S R, Gehm M E, OHara K M and Thomas J E 2002 *Phys. Rev. Lett.* **88** 120405
[9] OHara K M, Hemmer S L, Gehm M E et al 2002 *Science* **298** 2179
[10] Hadzibabic Z, Stan C A, Dieckmann K et al 2002 *Phys. Rev. Lett.* **88** 160401
[11] Silber C, Gunther S, Marzok C et al 2005 *Phys. Rev. Lett.* **95** 170408
[12] Li X L, Ke M, Tang J Y et al 2005 *Chin. Phys. Lett.* **22** 2526
[13] Williamson III R S 1997 *PhD dissertation* (University of Wisconsin-Madison)
[14] Cataliotti F S, Cornell E A, Fort C et al 1998 *Phys. Rev.* A **57** 1136
[15] Alkali metal dispenser is available from SAES Getters http://www.saesgetters.com
[16] DeMarco B, Rohner H and Jin D S 1999 *Rev. Sci. Instrum.* **70** 1967
[17] McKay D *Summer 2004 Report* 16 October 2004
[18] Different abundance ^{40}K enriched KCl is available from Trace Sciences International Inc. www.isotopetrace.com
[19] Wei D, Chen H X, Xiong D Z et al 2006 *Acta Phys. Sin.* **55** 6342 (in Chinese)