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Simultaneous magneto-optical trapping of two lithium isotopes

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We confine 4×10^8 fermionic ^{6}Li atoms simultaneously with 9×10^9 bosonic ^{7}Li atoms in a magneto-optical trap based on an all-semiconductor laser system. We optimize the two-isotope sample for sympathetic evaporative cooling. This is an essential step towards the production of a quantum-degenerate gas of *fermionic* lithium atoms.

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The observation of Bose-Einstein condensation in atomic vapors [1] has made dilute *bosonic* quantum gases experimentally accessible and the study of these systems has thus been very fruitful. Quantum degenerate gases of fermions also offer novel physical properties. At temperatures below the Fermi temperature, energy and momentum transfer is modified by Fermi statistics [2,3]. One striking prediction is the partial suppression of spontaneous emission [4]. Also, a Fermi gas of atoms in a mixture of different hyperfine (HF) states might undergo a BCS pairing transition and exhibit long-range coherence and superfluid behavior [5]. Recently the onset of quantum degeneracy of a gas of *fermionic* ^{40}K atoms has been observed by DeMarco and Jin, and a temperature half of the Fermi temperature has been reached [6].

Evaporative cooling of polarized atoms has so far been essential for the production of quantum degenerate gases [7]. It is driven by elastic collisions. At ultralow temperature T, i.e., below a few millikelvin for lithium, collisions between bosons or distinguishable particles are predominantly *s*-wave collisions, while Pauli exclusion prohibits *s* partial waves of polarized fermions. In an ultracold gas of indistinguishable fermions the elastic collision rate diminishes proportionally to T^2, as recently confirmed in [8]. Fermionic atoms can be cooled *sympathetically* by collisions in a mixture of different internal states [6,9] or of different species, which are yet to be implemented.

We intend to sympathetically cool fermionic ^{6}Li with the bosonic ^{7}Li isotope. This could produce not only a quantum degenerate Fermi gas but also a Bose-Einstein condensate of ^{7}Li in both HF ground states as well as a mixture of quantum degenerate gases of fermions and bosons [10]. One can also employ ultracold bosons to probe collisional properties of a degenerate Fermi gas [3].

Previously several groups have studied samples of two atomic species in a magneto-optical trap (MOT) [14]. In this article we describe realization of a MOT containing both fermionic and bosonic lithium and its optimization for sympathetic cooling. 4×10^8 ^{6}Li atoms and 9×10^9 ^{7}Li atoms are simultaneously confined. These numbers together with the density and temperature achieved should be sufficient to produce a Fermi gas with a Fermi temperature on the order of 10 μK in a harmonic magnetic trap of frequency $\overline{\omega}/2\pi=400\ \mathrm{s}^{-1}$. The phase-space density $\mathcal{D}=n_0\Lambda^3/f$ of unpolarized atoms (f internal states) with a peak density n_0 and temperature T is the number of identical atoms per cubic thermal De Broglie wavelength $\Lambda=(2\pi\hbar^2/mk_BT)^{1/2}$. The achieved phase-space density in the two-isotope magneto-optical trap is 4×10^{-6} for $^7\mathrm{Li}(f=3)$ and 0.8×10^{-6} for $^6\mathrm{Li}(f=2)$. In single-isotope traps, the number of fermions (1.5×10^9) exceeds the best previous realization of laser-cooled fermions by one order of magnitude [6,11]. The number of trapped ^{7}Li (1.8×10^{10}) is also a factor of 10 improvement [12].

