Bose-Fermi Mixtures in a Three-Dimensional Optical Lattice

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We have studied mixtures of fermionic ^{40}K and bosonic ^{87}Rb quantum gases in a three-dimensional optical lattice. We observe that an increasing admixture of the fermionic species diminishes the phase coherence of the bosonic atoms as measured by studying both the visibility of the matter wave interference pattern and the coherence length of the bosons. Moreover, we find that the attractive interactions between bosons and fermions lead to an increase of the boson density in the lattice which we measure by studying three-body recombination in the lattice. In our data, we do not observe three-body loss of the fermionic atoms. An analysis of the thermodynamics of a noninteracting Bose-Fermi mixture in the lattice suggests a mechanism for sympathetic cooling of the fermions in the lattice.

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Quantum liquids and quantum gases are remarkable objects which reveal macroscopic quantum phenomena, such as superfluidity and Bose-Einstein condensation. These fundamental concepts have profoundly influenced our understanding of quantum many-body physics. The distinct behavior observed for purely bosonic or purely fermionic systems sheds light on the role played by quantum statistics. New insights can be attained by mixing bosonic and fermionic species. One of the most prominent examples is a mixture of bosonic ^{4}He and fermionic ^{3}He. There it has been observed that, with increasing admixture of ^{3}He, the critical temperature of the transition between the superfluid and the normal fluid phase is lowered, and below the tricritical point phase separation is encountered [1].

In trapped atomic gases, mixing of bosonic and fermionic species has led to the observation of interaction induced losses or collapse phenomena [2,3] and collisionally induced transport in one-dimensional lattices [4]. In this Letter, we report on the creation of a novel quantum system consisting of a mixture of bosonic and fermionic quantum gases trapped in the periodic potential of a three-dimensional optical lattice. The optical lattice allows us to change the character of the system by tuning the depth of the periodic potential. This leads to a change of the effective mass and varies the role played by atom-atom interactions. The interaction between bosonic and fermionic atoms interconnects two systems of fundamentally different quantum statistics, and a wealth of physics becomes accessible which is beyond that of the purely bosonic [5,6] or purely fermionic [7,8] case. A variety of theoretical work has been devoted to Bose-Fermi mixtures in optical lattices, and new quantum phases have been predicted at zero temperature [9–12]. Moreover, the coupling between a fermion and a phonon excitation in the Bose condensate mimics the physics of polarons [13]. At finite temperature, phase transitions to a supersolid state and phase separation are expected [14].

In our experiment, we prepare fermionic ^{40}K atoms together with a cloud of Bose-Einstein condensed ^{87}Rb atoms. The qualitative behavior when changing the mixing ratio between bosons and fermions is depicted in Fig. 1. The momentum distribution of the pure bosonic sample shows a high contrast interference pattern reflecting the long-range phase coherence of the system. Adding fermionic particles results in the loss of phase coherence of the Bose gas, i.e., a diminishing visibility of the interference pattern and a reduction of the coherence length.

Our experimental setup used to produce a degenerate mixture of a Bose and a Fermi gas has been described in detail in previous work [8]. In brief, fermionic ^{40}K atoms are sympathetically cooled by thermal contact with bosonic ^{87}Rb atoms, the latter being subjected to forced microwave evaporation. The potassium atoms are in the hyperfine ground state $|F = 9/2, m_F = 9/2\rangle$ and the rubidium atoms in the hyperfine ground state $|F = 2, m_F = 2\rangle$. After reaching quantum degeneracy for both species, we transfer both clouds into a crossed beam optical dipole trap operating at a wavelength of 826 nm. The laser beams for the optical dipole trap are aligned in a horizontal plane, and their elliptical waists have $1/e^2$ radii of approximately 50 and 150 μm in the vertical (z) and horizontal (x, y) directions, respectively. In the optical trap, we perform evaporative cooling by lowering the power in each of the

