Quantum degenerate Bose–Fermi atomic gas mixture of ^{23}Na and ^{40}K

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We report a compact experimental setup for producing a quantum degenerate mixture of Bose ^{23}Na and Fermi ^{40}K gases. The atoms are collected in dual dark magneto–optical traps (MOT) with species timesharing loading to reduce the light-induced loss, and then further cooled using the gray molasses technique on the D_2 line for ^{23}Na and D_1 line for ^{40}K. The microwave evaporation cooling is used to cool ^{23}Na in $|F=2,m_F=2\rangle$ in an optically plugged magnetic trap, meanwhile, ^{40}K in $|F=9/2,m_F=9/2\rangle$ is sympathetically cooled. Then the mixture is loaded into a large volume optical dipole trap where ^{23}Na atoms are immediately transferred to $|1,1\rangle$ for further effective cooling to avoid the strong three-body loss between ^{23}Na atoms in $|2,2\rangle$ and ^{40}K atoms in $|9/2,9/2\rangle$. At the end of the evaporation in optical trap, a degenerate Fermi gas of ^{40}K with 1.9×10^5 atoms at $T/T_F=0.5$ in the $|9/2,9/2\rangle$ hyperfine state coexists with a Bose–Einstein condensate (BEC) of ^{23}Na with 8×10^4 atoms in the $|1,1\rangle$ hyperfine state at 300 nK. We also can produce the two species mixture with the tunable population imbalance by adjusting the ^{23}Na magneto–optical trap loading time.

Keywords: ultracold gases, degenerate Bose–Fermi mixture

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1. Introduction

Quantum degenerate gases mixture composed of different species provides an ideal physical platform for studying strongly correlated many-body physics in a clean and well-controlled environment.[1] The existence of the specific parameter of the interplay between the inter- and intra-interactions provides the rich and various subjects, compared to the single species experiment, such as ultracold chemistry,[2–4] fermionic heteronuclear molecules,[5] precision measurement,[4] dual superfluidity,[6] vortices in superfluids,[7] polaron physics,[8,9] fermion-mediated long-range interactions between bosons,[10,11] and so on. To date, many different kinds of Bose–Fermi gas mixtures have been cooled to quantum degeneracy, including ^{6}Li–^{7}Li,[12,13] ^{87}Rb–^{40}K,[14] ^{23}Na–^{6}Li,[15] ^{87}Rb–^{6}Li,[16] ^{3}He–^{4}He,[17] ^{173}Yb–^{174}Yb,[18] ^{87}Sr–^{84}Sr,[19] ^{6}Li–^{174}Yb,[20,21] ^{40}K–^{23}Na,[22] ^{87}Rb–^{171}Yb,[23] ^{41}K–^{6}Li,[7] ^{174}Yb–^{6}Li,[24] ^{6}Li–^{133}Cs,[25] and ^{6}Li–^{84}Sr.[26]

The ultracold Bose–Fermi mixture of ^{23}Na and ^{40}K atoms with rich Feshbach resonances has attracted enormous attention, such as forming the fermionic ground-state ^{23}Na^{40}K molecules with a large electric dipole moment of 2.72 Debye and the special property of chemical stability,[27–29] and creating the Bose polarons near quantum criticality in the unitary regime.[30,31] The prospect is exciting, nevertheless cooling the mixture to the nanokelvin regime is more difficult than single atomic species. There are many problems that prevent the effective cooling of the mixture to quantum degeneracy. Firstly, the light-assisted loss in the loading stage of two species magneto–optical trap (MOT) results in a shorter lifetime and less number of the mixture. Secondly, the background triplet scattering length of interspecies between ^{23}Na and ^{40}K is large with $\approx -824.7(30)a_0$[32,33] and induces less efficiently sympathetic cooling in the magnetic trap than other mixtures.[22,34] Thirdly, due to the temperature-dependent three-body loss, ^{23}Na and ^{40}K atoms in the low field seeking stretched states $|2,2\rangle$ and $|9/2,9/2\rangle$ in the magnetic trap were not able to be effectively cooled to quantum degeneracy. Lastly, the spin relaxation of the mixture of ^{40}K in $|9/2,9/2\rangle$ and ^{23}Na in $|1,-1\rangle$ is strong, which makes it impossible to coexist in the magnetic trap.

In this paper, we present a compact vacuum system without the standard Zeeman slower and an optimized cooling route for preparing the quantum degenerate atoms mixture of ^{23}Na and ^{40}K in an optical dipole trap, and demonstrate that ^{23}Na atoms could be an efficient coolant for sympathetic cooling of ^{40}K atoms. In order to tackle the above mentioned problems, we use state-of-the-art cooling techniques in the experiment. Dual dark MOTs and timesharing loading of two species are used to reduce the light-induced loss in the MOT loading stage as much as possible. To effectively cool the mixture before loading atoms into the magnetic trap, the gray molasses technology on D_1 line for ^{40}K and on D_2 line for ^{23}Na are used to provide a good start point for the further evaporation cooling. The pre-cooling of the mixture is done by microwave (MW) evaporation of ^{23}Na to 12 μK in an optically plugged magnetic trap with ^{40}K in $|9/2,9/2\rangle$ and ^{23}Na atoms in $|2,2\rangle$. In order to reduce the three-body loss between

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atoms in this forced evaporation process, the magnetic field gradient is reduced simultaneously to reduce the atoms peak density. At last, both species are transferred into a large volume, far-detuned optical dipole trap (ODT) at the end of MW evaporation and prepared ^{40}K in $|9/2,9/2\rangle$ and ^{23}Na atoms in $|1,1\rangle$ quickly. After an evaporation of 5 s in an optical trap, we prepare a degenerate Fermi gas of ^{40}K in $|9/2,9/2\rangle$ with 1.9×10^5 atoms at T/T_F=0.5, and a sample of ^{23}Na atoms in $|1,1\rangle$ with 8×10^4 in BEC and 1.5×10^5 thermal atoms at a temperature of 300 nK.

