

Hybridization of the amplitude mode in a confined fermionic superfluid

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In phase transitions, spontaneous symmetry breaking results in a nonzero order parameter and two collective excitations: the Goldstone and the amplitude mode. These modes, which define key properties of superconductors and fermionic superfluids, are well understood in homogeneous systems. However, their behavior under strong confinement remains largely unexplored, particularly when their excitation energy becomes comparable to the imposed discrete level spacing. In this scenario, hybridization between different collective modes is expected to take place. Here, we show how the amplitude mode hybridizes with a spatial mode in a confined fermionic superfluid. Using lattice modulation spectroscopy, we observe the evolution of the mode throughout the entire crossover from the Bardeen-Cooper-Schrieffer (BCS) state to Bose-Einstein condensation (BEC) of molecules. In the BCS regime, the excitation energy is located at twice the pairing gap, then gradually becomes an in-gap excitation in the strongly correlated regime. Further to the BEC limit, the excitation energy approaches twice the level spacing. The spectral weight of this mode vanishes when approaching the superfluid critical temperature. Our experimental results are in excellent agreement with an effective field theory, providing strong evidence that amplitude oscillations hybridize with and eventually transform into breathing oscillations of the order parameter. The strong modification of the excitation spectrum reveals how confinement and finite-size effects impact fundamental modes of symmetry-broken states.

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Bardeen-Cooper-Schrieffer (BCS) theory [1] provides the framework for understanding superconductivity. It describes the formation of Cooper pairs and the emergence of a superconducting energy gap, 2Δ , corresponding to the minimum energy required to break them. However, as Anderson noted, significant deviations from this framework can occur in finite-size systems when the characteristic length or energy scale imposed by the confinement approaches the Cooper pair size or the pairing gap energy, respectively [2]. These finite-size effects have been predicted and observed in systems such as nanowires and thin films [3–5], where confinement can modify the dimensionality, enhance the superfluid gap, or increase the critical temperature (T_c), see review [6]. Such phenomena highlight how confinement can be used to engineer superconducting properties.

A key open question we address in this work is how confinement influences the fundamental collective modes of fermionic superfluids and superconductors. These systems are characterized by an order parameter, $\Psi = |\Psi|e^{-i\theta}$, supporting

fluctuations in θ and $|\Psi|$, which correspond to the Goldstone mode (gapless phononic excitation) and the amplitude mode (gapped Higgs-like excitation at energy 2Δ), respectively [7,8]. While these collective modes are well understood in homogeneous systems, their behavior in the presence of confinement remains largely unexplored. For instance, the excitation spectrum is expected to change qualitatively [9–12], featuring a hybridization of oscillations of the amplitude and the spatial distribution of the order parameter.

In previous work, evidence for amplitude oscillations of the order parameter has been reported in superconductors [13–16], as well as in ultracold bosonic and fermionic superfluids [17–22]. Additionally, a mesoscopic system has been used to explore precursors of the amplitude mode and its interplay with discrete energy shells [23]. In contrast to these experiments, we study the effect of confinement on the amplitude mode in a macroscopic fermionic superfluid and observe strong evidence of its hybridization with a collective mode of the trap. This is achieved by exploiting the BEC-BCS crossover to tune the pairing gap energy, bringing it close to the trap level spacing. The resulting hybridization is depicted in Fig. 1(a). In the BCS regime, the pairing gap energy is smaller than the trap level spacing. Here, the system exhibits a well-defined resonance with frequency ω_R located at 2Δ [left panel of Fig. 1(a)], where the superfluid density $n_s = \int |\Psi|^2 dz$ oscillates in amplitude (red curves). Its frequency coincides with the onset of pair breaking, however, it is a coherent excitation. Toward the strongly interacting regime, the

