Supporting Online Material for

Probing Interactions Between Ultracold Fermions

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Materials and methods

To first cool and trap the atoms, ^{87}Sr is loaded into a magneto-optical trap (MOT) from a slowed atomic beam. Fig. S1a shows a diagram of relevant energy levels used in cooling, trapping and detecting ^{87}Sr. The MOT is operated on the strong $^1S_0 - ^1P_1$ transition, and cools the atoms to millikelvin temperatures. A second MOT stage operated on the narrow $^1S_0 - ^3P_1$ transition is then used to cool the atoms further to microkelvin temperatures. This second stage MOT uses dual-frequency narrow line cooling (*S1,S2*). During the MOT phase the one-dimensional optical lattice is superimposed on the atoms in the vertical direction. After the second stage MOT, the MOT cooling beams and magnetic gradient are turned off, leaving $\sim$2000 atoms trapped in the

optical lattice. After the lasers and magnetic fields are turned off, the temperature of atoms remaining in the lattice is ~ 3 μK.

To vary the temperature of the atoms, additional cooling or heating is performed on the lattice-trapped atoms. The cooling is performed in three dimensions, with Doppler cooling applied along the transverse direction of the lattice, and sideband cooling (heating) along the longitudinal axis. The laser beams used for cooling (heating) are red (blue) detuned from the $^1S_0$(F = 9/2)$-^3P_1$(F = 11/2) transition. $\vec{F} = \vec{I} + \vec{J}$ is the total angular momentum, with $\vec{I}$ the nuclear spin and $\vec{J}$ the total electron angular momentum. The cooling (heating) beams are applied first along the transverse direction for 20 ms, followed by 30 ms along the longitudinal direction. Simultaneous with the sideband cooling (heating) the atoms are spin-polarized in a weak magnetic bias field ($\sim$ 30 mG) using an optical pumping beam resonant with the ^{1}S$_0$(F = 9/2)$-^3$P$_1$(F = 9/2) transition. By choosing the correct polarization for the optical pumping beam, atoms are polarized into either the m_F = +9/2 (m_F = magnetic quantum number) or m_F = -9/2 ground state. To measure the final temperature of the atoms, two different techniques are used. From time-of-flight analysis the temperature of both the longitudinal and transverse directions can be directly measured. By examining the spectral components of sideband spectroscopy as shown in Fig. 1A, the longitudinal temperature can also be accurately extracted. The total atom number is determined by fluorescence measurements. The average density is then calculated using the trap volume. The trap volume is determined using our measured trap frequencies and temperatures and assumes a Maxwell-Boltzmann distribution.

Orienting the lattice in the vertical direction breaks the energy degeneracy between lattice sites, strongly prohibiting inter-site tunneling (*S3*). This ensures that collisions occur only between atoms in the same lattice site. The lattice is aligned with a slight angle with respect to gravity, to accommodate the vertical MOT beams. The probe beam used for spectroscopy is aligned collinear with the optical lattice, and the polarization of the beam is also parallel to that

of the lattice. To minimize inhomogeneity due to probe beam focusing, the waist of the probe beam is ∼5 times larger than the waist of the lattice focus.

Supporting text

For a given atom in the electronic ground state $^1S_0$ and motional state (n_x, n_y, n_z), the excitation probability during the spectroscopy pulse is

$$p_e(\Delta, t) = \frac{\Omega_{\vec{n}}^2}{\Omega_{\vec{n}}^2 + \Delta^2} \sin^2\left(\frac{t\sqrt{\Omega_{\vec{n}}^2 + \Delta^2}}{2}\right), \tag{S1}$$

where Δ is the detuning of the clock laser from resonance, t is the length of the spectroscopy pulse, and the modified Rabi frequency is given by (*S4*):

$$\Omega_{\vec{n}} = \Omega_{n_x,n_y,n_z} = \Omega_0 e^{(-\eta_x^2-\eta_y^2-\eta_z^2)/2} L_{n_x}(\eta_x^2) L_{n_y}(\eta_y^2) L_{n_y}(\eta_y^2). \tag{S2}$$

Here Ω_0 is the bare Rabi frequency, $L_{n_{x,y,z}}$ are Laguerre polynomials, and $\eta_{x,y,z}$ are the Lamb-Dicke parameters for the transverse and longitudinal directions (assuming the projection of the misalignment on the transverse plane bisects x and y axes):

$$\begin{aligned} \eta_x = \eta_y &= \frac{\sin(\Delta\theta)}{\sqrt{2}\lambda_L}\sqrt{\frac{h}{2m\nu_x}} \\ \eta_z &= \frac{1}{\lambda_L}\sqrt{\frac{h}{2m\nu_z}}. \end{aligned} \tag{S3}$$

To calculate the density shift, we return to our two-atom model. As discussed in the main text we can explicitly calculate $G_{12}^{(2)}$ from the anti-symmetrized overlap of the two wavefunctions. The antisymmetrized wavefunction $|\Psi_{AS}\rangle$ is given by

$$|\Psi_{AS}\rangle = \frac{1}{\sqrt{2}}\left(\psi_1\psi_2 - \psi_2\psi_1\right) \tag{S4}$$

$$= \frac{1}{\sqrt{2}}\left((\alpha|g\rangle + \beta|e\rangle)(\gamma|g\rangle + \delta|e\rangle) - (\gamma|g\rangle + \delta|e\rangle)(\alpha|g\rangle + \beta|e\rangle)\right) \tag{S5}$$

and

$$G_{12}^{(2)}(\alpha(t),\beta(t),\gamma(t),\delta(t)) = \langle \Psi_{AS}|\Psi_{AS}\rangle \tag{S6}$$