2. Experiment setup

2.1. Vacuum setup

The vacuum system of the experimental apparatus is shown in Fig. 1(a), which has been used to create BEC of ^{23}Na.[35–38] The vacuum setup is composed of two parts connected through a differential pumping tube with internal diameter of 6 mm and length of 190 mm. The first part is for a two-dimensional (2D) magneto–optical trap (2D-MOT) which is devoted to the atomic source with a pre-cooling stage with a background pressure of 1×10^{-7} Pa maintained by an ion pump with a pumping speed of 40 L/s. The two species atoms are loaded in the independent vacuum chambers. A stainless steel square chamber for ^{40}K and a metallic stainless steel 316 L octagonal cavity for ^{23}Na are connected in series. The second part is an ultrahigh vacuum science chamber, which is composed of a quartz glass cell with a background pressure of 9×10^{-10} Pa maintained by an ion pump with a pumping speed of 150 L/s. Here, the ^{23}Na and ^{40}K are trapped in a two-species dark MOT and then cooled in an optically plugged magnetic trap and an optical dipole trap in sequence.

The Na oven is heated to 200 °C for the sodium source and the K oven at 50 °C, resulting in the background pressure increasing to 2×10^{-7} Pa in the first vacuum part. To prevent atoms from sticking to the walls and glass windows of the vacuum chamber, all viewports of the Na 2D chamber are heated at $\sim$ 70 °C.

The ^{40}K atoms in 2D-MOT are collected from the background gas. In order to increase the background pressure and prevent atoms from sticking to the glass windows, the entire K 2D chamber is heated at $\sim$ 50 °C, and at the same time, we use ten light-emitting diodes (LEDs) to emit light at nearly 405 nm (NCSU233B, Nichia Corp.) for light-induced atomic desorption on the glass windows. The LEDs are mounted on a heat sink around the K 2D chamber and each LED emits about 1.4 W of light power. This light-induced desorption technique has been successfully used in the experiments of quantum gas for ^{87}Rb,[39,40] ^{133}Cs,[41] ^{40}K,[42] ^{7}Li,[43] and ^{23}Na.[44,45]

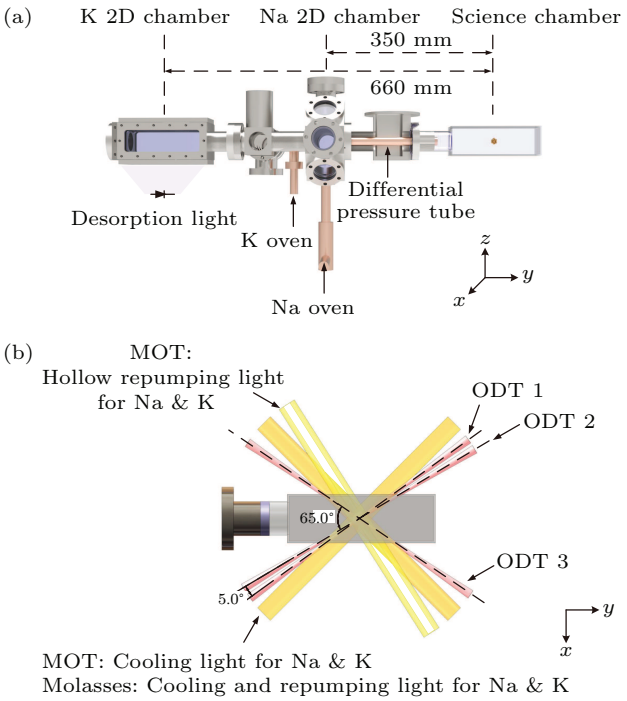

Fig. 1. (a) Front view of the compact vacuum system for the production Bose–Fermi quantum degenerate, consisting of two major parts: 2D-MOT chamber of ^{23}Na and ^{40}K and a glass science chamber. (b) Top view of the glass science chamber with the optical setup, which collects atoms in the 3D-MOT by six overlapped cooling light beams and a hollow repumping beam and is used for the gray molasses by the light beams with cooling and repuming frequency. The far-off resonant 1064-nm crossed optical dipole trap is consisted of three laser beams (ODT 1, ODT 2, and ODT 3) in the x–y plane.

2.2. Laser setup system

In this section, we briefly describe the laser systems designed for potassium atoms on D_2 line and D_1 line. The sodium laser system has been described in our previous works.[35–37] The laser frequencies for double dark three-dimensional (3D) MOT of Na and K atoms and the gray molasses cooling of K atoms on D_1 line are shown in Fig. 3(a).