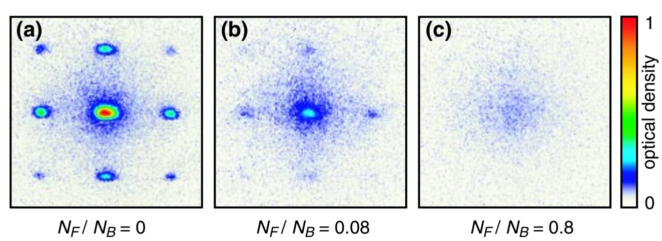

FIG. 1 (color online). Interference pattern of bosonic atoms released from a three-dimensional optical lattice for varying admixture of N_F fermionic atoms at a value $U_{BB}/zJ_B = 5$. The bosonic atom numbers are (a) and (b) $N_B = 1.2 \times 10^5$ and (c) $N_B = 8 \times 10^4$, and the image size is 660 μm × 660 μm. The coordination number of our lattice with simple cubic geometry is $z = 6$.

laser beams to $\simeq 35$ mW. After recompression, the optical dipole trap has the final trapping frequencies $(\omega_x, \omega_y, \omega_z) = 2\pi \times (30, 35, 118)$ Hz for the rubidium atoms. We estimate the condensate fraction to be 90% and use this value to obtain the temperature of both clouds. The Fermi temperature T_F in the optical dipole trap is set by the number of potassium atoms and the trapping frequencies, and we obtain $T/T_F \simeq 0.3$, which is in agreement with a direct temperature measurement of the fermionic cloud.

The three-dimensional optical lattice is generated by three mutually orthogonal laser standing waves at a wavelength of $\lambda = 1064$ nm and a mutual frequency difference of several 10 MHz. Each of the standing wave fields is focused onto the position of the quantum degenerate gases, and the $1/e^2$ radii of the circular beams along the (x, y, z) directions are $(160, 180, 160)$ μm. To load the atoms into the optical lattice, we increase the intensity of the lattice laser beams using a smooth spline ramp with a duration of 100 ms. This ensures adiabatic loading of the optical lattice with populations of bosons and fermions in the lowest Bloch band only. We have checked the reversibility of the loading process into the optical lattice by reversing the loading ramp and, subsequently, let the particles equilibrate during 100 ms in the optical dipole trap without evaporation. We measure that for both the pure Bose gas and the Bose-Fermi mixture the condensate fraction decreases by $\simeq 1.4\%$ per E_R of lattice depth, where $E_R = h^2/2m_{\rm Rb}\lambda^2$ denotes the recoil energy and $m_{\rm Rb}$ the mass of the rubidium atoms.

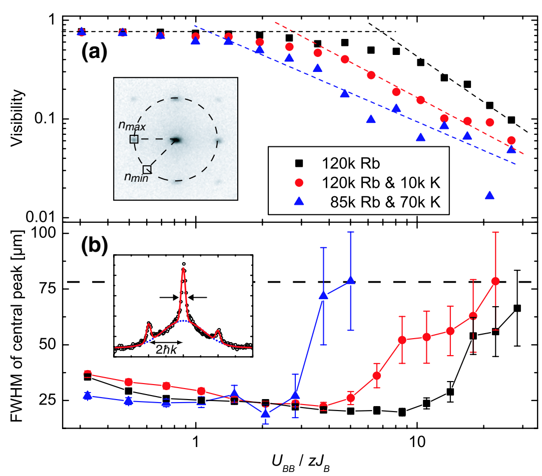

FIG. 2 (color online). (a) Visibility of the Bose-Fermi mixture in the optical lattice for various mixing ratios between bosons and fermions. The intersection between the dashed lines defines the characteristic value $(U_{BB}/zJ_B)_c$. The inset shows the principle of the measurement (see text). (b) Measurement of the width of the central momentum peak which reflects the inverse of the coherence length of the gas. The inset shows how the peak width is extracted from the column sum of the optical density. The dashed line indicates the upper constraint of the width imposed by the fitting routine, and the error bars reflect the fit uncertainty.

The physics of the Bose-Fermi mixture in an optical lattice can be described by the Bose-Fermi Hubbard model (e.g., [10]). The parameters of the model are the tunneling matrix elements $J_{B,F}$ for bosons and fermions, respectively, and the on-site interaction strength U_{BB} between two bosons and U_{BF} between bosons and fermions. Using the most recent experimental value of the K-Rb s-wave scattering length [15], we obtain $U_{BF}/U_{BB} \approx -2$.

