Two-species magneto-optical trap with ^{40}K and ^{87}Rb

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We trap and cool a gas composed of ^{40}K and ^{87}Rb, using a two-species magneto-optical trap (MOT). This trap represents the first step towards cooling the Bose-Fermi mixture to quantum degeneracy. Laser light for the MOT is derived from laser diodes and amplified with a single high power semiconductor amplifier chip. The four-color laser system is described, and the single-species and two-species MOTs are characterized. Atom numbers of 1×10^7 ^{40}K and 2×10^9 ^{87}Rb are trapped in the two-species MOT. Observation of trap loss due to collisions between species is presented and future prospects for the experiment are discussed.

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The first experimental realizations of Bose-Einstein condensation in dilute atomic gases [1–3] brought with them an ever-increasing interest in the quantum behavior of such systems. These systems exhibit weak and controllable interactions, and are typically simpler to describe theoretically than their condensed matter counterparts. The quantum statistics of fermions, however, initially prevented the production of a quantum degenerate Fermi gas of atoms. Specifically, the challenge came in maintaining the rethermalizing collisions necessary for forced evaporative cooling of the gas — the Pauli exclusion principle forbids *s*-wave collisions between identical fermions at the ultralow temperatures necessary to reach quantum degeneracy. To circumvent this limitation, the first experiment to produce a quantum degenerate Fermi gas [4] used two spin states of a single fermionic isotope, thus allowing the rethermalizing collisions necessary for evaporative cooling. Sympathetic cooling of fermionic atoms to quantum degeneracy using a thermal bath of bosonic atoms has more recently been demonstrated in systems using ^{6}Li and ^{7}Li [5,6].

In this paper we report on the simultaneous trapping of ^{40}K (a fermion) and ^{87}Rb (a boson) using a two-species magneto-optical trap (MOT). This MOT will be used as a pre-cooling stage prior to forced evaporation of the ^{87}Rb and sympathetic cooling of the ^{40}K gas. To produce the four frequencies of light necessary to operate the MOT, we have developed a relatively simple laser scheme that includes the use of a single high power semiconductor amplifier. With this system we are able to trap 2×10^9 ^{87}Rb atoms and 1×10^7 ^{40}K atoms simultaneously. In addition we can monitor either species during the operation of the MOT, and have observed number loss in the ^{40}K cloud due to the presence of trapped rubidium.

A MOT for trapping two different elements requires twice as many laser frequencies as a single-species MOT. All of the light for our MOT is generated by laser diodes and amplified by a single high power tapered semiconductor amplifier chip (Toptica Photonics TAE 780 [7,8]). The design of the laser system and MOT optics exploits the similar wavelengths of the D_2 lines in rubidium and potassium, whose energy levels are shown schematically in Fig. 1.

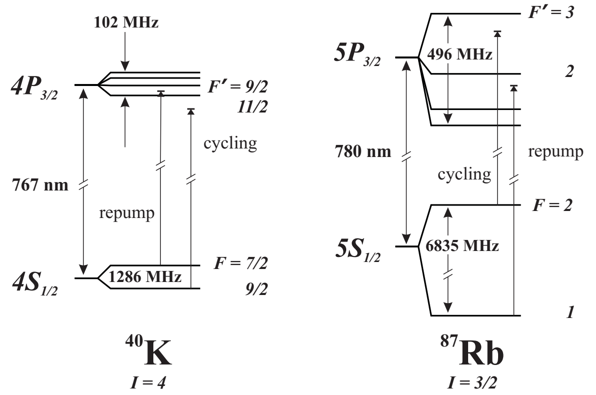

FIG. 1. Schematic hyperfine energy level diagrams for ^{40}K and ^{87}Rb, showing the cycling and repump transitions used in the experiment. Note the inverted structure and considerably smaller splittings for ^{40}K, whose excited state manifold spans only $\sim$ 100 MHz. F and F' are the total atomic angular momentum quantum numbers for the ground and excited states, respectively, and I is the nuclear spin quantum number.