A layout of the ^{40}K laser setup is presented in Fig. 2. In order to overlap perfectly the laser beams on D_1 line for gray molasses cooling with D_2 line for MOT trapping, the injection locking laser frequency technique is used. Two master lasers are used in experiment, one operating at $\lambda = 766.7$ nm, which is locked at the D_2 transition of ^{39}K $4\,^2S_{1/2}\,|F=1\rangle \rightarrow 4\,^2P_{3/2}\,|F''=0-2\rangle$ crossover signal via absorption spectroscopy, the other operating at $\lambda = 770$ nm, and is locked at the D_1 line transition of ^{39}K, $4\,^2S_{1/2}\,|F=1\rangle \rightarrow 4\,^2P_{1/2}\,|F'=2\rangle$. Thanks to the ground state hyperfine splitting of 1285.8 MHz of ^{40}K, the required repumping and cooling frequencies could be obtained by means of acousto–optic modulators (AOMs). The AOMs are used as the frequencies tuners and fast switchers on the nanosecond timescale, which could meet the requirement on the fast frequency handoff of the slaver lasers from D_2 line to D_1 line.

Using the injection locking laser frequency technique, the

slave laser frequency follows the chosen injection laser beam on D_1 or D_2 line from two master lasers using a polarization beam splitter (PBS). Then the output laser beam from slave cooling laser is amplified by a tapered amplifier (TA). And the repumping beam have a similar setup. The amplified laser beams are delivered to 2D and 3D dark MOTs. The laser beams for 3D dark MOT include six cooling beams and one repumping beam by seven polarization maintaining optical fibers and expanded $1/e^2$ diameter to 25 mm, as shown in Fig. 1(b).

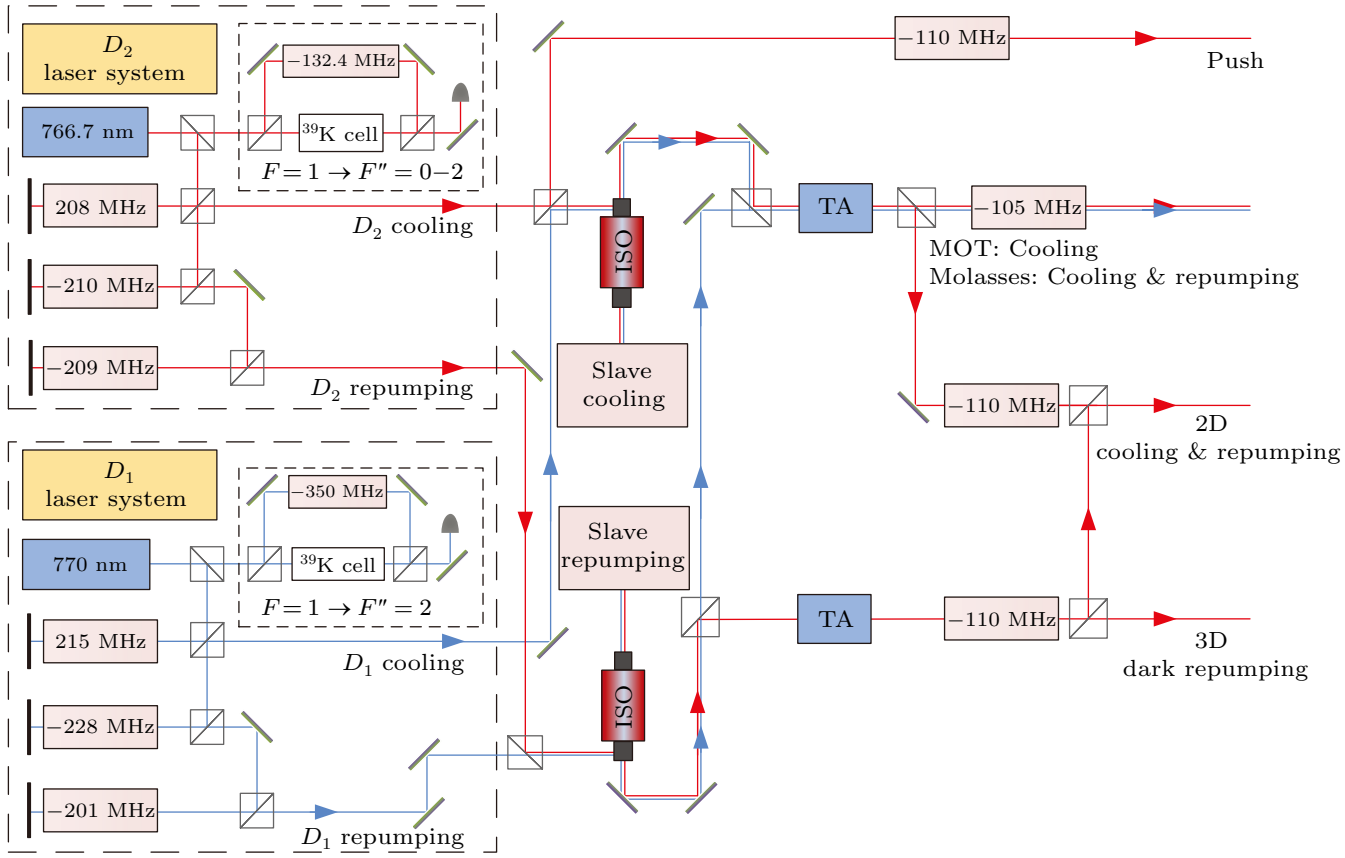

Fig. 2. The optical setup of the D_1 and D_2 line laser systems for ^{40}K.

