Strongly Interacting Isotopic Bose-Fermi Mixture Immersed in a Fermi Sea

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We have created a triply quantum degenerate mixture of bosonic $^{41}$K and two fermionic species $^{40}$K and $^6$Li. The boson is shown to be an efficient coolant for the two fermions, spurring hopes for the observation of fermionic superfluids with imbalanced masses. We observe multiple heteronuclear Feshbach resonances, in particular a wide s-wave resonance for the combination $^{41}$K-$^{40}$K, opening up studies of strongly interacting isotopic Bose-Fermi mixtures. For large imbalance, we enter the polaronic regime of dressed impurities immersed in a bosonic or fermionic bath.

Strongly interacting quantum mixtures of ultracold atoms provide an extremely rich platform for the study of many-body physics. They offer control over macroscopic quantum phenomena in and out of equilibrium, enabling a direct quantitative comparison to theoretical models. Two-state mixtures of fermionic atoms near Feshbach resonances allow the creation of fermionic superfluids in the crossover between Bose-Einstein condensation and Bardeen-Cooper-Schrieffer (BCS) superfluidity. Combining different atomic species gives access to Bose-Bose, Bose-Fermi, and Fermi-Fermi mixtures that each connect to many different areas in condensed matter, high energy or nuclear physics. Bose-Fermi mixtures may provide insight into, for example, boson-mediated Cooper pairing, QCD matter, and into theoretical models of High-$T_c$ superconductivity. A mixture of two different fermions might allow access to a superfluid of unlike fermions. In contrast to superconductors or neutron stars, superfluid pairing will occur between particles that are not related via time-reversal symmetry. Very recently, Fermi-Fermi mixtures of unlike fermionic species have been brought into the strongly interacting regime, offering prospects to observe universal physics in imbalanced mixtures, such as universal transport.

An important class of many-body problems involves the interaction of impurities with a Fermi sea or a bosonic bath, dressing them into quasi-particles known as polarons. For the Fermi polaron, an impurity interacting with a fermionic environment, the resulting energy shift has been experimentally measured and calculated. Due to the fermionic nature of the environment, the effective mass is only weakly enhanced even for resonant interactions. However, if the impurity swims in a bosonic bath, there is no limit in the number of bosons that interact at close distance with the impurity, and the mass-enhancement can be enormous.

In this work we present a rather ideal system to study strongly interacting quantum mixtures of different atomic species, a heavy, isotopic Bose-Fermi mixture of $^{40}$K-$^{41}$K with widely tunable interactions coexisting with a light Fermi sea of $^6$Li. $^{41}$K is used to sympathetically cool both $^6$Li and $^{40}$K, leading to a triply degenerate quantum mixture. Apart from a strong p-wave Feshbach resonance, we find a wide s-wave Feshbach resonance between the potassium isotopes. At our lowest temperatures at the Feshbach resonance, the mixture should be in a regime where both Bose and Fermi polarons exist. Finally, the mass-imbalanced Bose-Fermi mixture $^6$Li-$^{41}$K also allows for tunable interactions at several Feshbach resonances.

Predating our work, Feshbach resonances in Bose-Fermi mixtures were found in $^{23}$Na-$^6$Li, $^{87}$Rb-$^{40}$K, and in Rb-$^6$Li. However, these systems are plagued by typically unequal trapping potentials and the large mass difference between unlike atoms, causing gravitational sag that has to be compensated. An atom-molecule mixture of $^6$Li-$^6$Li$_2$ allowed access to a part of the phase diagram of strongly interacting bosons and fermions. However, for too strong an interaction the composite nature of the bosonic molecules becomes apparent. With $^{40}$K-$^{41}$K, we have a Bose-Fermi mixture at our disposal
with identical external potentials and essentially equal mass for bosons and fermions, so that the only relevant difference lies in quantum statistics.

