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Tunneling transport of atomic Fermi gases across the superfluid phase transition

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Summary. — In this article, I review on two recent experiments on tunneling transport of atomic Fermi superfluids. By injecting controlled currents in a two-reservoir system coupled through a thin barrier, Josephson critical currents are directly accessed and employed to extract the condensed fraction of strongly interacting fermionic superfluids. At finite temperature, Josephson supercurrents are observed to breakdown when approaching the critical temperature of the superfluid phase transition, thus demonstrating them as a reliable probe of condensation at any temperature. Furthermore, the study of resistive currents reveals the importance of Bogoliubov-Anderson sound modes in the conduction of a unitary gas, increased by the phonon-condensate coupling at low temperature. These works highlight how transport measurements can unveil both the coherence properties and the role of excitations in quantum matter.

The study of strongly interacting Fermi systems is a central problem in modern physics, spanning from nuclear to astrophysics interest, yet it is also one of the hardest [1]. In the last decades, quantum simulation has arisen as a complementary approach to understand such many-body systems. Following the seminal idea of Feynman [2], a quantum system well under experimental control could be engineered to mimic the behavior of another quantum system, surpassing the performances of classical computer simulations. Ultracold fermionic gases close to a Feshbach resonance offer the ideal quantum simulator to study strongly interacting materials [3, 4], realizing the celebrated crossover from Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS) superfluid [5]. Yet, the order parameter of strongly interacting Fermi gases, namely their wavefunction, has for long remained elusive and hard to access experimentally in a direct manner [5]. In this article, I review on two recent experiments on tunneling transport of ultracold Fermi gases of lithium-6 close to a Feshbach resonance [6, 7], that led to a direct measurement of the order parameter of strongly interacting Fermi gases based on the Josephson effect.

In a superconducting Josephson junction (SJJ), *i.e.*, two superconductors weakly coupled by a thin insulating barrier, a dissipationless current of fermionic pairs may arise

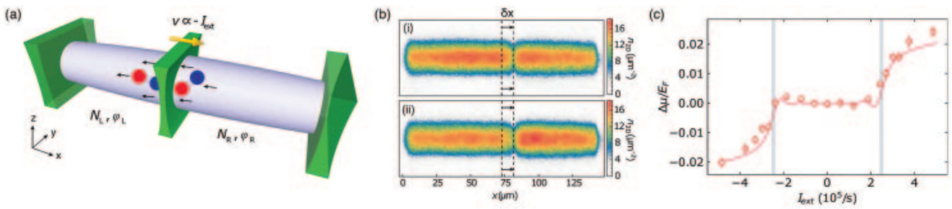

Fig. 1. – Experimental realization of an atomic current-biased Josephson junction. (a) The two-reservoir junction geometry is realized by dividing an atomic fermionic superfluid with an optical repulsive barrier, which is successively set into motion with constant velocity v. (b) *In situ* absorption image of the atomic junction acquired at the end of the barrier displacement for $I_{ext} < I_c$ (i) and $I_{ext} > I_c$ (ii). (b) Current-voltage characteristic of a molecular BEC, fitted with an RCSJ circuit model (solid line) to extract I_c (gray shaded region) and G.

merely driven by the phase difference ϕ between the two reservoirs [8]. Such a current shows a sinusoidal dependence on ϕ and flows without developing any drop of potential V up to a critical value I_c, according to the following Josephson-Anderson equations: $I = I_c \sin(\phi)$, $\dot{\phi} = \frac{2e}{\hbar} V$, where e is the electron charge and $\hbar$ the Plank constant [9]. The Ambegaokar-Baratoff relation directly links I_c with the superconductors' order parameter, namely their gap Δ [9], which is routinely measured by employing SJJs.

In an atomic Josephson junction (AJJ), with a repulsive optical barrier bisecting the sample to create the two-reservoir geometry, the Josephson-Anderson equations hold, with the chemical potential μ playing the role of the electric potential. Because of the difficulties in injecting a particle current in neutral and isolated AJJs, the Josephson effect has been so far observed by employing a voltage-biased junction protocol [10, 11]: an initial chemical potential difference $\Delta\mu$ is created to trigger ac Josephson oscillations across the junction, characterized by a plasma frequency that depends on I_c [12]. To directly measure the critical current of an AJJ, a current-biased junction should be implemented [13, 14]: as sketched in fig. 1(a) for fermionic superfluids, the repulsive barrier can be translated with constant velocity v to induce a pair current in the opposite direction, $I_{ext} \propto -v$. By acquiring *in situ* absorption images of the AJJ at the end of the barrier translation (fig. 1(b)), the final $\Delta\mu$ can be obtained from a measurement of the relative densities [6]. The injected current either flows without dissipation, *i.e.*, $\Delta\mu$ is kept constant to zero for $I_{ext} \leq I_c$ (i), or manifest a finite conductance G that introduces a $\Delta\mu \neq 0$ during the motion (ii). By tuning v, in ref. [6] the complete current-voltage characteristic of fermionic AJJs could be measured, as reported in fig. 1(c) for a molecular BEC. The $I - \Delta\mu$ curve clearly shows the two regimes of dc Josephson effect ($|I_{ext}| \leq I_c$) and resistive behavior of junction ($|I_{ext}| > I_c$) , and is fitted via an RCSJ circuit model to extract I_c and G [6]. Furthermore, from the interference fringes arising after a time-of-flight expansion of the AJJ, the relative phase ϕ could be measured for $|I_{ext}| < I_c$, observing the sinusoidal current-phase relation that characterizes the dc Josephson effect [6]. The $I - \Delta\mu$ curve gave access to the first direct measurement of the critical current of fermionic superfluids in the BEC-BCS crossover (fig. 2(a)) [6]. The critical current shows a non-monotonic behavior, consistently with theoretical simulations [15,16] and previous experimental results [11]. Experimental data are found to be well in agreement with the calculated value of I_c according to the semi-analytic model of ref. [17] (shaded regions in fig. 2(a)), that writes the critical current density as directly proportional to the density of condensed pairs n_0. Given such proportionality, the theory model of ref. [17] also allowed extracting from I_c the value of the