We have studied the phase coherence of the bosonic atoms in the optical lattice for various admixtures of fermionic particles. We switch off the optical lattice quickly and allow for 25 ms of ballistic expansion before taking an absorption image of the atomic cloud. From the absorption image, we measure the visibility of the interference pattern. We determine the maximum $n_{\rm max}$ and the minimum $n_{\rm min}$ of the density of the atoms at a momentum $|\vec{q}| = 2\hbar k$, with $k = 2\pi/\lambda$ [see inset in Fig. 2(a)] [16]. From this, we calculate the visibility $\mathcal{V} = (n_{\rm max} - n_{\rm min})/(n_{\rm max} + n_{\rm min})$.

For the purely bosonic case, we obtain results similar to previous measurements [16–18]. In our data [see Fig. 2(a)], the visibility $\mathcal{V}$ starts to drop off at a characteristic value $(U_{BB}/zJ_B)_c \approx 6.5$. For larger values of U_{BB}/zJ_B, the decrease in visibility is approximated by $\mathcal{V} \propto (U_{BB}/zJ_B)^\nu$, with $\nu = -1.41(9)$, which is consistent with our earlier measurement in a different lattice setup giving $\nu = -1.36(5)$ [17] but different from the exponent $\nu = -0.98(7)$ obtained in Ref. [16]. For a mixture of bosonic and fermionic atoms, the results change; see also [19]. Whereas in the superfluid regime for very low values of U_{BB}/zJ_B the visibility is similar to the pure bosonic case, the presence of the fermions decreases the characteristic value $(U_{BB}/zJ_B)_c$ beyond which the visibility drops off significantly. Nevertheless, the visibility still shows a power-law dependence on U_{BB}/zJ_B with an exponent in the range of $-1 < \nu < -1.5$.

To quantify the shift of the visibility data towards smaller values of U_{BB}/zJ_B, we have fitted the power-law decay for large values of U_{BB}/zJ_B and extrapolated the slope to the visibility for the superfluid situation [dashed lines in Fig. 2(a)]. The intersection defines the character-

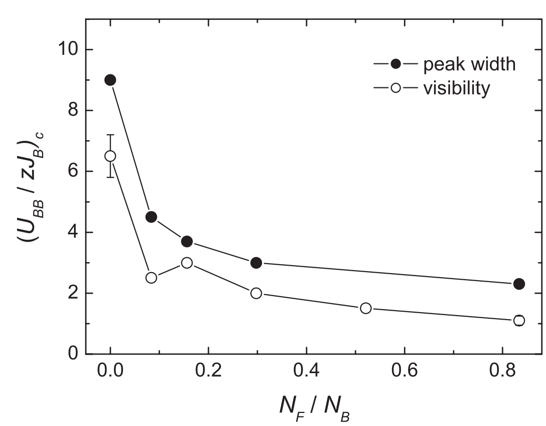

FIG. 3. Decrease of the coherence of the Bose gas in the lattice vs the admixture of fermions.

istic value $(U_{BB}/zJ_B)_c$, which depends on the mixing ratio between fermions and bosons N_F/N_B as shown in Fig. 3. From this graph, it is evident that even very small admixtures of fermionic atoms change the coherence properties of the bosonic cloud significantly.

The phase coherence of the bosons in the lattice is not only described by the visibility of the interference pattern but also by the coherence length of the sample [17,20]. In a superfluid state, the coherence length is comparable to the size of the system. The coherence length is related to the inverse of the width of the zero-momentum peak plus a small contribution from the repulsive interaction between the bosonic atoms. For the pure bosonic case, we find that this width starts to increase at a value of $(U_{BB}/zJ_B)_c \approx 9$ [see Fig. 2(b)]. For the case of a Bose-Fermi mixture, this value is dramatically altered: For an increasing admixture of fermionic atoms to the bosonic sample, the value decreases and it behaves very similar to the corresponding value $(U_{BB}/zJ_B)_c$ for the visibility (see Fig. 3).