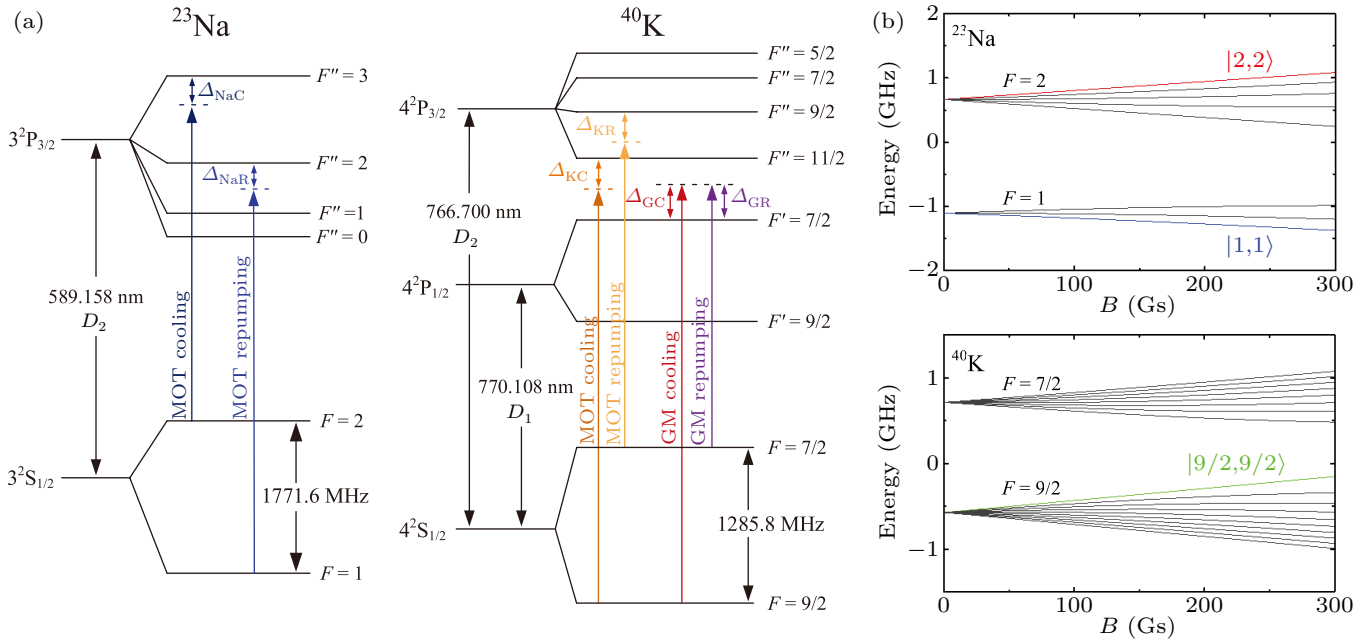

Fig. 3. (a) Energy level diagram for ^{23}Na and ^{40}K. The Δ_{NaC} and Δ_{NaR} are the detunings of the cooling and dark repump laser shown in the D_2 line of ^{23}Na. The Δ_{KC} and Δ_{KR} are the detuning of the cooling and dark repump laser from the atom transition in the D_2 line (766.7 nm). The Δ_{GC} and Δ_{GR} are the GM cooling and repump laser detuning from the atom transition in the D_1 line (770 nm). (b) The ground-state hyperfine structure of ^{23}Na and ^{40}K in an external magnetic field. The spin states prepared in the experiment are highlighted through color. The unit 1 Gs = 10^{-4} T.

3. Dual species dark MOT and gray molasses

The ^{40}K atoms are collected from a 2D MOT. Two pairs of rectangular coils around the vacuum chamber generate a magnetic field gradient of about 9 Gs/cm for 2D MOT. The cooling beams with red detuned frequency 10 MHz from the $|F=9/2\rangle \rightarrow |F=11/2\rangle$ transition and repumping beam with red detuned frequency 4 MHz from the $|F=7/2\rangle \rightarrow |F=9/2\rangle$ transition are used for ^{40}K. The ^{40}K atoms are pushed to the science chamber by a push beam with blue detuning of 5 MHz along the y direction about 660 mm from 2D MOT to 3D MOT. The 2D MOT for ^{23}Na has been described in our previous works.[35–37] The ^{23}Na atoms are pushed to the science chamber by a push beam with a distance of about 350 mm from 2D MOT to 3D MOT.

In the science chamber, the ^{23}Na and ^{40}K atoms are collected by the dark MOT of two species. For the operation of dark-spot MOT, six cooling beams combining ^{23}Na with ^{40}K light counter-propagate in pairs and are orthogonal to each other in three directions. A single repumping beam with a black spot of 10-mm diameter at the beam center is applied, where two species' repumping laser beams are overlapped through dichroic mirrors, as shown in Fig. 1(b). This method could create a dark regime in the center of MOT, where the atoms of ^{23}Na and ^{40}K stay at the dark ground states $|F=1\rangle$ and $|F=7/2\rangle$. Therefore, the light-assisted loss in the two species' MOT is reduced significantly. The quadrupole magnetic field with a gradient of 9.5 Gs/cm along the z direction, generated by a pair of coils in the anti-Helmholtz configuration, is used for loading atoms in the 3D MOT.