The generation of the laser light for the ^{87}Rb MOT begins with a grating-feedback stabilized external cavity diode laser [9]. The laser generates 20 mW of single mode, narrow-band light. Some of this light is used to frequency lock the laser via saturated absorption spectroscopy to the peak of the ^{87}Rb $F = 2 \rightarrow F' = 2-3$ crossover line. The rest of the light is then frequency shifted via a double-passed 80 MHz acousto-optic modulator (AOM), and less than a milliwatt is sent to a second laser diode for injection locking. The remaining light is then available for optically pumping and/or probing the atom sample.

The current to the injection locked laser is modulated to create sidebands for hyperfine repumping [10–12]. The modulation source is an yttrium iron garnet crystal oscillator (Microsource Inc. MCO-0207) whose output is coupled into the diode current using a bias "T" (Picosecond Pulse Labs 5585). In this way we produce repump and cycling light for the MOT in a single beam and without the need for a second external cavity diode laser. We can generate repump light on either the ^{87}Rb $F = 1 \rightarrow F' = 1$ or $F = 1 \rightarrow F' = 2$ transition. Up to 10% of the total 780 nm MOT light is available for hyperfine repumping, which is sufficient for the ^{87}Rb MOT.

The 767 nm light for the ^{40}K MOT is also generated using a master-slave injection locking setup. To reach the wavelength of the potassium D_2 lines the laser diodes must be cooled using multiple stages of thermo-electric coolers. In addition, a water heat exchange plate was necessary to cool the slave laser to $-40\,^{\circ}$C. Each laser is housed in a hermetically sealed can with dessicant to prevent water condensation.

The 767 nm master laser is frequency locked to the peak of a ground state feature of ^{41}K via saturated absorption spectroscopy [13]. The remaining light is then used to injection lock the 767 nm slave laser diode for amplification. A ^{40}K MOT typically requires more light for repumping than ^{87}Rb due to the small excited state hyperfine splitting [14,15] (see Fig. 1). We found a modulation scheme similar to that described above incapable of stably generating sidebands with >15% of the total output power. To allow for more ^{40}K repump power, we instead frequency shift the light from the 767 nm slave laser via a double-passed 500 MHz AOM for repumping. The unshifted light is double-passed through a 110 MHz AOM to generate light on the potassium cycling transition. The slave laser thus provides enough power to generate both frequencies for the ^{40}K MOT.

High laser power for the MOT is obtained using a single tapered semiconductor amplifier chip. A schematic summary of the laser system is shown in Fig. 2. This type of single-amplifier system has been used in experiments with two isotopes of a single atom [16,17] to provide amplification with up to 12 GHz of bandwidth. In our system we exploit an amplification bandwidth of 7 THz. At $23\,^{\circ}$C the chip has an amplified spontaneous emission (ASE) gain profile centered at 773 nm and with a full-width at half-maximum (FWHM) of 16 nm. We measure an amplifier gain of roughly 100 at 767 and 780 nm, and we can vary the amplified powers in the four frequencies by controlling the relative powers of the injected beams. This system produces all of the light necessary for the two-species MOT in a single beam.

The four frequencies injecting the amplifier are coupled together with a series of polarizing beam splitter cubes and half-wave retardation plates. Adjusting the orientations of the retarders allows simple control of the relative power in each frequency sent to the MOT. Figure 3 shows the optical spectrum of the injected amplifier. The single beam output from the amplifier is expanded and shaped into a roughly gaussian beam with a $1/e^2$ diameter of 3 cm. Running the amplifier with 500 mW of total output light results in ~ 300 mW for the MOT after beam shaping and spatial filtering. The beam from the amplifier is then split three ways with each beam retroreflected for the MOT.

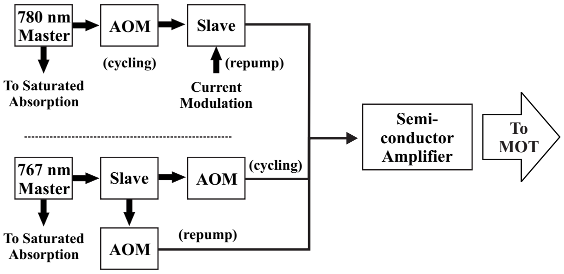

FIG. 2. Schematic of the laser system used in these experiments. All four frequencies used for the two-species MOT are produced in three independent beams and combined before injection into a single semiconductor tapered amplifier chip. The amplifier output then consists of a single beam capable of trapping and cooling ^{87}Rb and ^{40}K simultaneously.