Our interpretation of the simultaneous decrease of both the coherence length and the visibility with increasing admixture of fermions is that the system leaves the superfluid phase. While for the pure bosonic case this indicates a Mott insulator transition [16,17], for the mixture the analysis is more delicate due to the different interactions and the different quantum statistics of the two species. The full understanding of the observed effects including strong interactions and finite temperature is challenging. We will consider two limiting situations, namely, a strongly interacting Bose-Fermi mixture at $T = 0$ in which polarons and composite fermions are formed and a noninteracting mixture at finite temperature. In both explanations, we encounter a destruction of the superfluid with increasing fermionic admixture which qualitatively reflects our results.

At zero temperature, several quantum phases of the system are predicted [10–14], depending on the sign and the strength of the Bose-Fermi interaction. At low depth of the optical lattice, the interaction of the Bose-Einstein condensate with the Fermi gas leads to the depletion of the condensate [21] and to the formation of polarons where a fermion couples to a phonon excitation of the condensate [13]. The coupling strength of the fermions to the phonon modes depends on U_{BF} and the ratio U_{BB}/J_B. If the coupling becomes very strong, the system is unstable to phase separation ($U_{BF} > 0$) or to collapse ($U_{BF} < 0$). In the stable regime, the polarons can form a p-wave superfluid or induce a charge density wave, as has been analyzed in one spatial dimension [13]. The enhanced bosonic density around a fermionic impurity increases the effective mass of the fermion and might enhance the tendency of the bosons to localize. For our parameters, the phonon velocity is comparable to the Fermi velocity, a regime that is usually inaccessible in solids. On the other hand, the interaction of the Bose gas with the second species leads to an effective attractive interaction between the bosons which would favor a Mott insulator transition at a larger depth of the optical lattice [13]. At a larger depth of the optical lattice, other effects also come into play. Composite fermions consisting of one fermion and n_B bosons form when the binding energy of the composite fermion exceeds the gain in kinetic energy that the particles would encounter by delocalizing. An effective Hamiltonian for these (spinless) composite fermions with renormalized tunneling and nearest neighbor interaction has been derived, and their quantum phases have been investigated theoretically [9,10]. In this situation, the Bose-Einstein condensate can be completely depleted by the interactions between bosons and fermions.

For the finite temperature model of the noninteracting gas, we consider the entropy of the cloud of bosons and fermions, which is $S = \alpha N_F T/T_F + \beta N_B (T/T_c)^3$. $T_F = \hbar\bar{\omega}_F (6N_F)^{1/3}$ denotes the Fermi temperature for N_F fermions in a trap with frequency $\bar{\omega}_F$ and $T_c = \hbar\bar{\omega}_B (N_B/\zeta(3))^{1/3}$ the critical temperature for Bose-Einstein condensation with α and β being numerical constants. When increasing the depth of the optical lattice adiabatically, the temperatures of the two species remain equal to each other due to collisions, while T_c and T_F evolve very differently. This is due to the fact that the tunneling rates for the fermions are up to an order of magnitude larger than for the bosons for our lattice parameters. Since the effective masses $m^*_{B,F} \propto 1/J_{B,F}$ enter into the degeneracy temperatures, T_c decreases much faster than T_F. At constant entropy, this results in adiabatic heating of the bosonic cloud and a reduction of the condensate fraction. Simultaneously, the fermionic cloud is cooled adiabatically, similar to the situation considered without a lattice in Ref. [22]. For the noninteracting mixture with our parameters, one expects a reduction of T/T_F by a factor of approximately 2 at a lattice depth of $20E_R$.

In the experiment, we have further studied the occupation of the optical lattice by measuring three-body recombination. Lattice sites with a higher occupation than two atoms are subject to inelastic losses where a deeply bound molecule is formed and ejected from the lattice together with an energetic atom. Independent of their occupation, all lattice sites are furthermore subject to loss processes such as off-resonant light scattering, background gas collisions, or photoassociation due to the trapping laser light. The attractive interaction between the bosons and the fermions changes the occupation of bosons on the sites of the optical lattice. For the given ratio of the on-site interaction strength of $U_{BF}/U_{BB} \simeq -2$, it is energetically favorable to have up to five bosons per site if a fermion is present.

