Observation of Spin-Spin Fermion-Mediated Interactions between Ultracold Bosons

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Interactions in an ultracold boson-fermion mixture are often manifested by elastic collisions. In a mixture of a condensed Bose gas (BEC) and spin polarized degenerate Fermi gas (DFG), fermions can mediate spin-spin interactions between bosons, leading to an effective long-range magnetic interaction analogous to Ruderman-Kittel-Kasuya-Yosida [Phys. Rev. **96**, 99 (1954); Prog. Theor. Phys. **16**, 45 (1956); Phys. Rev. **106**, 893 (1957)] interaction in solids. We used Ramsey spectroscopy of the hyperfine clock transition in a ^{87}Rb BEC to measure the interaction mediated by a ^{40}K DFG. By controlling the boson density we isolated the effect of mediated interactions from mean-field frequency shifts due to direct collision with fermions. We measured an increase of boson spin-spin interaction by a factor of $\eta = 1.45 \pm 0.05^{\mathrm{stat}} \pm 0.13^{\mathrm{syst}}$ in the presence of the DFG, providing clear evidence of spin-spin fermion mediated interaction. Decoherence in our system was dominated by inhomogeneous boson density shift, which increased significantly in the presence of the DFG, again indicating mediated interactions. We also measured a frequency shift due to boson-fermion interactions in accordance with a scattering length difference of $a_{bf_2} - a_{bf_1} = -5.36 \pm 0.44^{\mathrm{stat}} \pm 1.43^{\mathrm{syst}} a_0$ between the clock-transition states, a first measurement beyond the low-energy elastic approximation [R. Côté, A. Dalgarno, H. Wang, and W. C. Stwalley, Phys. Rev. A **57**, R4118 (1998); A. Dalgarno and M. Rudge, Proc. R. Soc. A **286**, 519 (1965)] in this mixture. This interaction can be tuned with a future use of a boson-fermion Feshbach resonance. Fermion-mediated interactions can potentially give rise to interesting new magnetic phases and extend the Bose-Hubbard model when the atoms are placed in an optical lattice.

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Mediated interactions are at the heart of modern physics. In the standard model, every interaction has a bosonic mediator. In solid state physics, electrons can form Cooper pairs by interacting via phonons, resulting in BCS superconductivity [1], or serve as mediators for interactions between magnetic impurities, leading to Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction [2–4]. This interaction is a spin-spin long-range mediated interaction, it was observed between spin impurities in metals [5–7] and quantum dots in semiconductors [8–10]. The mechanical effects of a mean-field spinless analog of RKKY were recently observed in ultracold atoms [11]. Theoretical studies proposed it should exist in graphene [12–14], and in an ultracold Bose-Fermi mixture [15,16].

Spin-spin magnetic interactions are ubiquitous in physics; NMR, the Kondo effect, and the Ising model are prime examples. Magnetic interactions lead to different magnetic phases in metals, such as ferromagnetic and antiferromagnetic ordered phases. Interactions in ultracold atomic gases can be also regarded as spin-spin interactions in the mean field approximation. Effective magnetic interactions were observed in spinor BEC [17,18] and fermions in optical lattices [19,20]. In a quantum degenerate Bose-Fermi mixture, fermion mediated interactions have been predicted to create spin-spin long-range interaction between bosons that can be tuned with a Feshbach resonance [15,16]. Mediated magnetic interactions may lead to interesting new magnetic phases of matter [21–23] and can extend the Bose-Hubbard model when the atoms are placed in an optical lattice [15].

Unlike superexchange interactions, which require the atoms to be at close contact, fermion mediated interactions have a range that exceeds the Fermi wavelength of the mediating DFG. Other forms of long-range interactions in ultracold gases have been observed in gases of highly magnetic atoms [24–26], Rydberg atoms [27–29], and in polar molecules [30,31]. Mediated interactions were previously seen in Bose-Einstein condensates coupled to an optical cavity [32–35], where photons act as mediators.