$$= 1 - |\alpha\gamma^* + \beta\delta^*|^2. \tag{S7}$$

Each atom has a slightly different $\Omega_{\vec{n}}$, as given in Eq. S2, and

$$\begin{aligned}
\alpha(t) &= i\frac{\Omega_1}{\Omega_{R1}}\sin\frac{\Omega_{R1}t}{2} \\
\beta(t) &= \cos\frac{\Omega_{R1}t}{2} + i\frac{\Delta}{\Omega_{R1}}\sin\frac{\Omega_{R1}t}{2} \\
\gamma(t) &= i\frac{\Omega_2}{\Omega_{R2}}\sin\frac{\Omega_{R2}t}{2} \\
\delta(t) &= \cos\frac{\Omega_{R2}t}{2} + i\frac{\Delta}{\Omega_{R2}}\sin\frac{\Omega_{R2}t}{2},
\end{aligned} \tag{S8}$$

where $\Omega_{R1,2} = \sqrt{{\Omega_{1,2}}^2 + \Delta^2}$ is the generalized Rabi frequency. The inhomogeneity is a consequence of the spread in Rabi frequencies Ω_{n_x,n_y,n_z}, due to the excitation of different motional states. We can characterize this by defining an average Rabi frequency $\overline{\Omega}$ and its RMS spread $\Delta\Omega$,

$$\overline{\Omega} = \sum_{n_x}\sum_{n_y}\sum_{n_z} q_x(n_x)q_y(n_y)q_z(n_z)\Omega_{n_x,n_y,n_z} \tag{S9}$$

$$\Delta\Omega^2 = \overline{\Omega^2} - \overline{\Omega}^2. \tag{S10}$$

Here $q_{x,y,z}(n_{x,y,z})$ is the normalized Boltzmann factor. The inhomogeneity in the Rabi frequencies ($\Delta\Omega$) is affected by T through the Boltzmann factor and by $\Delta\theta$ through the probe misalignment. To approximate the average density shift for the entire atomic ensemble, we set $\Omega_1 = \overline{\Omega} + \Delta\Omega$ and $\Omega_2 = \overline{\Omega} - \Delta\Omega$ in Eq. S8 for our two-atom model. At a time t during the spectroscopy pulse, the atoms experience an ensemble-averaged shift:

$$\Delta\nu(t) = \frac{2\hbar a_{ge}}{m} G_{12}^{(2)}(\overline{\Omega} + \Delta\Omega, \overline{\Omega} - \Delta\Omega)(\rho_g - \rho_e). \tag{S11}$$

This shift evolves during the spectroscopy pulse, and for the final density shift we time-average $G_{12}^{(2)}$ over the total pulse length t_F as

$$\Delta\nu_{ave} = \frac{1}{t_F}\int_0^{t_F} \Delta\nu(t)dt. \tag{S12}$$

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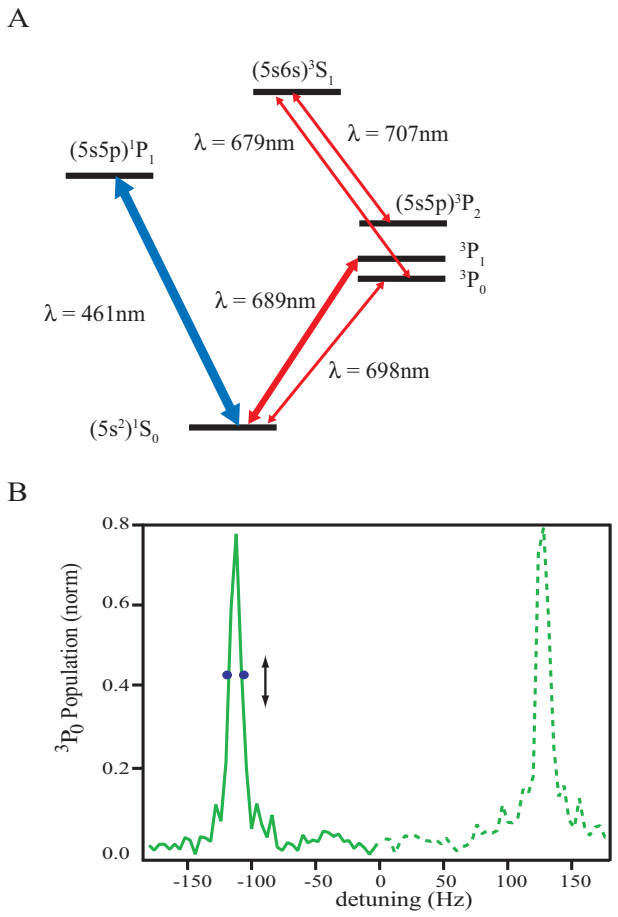

Figure S1: Experimental setup for the ^{87}Sr optical clock. (a) Relevant energy levels for laser cooling and trapping are shown. The first MOT stage is operated on the strong transition at 461 nm. During this MOT stage atoms that are lost to the $^3P_2$ and $^3P_0$ states are pumped back to the $^1S_0$ state using two repump beams at 679 nm and 707 nm. The second MOT is operated on the narrow 689 nm transition, and the wavelength of the clock laser used for spectroscopy is 698 nm. After the experiment is performed, atoms in the $^1S_0$ state are detected by measuring fluorescence on the strong $^1S_0 - ^1P_1$ transition. Atoms that have been excited to $^3P_0$ by the clock laser pulse are transferred back to the $^1S_0$ using the two repumping beams, and are again measured by fluorescence. (b) Two sample spectra. Here, ^{87}Sr atoms are successively polarized into either the m_F = 9/2 or -9/2 state. The separation between the two spectroscopy lines is $\sim$250 Hz. During the actual experiment, we polarize the atoms to each pure state successively, and lock near the full-width at half-maximum of the peak (indicated by dots). By moving these lock points the desired excitation fraction is selected.