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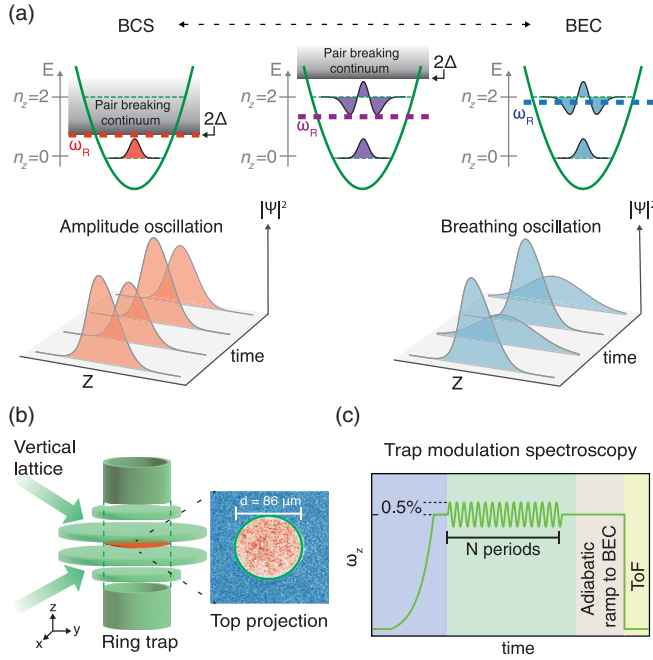


FIG. 1. (a) Hybridization of amplitude oscillations with spatial excitations. In our confined fermionic superfluid, a well-defined excitation of the order parameter with frequency ω_R is observed throughout the entire BEC-BCS crossover (dashed lines). In the BCS regime, this excitation corresponds to a pure amplitude oscillation of the order parameter located at the onset of the pair-breaking continuum 2Δ . This oscillation conserves the quantum number $n_z = 0$, but the superfluid density $n_s = \int |\Psi|^2 dz$ oscillates in amplitude, illustrated with red curves. In the BEC regime, the excitation at ω_R corresponds to a breathing mode with energy approaching $2\hbar\omega_z$, involving the quantum numbers $n_z = 0$ and $n_z = 2$. This oscillation is sketched with blue curves. In the strongly interacting regime, when Δ becomes comparable to $\hbar\omega_z$, the resulting excitation is a hybridized mode with both breathing and amplitude character. Here, the mode frequency drops below the pair-breaking continuum. (b) We prepare a homogeneous Fermi gas in a ring-shaped box potential, strongly confined along z with a repulsive lattice potential. The harmonic confinement is comparable to the Fermi energy E_F with $1.5 < E_F/\hbar\omega_z < 2$. (c) The trapping frequency ω_z is weakly modulated to excite spatial oscillations of the order parameter and amplitude oscillations via the corresponding modulation of the interaction strength. The deposited heat is measured by performing ToF after an adiabatic ramp to the BEC regime.

pairing gap increases, and the amplitude mode hybridizes with the nearest spatial mode of the trap with equal parity, specifically the quantum number $n_z = 2$ (central panel). In this intermediate regime, the resonance energy ω_R drops below 2Δ , and the order parameter acquires a spatially oscillating component, admixing state $n_z = 2$ to the ground state $n_z = 0$. Finally, deep in the BEC regime, the resonance approaches twice the trap level spacing (right panel), resembling a pure breathing mode (blue curves). Our interpretation is based on an effective field theory, which continuously connects the Gross-Pitaevski and Klein-Gordon functionals [7,24], showing remarkable agreement with our experimental results.

To engineer the mode hybridization, we prepare a homogeneous fermionic superfluid ($T^* < 0.02 T_F$) of ^6Li atoms in the

lowest two hyperfine states [25,26]. The system is subjected to strong vertical confinement $\hbar\omega_z = h \cdot 8.7 \text{ kHz}$ [Fig. 1(b)], comparable to the Fermi energy $E_F = \hbar^2 4\pi n_{2D}/2m$ [25]. Here, T_F is the Fermi temperature, T^* is the temperature measured after an adiabatic sweep into the BEC regime [25], m is the atom mass, $\hbar$ is the reduced Planck's constant, and n_{2D} is the fermionic density per spin state. To reach the regime where the pairing energy is comparable to the vertical confinement energy, we tune the interaction parameter $\eta = \ln(k_F a_{2D})$ using a Feshbach resonance, where $k_F = \sqrt{4\pi n_{2D}}$ is the Fermi momentum and a_{2D} is the 2D scattering length [27–29]. To probe both spatial and amplitude oscillations of the order parameter, we vary the interaction strength [21,22] by employing trap modulation spectroscopy [17,18]. This modulates the harmonic oscillator length l_z and hence the scattering length a_{2D} [25].