Fermion mediated interactions can be intuitively understood. A boson immersed in a Fermi sea induces a perturbation to the fermion density that oscillates with a typical length inversely proportional to the Fermi wave number k_f, known as Friedel oscillations [36]. When another boson interacts with the deformed Fermi sea, interaction is mediated between the bosons. Spin-dependent coupling of the bosons to the Fermi sea leads to spin-spin magnetic mediated interactions.

In a quantum degenerate mixture of Bose-Einstein condensate (BEC) and a polarized degenerate Fermi gas (DFG), atoms interact via s-wave collisions, characterized by scattering lengths a_{bb} and a_{bf} for boson-boson and boson-fermion interactions, respectively. Boson-boson

s-wave collisions in a BEC cause a mean field energy shift $E_{bb} = 2\pi(\hbar^2/m_b)a_{bb}n_b$ [37] where $\hbar$ is the reduced Planck constant, n_b, m_b are boson density and boson mass, respectively. For light fermions ($m_f \ll m_b$, where m_f is the fermion mass), an exchange of fermionic excitation between bosons results in a long-range potential, analogous to RKKY interaction in solids $V(R) \propto -a_{bf}^2\{[\sin(2k_fR) - 2k_fR\cos(2k_fR)]/[(2k_fR)^4]\}$ [15,16], where R is the distance between bosons. In a mean field approximation, the energy shift due to this potential is $E_{\mathrm{med}} = (2\pi\hbar^2/m_b)a_{\mathrm{med}}n_b$, where $a_{\mathrm{med}} = (\xi/2\pi)\{[(m_b+m_f)^2]/m_bm_f\}(6\pi^2n_f)^{1/3}a_{bf}^2$ is the mediated interaction scattering length, n_f is the fermion density, and ξ is a dimensionless parameter that characterizes the strength of the fermion-mediated interaction, predicted to be π^3 [15] or 1 [16]. We note that this potential is expected to have corrections beyond the mean-field approximation since it decays as $1/R^3$ and partial waves of higher order contribute even at zero temperature. We also note that the bosons are in a BEC at the ground state of the system, and the healing length of the BEC is longer than the typical length scale of the potential $1/2k_f$.

In our experiment, a BEC of $\sim 5\times10^5$ ^{87}Rb atoms was in thermal contact with a DFG of $\sim 1.4\times10^5$ ^{40}K atoms in a crossed dipole trap of frequencies $\omega_{x,y,z} = 2\pi\times(27,39,111)$ Hz $[\omega_{x,y,z} = 2\pi\times(29,49,182)$ Hz$]$ for bosons (fermions) at a temperature of ~ 90 nK ($T/T_c \sim 0.55$ and $T/T_f \sim 0.35$), with mean BEC (DFG) Thomas-Fermi (Fermi) radius of ~ 11 μm (~ 26 μm). The fermions are spin polarized in state $|F=9/2, m_f=-9/2\rangle$. When calculating fermion mediated interaction, we assume that the bosons are stationary ($m_f \ll m_b$) and the change in their energy after a boson-fermion collision is negligible, while in our system the mass ratio is ~ 2. However, the fermions involved in the process are close to the Fermi momentum and the BEC has essentially zero momentum. After an exchange of momentum $q \ll k_f$, the change in energy for fermions $\Delta\epsilon_f$ is much larger than for bosons $\Delta\epsilon_b$, since $(\Delta\epsilon_f/\Delta\epsilon_b) = (k_f/q)(m_b/m_f) \gg 1$.