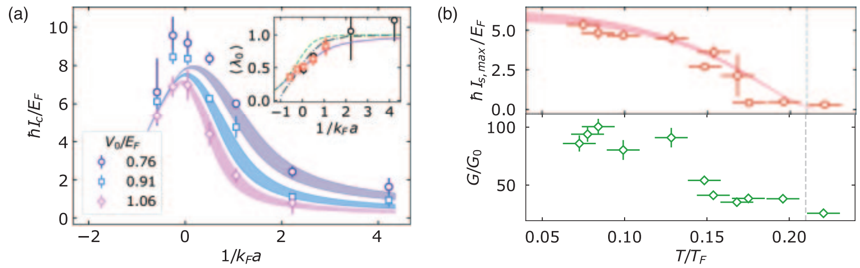

Fig. 2. – Tunneling transport of fermionic superfluids across the phase transition. (a) Measurement of I_c in the zero-T limit BEC-BCS crossover for different barrier heights V_0. The interaction strength is parametrized as $1/k_F a$, where a is the s-wave scattering length and $k_F = \sqrt{2E_F/m}$ the Fermi wavevector, with $E_F = 2\pi\hbar \times 6$ kHz. The shaded regions indicate the calculated value of I_c with the theory model of ref. [17]. Inset: extracted value of the density weighted condensed fraction of fermionic superfluids, obtained averaging over all barrier heights (black circles) or considering only the $V_0/E_F \simeq 1.06$ dataset (red squares). Theoretical predictions of $\langle\lambda_0\rangle$ are reported as a solid purple line for homogeneous Luttinger-Ward calculations of ref. [18], dot-dashed gray and dashed green lines for Monte Carlo simulations and mean field theory of ref. [19], respectively. (b) Measured (red circles) and calculated (shaded region) maximum Josephson supercurrent $I_{s,max}$ and resistive current conductance G of a unitary AJJ as a function of T/T_F, where $T_F = E_F/k_B$ is the Fermi temperature with k_B the Boltzmann constant. The conductance is normalized by $G_0 = 102(15)\,h^{-1}$ measured for a non-interacting Fermi gas at $T/T_F = 0.21(1)$. The vertical dashed line represents the critical temperature of a harmonically trapped unitary gas, $T_c = 0.21\,T_F$ [20].

density weighted condensed fraction, $\langle\lambda_0\rangle$ (inset of fig. 2(a)), providing the first direct measurement of the order parameter of strongly interacting Fermi superfluids.

Current-biased AJJs are able to benchmark strongly interacting Fermi gases even at finite temperature T, as demonstrated in ref. [7] for a junction at unitarity. Figure 2(b) reports the measured maximum Josephson supercurrent $I_{s,max}$, which plays the role of I_c at finite temperature, and the conductance G, rescaled by G_0 of a non-interacting Fermi gas, as a function of temperature. The finite-T extension of the theory model in ref. [17] (red shaded region) is observed to well approximate the experimental data, demonstrating the reliability of Josephson supercurrents as a probe for condensation at any temperature. On the other hand, the measured trend of G, dropping at about the same T of $I_{s,max}$, reveals the condensed nature of the gas to influence also the resistive currents. The high conductance measured at low temperature is in fact fed by condensate elements transforming into gapless Bogoliubov-Anderson phonons in the tunneling process [7]. Similarly to what expected for weakly interacting BECs [21, 22] and neutral BCS superfluids [23], such coupling gives rise to an anomalous contribution on G proportional to n_0 that dominates the resistive transport at low temperature.

In conclusion, current-biased AJJs exposes the complete $I - \Delta\mu$ curve, that measures both the critical current and the conductance of the atomic sample. One the one hand, the study of I_c in the zero-T BEC-BCS crossover and as a function of temperature demonstrated Josephson supercurrents to be a powerful probe of condensation at any temperature, yielding to the direct measurement of the order parameter of fermionic superfluids. On the other hand, resistive currents provided information on the main excitations on top of the ground state, demonstrating the twofold importance of transport measurements to investigate both coherence properties and excitations of quantum materials.

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