In future experiments, this two-isotope sample will be polarized and transferred into a magnetic trap. Bosonic lithium will be evaporatively cooled. Fermionic lithium thermalizes with the bosons via elastic collisions. Neglecting inelastic losses for mixtures of $^7\mathrm{Li}(F=2,m_F=2)+{}^6\mathrm{Li}(F=3/2,m_F=3/2)$ [and $^7\mathrm{Li}(F=1,m_F=-1)+{}^6\mathrm{Li}(F=1/2,m_F=-1/2)$], as justified in [13], all initially confined fermions should reach the quantum degenerate regime, i.e., $T\leqslant T_F$. Note that reaching $T\ll T_F$ might become difficult because Fermi blocking will slow down the thermalization process since only fermions near the Fermi surface contribute [6,3,10]. In a typical evaporative cooling sequence the phase-space density $\mathcal{D}$ is increased by $\sim10^6$ by decreasing the atom number by ~100 [7]. For sympathetic cooling this implies that N initially confined ^{7}Li atoms can sympathetically cool a sample of $N/100$ ^{6}Li atoms into the quantum degenerate regime. We therefore aim to maximize the number N of ^{7}Li atoms in the two-isotope trap while simultaneously confining on the order of $N/100$ ^{6}Li atoms. It is equally crucial that atoms thermalize quickly during the trap lifetime. Thus the initial elastic collision rate Γ_i between ^{7}Li atoms in the magnetic trap must be maximized. For a linear trapping potential in three dimensions Γ_i can be related to quantities of the MOT as follows:

$$\Gamma_i\propto N^{4/9}\mathcal{D}_i^{5/9}\propto NT^{-5/6}\sigma^{-5/3}, \tag{1}$$

where N is the number of trapped atoms, T is the temperature of the sample and σ the width of the Gaussian density distribution $n(r)=[N/(\sqrt{2\pi}\sigma)^3]\exp(-r^2/2\sigma^2)$ in the MOT. We have optimized the laser-cooled sample of ^{7}Li with respect to Γ_i in the presence of ^{6}Li.

In the experiment, the MOT is loaded from a Zeeman slowed lithium beam. ^{6}Li in the beam is enriched and has an abundance of about 20%. Both isotopes are slowed and confined in the MOT with 671-nm light that is near resonant with the $D2$ line, the $2S_{1/2}\rightarrow2P_{3/2}$ optical transition. The isotopic shift for this transition is 10 GHz. Each isotope re-

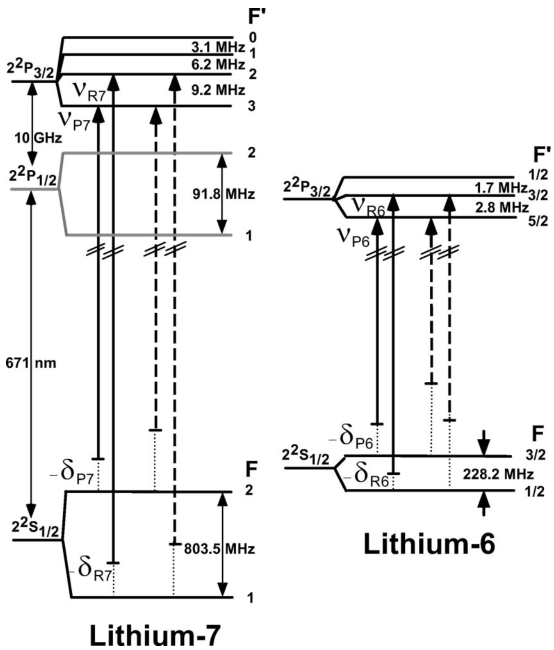

FIG. 1. Frequencies employed to slow (dashed arrows) and magneto-optically trap (solid arrows) both lithium isotopes. The detunings of the frequencies from the respective resonances are marked with a dotted line. The detuning of the slowing light from the respective zero magnetic field transitions for ^{7}Li is -426 MHz and -447 MHz for ^{6}Li.

quires two frequencies to excite from the two HF ground states. The HF splitting is 803.5 MHz for ^{7}Li and 228.2 MHz for ^{6}Li. Hence simultaneous laser cooling of both lithium isotopes requires *eight* different laser frequencies: four frequencies for Zeeman slowing and four frequencies for magneto-optical trapping, as shown in Fig. 1.