We used microwave spectroscopy to measure the $|F=1, m_f=0\rangle = |1\rangle \leftrightarrow |F=2, m_f=0\rangle = |2\rangle$ hyperfine clock transition frequency in ^{87}Rb with and without ^{40}K atoms. The clock transition frequency shift includes three contributions—boson-boson interaction Δf_{bb}, boson-fermion interaction Δf_{bf}, and mediated interaction Δf_{med},

$$\Delta f = \underbrace{2\frac{\hbar}{m_b}(a_{bb_2}-a_{bb_1})n_b}_{\Delta f_{bb}} + \underbrace{\hbar\left(\frac{1}{m_b}+\frac{1}{m_f}\right)(a_{bf_2}-a_{bf_1})n_f}_{\Delta f_{bf}} + \underbrace{2\frac{\hbar}{m_b}(a_{\mathrm{med}_2}-a_{\mathrm{med}_1})n_b}_{\Delta f_{\mathrm{med}}}. \quad (1)$$

Δf_{bb} and Δf_{med} are proportional to boson density, while Δf_{bf} is independent of it. To distinguish between the three contributions, we measured frequency shifts for different boson densities, with and without fermions. With only bosons present, we measured Δf_{bb}, the change in frequency per boson density $(d\Delta f/dn_b)_b$ which is a direct measure of boson-boson interaction. When we added fermions, we measured a constant term Δf_{bf} that does not depend on boson density and Δf_{med}, which causes change in frequency that is proportional to boson density. A change in the slope $(d\Delta f/dn_b)_{b+f}$ (measurement with bosons and fermions) compared to $(d\Delta f/dn_b)_b$ (measurement with bosons only) is a clear indication of fermion mediated interactions between bosons in our mixture.

The clock transition states are first-order magnetic insensitive at zero magnetic field and thus also have the same electronic triplet and singlet components when colliding with another atom. This renders the difference in scattering lengths $a_{bf_2} - a_{bf_1}$ between these two states small as compared with other transitions [38,39] and thus decreases the mediated interaction shift Δf_{med} and the boson-fermion shift Δf_{bf}.

Following a Ramsey experiment of variable duration t_R, we released the atoms from the dipole trap. After a long time of flight (20 ms for the bosons and 12 ms for the fermions) we used absorption imaging to measure $P = N_2/N_{\mathrm{tot}}$, the boson population in state $|2\rangle$, and the BEC chemical potential and the fermion fugacity, which we used to determine boson and fermion densities in each run. The BEC chemical potential μ_b is determined from a bimodal fit function to the column density [40] of the BEC in the tightly confined direction of our trap ($\omega_z > \omega_{x,y}$) after expansion, from that we calculate the average boson density $\bar{n} = \frac{4}{7}n_0 = (\mu_b/7\pi\hbar^2a_{bb})$, here n_0 is the peak density [41].

The presence of the fermions may distort our boson density measurements as the chemical potential of the BEC changes due to boson-fermion interaction [16]. This change is $\sim\frac{1}{7}\mu_b$, it is uniform across the BEC (since the size of the fermions cloud is larger due to Fermi pressure), and fairly constant throughout our measurement. During the release from the trap the interaction energy is divided between bosons and fermions as the clouds expand. To verify that it does not introduce a significant systematic error to our density evaluation, we compared the chemical potential of BECs with similar atom number (determined from absorption imaging) with and without fermions. We did not observe a change in measured chemical potential after expansion in the presence of fermions [40].

We controlled the boson density during state preparation, by transferring a predetermined fraction of ^{87}Rb atoms to state $|2\rangle$, and removing this fraction from the trap using a resonant laser pulse. Measurements without fermions were performed in an identical fashion to obtain similar boson densities, expelling the fermions at the end of the preparation stage, immediately before the Ramsey measurement.