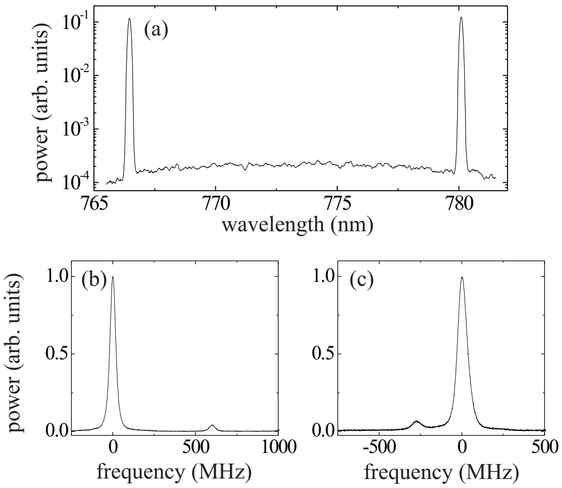

FIG. 3. Optical spectrum of the injected amplifier. (a) The MOT beam, measured with an optical spectrum analyzer, showing the narrow 767 and 780 nm peaks above a highly suppressed ASE floor. The widths of the peaks are resolution limited. (b) Closeup of the ^{87}Rb cycling and repump frequencies, measured with a Fabry-Perot spectrometer with a free spectral range of 1.5 GHz. The frequencies are referenced to the cycling transition. The repump power shown here is approximately 4% of the total 780 nm light. (c) ^{40}K trap and repump frequencies on the same spectrometer. The repump power is approximately 6% of the total 767 nm light.

The MOT itself is formed in a $2 \times 2 \times 6$ inch rectangular glass cell, with a one inch diameter window at one end for imaging. This cell is maintained at a pressure $\lesssim 10^{-10}$ Torr. Alkali metal dispensers provide the background vapor for the MOT. The dispensers are housed in two glass arms attached to the cell — one for potassium and the other for rubidium. The ^{87}Rb source is a commercially available dispenser (SAES Getters), while the potassium source is made in-house from a KCl sample enriched in ^{40}K (Trace Sciences International), as described previously [15]. The vapor pressure for each species can be independently controlled by varying the currents used to heat the dispensers.

In characterizing the behavior of the system we began by optimizing each single-species MOT for number of trapped atoms. In the case of ^{87}Rb, with a peak light intensity of 70 mW/cm^2 at the MOT we are able to trap 2×10^9 atoms in the absence of trapped potassium. The atom number is determined from fluorescence collected onto a photodiode or captured onto a charge coupled device array (CCD). The ^{87}Rb cloud is about 5-10 mm in diameter. We find that a detuning of $\Delta \approx -4\,\Gamma_{Rb}$ optimizes the number of trapped ^{87}Rb atoms, where $\Gamma_{Rb} = 5.98\,\mathrm{MHz}$ is the natural linewidth of the D_2 lines in rubidium. As mentioned above we can repump on either the ^{87}Rb $F = 1 \rightarrow F' = 1$ or $F' = 2$ transition. We measured a slight increase in atom number when repumping on the $F' = 2$ transition. The magnetic field gradient provided by our coils is typically 13-18 G/cm.

With no ^{87}Rb MOT, and with 70 mW/cm^2 peak intensity of 767 nm light, we obtain a ^{40}K cloud with 2×10^7 atoms, and measuring 0.1-0.3 mm in diameter. The MOT is operated at a detuning of $\Delta \approx -3\,\Gamma_K$, where $\Gamma_K = 6.09\,\mathrm{MHz}$ is the natural linewidth of the D_2 lines in potassium. The low ^{40}K number is due to the lower room temperature vapor pressure of potassium. Our previous experience with ^{40}K suggests that more atoms can be trapped by heating the glass cell, however we believe these numbers are sufficient for our purposes. Because the ^{40}K gas will be sympathetically cooled in the next stage of the experiment, it is not necessary or desirable to have a relatively large ^{40}K MOT.

The two-species MOT is then operated with the same laser detunings and magnetic field gradient used to optimize N_{Rb} and N_K in the single-species MOTs. With these parameters fixed, changing the relative powers in each beam injecting the amplifier allows us to tune the relative number N_{Rb}/N_K from 100-500 while maintaining at least 5×10^6 trapped ^{40}K atoms. This will enable us to optimize the initial conditions for sympathetic cooling. The ^{40}K cloud, which is smaller in diameter, forms completely within the center region of the larger ^{87}Rb cloud. Typical conditions of operation and the atom numbers obtained for the single-species and two-species MOTs are compared in Table I.