All frequencies are derived with acousto-optical modulators from two grating-stabilized external-cavity diode lasers based on 30-mW laser diodes. The lasers are frequency locked in saturated absorption to the $D2$ lines of ^{6}Li and ^{7}Li, respectively. The slowing light is produced by geometrical superposition of the output of four injection seeded 30-mW laser diodes. Four trapping frequency components are geometrically superposed and 15 mW of this light is injected into a tapered semiconductor amplifier chip. After spatial filtering, the chip produces up to 140 mW of trapping light containing the four frequency components in a Gaussian mode at an identical polarization, as described in [15]. The intensity ratio of the frequency components in the trapping beams can be adjusted. This light is split up into six independent Gaussian trapping beams, each with a maximum peak intensity of $I_{max}=6$ mW/cm^2, a $1/e^2$ intensity width of 3 cm, and an apertured diameter of 2 cm. The MOT is operated in a 4cm $\times$ 4cm $\times$ 10 cm Vycor glass cell of optical quality $\lambda/2$. Background gas collisions limit the $1/e$ MOT lifetime τ to about 25 s.

The trapped atom clouds of both isotopes are separately observed in absorption imaging. For observation, the trapping light and magnetic field are switched off abruptly. The induction limited $1/e$ decay time of the magnetic field is less than 50 μs. After free ballistic expansion with an adjustable time of flight between 150 μs and 7 ms the sample is illuminated for 80 μs by a probe beam. This probe excites either ^{7}Li from the $F=2$ ground state or ^{6}Li from the $F=3/2$ ground state to the $2P_{3/2}$ excited-state manifold. The absorption shadow of the sample is imaged onto a charge-coupled device (CCD) camera. A separate repumping beam that is not projected onto the camera excites atoms in the other HF ground state to avoid hyperfine optical pumping. The density distribution, atom number, and temperature of the sample are obtained from absorption images for different ballistic expansion times.

TABLE I. Comparison of atom number N, peak density n_0, temperature T, and frequency detunings for the single-isotope and two-isotope MOT.

	Single-isotope MOT		Two-isotope MOT	
	^{7}Li	^{6}Li	^{7}Li	^{6}Li
N	1.8×10^{10}	1.5×10^{9}	9×10^{9}	4×10^{8}
n (cm^{-3})	3×10^{11}	1.0×10^{11}	2.5×10^{11}	5×10^{10}
T (mK)	1.5	0.7	1.0	0.7
$\delta_{P7,6}$ (units of Γ)	-8.0	-2.7	-8.0	-2.7
$\delta_{R7,6}$ (units of Γ)	-5.8	-5.1	-5.8	-5.1

Both isotopes are magneto-optically trapped in two steps: In the first step, *the loading phase*, the capture volume and velocity of the trap are large, such that the number of trapped atoms is maximized. In the second step, *the compression phase*, the already trapped atoms are compressed in phase space, such that the initial elastic collision rate Γ_i is maximized.

All four frequencies ν_{P7}, ν_{R7}, ν_{P6}, and ν_{R6} of the MOT are exciting on the $D2$ line. We maximized the number of ^{7}Li atoms and ^{6}Li atoms in separate MOTs as well as the number of ^{7}Li atoms in the two-isotope trap. The maximization involved the detunings $\delta_{P7},\delta_{R7},\delta_{P6},\delta_{R6}$ of the light components from the cooling and repumping transitions of the two isotopes (Fig. 1), the intensities of all frequency components, and the strength of the magnetic field of the MOT.

First, the atom number was optimized in separate *single-isotope* MOTs with only the two frequencies for the respective isotopes present. We were able to capture up to 1.8×10^{10} ^{7}Li atoms and 1.5×10^9 ^{6}Li atoms. The atom number N, peak density n_0, temperature T, and the respective detunings are listed in Table I. The atom number is accurate to within a factor of 2, and this dominates the uncertainty in the density determination. This uncertainty arises from a conservative estimate for the absorption cross section because the probe beam polarization is not well defined with respect to the local magnetic field and the HF structure splitting in the excited state is small. The temperature uncertainty is 0.2 mK. For both isotopes the atom number is maximized at large frequency detunings and equal intensities in both frequency components. The optimum magnetic-field gradient B' along the symmetry axis of the magnetic quadrupole field of the MOT is about 35 G/cm for both isotopes. The MOT was operated at maximum intensity $I_{max}=6$ mW/cm^2 in each of the six beams.