Our results are shown in Fig. 1. Red (blue) solid circles show the measured populations without (with) fermions. Solid lines are the result of a maximum likelihood fit to the data using the fit function

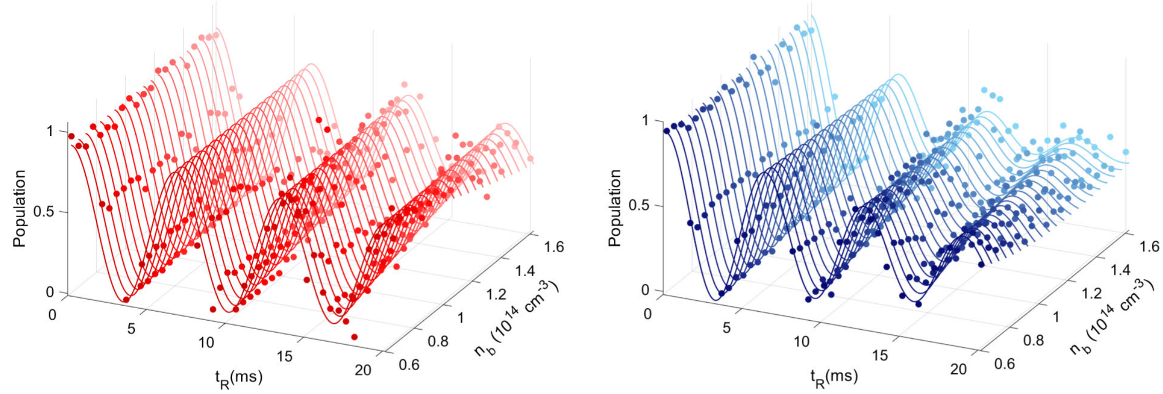
$$P(n_b, t_R) = Ae^{-g_c n_b t_R} \cos[(\delta + g n_b) t_R] + C. \qquad (2)$$

Here, A is the contrast, g_c is decoherence rate per boson density, δ is detuning between the MW driving field and the transition, $g = (d\Delta f/dn_b)$ is the boson density frequency shift, and C is a constant term to account for a finite population in state $|2\rangle$. We extracted three frequency shifts from the fits. The boson density shift in the absence of fermions Δf_{bb}, the mean-field shift due to direct boson-fermions collisions Δf_{bf}, and the boson density shift which was mediated by the presence of fermions Δf_{med}.

The measured frequencies and decay rates are shown in Fig. 2. Red (blue) lines show the result from our fit function [Eq. (2)] without (with) fermions. Solid circles show frequencies taken from a fit function $P(t_R) = Ae^{-\Gamma t_R} \cos(2\pi f t_R) + C$ to averaged data for different densities. Here, A is the contrast, Γ is the decay rate, f is the oscillation frequency, and C is a constant term to account for a finite population in state $|2\rangle$. Since the light shifts, local-oscillator detuning, and Zeeman shifts are independent of the presence of fermions, the difference in frequency between measurements with and without fermions is a result of boson-fermion density shift $\delta_{b+f} - \delta_b = \Delta f_{bf}$. Our frequency measurements [Fig. 2(a)] show a constant shift with respect to boson density due to boson-fermion interaction $(d\Delta f_{bf}/dn_f) = 6.57 \pm 0.53^{\mathrm{stat}} \pm 1.75^{\mathrm{syst}} \times 10^{-13}$ Hz cm^3 from which we calculate a boson-fermion scattering length difference $a_{bf_2} - a_{bf_1} = -5.36 \pm 0.44^{\mathrm{stat}} \pm 1.43^{\mathrm{syst}} a_0$, where a_0 is the Bohr radius (all errors reported are of 1 standard deviation [40]). To the best of our knowledge, the scattering length for $^{87}\mathrm{Rb} - {}^{40}\mathrm{K}$ collisions is only previously known from Feshbach spectroscopy measurement [42]. Our measured value is a correction to the low-energy elastic approximation [38,39] and can be used to calibrate inter atomic potential calculations.

When measuring without fermions, g is a direct measurement of boson-boson interaction. We measure a shift $(d\Delta f/dn_b)_b = 10.77 \pm 0.27^{\mathrm{stat}} \pm 1.69^{\mathrm{syst}} \times 10^{-14}$ Hz cm^3 that corresponds with a difference in scattering lengths $a_{bb_2} - a_{bb_1} = -1.40 \pm 0.04^{\mathrm{stat}} \pm 0.22^{\mathrm{syst}} a_0$, in agreement with previously measured values [43,44] (after taking into account a factor of 2 for BEC statistics [37] and uncertainties in atom numbers).