In order to overcome the light-assisted loss in two species MOT,[46] there are many techniques developed for the mixture of ^{23}Na and ^{40}K atoms, such as the dark MOT of two species, two-stage MOT loading approach,[47] and mismatch of the atomic cloud position of two species realized by slight displacement of the MOT laser beams.[48] In our experiment, we could not observe any ^{40}K atoms after two species loading in the dual-species dark MOT of 30 s at the same time, which maybe due to the enhanced loss from the same loading road from 2D MOT to 3D MOT. Benefiting from the faster loading rate of Na than K, we use a timesharing loading technique for the two-species atoms, firstly only loading K for 50 s and then loading Na in the last 4.5 s. The time sequence is shown in Fig. 4(a).

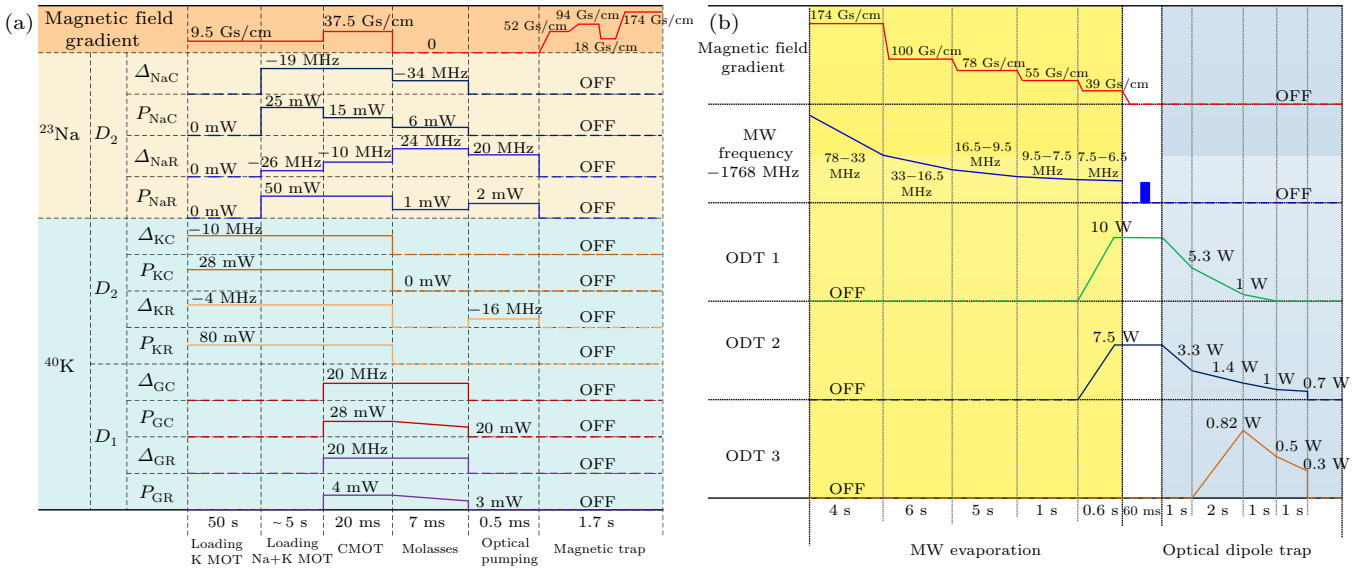

Fig. 4. Experimental sequence for the loading processes (a) and the evaporation (b).

Generally, the dark MOT could capture more dense atoms than bright MOT, and then is followed directly with the optical molasses in sequence.[49,50] In our experiment, we optimized the following cooling steps after the dark MOT loading stage. A quick transfer process to bright MOT of ^{23}Na is accomplished in 10 ms, and then a compressed MOT (CMOT) step is followed during 20 ms by increasing the magnetic field gradient to 37.5 Gs/cm and changing the power and detuning of the cooling and repumping light. For ^{40}K atoms, a hybrid D_1–D_2 technique is implemented.[51] The slave repumping laser is switched to be injected into TA with the slave cooling laser together, which corresponds to the bright MOT configuration for ^{40}K. The frequencies and powers of the lasers are shown in Fig. 4(a).

An optical molasses step follows the CMOT step. The six beams are switched to carry the ^{23}Na and ^{40}K cooling and repumping light simultaneously and the single repumping beam with a black spot is switched off. The magnetic field has been turned off 1 ms in advance. The ^{23}Na atoms are cooled to 56 μK in 7 ms by the gray molasses of D_2 line. This technology has been used in Refs. [35,52]. The ^{40}K atoms are cooled to about 20 μK during the same time by the gray molasses

of D_1 line,[53] in which both frequencies of cooling and repumping laser, are blue detuning ($\Delta_{GC} = \Delta_{GR} = 20$ MHz) that form Λ-type three-level system, as shown in Fig. 3(a). The cooling/repumping intensity ratio is optimized at about 7:1 by measuring the loading rate in the optically plugged magnetic trap. The laser power and duration time are given in Fig. 4(a).

4. Precooling in an optically plugged magnetic quadrupole trap

To effectively load the two species mixture into the magnetic trap for further cooling, an optical pumping stage of 0.5 ms is used to prepare the atoms in the double spin-polarized states. We prepare the mixture in the hyperfine ground state $|2,2\rangle$ for sodium and $|9/2,9/2\rangle$ for potassium by using a circularly polarized light on the $|F=2\rangle \rightarrow |F''=2\rangle$ and $|F=9/2\rangle \rightarrow |F''=9/2\rangle$ transition respectively. At the same time, about 1-Gs homogeneous magnetic field is applied along the y direction.