In the ^{7}Li trap, at low atom number ($\leqslant 10^9$) the temperature is the Doppler temperature (1.1 mK at $\delta_{P7}=-8\Gamma$), as shown in Fig. 2. At large atom numbers, for 5×10^9 to 2×10^{10} trapped atoms, the temperature is 1.5(2) mK and

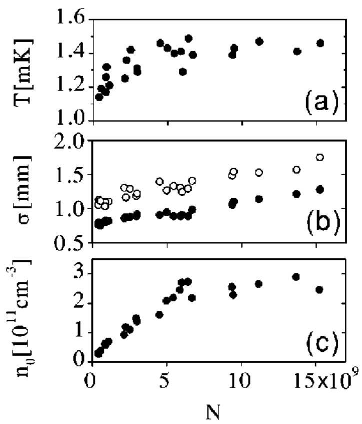

FIG. 2. Temperature T, one-dimensional rms width σ and peak density n_0 in a ^{7}Li MOT versus atom number N. N was varied by changing the loading time. In (b) the width along the symmetry axis z of the magnetic field (solid data points) is $\sim$40% smaller than in the radial direction (hollow points) as expected from a simple MOT model $(1/\sqrt{2})$.

nearly constant, while the density typically saturates at $n_0 = 3\times10^{11}$ cm^{-3}. In this regime the number of trapped ^{7}Li atoms is limited by loss due to inelastic radiative escape (RE) or fine-structure (FS) changing collisions. In steady state, the flux of slow atoms $\mathcal{F}=2\times10^9$ s^{-1} is balanced by the trap loss according to

$$\mathcal{F}=N/\tau+\beta n_0 N/\sqrt{8}, \quad (2)$$

$\tau=25$ s is the background-gas-limited lifetime of the MOT. The two-body loss coefficient $\beta=6\times10^{-13}$ cm^3/s was experimentally determined and is consistent with previous studies of trap loss in a ^{7}Li MOT [16].

In ^{7}Li the HF splitting between the $F'=3$ and the $F'=2$ excited states is 1.6 Γ, and in ^{6}Li, 0.5 Γ between the $F'=5/2$ and the $F'=3/2$ excited states, where $\Gamma=5.9$ MHz is the natural width of the lithium D lines. Despite the inverted excited-state HF structure of both lithium isotopes, the small HF splitting leads to off-resonant excitation of the $F=2\rightarrow F'=2$ transition in ^{7}Li, and the $F=3/2\rightarrow F'=3/2$ transition in ^{6}Li and frequent decay into the lower HF ground state. The repumping light component is therefore of equal importance as the principal trapping light. In fact, we only obtained a MOT with the repumping light also in a six-beam MOT configuration. This is not required in MOTs of other alkali metals with larger HF splitting, such as Cs, Na, or Rb.

For the two-isotope trap, the ^{6}Li repumping transition $F=1/2\rightarrow F'=3/2$ is about 7 Γ to the blue of the $F=2\rightarrow F'=1$ resonance in the $D1$ line of ^{7}Li. If both lithium isotopes are simultaneously confined, the ^{6}Li repumping light component ν_{R6} frequently excites this *noncooling* transition and significantly weakens the confinement of the trap for ^{7}Li. This leads to a smaller number of trapped ^{7}Li atoms in the presence of ^{6}Li light. We reduce this harmful effect by detuning towards the $D1$ resonance while reducing the ^{6}Li repumping intensity. The coincidence could also be avoided by repumping ^{6}Li on the $D1$ line instead. Aside from the light-induced trap loss we do not observe mutual effects due to the presence of both isotopes (such as collision-induced trap loss, heating, or a modification of the spatial distribution). With an intensity relation between the four frequency components ν_{P7}, ν_{R7}, ν_{P6}, and ν_{R6} of 8:8:2:1, we are able to confine 9×10^9 ^{7}Li atoms together with 4×10^8 ^{6}Li atoms. This ratio of $\sim$20 between the two isotopes can obviously be increased without loss of ^{7}Li atoms. N, n_0, T, and the respective detunings for the two-isotope MOT are listed in Table I.

TABLE II. Comparison of atom number N, peak density n_0, temperature T, and frequency detunings for the single-isotope and two-isotope compressed MOT.