When adding fermions we measure a change in the slope $(d\Delta f/dn_b)_{b+f}$ by a factor $\eta = 1.45 \pm 0.05^{\mathrm{stat}} \pm 0.13^{\mathrm{syst}}$ compared to our measurement without fermions, which is a clear indication of spin-spin mediated interactions. The mediated interaction frequency shift is $(d\Delta f_{\mathrm{med}}/dn_b) = 4.76 \pm 0.47^{\mathrm{stat}} \pm 0.75^{\mathrm{syst}} \times 10^{-14}$ Hz cm^3. Our measurements were done in a randomized fashion, interlacing different boson densities with or without fermions. Any systematic errors we have regarding our estimation of boson densities is common in both measurements. The slope ratio $\eta = (d\Delta f/dn_b)_{b+f}/(d\Delta f/dn_b)_b = 1 + (\Delta f_{\mathrm{med}}/\Delta f_{bb})$ only depends weakly on the fermion density $(\eta - 1 \propto n_f^{1/3})$. The fermion density in our



(a) (b)

FIG. 1. Ramsey spectroscopy—^{87}Rb $F = 2$ population vs Ramsey time measured at different boson densities for (a) bosons only and (b) a mixture of bosons and fermions. Data points are averaged for different boson densities to avoid cluttering (1 standard deviation errors are comparable to marker size). The solid lines are the result of a single 2D fit to all data points [see Eq. (2) in the text]. We measured a boson density shift of $(d\Delta f/dn_b)_b = 10.77 \pm 0.27^{\mathrm{stat}} \pm 1.69^{\mathrm{syst}} \times 10^{-14}$ Hz cm^3 for bosons (a) and $(d\Delta f/dn_b)_{b+f} = 15.53 \pm 0.39^{\mathrm{stat}} \pm 2.37^{\mathrm{syst}} \times 10^{-14}$ Hz cm^3 for the boson-fermion mixture (b); this change is a clear effect of spin-spin mediated interaction. The signal decays when increasing boson density in both cases, and to a larger extent when fermions are present, another indication of mediated interactions.