Cooling of spin-polarized fermions to degeneracy is hindered by insufficient thermalization due to the lack of “head-on” collisions in the s-wave regime at low temperatures, rendering Fermi gas experiments more complex than their bosonic counterparts. Common solutions include direct cooling of two hyperfine spin populations, or sympathetic cooling using another atom as a coolant. The latter method has the advantage of mostly conserving the fermionic species in the cooling process. Adverse spin-changing collisions between the coolant and the fermionic atoms can still reduce the fermion number. Here we employ $^{41}$K for sympathetic cooling and find it to be an efficient coolant for both $^{40}$K and $^6$Li, with negligible loss of fermions.

The experimental setup, shown in Fig. 1, consists of two independent Zeeman slowers for lithium and potassium, allowing us to simultaneously load large samples of each of the three atomic species directly into a UHV chamber. Although the natural abundance of $^{40}$K is only 0.01%, the Zeeman slower with a typical flux of $10^{11}$ atoms/s for abundant species still yields $5 \times 10^7$ $^{40}$K atoms loaded within two seconds into the magnetic trap. The slower yields $3 \times 10^9$ $^{41}$K atoms (natural abundance 7%) loaded in 2 s. We can trap $10^9$ $^6$Li atoms within 1 s.

To increase the initial atom density, a 40 ms compressed MOT phase and a 6 ms optical molasses stage compresses and cools each gas before loading into the magnetic trap. For $^{41}$K, we follow closely the procedure laid out in [31]. $^{40}$K and $^6$Li require less care, as we deliberately co-trap only a few $10^5$ fermionic atoms with the coolant. The maximum number of fermions that can be brought into degeneracy by a given bosonic coolant is roughly given by the number of degenerate bosons the apparatus can provide. For $^{41}$K, this limits the fermion number to about $2 \times 10^5$, while for $^{23}$Na, the number can be as large as $7 \times 10^5$ [30].

After the molasses stage, atoms are prepared in the stretched hyperfine states of $|F_\ell,m_\ell\rangle = |2,2\rangle$ for $^{41}$K, $|9/2,9/2\rangle$ for $^{40}$K, and $|3/2,3/2\rangle$ for $^6$Li via optical pumping. Evaporative cooling of $^{41}$K is performed in a quadrupole magnetic trap with a $B'_z = 220$ G/cm ($B'_z = 110$ G/cm) magnetic field gradient along the vertical (horizontal) direction. To avoid Majorana spin flips, the magnetic field zero is “plugged” by a repulsive laser beam (power 15 W, wavelength 532 nm) focused to a waist of 20 $\mu$m [32]. Unwanted hyperfine states from imperfect optical pumping are removed by reducing $B'_z$ for 200 ms to 15 G/cm, only supporting stretched states sufficiently against gravity. Without this cleaning procedure, spin-changing collisions would strongly reduce the atom number during evaporation. Evaporation is performed on $^{41}$K by driving $|2,2\rangle \to |1,1\rangle$ rf-transitions above the hyperfine transition of 254.0 MHz. For the last 2 s of evaporation, the trap is decompressed to $B'_z = 110$ G/cm to suppress three-body losses. A well-centered plugged trap allows for two trap minima on each side of the plug laser (see Fig. 1). To obtain only a single trap minimum, in the final 2 s of evaporation a horizontal bias field is applied in the $y$-direction, perpendicular to the plug beam, thus displacing the center of the magnetic trap by 10 $\mu$m. The resulting trapping potential, shown in the inset of Fig. 1, is approximately harmonic for atoms at energies of $\lesssim 2\mu$K. The effect of anharmonicities is strongest along the $y$-direction, and most important for the light fermion $^6$Li at a typical Fermi energy of $E_F = k_B \cdot 5\mu$K ($^{40}$K only has $E_F \approx k_B \cdot 1.5\mu$K).