The experimental sequence to study the three-body decay starts from an initially superfluid Bose gas at a potential depth of $10E_R$. We use a ramp time of 30 ms to increase the potential depth of the lattice from zero to $10E_R$ during which we do not observe a loss of atoms. Subsequently, we freeze the atom number distribution by quickly changing the lattice depth to a large value of $18E_R$, where the tunneling time of the bosons is $\tau_B = 1/zJ_B = 23$ ms. We monitor the total atom number as a function of the hold time in the deep optical lattice (see Fig. 4) and observe two

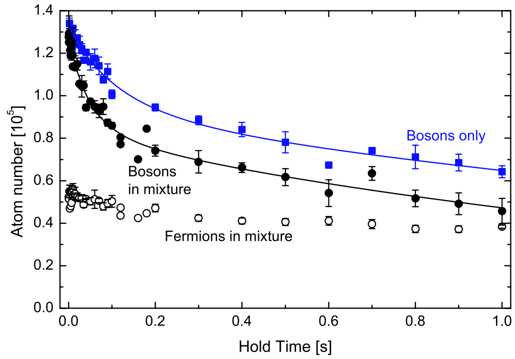

FIG. 4 (color online). Decay of a pure bosonic gas (squares) and a Bose-Fermi mixture (circles) in the optical lattice. The fast initial decay of the bosons is much more pronounced in the mixture, reflecting the higher density due to Bose-Fermi attraction. For the fermions, hardly any loss is observed. The error bars indicate statistical errors from three repetitive measurements.

distinct time scales of the decay of the atoms. The fast initial time scale is due to three-body losses from multiply occupied lattice sites. The slower decay is due to single-particle loss processes.

To extract quantitative information from the loss curves, we fit the data with the following model. We assume that any singly or doubly occupied site decays with a single-particle loss rate Γ_1. Multiply occupied sites decay with a rate determined by the three-body loss constant $K_3^B = 1.8 \times 10^{-29}$ cm^6/s [23] and the three-body density $[n(\mathbf{r})]^3$ at the lattice site. Since we start from a superfluid, the number distribution at the lattice sites can be approximated by a coherent state with a third order correlation function being equal to unity [24]. We calculate the three-body loss rate assuming Gaussian ground state wave functions at each lattice site to be $\Gamma_3 = 0.24 \times n_B^3$ s^{-1}, where n_B is the number of bosons on the site. By fitting the data with this model, we extract the occupation of the lattice. We obtain $n_{1,2} = 67(3)\%$ of the sites with single or double occupation, $n_3 = 23(9)\%$ sites with triple occupation, and $n_4 = 10(8)\%$ of lattice sites with occupation four. A mean field calculation neglecting tunneling yields the theoretical values $\bar{n}_{1,2} = 58\%$, $\bar{n}_3 = 33\%$, and $\bar{n}_4 = 17\%$, which gives reasonable agreement given the simplicity of the model. The slow decay rate is determined to be 0.35(7) s^{-1}.

Upon adding fermions to the system, we find a much faster initial decay due to three-body loss for the rubidium atoms. The single-particle loss constant is, however, the same. In contrast, for the fermionic atoms, we do not observe a particle loss of a comparable order of magnitude. This suggests that the observed loss is only due to three-body recombination between three rubidium atoms. Recent results have suggested that the three-body loss constant K_3^{BF} for K-Rb-Rb collisions is an order of magnitude larger than for Rb-Rb-Rb collisions [3]. This is not consistent with our data, since we do not observe the corresponding fast loss of potassium atoms, similar to previous results [25].

In conclusion, we have investigated a Bose-Fermi mixture in a three-dimensional optical lattice. We have observed that the presence of fermions changes the coherence properties of the Bose gas and substantially enhances the three-body loss of bosonic atoms. Bose-Fermi mixtures in an optical lattice promise to be an incredibly rich quantum system [9–14]. A number of Feshbach resonances between ^{87}Rb and ^{40}K [15,26] exist which will give access to various quantum many-body regimes predicted in the literature as well as to the creation of ultracold heteronuclear molecules.

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