Specifically, we modulate the trapping frequency with an amplitude $\alpha \leq 0.5\%$ at a frequency ω_m for a fixed number of periods, $N = 240$, followed by a rethermalization time of 20 ms. To obtain the deposited energy, we adiabatically ramp into the BEC regime ($\eta = -1.7$) and measure the bimodal momentum distribution after time of flight (ToF). Here, we extract the condensate amplitude $A(\omega_m)$. This is compared to the condensate amplitude of the unperturbed system $A(0)$, defining our response function $R(\omega_m) = A(0)/A(\omega_m) - 1$ [25]. This normalized function deviates from zero when energy is deposited in the system, revealing resonant frequencies.

In the first series of experiments, we start with a fermionic density of $n_{2D} \approx 1.5 \text{ atoms}/\mu\text{m}^2$, resulting in a ratio of $E_F/\hbar\omega_z = 1.8$. A typical response from trap modulation is shown in the inset of Fig. 2(a). This measurement is extended throughout the entire BEC-BCS crossover in Fig. 2(a), where the color encodes the response $R(\omega_m)$. The vertical axis is normalized to the trapping frequency ω_z , which is independently determined using a fermionic gas with negligible interactions. The system exhibits two distinct excitations. Within the BCS regime, one appears as a broad resonance located at $\omega_m \approx 2\omega_z$, corresponding to single-particle excitations of unpaired atoms to the energy level $n_z = 2$. The other manifests as a narrower resonance at lower frequency, gradually increasing from the BCS ($\eta = 3$) to the BEC ($\eta = -2$) regime, eventually approaching $2\omega_z$.

In the weakly interacting BCS regime, the well-defined resonance is located at nearly twice the pairing gap Δ . It agrees with the mean-field prediction of $\Delta = \sqrt{2E_b E_F}$ (red dotted line), where the binding energy E_b is calculated in the 2D limit [25]. This agreement breaks down toward the strongly interacting regime for $\eta < 1.9$, where the observed mode deviates from the onset of the pair-breaking continuum, measured independently via Bragg spectroscopy [red points in Fig. 2(a)] [25,30–33], and instead becomes an in-gap excitation. Finally, in the BEC regime, the order parameter is directly related to the total density, and hence only supports spatial oscillations along the vertical confinement [7]. Here, the resonance corresponds to a breathing excitation of the condensate shifted downwards from $2\hbar\omega_z$ due to repulsive dimer-dimer interactions.

To understand the continuous evolution and character of the resonance, we develop a theoretical model in which the dynamics of the order parameter $\Psi(z, t)$ are described by the