After the spin state preparation, the magnetic field gradient of the quadrupole magnetic trap is ramped from 0 Gs/cm up to 52 Gs/cm in 10 ms, then up to 94 Gs/cm for 500 ms and holds on 20 ms for thermalization. Then it is reduced to 18 Gs/cm in 200 ms and holds this value on 500 ms for spin-purification to remove the ^{23}Na atoms in $|2,1\rangle$ and $|2,0\rangle$. Because the spin exchange collision between two states induces the atoms heating strongly.[47]

$$\begin{aligned} &^{23}\mathrm{Na}(F=2,m_F=1) + {}^{23}\mathrm{Na}(F=2,m_F=0) \\ \rightarrow\ &^{23}\mathrm{Na}(F=2,m_F=2) + {}^{23}\mathrm{Na}(F=2,m_F=-1). \end{aligned} \quad (1)$$

In this process, the magnetic field gradient can only hold the sodium atoms in $|2,2\rangle$ state, the atoms at other hyperfine states leave the trap in the direction of the gravity, which prevent the spin collision relaxation and heating process in the atoms sample. In this step, the potassium atoms can not be influenced because of the larger magnetic moment.

The trap gradient is then again increased to 174 Gs/cm in 500 ms to compress the atoms sample for effective elastic collision in the following MW forced evaporation. At the end of this stage, a plug laser beam operating on 532 nm of 18 W with $1/e^2$ radius of 35 μm provides a potential barrier of about 615 μK in the center of the magnetic quadrupole trap to prevent the Majorana losses at the zero magnetic field regime. At this time, the optically plugged magnetic quadrupole trap is created.

After a thermalization of 100 ms, the mixture is cooled with 16.6 s by MW forced evaporation ^{23}Na in the optically plugged magnetic trap, where the transition of ^{23}Na $|2,2\rangle \rightarrow |1,1\rangle$ is used for evaporation. Thermal ^{23}Na atoms in $|2,2\rangle$ state are removed from the trap by coupling to the high field seeking state $|1,1\rangle$, while ^{40}K atoms are sympathetically cooled by elastic collisions with ^{23}Na atoms.

Figure 5 shows the MW field scheme for evaporation of Na transition from $|2,2\rangle$ state to the untrapped hyperfine state $|1,1\rangle$. Two signal generators are used to create the MW field between 1.77 GHz–1.85 GHz by mixing a fixed MW signal of 1.768 GHz (from N5183B, Keysight Corp.) with a tunable RF signal (from 33250A, Keysight Corp.). A mixer (ZX05-U432H-S-4+, Mini-Circuits Corp.) is used for the frequency up-converter to generate the MW field for evaporation. The MW signal passes through a broadband switcher (F9114A, General Microwave Corp.), then is amplified to a maximum output power of 30 W by an amplifier (MPA-1600-2000-30, Micotop Corp.), and then sent to a home-build single-loop antenna made of copper bar. In order to protect the amplifier, a circulator is connected in series with the antenna.

In experiment, we also tried the RF evaporative cooling in optically plugged magnetic quadrupole trap for comparison, but found stronger loss which is mainly attributed to the strong inelastic collision of $|9/2,9/2\rangle$ for potassium and $|2,1\rangle$ hyperfine ground state for sodium.

How to obtain high atoms density is a challenge in evaporation by balancing enough elastic collision for cooling with the three-body loss of the mixture of Na–K. The elastic collision rate of Na–Na and Na–K for the thermalization process in evaporation is dependent on the atoms density, and the three-body loss rate is also proportional to the density of the mixture $n(\boldsymbol{r},t)_{\mathrm{Na}}$ and $n(\boldsymbol{r},t)_{\mathrm{K}}$. The three-body collision can be characterized by a loss rate coefficient β_{NaK}, which depends on the microscopic behavior of the collision process[54,55]

$$\frac{\mathrm{d}N_{\mathrm{Na}}(t)}{\mathrm{d}t} = 2\frac{\mathrm{d}N_{\mathrm{K}}(t)}{\mathrm{d}t} = -\beta_{\mathrm{NaK}}\int \mathrm{d}\boldsymbol{r} n(\boldsymbol{r},t)^2_{\mathrm{Na}} n(\boldsymbol{r},t)_{\mathrm{K}}. \quad (2)$$

By optimizing the evaporation efficiency of the atoms mixture, we design five magnetic gradient decompress steps from 175 Gs/cm to 39 Gs/cm in the entire cooling process to reduce three-body loss. The time sequence is shown in Fig. 4(b). At this moment, we have prepared an atomical sample of ^{40}K atoms at $|9/2,9/2\rangle$ state of 4.5×10^5 and ^{23}Na atoms at $|2,2\rangle$ state of 2.5×10^7 at 12 μK. The three-body loss evidently increases below 10 μK and prevents the mixture from further cooling to the nK regime in the magnetic trap. The good solution is to further cool the mixture to degenerate in ^{40}K $|9/2,9/2\rangle$ and ^{23}Na $|1,1\rangle$ state in an optical trap.