Even for anharmonic traps, long time of flight expansion reveals the momentum distribution of the gas [33]. Time of flight images of triply degenerate quantum mixtures are shown in Fig. 2. Condensation of $^{41}$K is observed at $T_\phi = 1.2 \mu$K with $3 \times 10^5$ atoms. In the harmonic approximation, this translates into a geometric mean of the trapping frequencies of $\bar{\omega}_{z,41} = 2 \pi \times 380$ Hz. Observing a $^{41}$K Bose condensate in thermal contact with a cloud of $^{40}$K and $^6$Li fermions each of roughly the same atom number already implies degeneracy of the fermionic species. If $T = T_{\phi,41}$, then $T/T_{\phi,^{40}K} = \frac{\bar{\omega}_{z,41}}{\bar{\omega}_{z,^{40}K}} \frac{1}{\bar{\omega}_{z,^{6}Li}} \approx 0.51$ and analogously $T/T_{\phi,^{6}Li} = 0.2$. Taking into ac-

![Image](image-url)
We determine the occupation in the triply degenerate quantum mixture. For the fermionic and bosonic distributions, and compare $T/T_F$ to the time of flight distributions in Fig. 2 reveal fits to the time of flight distributions in Fig. 2 reveal $\sim 3.5\%$. Consistent with this expectation, Thomas-Fermi atoms gives a small correction to the Fermi energy of $-\sim 0.1\%$.

We directly observe Pauli pressure and Bose condensation in a triply degenerate quantum mixture. Shown is the normalized release energy $E/E_F$ of each cloud versus the normalized temperature $T/T_F$. Bose condensation of $^{41}\text{K}$ occurs at $T_c/T_F = 0.52$, causing a sudden reduction in release energy below $T_c$. For fermions, in contrast, the release energy saturates due to Pauli pressure. Solid circles: $^{6}\text{Li}$, open circles: $^{40}\text{K}$, solid squares: $^{41}\text{K}$. Solid lines: theory for an interacting Bose gas and a non-interacting Fermi gas. Dashed line: Boltzmann gas.

The inset shows the evolution of the phase space density (PSD) of each atom cloud versus atom number $N$ during evaporation of $^{41}\text{K}$. Open squares: Evaporation of $^{41}\text{K}$ without $^{6}\text{Li}$ and $^{40}\text{K}$.

Anharmonicities along the $y$-direction for $10^5$ $^{6}\text{Li}$ atoms gives a small correction to the Fermi energy of $\sim 3.5\%$. Consistent with this expectation, Thomas-Fermi fits to the time of flight distributions in Fig. 2 reveal $T/T_{F,^{6}\text{Li}} = 0.16$ ($N_{^{6}\text{Li}} = 2.0 \cdot 10^5$) and $T/T_{F,^{40}\text{K}} = 0.51$ ($N_{^{40}\text{K}} = 1.1 \cdot 10^4$), while $T/T_{C,^{41}\text{K}} = 0.9$. Evaporating further to obtain essentially pure condensates, we achieve $T/T_{F,^{6}\text{Li}} = 0.10$ for $^{6}\text{Li}$ and $T/T_{F,^{41}\text{K}} = 0.35$ for $^{40}\text{K}$.

We observe a wide Feshbach resonance in collisions of $^{40}\text{K}$ in state $|9/2, 9/2\rangle$ with $^{41}\text{K}$ in state $|1, 1\rangle$ at 543 G (Fig. 4). This resonance is theoretically predicted to occur at $B_0 = 541.5$ G with a width of $\Delta B = 52$ G, defined via the scattering length $a = a_{bg}(1 + \Delta B/(B - B_0))$, where $a_{bg} = 65a_0$ is the background scattering length in the vicinity of the resonance. This isotopic Bose-Fermi mixture with essentially no gravitational sag and wide tunability of its interaction strength is very promising for controlled many-body experiments, where the only relevant difference between the two atoms is that of quantum statistics. Fig. 4) shows the immersing of a Bose-Einstein condensate of $^{41}\text{K}$ into a Fermi sea of $^{40}\text{K}$ with resonant interactions. The condensate survives for about 5 ms, and the remaining thermal atoms decay with a $1/e$ lifetime of 25 ms at initial densities $1 (3) \times 10^{12}$ cm$^{-3}$ for $^{40}\text{K}$ ($^{41}\text{K}$). Our initial temperatures might be low enough, and the condensate lifetime long enough so that polarons form. At the rim of the condensate, where bosons are the minority, bosons are dressed into Fermi polarons, possibly yielding a Fermi polaron condensate.