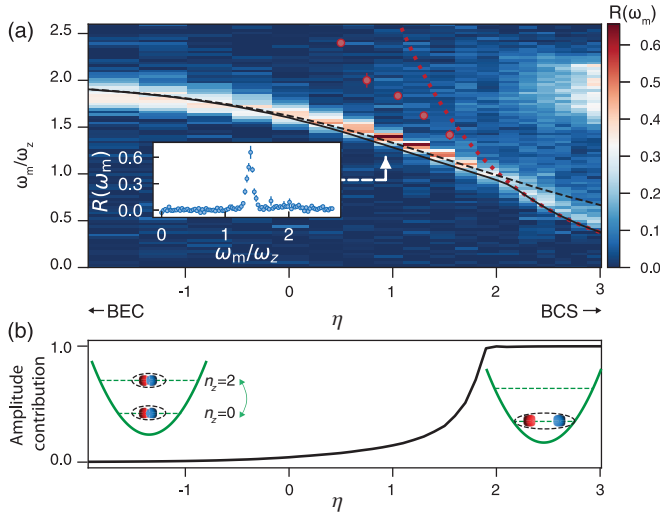


FIG. 2. (a) Spectral response $R(\omega_m)$ of a confined fermionic superfluid throughout the BEC-BCS crossover, measured via trap modulation spectroscopy. The inset shows a typical response $R(\omega_m)$ for $\eta = 0.97$, with a resonance located below the single-particle excitation energy $2\hbar\omega_z$. In the BCS limit ($\eta \gg 0$), the energy of the resonance agrees with the mean-field value 2Δ (red dotted line). At $\eta = 2$, it deviates from 2Δ , evolving into an in-gap excitation. This is supported by an experimental measurement of 2Δ using Bragg spectroscopy (red points). In the BEC regime ($\eta \ll 0$), where no amplitude mode exists, the excitation corresponds to a breathing mode along the confined direction. Here, its energy is in good agreement with an analytical calculation of the energy difference between the $n_z = 0$ and $n_z = 2$ eigenmodes (black dashed line) extracted from an effective field theory (see main text). The full numerical simulation shows excellent agreement in the entire crossover (black solid line). The error bars show the standard deviation of the mean. (b) Hybridization of the amplitude mode. For values $\eta > 1.9$, the amplitude character is dominant, quantified by the amplitude contribution extracted from the effective field theory (black line). Here, the excitation does not conserve the total superfluid density, while conserving the quantum number $n_z = 0$. In the BEC regime, the superfluid density is conserved and oscillates spatially involving the $n_z = 2$ eigenmode. In the crossover, the composition of the collective mode corresponds to both amplitude and spatial oscillations of the order parameter.

equation of motion

$$iK_1 \frac{\partial \Psi(z, t)}{\partial t} - K_2 \frac{\partial^2 \Psi(z, t)}{\partial t^2} = \left(-\frac{\hbar^2 \partial_z^2}{2M} + V(z, t) - r_0 + u_0 |\Psi(z, t)|^2 \right) \Psi(z, t), \quad (1)$$

derived from a zero-temperature effective field theory [25]. We consider a homogeneous system along the x - y plane and decompose $\Psi(z, t)$ into the $n_z = 0$ and $n_z = 2$ eigenstates of the harmonic potential $V(z, t)$ [25]. In this model, the coefficients K_1 , K_2 , r_0 , and u_0 parametrize the BEC-BCS crossover. These are determined from theoretical predictions for the energy gap, condensate density [34], and speed of sound [35] in the crossover [25]. In the limit where $K_1 = 0$, Eq. (1) reduces to a nonlinear Klein-Gordon equation, describing the order parameter dynamics in the weakly interacting BCS regime.

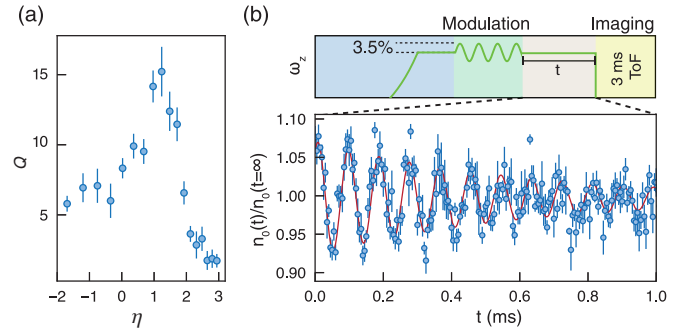


FIG. 3. (a) Quality factor along the BEC-BCS crossover. We quantify the spectral width via the quality factor Q , extracted from the spectral response in the BEC-BCS crossover. For all interaction strengths we find $Q > 1$, signaling a long-lived excitation throughout the BEC-BCS crossover. The maximum value $Q = 15 \pm 2$ occurs in the strongly correlated regime. (b) In this regime ($\eta = 1.2$), the collective mode is resonantly excited with a four-period modulation of the trapping frequency. This is followed by a free evolution for a time span t . We observe oscillations of the central density n_0 after a ToF expansion of 3 ms. The experimental data is fitted with a damped oscillation yielding a decay time $\tau = (610 \pm 60) \mu\text{s}$ which results in $Q = 21 \pm 2$.