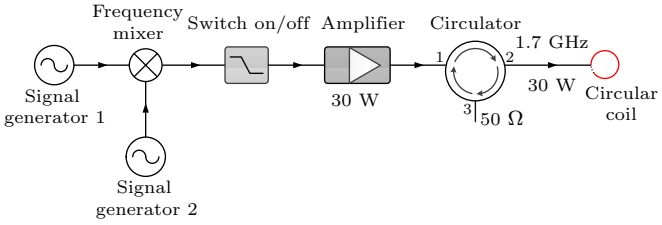

Fig. 5. Sketch of the MW setup used for the evaporation in the magnetic trap and state preparation.

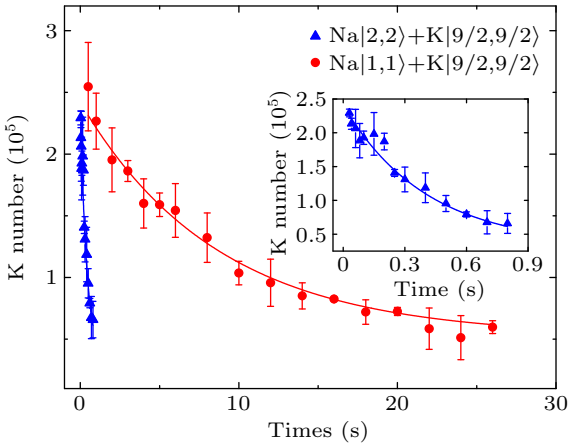

Fig. 6. The lifetime of the ^{40}K atoms with ^{23}Na atom in $|2,2\rangle$ state (blue triangle) and $|1,1\rangle$ state (red dot) in the optical dipole trap. The solid lines show the numerical fits to the experimental data, which give the lifetime of 400 ms for the mixture of ^{23}Na $|2,2\rangle$+^{40}K $|9/2,9/2\rangle$ and 8.7 s for the mixture of ^{23}Na $|1,1\rangle$+^{40}K $|9/2,9/2\rangle$. The inset shows the enlarged evolution of the ^{40}K atoms for the first case.

5. Degenerate Bose–Fermi gases in an optical trap

For cooling to quantum degenerate regime, the atomic sample is transferred into a far detuning, large volume crossed optical dipole trap ($\lambda = 1064$ nm) consisting of two beams with small intersection angle in the x–y horizontal plane, as depicted in Fig. 1(b). Two beams (ODT1 and ODT 2) crossed with the angle 5° have the focus waist of 100 μm and 90 μm and ramp up to maximum power of 9 W in 100 ms, which improves the loading efficiency by enlarging the trapping volume to reduce the strong three-body losses. Meanwhile, the green laser is switched off, and the magnetic field gradient is ramped down to 0 Gs in 30 ms. The experimental sequence shows the optimized sympathetic cooling, as shown in Fig. 4(b).

After the transfer step, there are 2.2×10^5 ^{40}K atoms at 8 μK, and the transfer efficiency from the quadrupole magnetic trap is about 65%. We compare the $1/e$ lifetimes of the mixture at the different spin states in the large-volume crossed optical trap depicted in Fig. 6. Due to the significant three-body loss, the lifetime is just 0.4 s of ^{40}K atom in the dipole trap while ^{23}Na atoms are in the $|2,2\rangle$ state. After the atoms are transferred into the optical trap, a rapid spin state transfer process is performed to prepare the sodium atoms in $|1,1\rangle$ via Landau–Zener sweep by an MW driven transition during 10 ms at a guiding field of 1 Gs, and remove the remaining atoms at $|2,2\rangle$ state via a resonance light. For the mixture of ^{23}Na$|1,1\rangle$+^{40}K$|9/2,9/2\rangle$, the lifetime can be significantly increased to about 8.7 s for ^{40}K.

The first step of forced evaporation of the mixture in the optical trap is to reduce the intensity of the laser beams (ODT 1 and ODT 2). Then in order to increase the collision rate, the other beam (ODT 3) perpendicular to ODT 2 with a waist of 63 μm is focused on the sample and ramped to the power of 0.82 W at the second step evaporation. Then the mixture is further evaporated accompanying a transfer procedure from the large-volume crossed optical trap to a highly confining potential formed by ODT 2 and ODT 3. At the end of the evaporation, a quantum degenerate Bose–Fermi mixture gas is created. Figure 7 gives the absorption images of sodium [panels (a), (c), (e)] and potassium [panels (b), (d), (f)] for the different atomic number ratio by changing the ^{23}Na atom loading time in the MOT stage.