We can independently monitor either species while the two-species MOT operates. This permits in-situ measurement of N_K and N_{Rb}. We image fluorescence from the atoms onto a CCD array and use narrow-band optical filters (CVI Laser Corp. F03-766.5-4, F03-780.0-4) to selectively view either species. These filters have center (transmission) wavelengths of 767 and 780 nm, respectively, and an optical depth of 4 outside the 3 nm FWHM bandwidth.

By taking a sequence of fluorescence images through the appropriate filter, we observe the time evolution of either cloud in the two-species MOT. Figure 4 shows the results of an experiment monitoring the ^{40}K cloud. Initially all of the MOT light is on, but the 780 nm light is locked far off resonance and the B-field is off so that no trapped atoms are present. After turning on the field and letting the ^{40}K MOT evolve for 25 seconds, the 780 nm light is quickly shifted onto the ^{87}Rb cycling transition, allowing the rubidium MOT to fill. After ten seconds in the presence of trapped ^{87}Rb, the 780 nm light is jumped back off resonance and the ^{40}K MOT is allowed to evolve again freely.

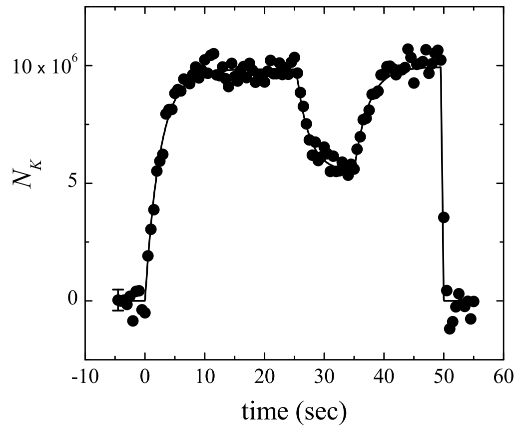

FIG. 4. Potassium MOT number loss in the presence of trapped rubidium. The data are averaged over nine consecutive experiments, and the solid line is a fit to exponential growth and decay in each region. The period from 25 sec to 35 sec, where the MOTs coexist, shows the loss in ^{40}K atom number, N_K, during operation of the two-species MOT. For comparison, the ^{40}K loading rate is $4 \times 10^6\,\mathrm{sec}^{-1}$, and the time constant for exponential decay during the loss is approximately 2 seconds.

In these data we observe a decrease in N_K of 45% in the presence of the rubidium cloud. This is attributed to light-assisted heteronuclear collisions in the MOT. A loss rate of 20% has been reported in a $^{85}\mathrm{Rb}-{}^{39}\mathrm{K}$ system with more evenly matched number between species [18]. If we reverse the above experiment to monitor the ^{87}Rb cloud for loss in the presence of trapped ^{40}K, we do not observe an effect. This agrees with the observations reported by the Sao Carlos group.

In summary we have demonstrated a two-species MOT for the simultaneous trapping of ^{40}K and ^{87}Rb. This trap will serve as a pre-cooling stage prior to the sympathetic cooling of the ^{40}K to quantum degeneracy. Using a relatively simple four-color diode laser scheme and a single high power semiconductor amplifier, atom numbers of $N_{Rb} = 2 \times 10^9$ and $N_K = 1 \times 10^7$ are obtained. In addition we have observed a pronounced number loss in the ^{40}K MOT due to heteronuclear collisions in the presence of trapped ^{87}Rb atoms. Current work progresses on loading into a purely magnetic trap for evaporative cooling.

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TABLE I. Experimental parameters and atom numbers for the single-species and two-species MOTs. I_c is the total peak light intensity on the cycling transition and I_r the total peak intensity of hyperfine repumping light for the given species.

	^{40}K	^{87}Rb
I_c (mW/cm^2)	70	70
I_r (mW/cm^2)	4	2
Δ_c	$-3\Gamma_K$	$-4\Gamma_{Rb}$
N (single-species)	2×10^7	2×10^9
N (two-species)	1×10^7	2×10^9

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