The resulting equation is Lorentz invariant which is a manifestation of particle-hole symmetry. In the BEC limit, where $K_2 = 0$, Eq. (1) reduces to the Gross-Pitaevskii equation.

The black dashed line in Fig. 2(a) represents the eigenfrequency difference between the ground and second excited state as analytically obtained from Eq. (1), taking into account interactions to leading order [25]. Toward the BEC regime, this analytical result is in excellent agreement with the experimental observation. The full numerical simulation in the presence of trap modulation (black solid line) extends the agreement throughout the entire BEC-BCS crossover without any fitting parameters. Beyond capturing the mode frequencies, this numerical approach also reveals the composition of the collective excitation due to hybridization, distinguishing between its amplitude and breathing mode components. The theoretical amplitude mode contribution is shown in Fig. 2(b), and represents the fraction of the response where the total superfluid density oscillates in time [25]. In the BCS regime ($\eta \gtrsim 1.9$), this contribution approaches its maximum value, resembling a pure amplitude mode [see red curves in Fig. 1(a)]. Toward the strongly correlated regime ($\eta \sim 1$), the amplitude mode contribution gradually decreases, and the mode gains breathing character. Finally, in the BEC limit, the dominant excitation is a pure breathing mode, where the superfluid density is constant in time, and oscillates spatially between $n_z = 0$ and $n_z = 2$ [see blue curves in Fig. 1(a)].

One feature not captured by our theoretical model is the behavior of the spectral width throughout the crossover, particularly its narrowing in the hybridization regime, which suggests a long-lived and well-defined mode. We quantify the coherence of the mode by computing the quality factor $Q = \omega_0/\delta\omega$, where ω_0 is the resonance frequency and $\delta\omega$ the full width at half maximum extracted from the spectrum. In the entire crossover, the mode remains underdamped with $Q > 0.5$ [Fig. 3(a)]. Notably, the largest quality factors are found at

$\eta < 1.9$, reaching a maximum value in the strongly interacting regime ($\eta \sim 1$). Here, the mode energy is below the onset of the pair-breaking continuum, suggesting that single-particle decay is suppressed, leading to longer lifetimes [10,36,37]. This contrasts with a conventional case, where the amplitude mode resides at the onset of the pair-breaking continuum, resulting in strong damping and limited visibility [38–41]. To further confirm the long-lived nature of the mode, we track the free coherent oscillations of the system at $\eta = 1.2$ after a short resonant excitation [Fig. 3(b)]. We observe a long-lived oscillation at the collective mode frequency ω_0 when measuring the change in the central density of the cloud after 3 ms of ToF [25]. Fitting the data with an exponentially damped oscillation with a decay time τ [25], we obtain a quality factor $Q = \tau\omega_0/2 \approx 21 \pm 2$, comparable with our results from trap modulation spectroscopy.

Since the observed dynamics are compatible with oscillations of the order parameter, we expect a strong temperature dependence, especially close to the superfluid critical temperature T_c . To explore this further, we prepare a strongly interacting system ($\eta = 1.2$) at different temperatures and perform trap modulation spectroscopy [25]. Figure 4(a) shows the spectral response as a function of temperature T^*/T_F . With increasing temperature, the resonance at $2\hbar\omega_z$ associated with single-particle excitations from thermally broken pairs becomes the dominant contribution to the spectrum [see Fig. 4(b)]. Meanwhile, the collective mode with lower frequency broadens, and its spectral weight decreases. The frequency remains constant, resembling the behavior previously observed in Refs. [21,22,42]. In Fig. 4(c), the peak amplitude of the mode as a function of temperature is plotted. The observed trend is well described by a bilinear fit, featuring a kink at a temperature of $T_c^* = 0.088(4) T_F$. Remarkably, our previous experiments on the critical velocity in 2D Fermi gases show a critical temperature of $T_c^* = 0.09(2) T_F$ [32]. This supports the interpretation that the collective mode is an excitation of the order parameter which vanishes above a critical temperature.