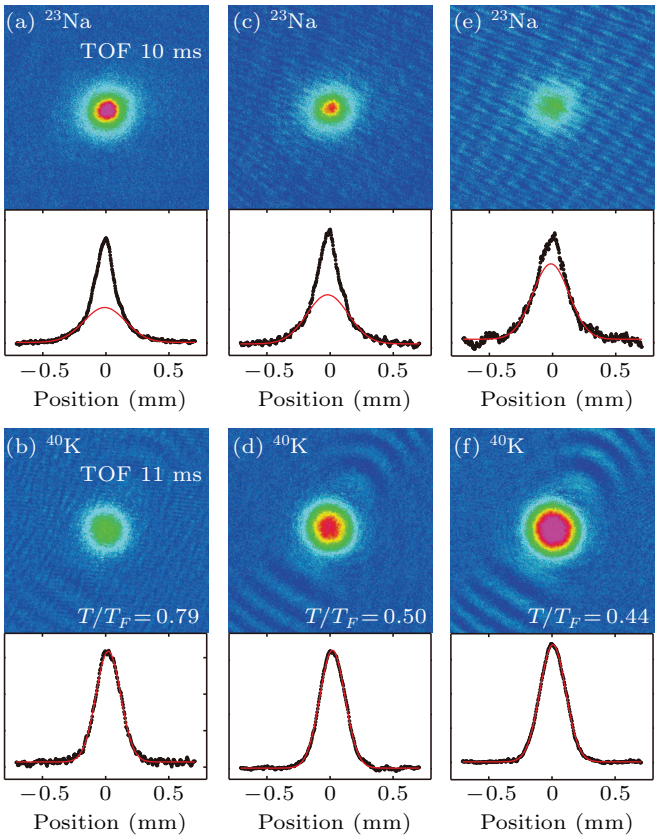

Fig. 7. Time of flight absorption images of ^{23}Na and ^{40}K atoms of degenerate Bose–Fermi mixtures. It takes 10 ms for ^{23}Na and 11 ms for ^{40}K of time of flight absorption images. Panels (a) and (b), (c) and (d), and (e) and (f) are pairs of images of ^{23}Na and ^{40}K corresponding to the different ratios of two species' atom numbers. The one-dimensional integrated optical density profiles are plotted at the bottom of the TOF pictures. Atom numbers are (a) 3.41×10^5, (b) 0.812×10^5, (c) 2.3×10^5, (d) 1.9×10^5, (e) 1.63×10^5, and (f) 3.17×10^5. Each image size is 1.6 mm × 1.6 mm.

We can produce 1.9×10^5 ^{40}K atoms with the trapping frequencies $(w_x, w_y, w_z) = 2\pi\times(98, 153, 182)$ Hz, and 2.3×10^5 of ^{23}Na atoms with 8×10^4 condensed atoms. The temperature of ^{40}K atoms is about $0.5T_F$, where T_F is the Fermi temperature $T_F = \hbar\bar{w}(6N)^{1/3}/K_B$, $\bar{w} = (w_x w_y w_z)^{1/3}$ is the mean trap frequency, $\hbar$ is Planck's constant and K_B is the Boltzmann constant. We determine the temperature by Gaussian fits to the wings of the ^{23}Na thermal cloud fraction (red lines in Figs. 7(a), 7(c), and 7(e)). If we only load ^{23}Na atoms with 5 s during the MOT loading stage, we could produce a pure Bose–Einstein condensate with 7×10^5 ^{23}Na atoms using the same cooling route.

Figure 8 shows the atom number in the mixture at the end of evaporation as a function of the varied loading time for ^{23}Na atoms, where the ^{40}K atoms are loaded with a fixed time of 50 s. We may create a mixture with a variable ratio of two species atoms by adjusting the loading time of ^{23}Na atoms, and use it to explore the physics of Bose or Fermi polarons. When ^{23}Na atoms are loaded with 4 s, the two species are equal in quantity about 2×10^5 and have the same temperature of 0.34 μK, which is a good start point for creating ultracold heteronuclear dipolar molecules.

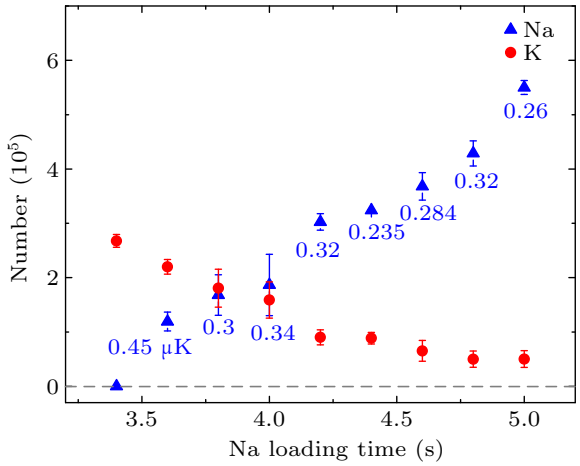

Fig. 8. Atom number of ^{23}Na (blue triangle) and ^{40}K (red circle) in the ODT at the end of evaporation as a function of the ^{23}Na MOT loading time. The loading time of potassium atoms is fixed at 50 s.

6. Conclusion

In conclusion, we have described a compact experimental setup and an optimized route in detail to produce a quantum degenerate mixture of Bose gas ^{23}Na and Fermi gas ^{40}K. We employ different technologies to improve the atomic numbers of the degenerate mixture including dual dark MOT, D_2 line gray molasses of ^{23}Na atoms and D_1 line gray molasses of ^{40}K atoms, the microwave evaporation in the optically plugged magnetic trap and transferring to a large volume optical dipole trap. We measure the lifetimes of the mixture in different hyperfine states and present the efficiently sympathetic evaporation cooling between Na and K atoms in a magnetic trap and optical trap. A degenerate Bose–Fermi mixture at $T/T_{\rm F} = 0.5$ with ^{40}K atom number of 1.9×10^5 and ^{23}Na 2.3×10^5 is produced. We also could obtain a mixture of tunable atom number ratio at the nK regime by adjusting the ^{23}Na MOT loading time.

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