Quantum Gases

An ideal Josephson junction in an ultracold two-dimensional Fermi gas

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The role of reduced dimensionality in high-temperature superconductors is still under debate. Recently, ultracold atoms have emerged as an ideal model system to study such strongly correlated two-dimensional (2D) systems. Here, we report on the realization of a Josephson junction in an ultracold 2D Fermi gas. We measure the frequency of Josephson oscillations as a function of the phase difference across the junction and find excellent agreement with the sinusoidal current phase relation of an ideal Josephson junction. Furthermore, we determine the critical current of our junction in the crossover from tightly bound molecules to weakly bound Cooper pairs. Our measurements clearly demonstrate phase coherence and provide strong evidence for superfluidity in a strongly interacting 2D Fermi gas.

Fig. 1. Josephson oscillations in a homogeneous 2D Fermi gas.

(A) Sketch of a Josephson junction consisting of two Fermi gases with chemical potential μ, particle numbers \( N_L \) and \( N_R \), and phases \( \phi_L \) and \( \phi_R \) separated by a tunneling barrier with height \( V_0 \). (B) Absorption images of cold atom Josephson junctions. The width of the barrier is held fixed at a waist of \( w = 0.81(6) \mu m \) while the size \( I_z \) of the system is increased. (C and D) Time evolution of the phase difference \( \Delta \phi \) (C) and relative particle number difference \( \Delta N/N \) (D) between the left and right side of the box after imprinting a relative phase difference of \( \Delta \phi = \pi/4 \). The red lines represent a damped sinusoidal fit. (E) Oscillation frequency as a function of barrier height \( V_0 \) for different system sizes [symbols as in (B)], where the error bars denote the 1σ fit error. The inductance \( L_B \) and capacitance \( C \) of the bulk system are proportional to the length \( I_z \) of the box, and therefore the oscillation frequency decreases with increasing system size for \( V_0 = 0 \). For nonzero values of \( V_0 \), the barrier adds a nonlinear Josephson inductance \( L_J \) to the system and the oscillation frequency decreases as a function of barrier height. (F) Josephson inductance \( L_{1/2}(V_0) \) extracted from the frequency measurements using an LC circuit model. The Josephson inductances for all system sizes collapse onto a single curve, which shows that the inductance of the junction depends only on the height of the barrier and validates our LC circuit model. We obtain the calibration of the barrier height \( V_0 \) by matching the data to a full numerical simulation (light red line with circles) (27). The data are obtained by averaging 20 (B), 42 (C), 130 (D), and 7 [(E) and (F)] individual measurements.

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a Gaussian beam waist of $w = 0.81(6)\ \mu m$ to split the system into two homogeneous 2D pair condensates connected by a weak link (Fig. 1, A and B). We imprint a relative phase $\phi_0$ between the two sides of the junction by illuminating one-half of the system with a spatially homogeneous optical potential for a variable time between 0 and 20 $\mu$s (27). We then let the system evolve for a time $t$ and extract the population imbalance $\Delta N = (N_L - N_R)$ and the phase difference $\phi$ between the two sides using either in situ or time-of-flight imaging. A typical Josephson oscillation of a molecular condensate at a magnetic field of $B = 731$ G (29) and a barrier height of $V_0/\mu = 1.08(5)$ featuring the characteristic $\pi/2$ phase shift between imbalance and phase is shown in Fig. 1, C and D. The oscillations are weakly damped with a relative damping of $\gamma/\omega = 0.07\%$, which, according to a full numerical simulation of our system, can be explained by phononic excitations in the bulk and the nucleation of vortex-antivortex pairs in the junction (fig. S3) (30).

To understand these Josephson oscillations, we use a simple circuit model commonly used to describe superconducting Josephson junctions (21, 31, 32). In this model, we describe our junction as a nonlinear Josephson inductance $L_J$, which is connected in series to a linear bulk inductance $L_B$ and a capacitance $C$ (Fig. 1F), where the bulk inductance $L_B$ characterizes the inertia of the gas and the capacitance $C$ its compressibility. For vanishing Josephson inductance, the model reduces to a linear resonator with frequency $\omega_0 = \sqrt{L_B/C} = 2\pi n_c/2L_J$, which corresponds to the frequency of a sound mode propagating with the speed of sound $c_0$ across the length $L$ of the system. Introducing a barrier with height $V_0$ adds a nonlinear inductance $L_J$ to the system and reduces the oscillation frequency $\omega_0$. Owing to the nonlinearity of the current phase relation, this $L_J$ depends on the phase difference $\phi(t)$ across the junction, but for small phase excitations, there is a linear regime where $L_J[\phi(t)]$ can be approximated by a time-independent Josephson inductance $L_{J,0}$ and the oscillation frequency is given by $\omega = \omega_0/\sqrt{L_B + L_{J,0}}/C$.