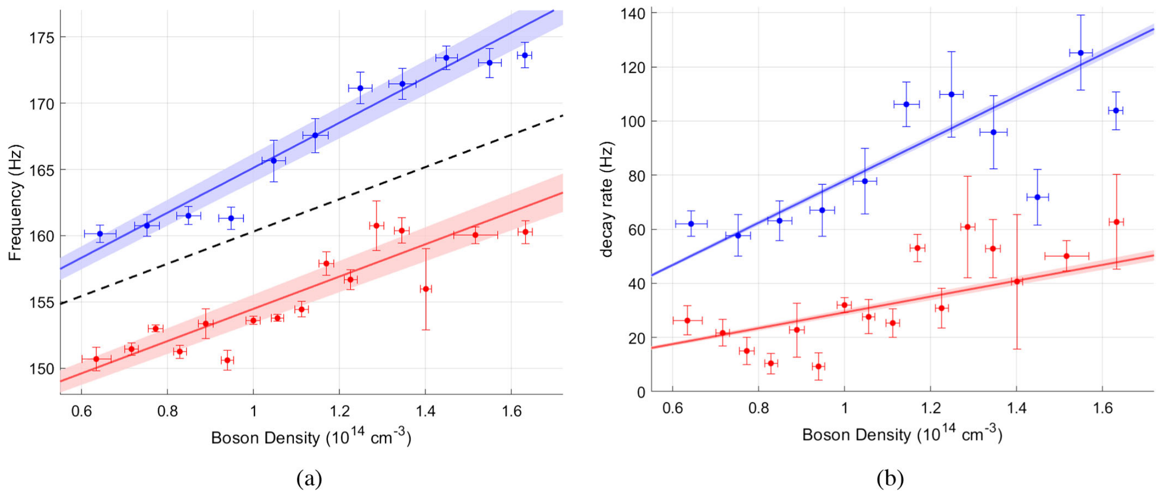


FIG. 2. Frequency shift (a) and decay rate (b) for different boson densities for bosons only (red) and a mixture of bosons and fermions (blue). The lines are extracted from a 2D fit to all data points (shaded area denotes 1 standard deviation), the solid circles are extracted from fits to averaged data for different boson densities (density errors are statistical standard deviation from binning). A dashed black line is shown in (a) parallel to the red line and crosses the blue line at zero density. (a) A constant frequency shift between the two lines (i.e., independent of boson density) is a measure of boson-fermion interaction with $a_{bf_2} - a_{bf_1} = -5.36 \pm 0.44^{\text{stat}} \pm 1.43^{\text{syst}} a_0$. A change in the slope by a factor $\eta = 1.45 \pm 0.05^{\text{stat}} \pm 0.13^{\text{syst}}$ is a clear effect of fermion mediated interaction. Both of these effects are insensitive to any systematic error that is common to measurements with or without fermions (i.e., light shift, magnetic field fluctuations, and errors in estimating the boson density). (b) The decay rate increases with boson density in both cases (with or without fermions), while the increase is faster when fermions are present, indicating mediated interactions.

measurements is $(8.6 \pm 2) \times 10^{12}$ cm^{-3}, we divided our data for different fermion densities and fitted to Eq. (2), but did not see significant change in η. When using our measured values for $a_{bf_2} - a_{bf_1}$ and a previously known value for $a_{bf_1} = -185 \pm 7a_0$ [42] we calculate the expected mediated interaction shift and find $\xi = 1.02 \pm 0.10^{\text{stat}} \pm 0.40^{\text{syst}}$, in good agreement with $\xi = 1$ theory [16] and a recent mechanical measurement [11].

The measured decay rates are shown in Fig. 2(b). Our coherence time is limited by inhomogeneous density shifts in the BEC, previous Ramsey measurements with thermal clouds and at lower densities have shown longer coherence times (> 0.5 s). Our results show [Fig. 2(b)] a clear dependence of the decay rate on the boson density. When adding the fermions the decay is faster and it also increases more rapidly with boson density by a factor of 2.3 ± 0.5. For a BEC immersed in a homogeneous cloud of fermions, the coherence decay should not be affected by direct collisions with the fermions. However, fermion mediated interactions should affect the decay as it changes the effective scattering length between the bosons in an inhomogeneous manner. We also note that, besides inhomogeneous density broadening, the spin-dependent coupling of bosonic superposition to a bath of fermions is expected to lead to increased decoherence, as an intrinsic aspect of mediated interactions. The change in the derivative of the decay rate with respect to boson density is another indication of mediated interactions in the mixture.

In summary, we have performed a first spectroscopic measurement of spin-spin fermion mediated interaction in a quantum degenerate Bose-Fermi mixture. We measure the long wavelength limit of the response function of bosons to a density perturbation caused by the fermions [15,16], a mean-field effect of fermion-mediated interaction in our mixture. We used precision spectroscopy to measure frequency shifts of internal states of the bosons due to mediated interactions, the accuracy of our measurement enables us to measure the spin dependence of mediated interaction which is only ~5% of the interaction itself. We measured an interaction of a $\sigma_z \sigma_z$ type, which is relevant in the Ising model and spin phases, among others. Our method can be used to measure other types of mediated interactions in mixtures. It is a first step towards realizing long-range mediated interaction between atoms in a lattice, extending the known Bose-Hubbard model beyond nearest neighbor interactions. While the effect is small in our measurement, it can be increased significantly using an interspecies Feshbach resonance or by probing a different transition where the scattering length difference is larger.

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