In conclusion, our study focuses on a fundamental feature of strongly confined fermionic superfluids: the hybridization of collective modes. We observe a well-defined resonance in the entire BEC-BCS crossover, which we interpret as an excitation of the order parameter. This interpretation is supported by the strong suppression of the resonance above the critical temperature and the excellent agreement with the effective field theory.

Additionally, we show that trap modulation spectroscopy is a powerful tool for determining the pairing gap in the BCS regime and the superfluid-to-normal transition in the crossover. This is of interest for studying spin-imbalanced superfluids and other strongly correlated 2D systems.

Beyond ultracold atoms, these results provide insights into the hybridization of modes in confined fermionic superfluids and superconductors, such as low-dimensional materials and nanosuperconducting devices. Here, the hybridization could influence fundamental properties such as the critical velocity or critical temperature. Our work paves the way to investigate more complex dynamics of the order parameter under confinement [43,44], such as frequency beating [45], drum modes

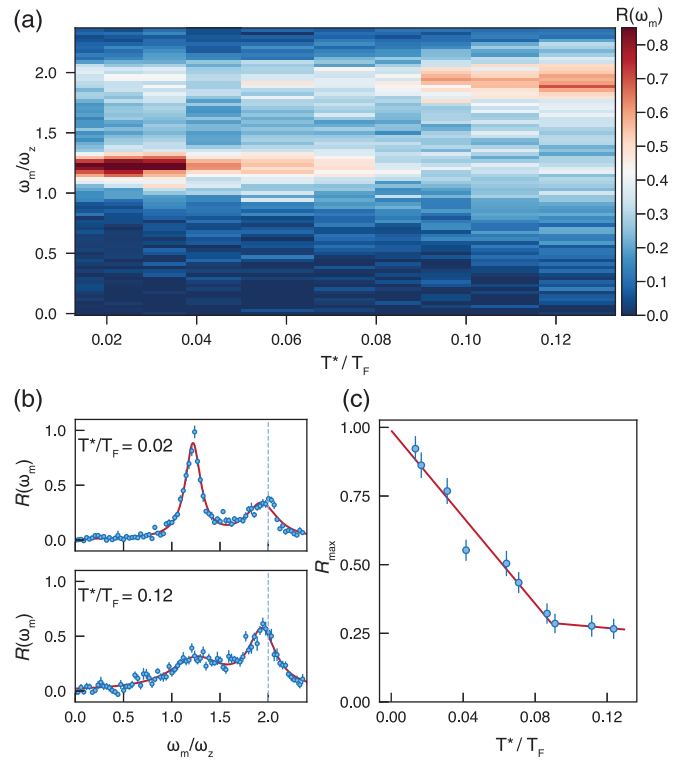


FIG. 4. (a) Vanishing of the collective mode above the critical temperature. We measure the spectral response $R(\omega_m)$ in the strongly correlated regime ($\eta = 1.2$) as a function of temperature. The collective mode frequency remains nearly constant at $\omega_m/\omega_z \sim 1.2$. As the temperature increases, the mode broadens and its visibility diminishes, signaling the loss of coherence. Above a critical temperature, single-particle transitions at $2\hbar\omega_z$ become the dominant process due to thermally broken pairs. (b) To extract the critical temperature, we fit the maximum response of the collective mode $R_{\max}$ by a double Lorentzian function (red line) shown for two vertical cuts of panel (a). (c) The temperature dependence of the maximum response shows a kink, which we identify as the critical temperature T_c^* . Employing a bilinear fit (red line), we obtain $T_c^* = 0.088(4) T_F$.

[18], exotic Higgs bound states [46,47], or Leggett modes [48–50]. Finally, it is an exciting prospect to use confinement to control the properties of many-body systems by admixing higher harmonic oscillator states [51,52].

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the interpretation of the results and to the preparation of the manuscript.

The authors declare no competing interests.

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