To confirm that our physical system is described by this model, we prepare a gas of deeply bound dimers, perform measurements of the oscillation frequency in the linear regime as a function of the barrier height for different system sizes (Fig. 1E), and extract the Josephson inductance $L_{J,0}$ (Fig. 1F). Because our system has a uniform density, the bulk inductance is given by the simple expression $L_B = 8m_L/\pi^2n_c^2$, where $n$ is the density per spin state, $m$ is the mass of a $^6$Li atom, and $L (L_J)$ is the diameter of the box perpendicular (parallel) to the barrier (27). Consequently, the Josephson inductance $L_{J,0}(\omega) = L_B(\omega^2/\omega^2 - 1)$ can be extracted from the frequency difference between the Josephson oscillations and the sound mode. Whereas the oscillation frequency is strongly dependent on the size of the box owing to the change in the bulk inductance $L_B$ and the capacitance $C$, the measured Josephson inductance $L_{J,0}$ should depend only on the coupling between the two reservoirs. As can be seen from Fig. 1 F, all measurements of $L_{J,0}$ versus barrier height collapse onto a single curve regardless of the system size, which confirms that our Josephson junction can be described by an inductor-capacitor (LC) circuit model. For the barrier heights used in our experiments, we also find very good agreement with a full numerical simulation of our system (27).

Next, we probe the fundamental property of Josephson junctions: the nonlinearity of the current phase relation (3, 26). For large phase excitations, the nonlinear current phase relation leads to anharmonic oscillations with an increased oscillation period. Our ability to imprint arbitrary phase differences $\phi_0$ across the barrier enables us to measure this reduction of the fundamental frequency $\omega(\phi_0)$ as a probe of the nonlinearity (Fig. 2). To extract the nonlinear response of the current from our measurements of $\omega(\phi_0)$, we first calculate $I_{J,0}[\omega(\phi_0)]$ and then apply the relation $dI/d\phi_0 = h/L_J$ to $I_{J,0}(\phi_0)$ to obtain an effective current $I_{J}(\phi_0)$. For an ideal Josephson junction, $I_{J}$ follows a rescaled current phase relation $I_J(\phi_0) = 2I_c \sin(\phi_0/2)$ (27). We find that our measurement is in excellent agreement with this current phase relation, indicating that our junction is an ideal Josephson junction (3, 26, 33). This implies that the current across the junction is indeed a supercurrent, driven by the phase difference between two superfluids.

Following this result, we can now use our Josephson junction as a probe for 2D superfluidity in the strongly correlated regime. We observe Josephson oscillations over a wide range of interaction strengths, indicating the presence of superfluidity in the entire crossover from tightly bound molecules to weakly bound Cooper pairs (Fig. 3). To quantify the effect of interactions on our system, we extract the critical current $I_c$ from the frequency of the Josephson oscillations. Because for a fixed barrier height $V_0$ the change in the critical current would be dominated by the interaction dependence of the chemical potential, we instead maintain a constant $V_0/\mu = 1.4(2)$ by adjusting the barrier height $V_0$ for each interaction strength according to a reference measurement of the equation of state (fig. S4). We observe that, within the uncertainty of our measurement, the critical current stays nearly constant, with a tendency toward smaller values of $I_c$ when approaching the Bardeen-Cooper-Schrieffer (BCS) side of the resonance. Although there is currently no theory available that quantitatively describes a 2D Josephson junction in the whole Bose-Einstein condensate (BEC)–BCS crossover, in the bosonic limit we can calculate the critical current from the condensate density $n_c$ and the overlap of the condensate wave functions (27, 34). We use this theory to determine the condensate fraction from the measured critical current for interaction strengths $\ln(k_BT_0)/\Delta = -0.9$ and obtain $n_c/n = 0.72(8)_{\text{stat}}(0.13)_{\text{exp}}$, where stat. denotes the statistical error and the
systematic error (systs.) arises from the 15% uncertainty in $V_0/\mu$. For our homogeneous 2D system, Berezinskii-Kosterlitz-Thouless theory relates the condensate fraction $n_c/n^{\infty}$ to the algebraic decay of phase coherence over the finite size $L$ of the box, where $n^{\infty} \approx T_n/L$ is the algebraic scaling exponent (35, 36). A measurement of the critical current as a function of system size can therefore be used to extract the algebraic scaling exponent and the superfluid density $n_c$, as recently suggested in (37).

Our homogeneous 2D Fermi gas provides an excellent starting point to study the influence of reduced dimensionality on strongly correlated superfluids in the crossover between two and three dimensions. The distinctive combination of reduced dimensionality, uniform density, low entropy, and high-resolution imaging makes our system a perfect platform to observe exotic phases such as the elusive Fulde-Ferrell-Larkin-Ovchinnikov state (38). Finally, our system is ideally suited to investigate whether periodic driving of Josephson junctions can strongly enhance coherent transport, as suggested by experiments with THz-driven cuprate superconductors (39, 40).

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SUPPLEMENTARY MATERIALS

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Figs. S1 to S4

References (44–49)

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