	Single-isotope CMOT		Two-isotope CMOT	
	^{7}Li	^{6}Li	^{7}Li	^{6}Li
N	7×10^9	5×10^8	6×10^9	3×10^8
n (cm^{-3})	4×10^{11}	1.5×10^{11}	4×10^{11}	6.5×10^{10}
T (mK)	0.6	0.4	0.6	0.7
$\delta_{P7,6}$ (units of Γ)	-3.0	-2.7	-3.0	-2.7
$\delta_{R7,6}$ (units of Γ)	-9.0	-2.7	-9.0	-5.8

After loading the trap it is possible to further compress the sample in phase space and maximize the initial elastic collision rate Γ_i by changing the laser parameters for the duration of a few milliseconds. From Eq. (1) follows that in the case of *no* loss of atoms during compression a maximization of Γ_i also maximizes $\mathcal{D}_i$. For the compression, we optimize Γ_i with respect to the total laser intensity and the frequency detunings δ_{P6}, δ_{P7}, δ_{R6}, δ_{R7} while keeping B' constant at 35 G/cm. We compress the single-isotope MOTs as well as the two-isotope sample. For sympathetic cooling we are especially interested in maximizing Γ_i for ^{7}Li in the presence of ^{6}Li. As shown in Table II, decreasing δ_{R7}, i.e., detuning ν_{R7} further to the red of the transition, and approaching ν_{P7} towards resonance while reducing the overall laser intensity to $0.3 I_{max}=1.8$ mW/cm^2, results in a 40% drop in temperature and increases the density by 70% (see Fig. 3). 30% of the initially confined atoms are lost during the first 3 ms of compression. This loss is probably due to FS- and RE-collision-induced heating during the initial compression stage. According to Eq. (1) compression increases Γ_i by 60%. After compressing the two-isotope trap for 3 ms, we

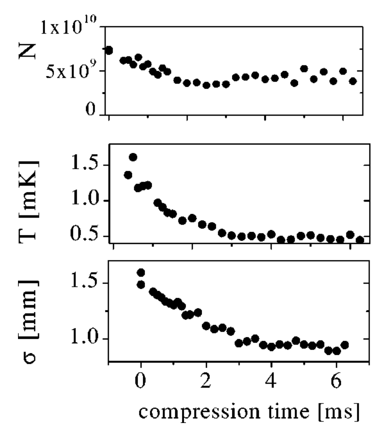

FIG. 3. Temporal dynamics of the compression phase of a ^{7}Li MOT. Atom number N, temperature T, and rms width σ_z after an abrupt change of the laser parameters at $t=0$.

obtain a maximum of 6×10^9 ^{7}Li atoms at a peak density of 4×10^{11} cm^{-3} and a temperature of 0.6 mK together with ^{6}Li at a density 6.5×10^{10} cm^{-3} and a temperature of 0.7 mK. Aside from the initial loss during the first few milliseconds, the 1/*e* trap lifetime also decreases to about 30 ms for both isotopes.

Figure 3 shows the typical temporal dynamics of atom number, width, and temperature of the ^{7}Li compressed MOT (CMOT) for the first 6.5 ms of compression. Γ_i and $\mathcal{D}_i$ reach a maximum after about 3 ms. The CMOT is rather insensitive to the repumping frequency ν_{R7}: detuning by 2 Γ above and below the optimized value of 5.8 Γ decreases Γ_i by less than 25%. The CMOT is much more sensitive to the detuning ν_{P7} of the trapping light. We optimized Γ_i with respect to the duration *t* of the compression phase and the detuning. The maxima of Γ_i and $\mathcal{D}_i$ remain at a constant value for $t \geqslant 3$ ms but shift to different detuning parameters with increasing CMOT duration.

To summarize, we showed that it is possible to trap about 6×10^9 ^{7}Li atoms together with 3×10^8 ^{6}Li atoms in the two-isotope MOT at at phase-space densities of $\sim10^{-6}$. These results are comparable to results achieved with single isotopes of Na or Cs in a *dark* SPOT [17]. In combination with a strong confining magnetic trap we expect an initial elastic collision rate well above 10 s^{-1}, despite the small triplet scattering length of 1.4 nm (^{7}Li-^{7}Li) and 2.0 nm (^{6}Li-^{7}Li) [18]. This can lead to the production of quantum degenerate Bose and Fermi gases of lithium by forced evaporation and sympathetic cooling within a few seconds.

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