| Mixture          | $B_0$ [G] | $\Delta B_{exp}$ [G] | Resonance type |
|------------------|-----------|----------------------|----------------|
| $^{6}\text{Li}\ | 1/2, 1/2\ |^{41}\text{K} | 1, 1\ | 31.9 | 0.2 | s-wave [34] |
| $^{8}\text{Li}\ | 1/2, 1/2\ |^{41}\text{K} | 1, 1\ | 335.8 | 1.1 | s-wave [34] |
| $^{40}\text{K}\ | 9/2, 9/2\ |^{41}\text{K} | 1, 1\ | 472.6 | 0.2 | s-wave [35] |
| $^{40}\text{K}\ | 9/2, 9/2\ |^{41}\text{K} | 1, 1\ | 432.9 | 2.5 | p-wave [35] |
| $^{40}\text{K}\ | 9/2, 9/2\ |^{41}\text{K} | 1, 1\ | 542.7 | 12 | s-wave [35] |

FIG. 3. Observation of Pauli pressure and Bose condensation in a triply degenerate quantum mixture. Shown is the normalized release energy $E/E_F$ of each cloud versus the normalized temperature $T/T_F$. Bose condensation of $^{41}\text{K}$ occurs at $T_c/T_F = 0.52$, causing a sudden reduction in release energy below $T_c$. For fermions, in contrast, the release energy saturates due to Pauli pressure. Solid circles: $^{6}\text{Li}$, open circles: $^{40}\text{K}$, solid squares: $^{41}\text{K}$. Solid lines: theory for an interacting Bose gas and a non-interacting Fermi gas. Dashed line: Boltzmann gas. The inset shows the evolution of the phase space density (PSD) with atom number ($N$) during evaporation of $^{41}\text{K}$. Open squares: Evaporation of $^{41}\text{K}$ without $^{6}\text{Li}$ and $^{40}\text{K}$.

| TABLE I. Observed interspecies Feshbach resonances between $^{6}\text{Li}$, $^{41}\text{K}$ and $^{40}\text{K}$- $^{41}\text{K}$ atoms. The width of the resonance, $\Delta B_{exp}$, is determined by a phenomenological gaussian fit to the observed loss feature (see e.g. Fig. 4). For the $p$-wave resonance, the width was measured at $T = 8$ $\mu$K. |
tion time of such a dressed quasi-particle state should be on the order of $\hbar/E_B \sim 1 \text{ ms}$, where $E_B = 0.6 E_{F,40K}$ is the polaron energy [21]. In the center of the gas, where fermions are the minority, the gas might be in the regime where fermions are dressed by the Bose condensate. It will be intriguing to perform local rf spectroscopy on this unconventional state of polaronic matter and to demonstrate dressing of fermionic and bosonic impurities [21].

In conclusion we have observed triply degenerate quantum gases of $^{41}\text{K}$, $^{40}\text{K}$ and $^6\text{Li}$, through sympathetic cooling of the fermionic species by the boson $^{41}\text{K}$. In the Bose-Fermi mixtures of $^6\text{Li}^{41}\text{K}$ and $^{41}\text{K}-^{40}\text{K}$, five interspecies Feshbach resonances are detected, with s- and p-wave character. The isotopic potassium gas could become a pristine model system for strongly interacting Bose-Fermi mixtures, for example for the study of polarons [21, 20], observation of polaron condensation, and universal transport of mixtures with unlike statistics [21]. The doubly degenerate $^{40}\text{K}-^6\text{Li}$ Fermi-Fermi mixture holds promise for the observation of fermionic superfluidity and Cooper pairing between unlike fermions. Imposing species-dependent optical potentials on mixtures will allow the study of systems with mixed dimensionality [37] and impurity physics such as Anderson localization [38] and the interaction of localized impurities with fermionic superfluids [39].

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